Satellite Use in Land Data Assimilation to support operational NWP

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Talk Outline

- 1. Purpose of Land DA for NWP
- 2. Development of Land DA systems
- 3. Soil Moisture: Remote Sensing Techniques
- 4. Active Soil Moisture: ASCAT
- 5. Passive Soil Moisture: SMOS, SMAP
- 6. Snow
- 7. Albedo & LAI
- 8. Conclusions

Acknowledgements

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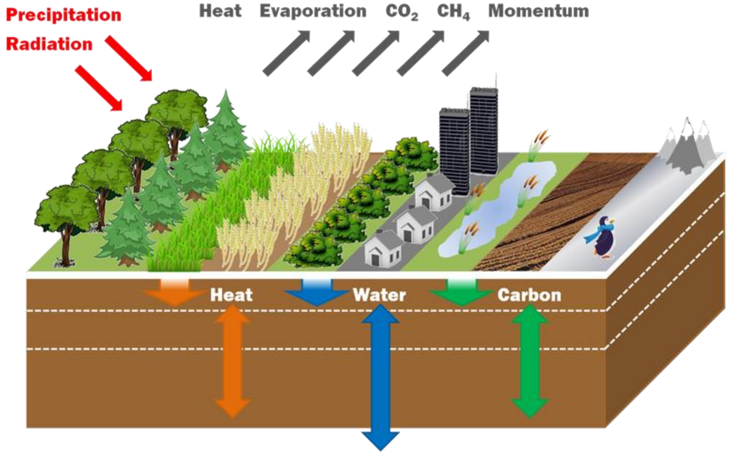
Focus of Land Data Assimilation for NWP

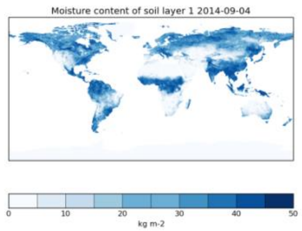
Land Surface Requirements - 1

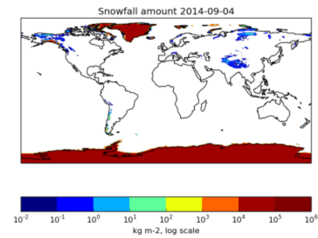
- NWP models contain embedded surface exchange models, such as JULES. Consequently models require an accurate representation of the land state and the key parameters
- In particular, parameters such as soil moisture and snow cover are critical in controlling the moisture and energy fluxes from the land into the atmosphere.
- As will be shown later improvements to the analysis of these (and other land parameters) have direct influence on the quality of atmosphere forecast variables such as precipitation and near surface air temperature.
- In addition to short range weather forecasting it is also recognised that at the seasonal timescales land variables are critical to aid the predictability of precipitation, etc.



Land Surface Requirements - 2

- Routine analyses of land variables are performed for parameters such as
  - Snow
  - Soil Moisture
  - Soil Temperature





- All of which make use of remote sensing data, in addition to in situ measurements

- Focus in this talk is on initialising short to medium range NWP models

- However there are a wider range of applications for such data. For example in the hydrology area:
  - initialising soil state for flood modelling (Flooding from intense Rainfall, SINATRA, Univeristy of Reading)
  - monitoring of drought and water state for agriculture/crop yeilds. (Agriculture Information Service Canada)
  - fire risk prediction (Australia CAWCR)
  - For more applications see 2014 esa soil moisture workshop [Netherlands]

- Several of these applications demand high resolution observations and additional (level 3) processing of the remote sensing products

Progression of land analysis methods for soil moisture

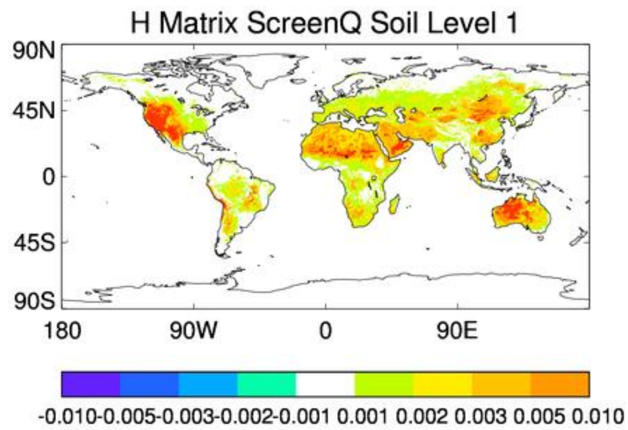
- Reset land to externally available climatologies
- As above but climatology created via offline land model driven by in situ observations (JULES + WATCH forcing data)
- Simplified Nudging scheme (simplified physics to diagnose error in soil moisture from model errors observed at screen level)
- Optimal Schemes: Kalman Filter based system. Main benefits
  - ability to use more satellite observations (passive and active microwave, Land Surface temperature,…)
  - Take advantage of developments in atmospheric DA (observation error background error diagnosis,…)

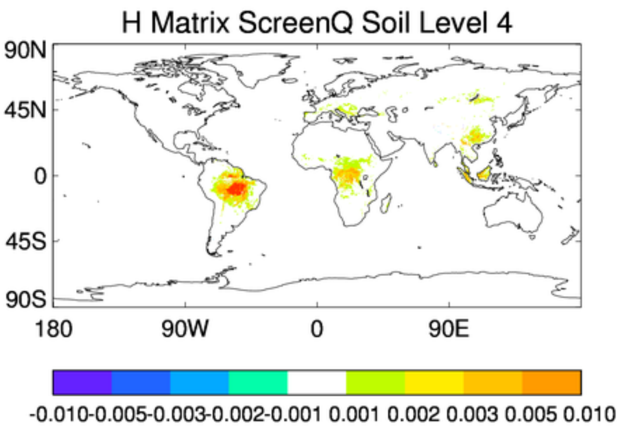
An Example Operational Scheme: EKF

- *Analysis Vector* – soil moisture and soil temperature at 4 depths down to 3m.
- *Observation Vector* – screen observations of temperature, humidity & remote sensing observations of top layer
- *Jacobians* are computed from the JULES land model via *finite difference* (as we have no access to an adjoint model of JULES) Represent instantaneous conditions
- Horizontal error correlations are ignored.
- We aim to use realistic observation and background errors (based on comparisons with in situ soil moisture networks & other sources of soil moisture)

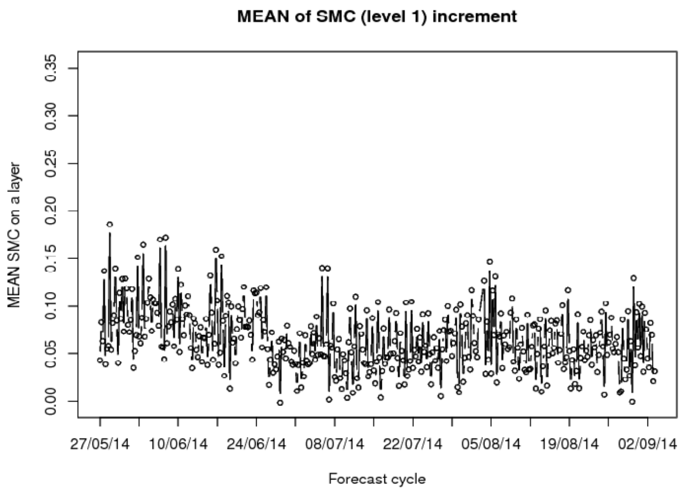
EKF (II) Performance

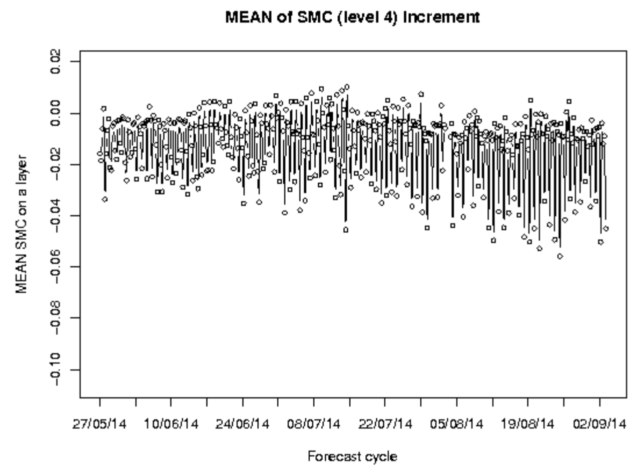
Jacobian Screen Humidity wrt soilmoist





Increment timeseries





What do Centres Use?

Current operational scheme for soil moisture

Centre	Scheme	In situ	Rem Sens.
ECMWF	ExtendedKF	•	• **[active,passive]**
Meteo-France	OI	•	R&D
Bureau of Met	Nudging	•	R&D
NCEP GFS	Relax towards climatology		R&D
Environment Canada	Ens KF	•	R&D
Met Office	ExtendedKF	•	• **[active]**
HIRLAM	OI	•	R&D

Met Office

Soil Moisture: Remote Sensing Techniques

Microwave Radiative Transfer over land

Met Office

- In the microwave region the dielectric constant of soil is strongly affected by soil moisture variation. This leads to a variation in the observed brightness temperatures *and* the layer over which the surface emission originates.
- Simplified radiative transfer models (e.g. Ulaby et al, 1990) have been developed to describe the emission of radiation from the surface and from an absorbing/emitting vegetation layer.

$$T_B = \tau_V \varepsilon T_{surf} + (1-w)T_{can}(1-\tau_v) + (1-\varepsilon)(1-w)T_{can}(1-\tau_v)\tau_v$$

Where the surface emissivity is a function of soil type, roughess and soil moisture



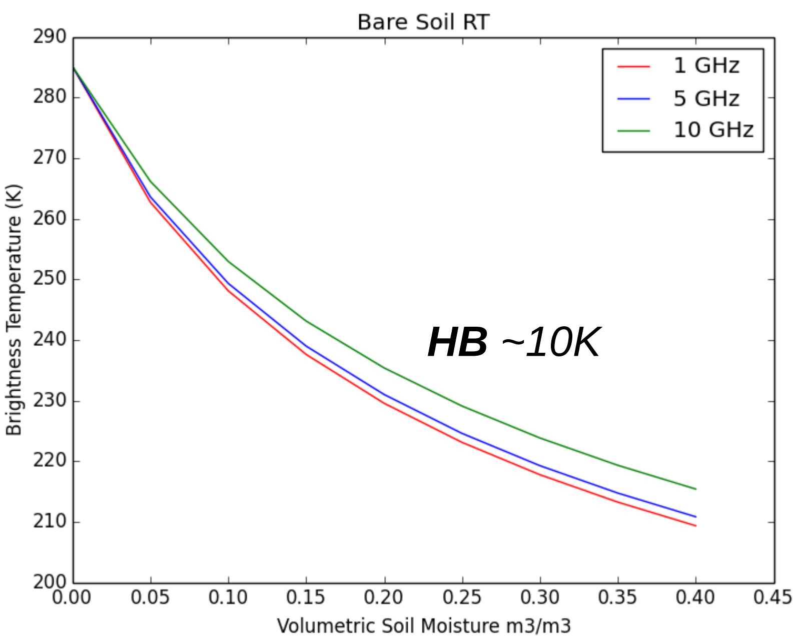

Microwave Radiative Transfer over land

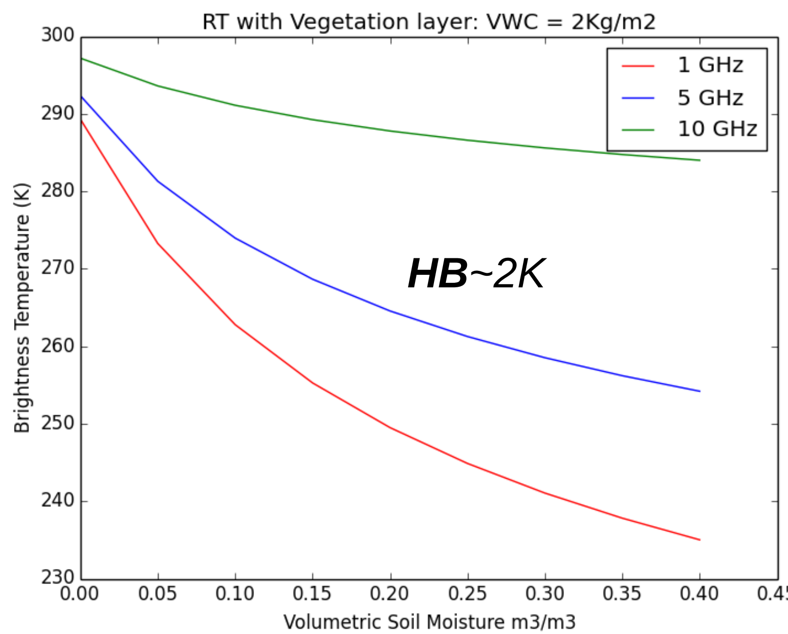
- Various components have been developed through various strands of research involving in field measurements from the 1970s onwards
- Surface emissivity. Dielectric mixing models of air,soil, water e.g. Wang 1980. This can yield the reflection coefficients via Fresnel
- But we need to account for the fact that the soil surface is not smooth – semi empirical modification to the reflection term via Choudhury et al 1979.
- Finally need an estimate of the transmittance through the vegetation. Parameterised as a function of vegetation water content (Schmugge et al, 1992). Optical depth ~ f*VWC

[N.B for any full description of the process we need to know, soil moisture, roughness and the vegetation water content as a minimum]

RT Simulations

- Nadir look for three typical frequencies. Using the RT model with the simplest surface models for emissivity etc.

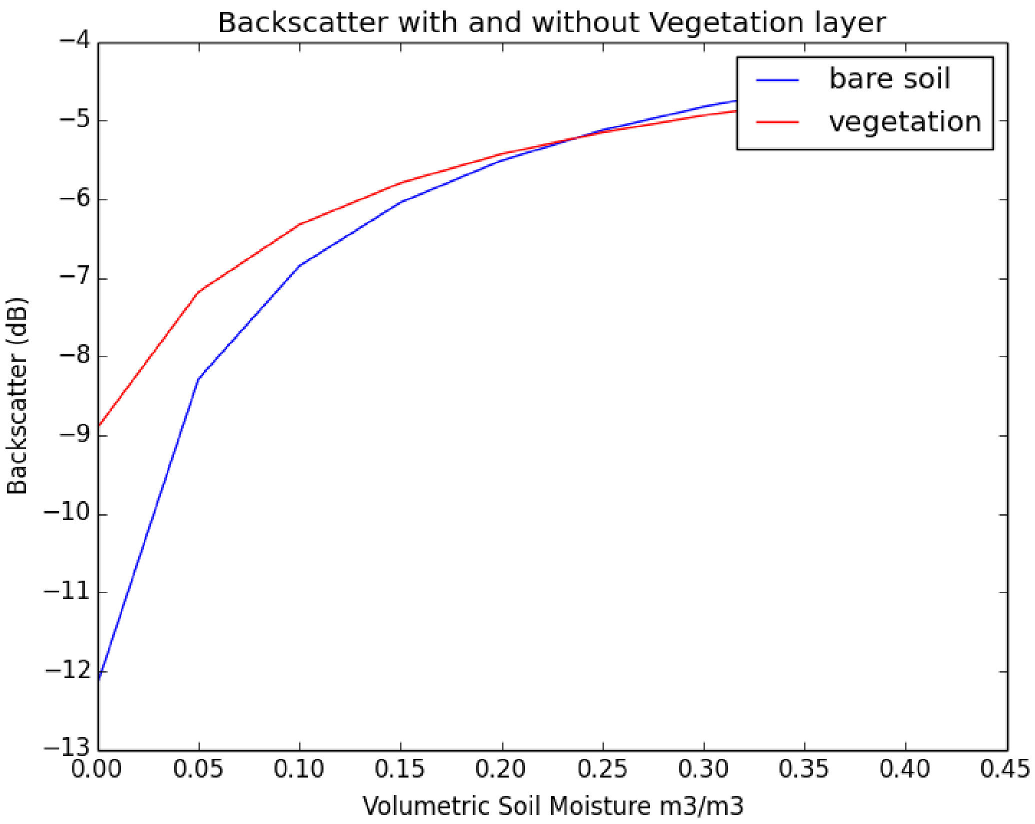




- In the presence of vegetation the sensitivity to soil moisture is reduced, particularly for the shorter wavelengths – C and L-band preferred (trade off with spatial resolution)

ASCAT

BackScatter Dependence on soil moisture



•C-band with surface roughness & dielectric model as before.

•Vegetation canopy backscatter modelled using simple scheme proposed by Ulaby 1979. [canopy backscatter+attenuated soil backscatter]

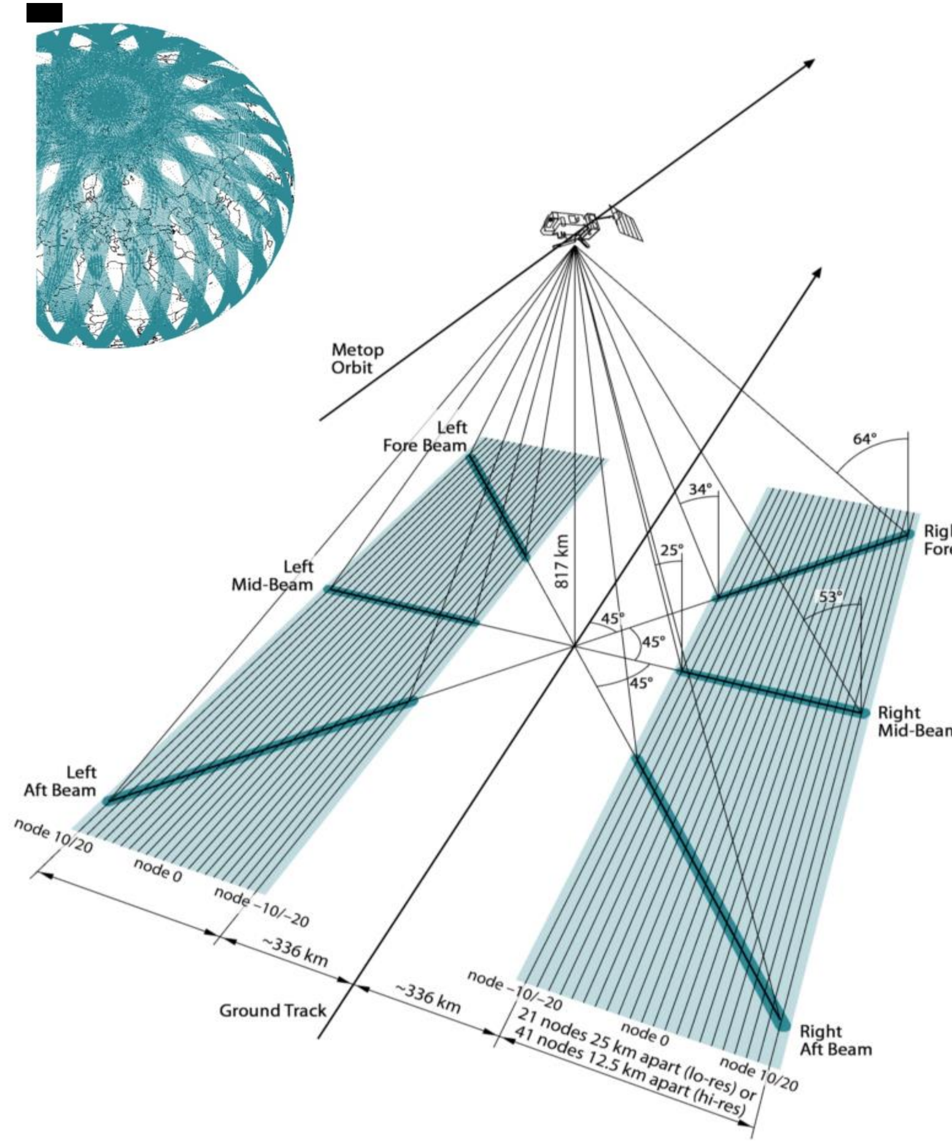
•Vegetation again in field of view reduces sensitivity to soil moisture.

•Dense vegetated regions will be difficult and improved penetration through the vegetation necessitates long wavelength

ASCAT Overview

- Instrument: Scatterometer
  - λ = 5.7 cm / 5.3 GHz
  - VV Polarization
  - Sampling: 12.5 and 25 km
  - Multi-incidence angle: 25 - 65°
- Orbit
  - Sun-synchronous
  - 29 day repeat cycle
  - 14 orbits per day (82% daily global coverage)
- Currently two satellites in space
  - METOP-A: since Oct 2006
  - METOP-B: since Sep 2012
  - Very good interannual stability as measured by fixed natural targets on ground

And Metop-C currently planned for 2017



ASCAT operational Soil Moisture Product

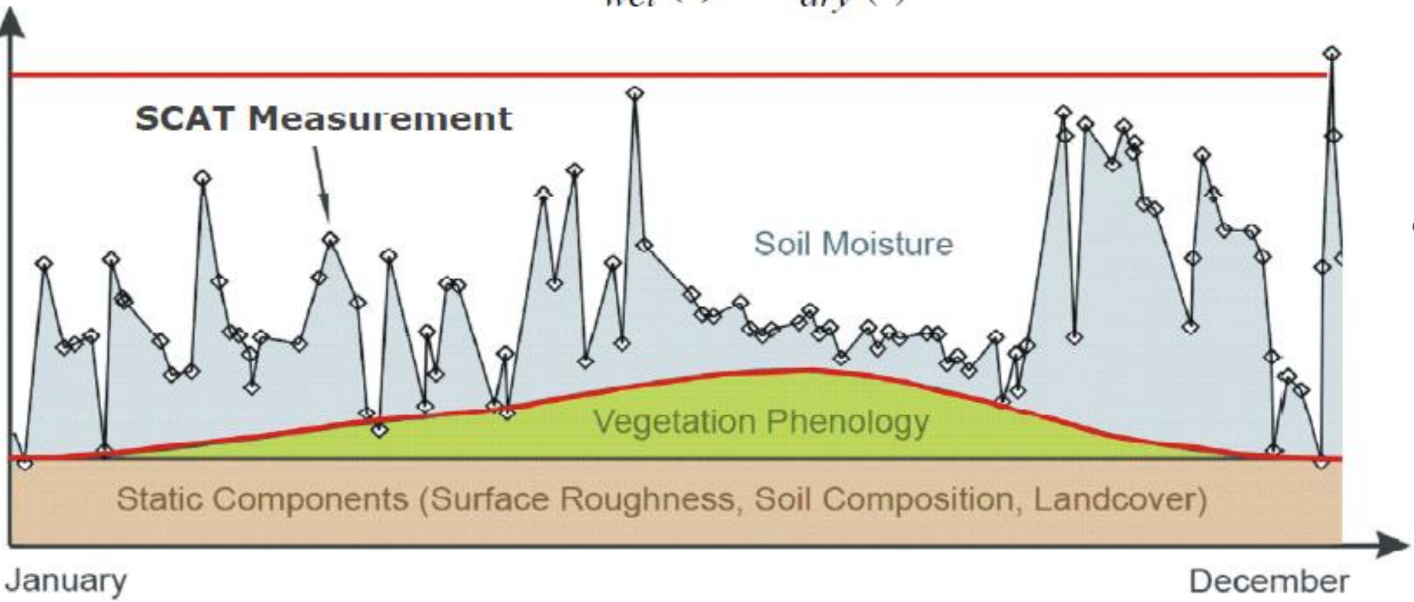
- A change detection scheme is used – avoids knowing implicit roughness, soil composition etc at every global point

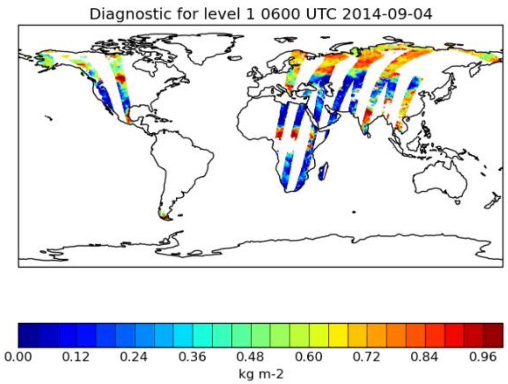
- Assumes that backscatter various linearly with soil moisture

- Land Cover does not change significantly from year to year – vegetation cycle also consistent.

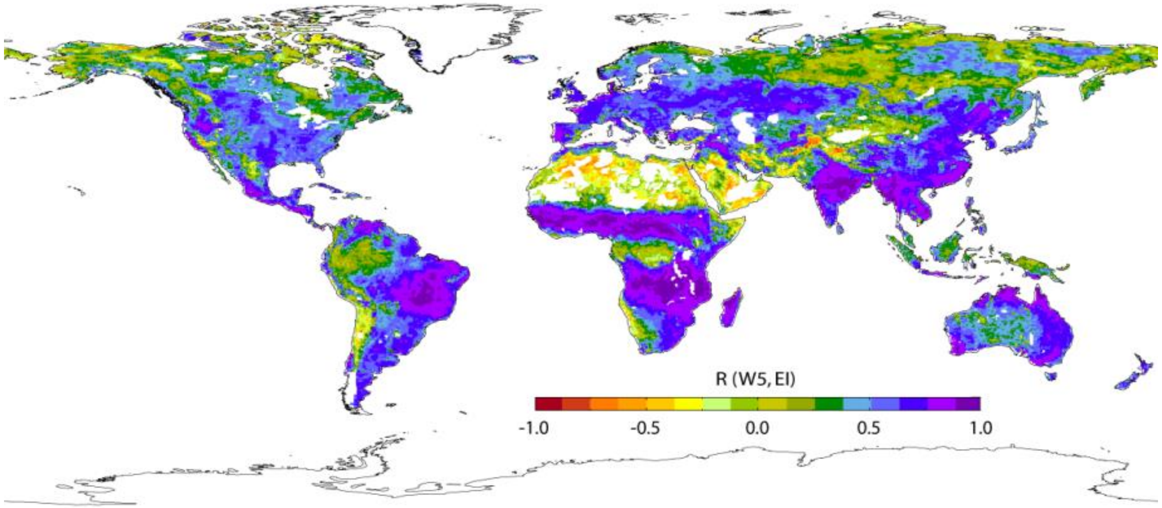
- Scheme developed by TUVienna and disseminated by Eumetsat in NRT as a Level -2 product

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





Ongoing Research Issues – Dry Soils



•Negative correlation between ERA soil moisture and ASCAT SWI over Arid regions such as the Arabian Desert. Other Datasets show this too

•Suggests that backscatter increases as soil dries out. Evidence that it is soil type dependent.

•Hypothesis (S Hahnn – TUWien) In dry conditions backscatter is coming from the rock layer below the soil

ASCAT Quality Control

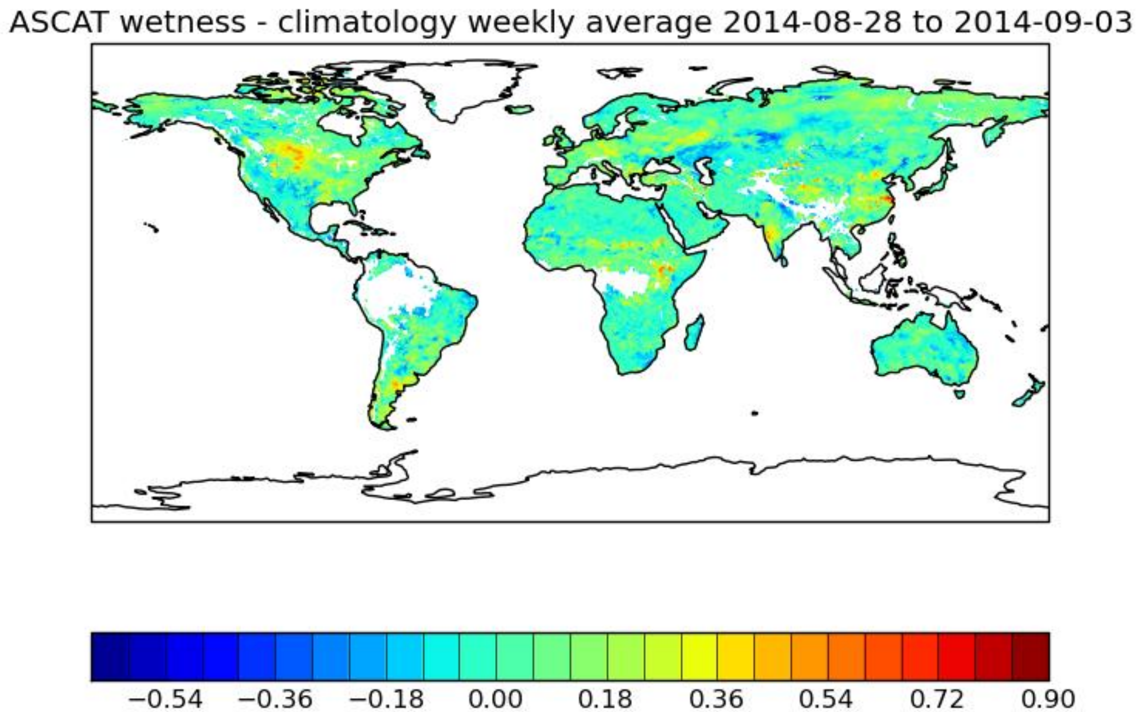
• **Data Not assimilated** where there is

Snow

Significant vegetation

Frozen soil (change in dielectric causes ambiguity with very dry regions?)

Potential issues with large scale flooding and very arid regions



ASCAT Soil Wetness Conversion & Bias Correction

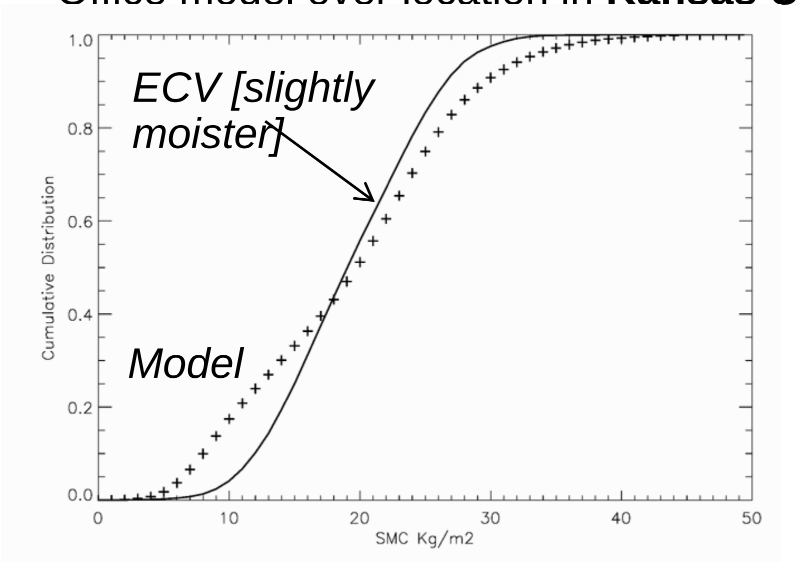
Met Office

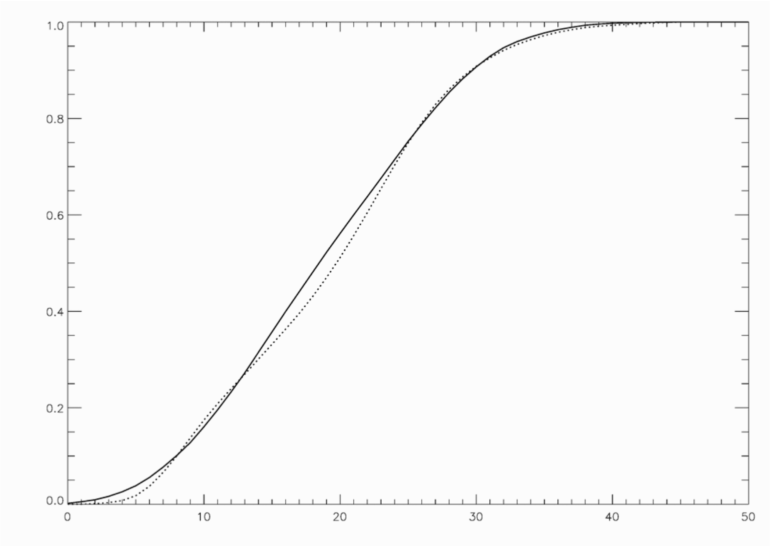
• Conversion of SWI to a scaled soil moisture e.g.

$$\theta_{wilt} + (\theta_{sat} - \theta_{wilt}) SWI * 0.01$$

• Then apply a bias correction or rescaling to remove bias with respect to the land surface predictions [why? Land level 1 does not match skin depth of satellite, error in forcing data etc]

•The most common approach is to match the Cumulative Distribution Function of the soil moisture values between the satellite and model. This can be performed to capture the mean, standard deviation and even higher moments (e.g. Mahfouf et al 2010 ASCAT assimilation over France). Example below is for ECV merged dataset compared to Met Office model over location in **Kansas U.S.**





July

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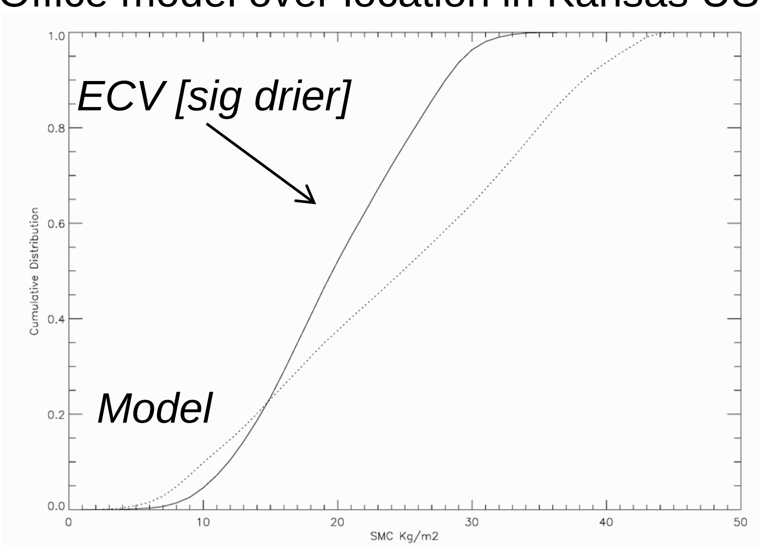
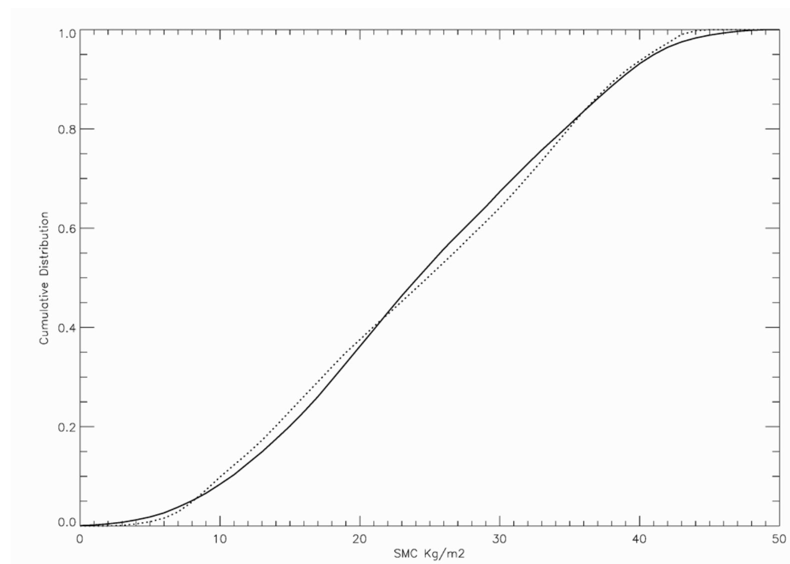


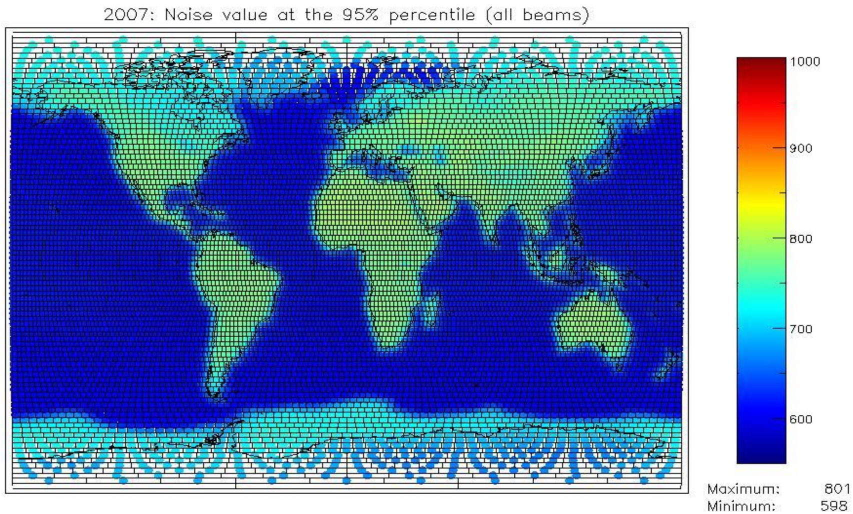


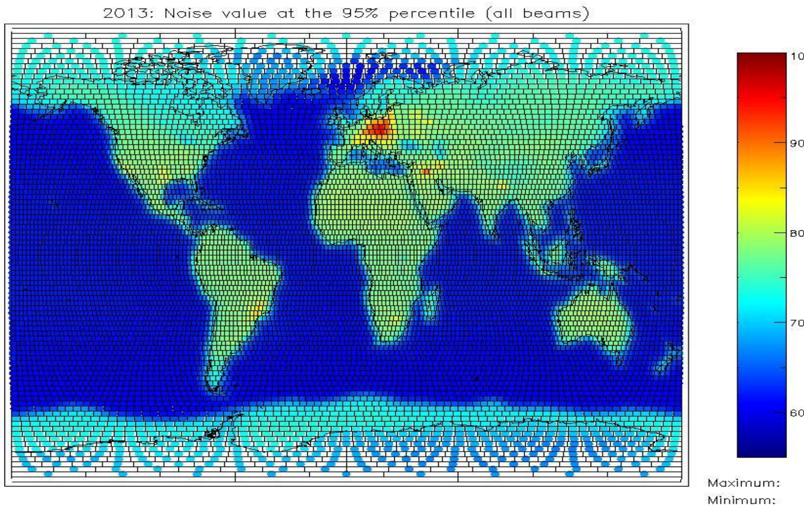
April

Ongoing Instrument Monitoring -RFI

2007

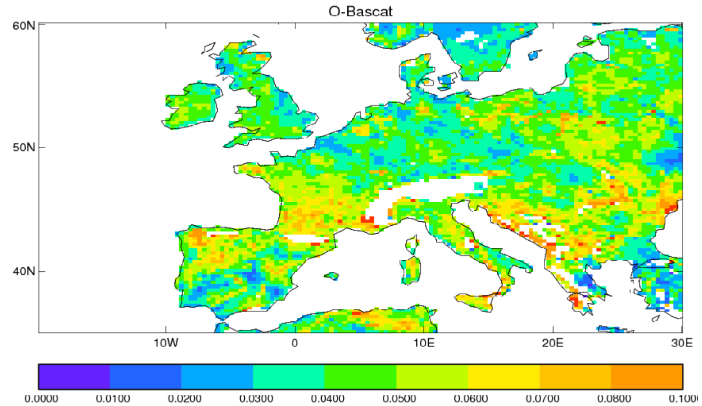
2013





Background noise:

1 dB increase over Europe – negligible effect on soil moisture values

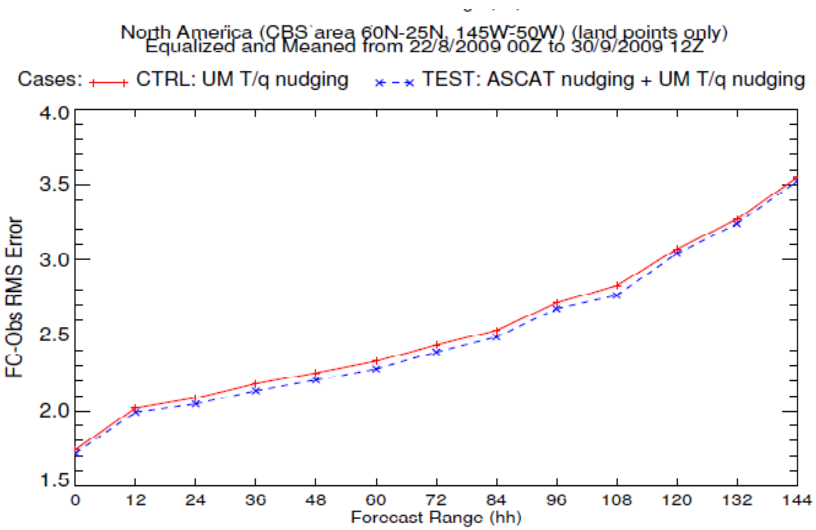


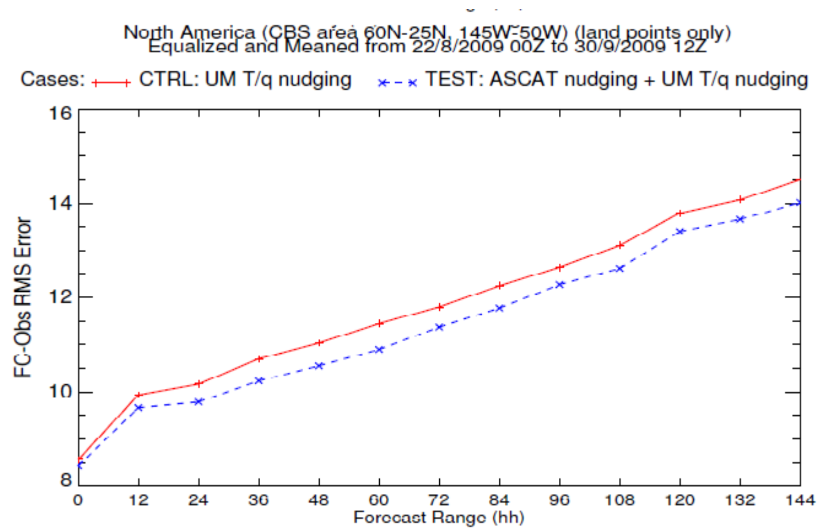
Std Dev ASCAT-model 2013

ASCAT Forecast Impacts [Met Office]

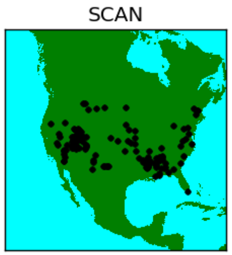
•Positive benefit on forecasts of screen temperature and humidity for the tropics,

•North America and Australia. Impact on the global UM NWP index neutral



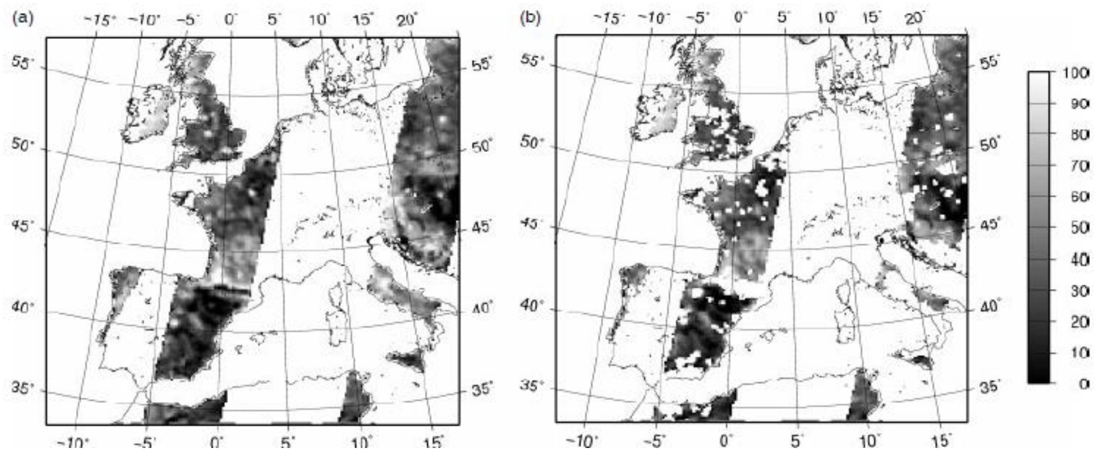


• Improved fit also observed of analysis wrt in situ observations of soil moisture from the SCAN network *(correlation and standard deviation)*

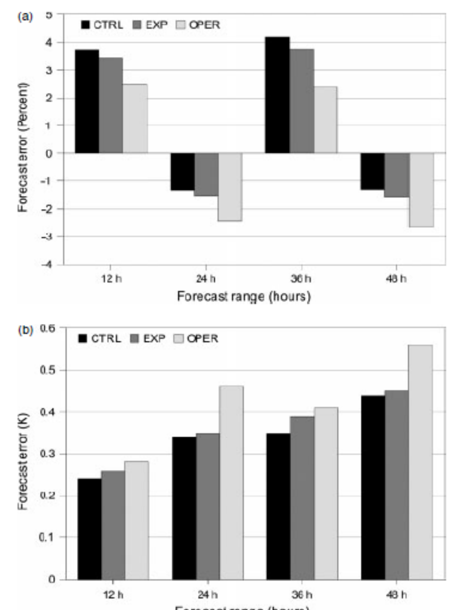


• ASCAT Forecast Impacts [Limited Area Model]

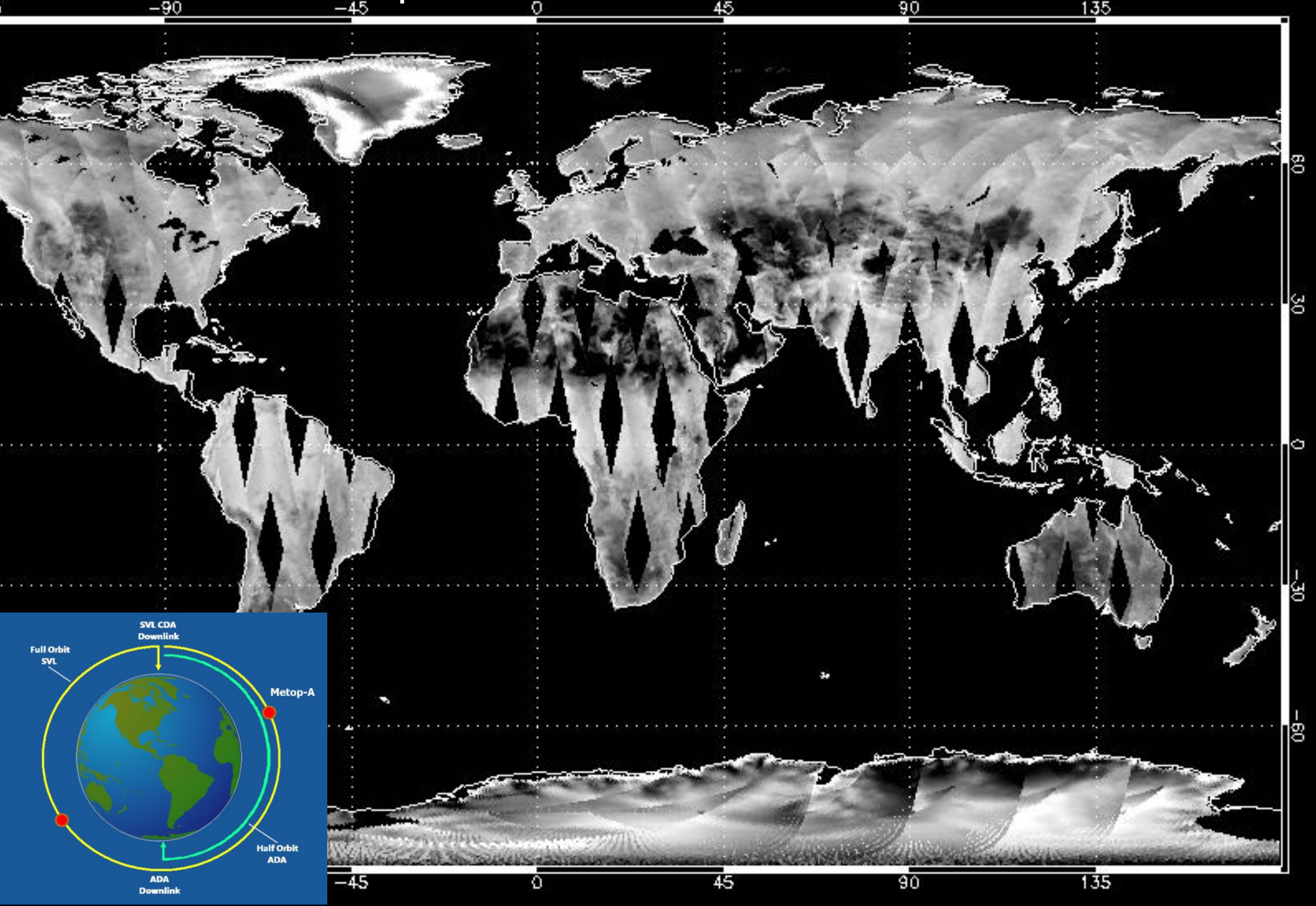
Work done by Mahfouf et al in the ALADIN European LAM using an extended EKF



- *Some improvement to humidiy forecast bias wrt no soil moisture analysis*
- *Small degradation in temperature forecast wrt control*
- *Conclusion: In a region with a large number of surface obs, the satellite data is likely to add a small beneficial impact.*

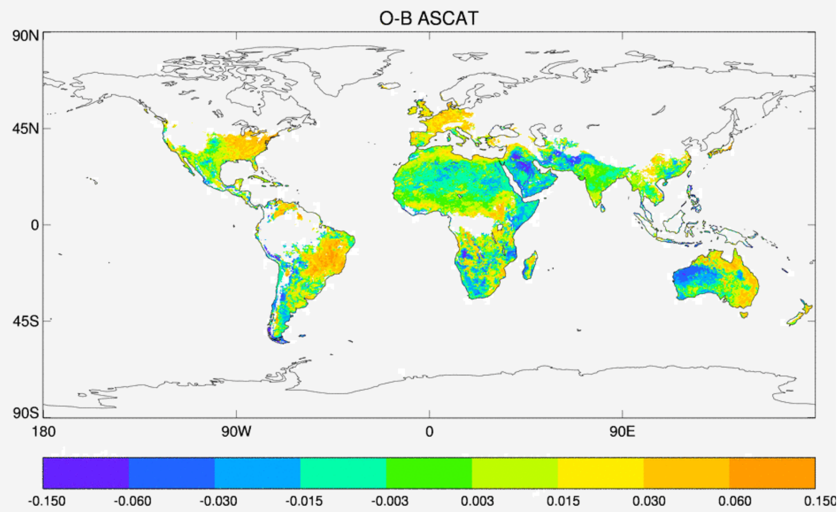


ASCAT Tandem Impacts

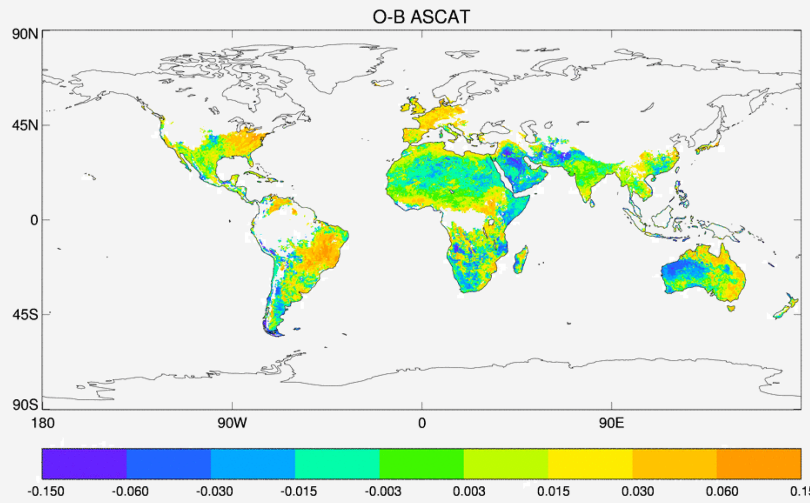


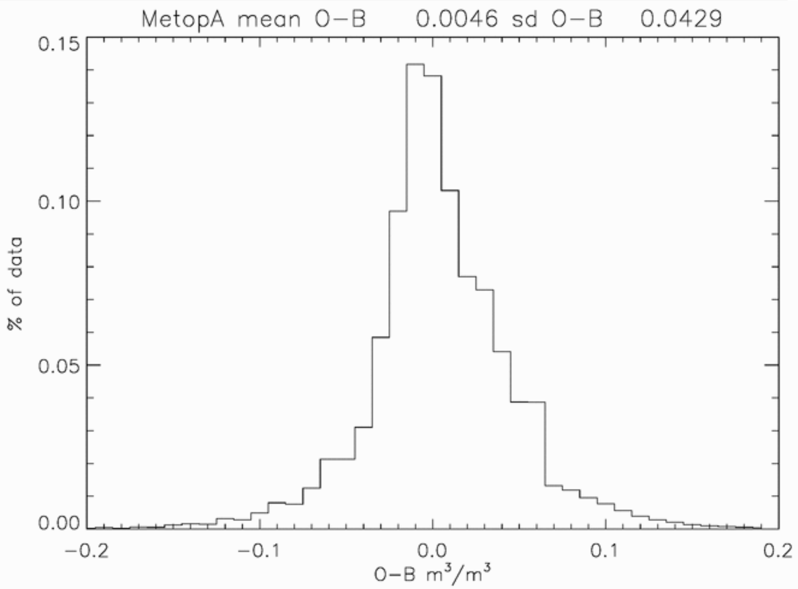
ASCAT instruments compared

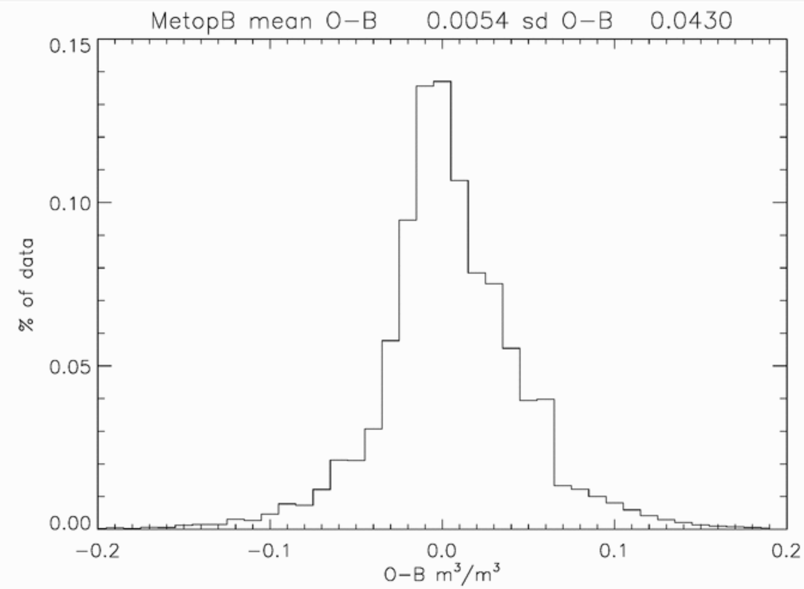
MetopA



MetopB

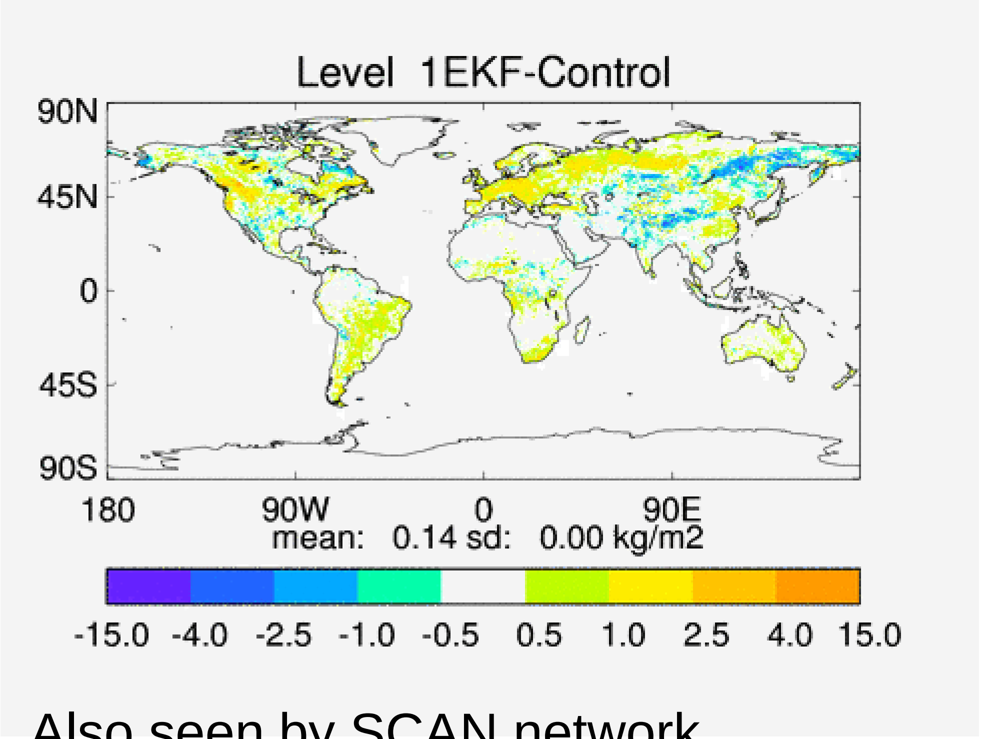






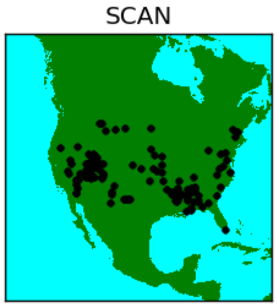
Analysis differences- Summer 2013

- Moister level 1 (10cm)



- Also seen by SCAN network

Experiment	Nstns passing QC	Correlation coefficient	Mean (station-model) m3/m3	SD (station-model) m3/m3
Control	61	0.55	-0.046	0.039
Upgrade	63	0.55	-0.053	0.039



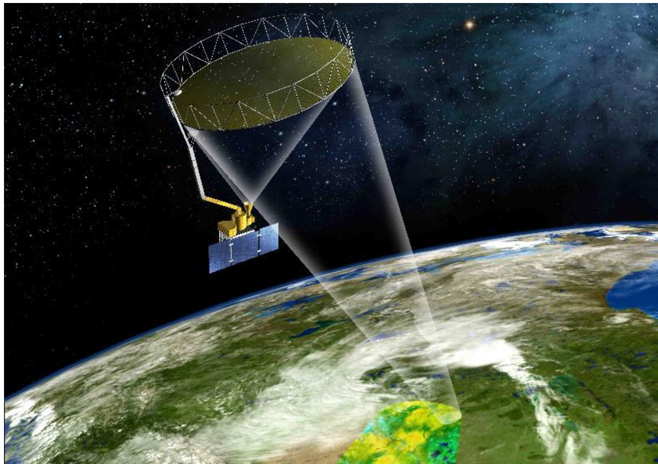
L-Band Passive Instruments: SMOS & SMAP

Instrument Overview

SMOS

- 2d interferometric radiometer
- Full polarisation
- 50 km resolution. Range of angles at each observation node from 5-55 degree inc angle
- Launched 2009

SMAP



- SAR & Radiometer system using a 6m mesh antenna
- SAR – VV, HH, HV Radiometer fully polarimetric
- 40km radiometer, radar 3km, plus intermediate disaggregated products
- Launch date *Nov 2014*

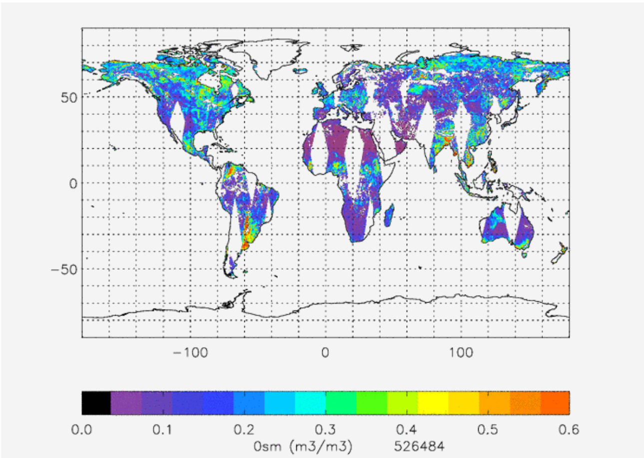
SMOS – data availability

Met Office

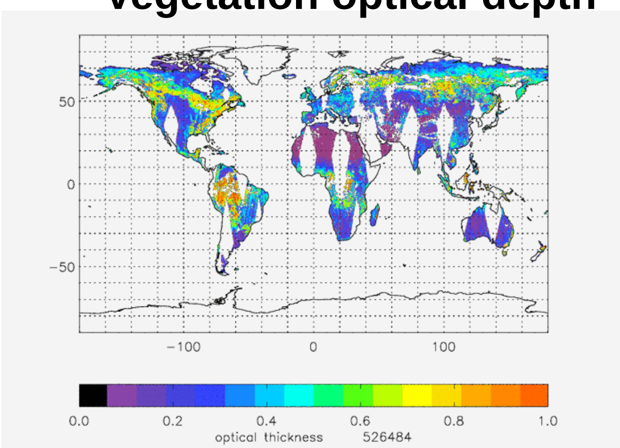
- Two forms of near real time data
- Level 1-B BUFR 'light' product disseminated in near real time. Cutdown version of the complete brightness temp record data volume ~4 GB/day
- Level 2 soil moisture (physical retrieval containing an Lband emission model – including roughness dependency on soil moisture)
  - Tricky retrieval areas – ponding after heavy rainfall, snow cover, dynamic change in water bodies, RFI.
  - Neural net retrieval is under evaluation to offer a fast delivery soil moisture product.

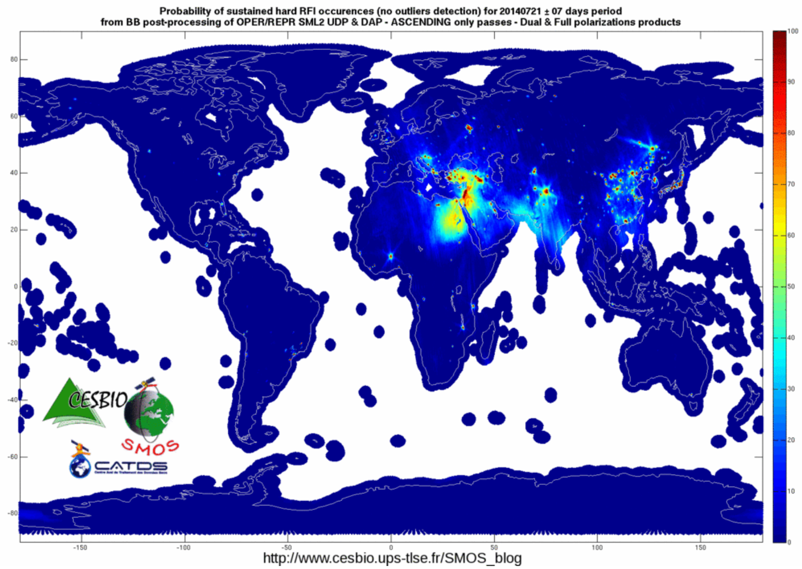
Example of the L2 product

Soil moisture



Vegetation optical depth





RFI probability of detection – the emissions are illegal e.g. radar satellite links etc.

(one detection mechanism uses 3 and 4th component of Stoke's vector – large values indicate RFI)

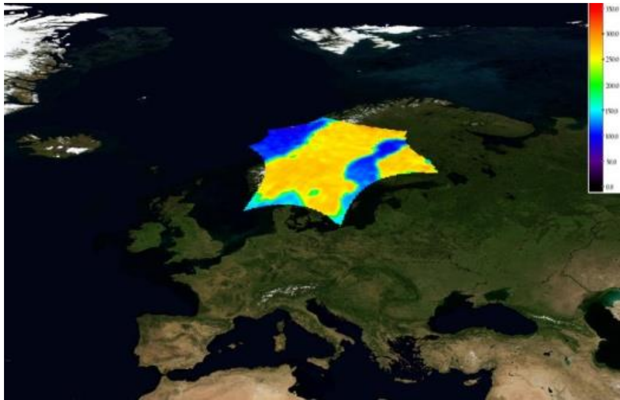
SMOS use in operational environment (ECMWF)

Met Office

- Aim is to assimilate SMOS brightness temperatures [previous experiments over US great planes with airborne L-band radiometer (Margulis et al, 2002) demonstrated improved analysis for both surface and root zone soil moisture]

- CMEM (deRosnay et al) Low Freqency microwave RT model is used as the forward model (and to compute the Jacobians). This is flexible with a choice of dielectric , vegetation and roughness models. [bias correction is performed in a similar manner to ASCAT but in brightness temperature space]

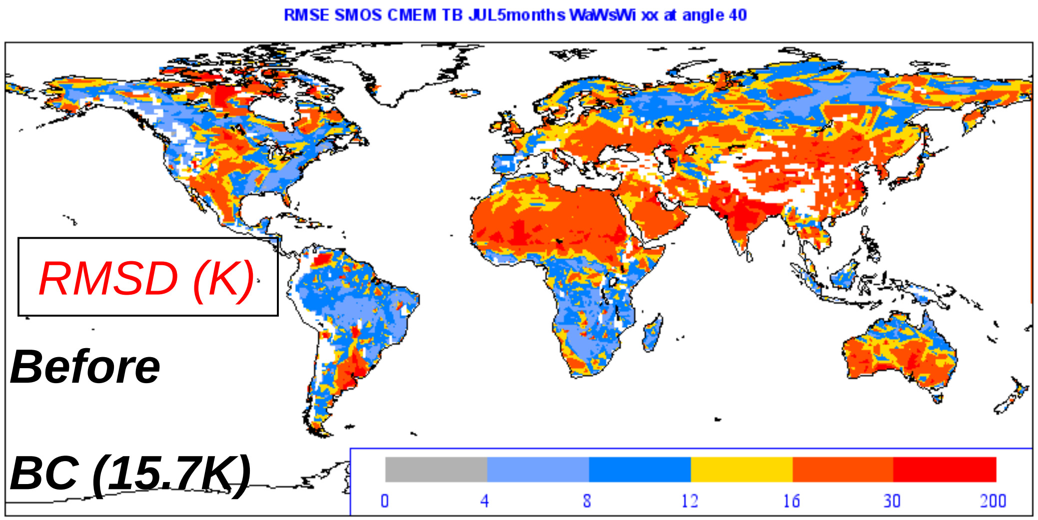
- Due to the large volumes of data, superobbing of data required. Data is binned into anglular bins centred around 30,40,50 degrees incidence angle. Prescreening for RFI also performed (~10% data assimilated)

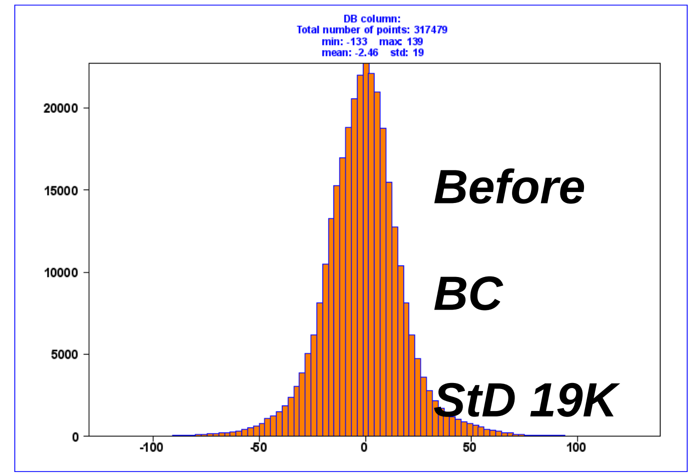


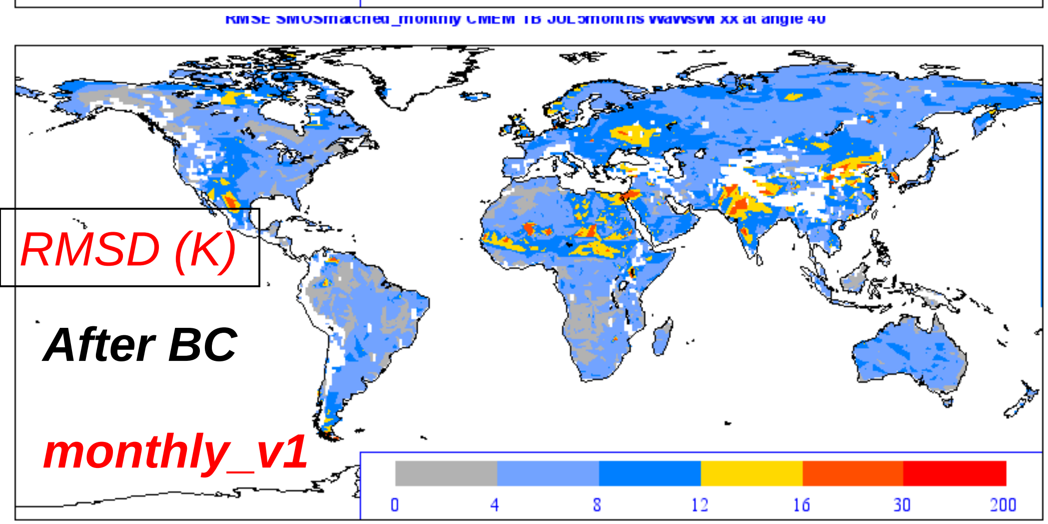
SMOS Bias correction monthly evaluation

July 2012

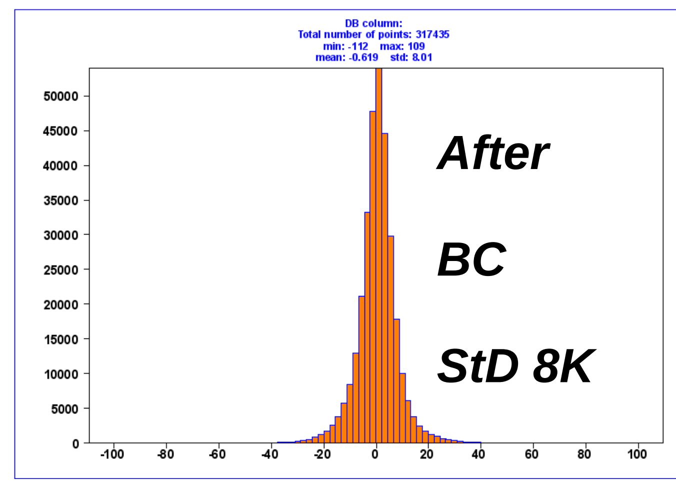
TBxx, 40 degrees







(6.7K)



- Low residual bias, except in RFI affected areas (Poland in 2012 and Asia)

ECMWF

SMOS Sensitivity Analysis – Seasonal Jacobians

$$Jacobian = \frac{dTb}{dsm}$$

•40XX

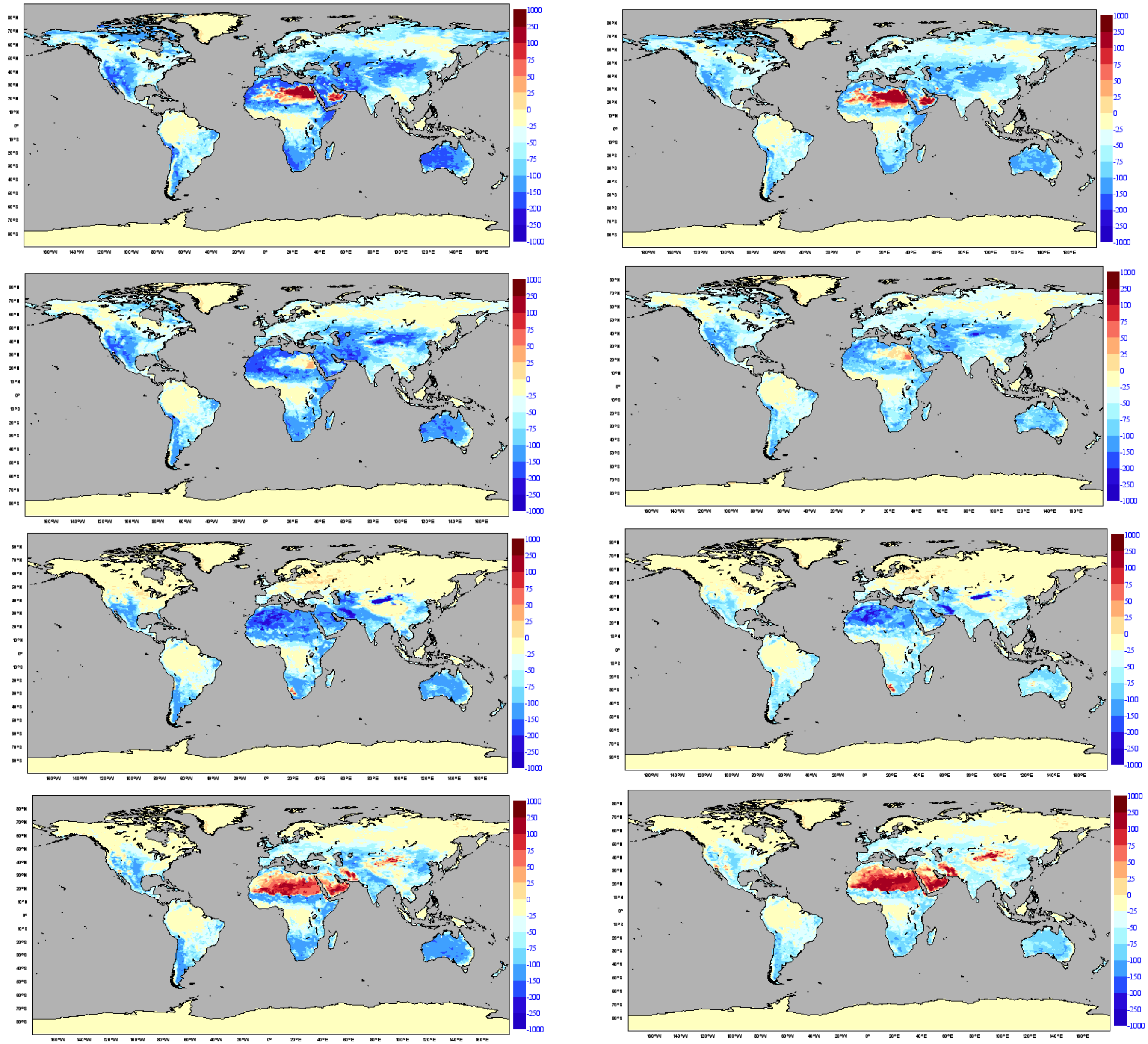
•40YY

•Summer

•Autumn

•Winter

•Spring



Generally as expected Jacobian is negative in most areas exception is deserts

Larger sensitivity in xxpol

Highly vegetated regions no sensitivity

Potential key regions US, Australia, S Africa. Sahel

ECMWF

ECMWF SMOS-DA SM product

SMOS-DA : SM product based on assimilation of SMOS T_B in the antenna reference

- Global scale product, obtained at the ECMWF **T511** (~40 km) reduced Gaussian Grid.
- Period: **1 May 2010** 00UTC – **31 October 2012** 12UTC analysis.
- Observations configuration:
  - NRT T_B from **second reprocessed dataset 2010-2011** + NRT (v5.05) for 2012,
  - **30, 40, 50** degrees ± ΔT_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 (based on yearly v_0 coefficients)
- CMEM configuration; best for R (Wang(DIEL), Wsimple(RGH), Wigneron(VEG))
- **Jacobians calibrated** ($\Delta\theta j$=0.01m^3m^{-3}, $|H^-_{max}| = |H^+_{max}|$ =250 K/m^3m^{-3})
- **STD of observations error** → radiometric accuracy ✔
- Full observational system used for the atmosphere,

Version 1

- Interface and vegetation usage **bugs fixed**,
- 2-degrees **binned observations** at 30, 40, 50 degrees ± ΔT_B=1 K, XX & YY polarisations,
- Observations bias corrected using **monthly CDF coefficients (v_2)** ✔
- Physics of **cycle 38r2**

Version 2

- Improved quality control check (fg check and Jacobians bounds revised. RFI prob occurrence maps?),
- 3D-error structures for B-matrix based on soil properties. Better definition of R matrix?
- Improved bias correction (CDF?, VARBC?, …)
- Larger use of incidence angles (25, 35, 45, 55)
- Physics of future cycle 41

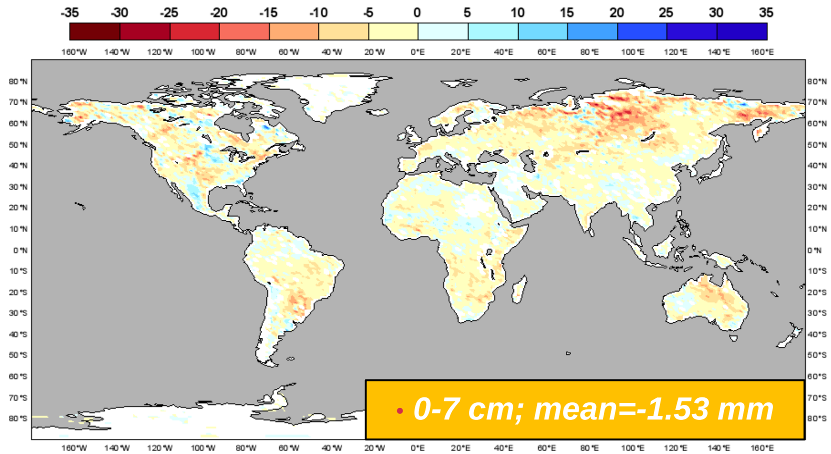
Version 3

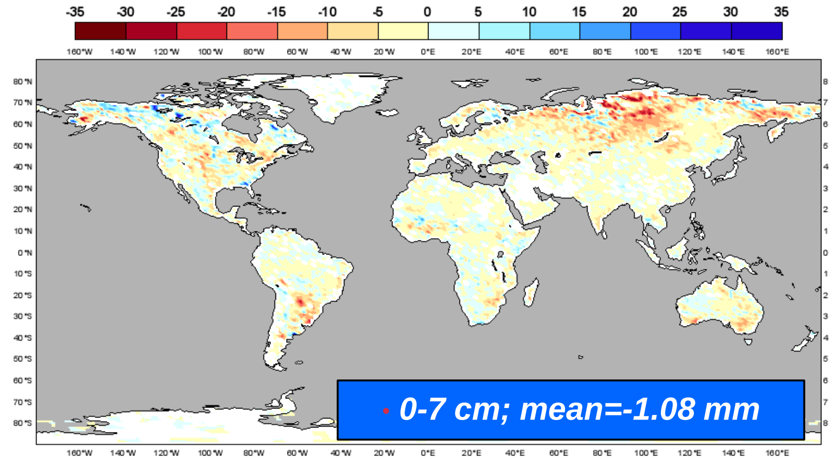
Accumulated soil moisture increments differences (mm)

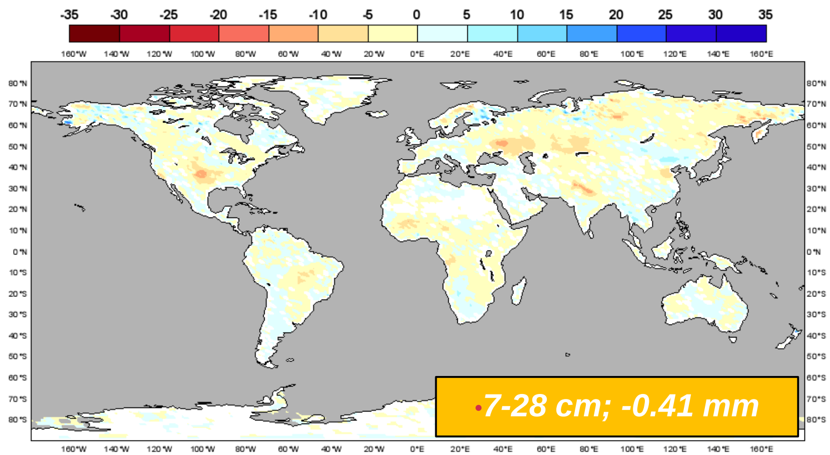
June 2010

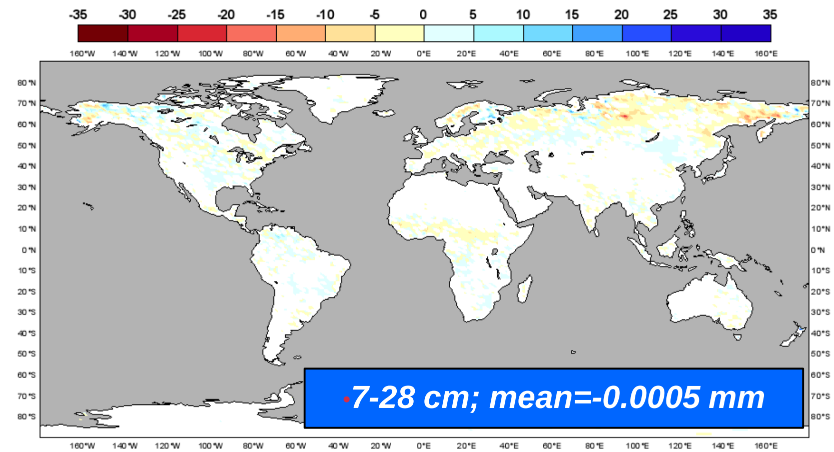
SMOS T^B – CTRL (screen)

[SMOS T^B , T^{2m}, RH^{2m}] – CTRL(screen)



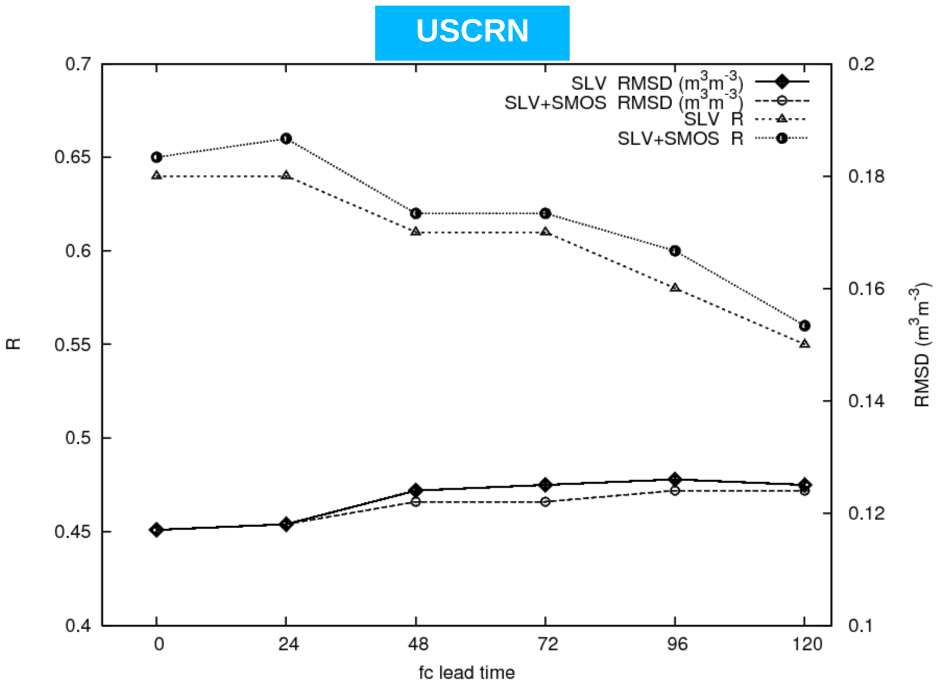


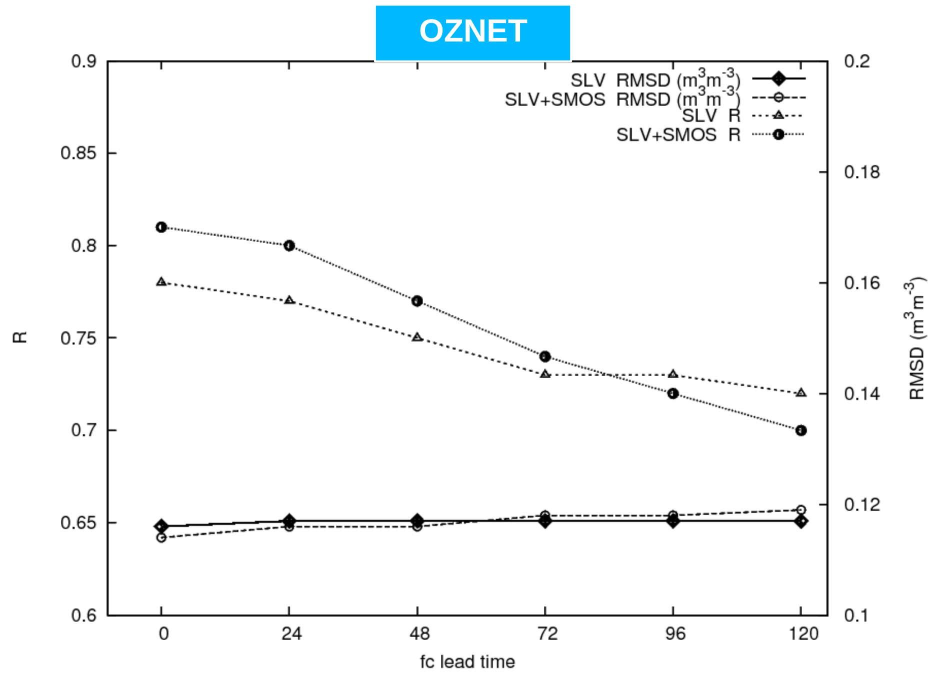




- Increment differences are dominated by the assimilation of SMOS rather than screen level variables, as increments introduced by SMOS are stronger. → Patterns for top soil layer are quite similar for both configurations. The assimilation of screen-level variables tends to smooth out the “SMOS increments”.
- The second soil layer is more affected if only SMOS TBs are assimilated

Validation of the soil moisture forecasts



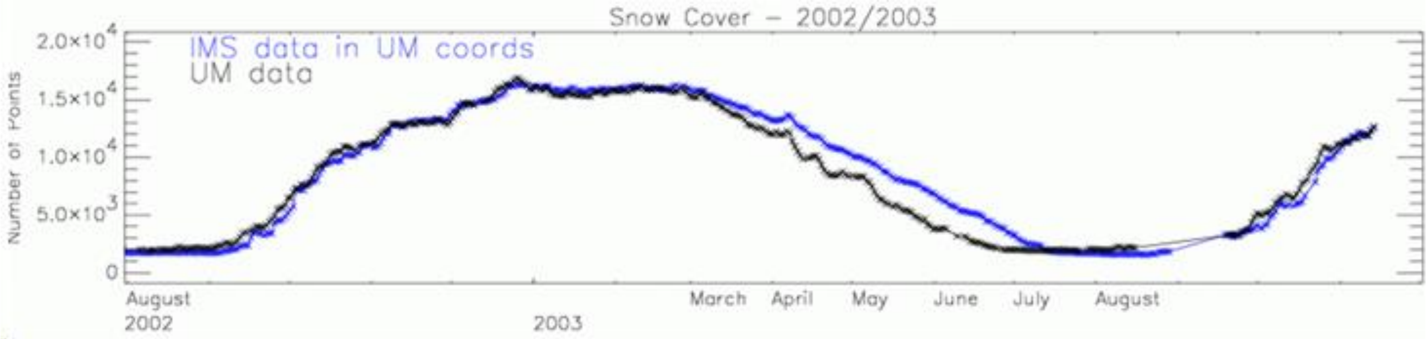


The correlation coefficient (R) decreases with fc lead time, and RMSD increases slightly.

Skill in the forecast of soil moisture with SMOS+Screen is superior to Screen at least up to 72h *(5 days for USCRN)*

In total extended assessment across 10 networks confirms improved model soil moisture through assimilation of SMOS

Motivation - Model Freely Evolving Representation of Northern Hemisphere Snow



- Models require snow extent and snow amount

•In particular Early Spring Melt – Also noted by other centres (e.g. Takala et al 2011)

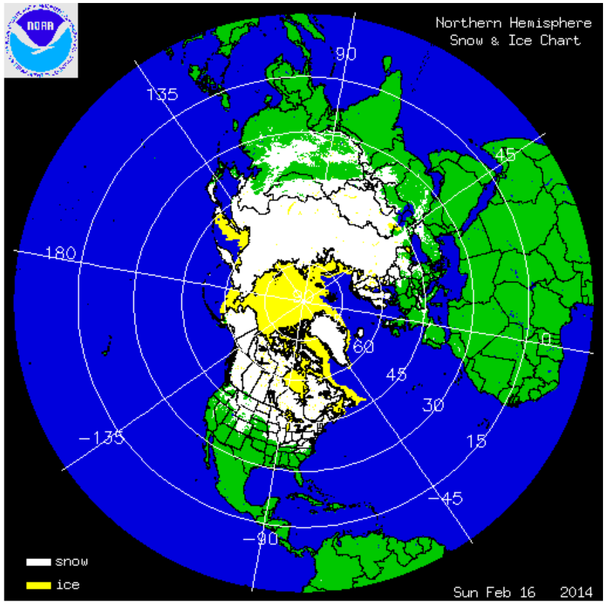
•Variability in snow leads to large changes in the surface SW and IR budgets -> large impact on near surface parameters such as temperature

•Most NWP schemes use a combination of snow depth reports & satellite estimates of snow extent to construct an analysis

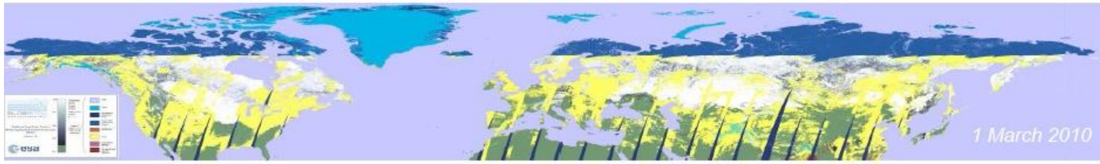
Snow Coverage Observation datasets

Met Office

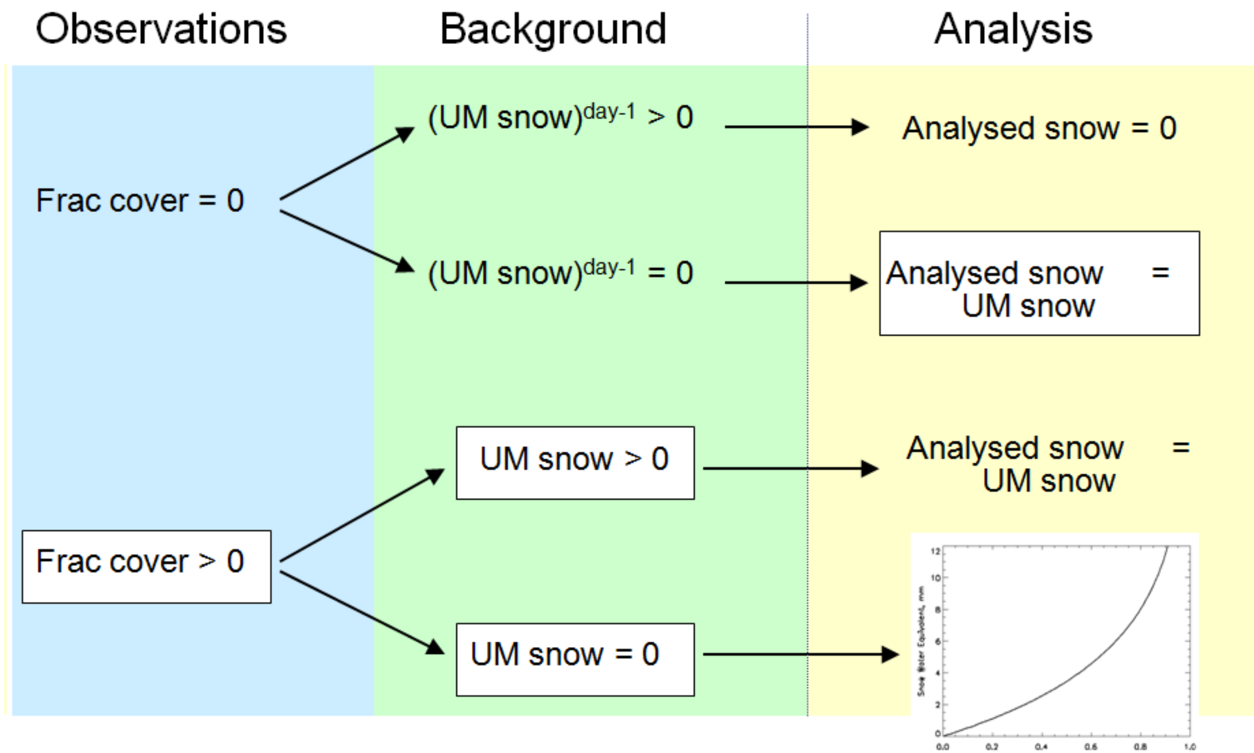
- **NESDIS Interactive MultiSensor Snow and Ice System (IMS)**
  - Snow, no Snow continuous product at 4km resolution for Northern Hemisphere. [also an automated SH product]
  - Merge of GEO, LEO information & Station Data
  - Available daily in near real time



- **GlobSnow** – ESA funded project to produce 15 year dataset of snow coverage from (A)ATSR reflectance measurements 1km, but not continuous [Also a longer SWE product from passive microwave / in situ merge]



Snow Analysis –MetO Scheme



•IMS snow product comprises data up to 36 hours old

•Genuine snowfall events may be removed by the snow analysis as the IMS data has not yet recorded the snowfall.

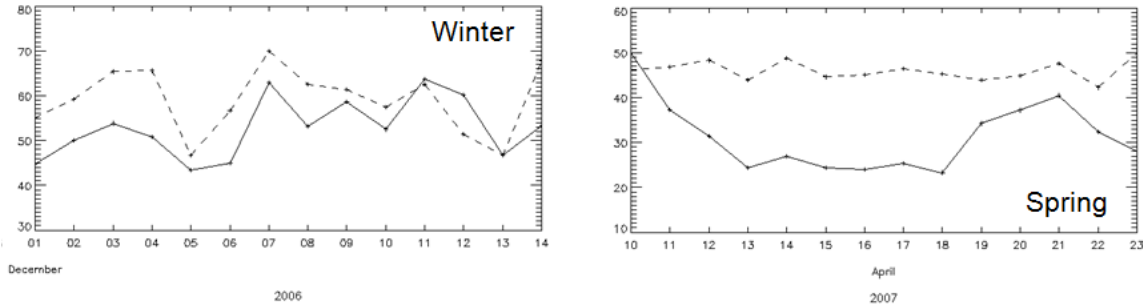
•Use previous day's background snow as additional constraint in cases of snow removal.

•Issue of what snow amount to add to a snow free grid point. Other operational centres such as **ECMWF, CMC** use OI to assimilate snow depth observations.

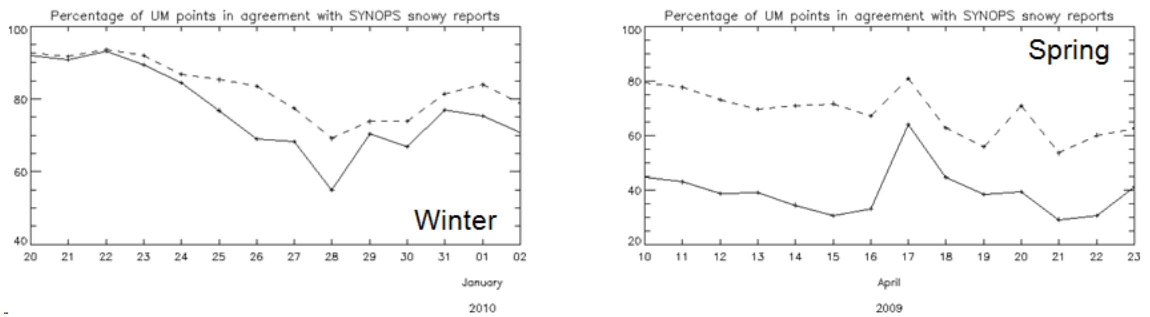
Snow Analysis Impacts [MetO Global]

Met Office

Snow analysis vs no snow analysis



Upgraded snow analysis vs basic snow analysis

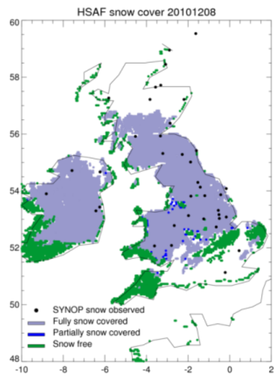


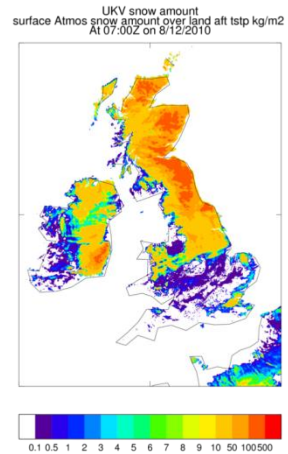
- Evidence of improvement to model RH bias in winter over Europe [generally removing snow]

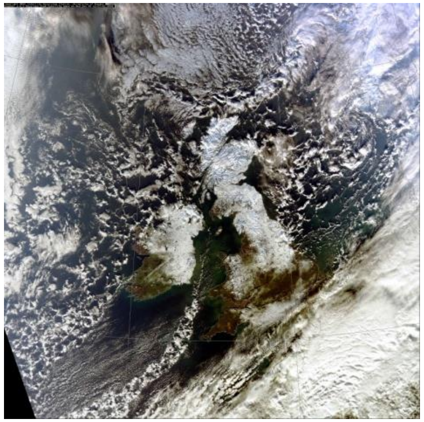
- Evidence of increase to model RH bias over US [generally adding snow]

- Updated version of the IMS due for testing in Autumn – in particular contain information on age of latest Observation& resolution enhanced to 1km.

Snow in convective scale models







•H-SAF product suitable as resolution is 3km and multiple views from MSG yield continuous product. Extended comparisons reveal that the UK convective scale model does pretty well for snow cover – thin snow layers can be an issue?

•Interest in planned high res SAR snow cover from Sentinal-1 – particularly wet snow events. Could offer important enhancements to optical snow cover products Well suited to UK snow detection

Land Surface Albedo

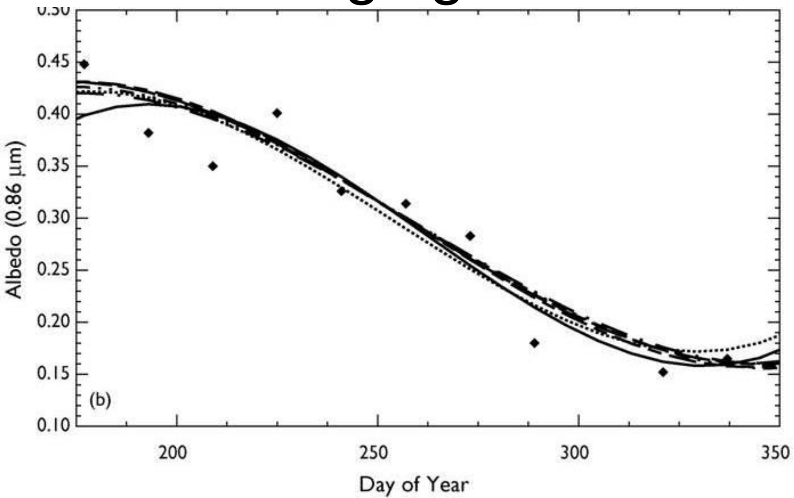
Met Office

- For Surface Energy balance generally require SW [broad band] albedo estimates at each grid point.

- Models tend to contain parameterisations to predict albedo e.g fn of LAI – or may require disaggregated albedos by tile type

$$\alpha = \alpha_b e^{-aL} + \alpha_{veg}(1 - e^{-aL})$$

So we would expect a seasonal variation in Albedo, and also a daily variation due to significant rain events changing albedo of bare (particularly sandy) soil

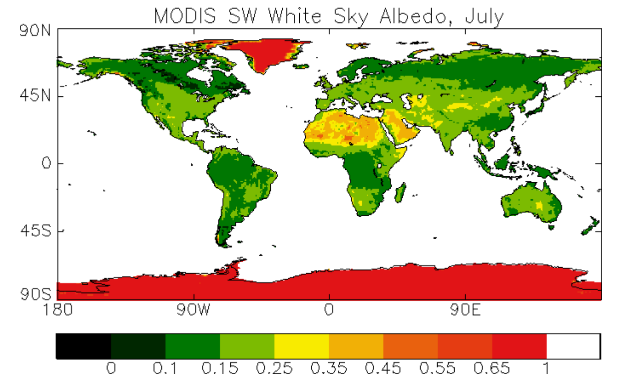


Near IR albedo from Modis processing for a NH deciduous forest (Moody et al 2005)

Satellite Albedo Products

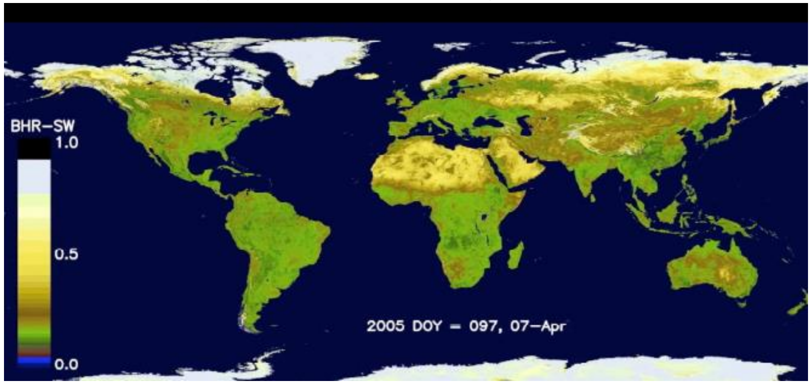
Met Office

- ***MODIS** – 1km product in 10 bands including 3 broadband. 16 day update. Includes in-filling for regions with semi permanent clouds using clear neighbours with similar plant type variation*

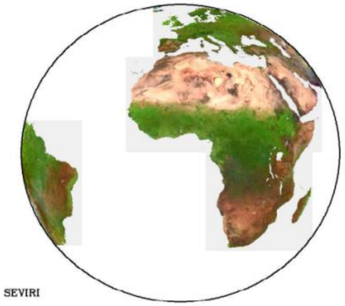


- *'**Glob Albedo** - Multi Sensor multi year product using MERIS, SPOT, etc - 3 bands and 8 day updates from 2005. Aim is for a 15 year dataset*

Monthly mean January



- ***Land SAF** - Daily Albedo estimates over MSG disc based on cloud free channel Reflectance. Available in near real time. Uncertainty attached to each observation.*



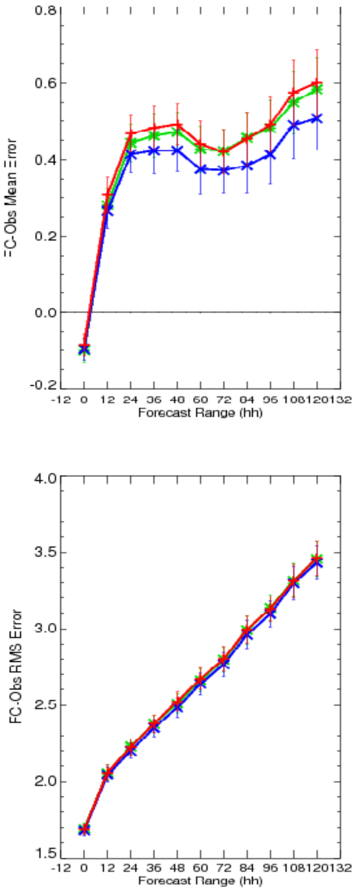
Satellite Albedo Impact (1)

- Met office experiments using MODIS diffuse albedos as a monthly climatology to adjust model derived vegetation and bare soil diffuse albedo values.

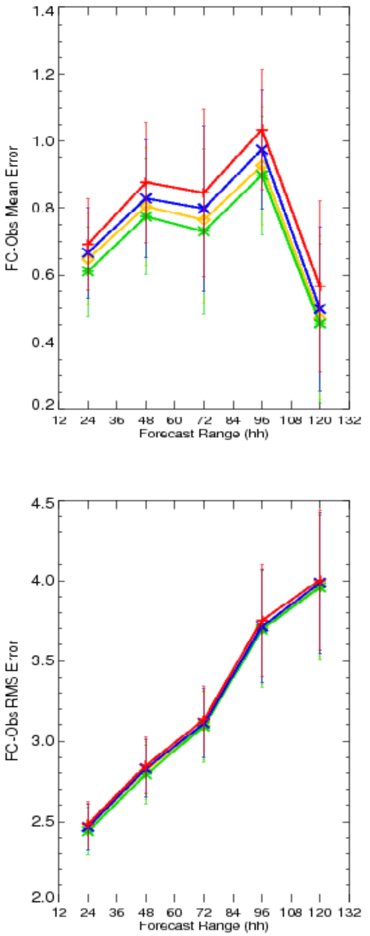
Generally neutral impact on forecast parameters globally, but important reduction in model near surface temperature bias over North America summer - seen in both extended trial and case study [Malcolm Brooks, Met Office]

Evidence that there are also improvements when the climatology is generated from Glob Albedo data – particularly over Asia

Summer 2012 trial



Set of model case studies 2010

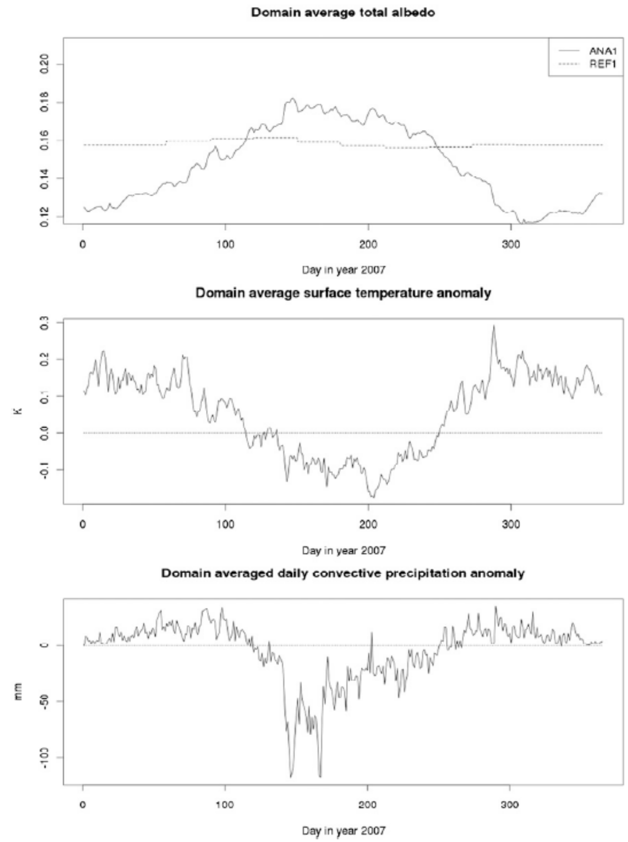


•*Red Control* *Blue Albedo obs*

Satellite Albedo Impact (2)

Met Office

- Work using Limited area model ALADIN for Central Europe – Cedilnik et al 2012
- Use the daily Land SAF albedos via an offline Kalman Filter to evolve the surface albedo as a daily analysis
- Observation vector (daily product + climatology)
- Background (persisitance).
- Analysis created over 1 year – Short range forecasts ran using these analyses



Model albedo too high in winter – too low in summer. Impacts on surface temp and summer convective events

Conclusions

Met Office

- **Soil Moisture -** General move to Kalman Filter Based analysis schemes, some multivariate, with aim of using more indirect satellite observations (SMOS Tb, LST,..) to update soil state at surface & root zone.
  - Both active & passive systems show benefit –
    - Metop-B ASCAT product continues the long term active dataset
    - Recent evidence that SMOS improves the analysed soil moisture wrt insitu measurements. Soon have two L-band systems available. Combined active/passive assimilation tests will be the next step
  - Improved impact is an area of ongoing research – in particular scene dependent obs errors, updated background errors. Insitu networks whilst limited to specific regions are an important validation tool (both for retrieval characteristics & assimilation scheme assessment). Some form of bias correction (CDF matching) appears critical.
- **Snow** – Combination of snow extent from merged satellite products + depth from SYNOPS used. IMS important real time dataset with improved resolution & ancilliary information expected soon. High resolution observations from SAR of interest for convective scale models over Europe.
- **Albedo –** Moving to satellite derived climatologies from either MODIS or GlobAlbedo products have helped to reduce model forecast bias of temperature in several domains. Assimilating albedo in a regional model suggests that further benefits may be accrued. LAI too?

Further Information

General Soil Moisture User Applications with Remote Sensing

- ESA soil moisture workshops Frascati 2013, Amsterdam 2014 , ?2015

ASCAT Soil Wetness

•Assimilation of satellite derived soil moisture from ASCAT in a limited-area NWP model, 2010, J-F Mahfouf, QJRMS

• Assimilation of ASCAT surface soil wetness, Imtiaz Dharssi, Keir Bovis, Bruce Macpherson and Clive Jones Met Office R&D Technical Report 548, 2010.

SMOS

•ECMWF SMOS monitoring website http://www.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/smos/

• SMOS Blog – particularly RFI http://www.cesbio.ups-tlse.fr/SMOS_blog/

•CMEM forward model https://software.ecmwf.int/wiki/display/LDAS/CMEM

Albedo

•Land Saf website [also snow] http://landsaf.meteo.pt/

• Chedinik et al, 2012, Impact Assessment of Daily Satellite Derived Surface Albedo in a Limited Area NWP Model, JAM

Snow

Takala et al, 2011, Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements.

Websites: globsnow: http://www.globsnow.info/ IMS: http://www.natice.noaa.gov/ims/

Thank you for listening…

ECMWF SMOS forward operator and Bias Correction

- ***TB simulations for 36 CMEM configurations***
- ***CMEM global scale Intercomparison (for 2010)*** *at 40° incidence angle*
- ***Bias correction*** *multi-angular* ***(2010-2012)*** *using best CMEM configuration,*
- *following Drusch et al., 2007 and Scipal et al., 2008*

On each grid point:

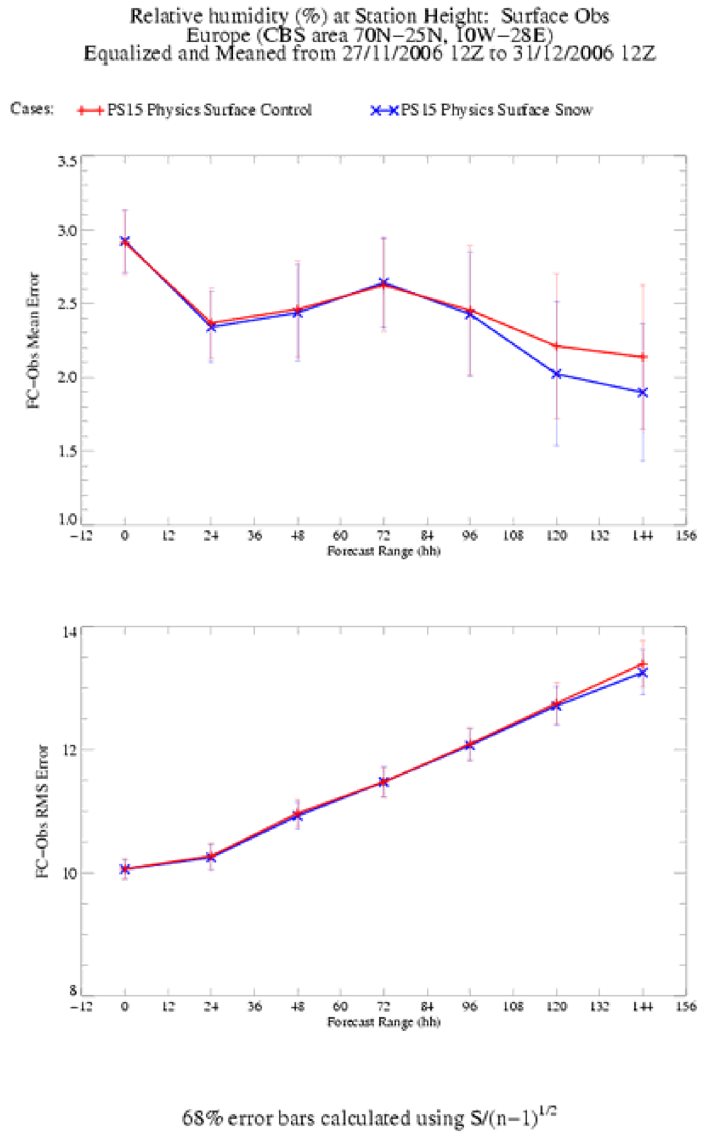
$$TB^*_{SMOS} = a + b\,TB_{SMOS}$$

with $a = TB_{CMEM} - TB_{SMOS}\,(\sigma_{CMEM}/\sigma_{SMOS})$

$b = \sigma_{CMEM} / \sigma_{SMOS}$

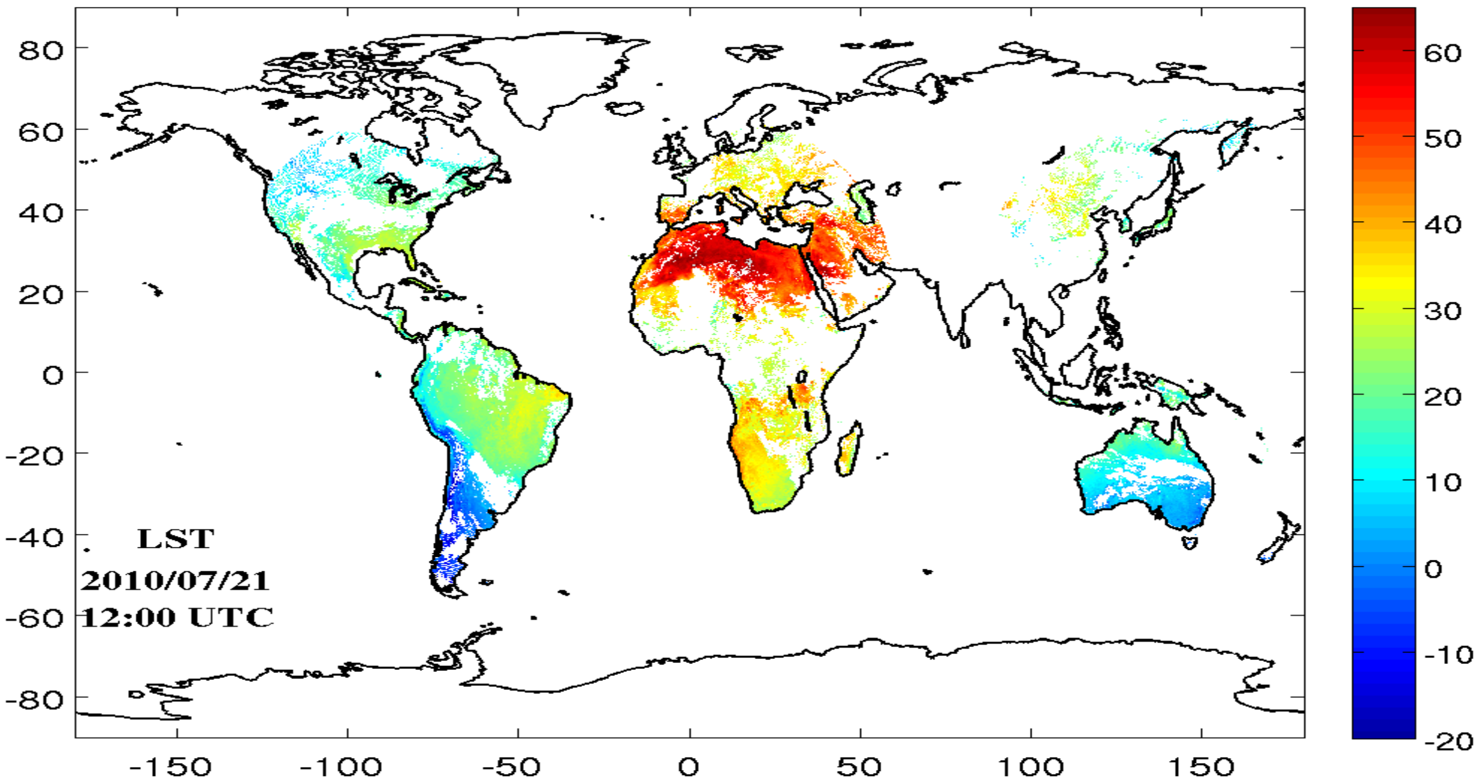
→ Matches mean and variance

Snow analysis impact on FC



• *Merging LST – Existing Products*

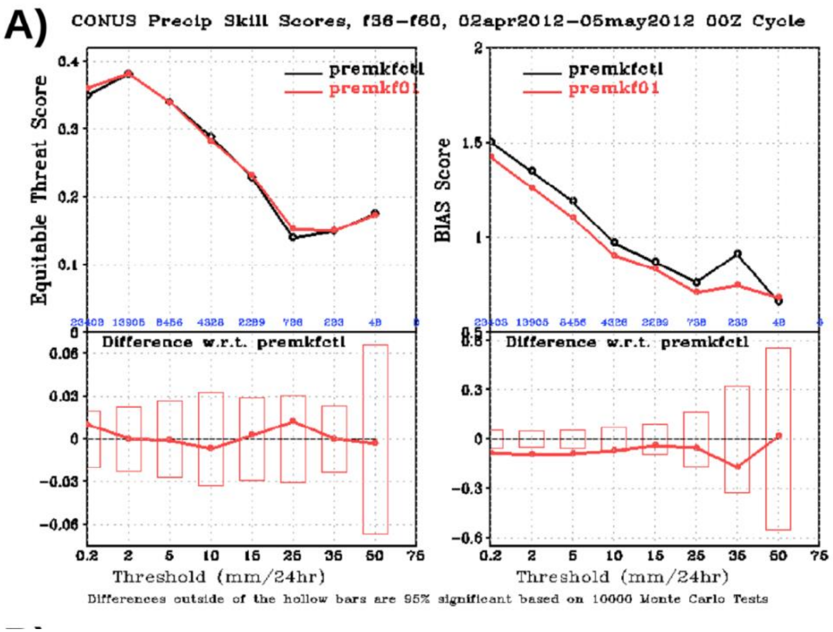
- ***Copernicus – Global Land*** *(currently available in NRT)*



- *Freitas, S. C., I. F. Trigo, J. Macedo, C. Barroso, R. Silva and R. Perdigão, 2013: Land surface temperature from Multiple Geostationary Satellites, Int J. Remote Sens., 34, 3051-3068, DOI:10.1080/01431161.2012.716925*

Other Soil moisture impacts

• NCEP – Assimilation of a blended daily dataset [AMSR, ASCAT, SMOS, Windsat] into GFS improves precipitation bias and slight improvement to the ETS



•*AMSRE experiments over regional models in Europe*

• *SSMI retrievals over Tibetan Plateau [low vegetation but complex soil structure]*