Can SMOS improve the weather forecast?

Joaquín Muñoz Sabater(1)


(1) European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK
(2) European Space Agency (ESA), ESTEC, Noordwijk, The Netherlands
(3) European Space Agency (ESA), ESRIN, Frascati, Italy
(4) CESBIO, Toulouse, France
Outline

- Background & context,
- ECMWF soil moisture analysis,
- New soil moisture product based on the assimilation of screen level variables and SMOS $T_B \rightarrow$ SMOS-DA-v1.0,
- Validation, Impact on the forecast skill and diagnostics,
- Conclusions
THE WATER CYCLE

- Snow
- Wind
- Rain
- Evaporation
- Trees
- Lakes
- Ground Water
- Run Off
- River
- Sea

Unknown source...
**SMOS**

- **Mission objective** provide global measurements of two key variables in the water cycle: soil moisture and ocean salinity.

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

- **Objectives at ECMWF:**
  - Global *monitoring* of $T_B$ at the satellite antenna reference frame, *in NRT*
  - 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*
How do we measure an improvement (or degradation) of the weather forecast?
Defining “weather forecast improvement”

- How do we measure an improvement (or degradation) of the weather forecast?

Necessity of defining:
- “Target” variable
  - atmospheric variables (pressure, temperature, wind speed, etc.)
  - land-variables (soil moisture, soil temperature, snow, etc.)
  - ocean variables (SST, ocean salinity, etc.)
- Validation metrics: R, RMSD, STD, persistence, etc.
- Independent data used as “true” or reference:
  - in-situ observations, remote sensed data, climatology, reanalysis
ECMWF soil moisture analysis: The SEKF

1. Initial state estimate at k=0:
   Mean state $x_0^*$
   Covariance $P_0^*$

2. Calculate Kalman gain:
   $$K_k = P_{-k}^*H^T_k[H_kP_{-k}^*H^T_k + R_k]^{-1}$$

3. Update the state estimate:
   $$x_k^* = x_{-k}^* + K_k[y_k - H_kx_{-k}^*]$$
   $$P_{-k}^* = P_{-k}^* - K_kH_kP_{-k}^*$$

4. Propagate state estimate in time:
   $$x_{-k+1}^* = f_k(x_k^*)$$
   $$P_{-k+1}^* = M_kP_{-k}^*M_k^T + Q_k$$

ECMWF implementation (Drusch et al. 2009, de Rosnay et al. 2012):
- $P$ and $R$ diagonal and static ($\sigma_{sm} = 0.01$ m$^3$m$^{-3}$; $\sigma_T = 2$ K; $\sigma_{rH} = 10\%$),
- $H = [H(x^n + \delta x^n) - H(x^n)] / \delta x^n$ with $\delta x^n = 0.01$ m$^3$m$^{-3}$ and n=3;

Introduction of SMOS data in the soil moisture analysis (Muñoz-Sabater et al., 2012)
- SMOS $T_B$ introduced in $R$ ($\sigma_{T Bj} == \text{rad\_acc}(TB_j)$)
- $H$ calibrated for SMOS ($\delta x^n [0.005, 0.01]$ m$^3$m$^{-3}$, $H_{-\max}^* = H_{-\max}^* = 250$ K/m$^3$m$^{-3}$)
- Point wise CDF matching as bias correction prior to assimilation.
CDF-matching $\rightarrow$ matches mean and variance of two distributions

$$T_B(BC) = A \times T_B^{SMOS} + B$$

$$A = \frac{\sigma_{CMEM}}{\sigma_{SMOS}}$$

$$B = T_B^{CMEM} - T_B^{SMOS} \times \left(\frac{\sigma_{CMEM}}{\sigma_{SMOS}}\right)$$
Bias correction

**CDF-matching** $\implies$ matches mean and variance of two distributions

$$T_B(BC) = A \times T_B^{SMOS} + B$$

\[A = \frac{\sigma_{CMEM}}{\sigma_{SMOS}}\]
\[B = T_B^{CMEM} - T_B^{SMOS} \times \left(\frac{\sigma_{CMEM}}{\sigma_{SMOS}}\right)\]
Assimilation of SMOS $T_B$ in the antenna reference frame at global scale (SEKF)

- Period: 1 May 2010 00UTC – 31 October 2012 12UTC analysis
- Resolution: T511 (~40 km)
- Observations:
  - NRT brightness temperatures (Reprocessed dataset 2010-2011),
  - 30, 40, 50 degrees ± $\Delta T_B$=0.5 K
  - XX & YY polarisations
  - Only AF-FOV
  - RFI flag used (BUFR info flag, bit-1)
  - Bias corrected using a point-wise CDF matching
- CMEM configuration; best for R (Wang(DIEL), Wsimple(RGH), Wigneron(VEG))
- Jacobians calibrated ($\Delta \theta_j=0.01 m^3 m^{-3}$, $H_{\text{max}}^- = H_{\text{max}}^+ =250 K/m^3 m^{-3}$)
- STD of observations error → radiometric accuracy
- Full observational system used for the atmosphere,

CTRL: assimilation of $T^{2m}$, $RH^{2m}$
SMOS-DA-v1.0: assimilation of $T^{2m}$, $RH^{2m}$ + SMOS $T_B$ CDF
Validation against ISMN - 2010

Taylor diagram

- Reference
- SCAN
- SNOTEL
- OZNET
- REMEDHUS
- MAQU
- SMOSMANIA
- SWATMEX
- HOBE
- AMMA

SMOS exp analysis against observations
Control analysis against observations
### Validation 2011

#### REMEDHUS

<table>
<thead>
<tr>
<th></th>
<th>CTRL</th>
<th>SMOS + CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>0.74</td>
<td>0.81</td>
</tr>
<tr>
<td>RMSD</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Bias</td>
<td>-0.07</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

#### AMMA

<table>
<thead>
<tr>
<th></th>
<th>CTRL</th>
<th>SMOS + CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>0.56</td>
<td>0.70</td>
</tr>
<tr>
<td>RMSD</td>
<td>0.049</td>
<td>0.047</td>
</tr>
<tr>
<td>Bias</td>
<td>-0.038</td>
<td>-0.029</td>
</tr>
</tbody>
</table>

---

**Surface Soil Moisture**

- **CTRL**
- **SMOS + CDF**
- **SMOS + ~BC**

**Observations (~5 cm)**

**Root Zone Soil Moisture**

- **CTRL**
- **SMOS + ~BC**
2m Temperature sensitivity and bias

Robust, location and time dependent $T^{2m}$ bias (verification against own analysis)

SM increments due to assimilation of SMOS data have an impact on $T^{2m}$ and partly explain the systematic bias.
## Verification on air temperature and humidity

### Summer-2010 (Jun, Jul, Aug)

<table>
<thead>
<tr>
<th>Level (hPa)</th>
<th>ccaf</th>
<th>msef</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Root-mean square forecast error**

**Anomaly correlation forecast**

### Diagram: mean-normalised ftec minus fsx2

- 1000hPa temperature
- Root mean square error
- N America (lat 25.0 to 65.0, lon -129.0 to -75.0)
- Date: 20100501 00UTC to 20100731 12UTC
- T[12 T=24 ... T=240] Confidence [95%] Population 184
Verification on air temperature and humidity

Root-mean square error forecast

Anomaly correlation forecast

Summer-2011
(Jun, Jul, Aug)
Verification on air temperature and humidity

Summer-2012 (Jun, Jul, Aug)

<table>
<thead>
<tr>
<th>Level (hPa)</th>
<th>ccaf</th>
<th>msef</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Root-mean square error forecast
Anomaly correlation forecast

**mean-normalised ftecc minus fsx2**

1000hPa relative humidity
Root mean square error

NHem Extratropics (lat 20.0 to 90.0, lon -180.0 to 180.0)
Date: 20120601 00UTC to 20120831 12UTC
T=12 T+24 ... T+240 | Confidence: 95.0% | Population: 92
Verification on air temperature and humidity

### Winter 2010-11 (Dec, Jan, Feb)

<table>
<thead>
<tr>
<th>s hem</th>
<th>ccaf</th>
<th>rmsef</th>
</tr>
</thead>
<tbody>
<tr>
<td>200hPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500hPa</td>
<td>▼</td>
<td>▼</td>
</tr>
<tr>
<td>700hPa</td>
<td></td>
<td>▲</td>
</tr>
<tr>
<td>850hPa</td>
<td></td>
<td>▲</td>
</tr>
<tr>
<td>1000hPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>500hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>700hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>850hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>1000hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
</tbody>
</table>

### Winter 2011-12 (Dec, Jan, Feb)

<table>
<thead>
<tr>
<th>s hem</th>
<th>ccaf</th>
<th>rmsef</th>
</tr>
</thead>
<tbody>
<tr>
<td>200hPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500hPa</td>
<td>▲</td>
<td></td>
</tr>
<tr>
<td>700hPa</td>
<td></td>
<td>▲</td>
</tr>
<tr>
<td>850hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>1000hPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>500hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>700hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>850hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>1000hPa</td>
<td>▲</td>
<td>▲</td>
</tr>
</tbody>
</table>

**mean-normalised fsx2 minus fte**

1000hPa relative humidity

Anomaly correlation

SHem Extratropics (lat: -90.0 to 30.0, lon: -180.0 to 160.0)

Date: 20111201 00UTC to 20120228 12UTC

T+12 T+24 ... T+240 | Confidence: [50.0%] | Population: 90
Impact on forecasted precipitation

- **“Truth”**: 6h accumulated precipitation from radar observations of the NEXRAD network,

- Target variable: \textbf{fg-departure fc error};

\[
\text{Impact } 6\text{h fc} = (\text{OBS}_{00-06} - \text{fc}_{06})_{\text{EXPT}} - (\text{OBS}_{00-06} - \text{fc}_{06})_{\text{CTRL}}
\]

\[\text{OBS} \quad 06 \quad 12 \quad 18 \quad 24 \quad \text{fc06} \]

June 2011 → The two areas with the largest improvements in forecasted precipitation (for the period 00-06h), coincide with two isolated convective cumulus of precipitation.

Impact of the fc precipitation limited to the first 12h fc.
Impact in the carbon cycle – July 2011

- New **CTESSEL** provides a vegetation-interactive formulation → coupling water-carbon cycles

\[
\text{NEE} = R_{\text{eco}} - \text{GPP}
\]

- Climate forcings:
  - \( R_{\text{eco}} \rightarrow f(\text{SM, T}) \)
  - \( \text{GPP} \rightarrow f(\text{SM, T, Rad}) \)

**High sensitivity** to SMOS data assimilation in:
- Summer of NH → increase of GPP at higher ratio than \( R_{\text{eco}} \) (NEE becoming more negative) → **Positive impact** because CTESSEL underestimates \( \text{CO}_2 \) sink in summer of NH,
- Sahel → Increase of soil moisture leads to increase in GPP during West African Monsoon,
- Rio de La Plata, Horn of Africa

- Other complex feedback, via Temperature and cloud/radiation, can interfere with soil moisture impact,
- Further evaluation with \( \text{CO}_2 \) observations required to confirm the positive impact in the carbon fluxes estimation
Conclusions (I)

- SMOS has shown very good sensitivity to sm variations → clear potential for NWP,
- ECMWF has successfully incorporated SMOS data in the IFS (monitoring & assimilation),
- ECMWF soil moisture analysis based on an EKF; ready to assimilate SMOS data,
- Production of a new SM product based on the assimilation of $T^2_m$, $RH^2_m$ and SMOS $T_B$, 
Conclusions (I)

- SMOS has shown very good sensitivity to sm variations → clear potential for NWP,
- ECMWF has successfully incorporated SMOS data in the IFS (monitoring & assimilation),
- ECMWF soil moisture analysis based on an EKF; ready to assimilate SMOS data,
- Production of a new SM product based on the assimilation of $T_{2m}$, $RH_{2m}$ and SMOS $T_B$,
- Evidence of positive impact of SMOS in:
  - Air temperature and humidity at 1000 and 850 hPa,
  - Up to 7-8 days,
  - In Europe, North America and NH, in summer of NH (J, J, A),
  - In South Hemisphere in summer of SH (D, J, F),
  - Low impact was found in spring and autumn → lower increments
- The data assimilation system needs to be tuned:
  - Over East of Asia (RFI quality control),
  - South Hemisphere (lower impact compared to NH),
  - Australia (less amount of data and lower soil moisture levels in general),
  - Tropics (special regions and still high bias remaining)
- Impact on the precipitation forecast at short term and in the carbon cycle.
Can SMOS improve the weather forecast?
Conclusions (II)

- **Can SMOS improve the weather forecast?**
  - There are clear signs of the potential of SMOS to improve the weather forecast, but...
    - Only observations of best quality should be used,
    - Greater chances of success will depend on the good use/tune of the assimilation system

- Further work with the data assimilation system is needed;
  - Quality control of the observations (RFI screening in DA),
  - Jacobians,
  - Model errors treatment

- Improved accuracy of L-band simulations through;
  - Improved model physics,
  - Improved climatic fields,
  - Improved radiative transfer model
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
**BUFR & ODB spaces:** quality checks, thinning, setup of SMOS monitoring and CMEM configuration, creation of internal database for SMOS, distribution of observations per processor and time slots, merging of remote sensing data in a single database for surface analysis, etc.

**4DVAR space:** collocation of observations with model grid, screening and flagging of each observation, forward model computation, feedback to ODB database, first-guess departures, monitoring statistics, etc.

**SEKF space:** retrieval of observations to assimilate and matching with modelled equivalents for same model time step and location, perturbed runs and storing of perturbed $T_B$, innovation vector and soil moisture increment computation, etc.
Jacobians calibration $H = \Delta T_B / \Delta \theta$

- Sensitivity of $T_B$ to soil moisture is negative,
- Larger sensitivity for first soil layer $\Rightarrow$ It is expected larger correction of first layer of SM to correct towards SMOS observations.
- The optimal perturbation value is between 0.005 m$^3$m$^{-3}$ and 0.01 m$^3$m$^{-3}$. For consistency with $T^{2m}$ and $RH^{2m}$, 0.01 m$^3$m$^{-3}$ will be used.