# Root zone soil moisture products based on scatterometer data assimilation

EUMETRAIN event week

David Fairbairn, Patricia de Rosnay, Phil Browne, Lars Isaksen and Clement Albergel

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# Introduction

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- I have a land surface DA position at ECMWF, funded by H SAF (started in 2017) ;

- H SAF aims to provide satellite products with sufficient time/spatial resolutions to satisfy needs of operational hydrology;

- ECMWF provides the core root-zone soil moisture (RZSM) products for H SAF using an advanced land-surface data assimilation system, running independently of the NWP system;

- Currently, there are two operational H SAF RZSM products:

    1. A global **near-real-time SM product** at 25 km resolution, delivered daily (called H14);

    2. A global **data record SM product** (1992-2016) at 16 km resolution forced by ERA-Interim atmospheric fields, consisting of H27 (1992-2014) and H140 (2015-2016).

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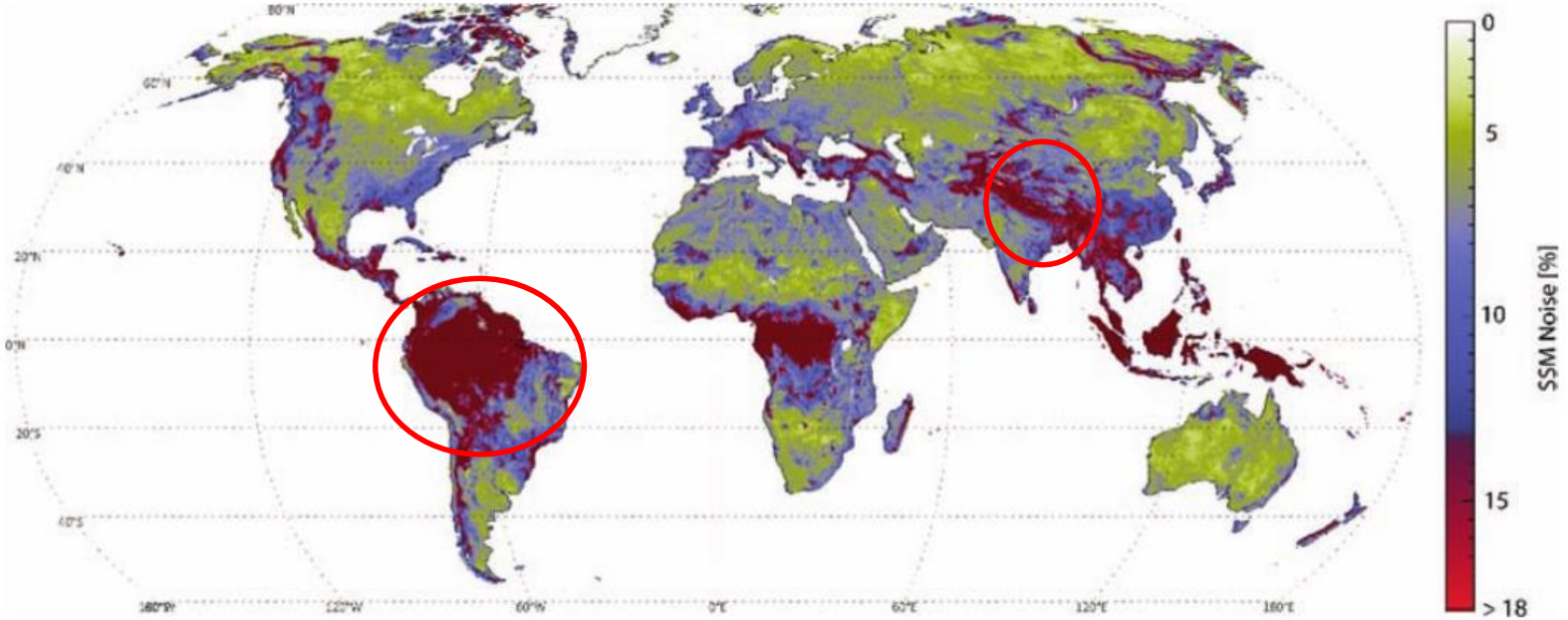
# Introduction to data assimilation

# ASCAT-derived observations

- Satellite derived global observations from the Advanced Scatterometer (ASCAT) measure the top few centimetres of soil;
- Soil moisture derived from C-band low-frequency microwave signal using the change detection technique (Wagner *et al*., 1999; Bartalis *et al*., 2007);
- ASCAT-derived surface soil moisture (SSM) observations are generally quite accurate (Unbiased RMSE of ~ 0.04 $m^3/m^3$ according to Brocca et al. (2010));
- However, frequency of the observations is limited by the temporal sampling of the satellite swath (~ every 2 days globally);
- Observations are not able to detect frozen soil moisture content and are unreliable in highly vegetated regions (e.g. Amazon rainforest) and mountainous regions (e.g. Himalayas).

# ASCAT observation accuracy




Estimate of noise (%) in ASCAT-derived observations. From Figure 6 of Wagner et al (2013). Based upon the methods presented in Naiemi et al. (2009).

- Most areas have a high signal-to-noise ratio. But observations in highly vegetated regions and mountainous regions are noisy.

# Land surface models

- Land surface models (LSMs) provide continuous and spatially complete estimates of root-zone soil moisture and other land related variables e.g. snow. They are forced by atmospheric variables, notably precipitation and radiative forcing;
- Atmospheric forcing for LSMs typically comes from reanalyses or a Numerical Weather Prediction forecast;
- LSMs require parameterizations (e.g. soil texture, vegetation type), which are not always accurate;
- Errors in root-zone soil moisture from LSMs are significant in some regions due to model errors and/or errors in the atmospheric forcing.

# H-TESSEL land surface model

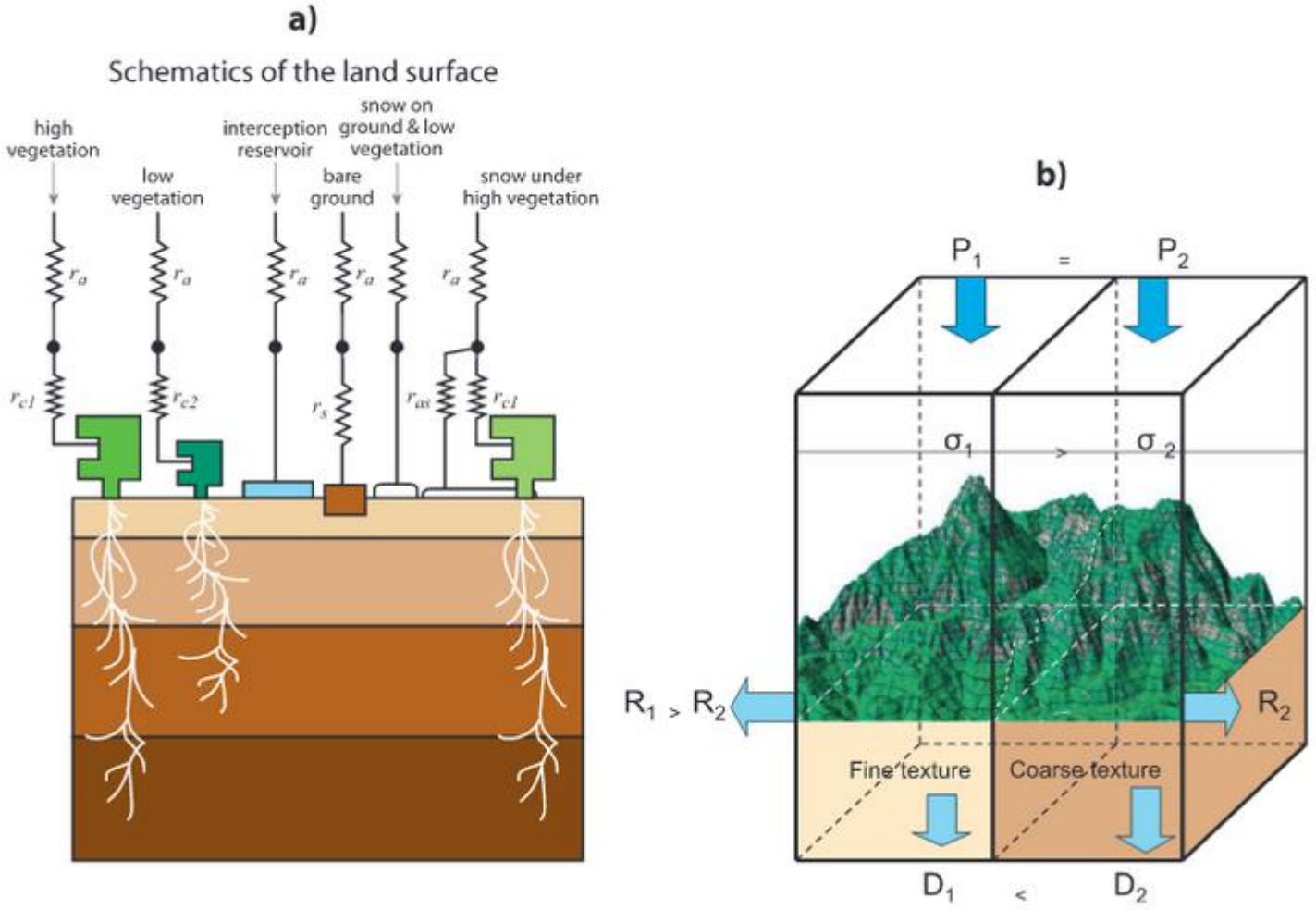



Figure 1: Schematic representation of the structure of (a) TESSEL land-surface scheme and (b) spatial structure added for H-TESSEL. From Balsamo *et al* (2009).

# Data assimilation

- Data assimilation (DA) aims to optimally combine observations with a model simulation, by weighting them according to their respective uncertainties;
- ASCAT-derived SSM observations are accurate in many regions, but are unreliable in certain areas and not frequent enough for some operational applications;
- The LSM ensures a continuous and complete global coverage of root-zone soil moisture, but suffers from model/forcing errors;
- The DA algorithm assimilates the ASCAT-derived SSM observations into the LSM, enabling the ASCAT observations to improve the entire root-zone soil moisture profile (0-1 m), while maintaining a continuous and complete global coverage.

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# Section 1

# NRT root-zone soil wetness index product (H14)

# H14 NRT root-zone SWI

- H14 is the near-real-time (NRT) root-zone soil wetness index (SWI) product at 25 km resolution and is bounded between 0 (residual soil moisture) and 1 (saturation);

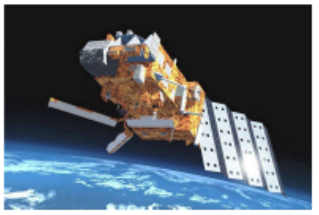
- H14 consists of global daily (00 UTC) grib files of the four model layers and a quality control flag (since October 2018). It has a latency of 12-36 hours;

- H14 is produced by assimilating a near-real-time (NRT) ASCAT-A/B derived SSM product (H102/H103) into the H-TESSEL LSM using a simplified Extended Kalman Filter (SEKF, de Rosnay et al, (2012)). It is run independently of the ECMWF NWP system;

- Additionally, H14 assimilates observations of 2m temperature and humidity, which ensures consistency between the land surface and the near-surface atmospheric conditions.

# H14 data assimilation

**Quality contol**
Use data when:
- Topographic complexity ≤ 20
- Wetland fraction ≤ 15
- Noise level ≤ 8
-Snow-free conditions
-Unfrozen soil



**Observations**: ASCAT, T2M and RH2M

Observations errors

**EKF Soil Moisture Analysis**

Background errors

**4D-Var upper air analysis**

**Atmospheric prior state**

**H-TESSEL Land Surface Model**

**H14 / SM-DAS-2 Liquid Root-Zone Soil Moisture**

**Simplified EKF analysis**

$$\mathbf{x}^{\mathrm{a}}(t_i) = \mathbf{x}^{\mathrm{b}}(t_i) + \mathbf{K}_i \left[ \mathbf{y}^{\mathrm{o}}(t_i) - \mathcal{H}_i(\mathbf{x}^{\mathrm{b}}) \right],$$

$$\mathbf{K}_i = \left[ \mathbf{B}^{-1} + \mathbf{H}_i^{\mathrm{T}} \mathbf{R}^{-1} \mathbf{H}_i \right]^{-1} \mathbf{H}_i^{\mathrm{T}} \mathbf{R}^{-1},$$

$$\mathbf{H}_{mn,i} = \frac{\mathcal{H}_{m,i}(\mathbf{x}^{\mathrm{b}} + \delta \mathbf{x}_n^b) - \mathcal{H}_{m,i}(\mathbf{x}^{\mathrm{b}})}{\delta x_n}.$$

**SM analysed over first 3 layers in H-TESSEL:**
Layer 1: 0-7 cm
Layer 2: 7-28 cm
Layer 3: 28-100 cm
Layer 4 (not analysed): 100-289 cm

- 12 hour assimilation windows
- Produced daily at 00 UTC (12-36 hour latency)

# H14 data assimilation

**Simplified EKF analysis**

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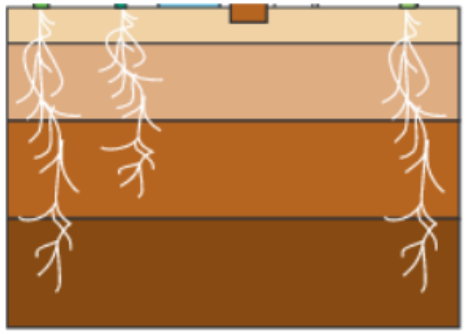

- SEKF based on de Rosnay et al, (2012);
- **B** is diagonal, with background-error standard deviation 0.01 $m^3m^{-3}$ for each layer;
- **R** is diagonal, with observation-error standard deviation 0.05 $m^3m^{-3}$ for ASCAT-derived SSM, 1 K for 2 m temperature and 4% for relative humidity.

# H14 data assimilation

**Simplified EKF analysis**

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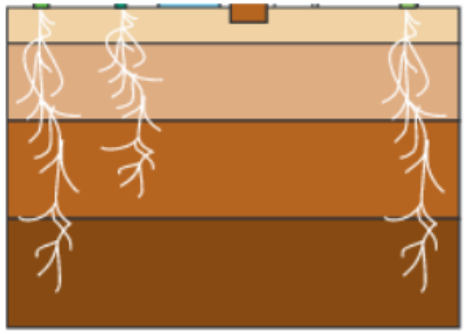

- Jacobian elements $H_{mn}$ for analysis variable n and observation m calculated using finite differences:

# H14 data assimilation

**Simplified EKF analysis**

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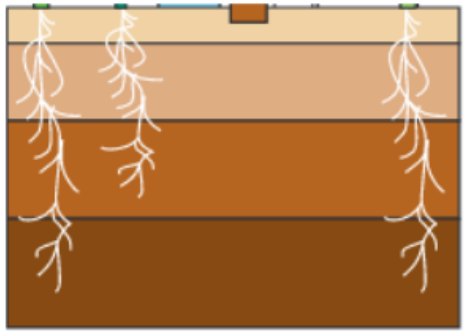

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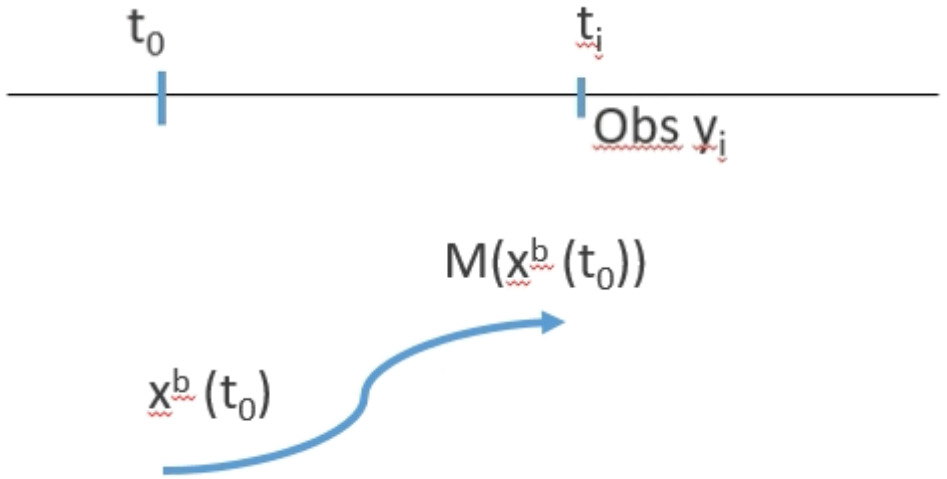

# H14 data assimilation

**Simplified EKF analysis**

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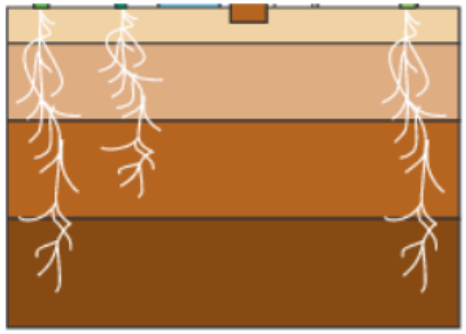

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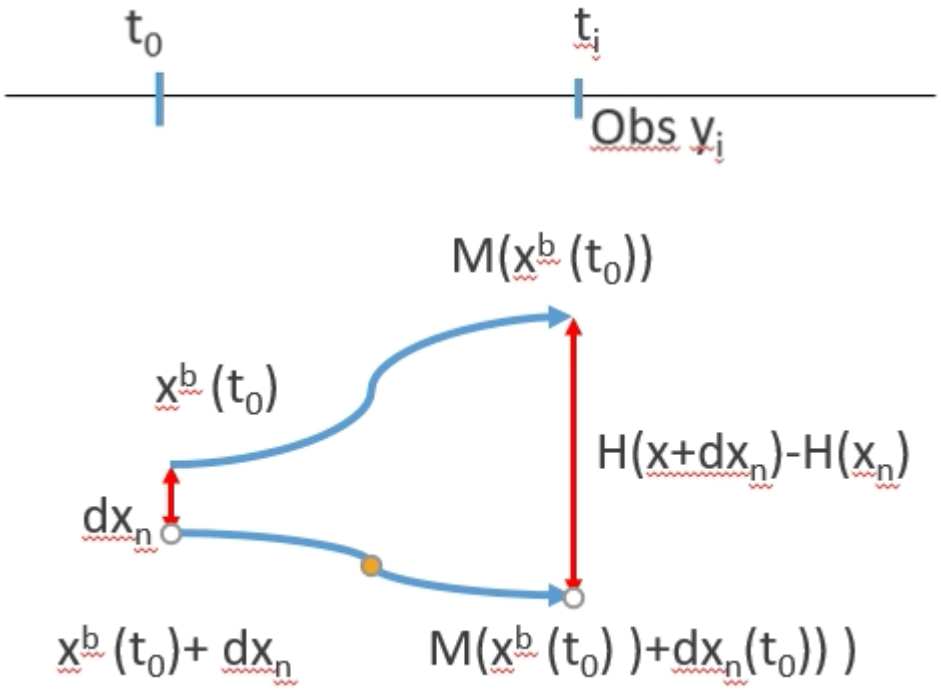
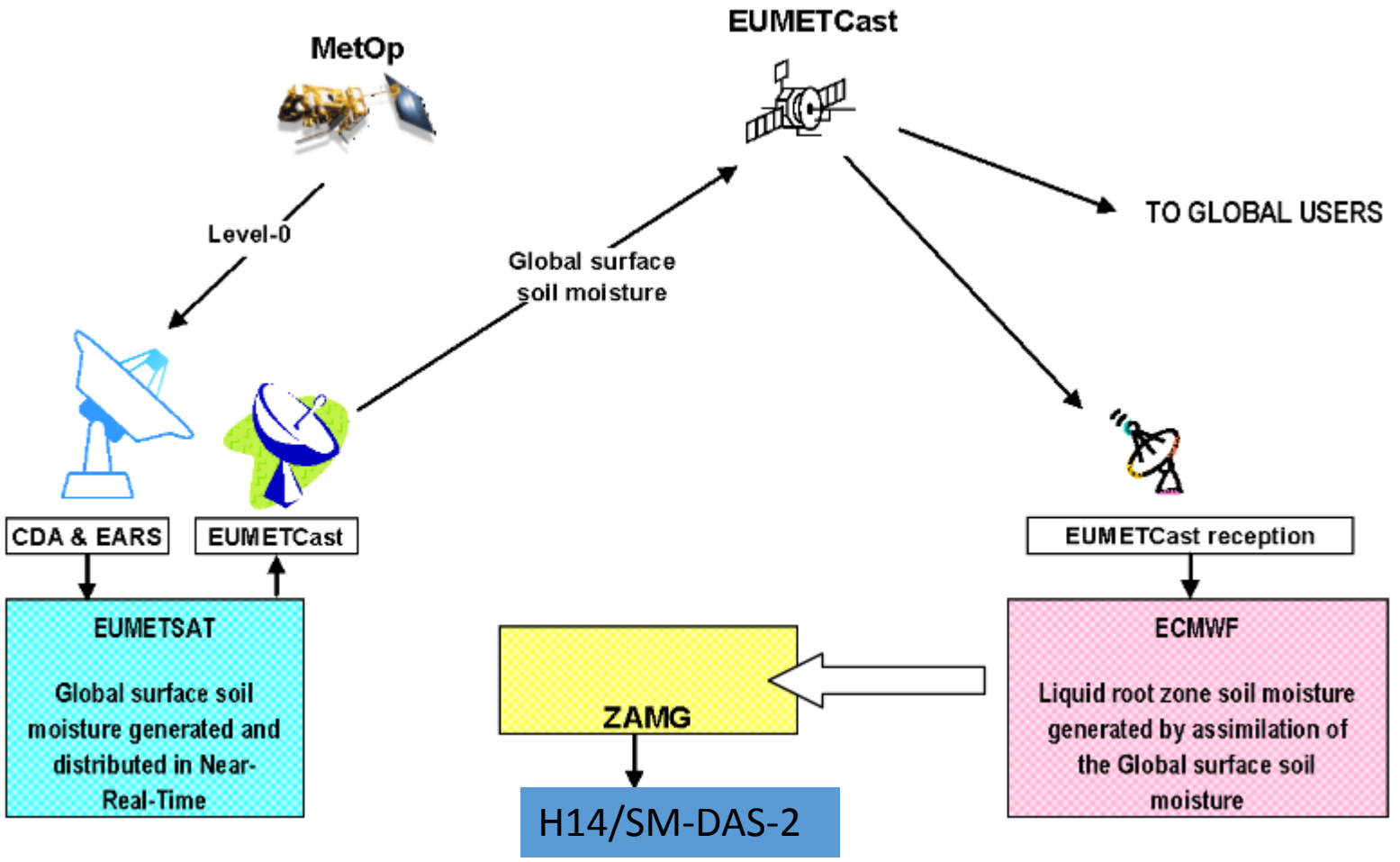


# H14 production chain



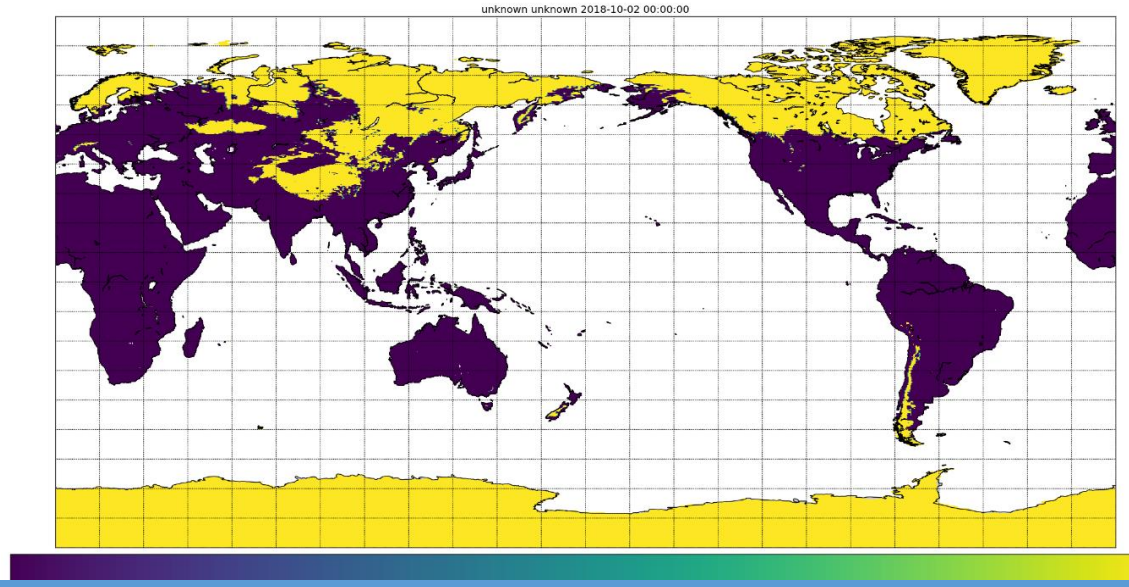
# H14 quality control

- The assimilated ASCAT-derived SSM observations (H102/H103) already undergo a rigorous quality control screening (see Sebastian Hahn's presentation);

- On 4/10/18, a quality control flag was introduced for H14, which identifies grid points where there is a risk of frozen conditions (modelled soil temperature in any layer < 4°C):

**QC code:**
1 = normal;
2 = risk of frozen conditions;
3 = outside nominal range (0-1)

H14 QC flag for 04/10/18




Purple=normal conditions, Yellow=risk of frozen conditions

# CDOP-3 developments

- Current H14 NRT 25 km product used in operational hydrological modelling/flood prediction (e.g. Artinyan, 2012, Massari, 2015). Also input for LANDSAF evapotranspiration estimates by Portuguese Met Agency (IMPA);
- Improvements to resolution/timeliness of H14 would be beneficial for end users;

**Future H26 NRT product:**

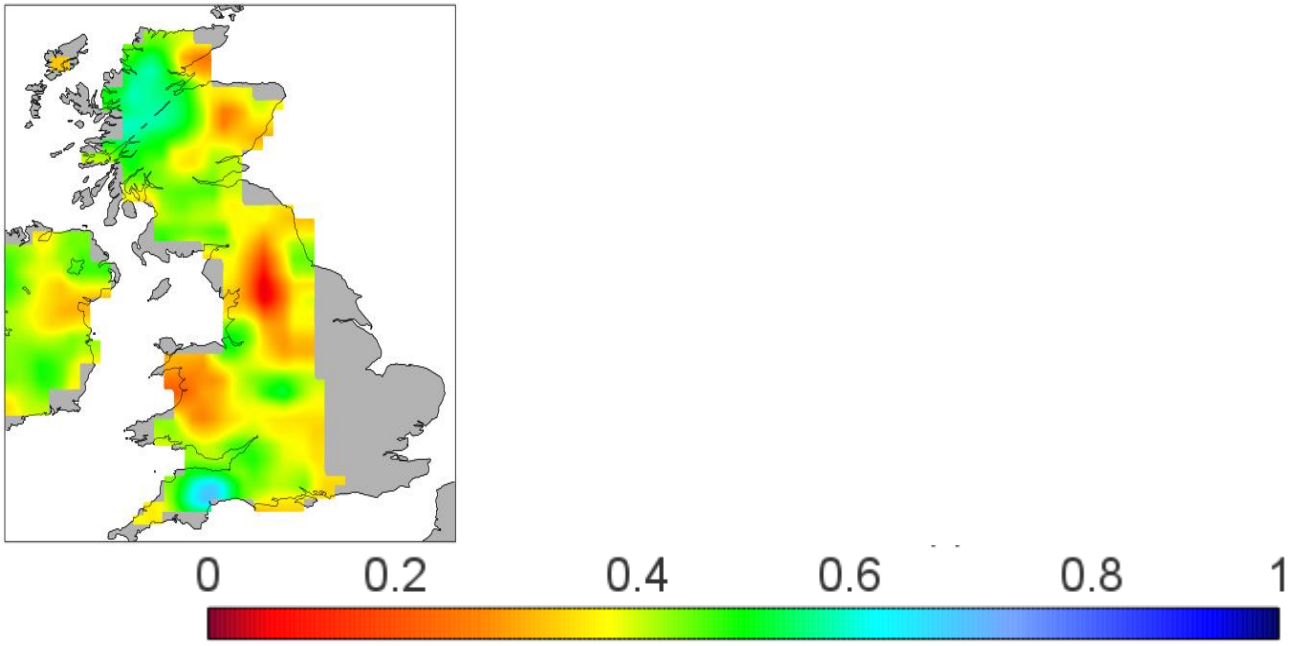
- Resolution to be increased from 25 km to 10 km;
- Latency to be reduced from 36 hours to 12 hours;
- Output in netCDF (regular lat-lon) and grib (original reduced Gaussian grid);
- Assimilation of ASCAT-C soil moisture (currently cal/val ongoing);
- New stand-alone surface analysis in H26, evaluated by Fairbairn *et al.,* 2019.

# Case study – Storm Callum

- Storm passed the UK on 12th/13th October 2018;
- Pressure deepened to 938 hPa (exceptional for midlatitude storm);
- 86 mph recorded at Capel Curig in Wales;
- >200 mm of rainfall in 24 hours over parts of Wales - Worst flooding for 30 years;
- Timeline of heavy precipitation reflected in ASCAT soil wetness index:

https://www.bbc.co.uk/news/uk-wales-45838058

**00UTC 11/10/18:**



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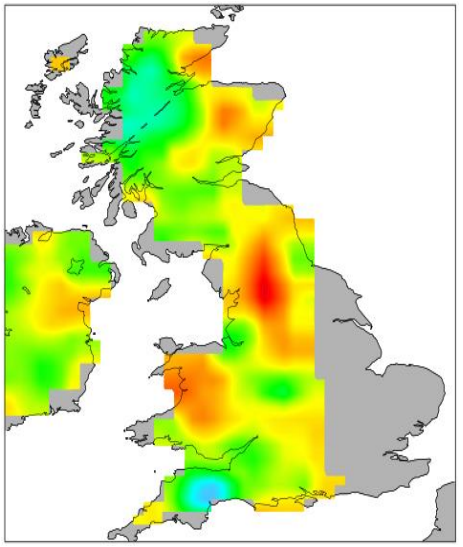

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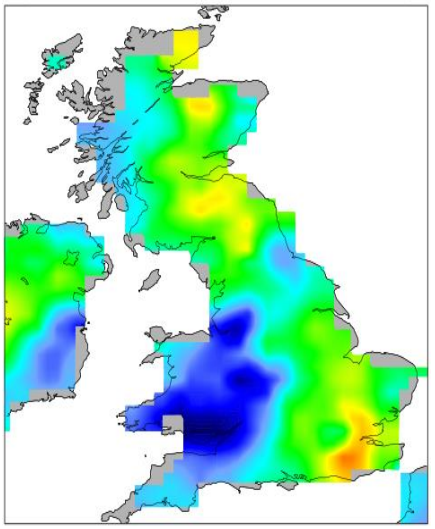

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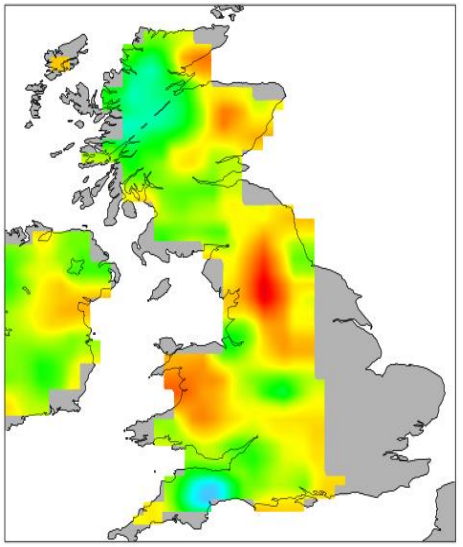

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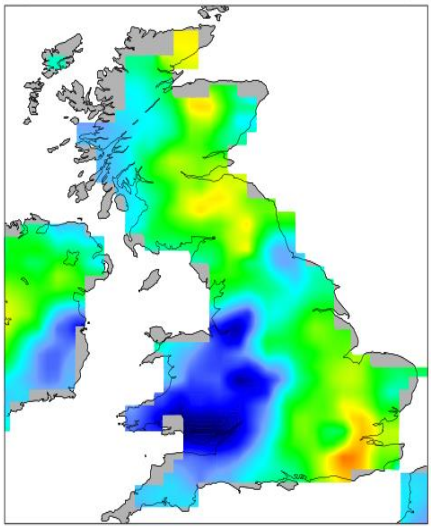

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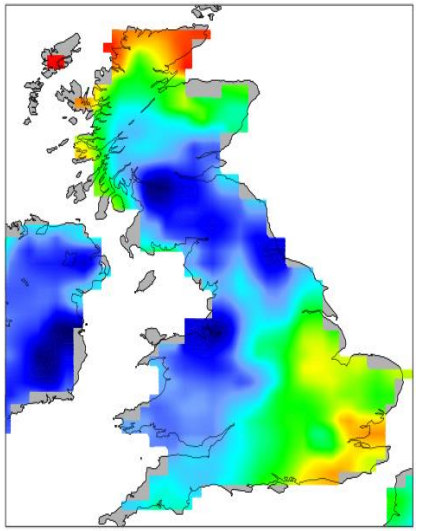
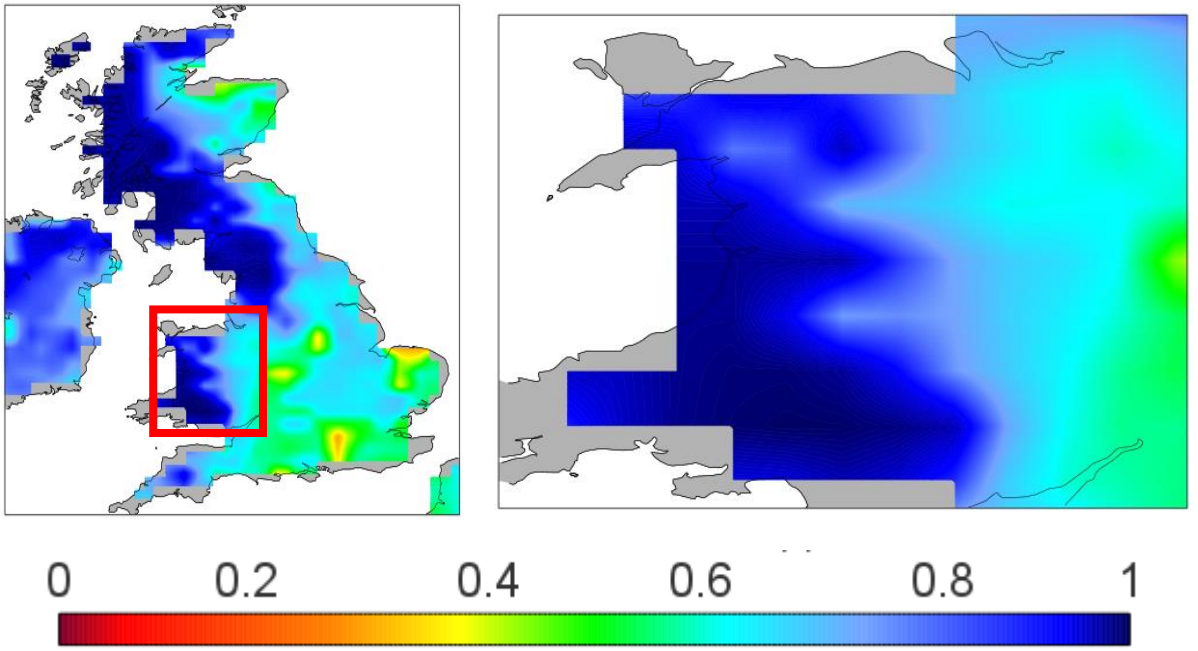


# Case study – Storm Callum

## H14 (25 km res)

- Saturated H14 root-zone soil wetness index across western UK
- Large scale west-east gradient well captured, but lacks detail




**Soil wetness index on 13/10/19 at 00 UTC**

# Case study – Storm Callum

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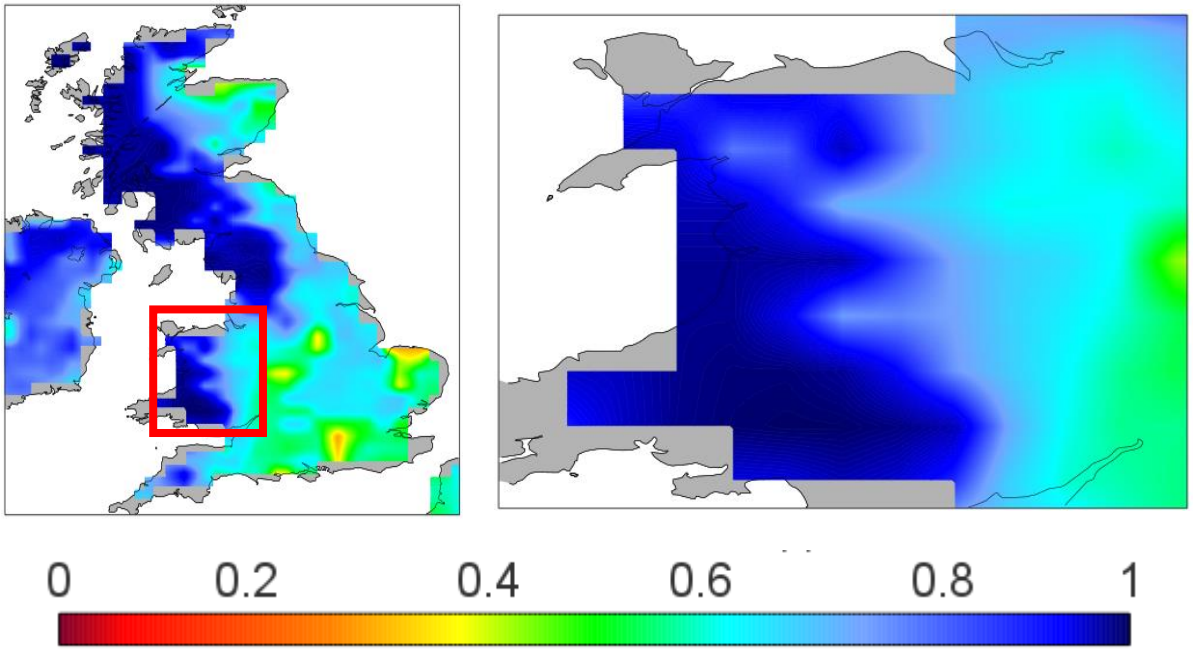
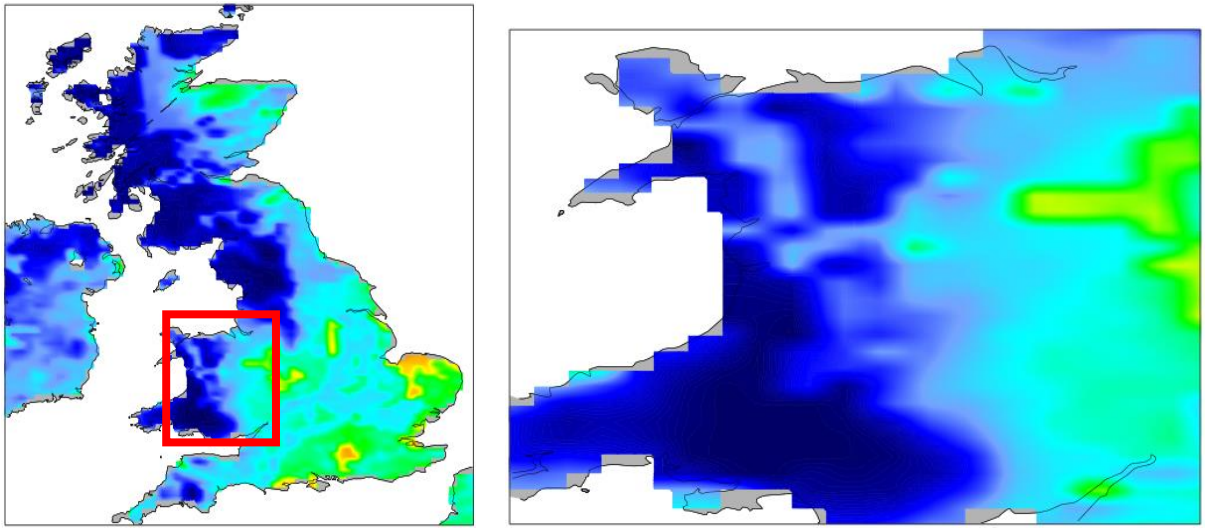



**Soil wetness index on 13/10/19 at 00 UTC**

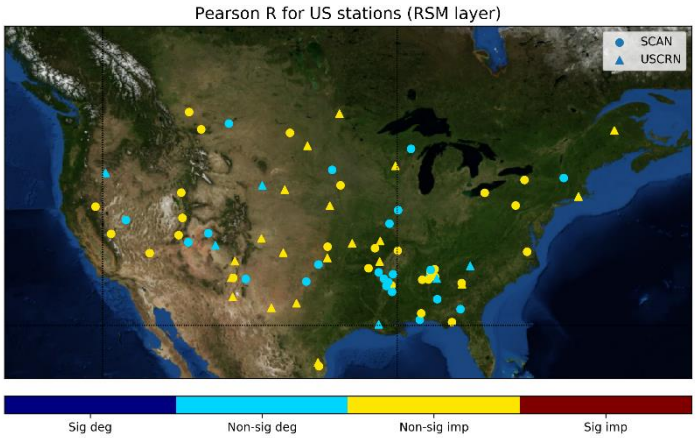
## H26 (10 km res)

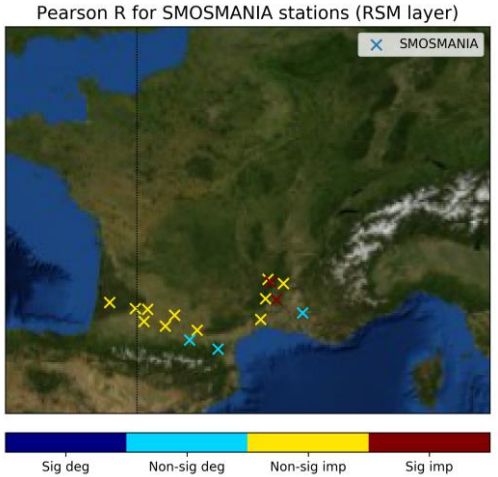
- Fine scale features much better captured in H26 than H14, including orographic enhancement and coastal areas over South Wales

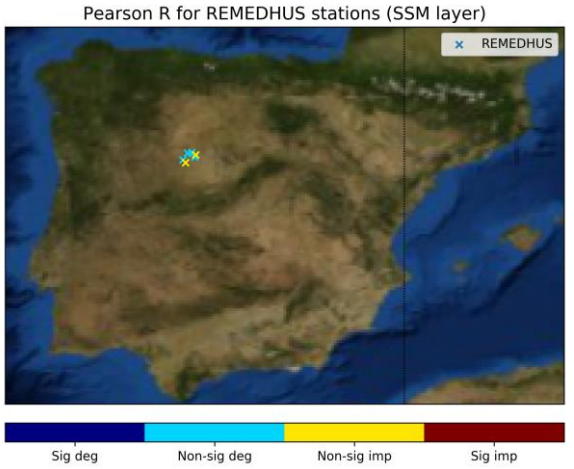


# Validation of H14 and H26

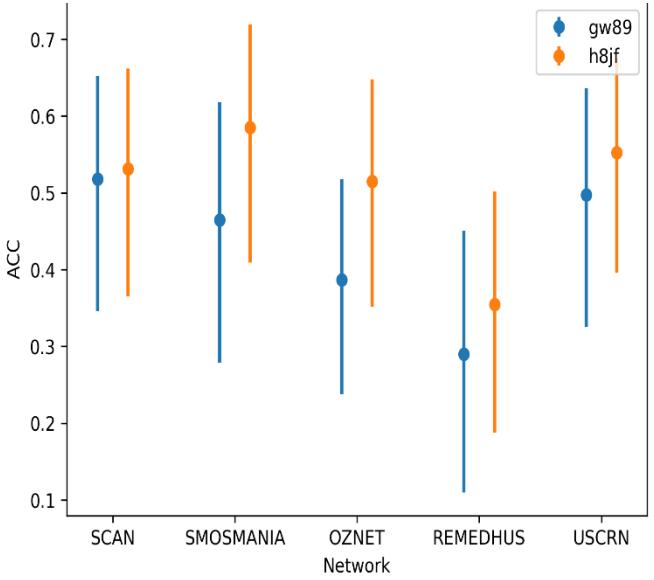
- Validation using in situ SM networks from the international SM network (Dorigo *et al.*, 2011) around the world over period (1/6/18-31/10/18): USCRN, SCAN (US), SMOSMANIA (France), REMEDHUS (Spain), OZNET (Australia).



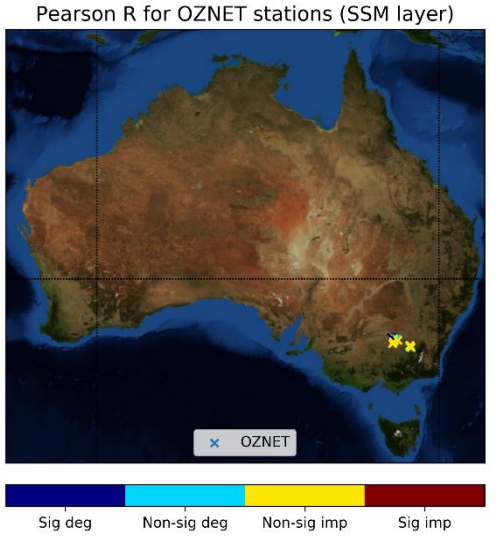




Root-zone Anomaly CC (H26 vs H14):




| | H14 (25 km res) | H26 (10 km res) |
|---|---|---|
| ACC (-) | 0.63 | **0.68** |
| RMSD (m3/m3) | 0.029 | **0.027** |

**H26 improves on H14**



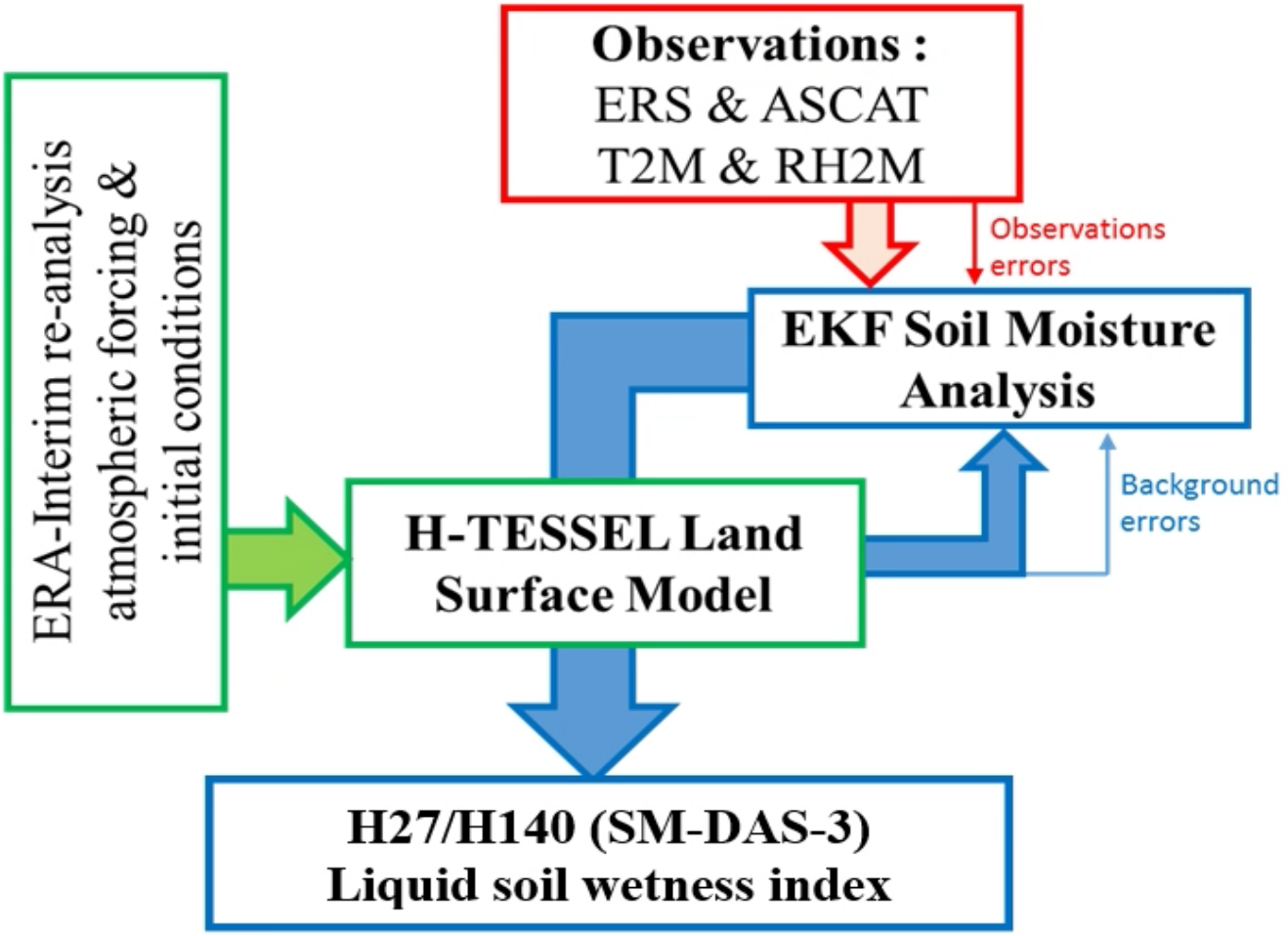
# Section 2

# Data record root-zone soil wetness index product (H27/H140)

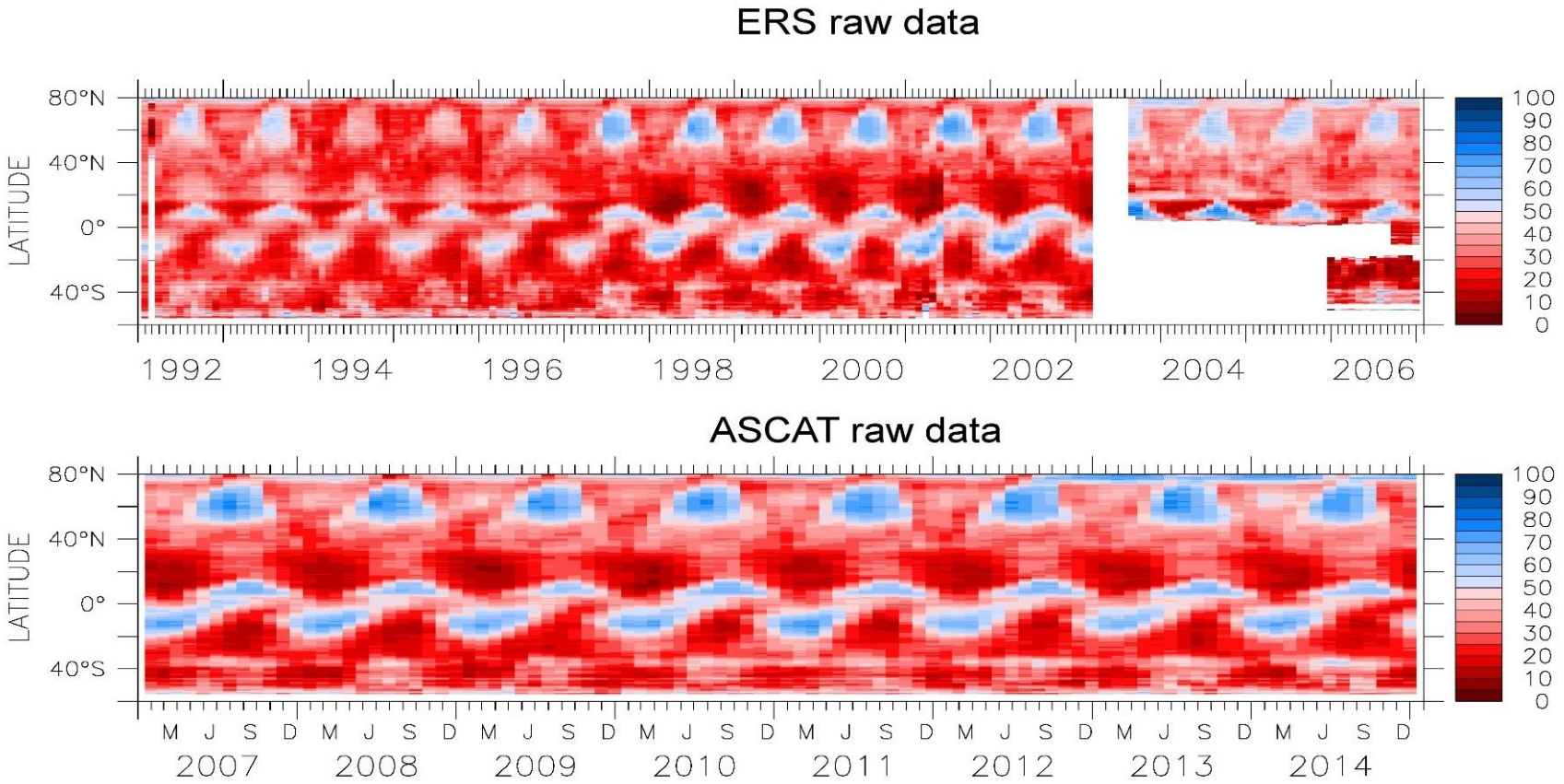
# H27/H140 data record products

- H27/H140 are the root-zone soil wetness index (SWI) data record products (1992-2016) at 16 km resolution. H27 covers the period (1992-2014) and H140 covers the period (2015-2016);
- H27/H140 consist of global daily (00 UTC) grib files of the four model layers;
- H27/H140 are produced by assimilating a reprocessed version of ERS-scatterometer (1992-2006) from TuWien and ASCAT-A SSM observations from EUMETCAST (2007-2016), as well as SLV observations (1992-2016);
- H27/H140 use an offline version of the ECMWF LDAS with ERA-interim atmospheric forcing.

# H27/H140 data assimilation

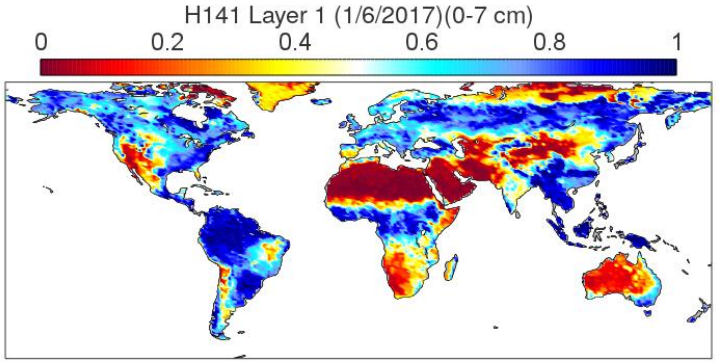


# Scatterometer data coverage



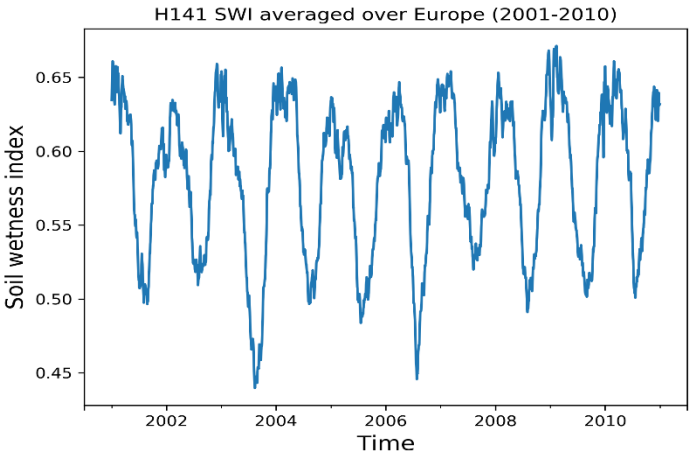

Longitudinal monthly mean of satellite derived surface soil moisture from the ERS-1/2 (top) and ASCAT-A (bottom) over 1992-2006 and 2007-2014, respectively.

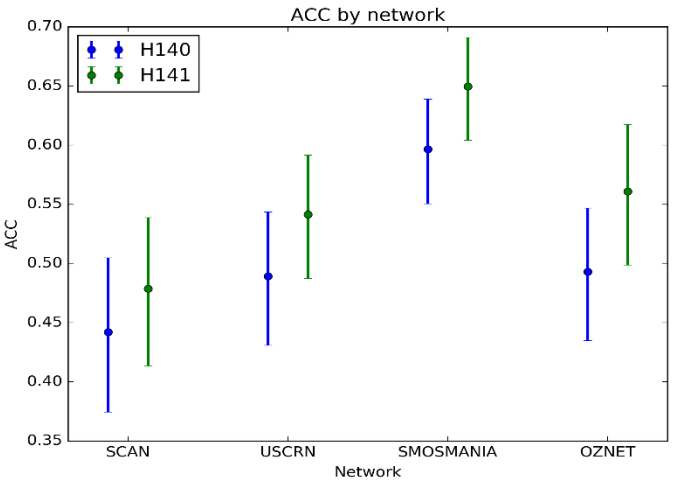
# New H SAF RZSM data record (1992-2018)










- H141: Global liquid soil wetness index available daily from 1992-2018 (at 00 UTC);
- Produced using offline version of IFS land data assimilation forced by ERA-5;
- Assimilates pre-processed scatterometer observations (1992-2018);
- Improves on H140 through increased res (10 km instead of 25 km) and improved atmospheric forcing (ERA-5 instead of ERA-interim);
- Improved correlations of H141 against in situ observations compared with H140.

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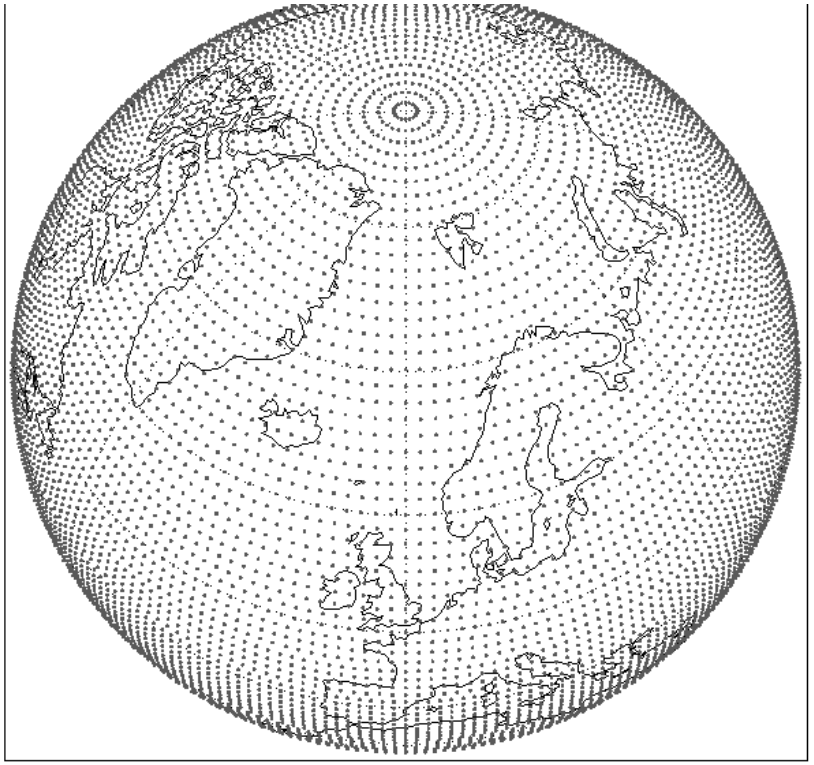
# Section 3

# Format and documentation

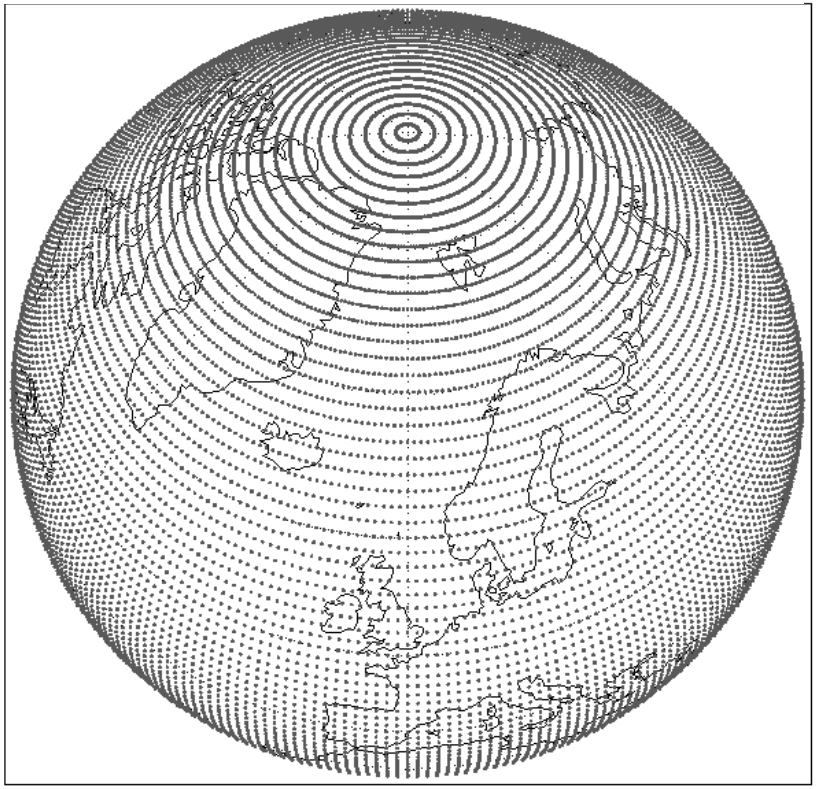
# Format

- H14 is available in grib format on a linear reduced Gaussian grid (T799~25 km resolution);
- H27/H140 are available in grib format at (T1279~16 km resolution).
- The reduced Gaussian grid maintains approximately equidistant grid-point distances between the poles and the equator (unlike regular lat/lon grid):

Reduced Gaussian grid:



Regular lat/lon grid:



For more info, see https://confluence.ecmwf.int/display/FCST/Gaussian+grids

# Download and documentation

- H14, H27 and H140 daily grib files can be downloaded via the H SAF ftp: ftp://ftphsaf.meteoam.it/products

- Register with H SAF: http://hsaf.meteoam.it/user-registration.php to obtain username and password

The documentation can be found via http://hsaf.meteoam.it/user-documents.php:

- Product user manual

- Algorithm theoretical baseline document

- Product validation report

If you have queries about the products or website, please contact the H SAF helpdesk: us_hsaf@meteoam.it

# Citation of H SAF RZSM products

How to cite H27 (DRR 1992-2014):

H SAF, “Scatterometer Root Zone Soil Moisture Data Record (1992-2014) at 16 km resolution, based on ERS/SCAT and Metop ASCAT assimilation (H27).” EUMETSAT SAF on Support to Operational Hydrology and Water Management, 2015, DOI: 10.15770/EUM_SAF_H_0003

For H140, one can simply cite H27 and state that H140 serves as the extension to H27 for 2015-2016.

For H14 (near-real-time), one can cite the original validation performed by Clement Albergel:

Albergel, C., 2011 Product Validation Report (PVR-H14). URL: http://hsaf.meteoam.it/documents/PVR/SAF_HSAF_PVR-14.pdf. Last accessed November 2019.

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# Section 5

# Summary and future work

# Summary

- The ECMWF land data assimilation system combines SSM observations with a land surface model in order to improve the root-zone soil moisture profile;
- The H14 NRT root-zone SWI product assimilates ASCAT-A/B derived SSM observations and SLV observations into the H-TESSEL LSM at ECMWF;
- H14 uses a NRT atmospheric forecast to force the LSM, but is run independently of the NWP system;
- H14 is available daily at 25 km resolution (since 2012);
- H27/H140 data record SWI products assimilate reprocessed ERS-scatterometer (1992-2006), ASCAT-A SSM observations (2007-2016) and SLV observations, at 16 km resolution;
- The products are available to download on the H SAF ftp in grib format.

# Future products

- Future NRT product:
  - Future NRT product (H26) will benefit from increased resolution (25 to 10 km), improved timeliness (36 hours 12 hours) and ASCAT-C assimilation;
  - Case study for storm Callum over UK (October 2018) demonstrates importance of finer resolution in H26 compared with H14;
  - Preliminary validation using in situ observations over US, France, Spain and Australia indicated better performance of H26 compared to H14;
  - Operational release of H26 expected in 2020 (after one-year pre-operational phase).

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  - Preliminary validation using in situ observations over US, France, Spain and Australia indicated better performance of H26 compared to H14;
  - Operational release of H26 expected in 2020 (after one-year pre-operational phase).

- New data record product
  - Data record product assimilates scatterometer-derived SM into H-TESSEL land surface model using an offline land data assimilation system;
  - Future data record product (H141) will benefit from increased resolution (25 to 10 km) and improved atmospheric forcing (ERA-5 instead of ERA-interim);
  - H141 expected to be released in 2019 (subject to external reviews).

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