Soil Moisture Measurements from Space and Application to Operational Hydrology

Wolfgang Wagner
ww@ipf.tuwien.ac.at

Department of Geodesy and Geoinformation (GEO)
Vienna University of Technology (TU Wien)
www.ipf.tuwien.ac.at
Soil Moisture

- Definition, e.g.
  \[ \theta = \frac{\text{Water Volume (m}^3\text{)}}{\text{Total Volume (m}^3\text{)}} \]

- Average
  \[ \langle \theta \rangle = \frac{1}{\text{Area} \cdot \text{Depth}} \int \int \theta(x, y, z) \, dz \, dx \, dy \]

Thin, remotely sensed soil layer

Root zone: layer of interest for most applications

Soil profile
Microwaves

- Microwaves (1 mm – 1 m wavelength)
  - All-weather, day-round measurement capability
  - Very sensitive to soil water content below relaxation frequency of water (< 10 GHz)
  - Penetrate vegetation and soil to some extent
    - Penetration depth increases with wavelength

The dipole moment of water molecules causes “orientational polarisation”, i.e. a high dielectric constant

Dielectric constant of water
Measurement Principles

- **Radars** measure the energy scattered back from the surface
- **Radiometers** measure the self-emission of the Earth’s surface

Active Sensors

- ERS-1/2
- SAR
- SCAT

Passive Sensor

SAR und scatterometer on European Remote Sensing Satellites ERS-1 and ERS-2
Microwave missions for soil moisture

- 33 years of passive and active satellite microwave observations for soil moisture
News Sensors & Products

SMOS

SMAP

ASCAT

AMSR-E
Recent Successes & Prospects

Recent successes

- 2002: First global soil moisture data set from ERS SCAT published
- 2003: NASA soil moisture product based on AMSR-E put into operations
- 2007: First merged multi-radiometer soil moisture product
- 2009: ASCAT soil moisture product available in NRT
- 2010: First SMOS soil moisture data released
- 2011: International Soil Moisture Network (ISMN) takes off
- 2012: First ECV soil moisture data set covering 1978-2010 released

Prospects

- 2013: Launch of Sentinel-1
  - First operational soil moisture product at ≤ 1 km spatial resolution
- 2014: Launch of SMAP
  - First active/passive sensor at L-band
European C-Band Scatterometers

- **ERS Scatterometer**
  - $\lambda = 5.7$ cm
  - VV Polarization
  - Resolution: 50 / 25 km

- **Data availability**
  - ERS-2: since 1995
    - gaps due to loss of gyros (2001) and on-board tape recorder (2003)
  - Operations conflict with ERS SAR

- **METOP Advanced Scatterometer**
  - $\lambda = 5.7$ cm
  - VV Polarization
  - Resolution: 50 / 25 km

- **Data availability**
  - >15 years
  - METOP-A: since 2006
  - METOP-B: launch in 2012

Daily global scatterometer coverage: ERS (left) and METOP (right)
Backscatter from Vegetated Surfaces

- Except for dense forest canopies, backscatter from vegetation is due to surface-, volume- and multiple scattering.

\[ \sigma^0_{total} = \sigma^0_{volume} + \sigma^0_{surface} + \sigma^0_{interaction} \]
Backscatter versus Soil Moisture & Vegetation

Simulations performed with a radiative transfer mixing model
SCAT Noise from Error Propagation
Validation

- Available independent data
  - In-situ measurements
  - Modelled soil moisture data
  - Other satellite products

- Best Practices
  - Assessment of absolute product accuracy (RMSE)
  - Assessment of relative accuracy and anomalies (R, unbiased RMSE)

- Methods
  - Direct comparisons
  - Triple collocation
  - R-metric
International Soil Moisture Network (ISMN)

http://www.ipf.tuwien.ac.at/insitu

35 networks
>1400 stations
Period 1952 - now
Soil Moisture Scaling Properties

- High variability in time
  - Remotely sensed layer exposed to atmosphere
- Distinct but temporally stable spatial patterns

- Temporal stability means that spatial patterns persist in time
  - Vachaud et al. (1985)
    - Practical means of reducing an in-situ soil moisture network to few representative sites
  - Vinnikov and Robock (1996)
    - Large-scale atmosphere-driven soil moisture field
    - Small-scale land-surface soil moisture field
In-Situ Soil Moisture Time Series

Mean (red) and station (black) in-situ soil moisture time series. REMEDHUS network in Spain. © University of Salamanca
Temporal Stability

Regional scale soil moisture

\[ \theta_r(t) = \frac{1}{A_r} \iiint \theta_p(x', y', t)dx'dy' = c_{rp}(x, y) + d_{rp}(x, y)\theta_p(x, y, t) \]

Local scale soil moisture

Model Error \(\approx 5\%\)
Scaling by CDF Matching

- Mainly due to uncertain soil hydrologic properties and soil moisture scaling properties (temporal stability), absolute soil moisture values from any source (in-situ, model, remote sensing) are highly uncertain.
- Biases are removed by Cumulative Distribution Function (CDF) matching.

ASCAT versus Model

ASCAT versus 3 cm simulated degree of saturation for products, ms, SWI, and SWI* and investigated sites: a) Vallaccia, b) Cerbara, and c) Spoleto.

ASCAT vs. AMSR-E

- Validation over networks in Italy, France, Luxemburg and Spain
- 3 AMSR-E products
- ASCAT and AMSR-E LPMR performed best
- ASCAT particularly good in case of anomaly correlations

Triple Collocation ASCAT vs. AMSR-E vs. ERA-Interim

- New statistical method for the estimation of errors of three data sets
  - Errors must not be correlated

Validation of SMOS and ASCAT over France

- Validation over SMOSMANIA network

Validation of SMOS and ASCAT (Operational & Assimilated)

- Validation over networks in the US, Europe and Australia
  - (Initial) operational ASCAT product performs similar to SMOS
  - Assimilation improves correlation to in-situ data

Correlations between ASCAT and in situ data against correlations between ECMWF SM-DAS-2 and in situ data, then same for SMOS and SM-DAS-2, SMOS and ASCAT.

Same as above but for anomaly correlation values instead of normalised time series.

Time Series Correlation ASCAT versus SMOS

Pearson correlation

-0.85  +1.00
Applications

- Monitoring of extreme hydrologic events
- Runoff forecasting
- Data assimilation
- Numerical Weather Prediction
- Landslide monitoring
- Vegetation monitoring
- Agricultural monitoring
- Epidemiological prediction
- GHG budget
- Climate studies
- Ground water modelling
Monitoring of Extreme Events: Heavy Rain & Hail

Heavy Rain & Hail on 1/7/2012
Monitoring of Extreme Events: Droughts

SWI anomaly mean October 2012
SCAT Soil Moisture versus River Runoff

Sambesi – Nana’s Farm

60 days shift

Runoff

Soil Moisture (Blue Line)

Time Shift and Catchment Size

![Water Level vs. BWI for Lukulu, Matonga, Senanga, and Sesheke](image)

![Map of the region showing catchment areas](image)

![Graph showing delay time vs. basin size](image)
Event-based Rainfall-Runoff Modelling

- "Curve Number Method"

\[ Q = \frac{(P - 0.2S)^2}{P + 0.8S} \]

with \[ S = c + d \cdot SWI \]

\( Q \) … runoff
\( P \) … precipitation
\( S \) … retention
\( SWI \) … Soil Water Index

Improving Runoff Prediction through Assimilation

- If improvement can be achieved depends on the quality of the in situ measurements and the applied calibration and data assimilation strategies.

Cumulated runoff for the observed and simulated data with and without ASCAT SWI assimilation for four catchments in Italy.

Improved Soil Moisture Estimates through Assimilation

ASCAT Assimilation at NWP Centres

- Impact on temperature and humidity
- Centres
  - ECMWF
  - Met Office
  - Meteo France
  - ZAMG

Skill of relative humidity forecasts

Afternoon rain more likely over drier soils

<table>
<thead>
<tr>
<th>Region</th>
<th>Observations</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moist tropics</td>
<td></td>
<td>&gt;99</td>
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<tr>
<td>Savanna</td>
<td>&lt;0.1 (2345 3)</td>
<td>&gt;99</td>
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<tr>
<td>Semi-arid</td>
<td>&lt;0.1 (2866 6)</td>
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<tr>
<td>Arid</td>
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<tr>
<td>Temperate</td>
<td>0.12 (4721 1)</td>
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</tr>
<tr>
<td>Continental</td>
<td>0.01 (5281 2)</td>
<td>&gt;99</td>
</tr>
</tbody>
</table>

Dark red = rain falls most likely over drier soils
Pink = rain falls likely over drier soils
Blue = rain falls likely over wetter soils
Dark blue = rain most falls likely over wetter soils

Prediction of Water-Borne Diseases

Unpublished results of Brocca, Montosi & Montanari

Sample size = 66
R(linear) = 0.73
R(log) = 0.80
Comparison between observed (circles) and estimated (triangles) crack aperture of the Torgiovannetto Landslide in Central Italy from the beginning to the end of the selected rainfall events.

Climate Change: Merging of Multi-Satellite Data Sets

Level 1 Data Sets
- ERS-1/2 SCAT 1991-2011
- METOP ASCAT 2006-now
- EOS/Acqua AMSR-E 2002-now
- Coriolis Windsat 2003-now
- TRMM TMI 1998-now
- DMSP SSM/I 1987-now
- Nimbus 7 SMMR 1978-1987

Merging Active Level 2 Data

Merging Passive Level 2 Data

Passive Level 2 Retrieval

Passive Level 2 Retrieval

Passive Level 2 Retrieval

Passive Level 2 Retrieval

Reference GLDAS, ERA-Interim

Active ECV Data 1978-now

Passive ECV Data 1978-now

Merging Active-Passive Data Sets

Active ECV Data 1991-now

Active ECV Data 1991-now

ECV Production System

Ancillary Data For Active Retrieval

Ancillary Data For Passive Retrieval

Ancillary Data For Active Retrieval

Ancillary Data For Passive Retrieval

Ancillary Data For Active Retrieval

Ancillary Data For Passive Retrieval
Trend 1988-2010

Conistent Trends in Modelled Soil Moisture (top), Precipitation (middle) and NDVI (bottom) Time Series

Outlook

- Availability and quality of satellite soil moisture data sets is improving
  - METOP-A + METOP-B
  - AMSR-2

- Future Opportunities
  - Sentinel-1
    - 1 km soil moisture and freeze/thaw
    - 30 m water bodies
  - Soil Moisture Active Passive (SMAP)

- Early Announcement
  - Satellite Soil Moisture Validation and Application Workshop
    - 1-3 July 2013 at ESA ESRIN, Frascati, Italy
    - Co-organisation ESA, EUMETSAT, WMO, GEWEX, CEOS and GCOS