# Assimilation of satellite derived soil moisture for weather forecasting

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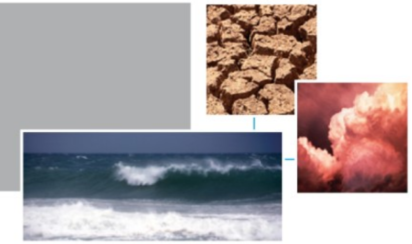
SMOS/SMAP workshop, Monash University

Australian Government
Bureau of Meteorology

The Centre for Australian Weather and Climate Research
A partnership between CSIRO and the Bureau of Meteorology

CSIRO

# Summary



- In preparation of the high quality measurements to come from SMOS and SMAP, the UK Met Office (UKMO) initiated a project in 2008 to assimilate measurements of surface soil wetness from the Advanced Scatterometer (ASCAT) on the MetOP satellite.
- Since June 2010, the UKMO has been operationally assimilating ASCAT surface soil wetness.
  - The Bureau of Meteorology will start to assimilate ASCAT surface soil wetness measurements later this year.
- Pre-operational trials show that assimilation of ASCAT surface soil wetness improves forecasts of screen temperature and humidity for the tropics, Australia and North America.
- Comparison with in-situ soil moisture observations from USDA-SCAN shows that assimilation of ASCAT surface soil wetness improves the soil moisture analysis.

# Why do we care about soil moisture?

- Soil moisture influences the exchange of heat and moisture between the atmosphere and land surface.
  - Soil moisture affects evaporation from plants and bare soil.
  - Soil moisture affects the soil heat capacity and soil thermal conductivity and thus the ground heat flux.

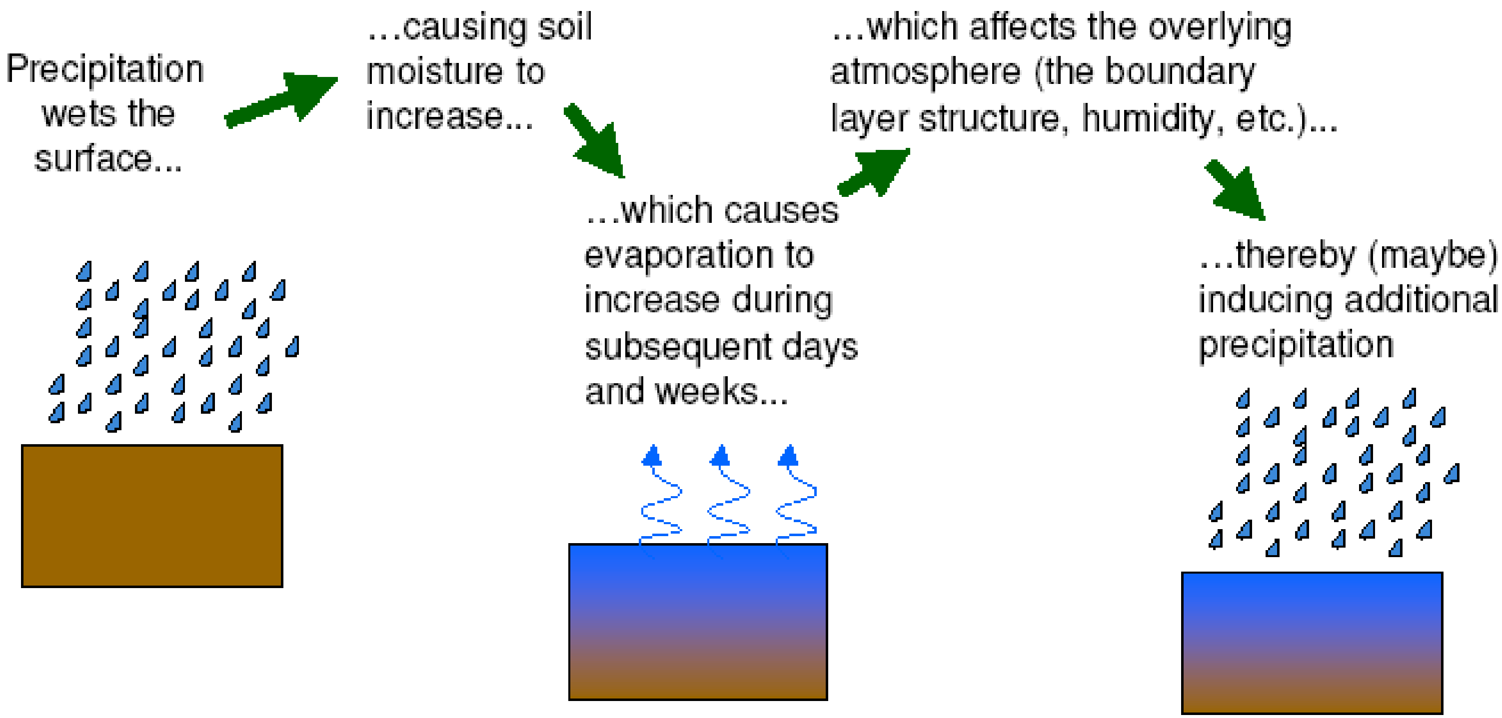
- Soil moisture is potentially very important for forecasts of precipitation and clouds.

- Soil moisture, together with other land properties, has a significant impact on forecasts of near surface temperature and humidity.

From Reichle and Koster:

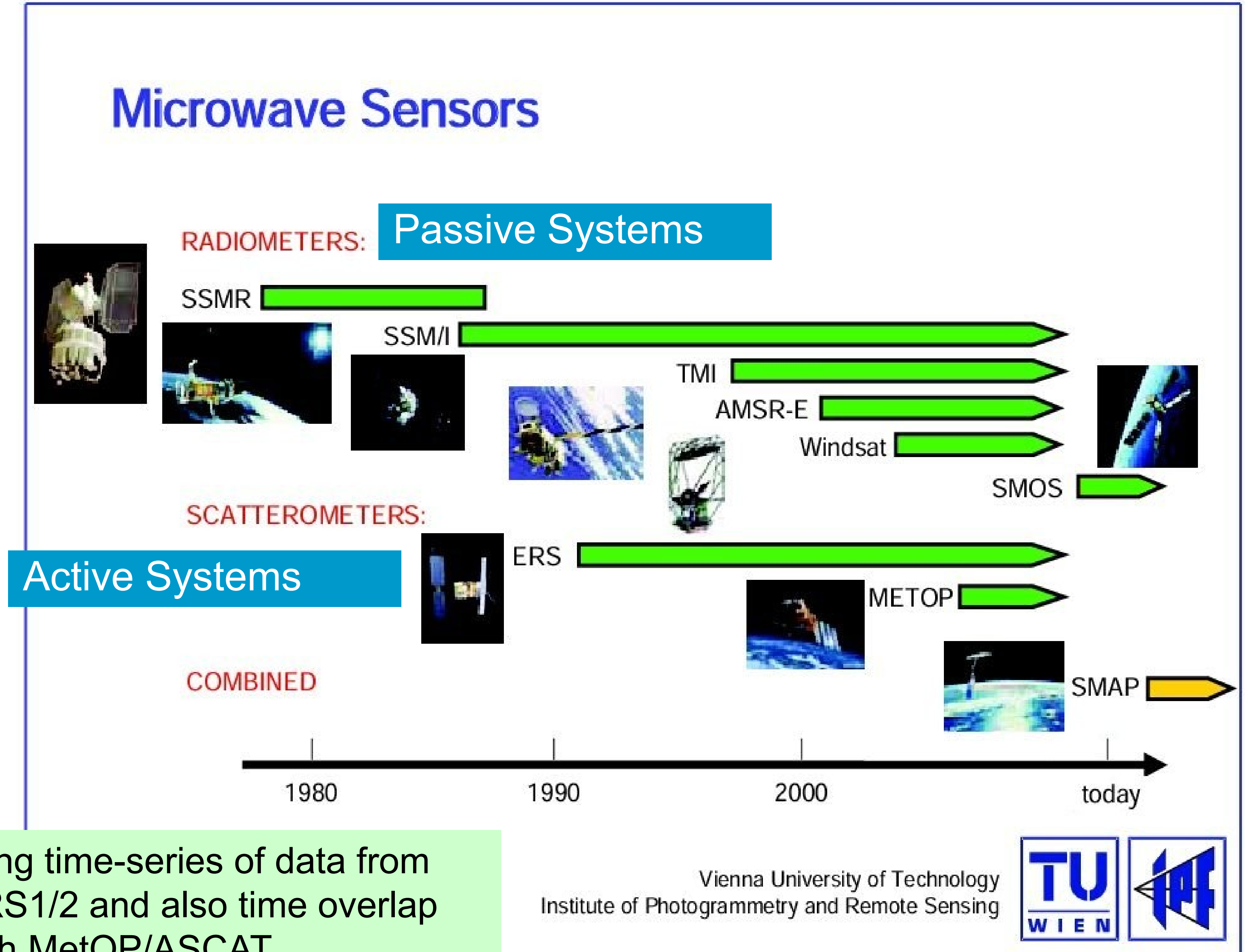
***Land data assimilation and sub-seasonal climate prediction***

## *A simple view of land-atmosphere feedback*



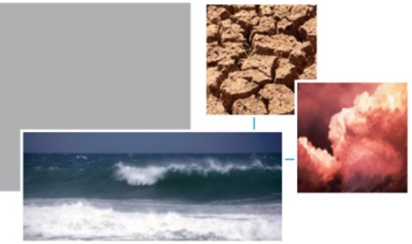
## Satellite based measurements of soil moisture

- Remote sensing by satellites is attractive since satellites offer **global data coverage.**
- At microwave frequencies the dielectric constant of liquid water (~70) is much higher than that of the soil mineral particles (< 5 ) or ice.
  - An increase in soil moisture leads to an increase in the dielectric constant of the soil which leads to a decrease in soil emissivity and an increase in soil reflectivity.
- Microwave backscatter/brightness temperature is affected by many factors, including:
  - Vegetation water content
  - Soil roughness
  - Lower frequencies are less affected so **SMOS and SMAP should be more accurate than ASCAT and AMSR-E**.



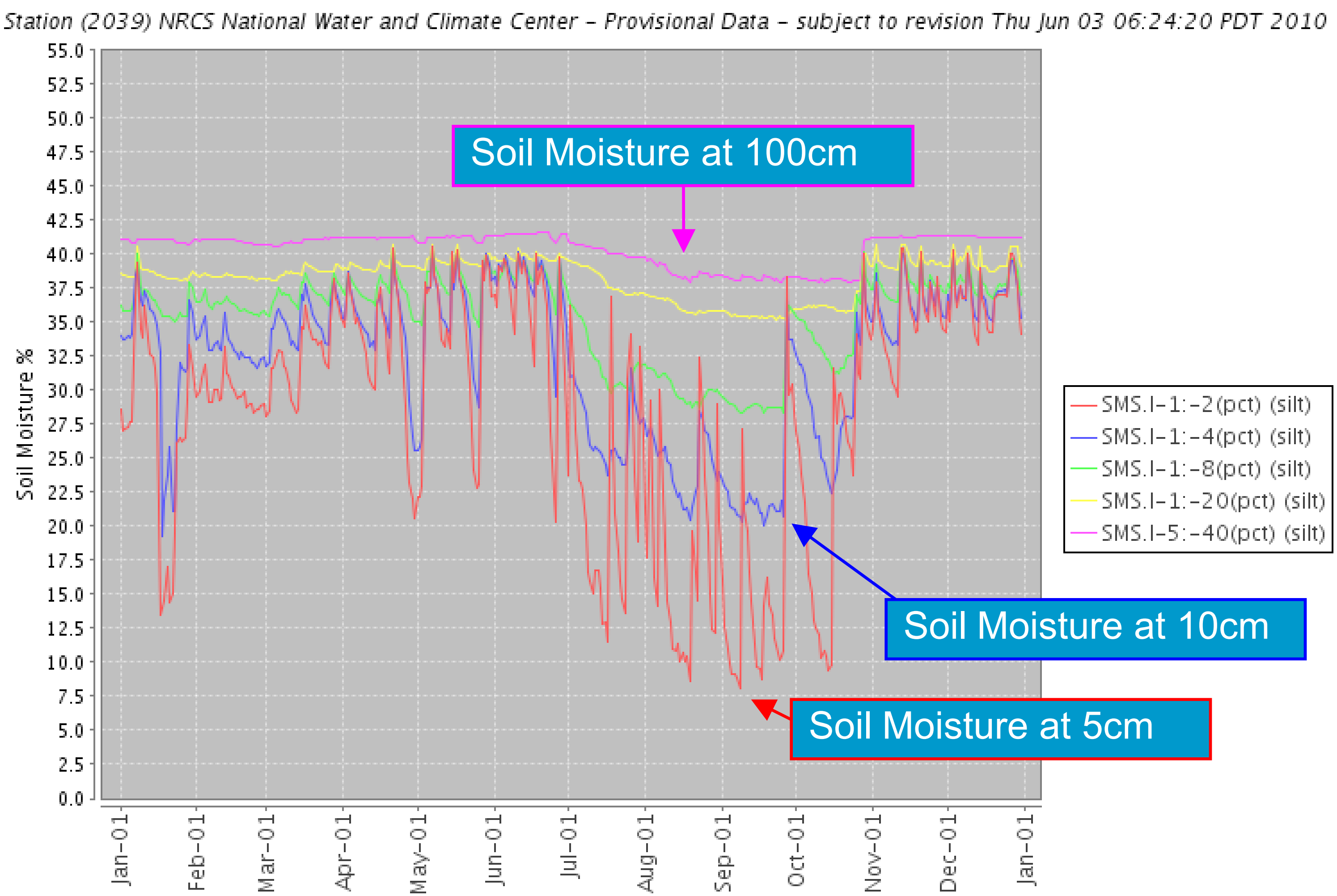

Long time-series of data from ERS1/2 and also time overlap with MetOP/ASCAT.

# Challenges to using Satellite derived soil moisture for weather forecasting (1)

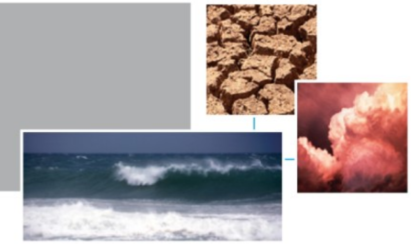


1. Satellites microwave sensors only sense a thin top layer of soil; ~1cm.
    i. Weather forecasting requires knowledge of soil moisture in the plant root-zone (~ top 1m of soil) since plants extract soil water through the roots which then evaporates from their leaves.
    ii. There are often significant vertical gradients in the soil moisture.
        - In the summer the surface soil can become very dry while the deep soil layers are close to saturation.

# Variation of soil moisture with depth: measurements from in-situ sensors at a station in Virginia state, US.



# Challenges to using Satellite derived soil moisture for weather forecasting (2)



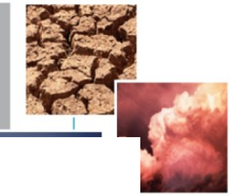
1. Satellites microwave sensors only sense a thin top layer of soil.

2. Retrieval algorithms are needed to convert satellite measurements of backscatter/brightness temperature into soil moisture. These **retrieval algorithms often produce very biased estimates of soil moisture.**

3. **Land surface and atmosphere models contain biases** and approximations so assimilating more accurate soil moisture may make the model's surface fluxes of heat and moisture worse and therefore make weather forecasts worse.
   i. Improving the models and parameters is as important as improving the soil moisture analysis.

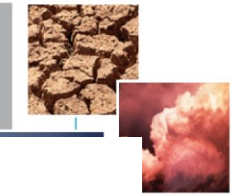
**Points 2 and 3 may be dealt with by "an ad-hoc" bias correction of the retrieved satellite soil moisture.**

# Case Study – New soil moisture analysis scheme (1)



- Pre Aug 2005: The UK Met Office used a scaled soil moisture climatology
  - Created by driving a bucket land surface model with observations.
  - This climatology is too moist and causes a cold bias of about 0.5K at the screen level.
- August 2005: The UK Met Office starts using a new soil moisture nudging scheme
  - Method uses observations of screen temperature and humidity.
- June 2006: Operational forecasts of screen temperature are too warm by about 1K (at T+6 days)
  - Ground based soil moisture observations (USDA: SCAN) show that:
    - In the surface soil layers the new soil moisture analysis is much more accurate.
    - However, the deep soil layers had incorrectly dried out to the wilting point.
- The past use of a very moist soil moisture climatology had hidden long standing model biases (next slide).

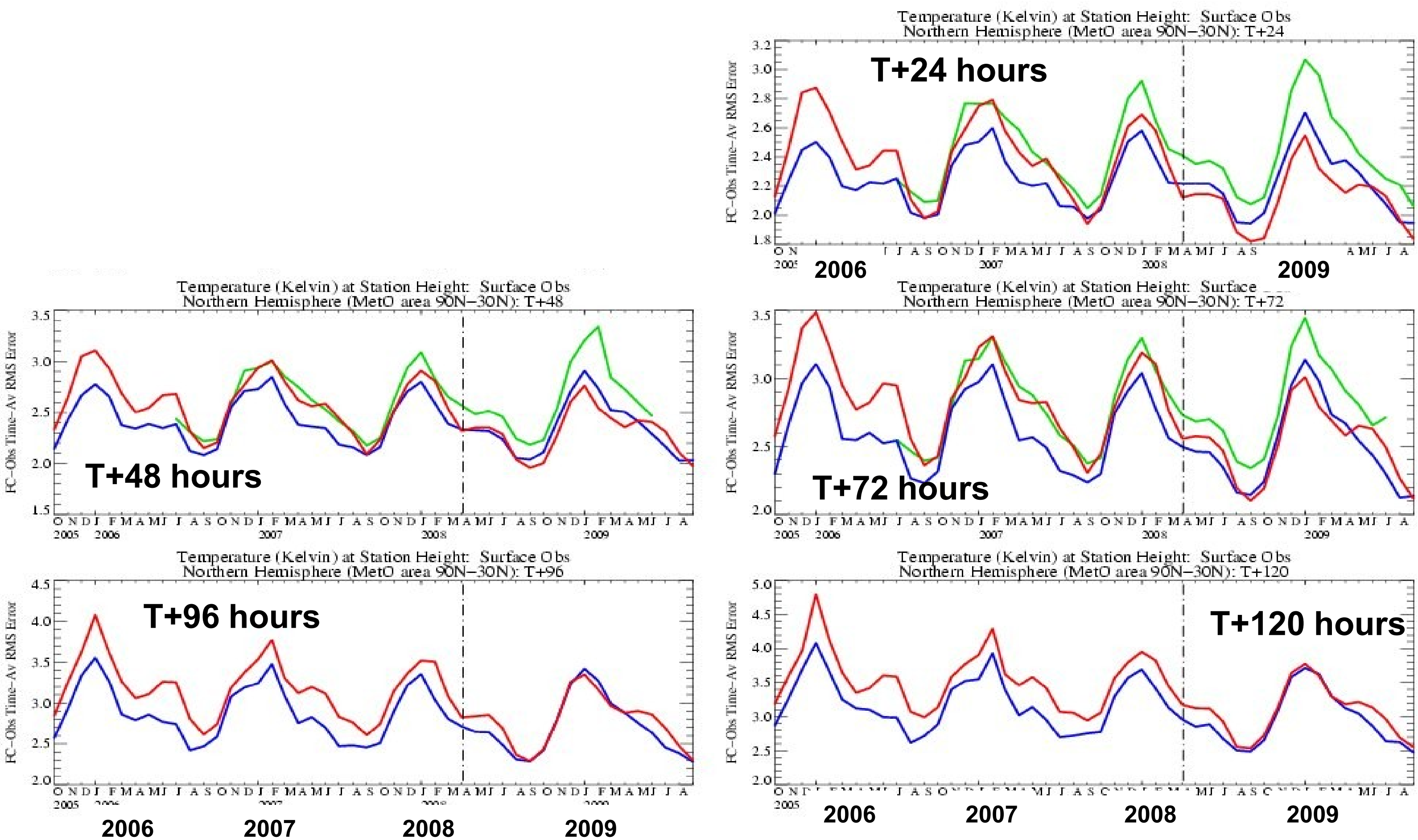
# Case Study – New soil moisture analysis scheme (2)



- The introduction of a new soil moisture analysis scheme resulted in significant improvements to the model through the efforts of many scientists over several years :
    - Improvements to the **soil hydraulic properties** (increase the wilting and critical points) which solves the problem of the deep soil layers drying out.
        - This change reduces evaporation so the summer warm bias actually becomes worse!
    - Improvements to the **soil thermal conductivity** which significantly reduces the summer warm bias and also the winter cold bias of the model.
    - New multi-layer **photosynthesis** model also reduces the summer warm bias.
    - Better treatment of **runoff** so that snow-melt over frozen soils gives moister soils.
    - New surface **albedos** based on satellite measurements.
    - Improvements to reduce biases in model **clouds** and the Introduction of a climatology for naturally produced biogenic **aerosols**.

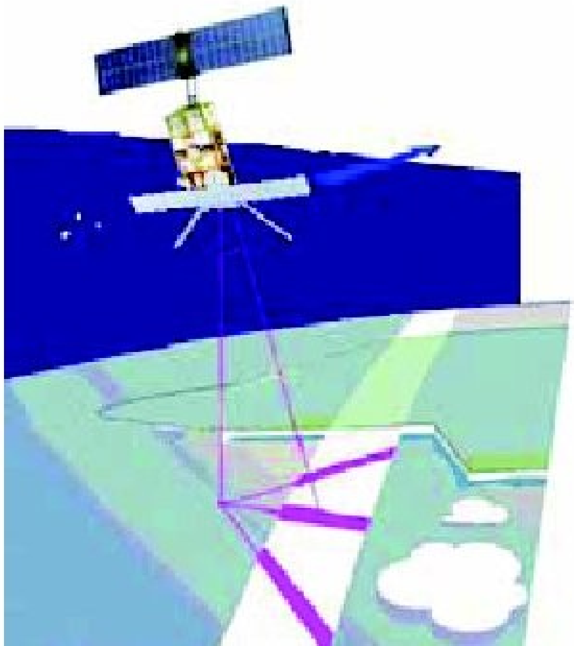
# Improvement in forecasts of Screen Temperature due to better parameterisation of soil properties

Cases: UKMO NWP Centre 1 NWP Centre 2

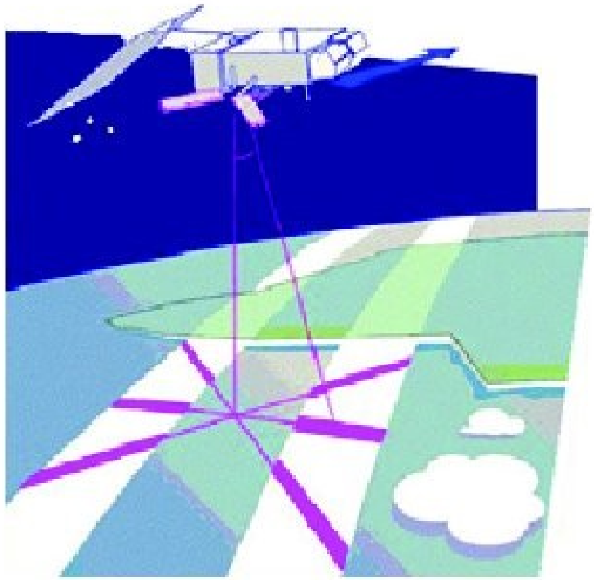


# Operational European C-Band Scatterometers

- <u>2</u> ERS scatterometers
  (1991, continuing until at least 2008)
  - 5.3 GHz
  - 3 Antennas
  - Swath width: 500 km
  - Resolution: 50 / (25) km
  - Daily coverage ~ 40%



- <u>3</u> METOP scatterometers (ASCAT)
  (launched October 2006, > 14 years)
  - 5.3 GHz
  - Two pairs of 3 Antennas
  - Swath width: 2 x 550 km
  - Resolution: 50 / 25 km
  - Daily coverage ~ 80%



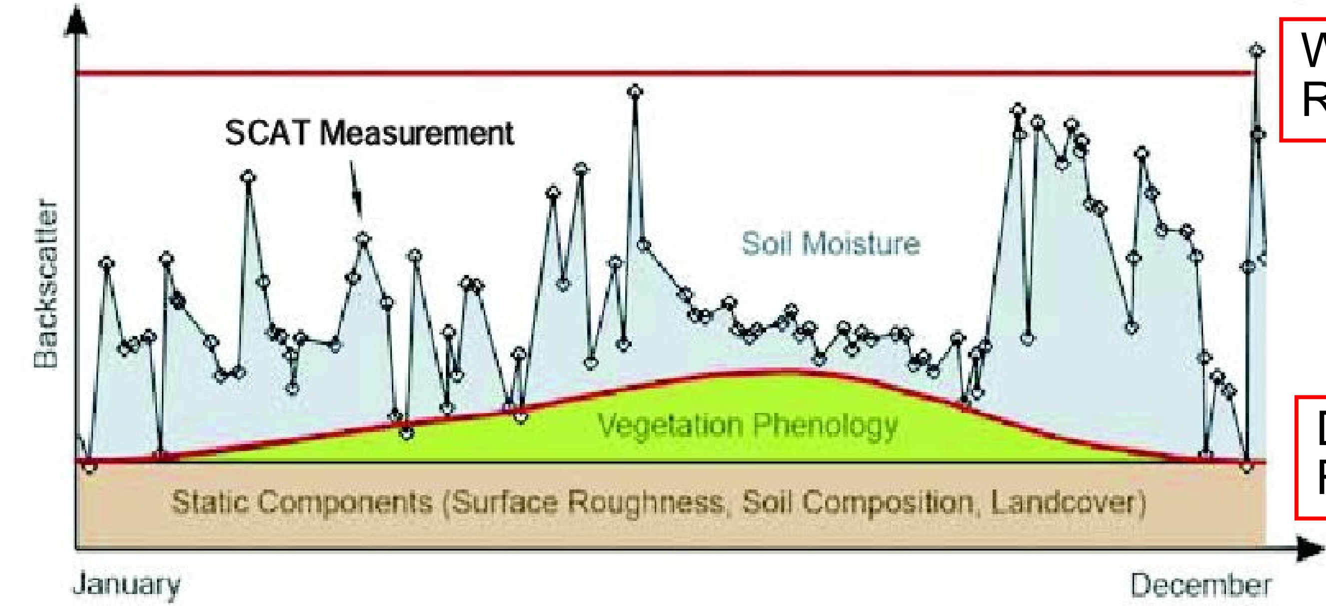
# TU Wien Retrieval Approach

Surface Soil Wetness

Backscatter at angle of 40 degrees

- **Change detection**
  - Accounts indirectly for surface roughness and land cover

$$m_s(t) = \frac{\sigma^0(t) - \sigma^0_{dry}(t)}{\sigma^0_{wet} - \sigma^0_{dry}(t)}$$

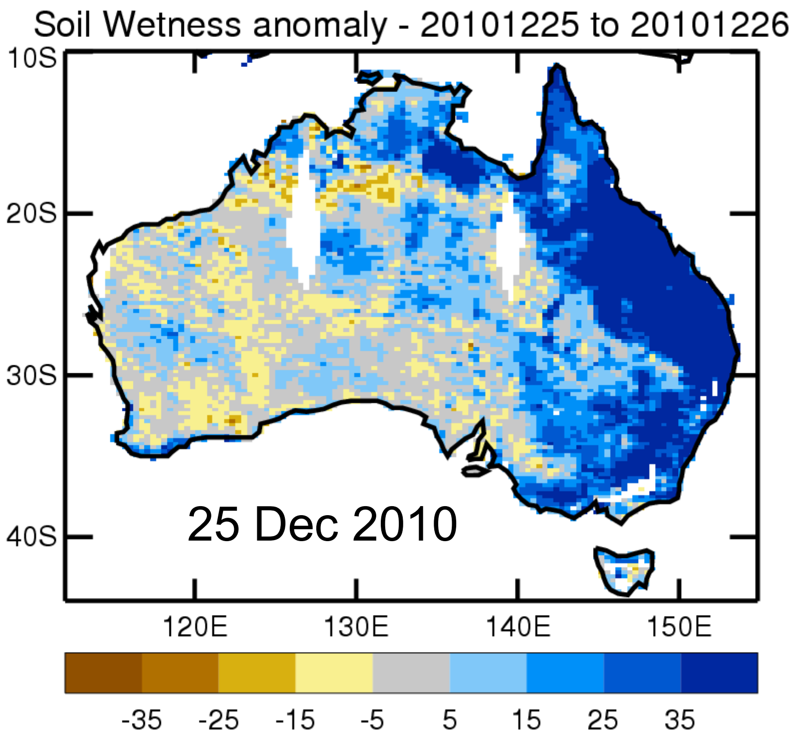


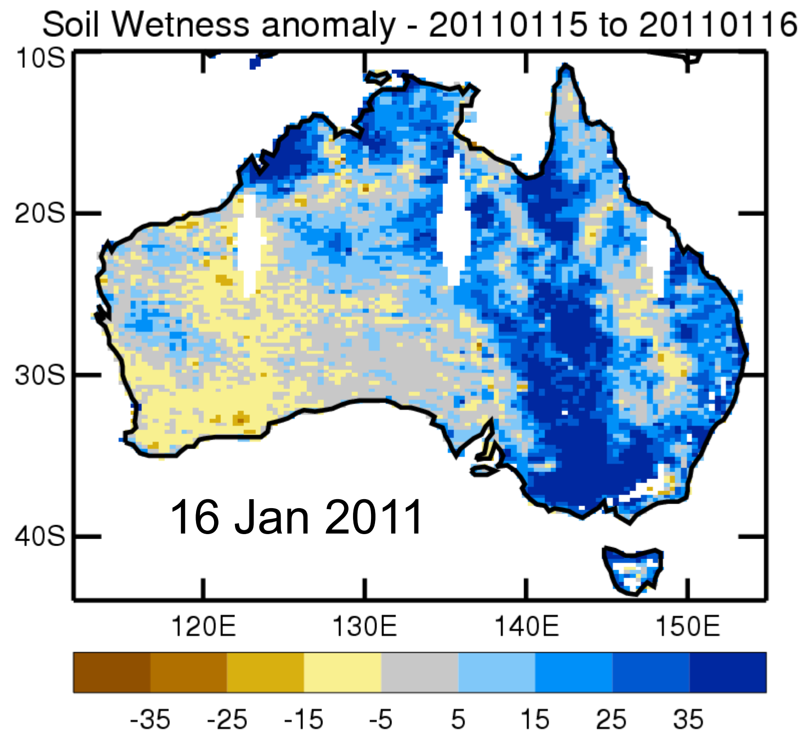

Wet Reference

Dry Reference

Vienna University of Technology
Institute of Photogrammetry and Remote Sensing

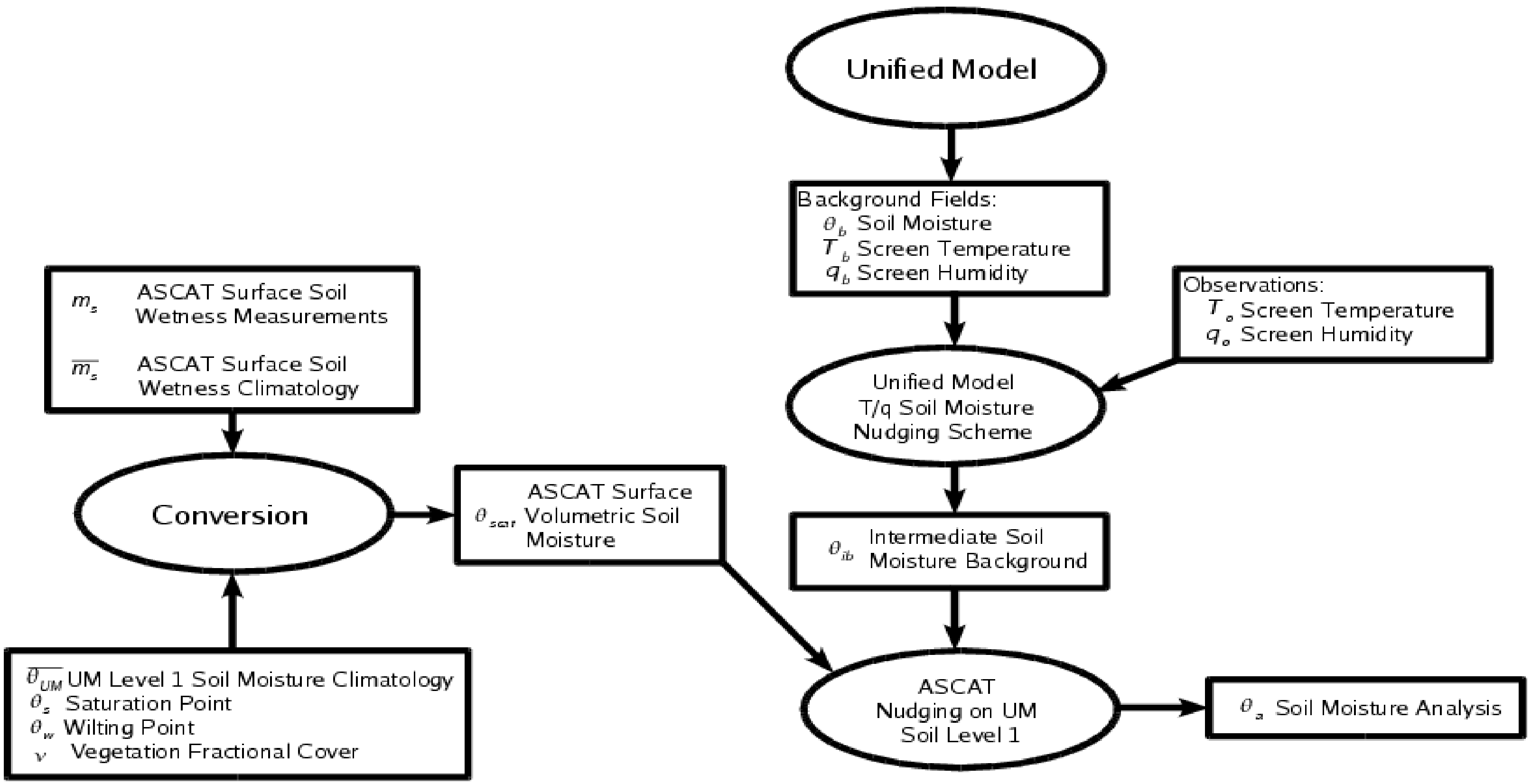
# ASCAT Surface Soil Wetness Anomalies



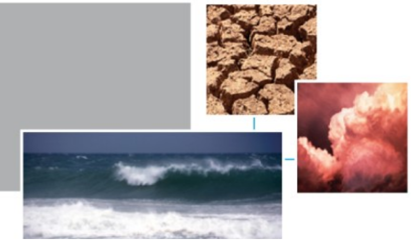



# Soil Moisture Analysis Scheme

- Assimilation of ASCAT surface soil wetness
  *Imtiaz Dharssi, Keir Bovis, Bruce Macpherson and Clive Jones*
  Met R&D Technical Report 548, 2010.
- http://research.metoffice.gov.uk/research/nwp/publications/papers/technical_reports/reports/548.pdf

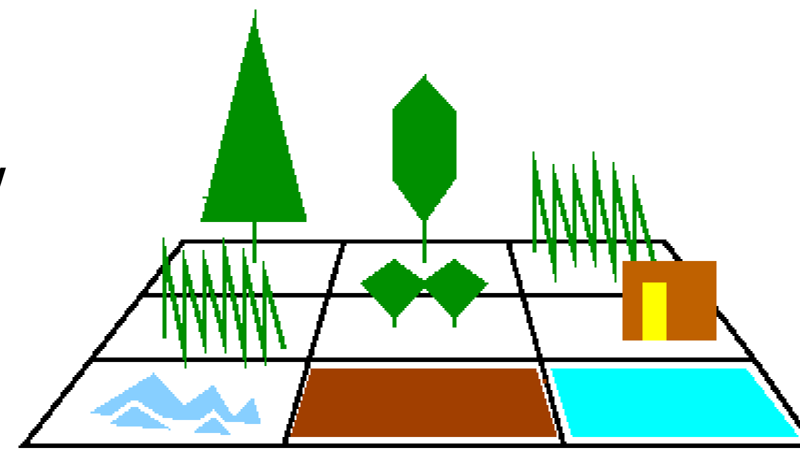


# Overview of the Land Surface Model



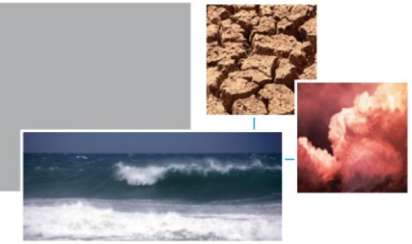
- 9 tiles
  - •5 veg + 4 non-veg
- 4 Soil Layers
  - •Thickness
    - •10cm, 25cm, 65cm, 200cm

•Independent soil columns



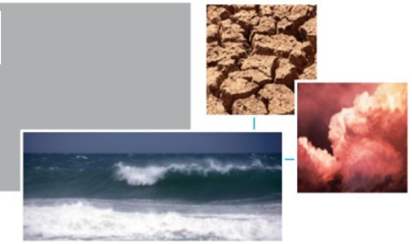
- Richards Equation and Darcy's Law
  - Movement of water in unsaturated soils
- van Genuchten soil hydraulics
  - Unsaturated hydraulic conductivity
- Multi-layer photosynthesis model
  - •Much improved description of light interception by the canopy
    - •More photosynthesis in bright sunlight
    - •Less photosynthesis in low light

# Bias Correction of the satellite data



- The model soil moisture climatology is used to bias correct the retrieved satellite soil moisture.
  - The available observation data is insufficient to determine the true soil moisture climatology.
- The climatology of the bias corrected satellite soil moisture will agree quite closely with the climatology of the model soil moisture.
  - This has the advantage that the bias corrected satellite soil moisture will be consistent with the assumptions made by the land surface model.
- Consequently, data assimilation of the bias corrected satellite soil moisture is more likely to improve model surface fluxes and lead to better weather forecasts.

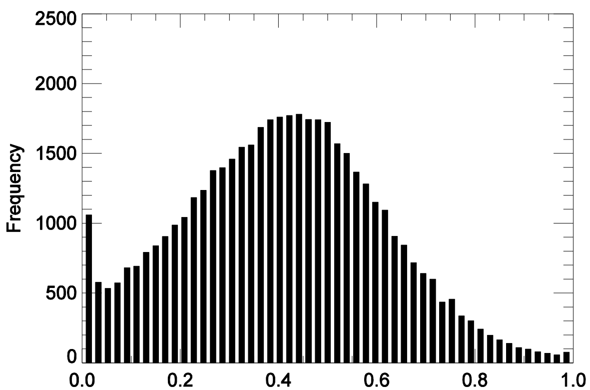
# Conversion of ASCAT Soil Wetness to Soil Moisture with bias correction



$$\theta_{SCAT}(t) = \overline{\theta_{UM}(t)} + b \times \{m_s(t) - \overline{m_s(t)}\}$$

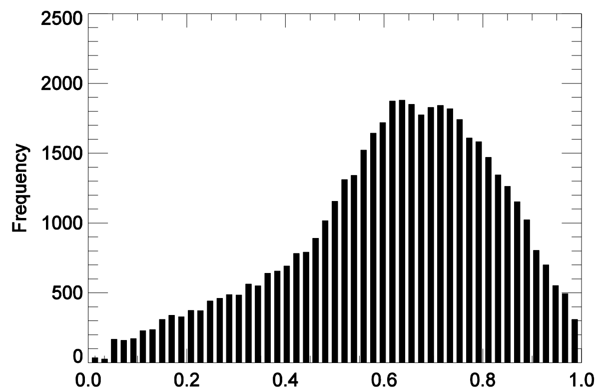
$$b = \theta_S - \nu\, \theta_W$$

Before Conversion



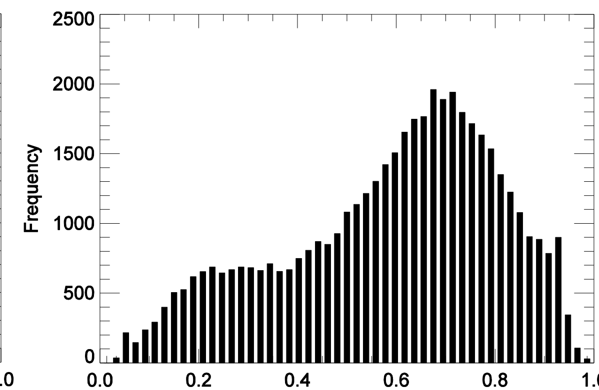

$m_S$

After Conversion




$\theta_{SCAT} / \theta_S$

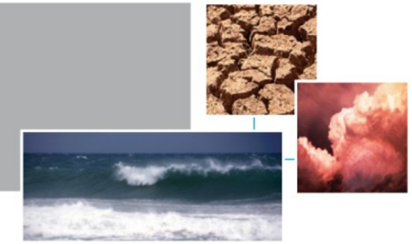
Model

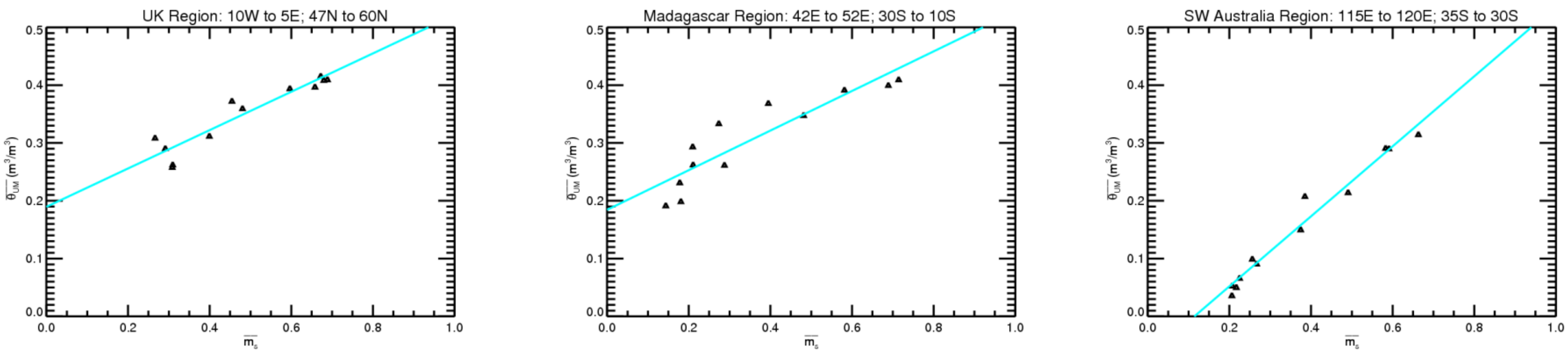



$\theta_{UM,1} / \theta_S$

Note the large range of model soil moisture values

$$b = \theta_S - \nu\,\theta_W$$

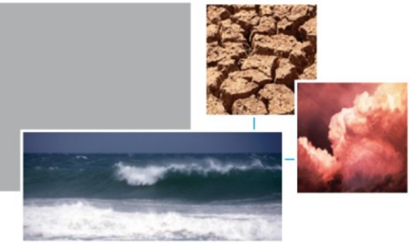





Scatter plots of $\overline{m_s}$ vs $\overline{\theta_{UM}}$ climatologies for three regions.

## UM soil moisture climatology

$$\overline{\theta_{UM}(t)}$$



- Drive the UM land surface model (JULES) with 10 years of observation based data from the Global Soil Wetness Project 2 (GSWP2)

**10 years of Driving Data**

Precipitation

Surface SW / LW Radiation

Screen Temperature

Screen Humidity

Surface Pressure

Surface Wind Speed

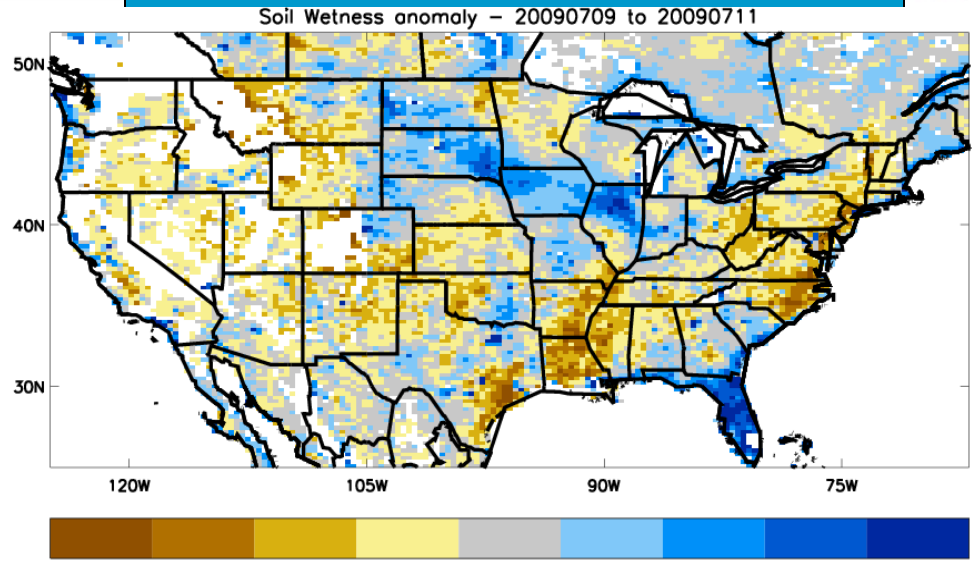
**Soil and Vegetation Parameters**

**UKMO Off-Line Land Surface Model**

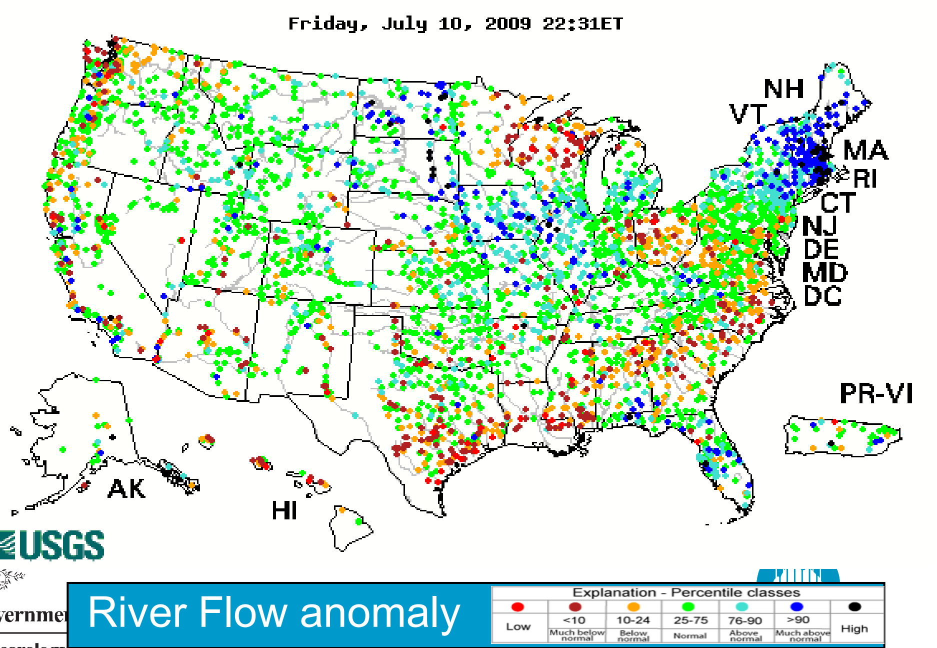
**10 Years of Soil Moisture Analyses**

# Water anomalies: 9 to 11 July 2009

ASCAT surface soil wetness anomaly




Good qualitative agreement between the two data.




River Flow anomaly

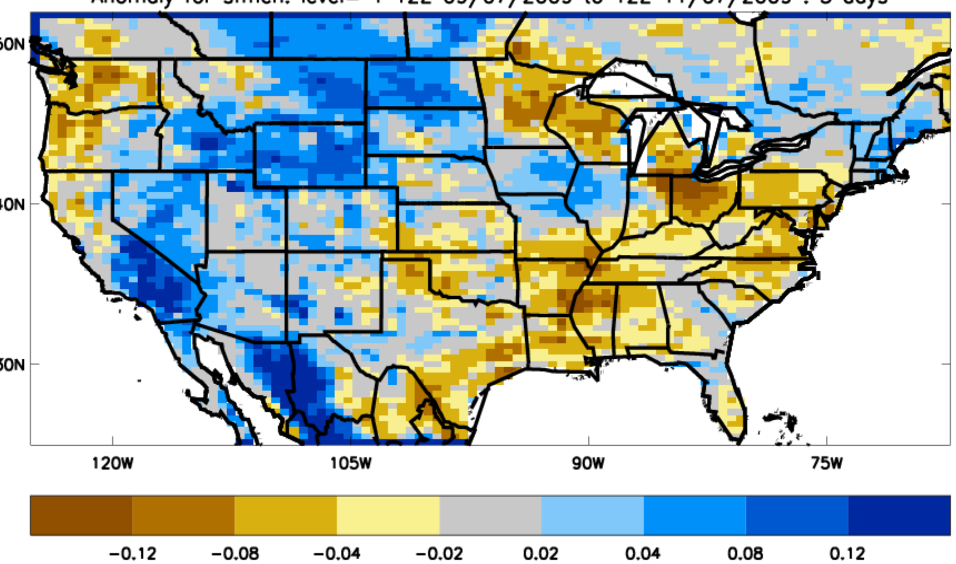
USGS

Australian Government

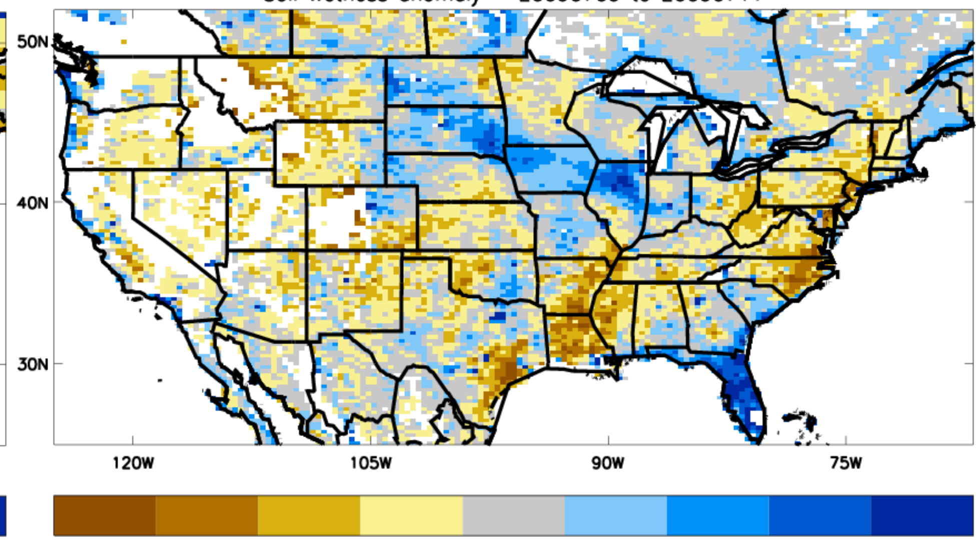
Bureau of Meteorology

# Water anomalies: 9 to 11 July 2009

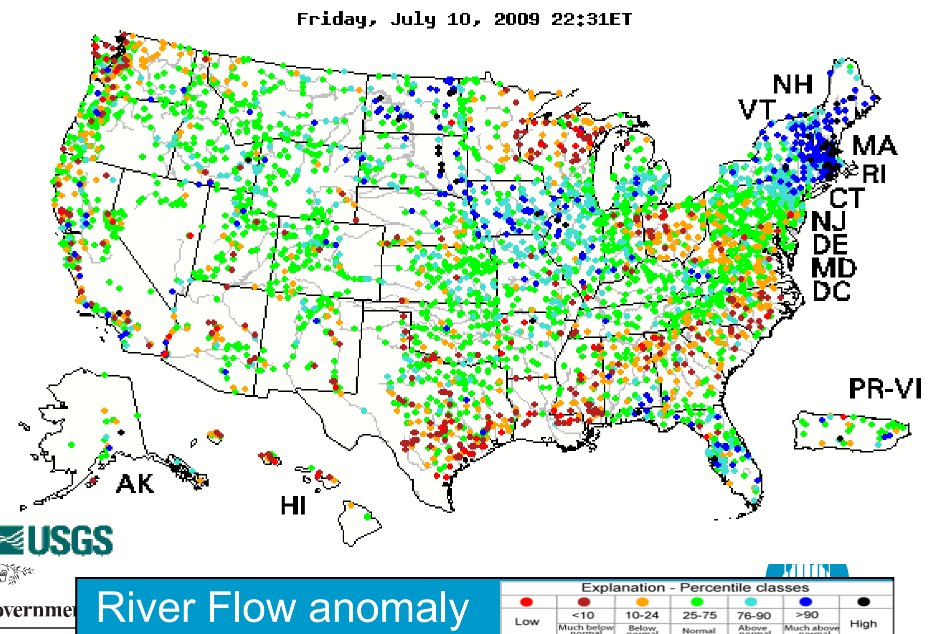
## Control run: top 10cm soil moisture anomaly




## ASCAT surface soil wetness anomaly




Model soil too wet in the west and possibly too dry in the east (e.g. Florida).




River Flow anomaly

USGS

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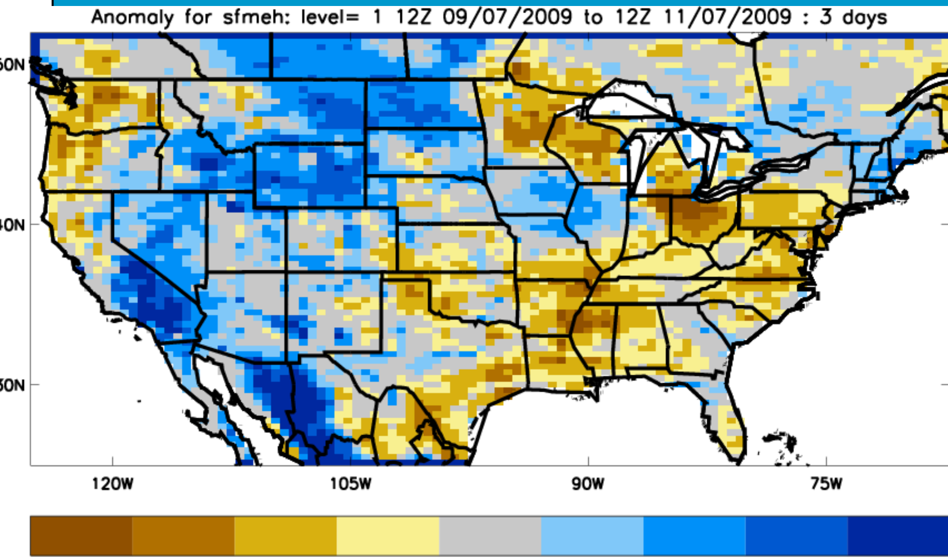
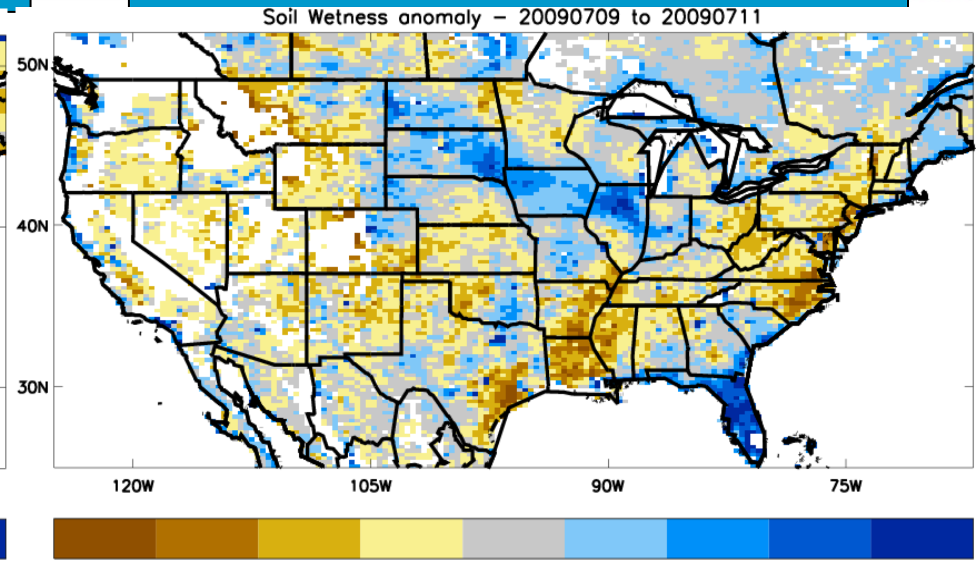
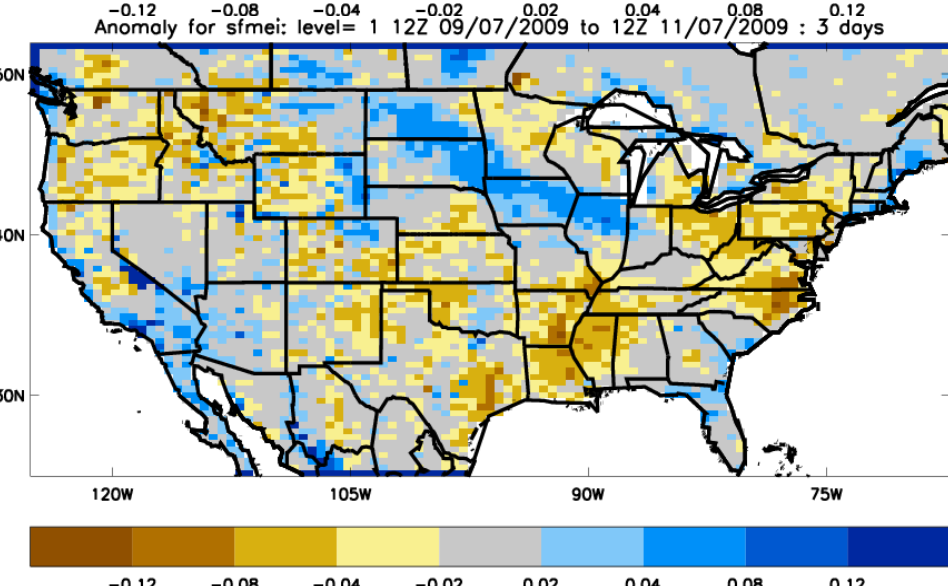
# Water anomalies: 9 to 11 July 2009

## Control run: top 10cm soil moisture anomaly

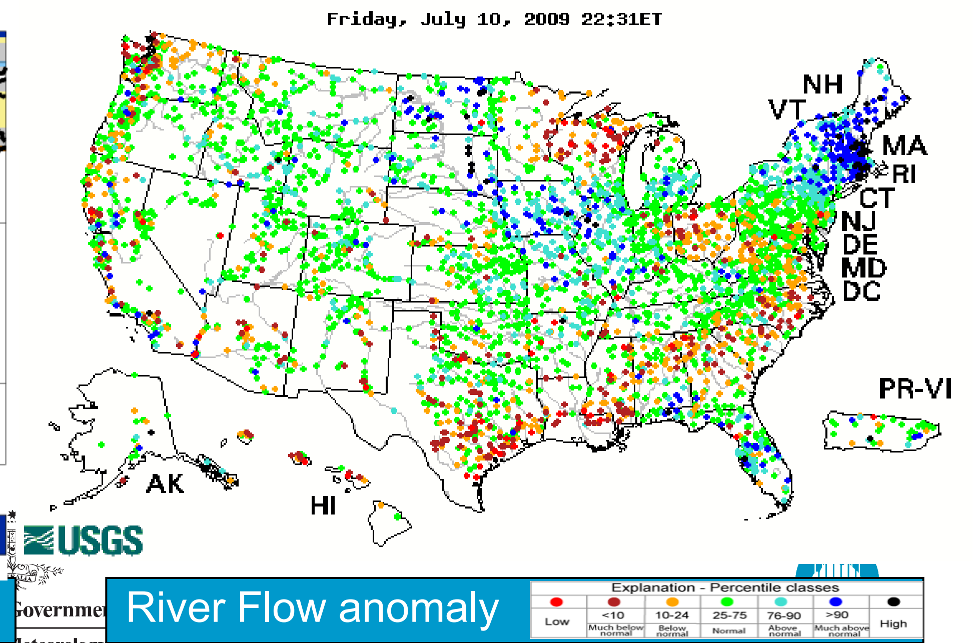



## ASCAT surface soil wetness anomaly




## Test run: top 10cm soil moisture anomaly




## River Flow anomaly

# Verification against ground based observations: June/July 2009

**Table 4.** Verification statistics for Trial 1 of UM level 1 soil moisture compared with USDA SCAN observations.

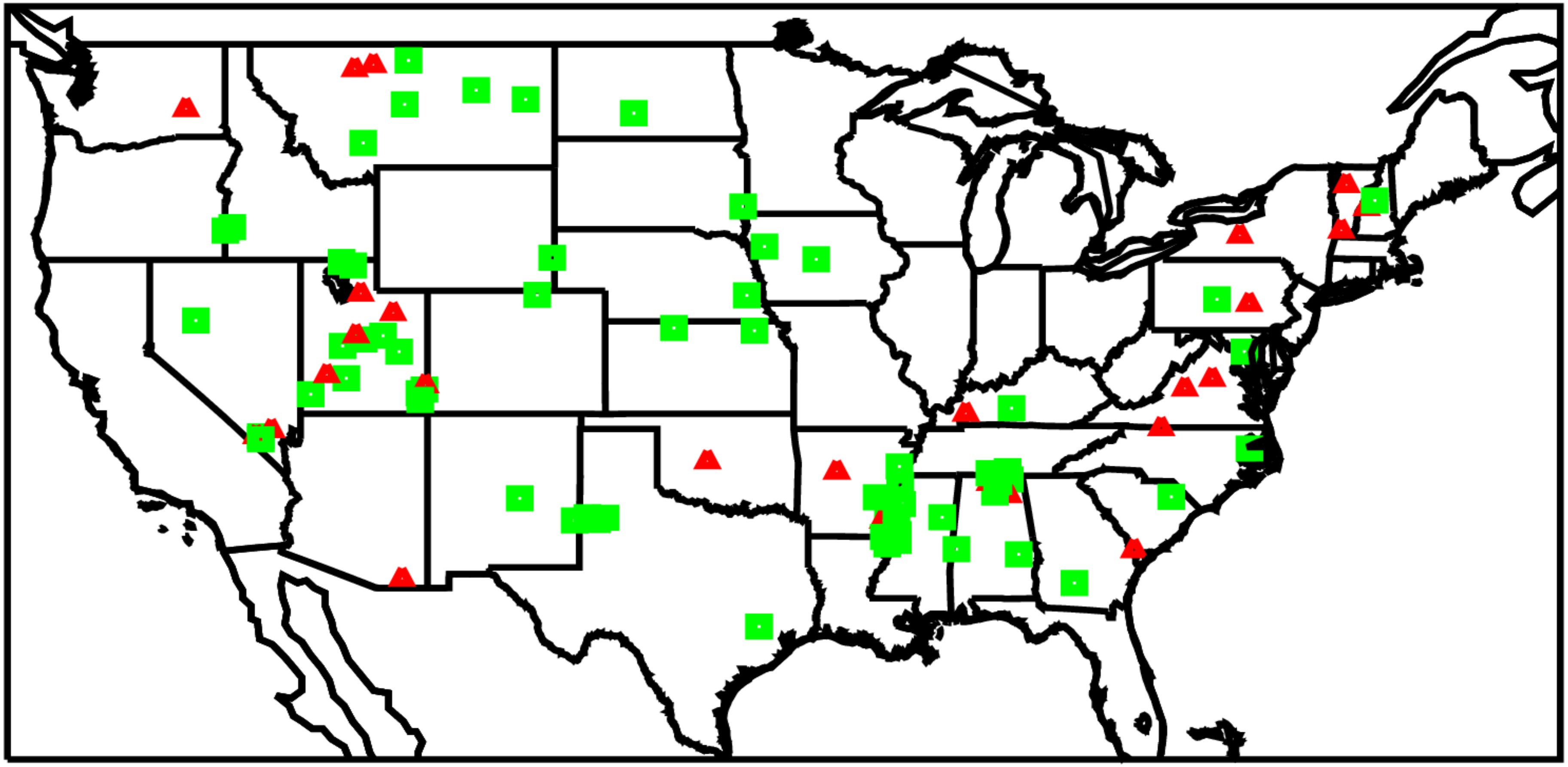
| | TEST ASCAT Assim. | CTRL No ASCAT Assim. | Number of USDA SCAN stations Better | Same | Worse |
|---|---|---|---|---|---|
| With quality control of USDA SCAN stations. | | | | | |
| SD ($m^3/m^3$) | $0.041 \pm 0.003$ | $0.046 \pm 0.003$ | 45 | 1 | 14 |
| RMS ($m^3/m^3$) | $0.075 \pm 0.007$ | $0.082 \pm 0.008$ | 38 | 1 | 21 |
| Correlation | $0.79 \pm 0.01$ | $0.73 \pm 0.02$ | 25 | 5 | 30 |
| Bias ($m^3/m^3$) | $0.01 \pm 0.02$ | $0.01 \pm 0.02$ | 24 | 9 | 27 |
| Without any quality control of USDA SCAN stations. | | | | | |
| SD ($m^3/m^3$) | $0.045 \pm 0.003$ | $0.051 \pm 0.004$ | 62 | 2 | 27 |
| RMS ($m^3/m^3$) | $0.108 \pm 0.011$ | $0.114 \pm 0.011$ | 55 | 2 | 34 |
| Correlation | $0.59 \pm 0.02$ | $0.52 \pm 0.02$ | 41 | 5 | 45 |
| Bias ($m^3/m^3$) | $0.03 \pm 0.02$ | $0.03 \pm 0.02$ | 41 | 15 | 35 |

- SD is a measure of the random error.
  - ASCAT assimilation reduces the random model error by about 10%.
- RMS is a measure of the random error + bias.
- Instrument error is about 0.03 $m^3/m^3$.
- Comparing point observations with model grid box averages, so:
  - Error of representativity is about 0.06 $m^3/m^3$ (Famiglietti et al., 1999).
    - Model horizontal resolution is about 40km.
  - Therefore, the total observation error is about 0.07 $m^3/m^3$.
- Model error is about 0.05 $m^3/m^3$.

# USDA SCAN stations – Impact of ASCAT nudging

□ Reduction in random errors (Better)

△ Increase in random errors (Worse)



# Impact on Forecasts of screen RH RMS errors

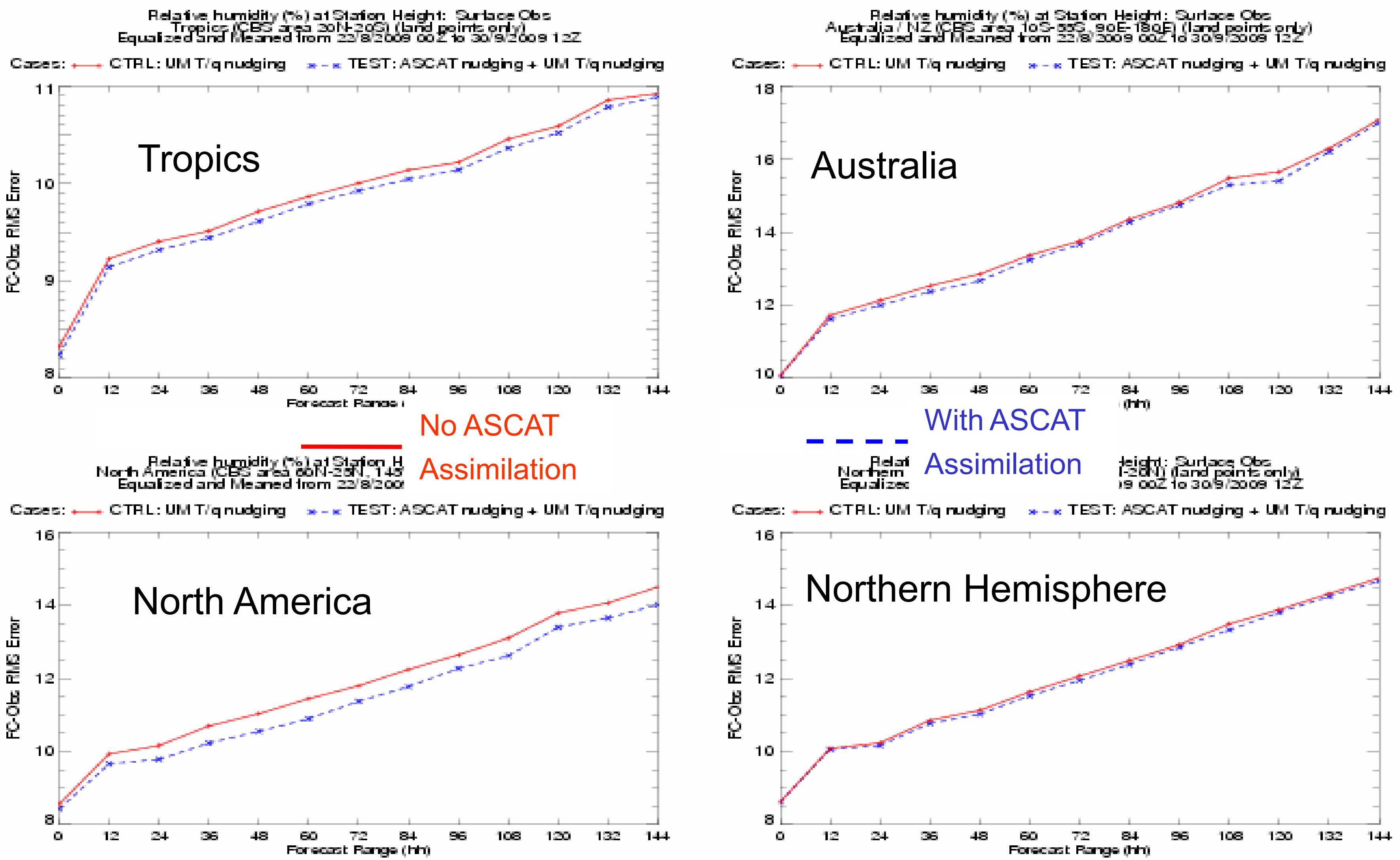



**Fig. 10.** Trial 4 verification of UM relative humidity forecasts against observations. The solid red lines (dashed blue lines) show RMS errors for the control experiment (test experiment that also assimilates

# Future Work

- Development of a Kalman Filter based land DA scheme to propagate surface information into the deeper soil layers.
- Use as many different sources of data as possible:
  - SMOS observations (and SMAP after launch)
  - ASCAT soil wetness measurements and screen T/q observations
  - Satellite observations of skin temperature
  - GRACE total water storage
  - Satellite derived Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation (FaPAR)

Australian Government

Bureau of Meteorology

The Centre for Australian Weather and Climate Research

A partnership between CSIRO and the Bureau of Meteorology

CSIRO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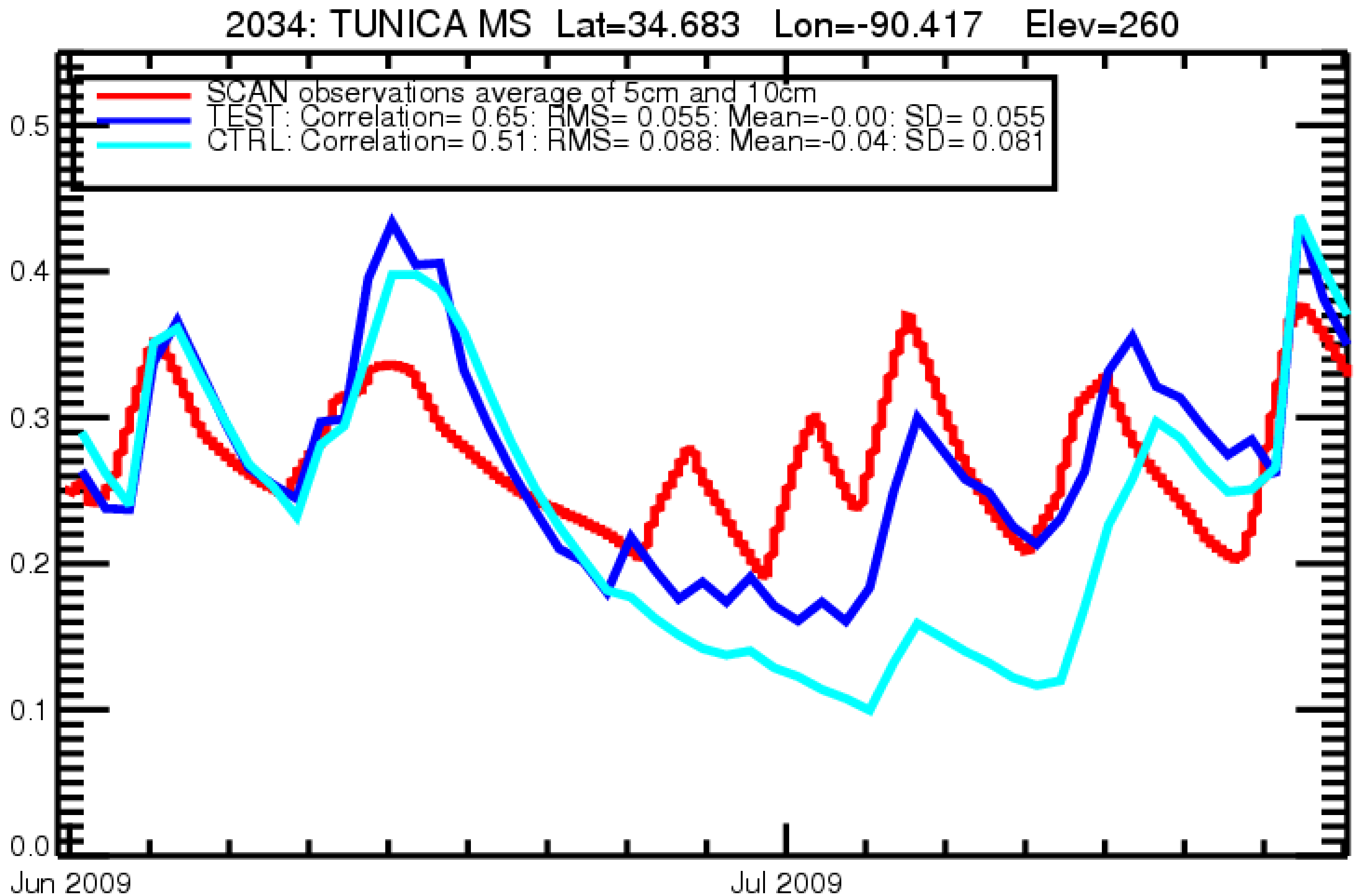
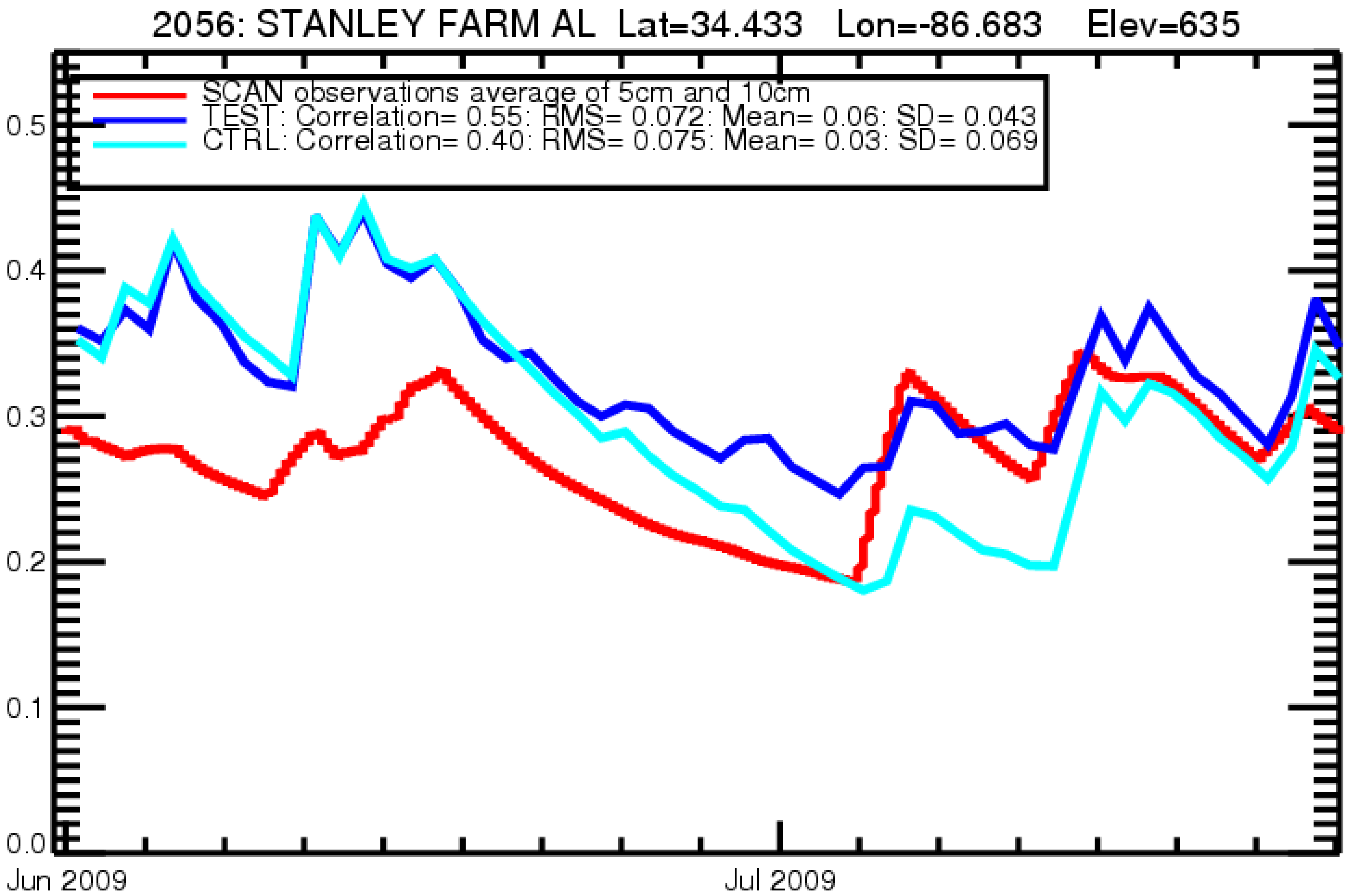
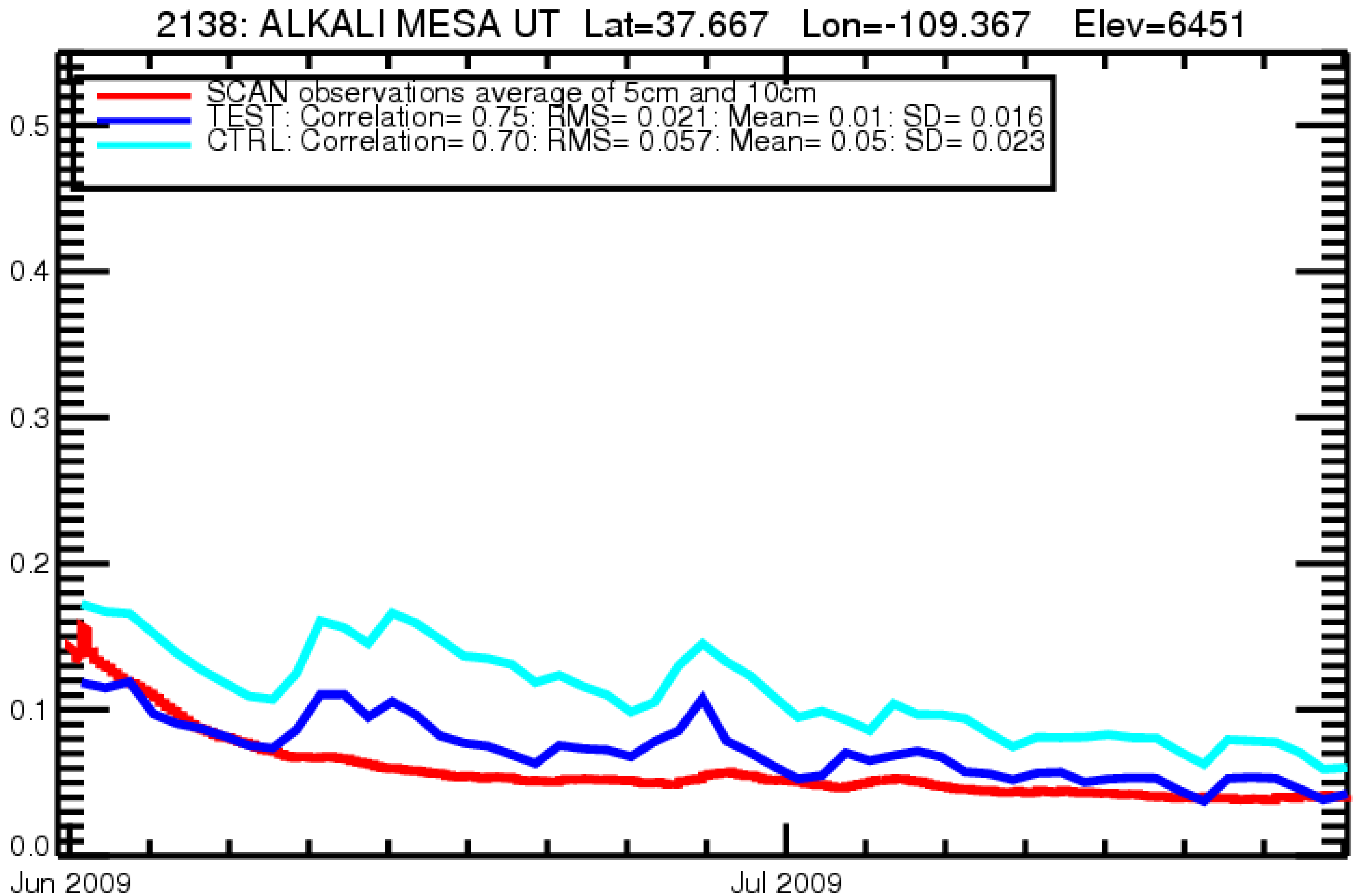
# Questions?

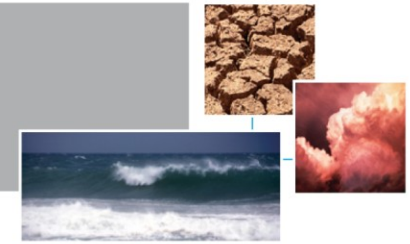
www.cawcr.gov.au


2034: TUNICA MS Lat=34.683 Lon=-90.417 Elev=260
SCAN observations average of 5cm and 10cm
TEST: Correlation= 0.65: RMS= 0.055: Mean=-0.00: SD= 0.055
CTRL: Correlation= 0.51: RMS= 0.088: Mean=-0.04: SD= 0.081
0.5
0.4
0.3
0.2
0.1
0.0
Jun 2009
Jul 2009


2056: STANLEY FARM AL Lat=34.433 Lon=-86.683 Elev=635
SCAN observations average of 5cm and 10cm
TEST: Correlation= 0.55: RMS= 0.072: Mean= 0.06: SD= 0.043
CTRL: Correlation= 0.40: RMS= 0.075: Mean= 0.03: SD= 0.069
0.5
0.4
0.3
0.2
0.1
0.0
Jun 2009
Jul 2009


2138: ALKALI MESA UT Lat=37.667 Lon=-109.367 Elev=6451
SCAN observations average of 5cm and 10cm
TEST: Correlation= 0.75: RMS= 0.021: Mean= 0.01: SD= 0.016
CTRL: Correlation= 0.70: RMS= 0.057: Mean= 0.05: SD= 0.023
0.5
0.4
0.3
0.2
0.1
0.0
Jun 2009
Jul 2009

# How does the model use soil moisture?



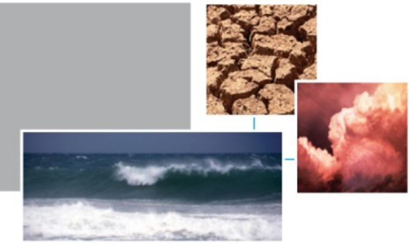
- Evaporation from plants

$$E = \rho \frac{\Delta q}{R_a + R_{s,veg}}$$

$$R_{s,veg} = \frac{R_s^{\min}}{\beta_{veg}}$$

| | |
|---|---|
| $E$ | Evaporation |
| $\rho$ | Density of Air |
| $\Delta q$ | Difference in Specific Humidity between the surface and model level 1 |
| $R_a$ | Aerodynamic Resistance between the surface and model level 1 |

# Bulk Stomatal Resistance

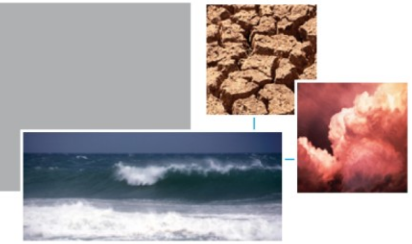


$$R_{s,veg} = \frac{R_s^{\min}}{\beta_{veg}}$$

Calculated by a photosynthesis model and depends on vegetation type, temperature, humidity and incident solar radiation.

The soil moisture availability depends on soil moisture, plant root fraction and soil texture.

# Soil Moisture Availability



$$\beta_{veg} = \sum_{k=1}^{4} f_k \beta_{veg,k} \qquad \sum_{k=1}^{4} f_k = 1$$

$$\beta_{veg,k} = \begin{cases} 0 & \theta_k < \theta_w \\ \dfrac{\theta_k - \theta_w}{\theta_c - \theta_w} & \theta_w < \theta_k < \theta_c \\ 1 & \theta_k > \theta_c \end{cases}$$

$\theta_k$ Soil Moisture in soil level k

$\theta_w$ Wilting Point

$\theta_c$ Critical Point