Monitoring the reliability of earth observation soil moisture data through ground measurements and land surface modelling

Albergel C.[(1)], Muñoz-Sabater J. [(1)], de Rosnay P. [(1)], Balsamo G. [(1)], Isaksen L. [(1)], Dorigo W. [(2)], Naemi V. [(2)] , Hasenauer S. [(2)], Wagner W. [(2)], Reichle R.[(3)] , de Jeu R. [(4)], Kerr Y. [(5)], Gruhier C. [(5,*)], Brocca L. [(6)]

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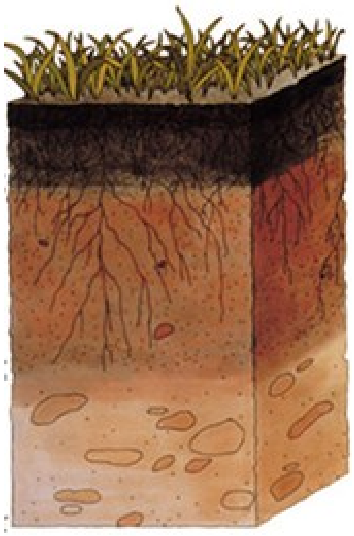
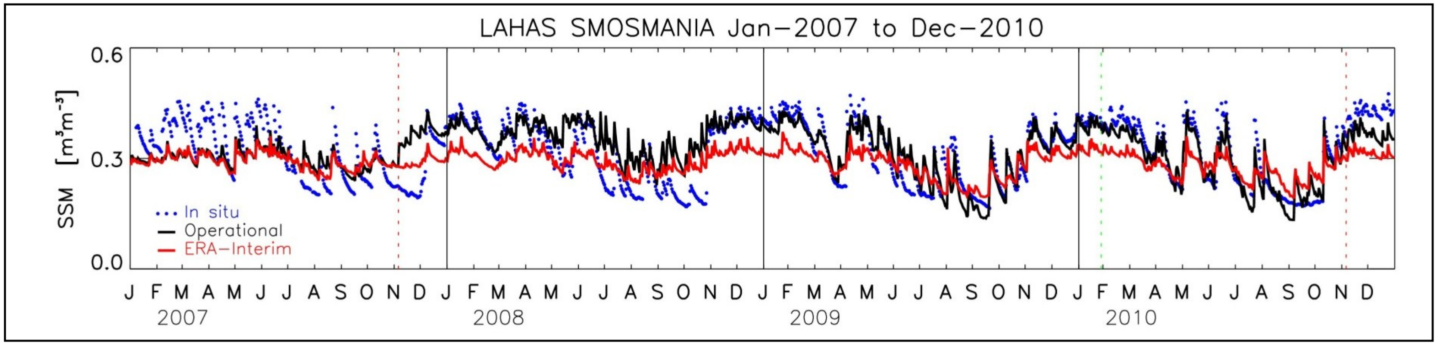
Soil moisture at ECMWF

- **Soil Moisture :** Essential Climate Variable (GCOS)
  - crucial variable for numerical weather and climate predictions
  - key role in hydrological processes





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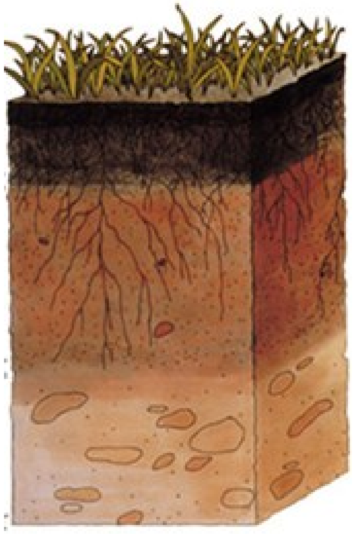
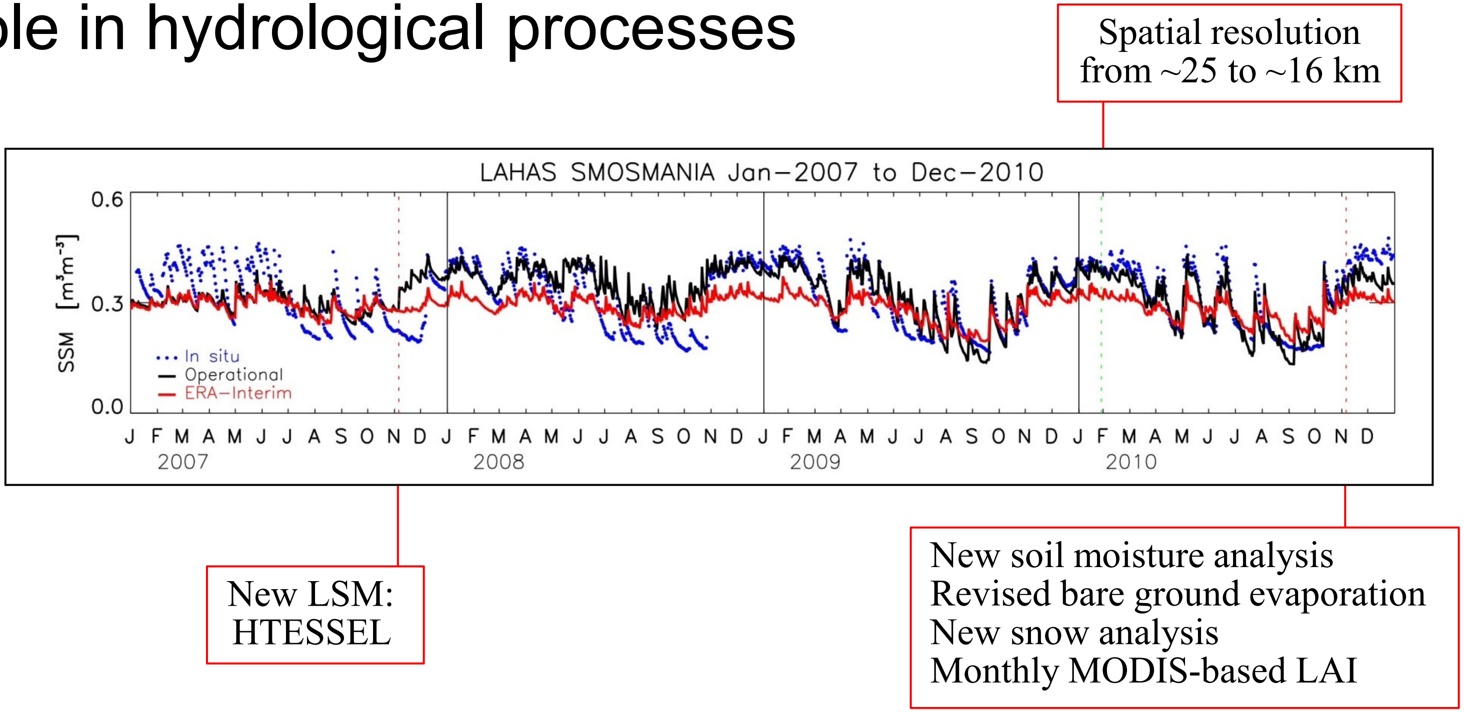




Soil moisture

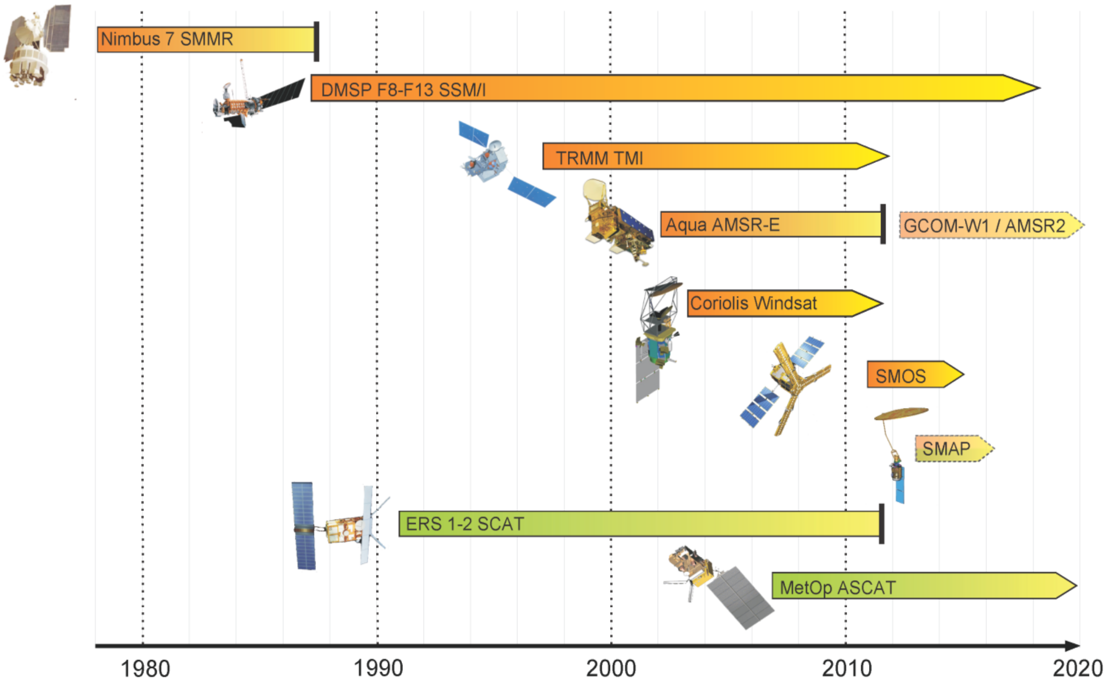
- Re-analyses of past land-atmosphere conditions:
    - Major numerical modelling and data assimilation undertaking
    - Re-run every 5 to 10 years (Balsamo et al., 2012)
- Attempt to solve this issue:

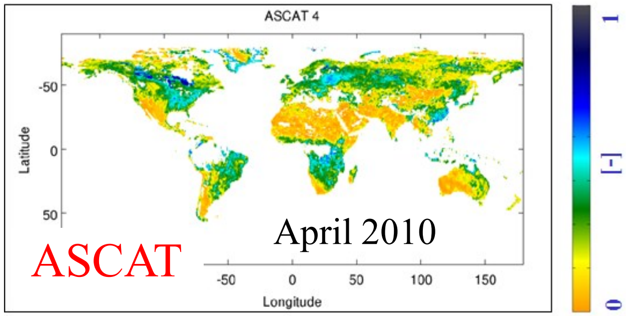
- **ERA-Interim near-surface meteorology is used as forcing term to produce a new land surface model trajectory based on ECMWF latest LSM improvements: ERA-Land (Balsamo et al., 2012 ERA report serie)**

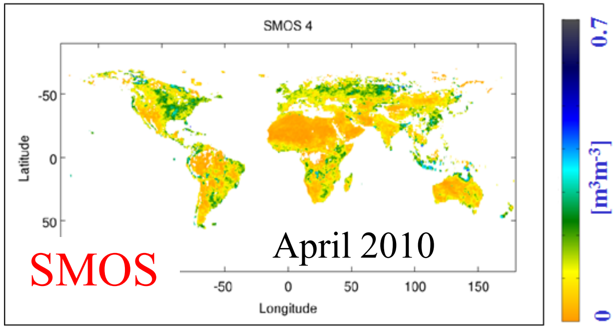
- **A revised version of the land component of the MERRA system (NASA GMAO): MERRA-Land ; improved set of land surface hydrological fields (Reichle et al., 2011)**

Soil moisture: Spatial Remote Sensing

- Spatial Remote Sensing: unique opportunity to observe SM at a global scale







- WACMOS and CCI Soil Moisture projects: merge data from various active and passive microwave sensors to produce the most complete and most consistent global soil moisture data record (1979-2010): **SM-MW**

http://www.esa-soilmoisture-cci.org/

Soil moisture: Remote Sensing & Modelling

The EUMETSAT Network of Satellite Application Facilities

H SAF Support to Operational Hydrology and Water Management

operational from Jul. 2012

ECMWF Atmospheric conditions

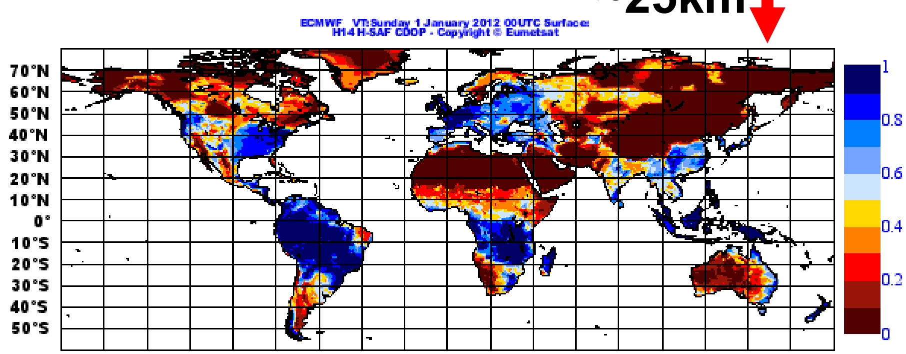
SYNOP
T2m RH2m

ASCAT
Surface SM

EKF Soil Moisture Analysis

SM-DAS-2: Soil Moisture Profile

~25km

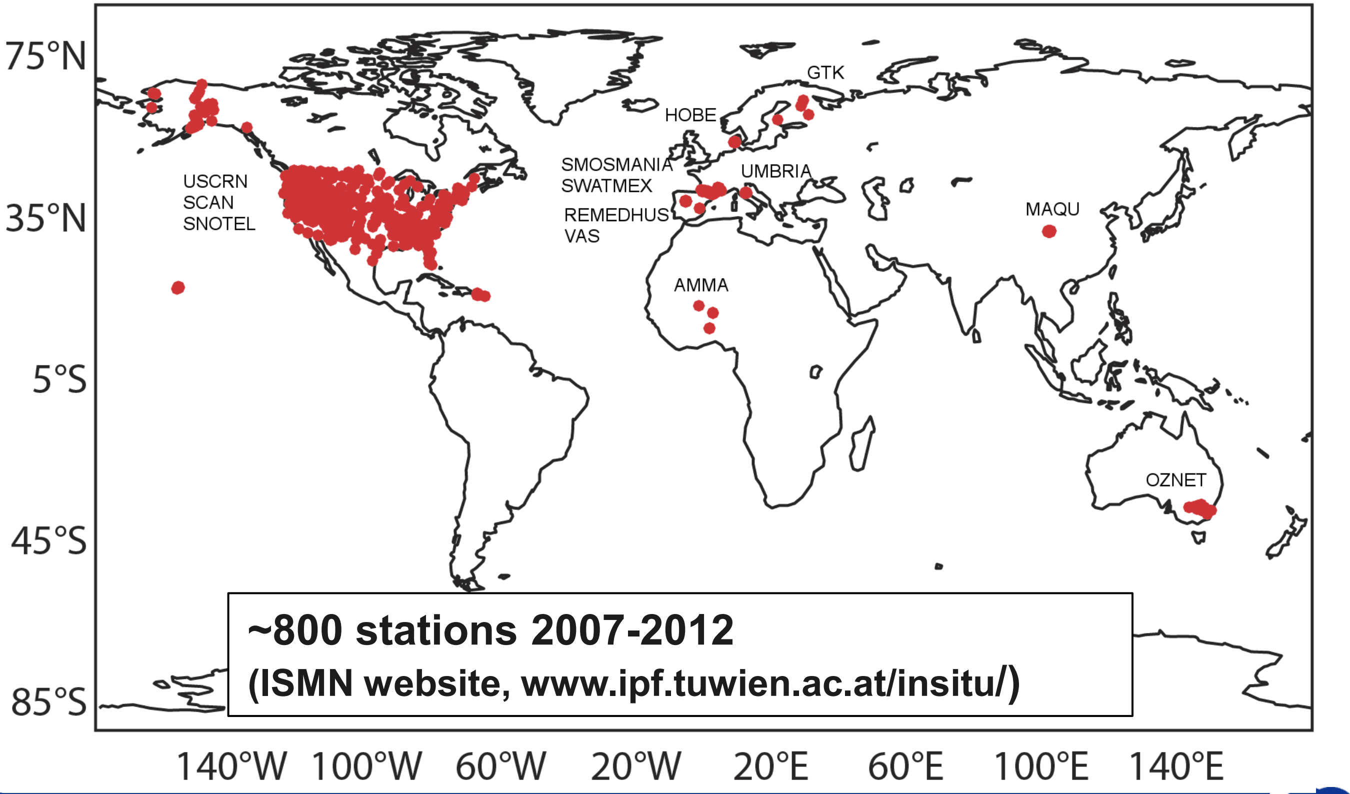


EKF corrects the trajectory of the Land Surface Model

http://hsaf.meteoam.it/soil-moisture.php

Evaluation of performances

- One important aspect of the environmental variables retrieval : the evaluation of their performance
- Determine whether their behaviour matches the observations ➔ Importance of in situ soil moisture



In situ measurement vs. coarse resolution products

- Even if local in situ observations do not measure the same quantity as coarse resolution products, significant correlation can be obtained between the two measures

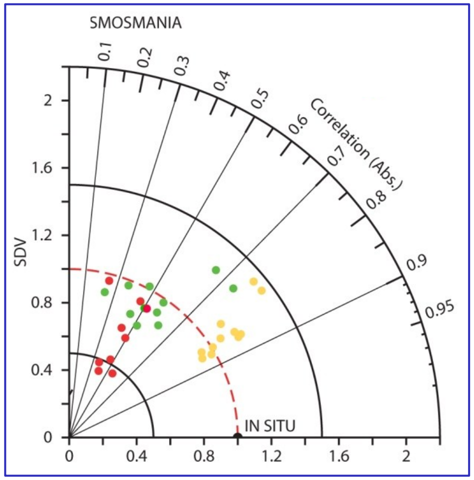
- Soil moisture variations in space and time are related:
  - Large scale components (atmospheric forcing)
  - Small scale components (soil properties, land cover, topography…)

- Temporal stability concept (Vachaud et al, 1985):
  - → Soil moisture patterns tend to persist in time,
  - → Soil moisture observed at a single point is often highly correlated with the mean soil moisture content over an area

Validation strategy : metrics

- R, RMSD, Bias (only cases with significant R, p-value <0.05)
- Normalized standard deviation (SDV), centered unbiased RMSD (E)

→ R, E and SDV are linked and can be displayed on a single diagram easy to interpret; Taylor diagram [$E^2 = SDV^2 + 1 - 2.SDV.R$]



- SDV ($\sigma_{product}$/ σ_{insitu}) as a radial distance
- R as an angle
- E the distance to the point 'INSITU'

- R applied on volumetric and anomaly time-series (remove seasonal cycle)

Applications

- Evaluation of ERA-Land, MERRA-Land & SM-MW
- Evaluation of ASCAT, SMOS and SM-DAS-2
- Use of ERA-Land to monitor SM-MW

ERA-Land, MERRA-Land & SM-MW

- **ERA-Land**
  - Global
  - ~80km
  - Four times a day (00, 06, 12, 18 h)
  - Four layers of soil (0-7, 7-28, 28-100, 100-189cm)
  - 1979-2010

http://apps.ecmwf.int/datasets

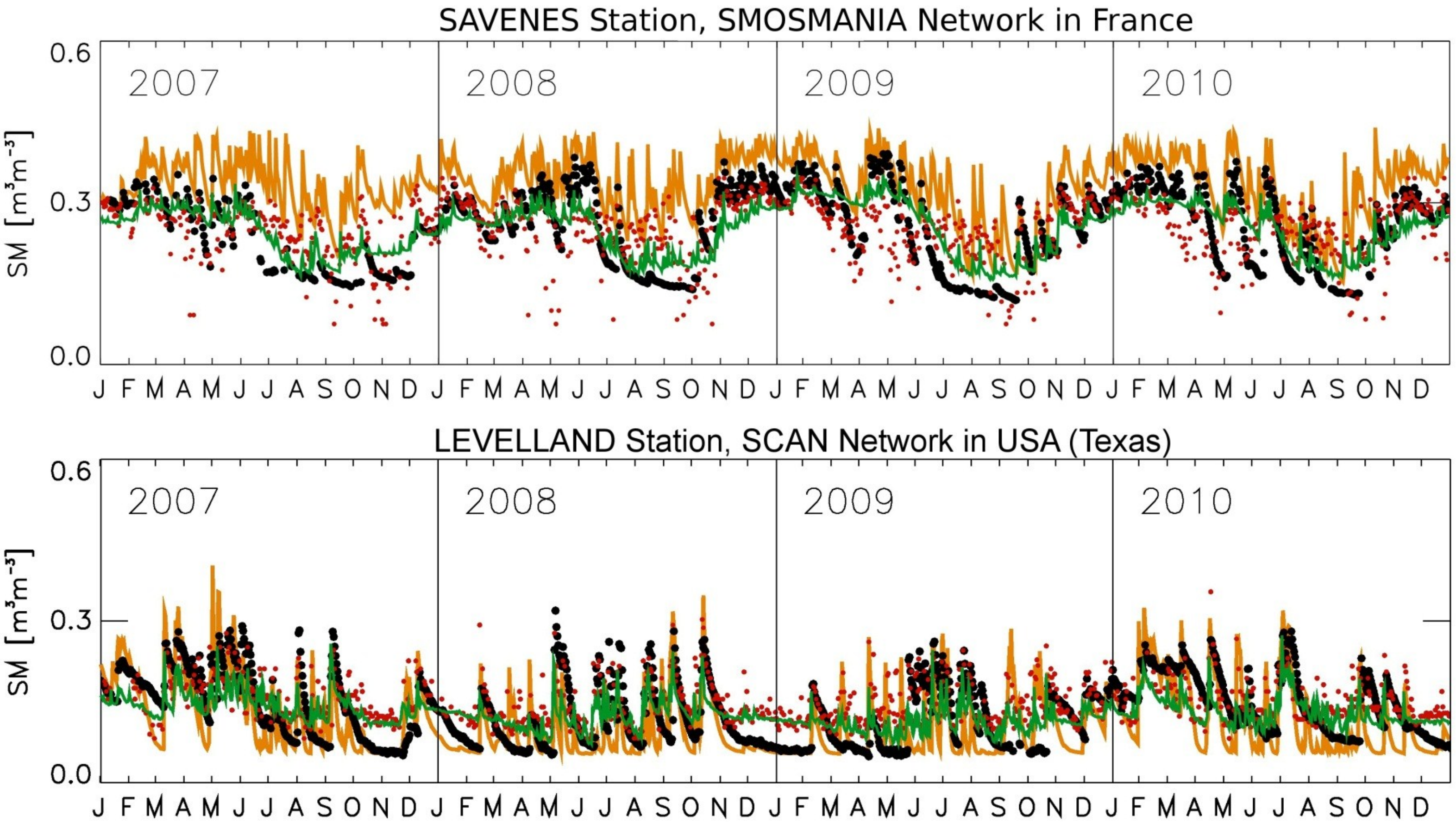
- **MERRA-Land**
  - Global
  - 1/2° lat and 2/3° lon
  - Hourly
  - 2 layers (0-2, 0-100 cm)
  - 1979-onward

http://gmao.gsfc.nasa.gov/research/merra/

- **SM-MW**
  - Global
  - ~25km
  - Daily
  - 0.5-2 cm
  - 1979-2010

http://www.esa-soilmoisture-cci.org/

ERA-Land, MERRA-Land & SM-MW



In situ (5cm) SM-MW MERRA-Land (0-2cm) ERA-Land (0-7cm)

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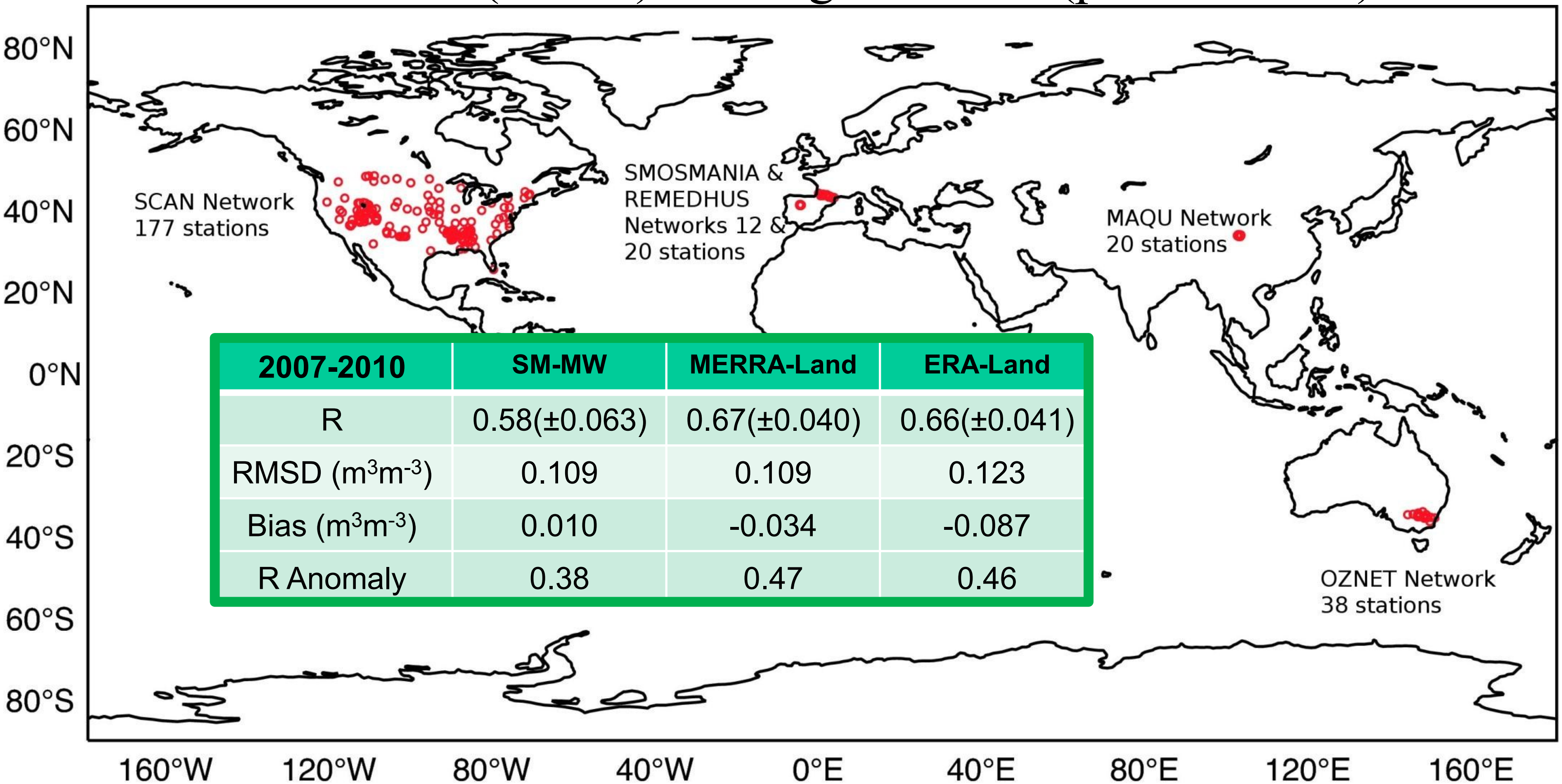
ERA-Land, MERRA-Land, SM-MW

196 stations (of 267) with significant R (p-value<0.05)



2007-2010	SM-MW	MERRA-Land	ERA-Land
R	0.58(±0.063)	0.67(±0.040)	0.66(±0.041)
RMSD (m^3m^{-3})	0.109	0.109	0.123
Bias (m^3m^{-3})	0.010	-0.034	-0.087
R Anomaly	0.38	0.47	0.46

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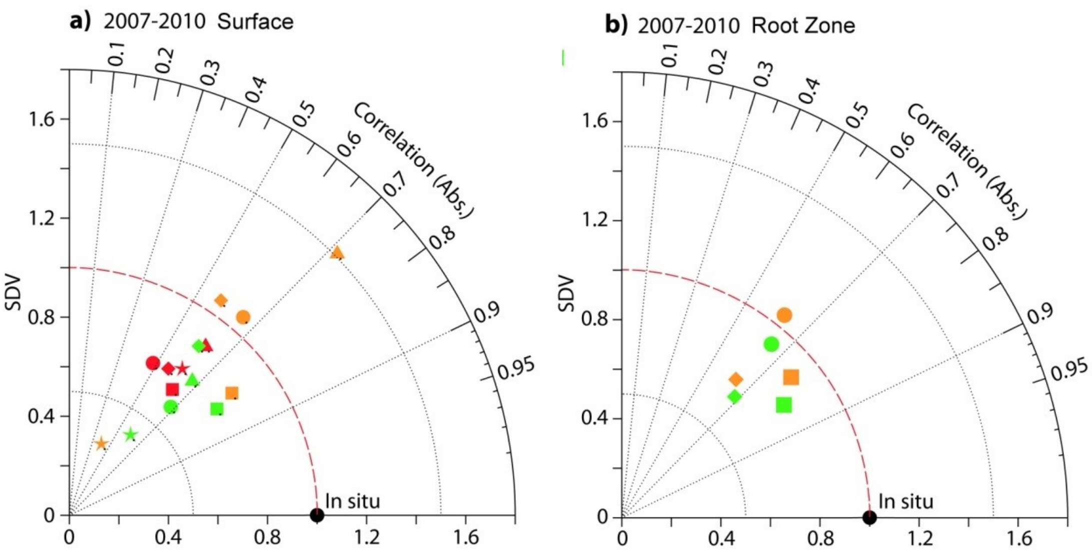
ERA-Land, MERRA-Land, SM-MW



SM-MW
MERRA-Land (0-2cm, 0-100cm)
ERA-Land (0-7cm, 0-100cm)

O (SCAN)
□ (SMOSMANIA)
Δ (REMEDHUS)
• (MAQU)
◊ (OZNET)

- **The three products capture well the temporal dynamics of the observed surface soil moisture (and that of the root zone for ERA-Land, MERRA-Land)**
- **If SM-MW agrees well with ground-based observations, its performance stays in most cases behind that of the latest generation of global Land Surface Models**
- **Interest of SM-MW in areas where land re-analyses might not realistically represent SM (e.g. Maqu network)**

Albergel et al., JHM 2013

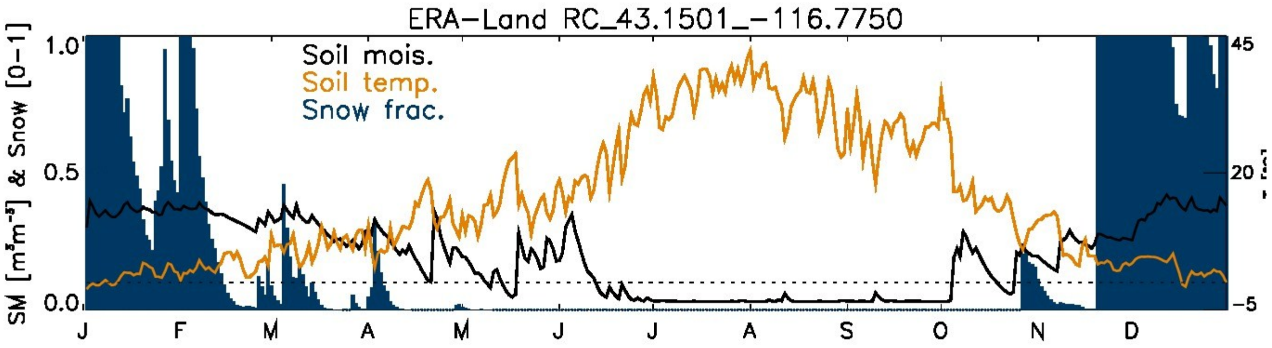
ASCAT, SMOS & SM-DAS-2 : Data preparation

- **ASCAT**
  - Global
  - ~25km
- **SM-DAS-2**
  - Global
  - ~25km
- **SMOS**
  - Global
  - ~43km

- 2012 times series
  - Index ([-]): SM-DAS-2, ASCAT
  - Volumetric: SM (m^3m^{-3}): SMOS, in situ

→ Each product is normalized using its own min and max

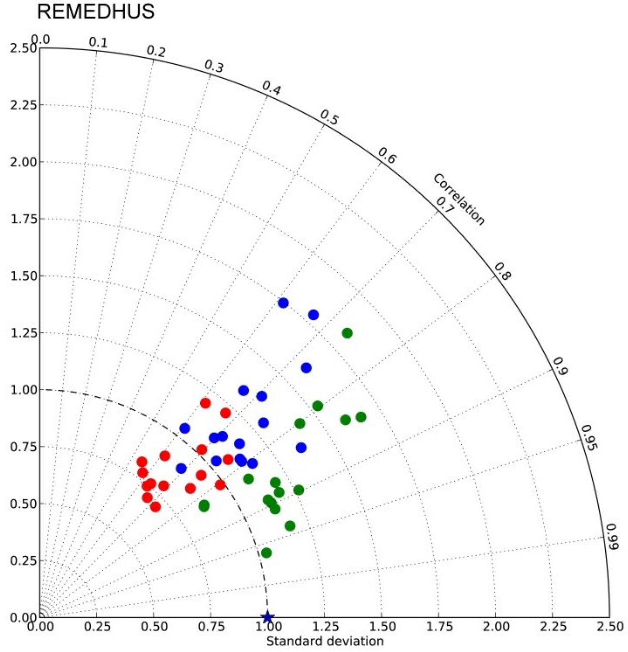
- ASCAT & SMOS filtered out using ERA-Land ST (<4°C) and snow



- SM-DAS-2 filtered out by its own ST (<4°C)
- In situ measurements are filtered out by their own ST (<4°C)

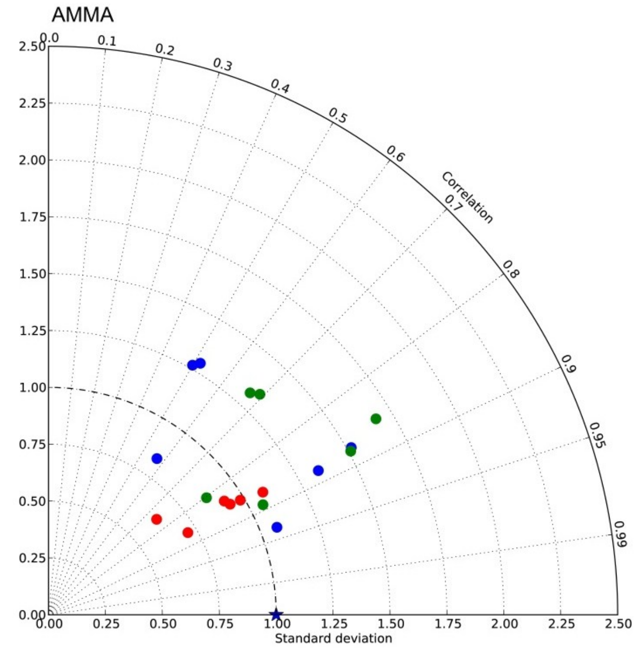
a)

REMEDHUS



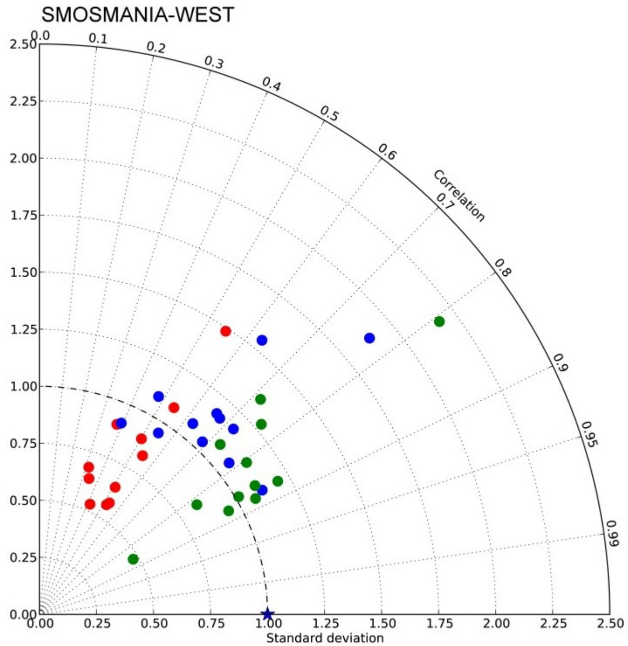
b)

AMMA



c)

SMOSMANIA



SM-DAS-2 ASCAT SMOS

Network	**Mean Correlation [-]** (for stations with significant values)		
	SM-DAS-2	***ASCAT***	***SMOS***
REMEDHUS (nb stations)	**0.84** (17)	**0.71** (17)	**0.67** (17)
AMMA (nb stations)	**0.80** (6)	**0.71** (6)	**0.84** (6)
SMOSMANIA (nb stations)	**0.82** (12)	**0.65** (12)	**0.47** (11)

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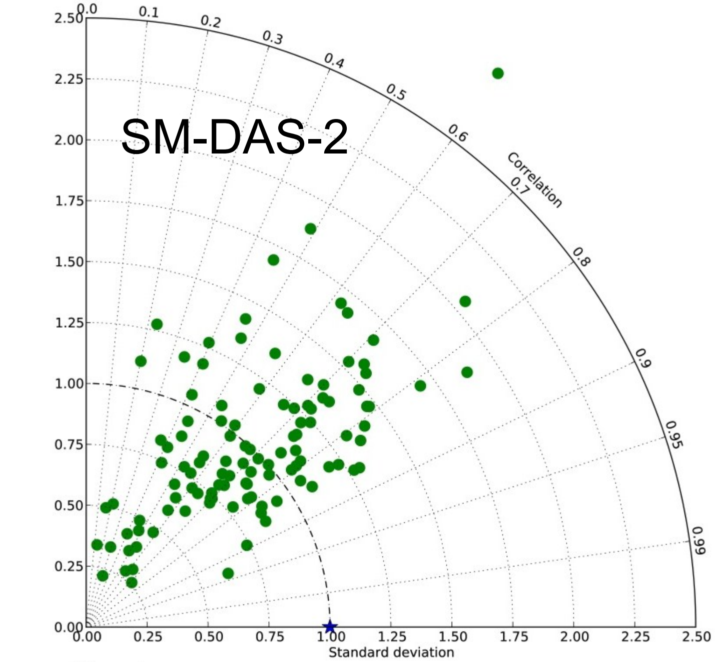
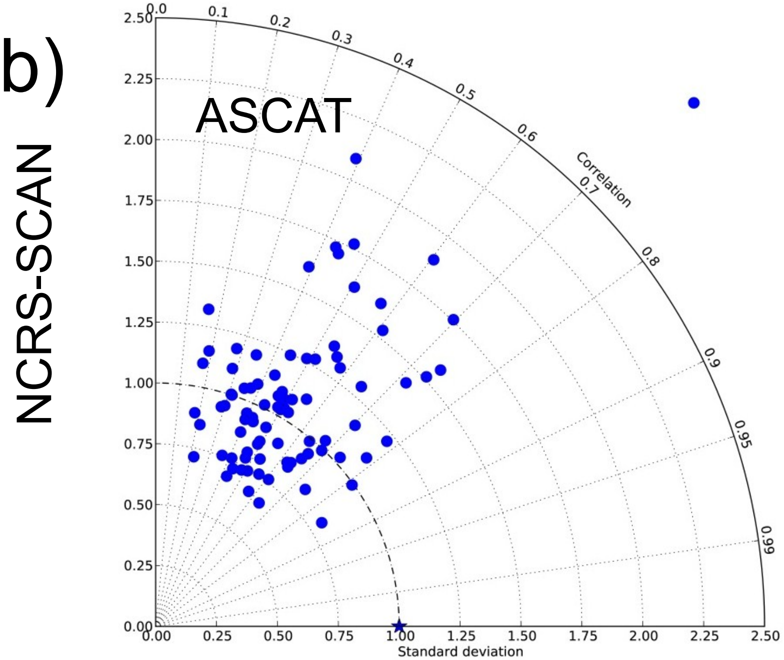
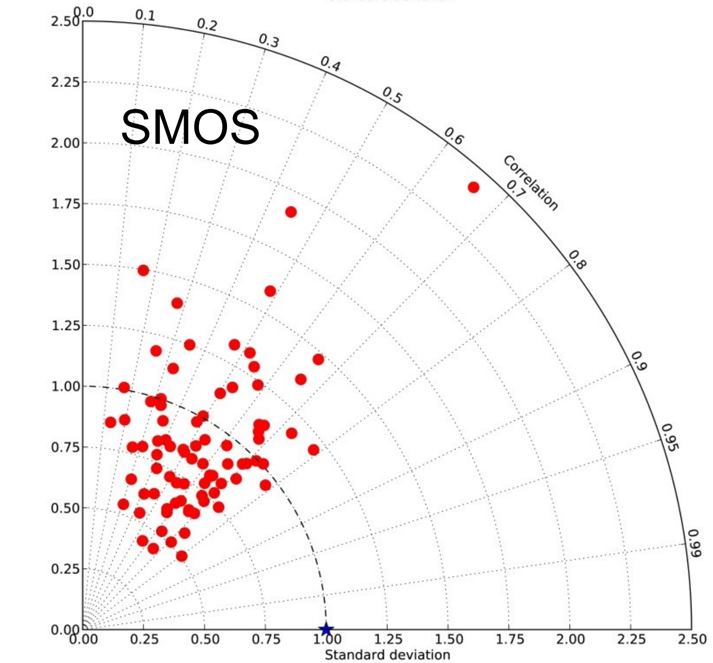
a)



b)



c)



SM-DAS-2 ASCAT SMOS

Correlation [-] (for stations with significant values)		
SM-DAS-2	***ASCAT***	***SMOS***
0.64 (111 stations)	**0.50** (85 stations)	**0.53** (82 stations)

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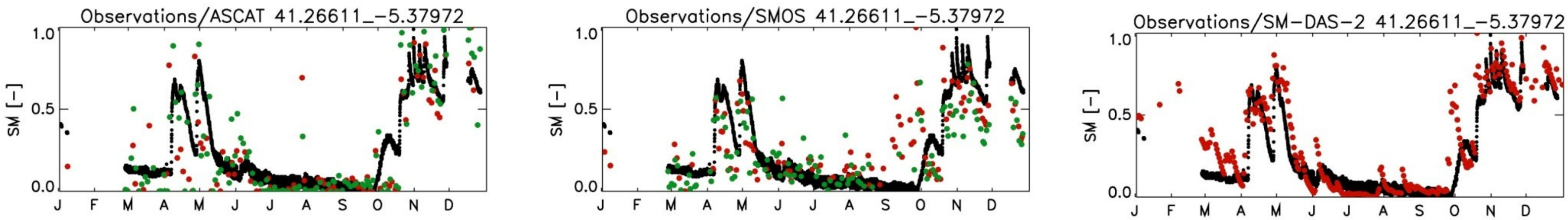
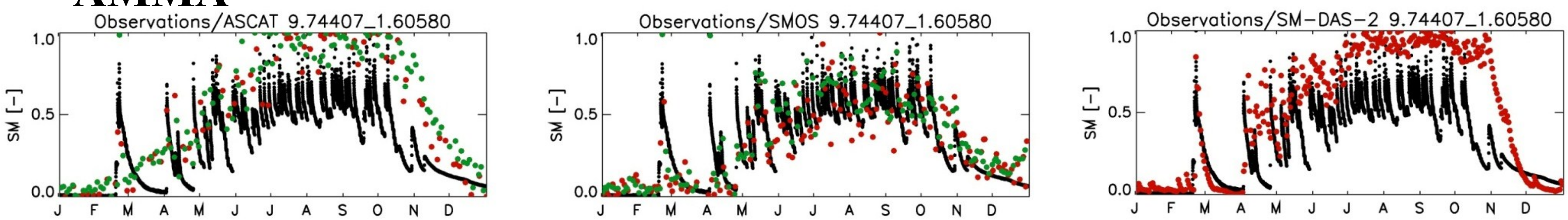
ASCAT, SMOS & SM-DAS-2- 2012 time series

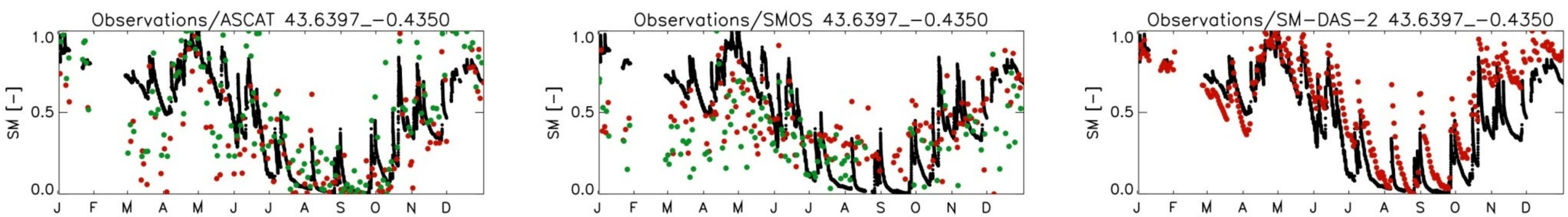
REMEDHUS



AMMA



SMOSMANIA-W

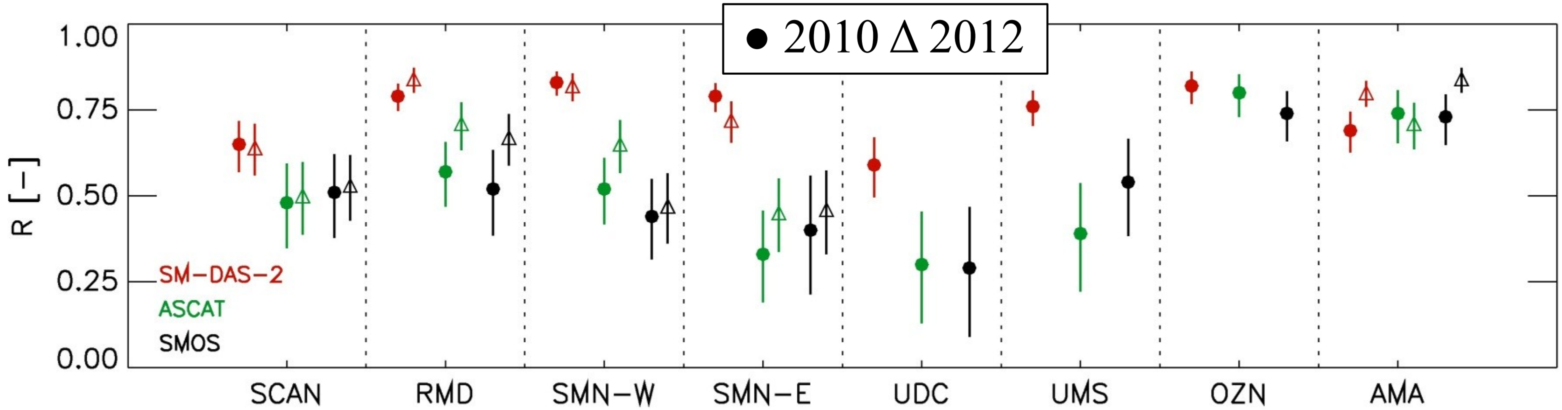


- For ASCAT and SMOS green is am, red is pm

ASCAT, SMOS & SM-DAS-2

Normalized Product (stations with significant R)	SM-DAS-2 (273)	ASCAT (235)	SMOS (216)
Correlation	0.68	0.53	0.53
Bias (index) (In Situ - Product)	-0.047	-0.032	0.034
RMSD (index)	0.230	0.246	0.228

Normalized Product (stations with significant R)	SM-DAS-2 (251)	ASCAT (222)	SMOS (215)
Correlation on Anomaly	0.57	0.39	0.42



[2010 data from Albergel et al. (2012), RSE]

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ASCAT, SMOS & SM-DAS-2

- Stations from 9 networks (USA, France, Spain, Italy, Germany, India, Africa)
- Good performances of the three products to capture surface soil moisture annual cycle, similar for ASCAT & SMOS
- ASCAT & SMOS present better R values for morning passes (not shown)
- Comparison with previous results (2010) suggests ASCAT & SMOS algorithms improvement (2012)
- Future work will investigate the use of ASCAT & SMOS flags (noise, dqx, RFI)

Use of in situ measurements : caveats

- **Very useful, however :**

→ Long term and large scale ground measurements networks are still sparse

→ Different networks will present different characteristics (e.g. measurement methods, installation depths, calibration techniques, temporal/spatial coverage)

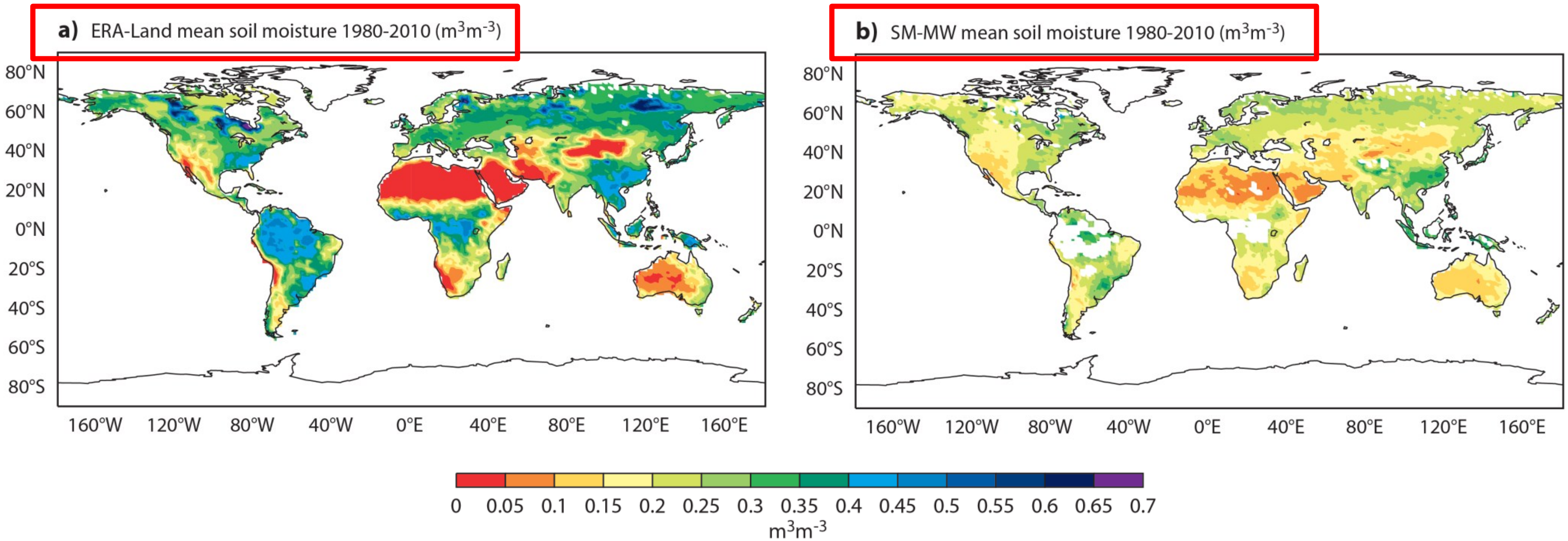
→ The quality of retrieved soil moisture can be accurately assessed for the locations of the stations

→ **Need to conceive new validation methods, complementing the existing soil moisture networks: <u>use of Land Surface Model such as ERA-Land</u>**

Monitoring of SM-MW performances using ERA-Land

- ERA-Land adequately captures the temporal dynamic of soil moisture
    - Large scale nature
    - Fixed configuration
    - Global availability

➔ make it suitable to complement the typical validation approach of soil moisture from remote sensing based on ground measurements



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ECMWF

Monitoring of SM-MW performances using ERA-Land: 2 strategies

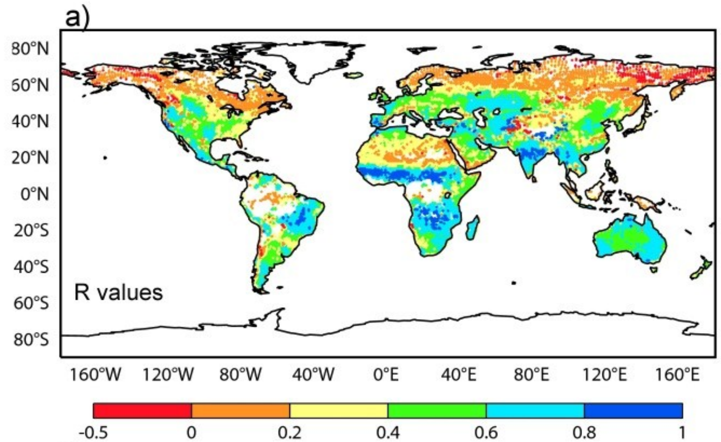
- Correlations (R) are calculated for 3-yr periods (1980-1982 to 2007-2009)
  - Each sub-periods individually (pixels with significant R)
  - Pixels presenting significant level of correlations for each sub-periods (more coherent evaluation)

- Different products used to develop SM-MW, vary over space and time ➔ potential effects, the evaluation is repeated for the following sub-periods:

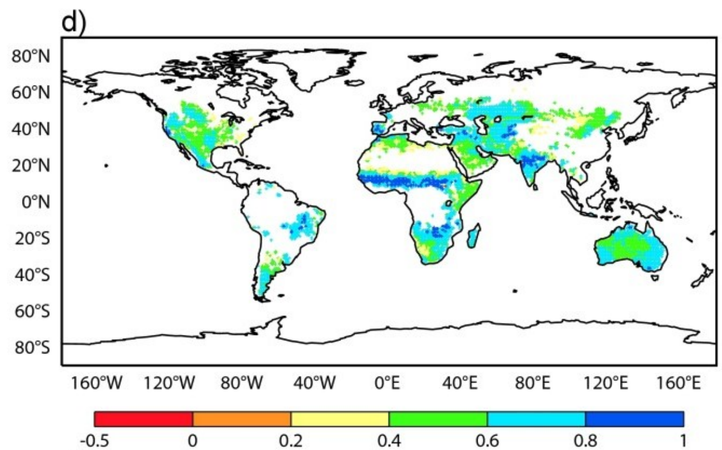
Sensor	Passive / Active µwaves	Channel used for soil moisture	Time-period used
SMMR	Passive	6.6 GHz	01/01/1980 – 31/08/1987
SSM/I	Passive	19.3 GHz	01/09/1987 – 30/06/1991
SSM/I & ERS-AMI	Passive & Active	19.3 & 5.3 GHz	01/07/1991 – 31/12/1997
TMI & ERS AMI [40°N, 40°S], of SSM/I & ERS AMI elsewhere	Passive & Active Passive & Active	10.7 & 5.3, 19.3 & 5.3 GHz	01/01/1998 – 31/06/2002
AMSR-E & ERS AMI	Passive & Active	6.9/10.7 & 5.3 GHz	01/07/2002 – 31/12/2006
AMSR-E & ASCAT	Passive & Active	6.9/10.7 & 5.3 GHz	01/01/2007 – 31/12/2010

Monitoring of SM-MW performances using ERA-Land: results

- Pixels that have significant R values (pvalue<0.05) over 1980-2010

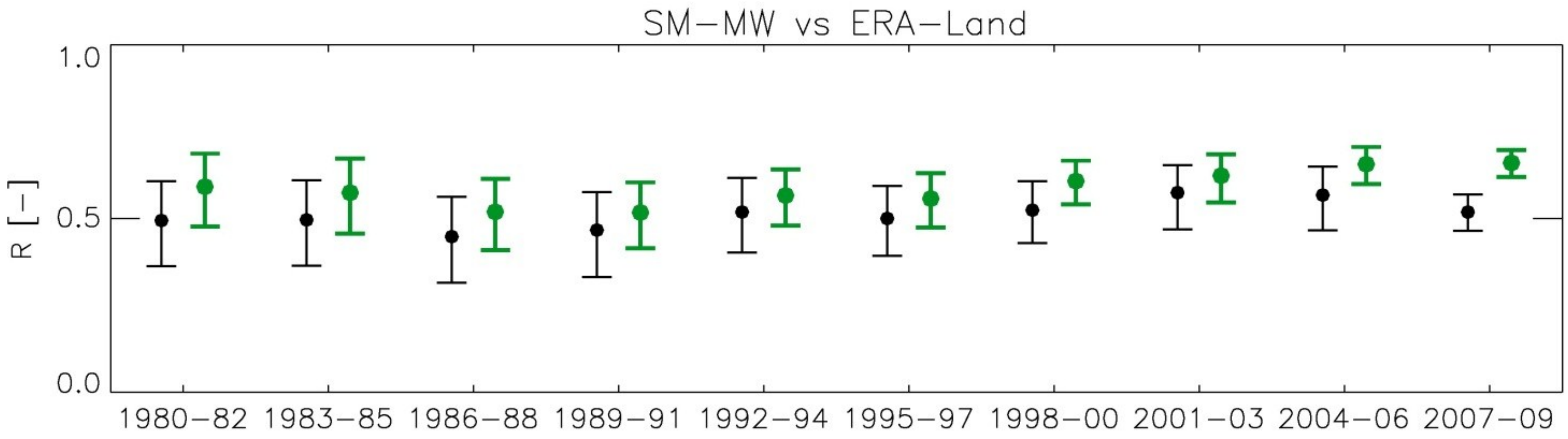


- Pixels that have significant R values (pvalue<0.05) for each 3-yr sub-periods



Monitoring of SM-MW performances using ERA-Land: results

- SM-MW is consistent over time with respect to ERA-Land when considering pixels that have significant R-values for each 3-yr sub-periods (**in green**)



- When considering sub-periods individually (**in black**)
  - Slightly lower R-value for 2006-2009, explained by the addition of data at high-latitude and high-elevation (e.g. European Alps)
  - → Areas where the quality of the retrieval is lower

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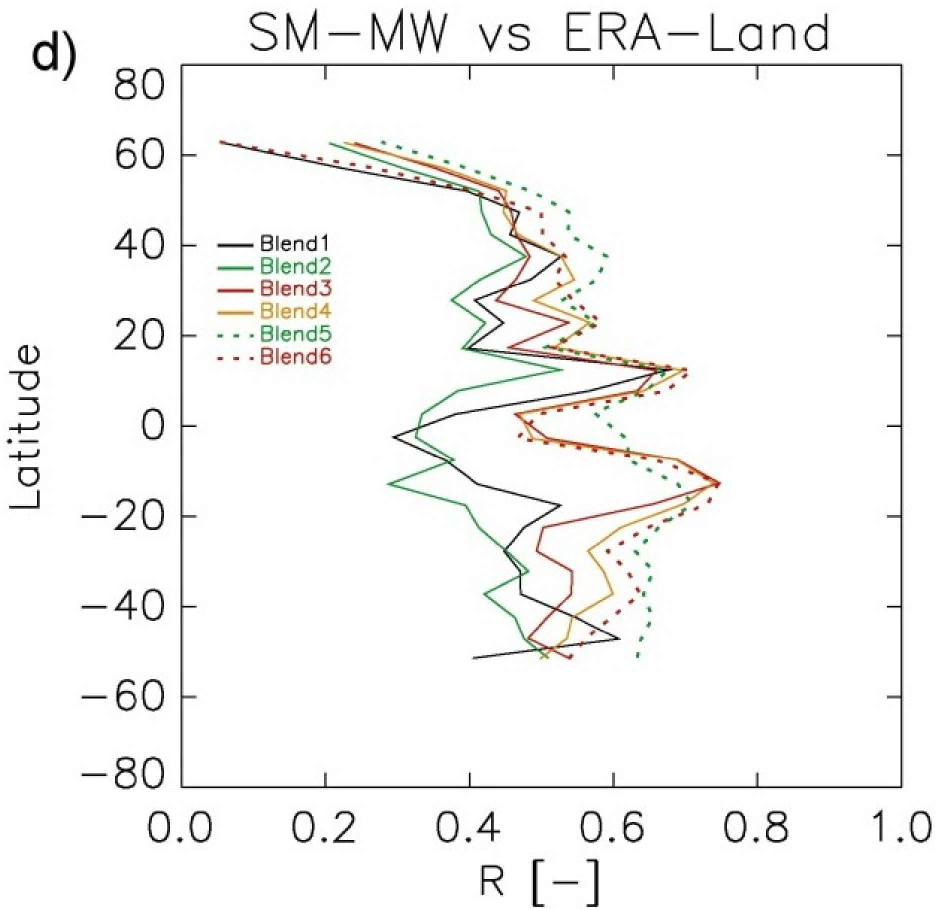
Monitoring of SM-MW performances using ERA-Land: results

1- SMMR
2- SSM/I
3- SSM/I & ERS AMI
4- TMI & ERS AMI [40°N, 40°S], of SSM/I & ERS AMI elsewhere
5- AMSR-E & ERS AMI
6- AMSR-E & ASCAT



Latitudinal plot of correlations between SM-MW and ERA-Land for blended periods, only pixels that have significant correlation value (p-value<0.05) for each blended periods

Monitoring of SM-MW performances using ERA-Land: results

- Retrievals more robust at longer wavelengths
- Lowest score for the period based on SSM/I (passive µwave, Ku-band 19.3GHz): radiance emitted from the soil surface at this wavelength strongly attenuated by the vegetation canopy ➔ increased uncertainty of the retrievals over sparsely vegetated & less data available

- Interpretation of the results hampered by the accuracy of the reference dataset (model itself and its inputs)
  - Albergel et al. (2010, HESS, 2012, JHM) found some non-realistic representation of soil moisture (shortcomings in the soil characteristics and pedotransfer functions…), e.g. over the Tibetan plateau

  ➔ Poor level of correlations in those areas

  ➔ Is the model OK for high latitude/altitude areas?

Evaluating earth observation soil moisture : My two pennies worth

- R, RMSD and Bias (only cases with significant R, p-value <0.05)
- Normalized standard deviation (SDV: $\sigma_{product} / \sigma_{insitu}$) and the centered unbiased RMSD (E) ➔ Taylor diagram
- R should be applied on both volumetric and anomaly time series (monthly sliding windows) to remove the seasonal cycle

- Consider soil moisture networks where soil temperature is also available
- Use of ancillary data if available (e.g. ERA-Land temperature and snow)
- Complementing the existing soil moisture networks using (re-)analyses (e.g. ERA-Land, MERRA-Land) to have a global view

Evaluating earth observation soil moisture : My two pennies worth

- Various products; good correlations, high biases and RMSD
- Spatial variability of in situ soil moisture is very high, differences in soil properties ➔ difference in the mean & variance on soil moisture
  - True information of modelled soil moisture does not necessarily relies on their absolute magnitudes but instead on their time variations
  - Soil properties at the station might be not representative of the area observed from space
- R is found to be more relevant than other standard metrics to evaluate earth observation soil moisture data
- Open question : define a better suited measure of accuracy to characterise the quality of soil moisture data (e.g. in areas with very low variability)

Thank you for your attention !

Contact : clement.albergel@ecmwf.int

Further reading :

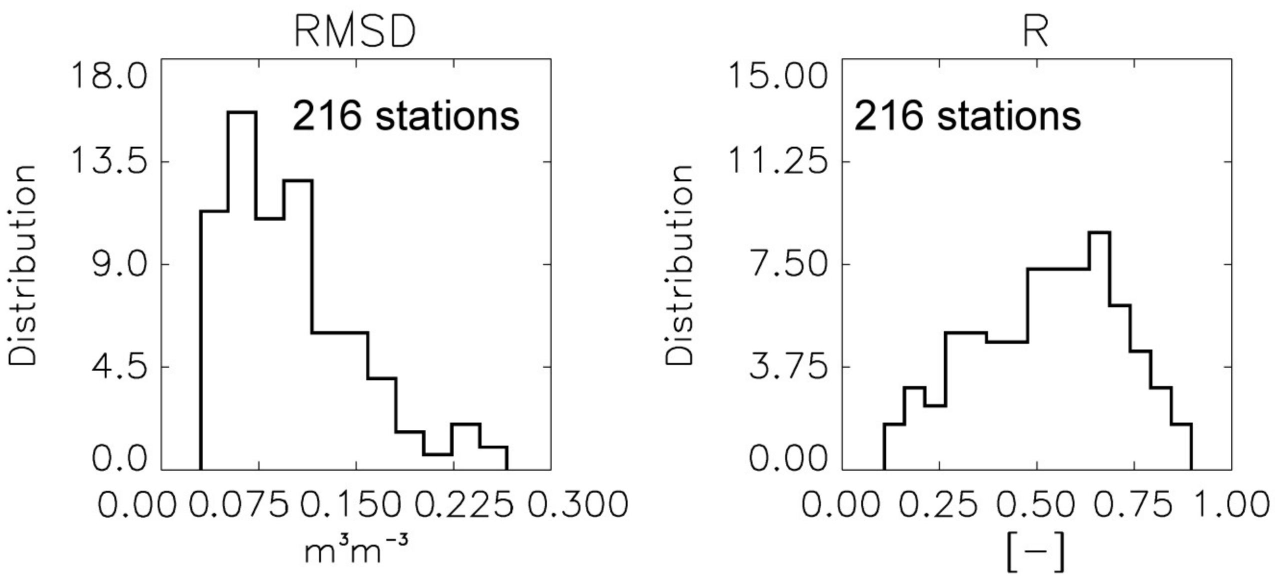
Albergel, C., de Rosnay, P., Gruhier, C., Muñoz-Sabater, J., Hasenauer, S., Isaksen, L., Kerr, Y. & Wagner, W.: **Evaluation of remotely sensed and modelled soil moisture products using global ground-based in situ observations**. *Remote Sensing of Environment*, 118, 215-226, 2012.

Albergel, C., De Rosnay, P., Balsamo, G., Isaksen, L. & Munoz-Sabater, J.: **Soil Moisture Analyses at ECMWF: Evaluation Using Global Ground-Based In Situ Observations**. *Journal of Hydrometeorology*, 13, 1442-1460, 2012

Albergel, C., W. Dorigo, R. H. Reichle, G. Balsamo, P. de Rosnay, J. Munoz-Sabater, L. Isaksen, R. de Jeu, and W. Wagner: **Skill and global trend analysis of soil moisture from reanalyses and microwave remote sensing**, *Journal of Hydrometeorology*, doi:10.1175/JHM-D-12-0161.1, 2013.
http://journals.ametsoc.org/doi/abs/10.1175/JHM-D-12-0161.1

Albergel, C, W. Dorigo, G. Balsamo, J. Munoz-Sabater, P. de Rosnay, L. Isaksen, L. Brocca, R. de Jeu, and W. Wagner: **Monitoring multi-decadal satellite earth observation of soil moisture products through land surface reanalyses**. *Submitted to Remote Sensing of Environment*, April 2013, RSE-D-13-00279

SMOS : m^3m^{-3}



2012	SMOS (216)
Correlation	0.53
Bias	0.024 (m^3m^{-3})
RMSD	0.105 (m^3m^{-3})

In situ measurement vs. coarse resolution products

- Even if local in situ observations do not measure the same quantity as coarse resolution products (e.g. remotely sensed), significant correlation can be obtained between the two measures
- Soil moisture variations in space and time related:
  - Large scale components (atmospheric forcing)
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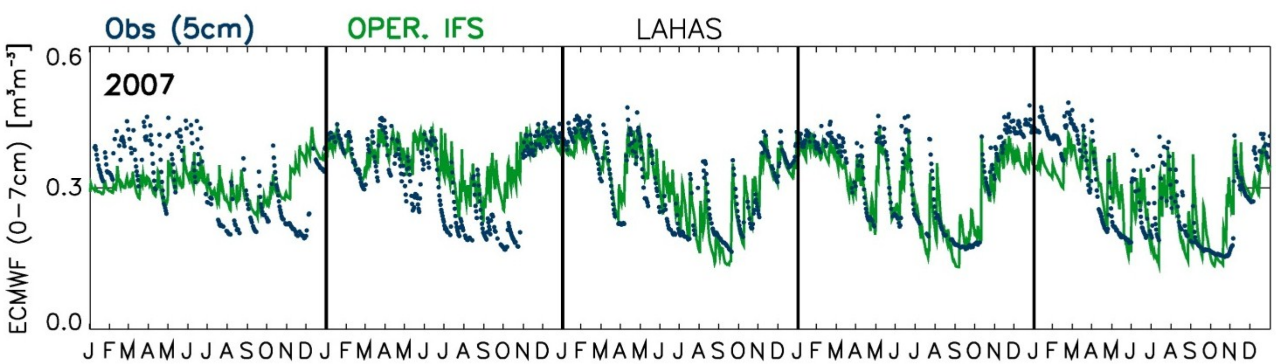
- Temporal stability concept (Vachaud et al, 1985): Soil moisture patterns tend to persist in time, soil moisture observed at a single point is often highly correlated with the mean soil moisture content over an area



Validation strategy : metrics

- **Monthly anomaly (remove seasonal effects, ability of SM products to reproduce SM short term variability):**
  - **The difference to the mean is calculated for a sliding window of five weeks 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]**

$$Ano(i) = \frac{SM(i) - \overline{SM(F)}}{stdev(SM(F))}$$

- **R computed on volumetric and anomaly time-series**

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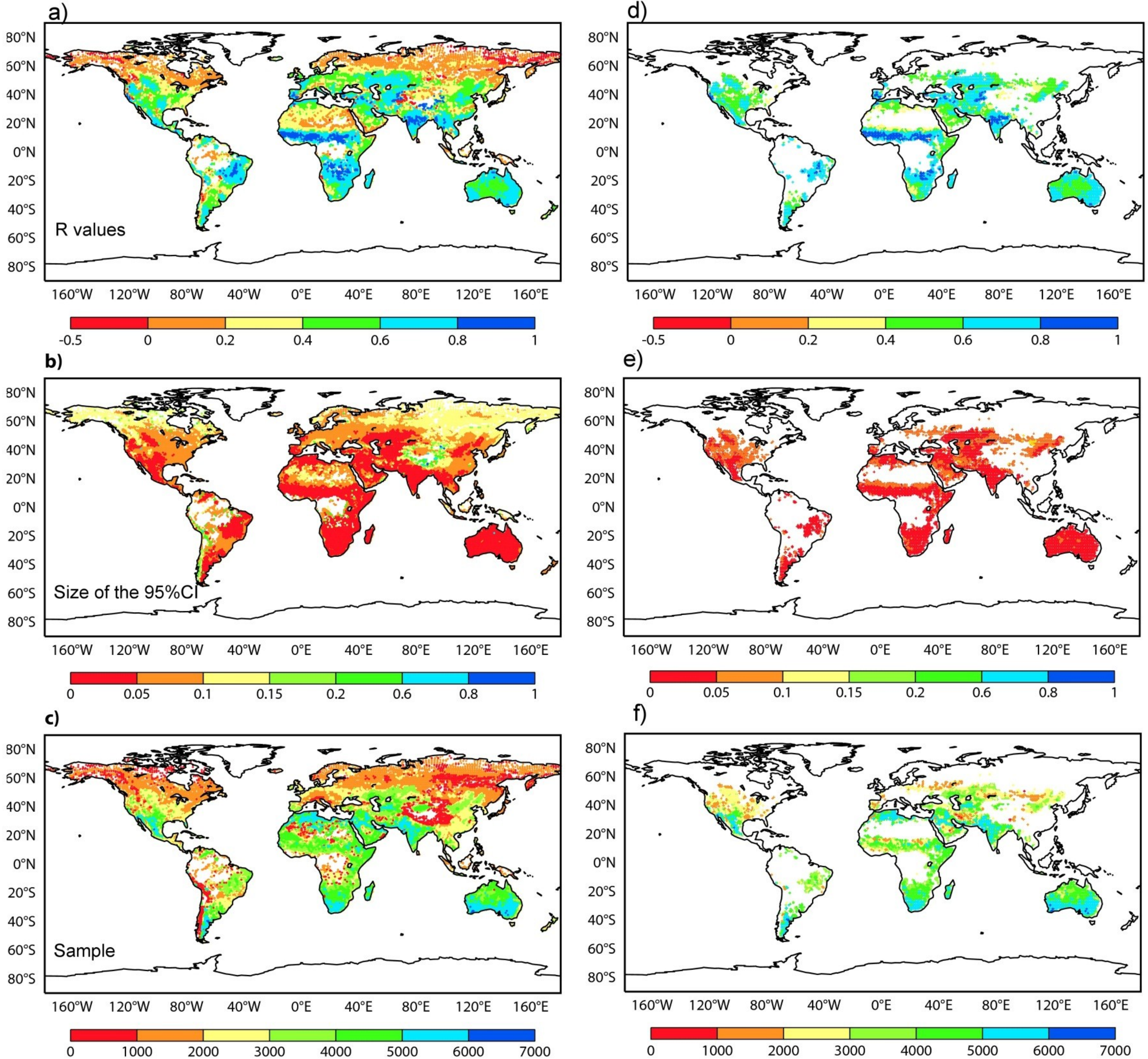
Evaluation of SM-MW performances using ERA-Land

- ERA-Land adequately captures the temporal dynamic of soil moisture
  - Large scale nature
  - Fixed configuration
  - Global availability
  - Ability to represent soil moisture variability well

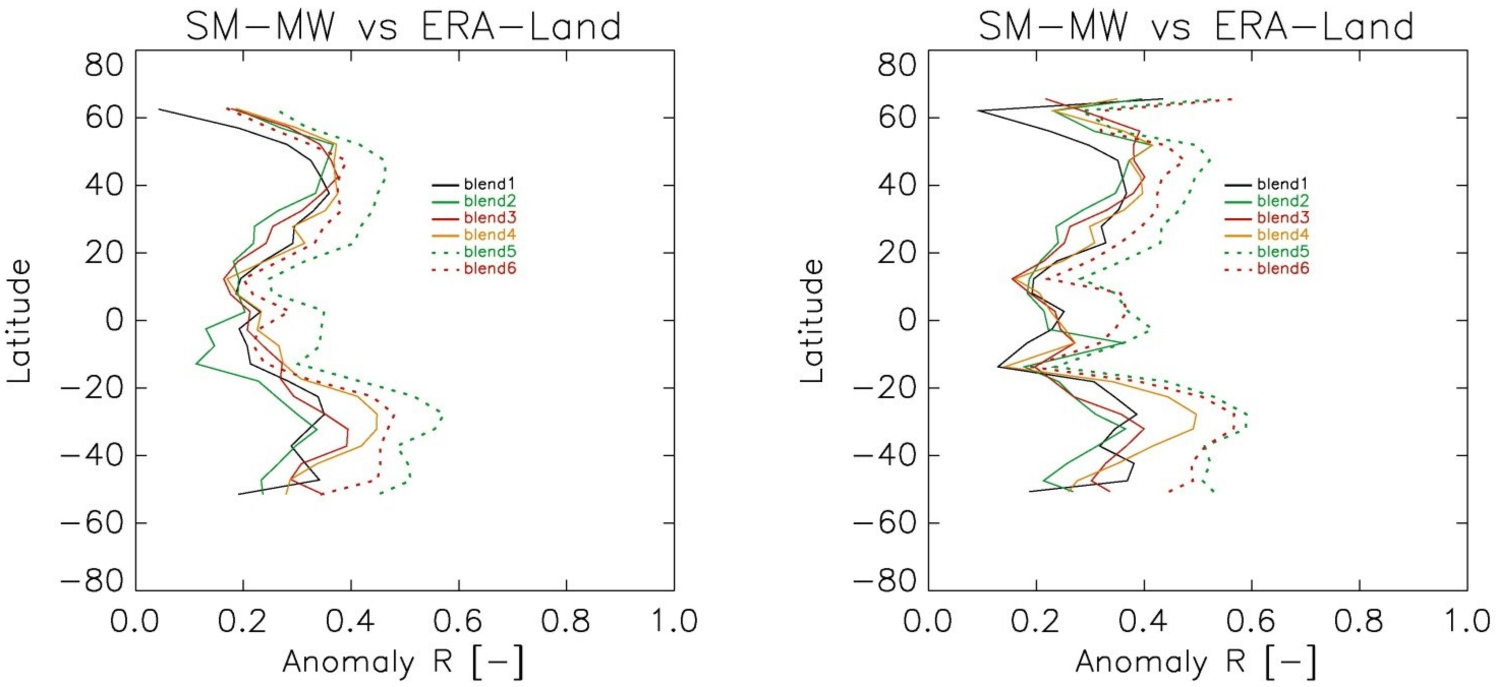
➔ make it suitable to complement the typical validation approach of soil moisture from remote sensing based on ground measurements

- **2010: 620 stations from 11 networks;**
  - **R(95%CI)=0.66(±0.08)** [(ranging from 0.57(±0.11) for the MAQU network in China to 0.84(±0.03) for the SMOSMANIA network in France]**,**
  - **RMSD=0.118 m^3m^{-3} and Bias=-0.063 m^3m^{-3}**


a)
R values
b)
Size of the 95%CI
c)
Sample
d)
e)
f)
80°N 60°N 40°N 20°N 0°N 20°S 40°S 60°S 80°S
160°W 120°W 80°W 40°W 0°E 40°E 80°E 120°E 160°E
-0.5 0 0.2 0.4 0.6 0.8 1
0 0.05 0.1 0.15 0.2 0.6 0.8 1
0 1000 2000 3000 4000 5000 6000 7000

Evaluation of SM-MW performances using ERA-Land: results

Correlations on anomaly time-series to remove the annual cycle



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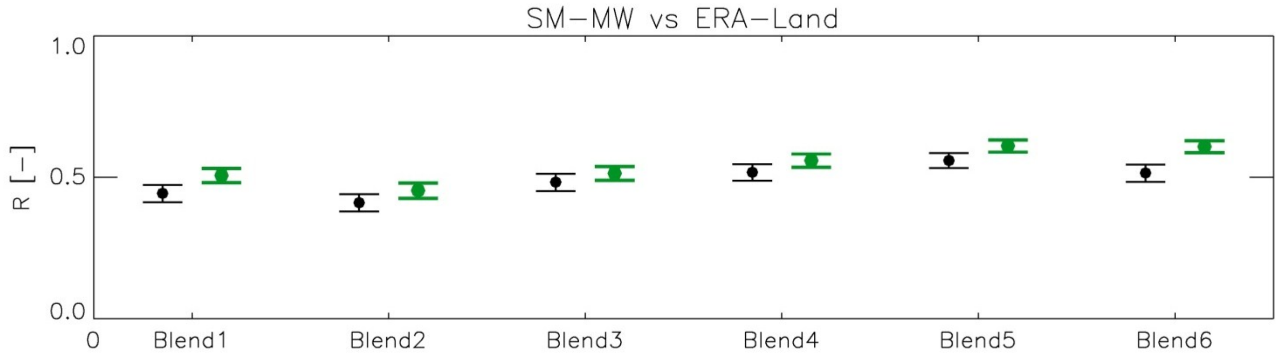
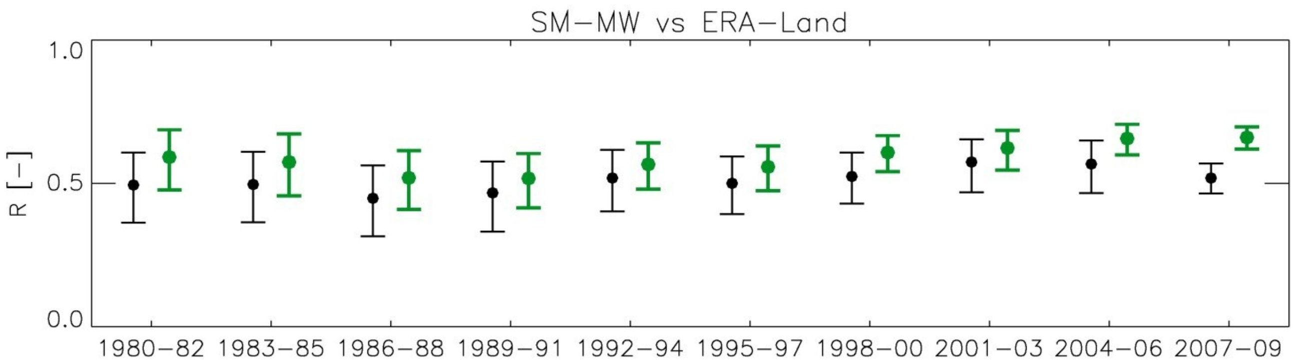
1- SMMR
2- SSM/I
3- SSM/I & ERS AMI
4- TMI & ERS AMI [40°N, 40°S], of SSM/I & ERS AMI elsewhere
5- AMSR-E & ERS AMI
6- AMSR-E & ASCAT



Averaged correlation values, R, (95% confidence Intervals) between SM-MW and ERA-Land for each blended period. Black dots represent each period considered individually, green dots represent for each periods pixels which have significant R values for all periods (only pixels with significant R values, p-values<0.05)



Averaged correlation values, R, (95% confidence Intervals) between SM-MW and ERA-Land for each 3-yr sub-periods within 1980-2010. Black dots represent each period considered individually (only pixels with significant R values, p-values<0.05), green dots represent for each periods pixels which have significant R values for all periods

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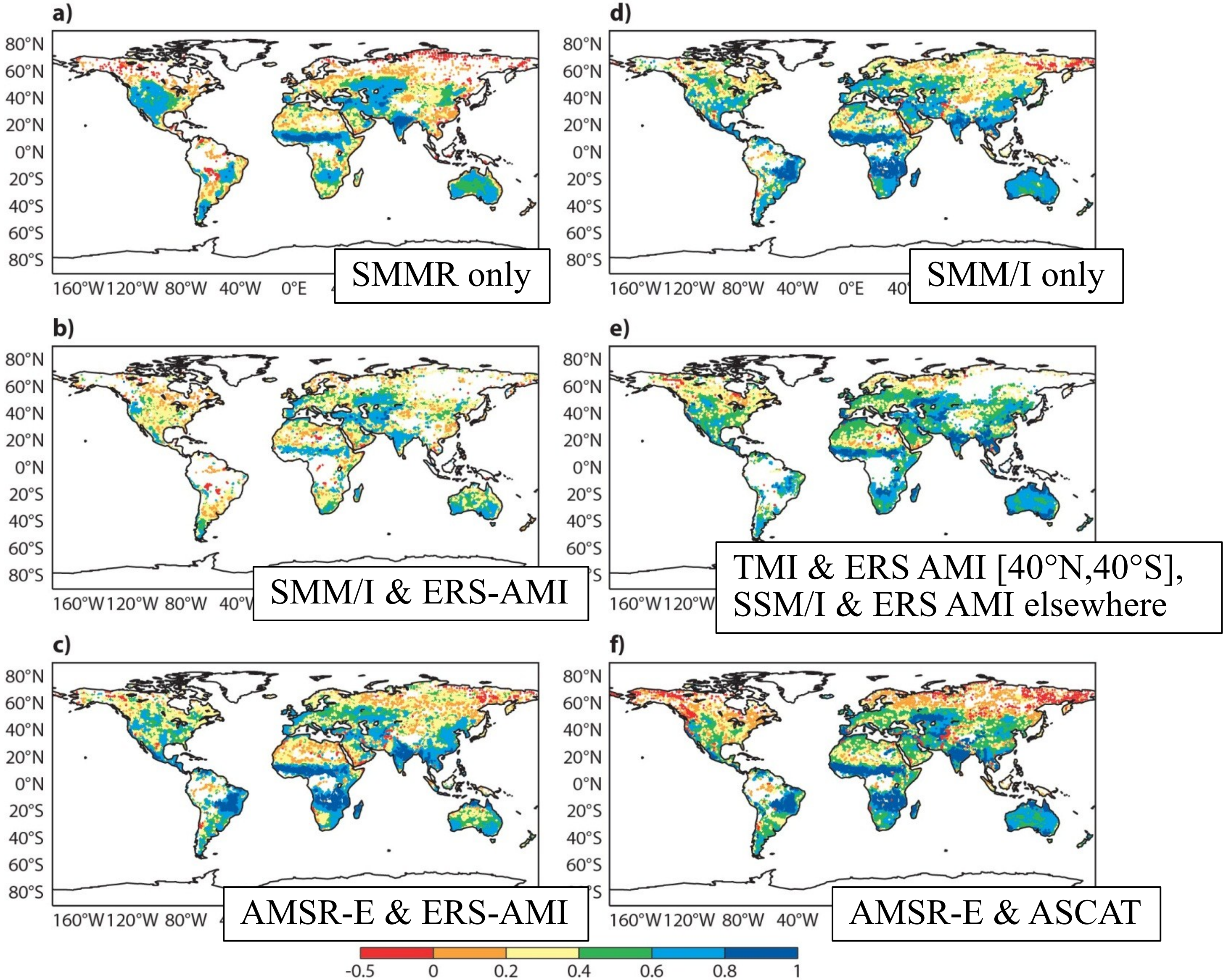
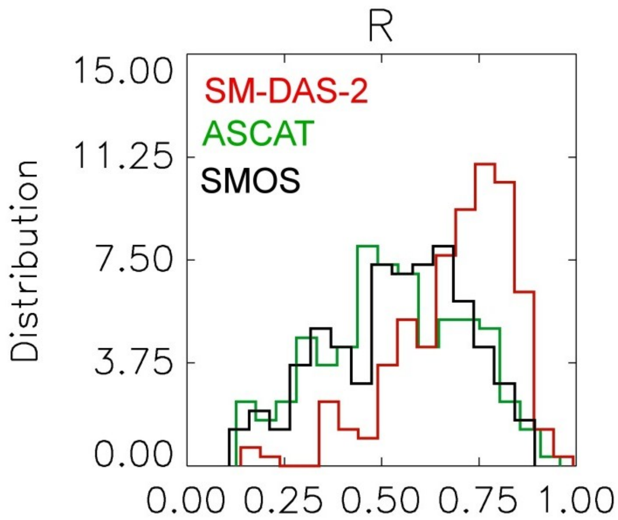


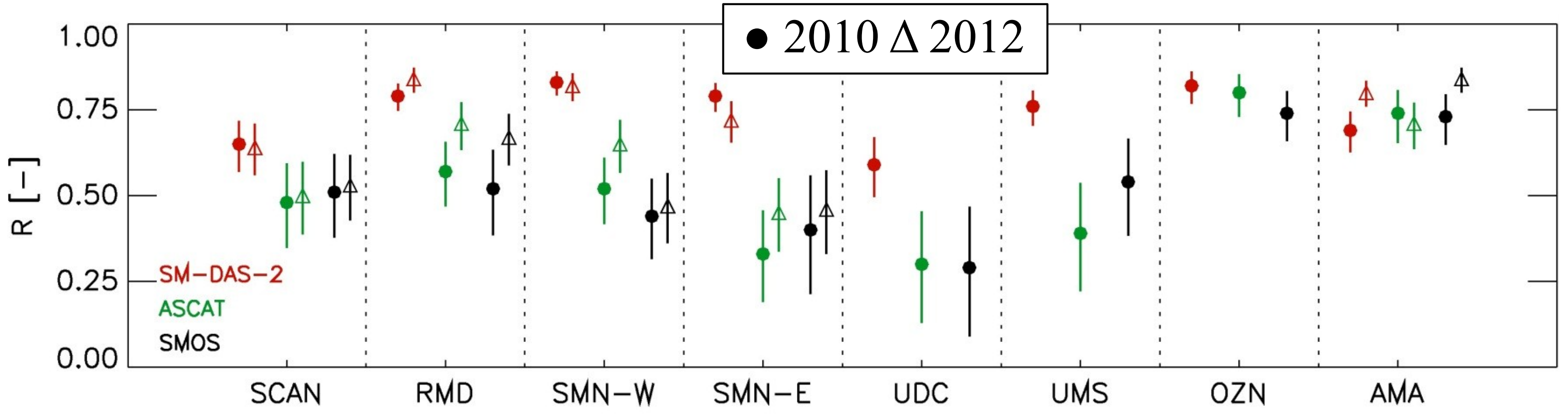
Correlations value between SM-MW and ERA-Land for the 6 blended periods considered individually. Only significant level of correlations, p-value<0.05

ASCAT, SMOS & SM-DAS-2

Normalized Product (stations with significant R)	SM-DAS-2 (273)	ASCAT (235)	SMOS (216)
Correlation	0.68	0.53	0.53
Bias (index) (In Situ - Product)	-0.047	-0.032	0.034
RMSD (index)	0.230	0.246	0.228

Normalized Product (stations with significant R)	SM-DAS-2 (251)	ASCAT (222)	SMOS (215)
Correlation on Anomaly	0.57	0.39	0.42





[2010 data from Albergel et al. (2012), RSE]

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Monitoring of SM-MW performances using ERA-Land: results

- Very good agreement in the tropics and close to the Equator, all over Australia and south Russia
- SM-MW is consistent over time with respect to ERA-Land when considering pixels that have significant R-values for each 3-yr sub-periods

ERA-Land vs. SM-MW	1980-82	1983-85	1986-88	1989-91	1992-94	1995-97	1998-00	2001-03	2003-05	2006-09	1980-2010
R (95%CI)	0.59 (±0.11)	0.57 (±0.11)	0.52 (±0.10)	0.52 (±0.10)	0.57 (±0.08)	0.56 (±0.08)	0.61 (±0.06)	0.62 (±0.07)	0.66 (±0.05)	0.66 (±0.04)	0.60 (±0.02)
RMSD m^3m^{-3}	0.100	0.101	0.104	0.105	0.103	0.104	0.098	0.096	0.095	0.094	0.099
Bias m^3m^{-3}	0.005	0.008	0.004	0.005	0.002	0.008	0.006	0.008	0.007	0.003	0.005

- When considering sub-periods individually, slightly lower R-value for 2006-2009, explained by the addition of data at high-latitude and high-elevation (e.g. European Alps) ➔ areas where the quality of the retrieval is lower

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