# Use of SMOS data in a coupled land-atmospheric model

*sensitivity to different model and observation error scenarios*

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P. de Rosnay, C. Albergel, G. Balsamo, L. Isaksen, M. Drusch and many other

# SMOS & ECMWF

➢ **<u>Mission objective:</u>** Provide global measurements of two key variables in the water cycle: soil moisture and ocean salinity.

**L-band mission (innovative 2D interferometric radiometer); transparent to clouds, large penetration depth, less sensitive to vegetation canopy and soil roughness.**

➢ **<u>Objectives at ECMWF:</u>**

- Global **monitoring** of $T_B$ at the satellite antenna reference frame, <u>in NRT</u>
- **Assimilation** of SMOS $T_B$ over continental surfaces & investigate the meteorological impact of SMOS data assimilation

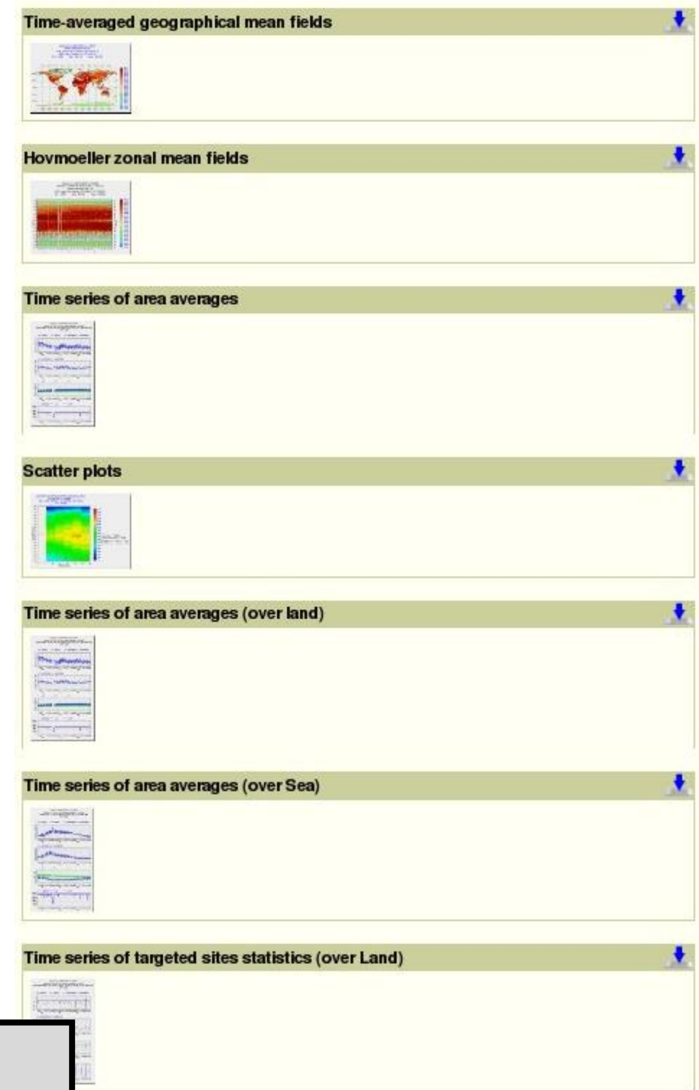
- **Introducing new observations is an efficient way to improve the forecast/analysis**

# Monitoring SMOS TB

- **Routinely production of statistics with SMOS $T_B$, model equivalents and background departures, <u>in NRT</u>**
  - Global scale
  - Land and oceans separately,
  - Several incidence angles [**10, 20, 30, 40, 50, 60**],
  - Two polarisations states [**XX, YY**],
  - Independently per continents and hemispheres,

- **Statistical products,**
  - Time-averaged geographical mean-fields (last 6 weeks of data),
  - Hovmöller zonal mean fields (last 3 months),
  - Time series of area averages (last 3 months),
  - Angular distribution of bias: background departures as function of incidence angle (last 5 weeks).

- **Support to CAL/VAL sites →** time series produced for 17 sites




*564 images are produced and updated daily → important contribution to the SMOS quality control*

**[http://old.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/smos/]**

# SMOS & ECMWF

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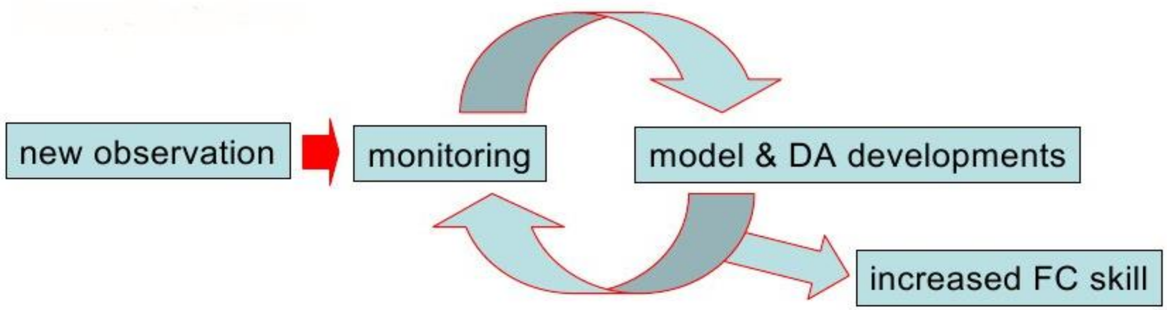


# Soil moisture analysis at ECMWF

**Simplified Extended Kalman Filter:**

For each grid point, analysed state vector $\boldsymbol{x}_a$:

$$\boldsymbol{x}_a = \boldsymbol{x}_b + \mathbf{K}\,(\boldsymbol{y} - \mathcal{H}[\boldsymbol{x}_b])$$

$\boldsymbol{x}_b$ : background state vector,

$\boldsymbol{y}$ : observation vector

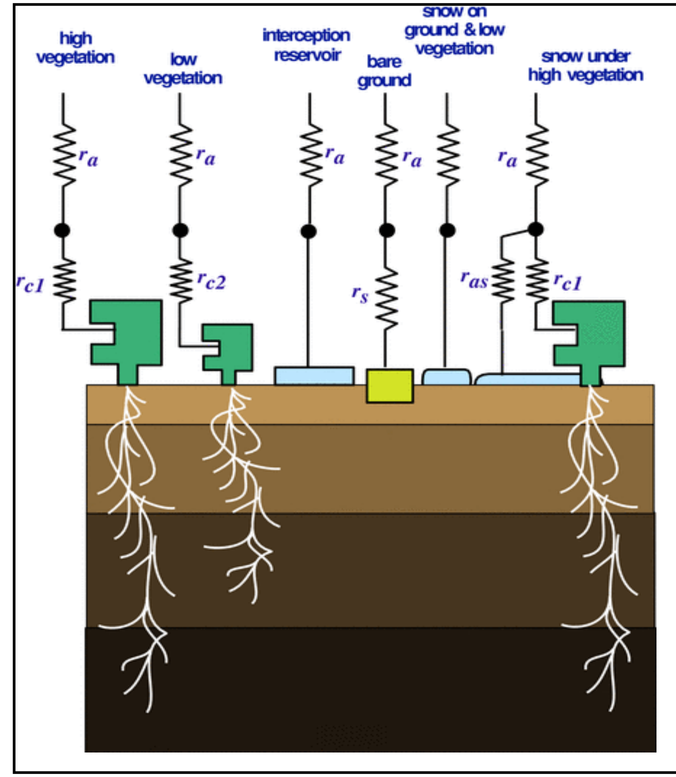
$\mathcal{H}$ : non linear observation operator

**K** : Kalman gain matrix

$$\mathbf{K} = [\mathbf{B}^{-1} + \mathbf{H}^T \mathbf{R}^{-1} \mathbf{H}]^{-1} \mathbf{H}^T \mathbf{R}^{-1}$$

**Observations:**

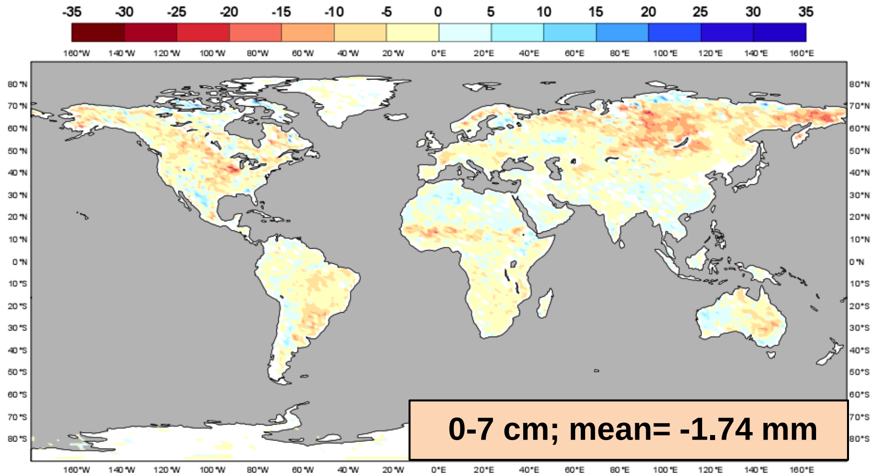
- Operations: screen level variables (SLV): $T^{2m}$, $RH^{2m}$
- Research:
  - ASCAT soil water index (METOP-A, METOP-B),
  - SMOS Brightness temperatures




**LSM : HTESSEL**
0-7cm, 7-28cm, 28-100cm, 100-289cm
(*Balsamo et al., JHM, 2009*)

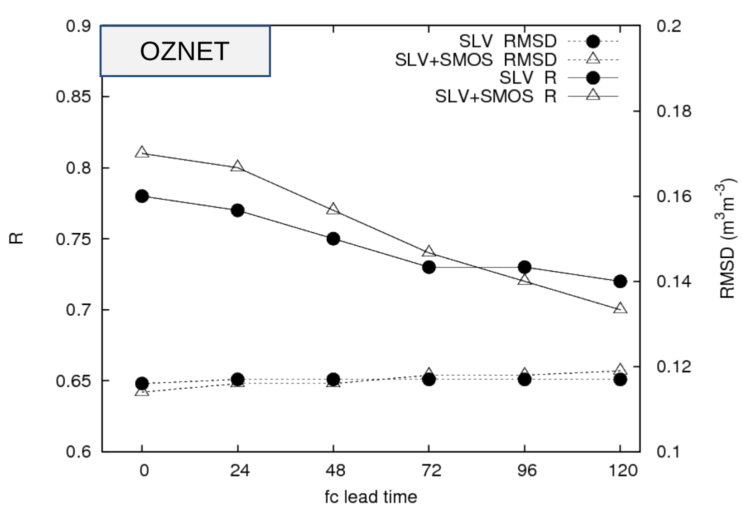
# SMOS DA impact experiments

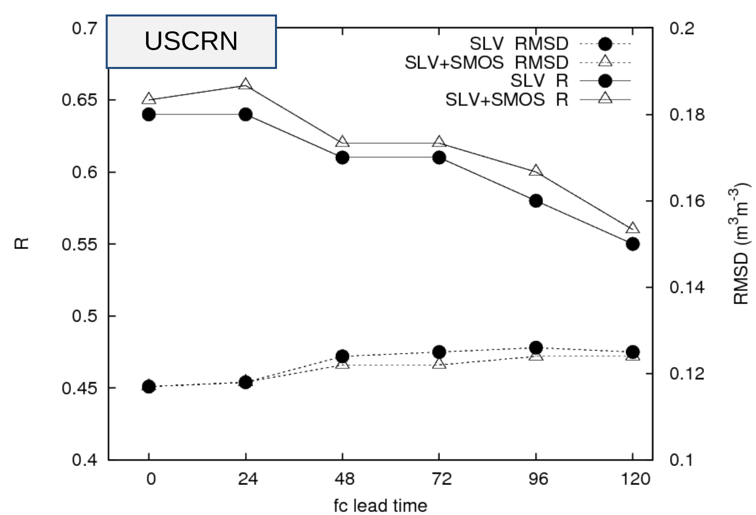
**SMOS $T_B$ – SLV (JJA)**



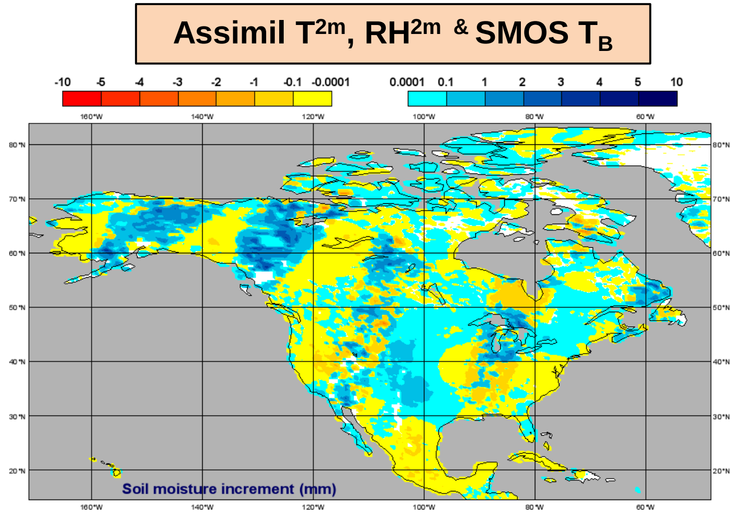

**SM analyses were validated against more than 600 in-situ stations in 10 different countries:**

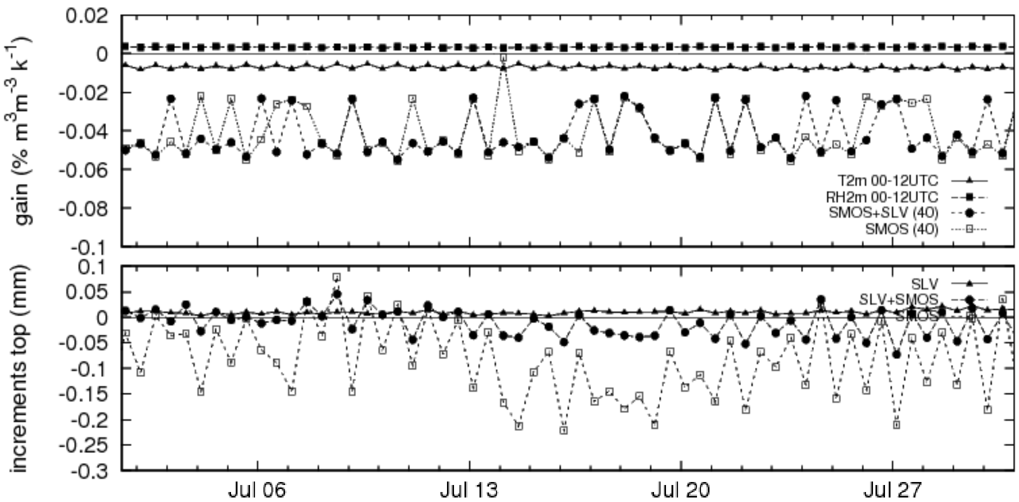
- Impact on soil moisture is high!,
- SM dynamic is improved and bias reduced,
- Root-zone is better characterised,
- Skill in the forecast of soil moisture is kept at least up to 72 h.



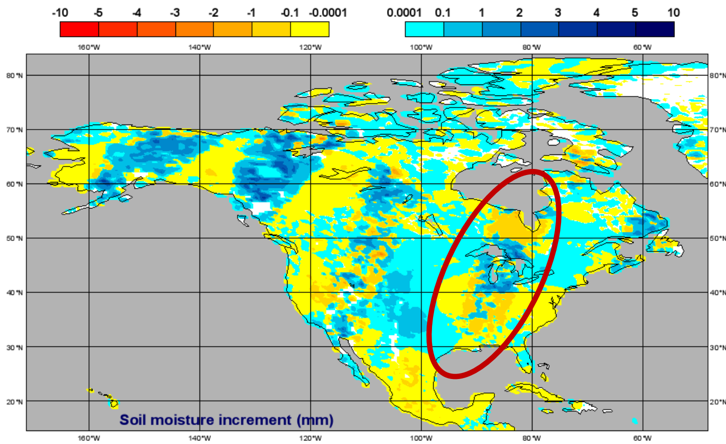
# SMOS DA impact experiments

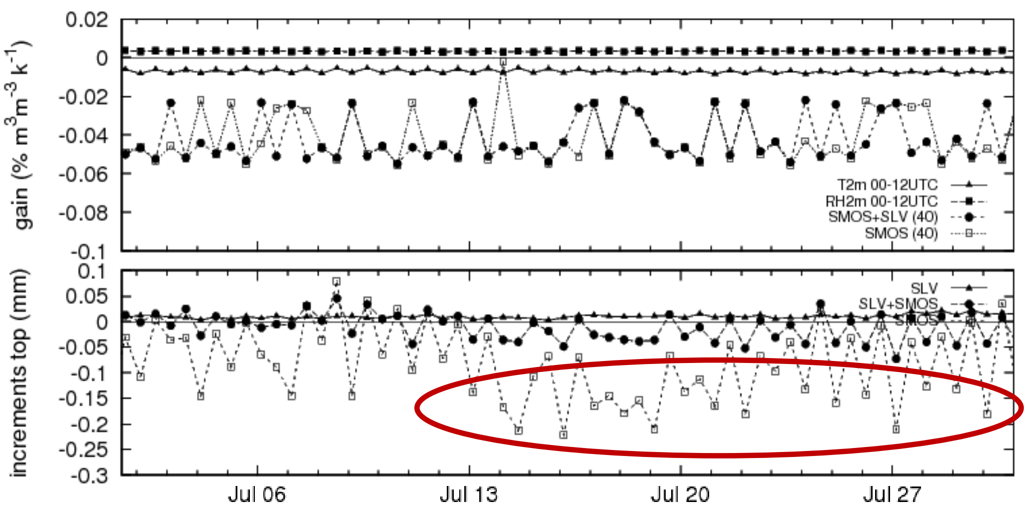


# SMOS DA impact experiments

**Assimil $T^{2m}$, $RH^{2m}$ & SMOS $T_B$**



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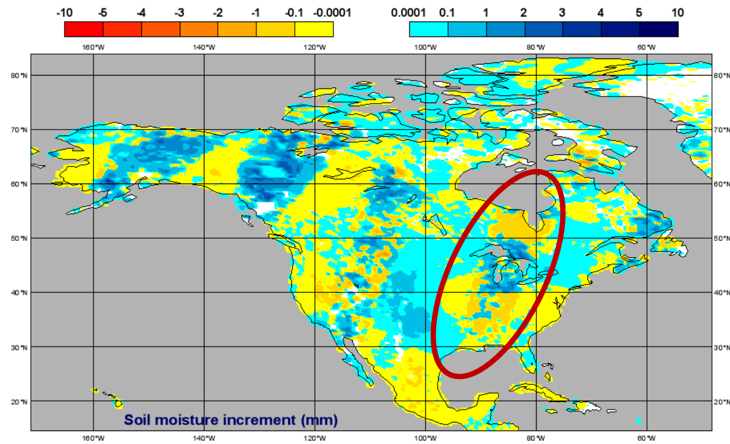
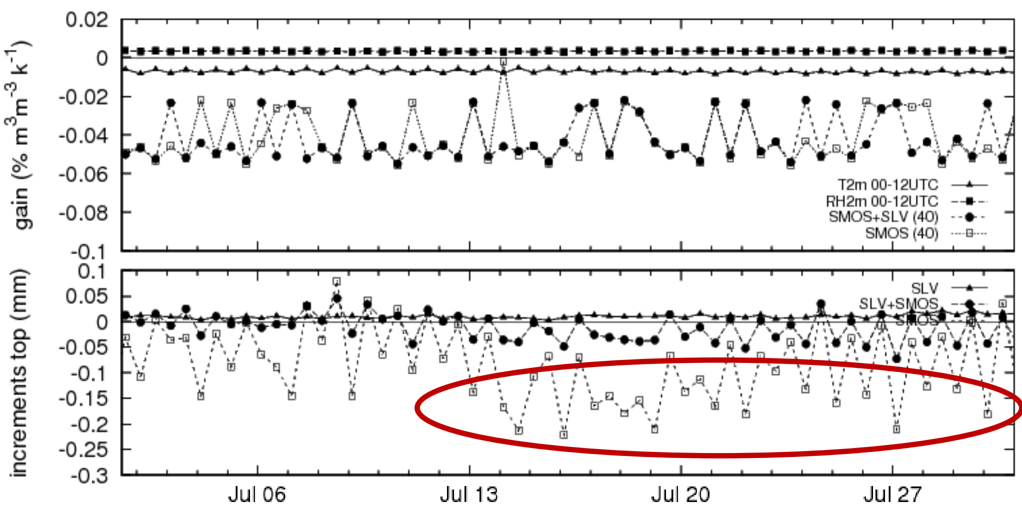


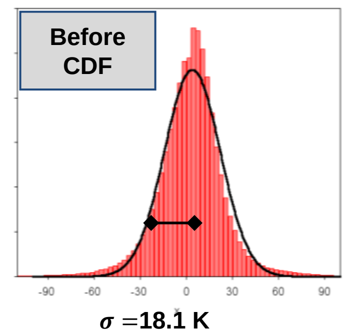

Large sensitivity → large Gain

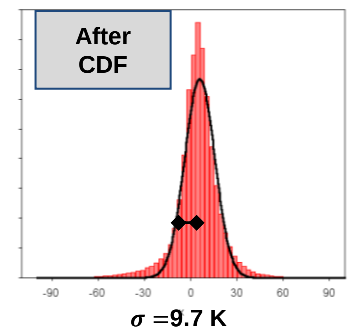
+

Residual large bias

=

Large increments



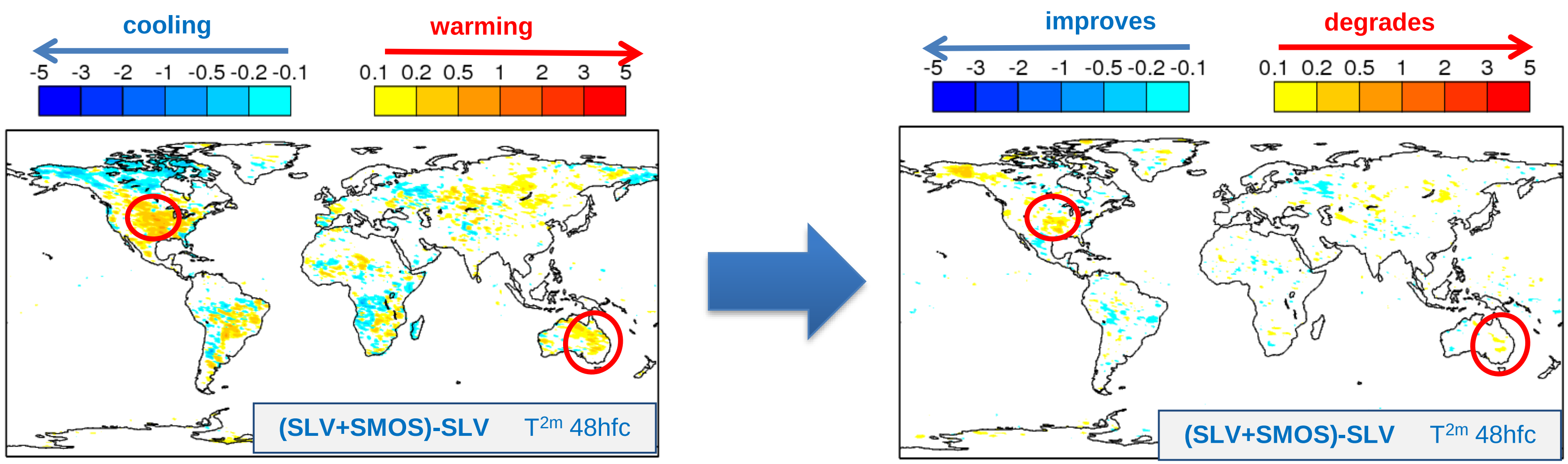




$$\mathbf{K} = [\mathbf{B}^{-1}+\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H}]^{-1}\mathbf{H}^T\mathbf{R}^{-1}$$

Gain (and increments) very sensitive to error covariance matrices

# Impact in the forecast skill

***Sensitivity*** ***FC impact***




→ SMOS increments produce warmer and drier atmosphere in center US, Sahel, South of Africa and Australia → hot-spots for NWP impact,

→ Small impact in the skill of the forecast by assimilating SLV+SMOS.

# Sensitivity experiments

Investigate the effect of various types of assimilated observations, assimilation approach and observation (**R**) and background error (**B**) specification in the soil moisture analysis.

- USA → best place for availability of observations and "cheaper" experiments,
- Period: 15 Sept- 14 Oct 2012 → recharge period, good variability of soil moisture,
- Full coupled system,
- 3 angles (30, 40, 50), 2 polarisations (XX, YY), AF-FOV, RFI flag,
- Physics of cy40r1,
- Reduced observing system for the upper-air atmosphere; ATOVS, GBRAD and NEXRAD observations used to limit number of observations, and still reasonable atmospheric constrain

- **R** cov matrix: $\sigma(T^{2m}) = 2$ K; $\sigma(RH^{2m}) = 10\%$; $\sigma(SMOS\ T^{B})$=rad_acc K
- **B** cov matrix: $\sigma(sm_{(0\text{-}7)\ cm}) = \sigma(sm_{(7\text{-}28)\ cm}) = \sigma(sm_{(28\text{-}100)\ cm}) = 0.01\ m^3m^{-3}$
- **Q** cov matrix: $\sigma(sm) = 0.01\ m^3m^{-3}$

# Experiment types

- **OL →** free soil moisture run,
- **SLV →** assimilation of only $T^{2m}$, $RH^{2m}$ (simulate surface operational conditions)
- **SLV+SMOS →** assimilation of $T^{2m}$, $RH^{2m}$ and SMOS $T_B$ with **B** static
- **SMOS →** assimilation of only SMOS $T_B$ with **B** static
- **SMOS PDI →** pseudo direct-insertion of SMOS $T_B$ . SEKF filters still apply to increments and departures
- **SMOS 2R →** assimilation of only SMOS $T_B$, doubling the observation error (2**R**),
- **SMOS B-prop →** assimilation of only SMOS $T_B$ with **B** propagated between two cycles. Background error grows along the assimilation window.
- **SMOS B-text →** assimilation of on

holding capacity (WHC). For a medium-texture soil, 10% of WHC is equivalent to doubling background error (0.02 $m^3m^{-3}$), or 20 mm for the 1st meter of soil.

- **SMOS 3DB →** an 3D structure background error is assumed. The model top layer is more affected by short term variability and more sensitive to precipitation errors → 20% of WHC for top layer (~ 0.04 $m^3m^{-3}$ for medium-type soil), 10% of WHC for 2nd layer and 5% of WHC for 3rd more stable layer.

Type of assimilated observation

# Experiment types

- **OL** → free soil moisture run,
- **SLV** → assimilation of only $T^{2m}$, $RH^{2m}$ (simulate surface operational conditions)
- **SLV+SMOS** → assimilation of $T^{2m}$, $RH^{2m}$ and SMOS $T_B$ with **B** static
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Weight given to SMOS observations

# Experiment types

- OL → free soil moisture run,
- SLV → assimilation of only $T^{2m}$, RH
- SLV+SMOS → assimilation of $T^{2m}$, RH

**Different B matrix structures**

- **SMOS B-fix →** assimilation of only SMOS $T_B$ with **B** static
- **SMOS PDI →** pseudo direct-insertion of SMOS $T_B$ . SEKF filters still apply to increments and departures
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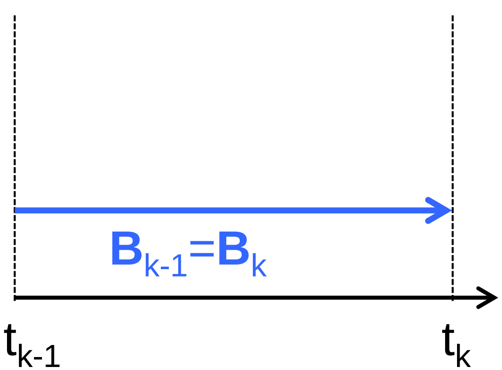
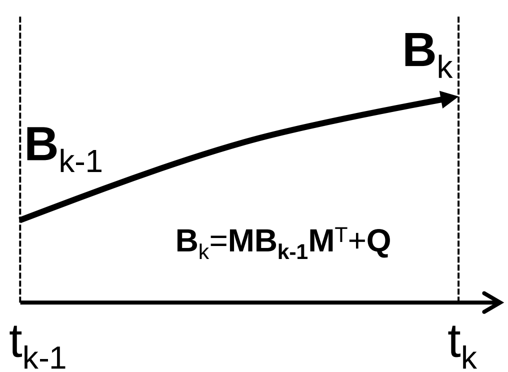
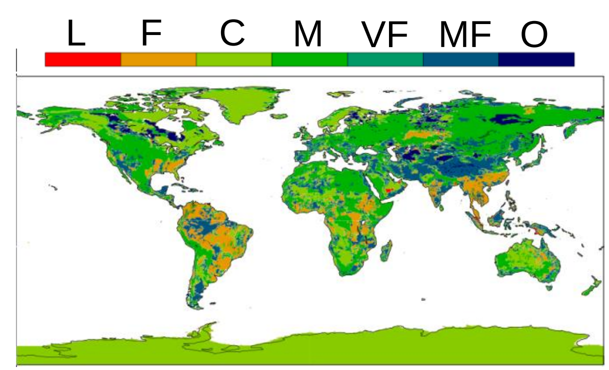


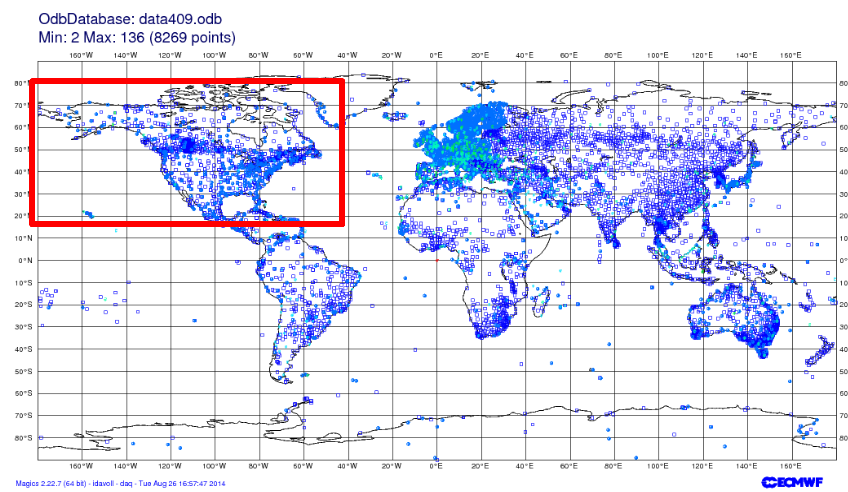



# Validation and verification

- Validation against in-situ soil moisture data from two independent networks: SCAN and USCRN
- Comparison against 2 m temp and 2 m dew point temp observations from the SYNOP network
- Atmospheric verification using a North-America mask


*http://ismn.geo.tuwien.ac.at/ismn/*

**SYNOP network**



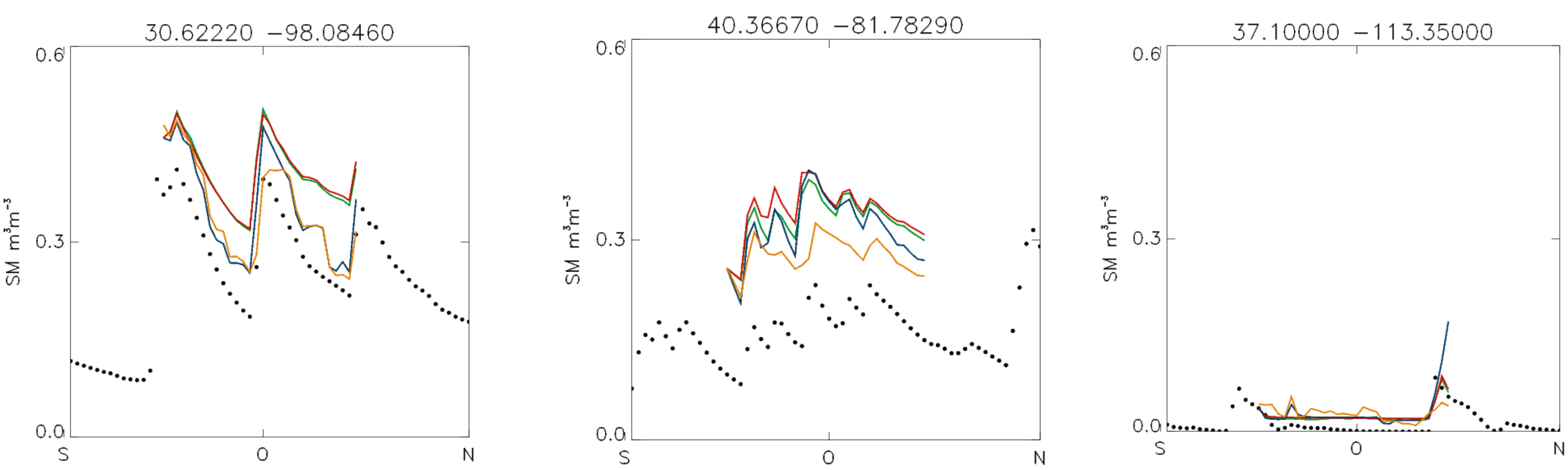
# Validation against in-situ data

| USCRN | Bias ($m^3m^{-3}$) | RMSD ($m^3m^{-3}$) | R | N |
|---|---|---|---|---|
| OL | -0.115 | 0.130 | 0.75 | 60 |
| SLV | -0.115 | 0.130 | 0.75 | 60 |
| SMOS+SLV | -0.097 | 0.121 | 0.76 | 60 |
| SMOS | -0.089 | 0.115 | 0.67 | 60 |

| SCAN | Bias ($m^3m^{-3}$) | RMSD ($m^3m^{-3}$) | R | N |
|---|---|---|---|---|
| OL | -0.062 | 0.104 | 0.74 | 86 |
| SLV | -0.061 | 0.104 | 0.74 | 86 |
| SMOS+SLV | -0.048 | 0.101 | 0.75 | 86 |
| SMOS | -0.035 | 0.101 | 0.68 | 86 |

*Only stations with significant correlation values Confidence 95% (p-value < 0.05)*

OL
SLV
SMOS + SLV
SMOS



# Atmospheric scores

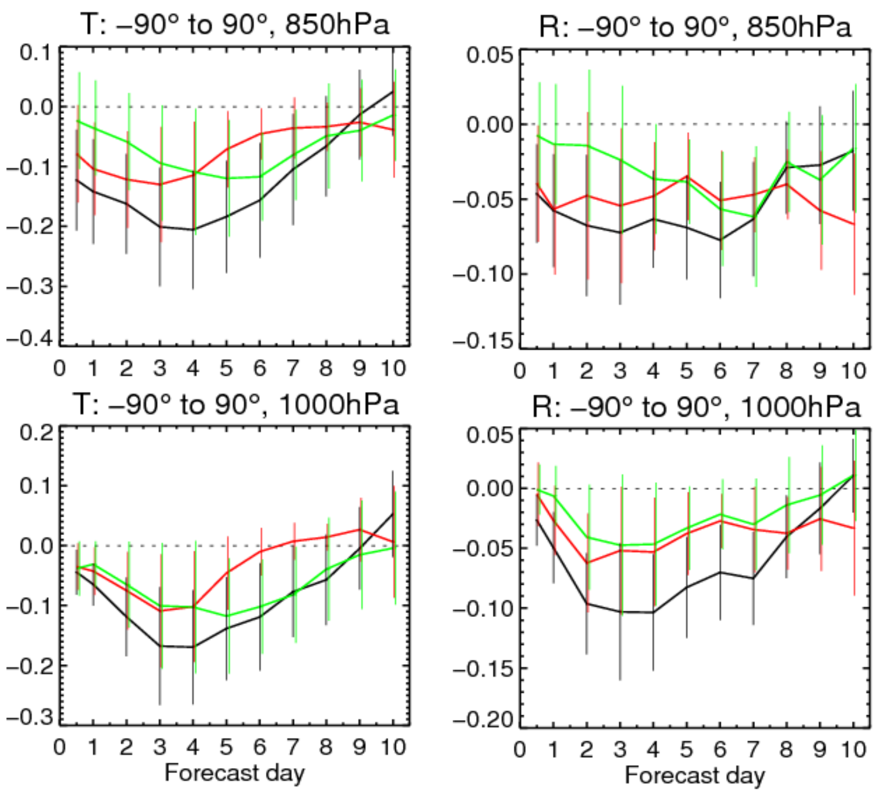
<u>Normalized change in rms of fc error:</u> drmse = $\frac{RMS(e^{SMOS}) - RMS(e^{CTRL})}{RMS(e^{CTRL})}$ ; $e^{EXPT} = fc^{EXPT} - an^{REF}$, $e^{CTRL} = fc^{CTRL} - an^{REF}$

SLV – OL
SMOS – OL
SLV+SMOS – OL

drmse>0 → expt increases error

drmse<0 → expt decreases error

***Temperature*** ***Humidity***



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$e^{CTRL} = fc^{CTRL} - an^{REF}$

SLV – OL

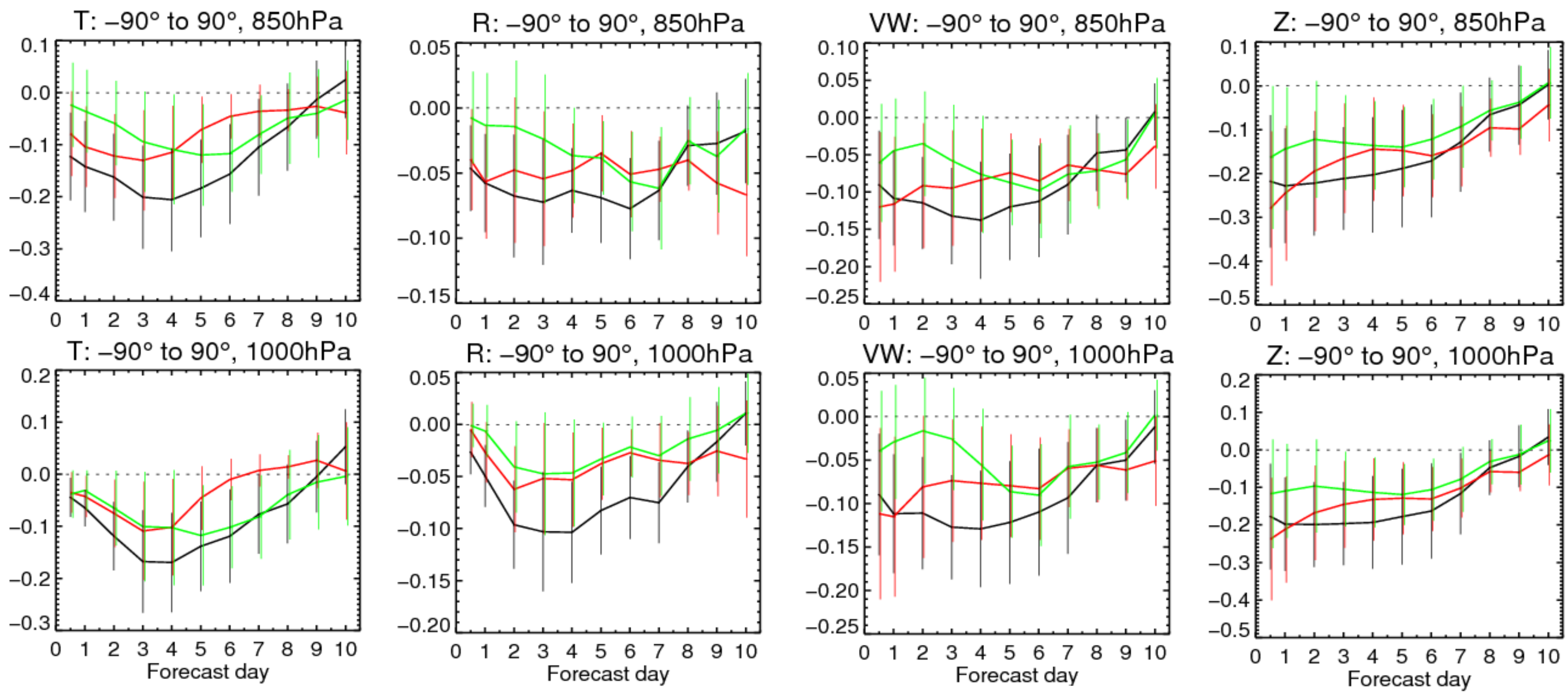
SMOS – OL

SLV+SMOS – OL

drmse>0 → expt increases error

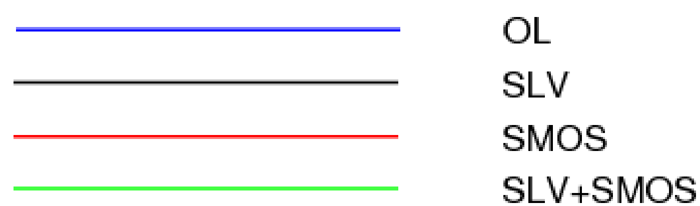
drmse<0 → expt decreases error

***Temperature*** ***Humidity*** ***Vector wind*** ***Geopotential***

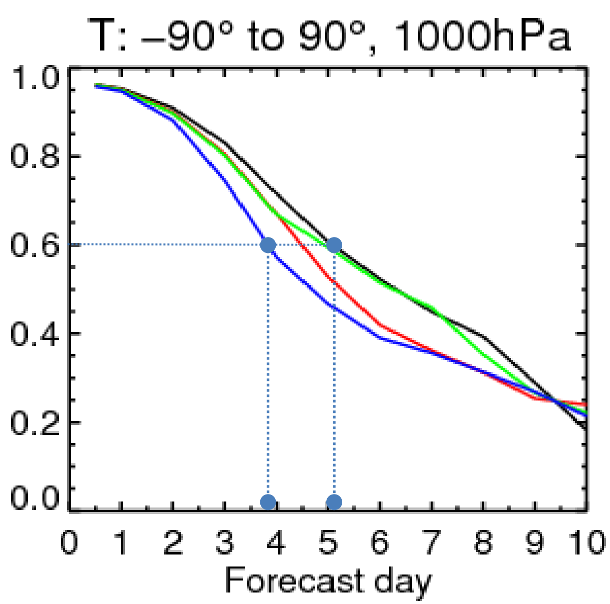


# Atmospheric scores

<u>Anomaly correlation</u>

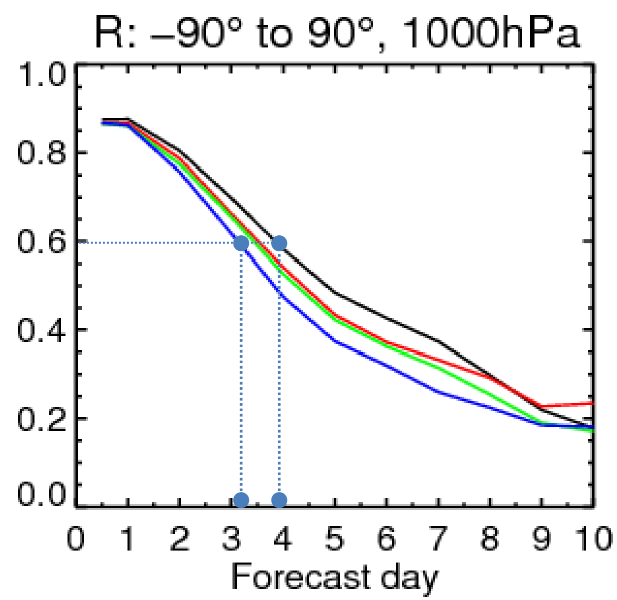



***Temperature***




***> 1 day***

***Humidity***



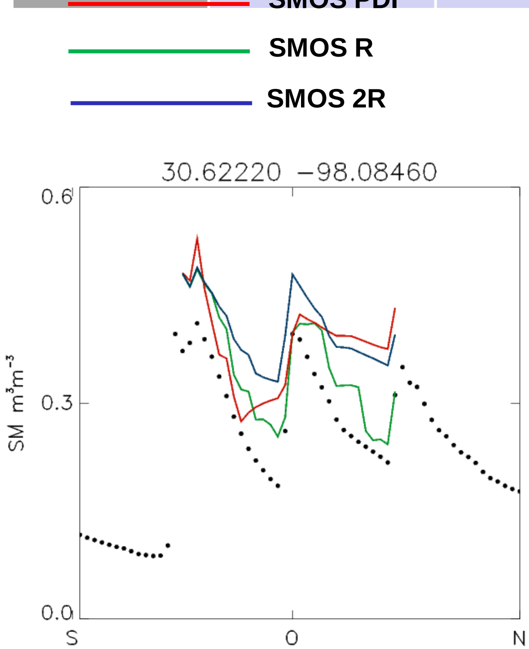

***~ 1 day***

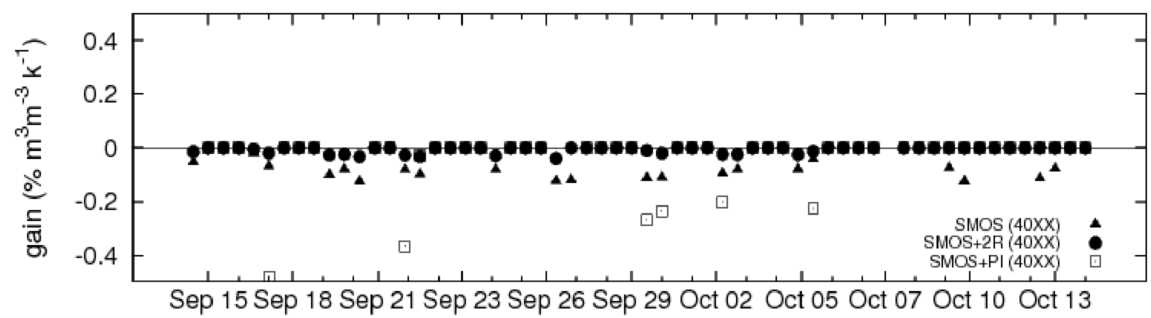
# Validation against in-situ data

| USCRN | Bias ($m^3m^{-3}$) | RMSD ($m^3m^{-3}$) | R | N |
|---|---|---|---|---|
| Direct Ins | -0.099 | 0.116 | 0.71 | 58 |
| SMOS + R | -0.086 | 0.113 | 0.69 | 58 |
| SMOS+2 R | -0.096 | 0.117 | 0.74 | 58 |

| SCAN | Bias ($m^3m^{-3}$) | RMSD ($m^3m^{-3}$) | R | N |
|---|---|---|---|---|
| Direct Ins | -0.051 | 0.106 | 0.68 | 83 |
| SMOS + R | -0.032 | 0.101 | 0.69 | 83 |
| SMOS+2 R | -0.044 | 0.104 | 0.72 | 83 |

*Only stations with significant correlation values*
*Confidence 95% (p-value < 0.05)*




→ **Good impact of SMOS+2R in the root-zone (R)**

# Atmospheric scores

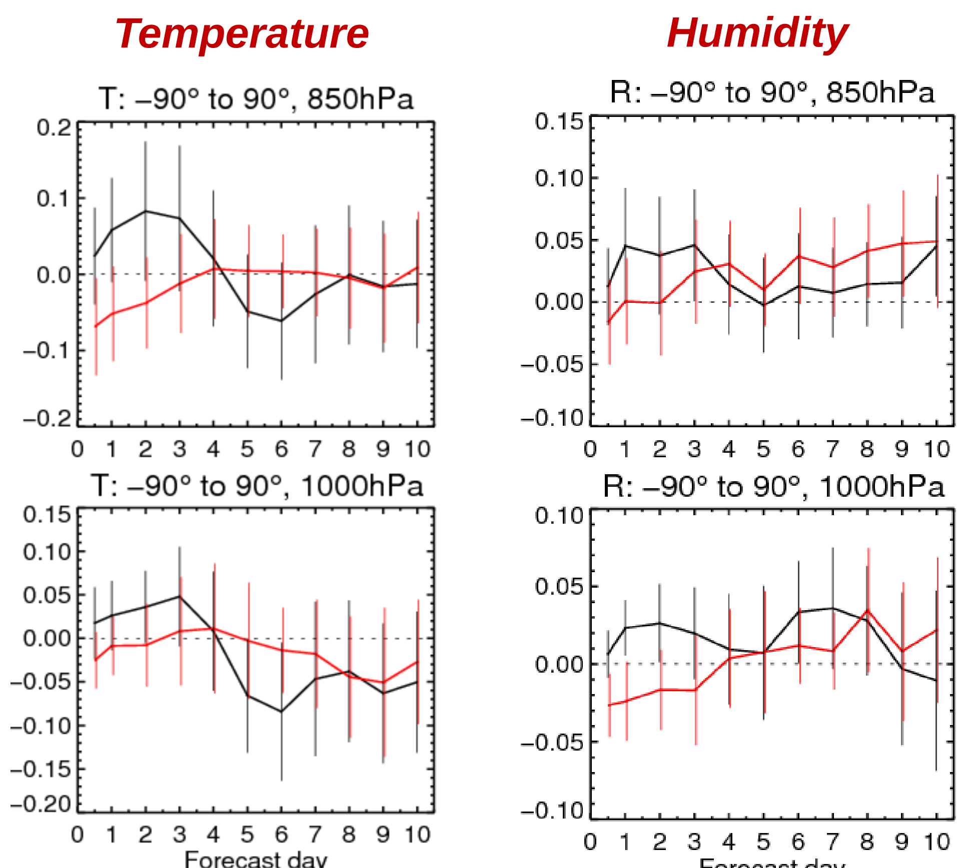
<u>Normalized change in rms of fc error:</u> drmse = $\frac{RMS(e^{SMOS})-RMS(e^{CTRL})}{RMS(e^{CTRL})}$ ; $e^{EXPT} = fc^{EXPT} - an^{REF}$, $e^{CTRL} = fc^{CTRL} - an^{REF}$

SMOS+PI – SMOS (black line)

SMOS+2R – SMOS (red line)

drmse>0 → expt increases error

drmse<0 → expt decreases error



# Validation against in-situ data

| USCRN | Bias ($m^3m^{-3}$) | RMSD ($m^3m^{-3}$) | R | N |
|---|---|---|---|---|
| SMOS B-fix | -0.085 | 0.109 | 0.70 | 64 |
| SMOS B-prop | -0.088 | 0.111 | 0.69 | 64 |
| SMOS Btext | -0.074 | 0.104 | 0.67 | 64 |
| SMOS + 3DB | -0.071 | 0.102 | 0.65 | 64 |

| SCAN | Bias ($m^3m^{-3}$) | RMSD ($m^3m^{-3}$) | R | N |
|---|---|---|---|---|
| SMOS B-fix | -0.022 | 0.095 | 0.70 | 77 |
| SMOS B-prop | -0.025 | 0.095 | 0.70 | 77 |
| SMOS Btext | -0.015 | 0.094 | 0.66 | 77 |
| SMOS + 3DB | -0.016 | 0.094 | 0.64 | 77 |

*Only stations with significant correlation values*
*Confidence 95% (p-value < 0.05)*

→ **Low impact in the root-zone**

# Atmospheric scores

Normalized change in rms of fc error: drmse = $\frac{RMS(e^{SMOS})-RMS(e^{CTRL})}{RMS(e^{CTRL})}$ ; $e^{EXPT} = fc^{EXPT} - an^{REF}$

$e^{CTRL} = fc^{CTRL} - an^{REF}$

**SMOS B-text - SMOS** (red)

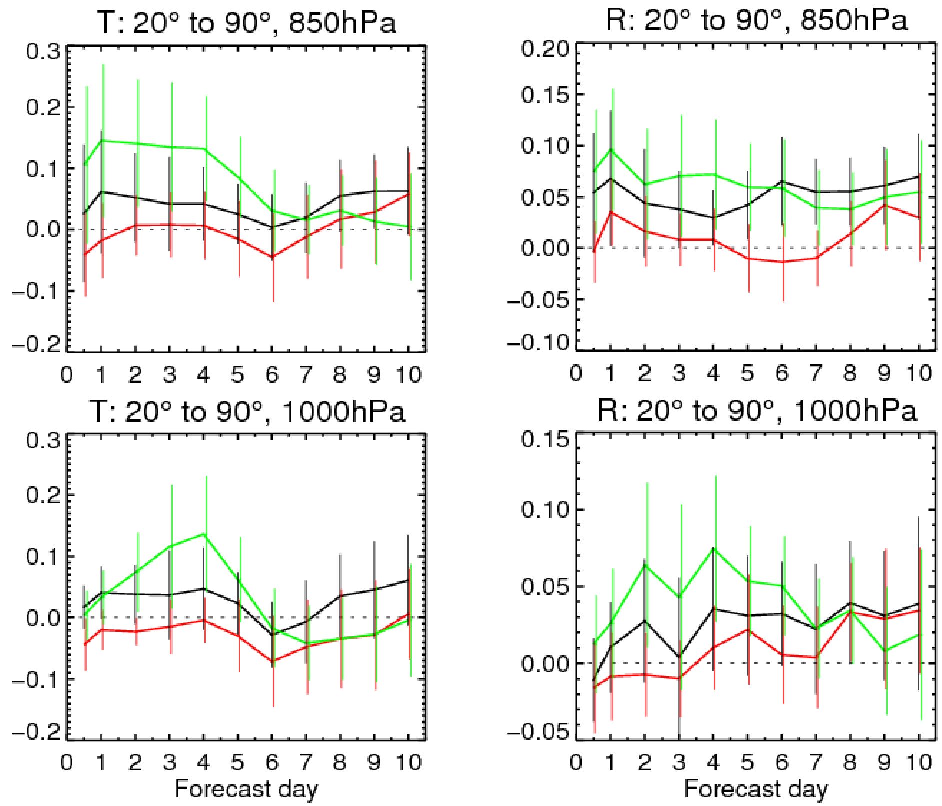
**SMOS 3DB - SMOS** (green)

**SMOS B-prop - SMOS** (black)

drmse>0 → expt increases error

drmse<0 → expt decreases error

***Temperature*** ***Humidity***



# Conclusions (I)

• SMOS data successfully integrated into a coupled land-atmospheric model,

• First seasonal experiments show that, compared to the operational system, the SMOS signal tend to dry the soil

→ positive results in terms of shallow and root-zone soil moisture,
→ Possible compensation mechanism in the atmosphere,

• Several diagnostics show that several components of the assimilation system should be adjusted to optimize the use of SMOS information in the land DA system,

• Sensitivity experiments:

➢ G-I: Type of observation:

- Constraining soil moisture through observations is important,
- Soil moisture analyses benefit of assimilating SMOS data,
- But main improvement of atmospheric variables produced by SLV (improvement up to 20% and 1-week)
- Compensation mechanisms in coupled system

# Conclusions (II)

➢ G-II: Weight of SMOS observation:

- Given total confidence to observations produces spurious increments,
- Doubling SMOS observation error does not reduce RMSD for top layer, but improves the correlation and slightly the atmospheric scores → fair increase of the observation error

➢ G-III: B-matrix error structures:

- Introducing soil texture information in the background error is beneficial for soil moisture,
- Atmospheric scores are neutral

→ Doubling SMOS observation error and introducing soil texture information in the background error, in combination with SLV, could improve land and atmospheric scores,

→ We are still learning!

# Thanks for your attention !

contact: joaquin.munoz@ecmwf.int

Further information:

SMOS online monitoring in NRT:
http://www.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/smos/

ECMWF SMOS website:
http://www.ecmwf.int/research/ESA_projects/SMOS/index.html

ECMWF CMEM website:
http://www.ecmwf.int/research/data_assimilation/land_surface/cmem/cmem_index.html

# Questions

- How is possible that sm is barely affected by assimilating SLV observations, and however it has a great impact in the atmosphere compared to the OL?
  - XXX (locally changes and degradations ??)
- Why when SMOS data is assimilated, the bias against in-situ is greatly reduced, but why not the RMSE?
  - XXX
- Should we use anomaly correlation as alternative metric?
  - Yes, I think we shouldn't to complement the metric observed here and to quantify the skill of SMOS data to predict short-scale variability.
- Why have you used the operational analysis as reference and not the own analysis?
  - Because the oper offers the best possible analysis as reference. In our case upper-air observing system is reduced as I wanted faster experiments, and the quality of the analysis are likely to be not as good as those of the oper.
- Why B-prop doesn't add any improvement?
  - Because the B matrix is not cycled but propagated during 12 h and reinitialized at the next cycle. The benefits of propagating the B-matrix are over a time scale of 3 and 9 hours, as the analysis are at 00 and 06 UTC. For these scales and the error given to Q, errors do not grow much and little impact is observed,