EUMETSAT Satellite Application Facility on
Support to Operational Hydrology and Water Management
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Product Validation Report (PVR)
H141

Soil Wetness Index in the roots region
Data Record

Revision History

Revision	Date	Author(s)	Description
0.1	2019/05/07	David Fairbairn and Patricia de Rosnay	First draft.
0.2	2019/11/06	David Fairbairn and Patricia de Rosnay	(i) Revised Table 3.1 to provide the correct producers and references of the H141 input scatterometer SSM products; (ii) The product name is now included in the title of the document.

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List of Acronyms

ASAR Advanced Synthetic Aperture Radar (on Envisat)

ASAR GM ASAR Global Monitoring

ASCAT Advanced Scatterometer

ATBD Algorithm Theoretical Baseline Document

BUFR Binary Universal Form for the Representation of meteorological data

DORIS Doppler Orbitography and Radiopositioning Integrated by Satellite (on Envisat)

ECMWF European Centre for Medium-range Weather Forecasts

Envisat Environmental Satellite

ERS European Remote-sensing Satellite (1 and 2)

ESA European Space Agency

EUM Short for EUMETSAT

EUMETCast EUMETSAT's Broadcast System for Environment Data

EUMETSAT European Organisation for the Exploitation of Meteorological Satellites

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 Near Weather Prediction

PRD Product Requirements Document

PUM Product User Manual

PVR Product Validation Report

SAF Satellite Application Facility

SAR Synthetic Aperture Radar

SEKF Simplified Extended Kalman Filter

SRTM Shuttle Radar Topography Mission

SSM Surface soil moisture

SWI Soil Wetness Index

TU Wien Technische Universität Wien (Vienna University of Technology)

WARP Soil Water Retrieval Package

WARP H WARP Hydrology

WARP NRT WARP Near Real-Time

ZAMG Zentralanstalt für Meteorologie und Geodynamic (National Meteorological Service of Austria)

1. Executive summary

This document describes the validation of the H SAF scatterometer root zone soil moisture product data record generation for 1992-2018 (H141). An introduction (section 2) is followed by general overview of the H SAF root zone data record product (section 3). The product validation is presented in section 4. Finally, the conclusion is given in section 4.6.

Further information on the implementation of the processing chain and individual processing steps are available in the H141 Algorithm Theoretical Basis Documents [1], and information on the product format can be found in the H141 Product User Manual [2]. Information about the H SAF consortium can be found in the Appendix.

2. Introduction

2.1. Purpose of the document

The Product Validation Report is intended to provide a description of the main product characteristics and validation results.

2.2. Targeted audience

This document mainly targets:

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

3. Introduction to the root-zone soil wetness data record (H141)

3.1. Principal of the product

H141 is a root zone soil moisture product derived from ERS/SCAT and Metop/ASCAT-A/B surface soil moisture (SSM) observations. The retrieval approach relies on an offline, sequential Land Data Assimilation System (LDAS). The LDAS is based on a Simplified Extended Kalman Filter (SEKF) following the approach of [3]. The SEKF constitutes the central component of the H141 production chain. The H-TESSEL Land Surface Model [4–6] 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. Table 3.1 below gives the details on the scatterometer SSM product used as input to the H141 production suite. In the ECMWF H141 algorithm the input scatterometer SSM products are assimilated in the H141 LDAS which propagates the scatterometer SSM information in space on the soil vertical profile and in time at a daily time scale. The main components of the data assimilation system are the SEKF, a land surface model and input data preprocessing. H141 shares the same algorithm as its predecessor H27/H141 and a detailed description of the data assimilation algorithm can be found in the H141 Algorithm Theoretical Baseline Document [1].

The H141 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 system is driven by state-of-the-art ERA-5 global atmospheric fields [7]. Figure 3.1 illustrates the H141 LDAS production suite.

Table 3.1: H141 input scatterometer SSM products.

	Scaterrometer SSM product used in H141 data record		
Period	Sensor	Producer	Reference
04-2014 to 12-2018	ASCAT-A (2014 to 2018) and ASCAT-B (2015 to 2018) 25 km sampling	EUMETSAT CAF	ASCSMO02: ASCAT-A/B 25 km swath grid product distributed by CAF. (https://vnavigator.eumetsat.int/product/EO:EUM:DAT:METOP:SOMO25). Equivalent to H SAF level 2 surface soil moisture products H102 (Metop-A 25 km sampling) and H103 (Metop-B 25 km sampling).
01-2007 to 03-2014	ASCAT-A 25 km sampling	TU Wien	H107: H SAF soil moisture data record reprocessed level 2 surface soil moisture.
01-1992 to 12-2006	ERS 1/2 AMI 50 km sampling	TU Wien	ERS-1/2 AMI WARP 5.5 R1.1: ERS-1/2 AMI 50km Soil moisture time series product. Produced as part of the Scirroco project (https://earth.esa.int/documents/) 700255/2925769/SCI-PRE-2015-0001-v-01-SM_reprocessing_TUW.pdf) using the Water Retrieval Package (WARP) version 5.5.

3.2. Main characteristics

H141 is produced daily (at 00 UTC) in two separate formats in order to meet the requirements of different users: 1) An octahedral reduced Gaussian grid ($T_{CO}1279$) in GRIB format, which has approximately equidistant grid points between the equator and the poles, and 2) a regular lat/lon grid in netCDF format. 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. H141 relies on a data assimilation approach that propagates the information in time and space (along the vertical dimension in the root zone). So, it enables the propagation of the swath SSM scatterometer products to daily root zone soil moisture with a global coverage. The H141 root-zone soil moisture product is expressed as a liquid soil wetness index (SWI), ranging from 0 for residual soil moisture values to 1 for saturated soil moisture. The conversion of volumetric root-zone soil moisture to the SWI is a post-processing step i.e. it occurs after the soil moisture analysis is performed. It is computed using the soil texture and the fraction of liquid water content (the fraction of water

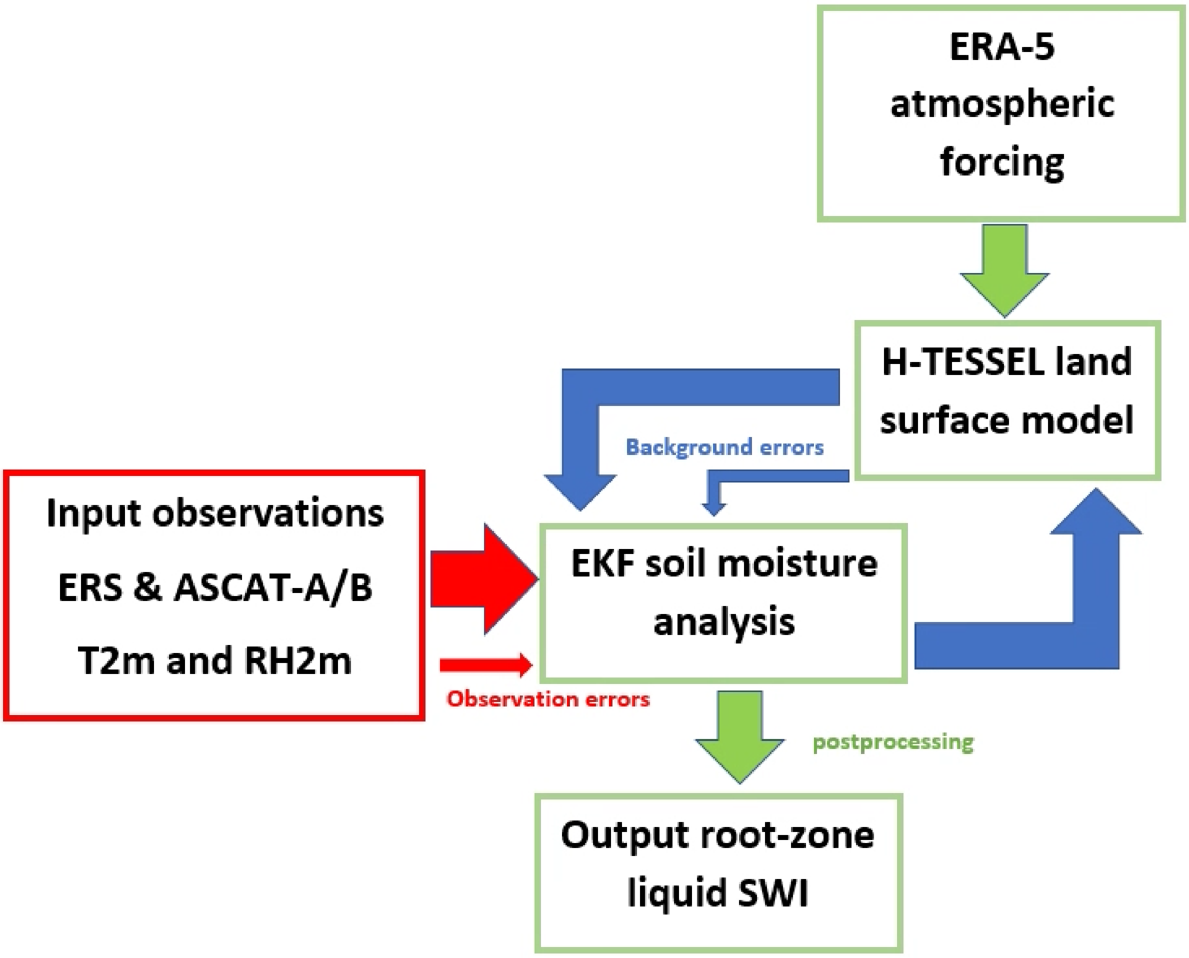


Figure 3.1: Illustration of the H141 root zone soil moisture production chain based on ERS-1/2 and ASCAT-A/B satellite derived surface soil moisture data assimilation.

that is not frozen) provided by the model. Having the H141 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 are all given the in terms of liquid SWI. It is relevant to various applications and can be combined with different hydrological models (e.g. [8]).

4. Product validation

4.1. Validation strategy

The H141 root zone soil wetness product is evaluated using in situ measurements of soil moisture. It is validated for both the top vertical layer (the SSM layer at 0-7 cm) and for the depth-integrated root-zone SM layer (0-100 cm). The main challenge in validating the data record is related to the length of the time series that spans three decades. The validation proposed here relies on in situ soil moisture networks that sample a range of biomass and climate conditions. Additionally, the previous data record product (H27/H140) is used as a benchmark, thereby providing an assessment of various improvements in H141 relative to H27/H140, including ERA-5 forcing instead of ERA-interim, improved resolution (10 km instead of 16 km) and the assimilation of ASCAT-B and ASCAT-A observations (instead of just ASCAT-A). The ATBD describes these modifications in more detail [1]. This sub-section gives a historic overview of the validation used in the previous (CDOP/CDOP-2) and current validation phases (CDOP-3).

Several authors have demonstrated that local measurements could be used to validate model output as well as remotely-sensed soil moisture (SM) at a different scale (e.g. [9–13]). However, spatial variability of SM is very high and can vary from centimetres to metres. Precipitation, evapotranspiration, soil texture, topography, vegetation and land use could either enhance or reduce the spatial variability of soil moisture depending on how it is distributed and combined with other factors [14–17]. Differences in soil properties could imply important variations in the mean and variance of soil moisture, even over such small distances. Each soil moisture data set is characterized by its specific mean value, variability and dynamical range. Therefore, [18] and [19, 20] suggested that the true information content of modelled soil moisture does not necessarily rely on their absolute magnitudes but instead on their time variation. The latter represents the time-integrated impacts of antecedent meteorological forcing on the hydrological state of the soil system within the model.

During the First and Second Continuous Development and Operations Phases (CDOP and CDOP-2), performance requirements for H SAF soil moisture products were given in volumetric units (m^3m^{-3}) and the main score to be evaluated was the Root Mean Square Difference (RMSD). The Mean Error (or bias, ME), the Standard Deviation (SD) and the Correlation Coefficient (CC) were supportive scroes. Table 4.1 presents the User requirements as they were for the Development Phase and CDOP (i.e. with respect to the RMSD).

Since the third Continuous Development and Operations Phase it was decided that the Correlation Coefficient (CC) would be the main validation metric. The requirements are listed in Table 4.2. An extensive justification for this change in performance requirements can be found in [21]. Supportive scores are the Root Mean Square Difference (RMSD) and the Mean Error (or bias, ME). The Correlation Coefficient should be applied to normalized time-series (H141 is an index) and monthly anomalies time series. In this report, both the surface and the root-zone SWI anomaly correlation coefficients for H141 are shown (as in [17, 22]). Cases with significant levels of correlations (p-value < 0.05) are considered only as discussed in section 4.3.

Table 4.1: Former accuracy requirements for product SM-DAS-2 [RMSD] used during the Development phase and CDOP.

Unit	Threshold	Target	Optimal
m^3m^{-3}	0.1	0.06	0.04

Table 4.2: Performance requirements for products H14 and H141 [CC]

Unit	Threshold	Target	Optimal
Dimensionless	0.5	0.65	0.8

4.2. In situ data

This study makes use of in situ soil moisture measurements obtained through the International Soil Moisture Network (ISMN [1], [23,24]), a data hosting centre where globally-available ground-based soil moisture measurements are collected, harmonized and made available to users. The performance of H141 is estimated by comparing it with in situ observations from 5 in situ networks in the US, Europe and Australia. The NRCS-SCAN network in the US [25] is the longest running network with observations available from 1997 to 2018. The USCRN network (U.S. Climate Reference Network, [26]) is used over the period 2010 to 2018. The SMOSMANIA (Soil Moisture Observing System Meteorological Automatic Network Integrated Application) network [27, 28] over southwest France has observations from 2007 to 2018. The REMEDHUS network in Spain [29] has data available from 2005 to 2018. Finally, the Oznet network in Australia [30] provides data from 2001 to 2018. Despite this geographical extent limitation, these networks sample a large diversity of soil and vegetation types. They cover most of the soil texture and vegetation types (forest, crops, natural fallow, bare soil) in plains, mountainous, and coastal areas. More information about the networks is given below.

The NRCS-SCAN network [25] is a comprehensive, USA-wide soil moisture and climate information system designed to provide data to support natural resource assessments and conservation activities with a focus on agricultural areas in the USA. The observing network is used to monitor soil temperature and soil moisture at several depths, soil water level, air temperature, relative humidity, solar radiation, wind, precipitation and barometric pressure amongst other variables. NRCS-SCAN data have been used for various studies ranging from global climate modelling to agricultural studies. The vegetation cover at these sites consists of either natural fallow or short grass. Data are collected by a dielectric constant measuring device and typically measurements are made at 5, 10, 20, 50 and 100 cm.

The U.S. Climate Reference Network National from the Oceanic and Atmospheric Administration's National Climatic Data Center (USCRN NOAA's NCDC) consists of over 100 stations developed, deployed, managed, and maintained by the National Oceanic and Atmospheric Administration (NOAA) in the continental United States for the express purpose of detecting the national signal of climate change [26]. The USCRN network is spread across many parts of the USA, from North to South and West to East (network map available on the ISMN website). USCRN sites sample a variety of natural environments in addition to agricultural settings that predominate in some networks. The main objective of USCRN is to provide climate-science-quality measurements of air temperature and surface conditions. The stations in the network

[1] https://ismn.geo.tuwien.ac.at/en/

were designed to be extensible to other missions and in 2011, the USCRN team completed at each station in the conterminous United States the installation of triplicate-configuration soil moisture and soil temperature probes at 5, 10, 20, 50, and 100 cm.

The SMOSMANIA project is a long-term data acquisition effort of soil moisture observations in Southwestern France [27, 28]. Soil moisture profile measurements at 12 automated weather stations of Meteo-France from the RADOME network (Réseau d'Acquisition de Données d'Observations Météorologiques Etendu), have been obtained since January 2007 at four different depths (5, 10, 20 and 30 cm) with 12 minutes time steps. Stations span from the Mediterranean Sea to the Atlantic Ocean. The soil moisture measurements (in units of m^3m^{-3}) are derived from capacitance probes: ThetaProbe ML2X of Delta-T Devices. Data was kindly provided by J.-C. Calvet from Meteo-France in the framework of the H SAF project.

The OZNET network [30] is located within the Murrumbidgee experimental catchment in southern New South Wales, Australia. Each soil moisture site of the Murrumbidgee monitoring network (38 sites) measures the soil moisture between 0-5 cm with a soil dielectric sensor (Stevens Hydraprobe) or 0-8 cm, 0-30 cm, 30-60 cm and 60-90 cm with water content reflectometers.

Finally, the REMEDHUS is located in the central sector of the Duero basin in Spain. Each station has been equipped with capacitance probes (Stevens Hydraprobe) installed horizontally at a depth of 5 cm. Analysis of soil samples were carried out to verify the capacitances probes and to assess soil properties at each station [31].

4.3. Data preparation and metrics

Observations of soil moisture closest to the analysis time (±30 minutes) are compared with the H141 soil moisture using the nearest neighbour approach. The rescaled in situ observations at the highest depth are used for the validation of the H141 surface layer (0-7 cm). The root-zone in situ soil moisture observations are approximated using a vertical average of the in situ measurements in the first metre of soil, with weights that are proportional to the spacing of the sensor depths (as in [13]). The REMEDHUS network is only used to validate the surface layer of H141, since deeper observations are not available from this network. For the SMOSMANIA (OZNET) networks, the deepest observations at 30 cm (60-90 cm) are assumed to represent the depth 30-100 cm (60-100 cm). The rescaled root-zone in situ observations are then used to validate the average H141 root-zone soil wetness index (0-100 cm). H141 is an index between 0 and 1 while in situ measurements of soil moisture are in m^3m^{-3}. To enable a fair comparison, it is then necessary to rescale the data. The 90% confidence interval was chosen to define the upper and lower values to exclude any abnormal outliers due to instrument noise using the following equations (as in [10, 11]):

$$\begin{aligned} \text{Int}^+ &= \mu_{\text{in-situ}} + 1.64\sigma_{\text{in-situ}} \\ \text{Int}^- &= \mu_{\text{in-situ}} - 1.64\sigma_{\text{in-situ}}, \end{aligned} \quad (1)$$

where Int^+ and Int^- are the upper and lower limits of the 90% confidence interval (i.e. 5th and 95th percentiles) calculated over the January 2015 to December 2016 period. Then the SWI is obtained using:

$$\text{SWI} = \frac{\text{SM} - \text{Int}^-}{\text{Int}^+ - \text{Int}^-}, \quad (2)$$

where SM stands for Soil Moisture (in volumetric units). It is assumed that the H141 data set does not have such a problem with outliers and is rescaled using the maximum and the minimum values of each individual times series considering the whole validation time period.

The comparison between the observation data and the H141 product is performed according to the following statistical scores:

- Mean difference (or Bias)
- Correlation coefficient (CC)
- Anomaly correlation coefficient (ACC)
- Root Mean Square Difference (RMSD). In situ data contain errors (instrumental and representativeness) so they are not considered as 'true' soil moisture. This is underlined here by using the RMS Difference terminology instead of RMS Error.
- p-value, a measure of the correlation significance should be calculated as well. It indicates the significance of the test, the 95% confidence interval should be used; configurations where the p-value is below 0.05 (i.e. the correlation is not a coincidence) have to be retained. This process has probably removed some good stations too (e.g., in areas where the model might not realistically represent soil moisture). However it also ensures that stations with non-significant R values can be considered suspect and are excluded from the computation of the network average metrics. It is commonly used for soil moisture validation activities against in situ as well as against model data sets [32, 33].

The RMSD represents the relative error of the soil moisture dynamical range. As H141 is an index, it has no units. It is possible to obtain an estimate of the error of the liquid root zone soil moisture retrieval in m^3m^{-3} by multiplication between the RMSD and the observed dynamical range (obs_{max}-obs_{min}). Usually, soil moisture time series show a strong seasonal pattern that could artificially increase the perceived agreement between satellite and in situ observations in terms of CC. Therefore, to avoid seasonal effects, time series of anomalies from a moving monthly average are also calculated [11]. The difference to the mean is calculated for a sliding window of five weeks (if there are at least five measurements in this period), and the difference is scaled to the standard deviation. For each SM estimate at day (i), a period F is defined, with F=[i-17, i+17] (corresponding to a 5-week window). If at least five measurements are available in this period of time, the average SM value and the standard deviation are calculated. The Anomaly (dimensionless) is then given by:

$$\text{Ano}(i) = \frac{\text{SM}(i) - \text{SM}(F)}{stdev(\text{SM}(F))}. \quad (3)$$

The anomaly transformation is used only to compute the ACC scores. All the other metrics (ME, CC, RMSD) are computed using the H141 time series without the anomaly transformation.

More often than not, soil moisture is measured along with soil temperature. In line with the validation of the previous data record product H27/H140 [21], the quality of H141 is assessed for all weather conditions, except when the soil temperature is below +4°C. The H27/H140 data record is used as a benchmark to validate the performance of H141 over the period when the two data records overlap (1992-2016). The root-zone and surface SWI scores are compared for the all the networks over the entire period when the data are available. In addition, the

95% statistical significance intervals of the ACC are calculated using a Fisher-Z transform (as in [22]). Note that the effective sampling size in the calculation of the confidence intervals is reduced by accounting for the temporal auto-correlation ([22] gives details).

4.4. Validation results

Firstly, maps are presented in Figure 4.1 showing the locations of the stations in each network used in the validation. On the maps, the average CC over the entire validation period is shown for the surface SWI layer for each station. Recall that the performance requirements for the correlation coefficients are listed in Table 4.2. While there is evidently some spatial variability in the performance across all 5 networks, most of the stations demonstrate CC values above the target requirement (CC>0.65). Similarly spatially distributed CC scores were found for the root-zone (not shown).

Spatially averaged yearly results of the H141 surface soil wetness validation against NCRS-SCAN are reported in Table 4.3 for the surface SWI and root-zone SWI. Over most years during the period the CC scores are above the target performance of 0.65 for both layers. The ACC scores are generally lower than the CC scores, which is expected because the autocorrelation in the annual SM cycle is reflected in the CC, but not in the ACC. Nevertheless, the ACC scores generally reach the threshold requirement of 0.50. Although the RMSD is not the main validation metric for H141, Table 4.1 serves as a useful guide to interpret the RMSD results. The estimated surface SWI volumetric RMSDs are reasonable (≈ 0.06 m^{3}m^{-3}) and the biases are much smaller than the RMSDs. Overall, the root-zone SWI performs slightly better than the surface SWI in terms of the CC/ACC and has a substantially smaller average RMSD. This is expected because the root-zone SWI is less sensitive to random errors in the atmospheric forcing than the surface SWI. Note that there are generally fewer stations used to validate the root-zone SWI than the surface SWI, since measurements across all the root-zone depths are needed to construct the root-zone layer and measurements are discarded if data is missing or if the temperature is below $4°C$. Figure 4.2 displays box plots of the distribution of the R values across all the stations using five metrics, namely the median, upper quartile, lower quartile, minimum and maximum values (excluding outliers more/less that 3/2 times the lower quartile). The boxes themselves contain the middle 50% of the data for each year. The upper edge of the box indicates the 75th percentile of the data set and the lower edge indicates the 25th percentile. The range of the middle two quartiles is known as the inter-quartile range. The number of stations used for each year is given in brackets below the year. Note that fewer stations are available earlier in the validation period, which explains the large deviations in performance in the first few years. At least 75% (50%) of the stations reach the threshold (target) requirement for every year in the validation period. Furthmore, at least 25% of the stations reach the optimal requirement during the whole period.

Table 4.4 shows the results for the OZNET network for both the surface and root-zone layers. Generally the CC performance is very good for both layers, with most years demonstrating CC values well above the target accuracy of 0.65. Interestingly the ACC values for OZNET are generally much higher than for SCAN, especially for the surface SWI layer. On average the ACC scores almost reach the target requirement of 0.65 for both layers. In contrast to SCAN, the inter-annual CC performance of OZNET is quite variable, especially for the root-zone SWI. This is emphasized in Figure 4.3(a), which shows a large spread in CC performance between the stations during some years (e.g. 2008). This is partly related to the much smaller number of stations in OZNET compared with SCAN i.e. OZNET is more sensitive to sampling errors. Also very little data is available for the root-zone over some years e.g. 2005 and 2017. The RMSD and Bias for the OZNET stations are generally small.

Table 4.5 shows the scores for the SMOSMANIA netork. In general the CC scores meet the optimal requirement (>0.80) for both the surface and the root-zone layers. As expected the ACC scores are lower than the CC, but still above 0.60 for most years in both layers. As with OZNET, the surface layer scores are superior to the root-zone layer. This may be related to sampling errors or the lack of deep observations (>30 cm depth) in SMOSMANIA. The RMSD is small for both layers but the bias (averaging about 0.03-0.05 m^3m^{-3}) indicates that H141 probably overestimates the soil moisture magnitude over the region. Figure 4.3(b) indicates that the root-zone SWI CC is consistently high throughout the validation period and at least 75% stations reach the target CC requirement every year.

The scores for the USCRN network are shown in Table 4.6. Evidently the CC scores are very good on average (>0.70) for both layers and meet the target requirements every year. Although lower on average, the ACC scores consistently meet the threshold requirement (>0.5). Figure 4.3(c) indicates that the root-zone CC performs consistently well, but with some years indicating a much greater spread in performance between the stations than others (e.g. 2017 compared with 2011). The RMSD is reasonable on average for both layers (<0.06 m^3m^{-3}), but there is a slight positive bias in the surface and root-zone soil moisture estimates.

Finally the surface SWI scores for the REMEDHUS network are shown in Table 4.7. Overall the CC performs very well most years (>0.7) but the ACC scores are rather poor and average just below the threhold requirement (0.48). It is not clear why this is, but it suggests there may be a problem with the atmospheric forcing in H141 over the region. Again a slight positive bias suggests that H141 is slightly overestimating soil moisture over the region.

4.5. Comparison of H141 with H27/H140

The performance of the H141 data record is compared with that if its predecessor H27/H140 over the years when the two data records overlap (1992-2016). Note that H140 (2015-2016) served as the extension of H27 (1992-2014) and both products were generated using the same production chain and resolution ([34] gives details). The H27/H140 data record is validated using the same approach used to validate H141 (described in Section 4.3). Only stations where both data records passed the quality control are considered in the comparison of their performance i.e. exactly the same in situ stations are used to compare their performance. Table 4.8 shows the mean scores over all the networks of the average annual root-zone SWI for H141 (left) and H27/H140 (right). Evidently over most years H141 demonstrates superior CC and ACC values compared to H27/H140. During the late 1990s very few in situ stations are available and therefore sampling error is problematic. Importantly, H141 performs best on average over the 1992-2016 period. Similarly, H141 demonstrates superior scores to H27/H140 for the surface layer (not shown). Whilst this improvement in both surface and root-zone scores is reflected in the correlations, there is very little difference in performance with respect to the RMSD and biases.

Figure 4.4 shows ACC comparisons between H141 and H27 for (a) the surface layer and (b) the root-zone layer for each network during the period when all 5 in situ networks are available (2010-2014). During this time-frame both data records are assimilating the same ASCAT-A observations. The H141 ACC scores improve on the H27 scores for all networks and for both surface and root-zone layers. In terms of the surface SWI performance, the improvement for

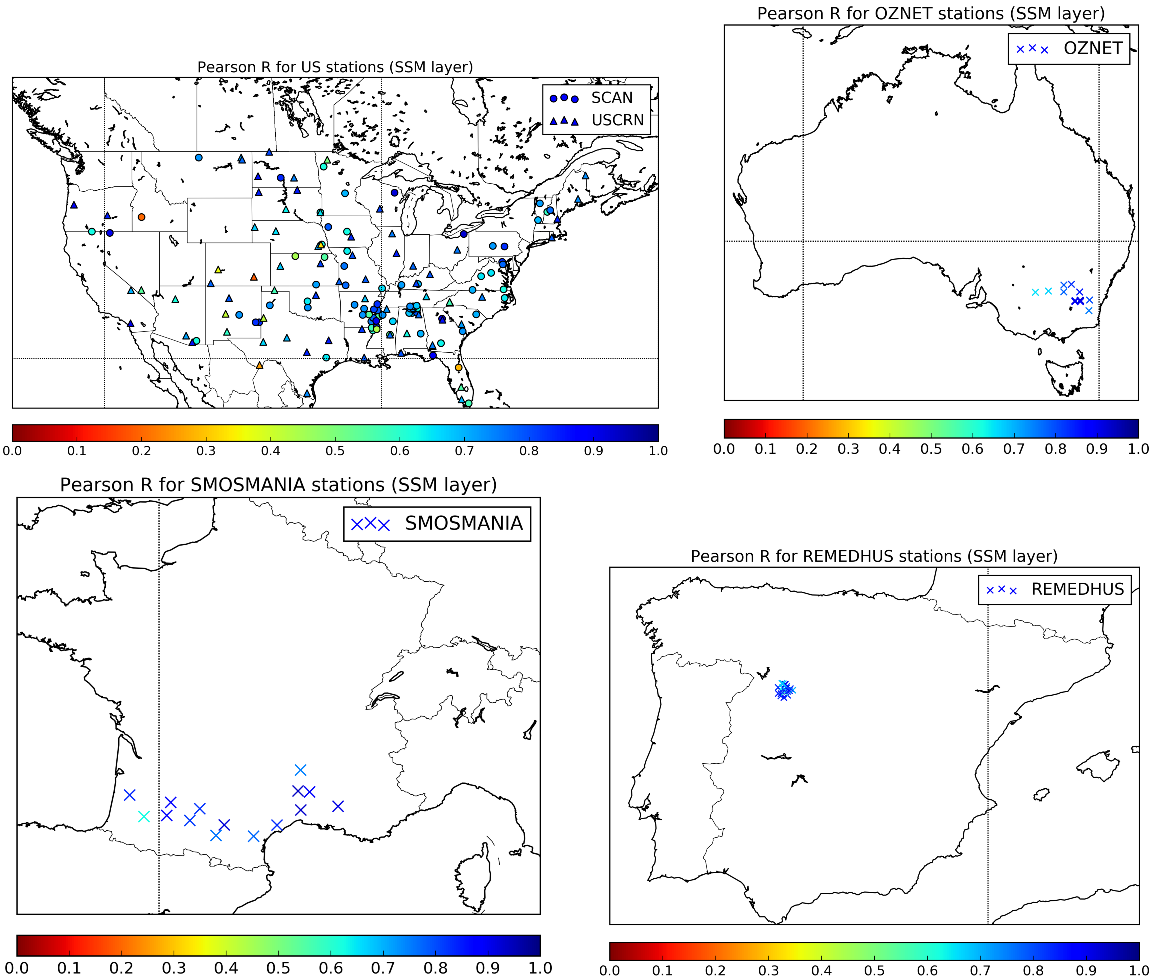
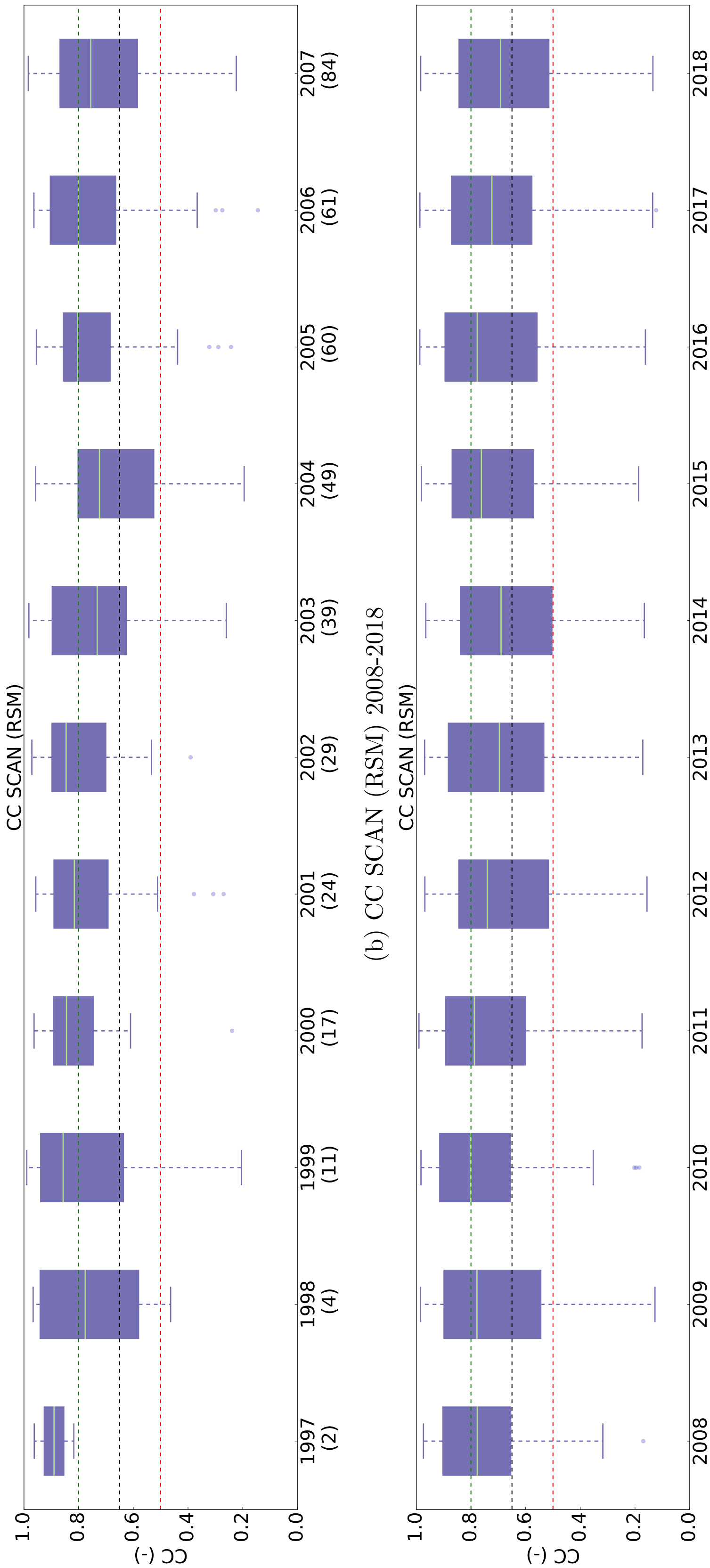


Figure 4.1: Locations of the stations of the US (top-left), French (top-right), Australian (bottom-left) and Spanish (bottom-right) networks used in the validation. Also shown is the correlation coefficient averaged over the period for each station.

REMEDHUS is substantially smaller than for the other networks. Although the 95% confidence intervals indicate that the superior performance of H141 over H27 is not statistically significant when averaged over the all the stations in each network, individually many stations demonstrated significant improvements. Indeed, 16% (20%) of the stations included in the validation demonstrated significant improvements for the surface (root-zone) SWI. In contrast, only 7% (4%) of stations demonstrated a significant degradation for the surface (root-zone) SWI in H141 compared with H27. The enhanced performance of H141 over H27 can be attributed to higher quality atmospheric forcing of the H-TESSEL land surface model (ERA-5 instead of ERA-interim) and increased resolution of the production chain (10 km instead of 16 km). It is obvious that the land surface model simulations should be improved by these developments. It is also important to point out, however, that the Simplified Extended Kalman Filter (SEKF) DA algorithm, which propagates information from the SSM scatterometer observations to the root-zone, is dependent on the model performance ([1] gives details).



(a) CC SCAN (RSM) 1997-2007

(b) CC SCAN (RSM) 2008-2018

Figure 4.2: Box plots of CC values between H141 root-zone SWI (0-1m) and depth-integrated in situ observations for the stations of the NRCS-SCAN network. Also shown are the threshold (red), target (black) and optimal (green) performance requirements.

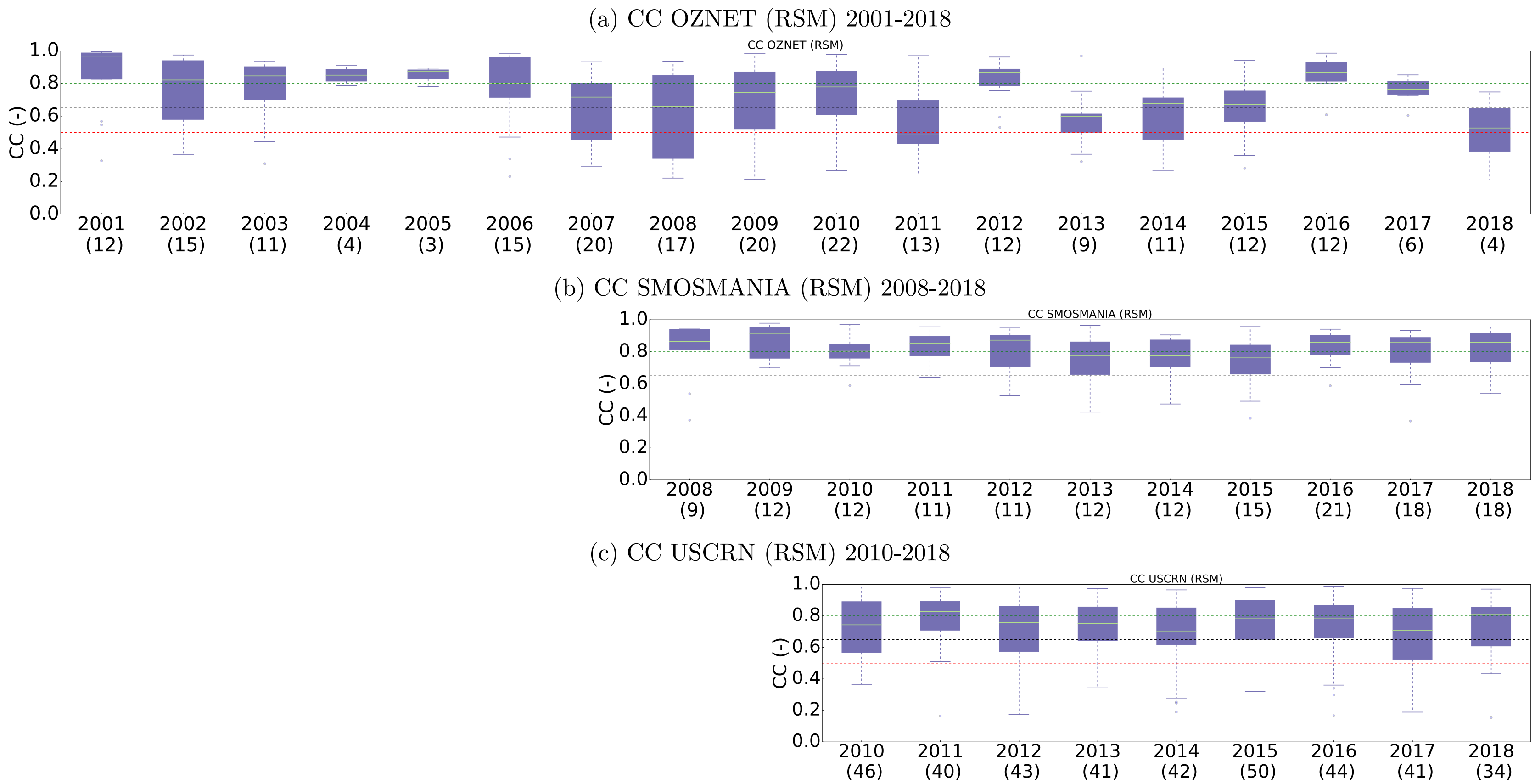


Figure 4.3: Box plots of CC values between H141 root-zone SWI (0-1m) and depth-integrated in situ observations for the stations of (a) the OZNET network (b) the SMOSMANIA network and (c) the USCRN network. Also shown are the threshold (red), target (black) and optimal (green) performance requirements.

Table 4.3: Mean scores for the H141 surface SWI layer (left) and root-zone SWI layer (right) against in situ measurements from the SCAN network.

Period (N stations)	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})	Period (N stations)	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})
1997 (2)	0.57	0.49	0.07	0.02	1997 (2)	0.89	0.54	0.03	-0.01
1998 (3)	0.72	0.52	0.03	0.00	1998 (4)	0.75	0.46	0.04	0.01
1999 (13)	0.75	0.63	0.05	0.00	1999 (11)	0.75	0.66	0.04	-0.01
2000 (23)	0.72	0.56	0.05	0.01	2000 (17)	0.78	0.59	0.03	-0.01
2001 (28)	0.71	0.60	0.05	0.01	2001 (24)	0.75	0.60	0.02	0.00
2002 (42)	0.70	0.55	0.06	0.01	2002 (29)	0.79	0.61	0.03	0.00
2003 (55)	0.70	0.58	0.05	0.01	2003 (39)	0.73	0.63	0.03	0.00
2004 (64)	0.68	0.6	0.05	0.00	2004 (49)	0.67	0.60	0.03	0.00
2005 (78)	0.69	0.57	0.06	0.01	2005 (60)	0.75	0.59	0.03	-0.01
2006 (81)	0.73	0.56	0.06	0.01	2006 (61)	0.76	0.59	0.03	0.00
2007 (98)	0.71	0.54	0.06	0.00	2007 (84)	0.71	0.54	0.03	-0.01
2008 (101)	0.70	0.56	0.06	0.00	2008 (74)	0.74	0.55	0.03	0.00
2009 (99)	0.65	0.55	0.06	0.01	2009 (63)	0.70	0.57	0.03	0.00
2010 (129)	0.70	0.52	0.06	0.01	2010 (90)	0.76	0.56	0.03	-0.01
2011 (133)	0.66	0.51	0.06	0.01	2011 (92)	0.73	0.51	0.03	0.00
2012 (126)	0.65	0.51	0.06	0.00	2012 (85)	0.68	0.53	0.03	0.00
2013 (136)	0.65	0.52	0.06	0.00	2013 (96)	0.67	0.49	0.03	0.00
2014 (149)	0.64	0.55	0.05	0.00	2014 (86)	0.66	0.53	0.02	0.00
2015 (157)	0.68	0.53	0.06	0.00	2015 (115)	0.71	0.50	0.03	-0.01
2016 (160)	0.68	0.51	0.06	0.00	2016 (120)	0.72	0.49	0.03	-0.01
2017 (154)	0.66	0.50	0.06	0.00	2017 (109)	0.69	0.51	0.03	-0.01
2018 (160)	0.65	0.48	0.06	0.00	2018 (104)	0.66	0.48	0.03	0.00
Average	0.68	0.54	0.06	0.01	Average	0.73	0.55	0.03	0.00

ACC comparisons between H141 and H140 for the surface layer and root-zone layer are shown in Figure 4.4(c) and 4.4(d) respectively over 2015-2016. During this period H141 is assimilating ASCAT-A and ASCAT-B observations whilst H140 is assimilating only ASCAT-A observations. Evidently H141 outperforms H140 for all 5 networks, although again the differences are not statistically significant when averaged over all the stations. However, 22% (25%) of the stations included in the validation demonstrated significant improvements for the surface (root-zone) SWI. In contrast, only 3% (2%) of stations demonstrated a significant degradation for the surface (root-zone) SWI in H141 compared with H140. Interestingly, this would suggest that the gap in performance between H141 and H140 is wider than between H141 and H27. One must be cautious in drawing conclusions from these two different comparisons because the time periods are different. However, it is possible that the assimilation of ASCAT-B observations has enhanced the H141 performance over the 2015-2016 period.

4.6. Conclusion

The H141 liquid SWI data record has been validated using in situ measurements from 5 networks belonging to the ISMN, namely SCAN and USCRN in the USA, SMOSMANIA in southwest France and OZNET in Australia. Averaged over the period, the correlation coefficient (CC) meets the target H SAF performance requirements (CC>0.65) for the surface and root-zone SWI for all the networks. Furthermore, for the SMOSMANIA network in southwest France,

Table 4.4: Same as Table 4.3 but for the the OZNET network.

Period (N stations)	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})	Period (N stations)	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})
2001 (9)	0.74	0.60	0.02	-0.01	2001 (12)	0.85	0.65	0.01	0.00
2002 (17)	0.83	0.73	0.03	-0.01	2002 (15)	0.75	0.71	0.02	0.00
2003 (17)	0.82	0.69	0.04	0.01	2003 (11)	0.75	0.64	0.02	-0.01
2004 (16)	0.85	0.59	0.03	0.00	2004 (4)	0.85	0.56	0.02	0.00
2005 (16)	0.88	0.70	0.03	0.00	2005 (3)	0.85	0.80	0.03	0.01
2006 (33)	0.87	0.70	0.03	-0.01	2006 (15)	0.76	0.65	0.01	0.00
2007 (32)	0.8	0.72	0.05	0.01	2007 (20)	0.64	0.64	0.03	0.00
2008 (36)	0.76	0.72	0.04	0.01	2008 (17)	0.61	0.73	0.02	0.01
2009 (36)	0.80	0.62	0.04	0.01	2009 (20)	0.70	0.56	0.02	0.00
2010 (35)	0.83	0.73	0.05	0.02	2010 (22)	0.73	0.66	0.03	-0.01
2011 (29)	0.67	0.64	0.05	0.02	2011 (13)	0.57	0.56	0.02	0.01
2012 (18)	0.67	0.56	0.05	0.02	2012 (12)	0.82	0.69	0.02	-0.01
2013 (12)	0.77	0.68	0.04	-0.01	2013 (9)	0.58	0.65	0.02	0.00
2014 (17)	0.69	0.61	0.06	0.02	2014 (11)	0.60	0.60	0.01	-0.01
2015 (16)	0.80	0.63	0.06	0.00	2015 (12)	0.65	0.62	0.04	-0.03
2016 (18)	0.83	0.47	0.07	0.01	2016 (12)	0.86	0.61	0.01	0.00
2017 (16)	0.64	0.47	0.05	0.01	2017 (6)	0.76	0.61	0.01	0.00
2018 (13)	0.72	0.51	0.04	0.01	2018 (4)	0.50	0.52	0.02	0.01
Average	0.78	0.63	0.04	0.01	Average	0.71	0.64	0.02	0.00

Table 4.5: Same as Table 4.3 but for the the SMOSMANIA network.

Period (N stations)	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})	Period (N stations)	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})
2008 (10)	0.80	0.67	0.05	0.04	2008 (9)	0.79	0.60	0.03	0.02
2009 (15)	0.85	0.65	0.05	0.04	2009 (12)	0.86	0.57	0.03	0.03
2010 (14)	0.85	0.68	0.05	0.04	2010 (12)	0.81	0.61	0.04	0.04
2011 (14)	0.82	0.65	0.06	0.04	2011 (11)	0.83	0.61	0.04	0.03
2012 (15)	0.83	0.66	0.05	0.04	2012 (11)	0.80	0.59	0.03	0.03
2013 (15)	0.83	0.70	0.06	0.05	2013 (12)	0.76	0.53	0.04	0.03
2014 (15)	0.82	0.65	0.06	0.05	2014 (12)	0.77	0.56	0.05	0.04
2015 (16)	0.78	0.72	0.06	0.05	2015 (15)	0.74	0.69	0.05	0.04
2016 (21)	0.86	0.70	0.05	0.04	2016 (21)	0.83	0.60	0.04	0.03
2017 (18)	0.78	0.62	0.06	0.05	2017 (18)	0.80	0.57	0.04	0.03
2018 (18)	0.86	0.61	0.05	0.04	2018 (18)	0.81	0.59	0.04	0.03
Average	0.83	0.66	0.05	0.04	Average	0.80	0.59	0.04	0.03

averaged over the period the CC meets the optimal requirement (CC>0.8) for both layers. As expected, the anomaly correlation coefficients (ACC) demonstrate generally lower values than the CC on average since the autocorrelation from the annual soil moisture cycle is reflected in the CC but not in the ACC. Nevertheless, for the root-zone SWI, the ACC performs in the range 0.56-0.64 when averaged over the period. These results are well above the threshold requirement of 0.50 for all networks and nearing the target requirement for the OZNET and SMOSMANIA networks. The ACC values for the surface layer mostly reach the threshold requirement. They exceed the target requirement on average for the SMOSMANIA network. However, they are rather poor for the REMEDHUS network (average CC=0.48), which might

Table 4.6: Same as Table 4.3 but for the the USCRN network.

Period (N stations)	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})
2010 (69)	0.71	0.57	0.06	0.05
2011 (71)	0.74	0.57	0.05	0.05
2012 (70)	0.70	0.55	0.06	0.05
2013 (74)	0.70	0.54	0.05	0.05
2014 (74)	0.68	0.56	0.05	0.05
2015 (75)	0.70	0.57	0.05	0.05
2016 (72)	0.70	0.55	0.06	0.05
2017 (69)	0.69	0.54	0.05	0.04
2018 (67)	0.68	0.51	0.05	0.05
Average	0.70	0.55	0.05	0.05

Period (N stations)	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})
2010 (46 stations)	0.72	0.62	0.03	0.02
2011 (40 stations)	0.78	0.57	0.03	0.02
2012 (43 stations)	0.71	0.53	0.03	0.03
2013 (41 stations)	0.73	0.56	0.03	0.03
2014 (42 stations)	0.68	0.56	0.03	0.02
2015 (50 stations)	0.75	0.58	0.03	0.02
2016 (44 stations)	0.73	0.55	0.03	0.03
2017 (41 stations)	0.68	0.54	0.03	0.03
2018 (34 stations)	0.74	0.57	0.03	0.02
Average	0.72	0.56	0.03	0.02

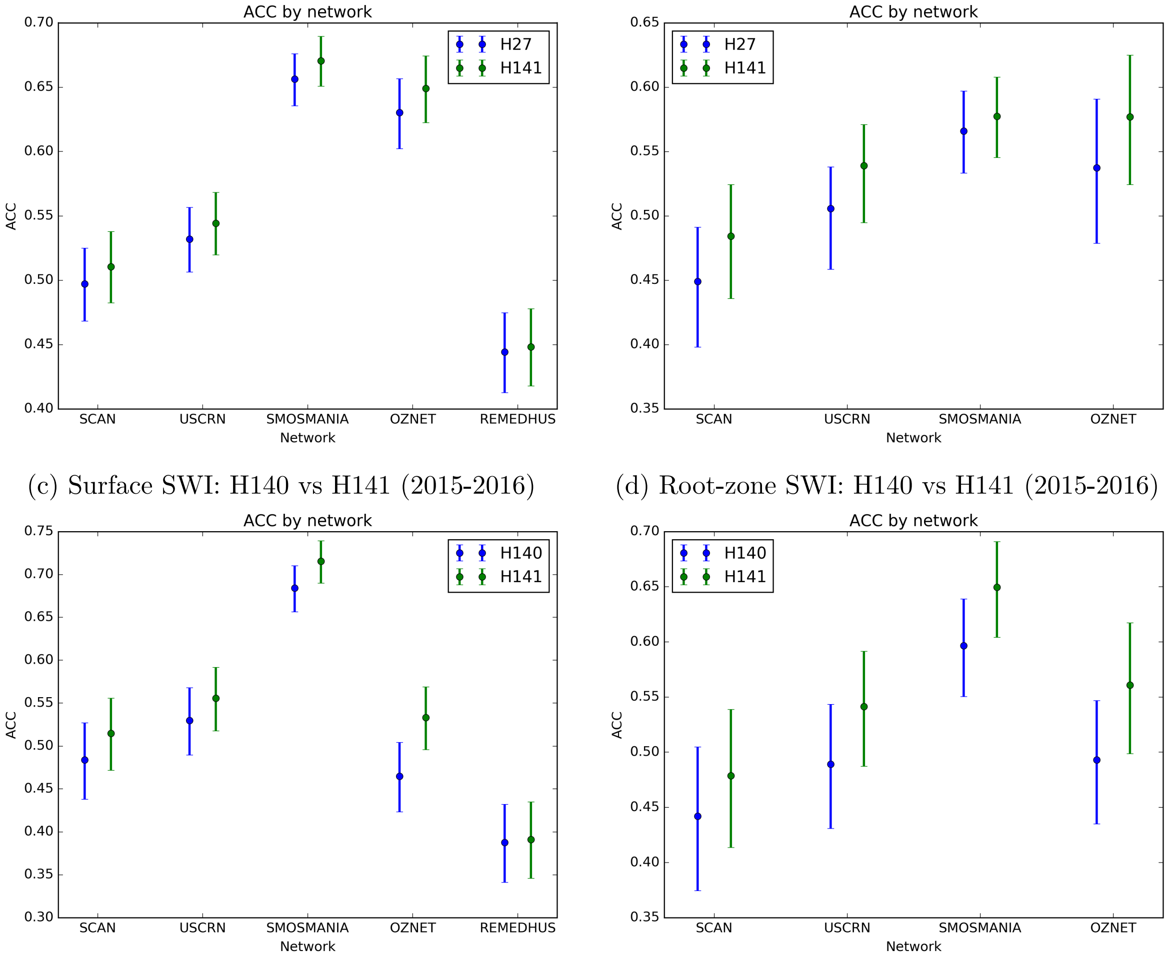
Table 4.7: Mean scores for the H141 surface SWI layer against in situ measurements from the REMEDHUS network.

Period (N stations)	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})
2005 (20)	0.86	0.50	0.04	0.03
2006 (20)	0.79	0.57	0.04	0.04
2007 (20)	0.75	0.61	0.05	0.04
2008 (16)	0.73	0.47	0.04	0.04
2009 (19)	0.71	0.46	0.04	0.04
2010 (18)	0.73	0.51	0.05	0.04
2011 (16)	0.76	0.35	0.04	0.04
2012 (21)	0.78	0.50	0.04	0.03
2013 (19)	0.76	0.51	0.04	0.03
2014 (15)	0.84	0.47	0.04	0.03
2015 (17)	0.66	0.43	0.04	0.04
2016 (17)	0.88	0.43	0.04	0.03
2017 (19)	0.69	0.38	0.04	0.04
2018 (18)	0.80	0.56	0.04	0.04
Average	0.77	0.48	0.04	0.04

be a result of inadequate atmospheric forcing in the region.

A comparison between H141 and the previous data record product (H27/H140) was performed over the 1997-2016 period when the two series overlap. The advantages of H141 over H27/H140 are 1) the resolution (10 km instead of 16 km), 2) the atmospheric forcing (ERA-5 instead of ERA-Interim) and 3) the usage of ASCATA-B data (instead of just ASCAT-A) since 2015. H141 outperformed H27/H140 over most years during the period.

Overall the validation results for H141 are highly encouraging and demonstrate the importance of using a range of in situ networks to validate the performance of a soil moisture data record. In future validations of the data record products, it is expected that the use of triple colocation analysis [35, 36] will add a new direction to the validation strategy for the surface SWI layer.



(a) Surface SWI: H27 vs H141 (2010-2014)

(b) Root-zone SWI: H27 vs H141 (2010-2014)

(c) Surface SWI: H140 vs H141 (2015-2016)

(d) Root-zone SWI: H140 vs H141 (2015-2016)

Figure 4.4: Comparison of the ACC between the SWI data records and in situ observations over the period 2010-2016. Left plots shows surface SWI scores, right plots show root-zone SWI scores. Top plots shows scores for H27 vs H141 (2010-2014) and bottom plots for H140 vs H141 (2015-2016).

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Table 4.8: Mean scores for the H141 (left) and H27/H140 (right) root-zone SWI layers against in situ measurements from the SCAN, USCRN, SMOSMANIA and OZNET networks combined. When a data record has a superior score to the other, it is highlighted in bold font.

	H141 scores				H27/H140 scores			
Period (N stations)	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})	CC	ACC	RMSD (m^3m^{-3})	Bias (m^3m^{-3})
1997 (2 stations)	**0.89**	0.54	**0.03**	0.03	0.78	0.54	0.04	0.03
1998 (4 stations)	0.75	0.46	0.04	0.04	**0.79**	**0.47**	0.04	**0.03**
1999 (8 stations)	0.68	0.68	0.05	0.04	**0.74**	**0.71**	0.05	0.04
2000 (17 stations)	**0.78**	**0.59**	0.03	**0.02**	0.74	0.56	0.03	0.03
2001 (33 stations)	0.80	**0.62**	0.02	0.02	**0.81**	0.60	0.02	0.02
2002 (43 stations)	**0.77**	**0.65**	**0.02**	0.02	0.75	0.63	0.03	0.02
2003 (46 stations)	**0.75**	**0.64**	**0.02**	0.02	0.67	0.59	0.03	0.02
2004 (49 stations)	**0.68**	**0.61**	0.03	0.02	0.65	0.58	0.03	0.02
2005 (60 stations)	**0.76**	**0.60**	0.03	0.02	0.74	0.55	0.03	0.02
2006 (74 stations)	**0.75**	**0.60**	0.03	0.02	0.73	0.55	0.03	0.02
2007 (97 stations)	0.72	**0.57**	0.03	0.02	**0.73**	0.56	0.03	0.02
2008 (93 stations)	**0.73**	**0.59**	0.03	0.02	0.70	0.57	0.03	0.02
2009 (90 stations)	**0.74**	**0.58**	0.03	0.02	0.72	0.53	0.03	0.02
2010 (159 stations)	**0.76**	**0.60**	0.03	0.02	0.72	0.57	0.03	0.02
2011 (147 stations)	**0.74**	**0.54**	0.03	0.02	0.73	0.51	0.03	0.02
2012 (139 stations)	**0.73**	**0.56**	0.03	0.02	0.70	0.53	0.03	0.02
2013 (132 stations)	0.70	**0.54**	0.03	0.02	**0.71**	0.50	0.03	0.02
2014 (138 stations)	**0.69**	**0.56**	0.03	0.02	0.68	0.52	0.03	0.02
2015 (173 stations)	**0.73**	**0.56**	0.03	**0.02**	0.69	0.51	0.03	0.03
2016 (183 stations)	**0.76**	**0.53**	0.03	0.02	0.73	0.49	0.03	0.02
Average	**0.74**	**0.58**	0.03	0.02	0.73	0.55	0.03	0.02

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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):

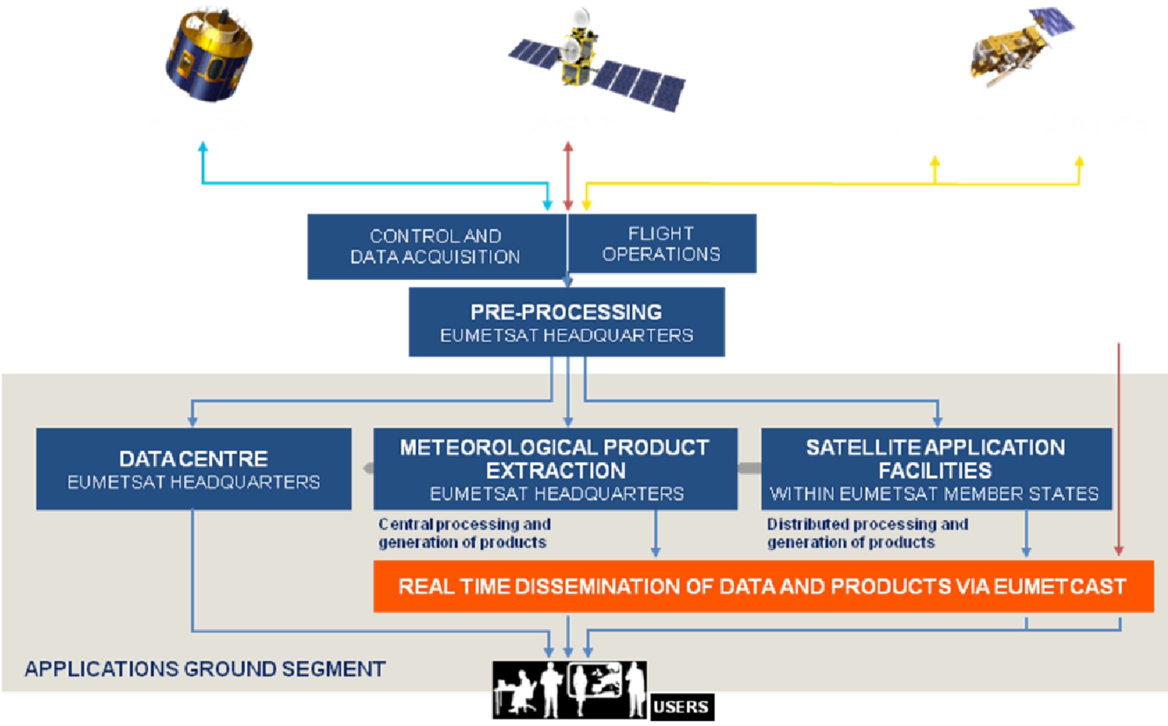

Figure A.1: Conceptual scheme of the EUMETSAT Application Ground Segment.

Figure A.2 here following 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);

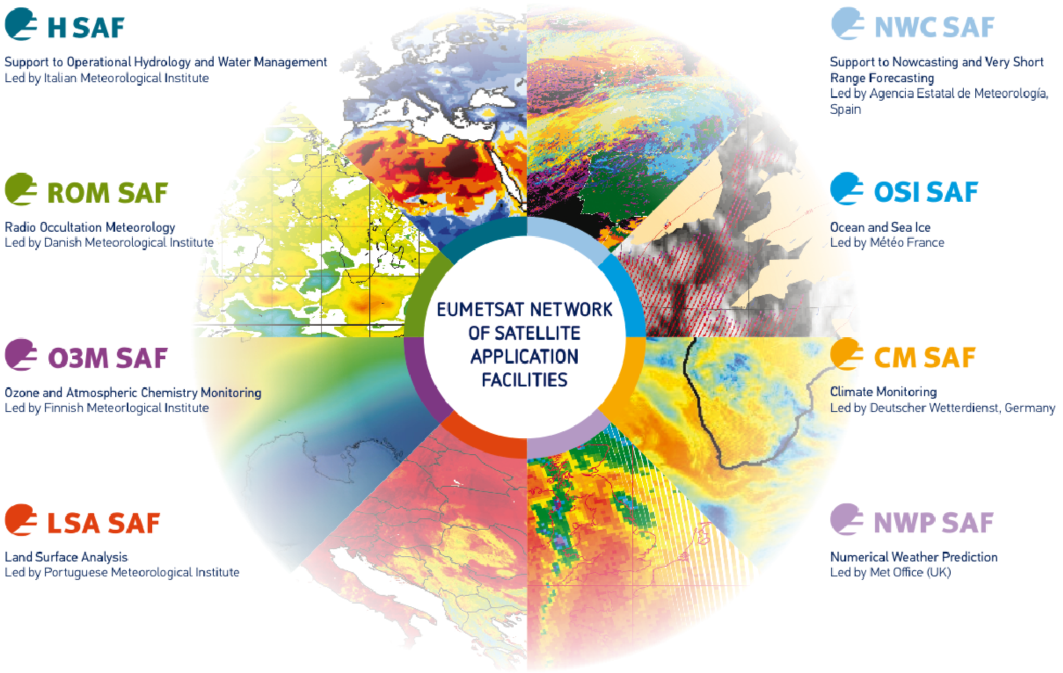

Figure A.2: Current composition of the EUMETSAT SAF Network.

- 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[1]), or via ftp download; they are also published in the H SAF website[2].

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.

[1] http://www.eumetsat.int/website/home/Data/DataDelivery/EUMETCast/index.html
[2] http://hsaf.meteoam.it

D. System Overview

H SAF is lead 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.