Use of Satellite Data for Land Surface Assimilation

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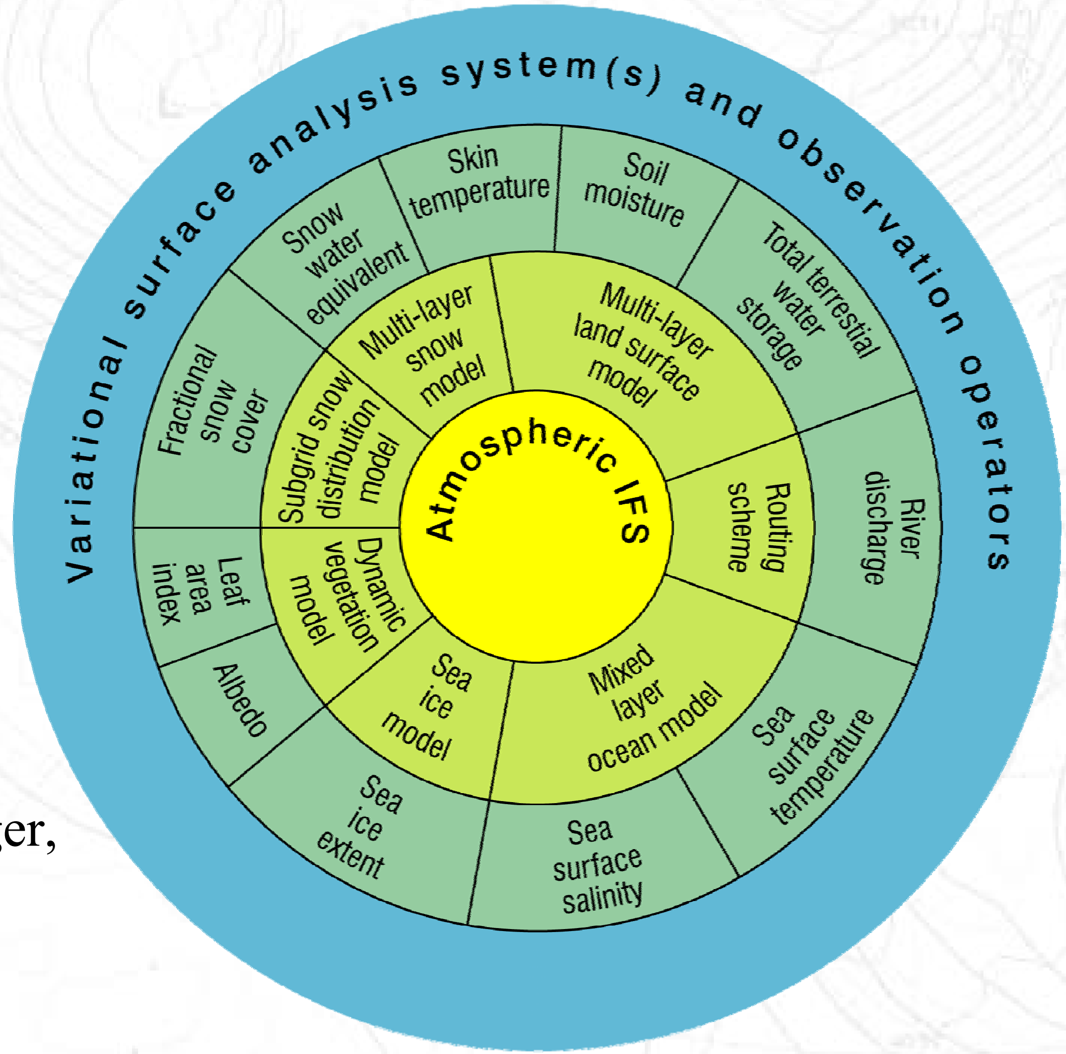
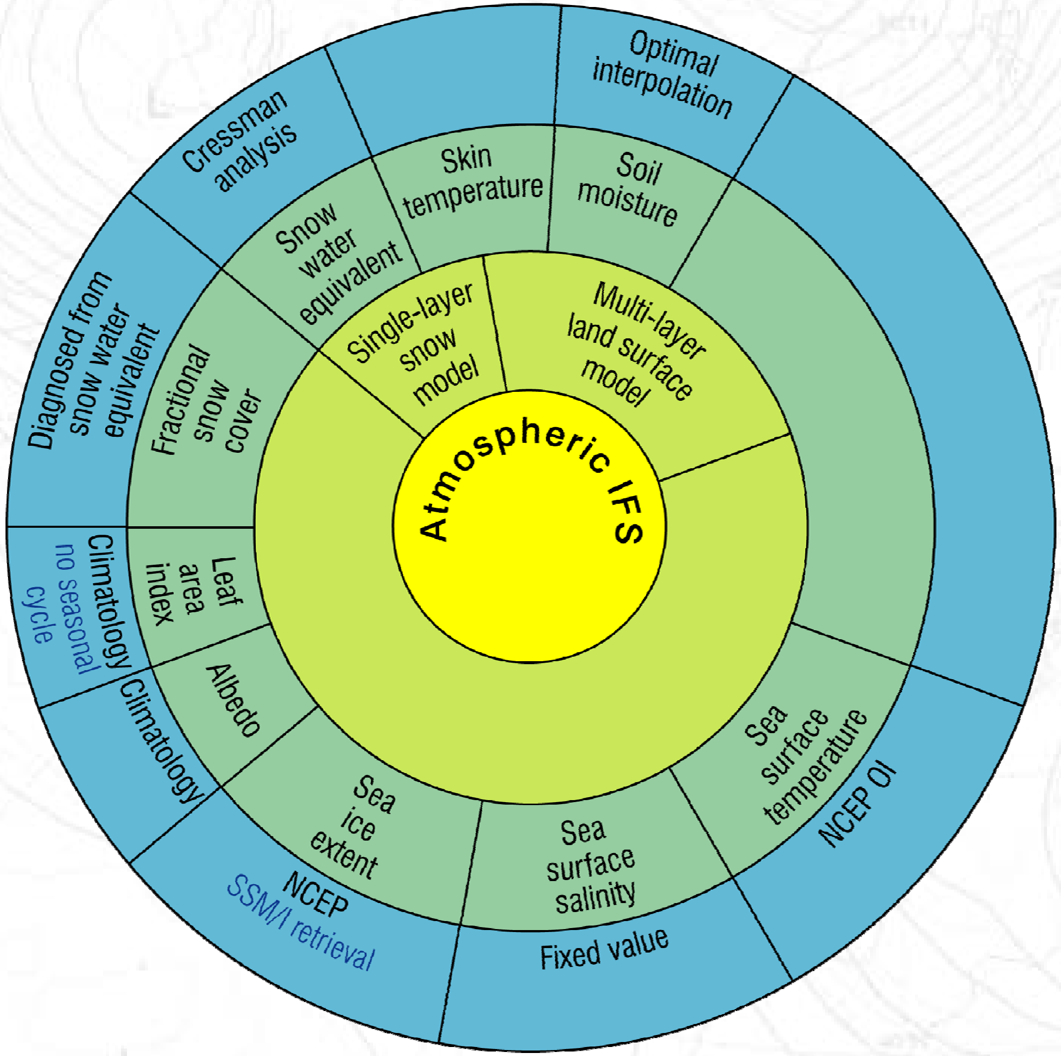
An Advanced Surface Analysis System

SMMR,
SSM/I,
TMI,
AMSR,
GRACE,
AVHRR,
MODIS,
MERIS,
ASCAT,
ERS scat.,
SEVIRI,
GOES Imager,
....



The Current Surface Analysis System



Overview

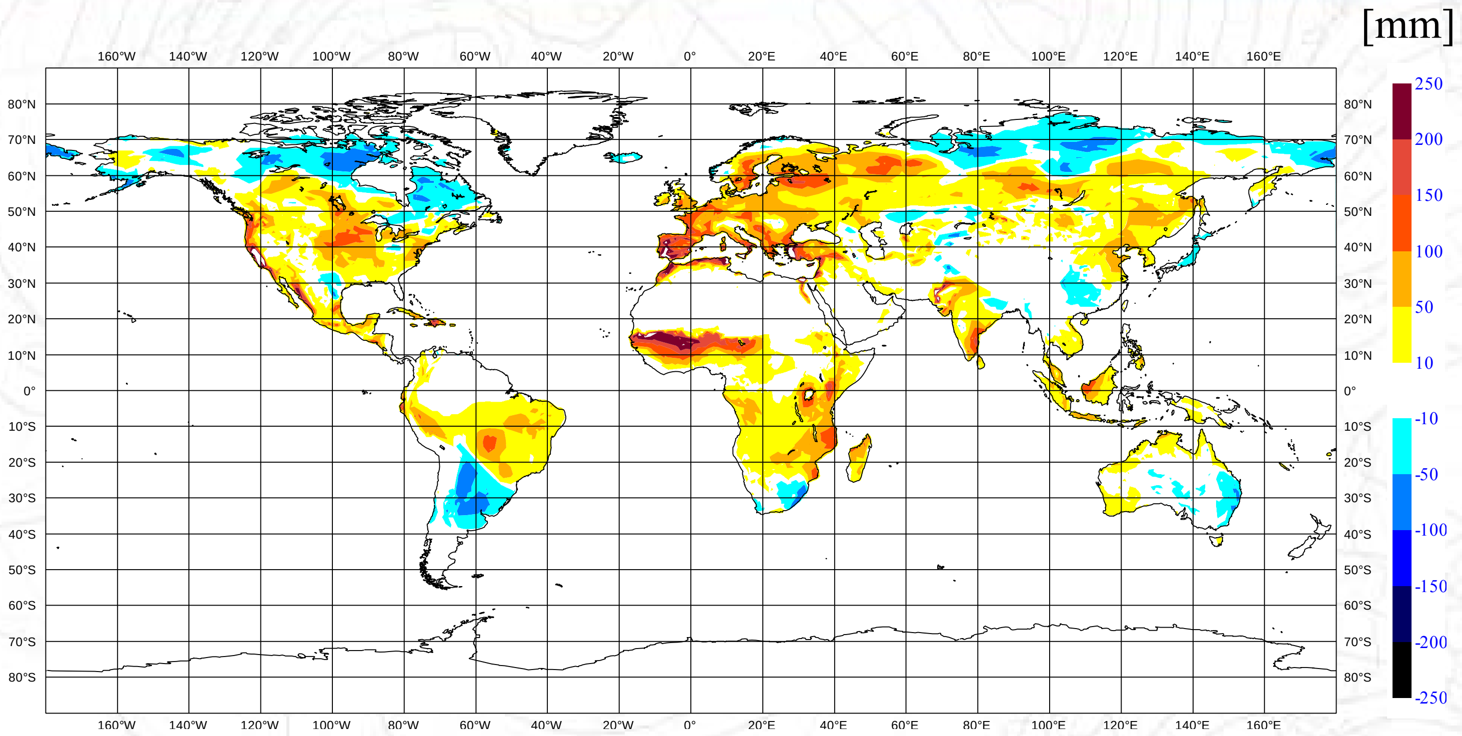
Future Use of Satellite Data for Land Surface Assimilation:

1. Soil Moisture
   - The current Optimal Interpolation soil moisture analysis.
   - A demonstration study using TMI derived soil moisture.
   - Soil moisture analysis using SMOS observations.
   - Using scatterometer derived soil moisture.
2. Snow Water Equivalent
   - Cressman Interpolation and observations.
   - Introducing satellite derived snow cover.
   - Analysis validation.
3. Synergies with the Atmospheric Analysis

Why should NWP centres improve surface analysis systems?

- To increase the number of satellite observations used over land in the atmospheric analysis and improve ‘classical’ skill scores at 500 hPa.
- To improve the atmospheric forecast with respect to weather parameters like screen level variables, precipitation, cloud coverage, etc. …
- Provide a more reliable estimate of core surface parameters, e.g. snow depth, to the users.
- ‘New’ applications including climate research, seasonal forecasting, environmental monitoring, and severe / extreme weather with new customers (policy makers, water resources management, hydrologists, crop growth modelling, …) require an accurate estimate of land surface properties.
- NWP centres operate the most powerful data assimilation systems and play a fundamental role in integrating observations from different sources. A well represented land surface is an added value to re-analyses.

Operational OI Analysis Increments



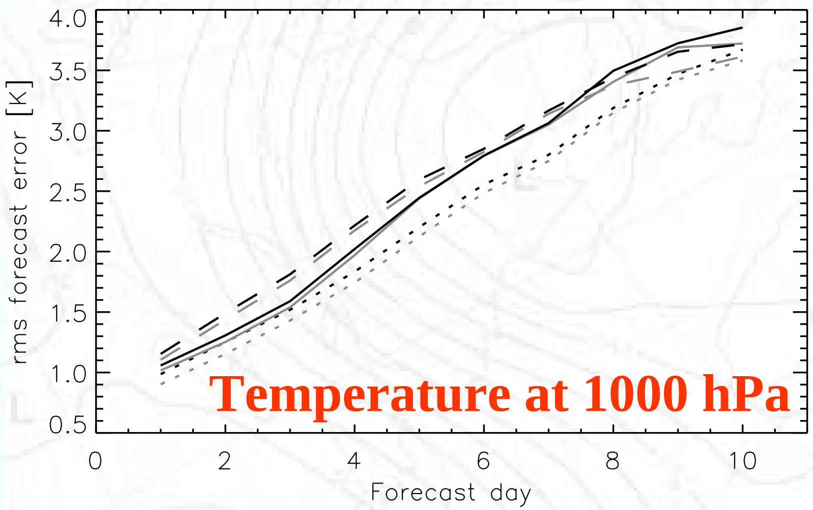
Analysis – First Guess, OI, June and July 2002

Analysed screen level parameters are used as proxy ‘observations’ for the root zone soil moisture analysis.

In general, the analysis tends to add water.

The amount of water is non-negligible and represents a sizeable part of the terrestrial water budget.

Forecast Skill



grey: OI analysis
black: OL no analysis
solid: North America
dotted: Europe
dashed: East Asia

area	height	24 h	72 h	120 h	168 h	216 h
Northern Hemisphere	1000	0.1	0.1	0.5	10.0	1.0
	850	0.1	0.1	5.0	-	5.0
	700	5.0	1.0	-	-	10.0
Europe	1000	0.1	0.1	0.1	-	-
	850	0.1	0.1	5.0	-	-
	700	-	10.0	-	-	-
East Asia	1000	0.1	0.1	5.0	5.0	0.5
	850	0.1	0.1	-	-	0.2
	700	-	-	-	-	5.0
North America	1000	0.1	0.1	-	-	-
	850	0.1	0.1	-	-	-
	700	5.0	-	-	-	-

The proxy 'observations' are efficient in improving the turbulent surface fluxes and consequently the weather forecast on large geographical domains.

Using TMI-derived Soil Moisture in the Soil Moisture Analysis

Motivation :

- The proxy 'observations' 2 m temperature and relative humidity in the soil moisture analysis are efficient in improving the turbulent surface fluxes and consequently the weather forecast on large geographical domains.
- Does the analysis result in more accurate soil moisture?
- Can satellite-derived soil moisture be used in the analysis?

NWP Experiments:

1. **Open Loop**, no soil moisture analysis.
2. **Optimal Interpolation** using 2m temperature and relative humidity analyses.
3. **Nudging** using TMI derived surface soil moisture.

- atmospheric 4-DVar (including ~ 5 Mio. Satellite observations per day)
- T511 spectral resolution (~ 35 km)
- June and July 2002

TMI Pathfinder Data Set

Data set produced by:

Dept. Civil and Environmental Engineering,
Princeton University, NJ

Basis:

brightness temperatures at 10.65 GHz horizontal polarization

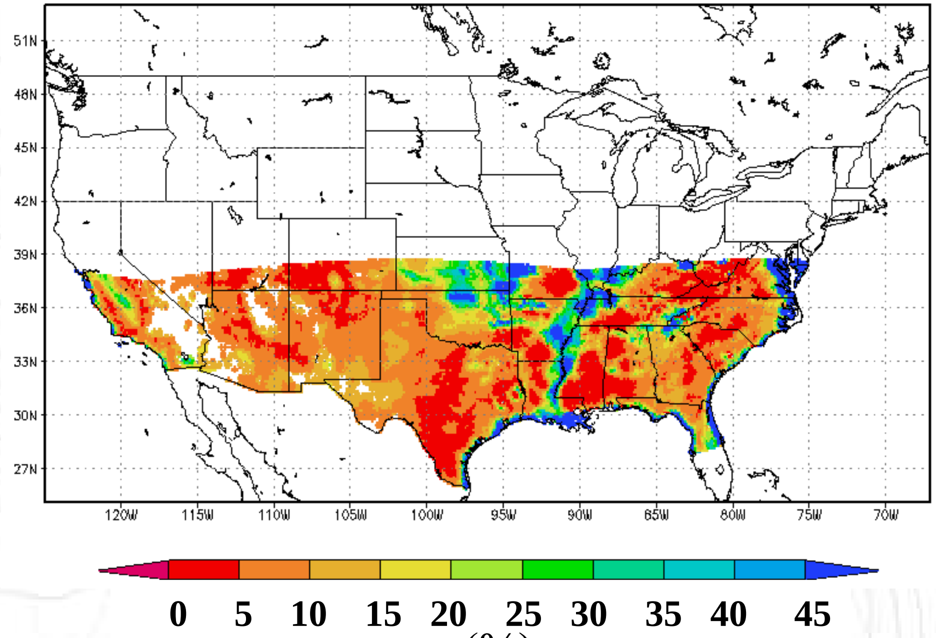
Method:

physical retrieval based on land surface microwave emission model and auxiliary data sets from the North American Land Data Assimilation Study project

Output:

surface soil moisture [$cm^3\ cm^{-3}$],

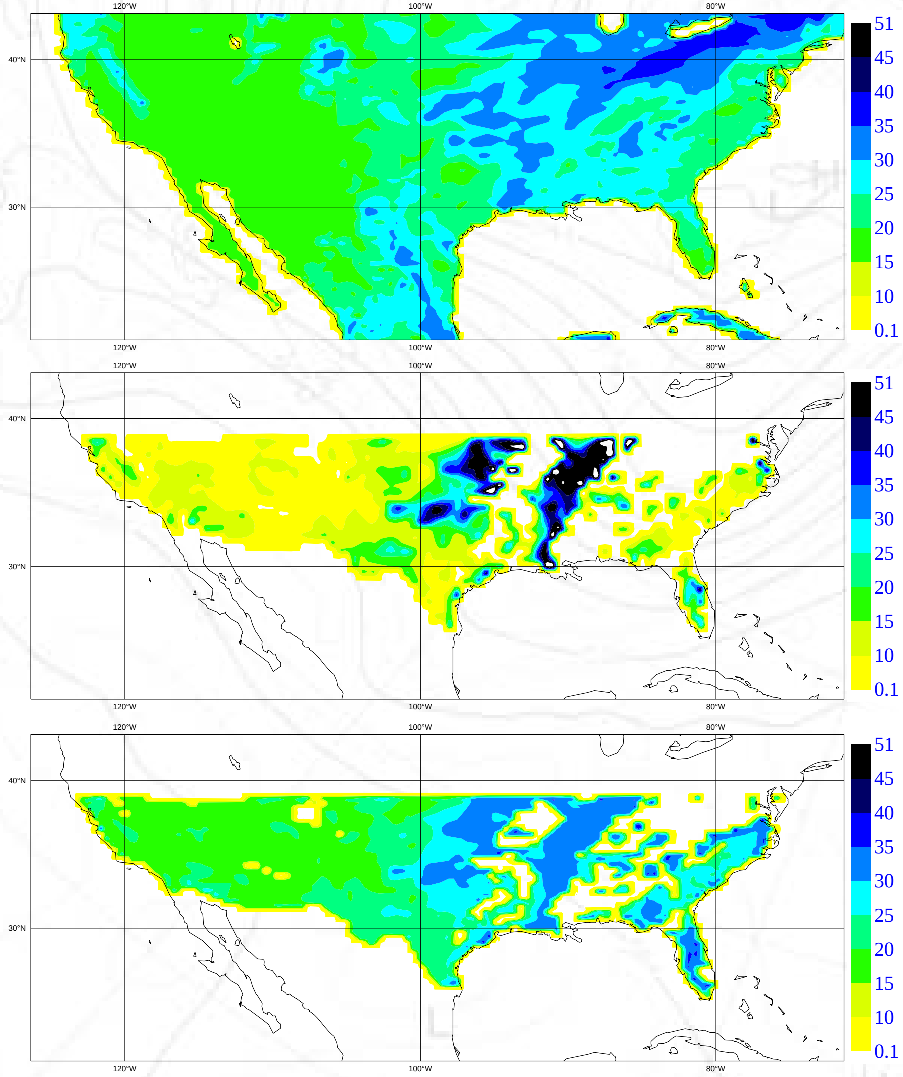
July 2nd, 1999



(Gao et al. 2006)

Bias-corrected TMI Soil Moisture

volumetric surface soil moisture [%]
for 06/06/2002



model first guess

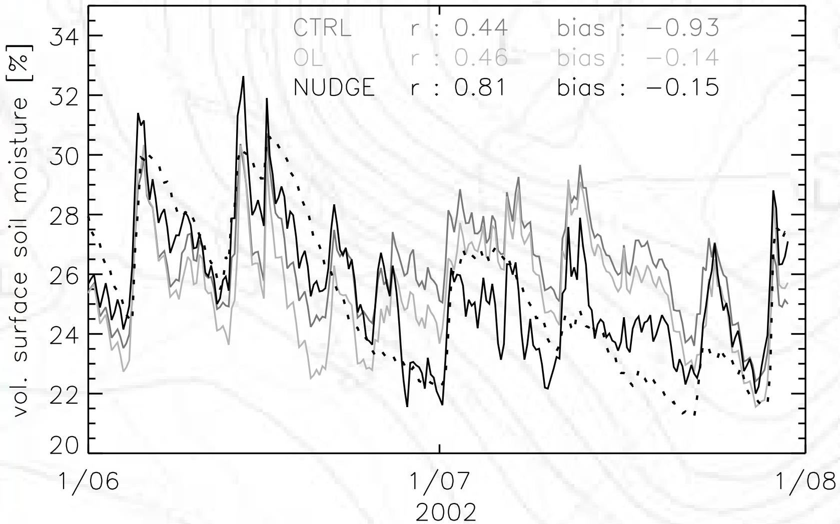
TMI Pathfinder data

bias-corrected TMI data set
(Cumulative Distribution Function matching)

Validation of Soil Moisture

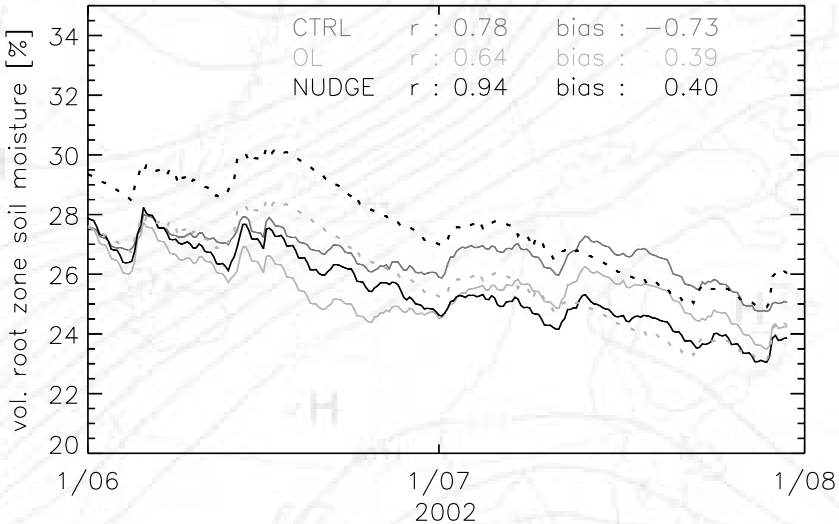
area averages for Oklahoma (72 stations Mesonet)

surface soil moisture



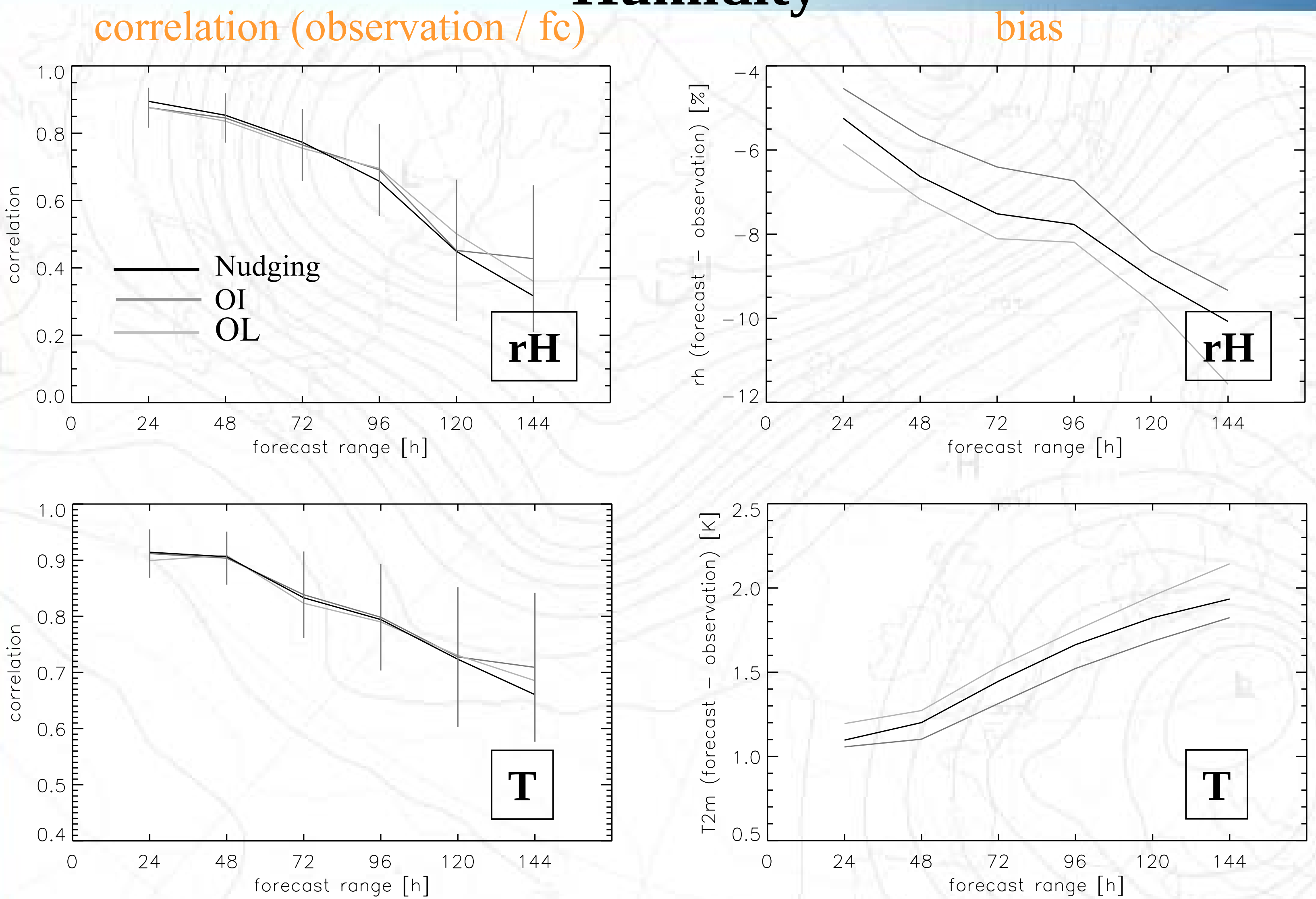
- Too quick dry downs (model problem).
- Too much precip in July (model problem).
- Too little water added in wet conditions (OI analysis problem).
- NO water removed in dry conditions (OI analysis problem).
- Nudging / satellite data remove water effectively and produce a realistic dry down.
- Nudging the satellite results in the most accurate surface soil moisture estimate.

root zone soil moisture



- Precipitation errors propagate to the root zone.
- Analysis constantly adds water.
- The monthly trend is underestimated.
- The information introduced at the surface propagates to the root zone.
- The monthly trend is well reproduced using the nudging scheme.

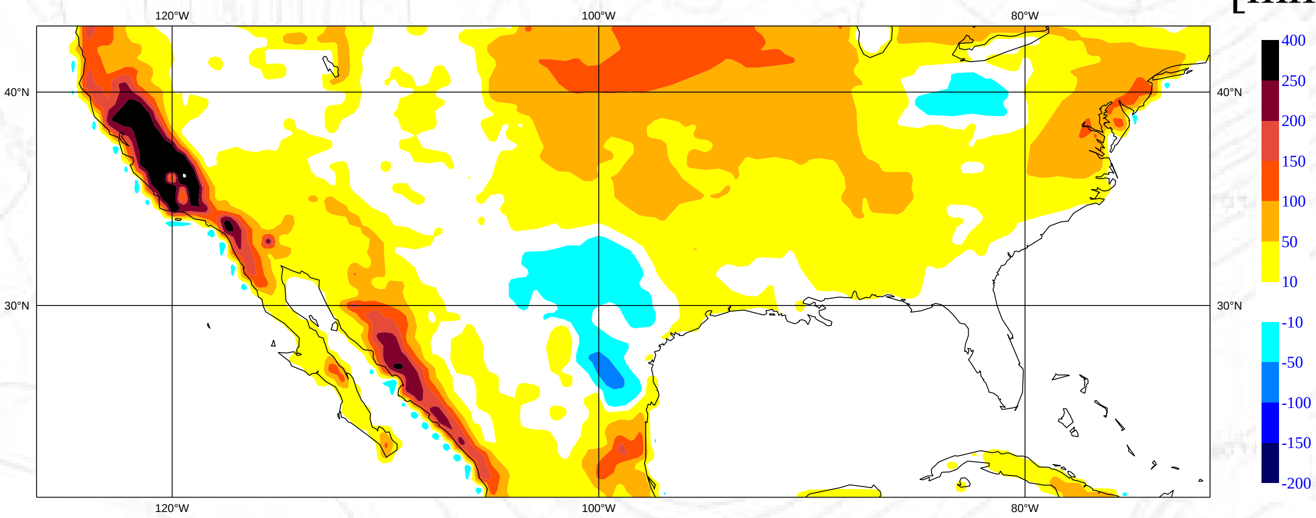
Impact on 2m Temperature and Relative Humidity



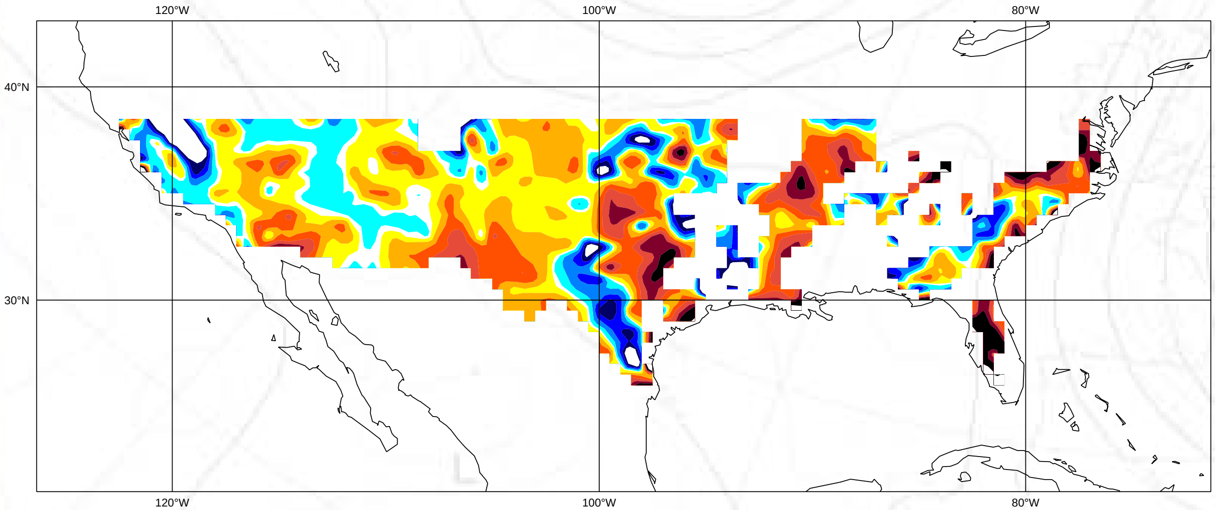
Nudging Soil Moisture Increments

accumulated increments over June and July 2002

[mm]



Optimal Interpolation (2 m T and RH)



Nudging (TMI soil moisture)

First Summary on Soil Moisture

- Soil moisture is a ‘sink variable’, which compensates systematic and random model errors.
- The analysis based on screen level parameters improves the forecast skill, the accuracy of soil moisture itself is NOT improved.
- Constraining soil moisture with satellite observations results in a more accurate soil moisture estimate. The bias in the forecast for screen level parameters is slightly increased.
- Analysis increments from the OI and the TMI nudging can be completely different. This will be a challenge for future operational applications.

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Surface Data Assimilation System:
Overview and Implementation Status

general information:

- extended Kalman filter (ELDAS, DWD)
- 12-hour assimilation window (identical to atmospheric 4DVar)
- NO horizontal correlations

technical information:

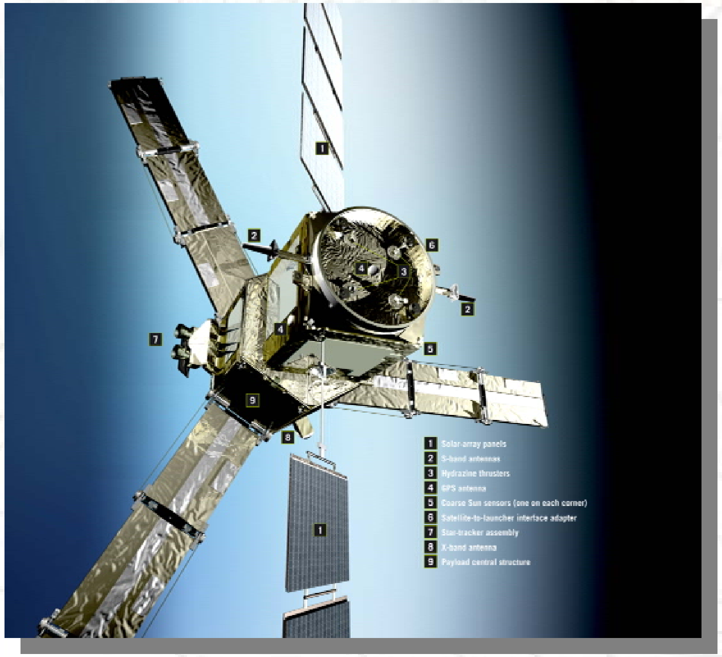
- part of the IFS as nconf = 302, passively in CY32R3 (FORTRAN only)
- cnt0.F90 -> csekf1.F90 -> csekf2.F90 -> cnt3.F90
- perturbation runs based on nconf = 1, model results are stored in global arrays
- observation processing and Kalman filtering are subsequent steps
- data monitoring will also be done in the atmospheric 4DVar

current schedule for the various 'observation' types:

- 2m temperature and relative humidity analysis increments (end 2007)
- ERS derived soil moisture (early 2008; RD only)
- ASCAT derived soil moisture (summer 2008)
- SMOS brightness temperatures (summer 2009)
- SSM/I / AMSR snow upgrade (2011+)
- SMOS-OPS brightness temperatures (?)

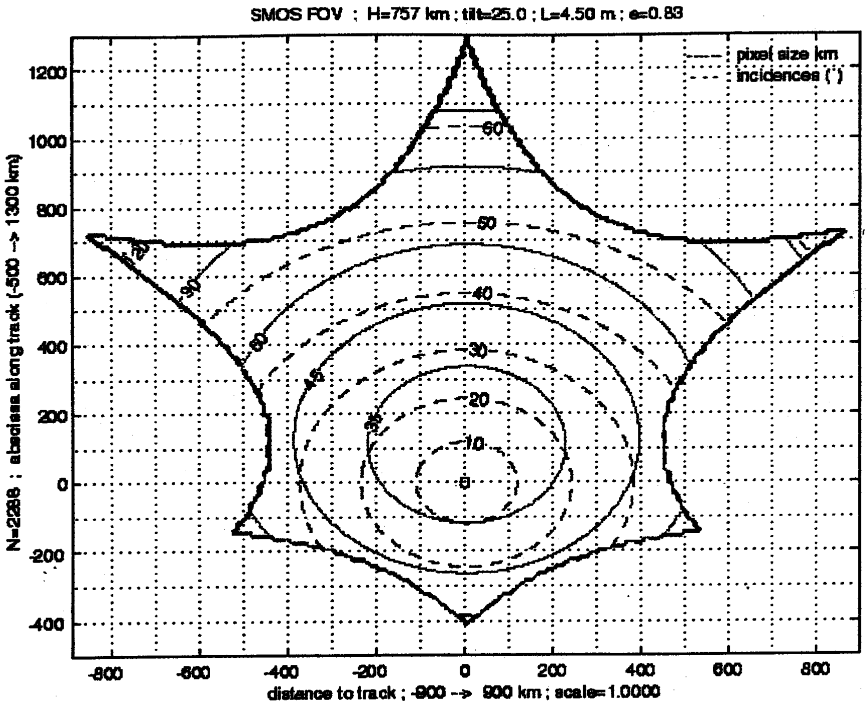
Observations:

ESA’s Soil Moisture and Ocean Salinity Mission



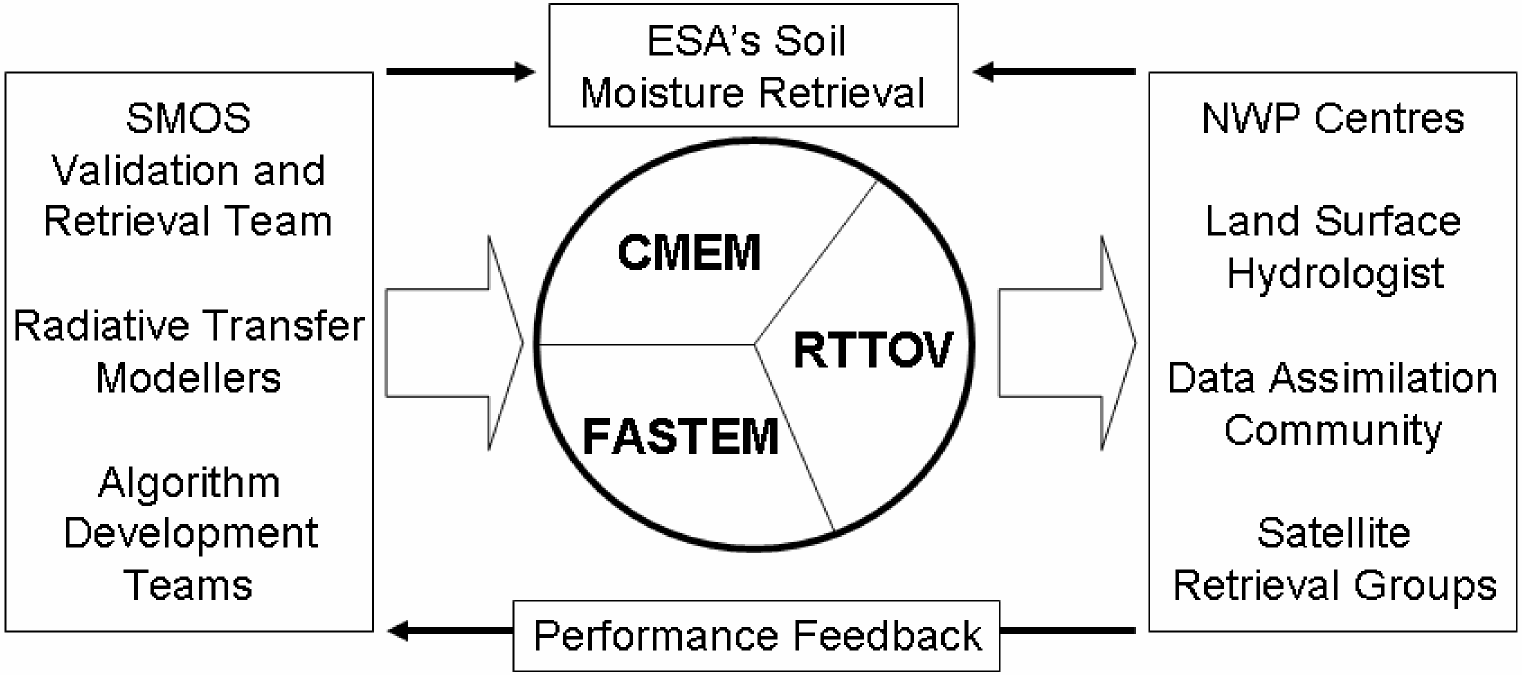
Instrument:
dual-pol., multi-angular, L-band brightness temperature measurement acquired by a 2D interferometer.

Launch:
May – September 2008



SMOS Observation Operator: Community Microwave Emission Model

- In general, NWP Centres do not have the man power to develop radiative transfer models.
- However, near-real time applications often require the assimilation of brightness temperatures or radiances (rather than derived parameters).
- There is a need for 'community models', which are well documented and maintained. Good example: RTTOV / NWP-SAF at the UK Met Office.



Observation Operator – Community Microwave Emission Model:

Schematic Structure

Provide a surface module for RTTOV, which can easily be used by the NWP community and the SMOS cal / val team and which mimic ESA's operational soil moisture retrieval.

Surface Component

- sand fraction
- clay fraction
- soil specific density
- soil bulk density
- soil roughness parameter
- soil temperature profile
- soil moisture profile
- salinity

⇒

- dielectric constant of the wet soil
- specular reflectivity
- rough reflectivity
- effective temperature

Vegetation Component

- leaf area index
- canopy structure
- coefficient (veg. type)
- canopy temperature
- salinity
- leaf thickness
- fractional coverage

⇒

- vegetation water content
- vegetation optical depth
- single scattering albedo

Atmospheric Component

- humidity profile
- temperature profile

⇒

- atmospheric optical depth
- atmospheric upward and downward contribution

Snow Component

- snow temperature
- snow water equivalent
- snow density
- snow grain size distr.

⇒

- absorption coefficient
- scattering coefficient

Community Microwave Emission Model

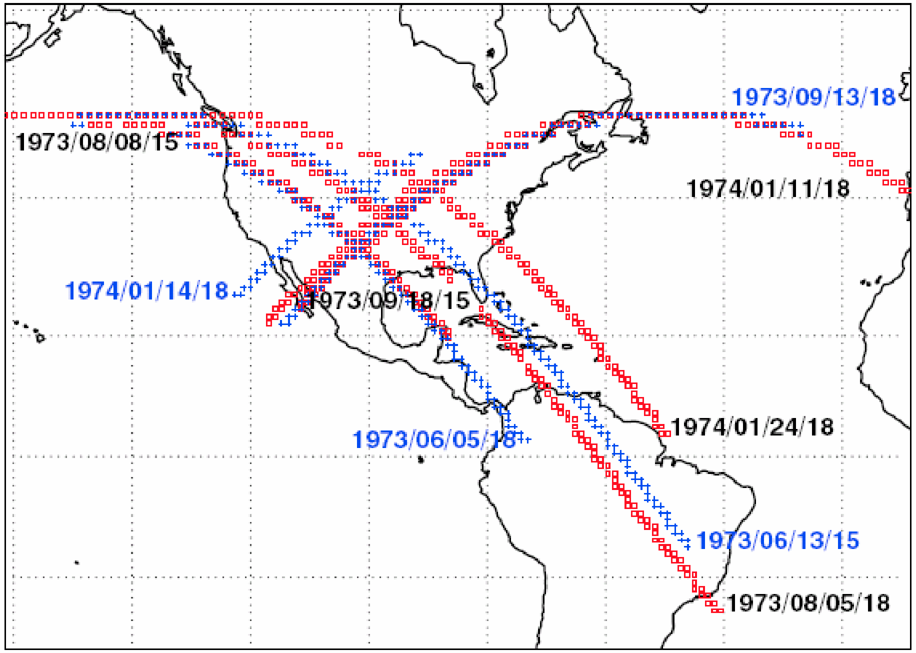
TABLE II
DEFAULT MODEL CONFIGURATION FOR L-BAND AND OPTIONAL MODULES. ALL MODULES ARE DESCRIBED IN SECTION II. VEGETATION PARAMETERS INCLUDE VALUES FOR LOW AND HIGH VEGETATION.

Components	*Default Module*	*Optional Modules*		
T_{eff}	Wigneron [22]	Holmes [23]	Choudhury [21]	
ϵ_{soil}	Dobson [25]	Wang-Schmugge [24]		
r_s	Fresnel law	Wilheit [18]		
r_r	Wigneron I [22]	Wegmüller [32]	Wigneron II [22]	Choudhury [30]
vegetation	Kirdyashev [33]	Wigneron [47]	Wegmüller [32]	
snow	Pulliainen [36]			
atmosphere	Pellarin [48]	Liebe [39]		

Parameters	*Default*	*L-MEB Setup*	*LSMEM Setup*
$sal_{soil}[psu]$	0	0	0.65
$sal_{veg}[psu]$	6	6	6
$sal_{sea}[psu]$	32.5	32.5	–
r_r- module	Wigneron I [22]	Wigneron II [22]	Wegmüller [32]
L_c/s or $\sigma[cm]$	$L_c/s = 6.0/2.2$	$L_c/s = 6.0/0.15$	$\sigma = 0.5$
$Q[-]$	0	0	$f(\sigma)$
Nrp	0	0	2
$VWC[kgm^{-2}]$ (L,H)	$f(vegtype)$	$f(vegtype)$	$(1.0, 4.0)$
$\omega[-]$ (L,H)	$(0.05, 0.05)$	$(0.\ to\ 0.05, 0.15)$	$(0.05, 0.05)$
vegetation module	Kirdyashev [33]	Wigneron [47]	Wegmüller [32]
a_{geo} or $b[m^2kg^{-1}]$ (L,H)	$a_{geo} = (0.33, 0.66)$	$b = (0.2, 0.33)$	$b = (0.33, 0.33)$

Calibrating CMEM Using ERA-40 and SKYLAB: The Mission

- Is it possible to calibrate CMEM to obtain bias free TBs on the continental scale?
- Are there any systematic differences between the obs. and the fg?
- What is the inter-annual / seasonal variability of TB?



SKYLAB facts:

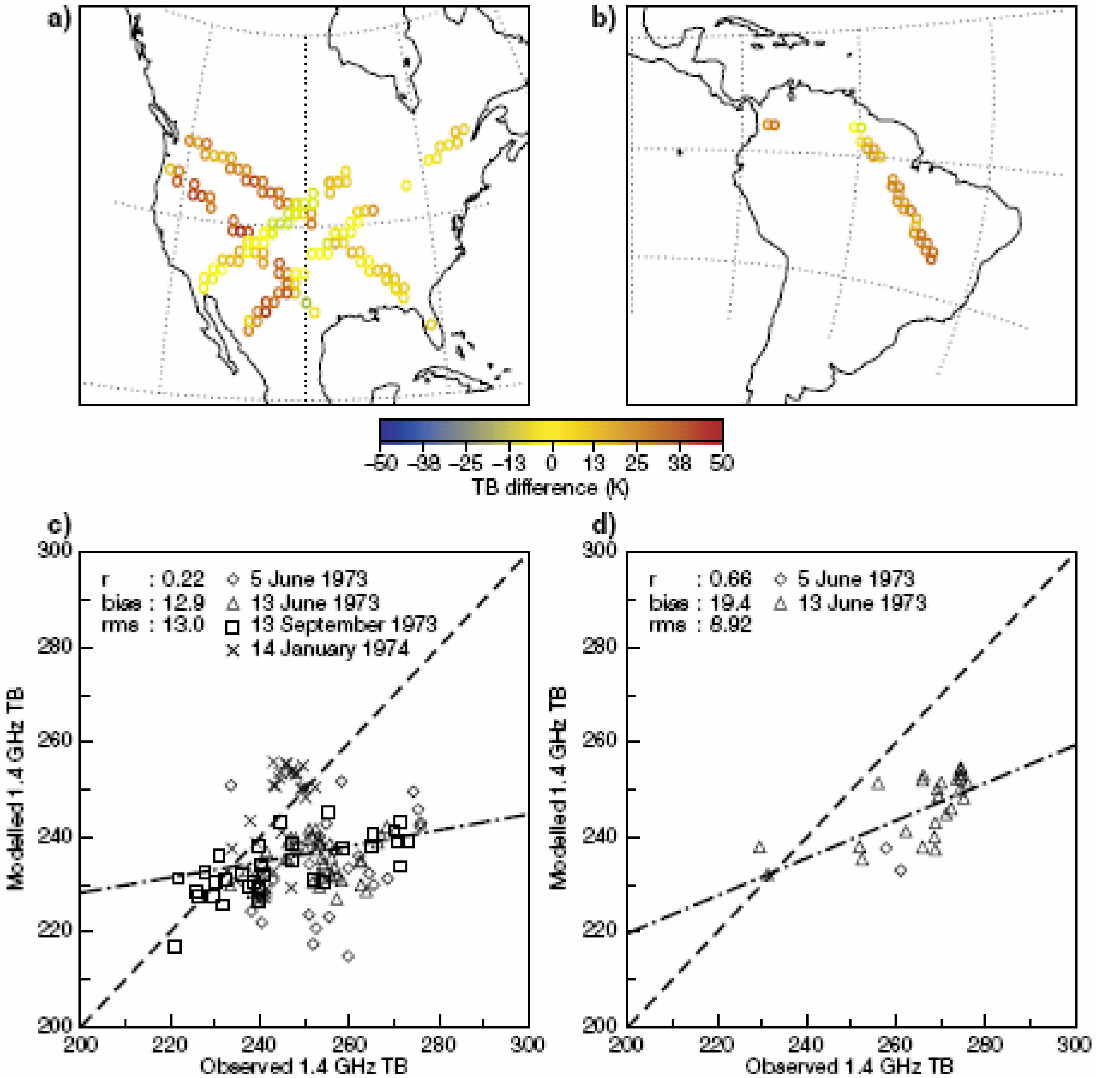
- launch 14 May 1973
- nominal altitude 435 km
- back on earth 11 July 1977
- data collection required astronaut

S-194 facts:

- L-band radiometer
- nadir looking
- 110 km resolution
- 2.5 km sampling
- most measurements were lost, 9 overpasses could be recovered from print-outs …

Observation Operator – CMEM:

Calibrating CMEM Using ERA-40 and SKYLAB



Data:

- •S-194 L-band TB
- •ECOCLIMAP LAI (C-TESSEL)
- •ERA soil moisture
- •ERA soil temperature
- •ERA 2 m temperature
- •ERA snow depth
- •FAO soil types (H-TESSEL)

Calibrating:

- •surface roughness,
- •vegetation structure coef.
- •single scattering albedo

L-MEB configuration

Calibrating CMEM Using ERA-40 and SKYLAB

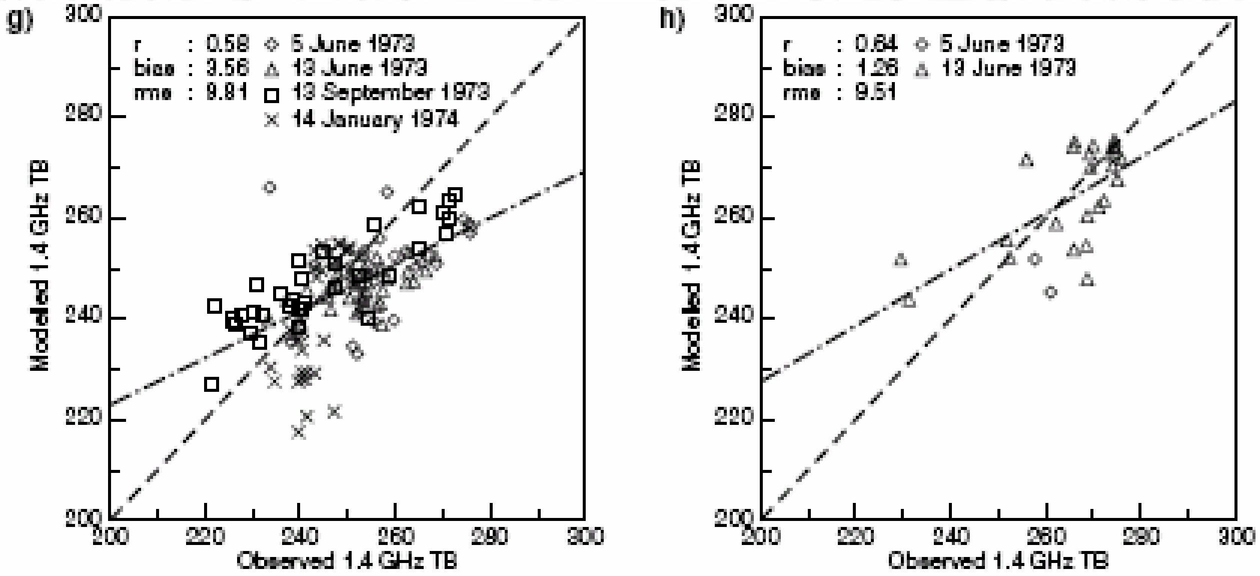
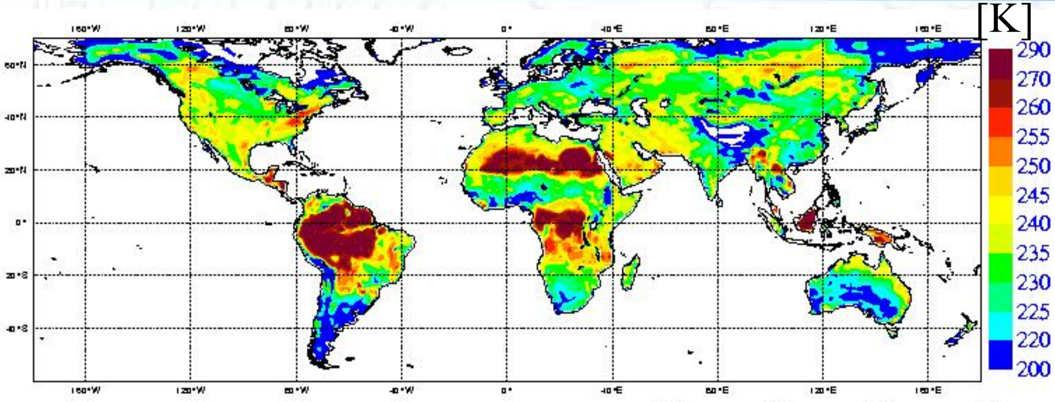


Table 1: CMEM model setup for the calibration and validation computations.

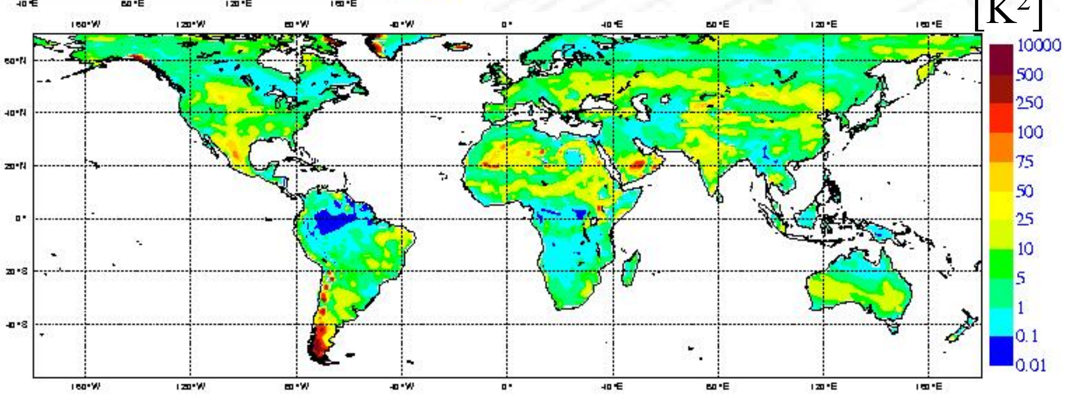
SetUp	Roughness	Vegetation	σ	$\omega(L, H)$	b (L,H)	$a_{geo}(L, H)$	$VWC_{trop.}$
A	Wigneron (Eq.4)	Wigneron	0.15	(0.05, 0.15)	(0.2, 0.33)		6
B	Wigneron (Eq.4)	Wigneron	2.2	(0.05, 0.05)	(0.2, 0.33)		6
C	Wigneron (Eq.5)	Wigneron	2.2	(0.05, 0.05)	(0.2, 0.33)		6
D	Wigneron (Eq.5)	Kirdyashev	2.2	(0.05, 0.05)		(0.33, 0.33)	6
E	Wigneron (Eq.5)	Kirdyashev	2.2	(0.05, 0.05)		(0.33, 0.66)	10

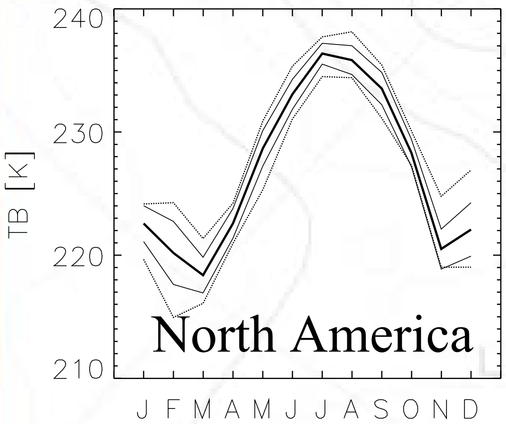
Observation Operator – CMEM:
ERA-40-based Climatology

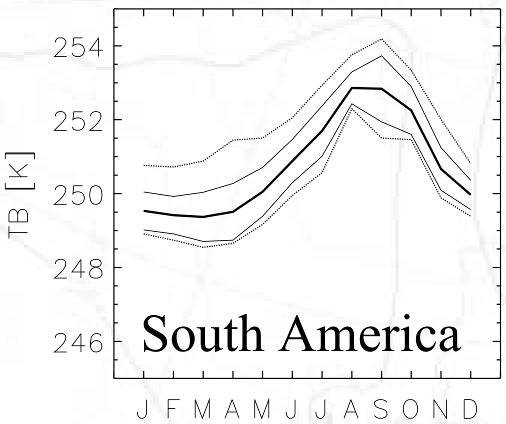


July mean (1990 – 2000)

July variance (1990 – 2000)

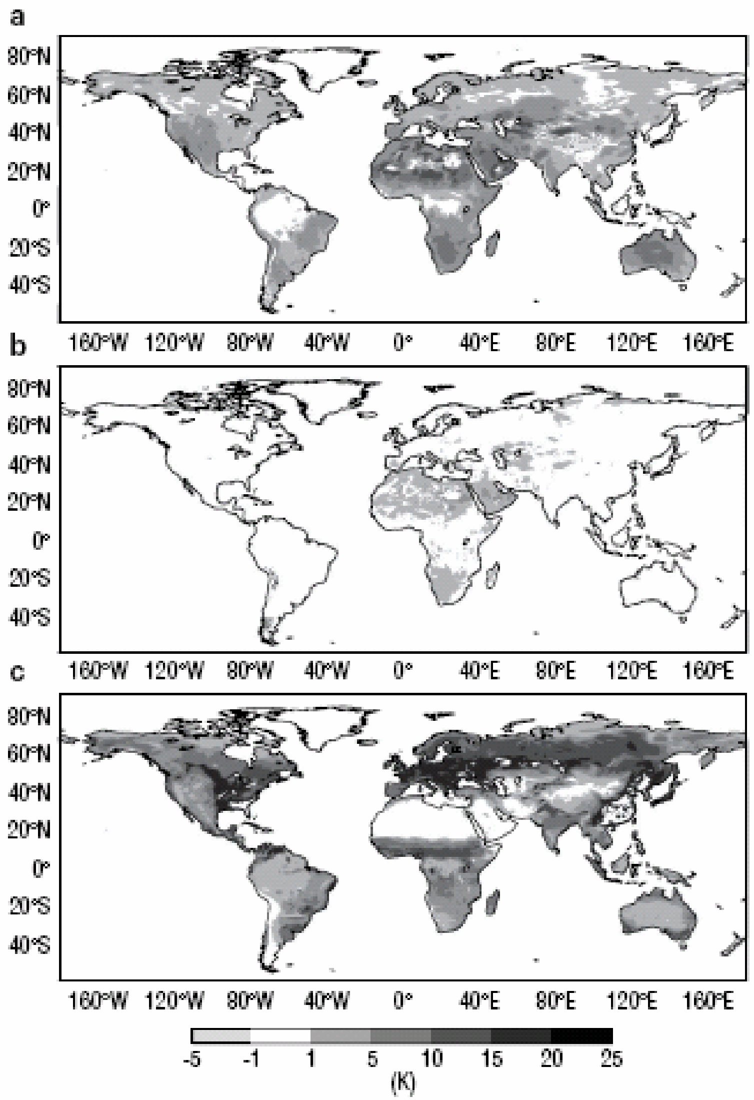






mean annual cycle in
TOA TB for 1991 to 2000

First Guess Errors:
Uncertainties in CMEM



L-band (1.4 GHz)
- brightness temperature differences
- h-polarization, 50° incidence angle
- 1 July 2005, 12:00 UTC, DA stream

a) dielectric model for the wet soil

([Wang and Schmugge, 1980]-[Dobson et al. 1985])

global mean: 4 K

b) effective soil temperature

([Wigneron et al. 2001] – [Wilheit 1978])

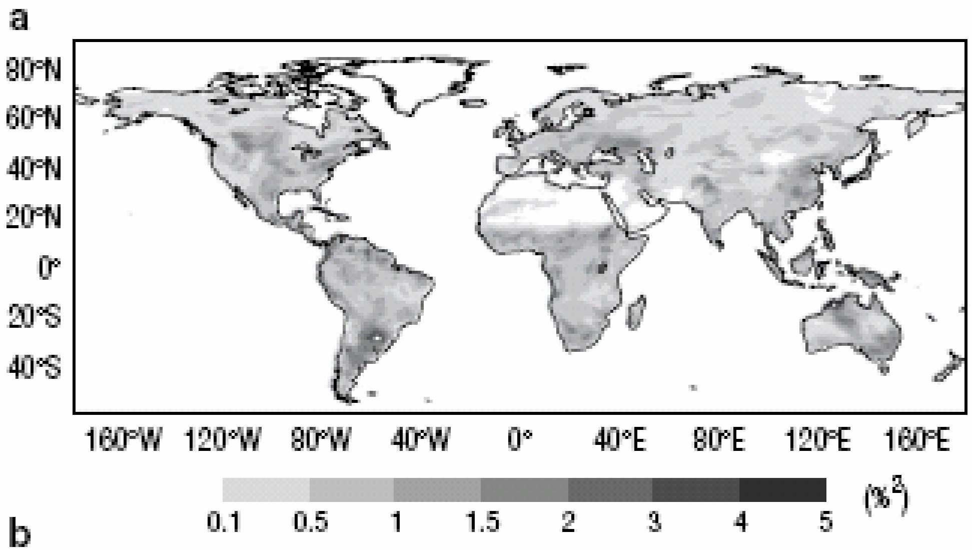
maximum < 5 K

c) vegetation model

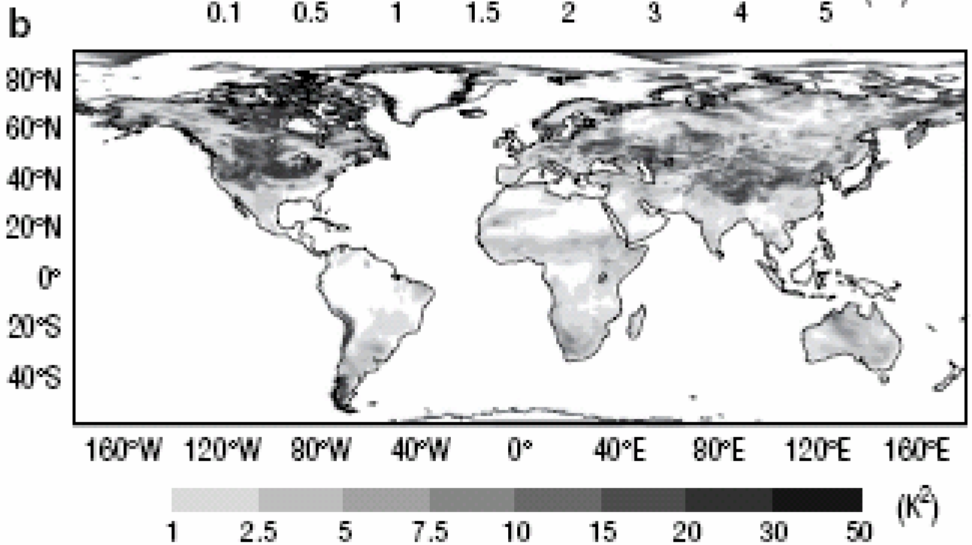
([Wigneron et al. 1995] – [Kirdyashev et al. 1979])

global mean: 8 K

First Guess Errors:
Uncertainties in modelled Soil Moisture (EPS-based)



Soil moisture variance:
- 50 EPS members at T+48 hours
- 12 UTC basetime
- 1st and 15 th of each month
- 2005
- mean variance of 24 scenes



Brightness temperature variance

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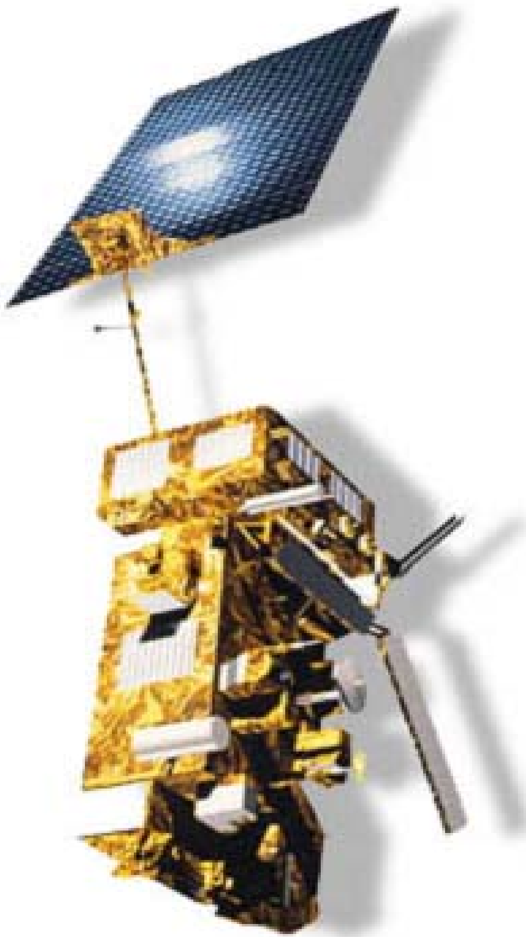
Scatterometer-based Soil Moisture

ERS scatterometer

- 1991 up to present
- 50 km spatial resolution
- Daily coverage < 41 %
- C-Band (5.3 GHz)
- Polarization VV
- Incidence Angles 18-59°

METOP ASCAT

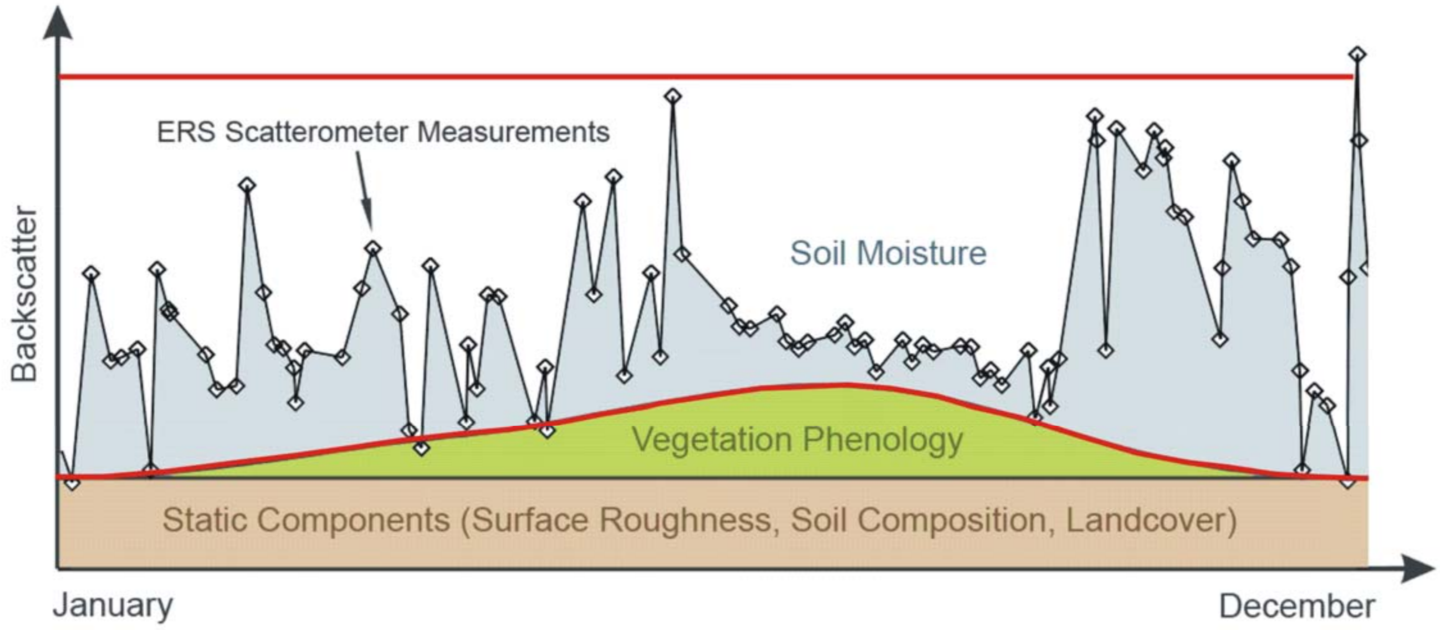
- 2007 up to present
- 50 / 25 km spatial resolution
- Daily coverage < 82 %
- C-Band (5.2 GHz)
- Polarization VV
- Incidence Angles 25-62°

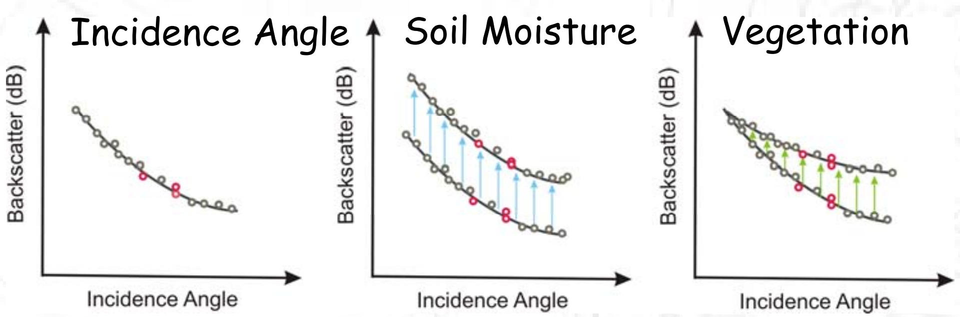


Observations

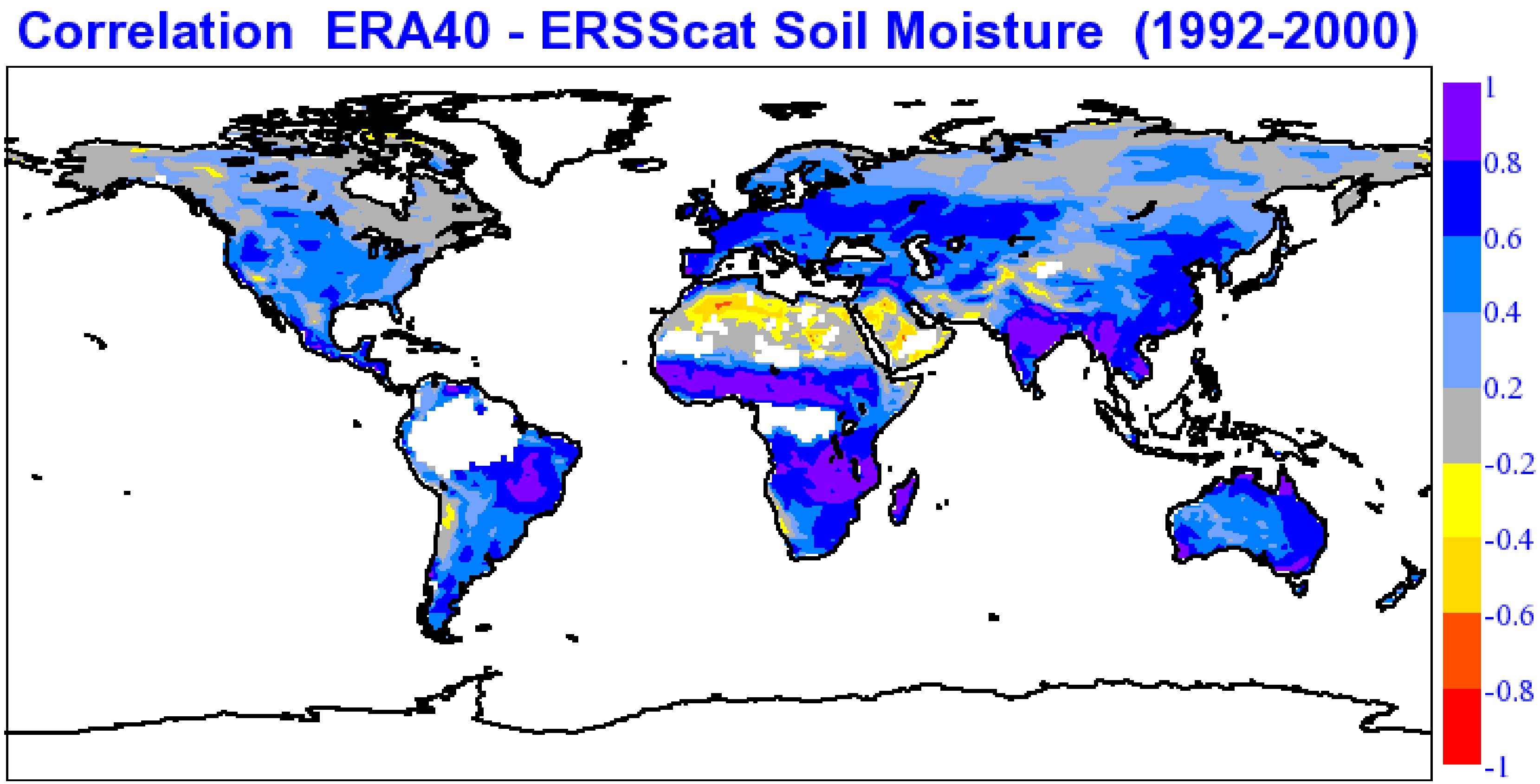
TU Vienna retrieval is a combination of a physical model and change detection:

- Vegetation Model: physical concept
- Soil Moisture Retrieval: Change Detection
- Final product is a soil water index ranging from 0 to 1.





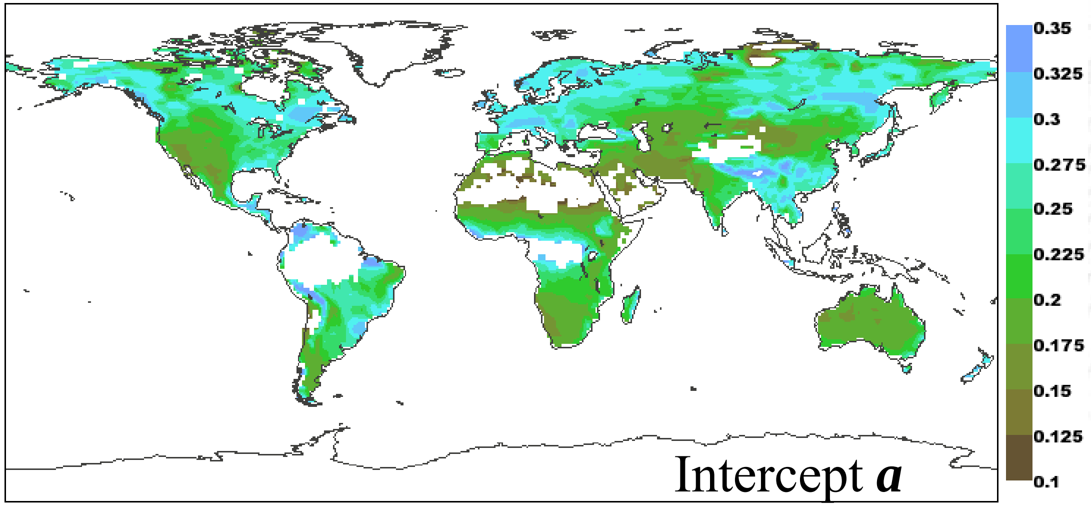
ERA-40 vs ERS Scatterometer

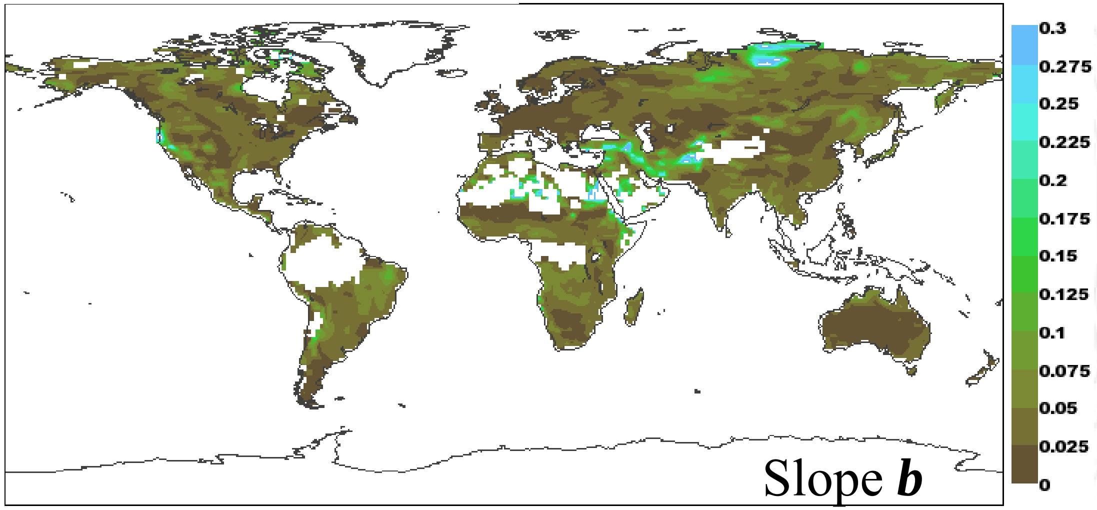


Observation Operator:

Linear CDF Matching ERA-40 / ERS SWI

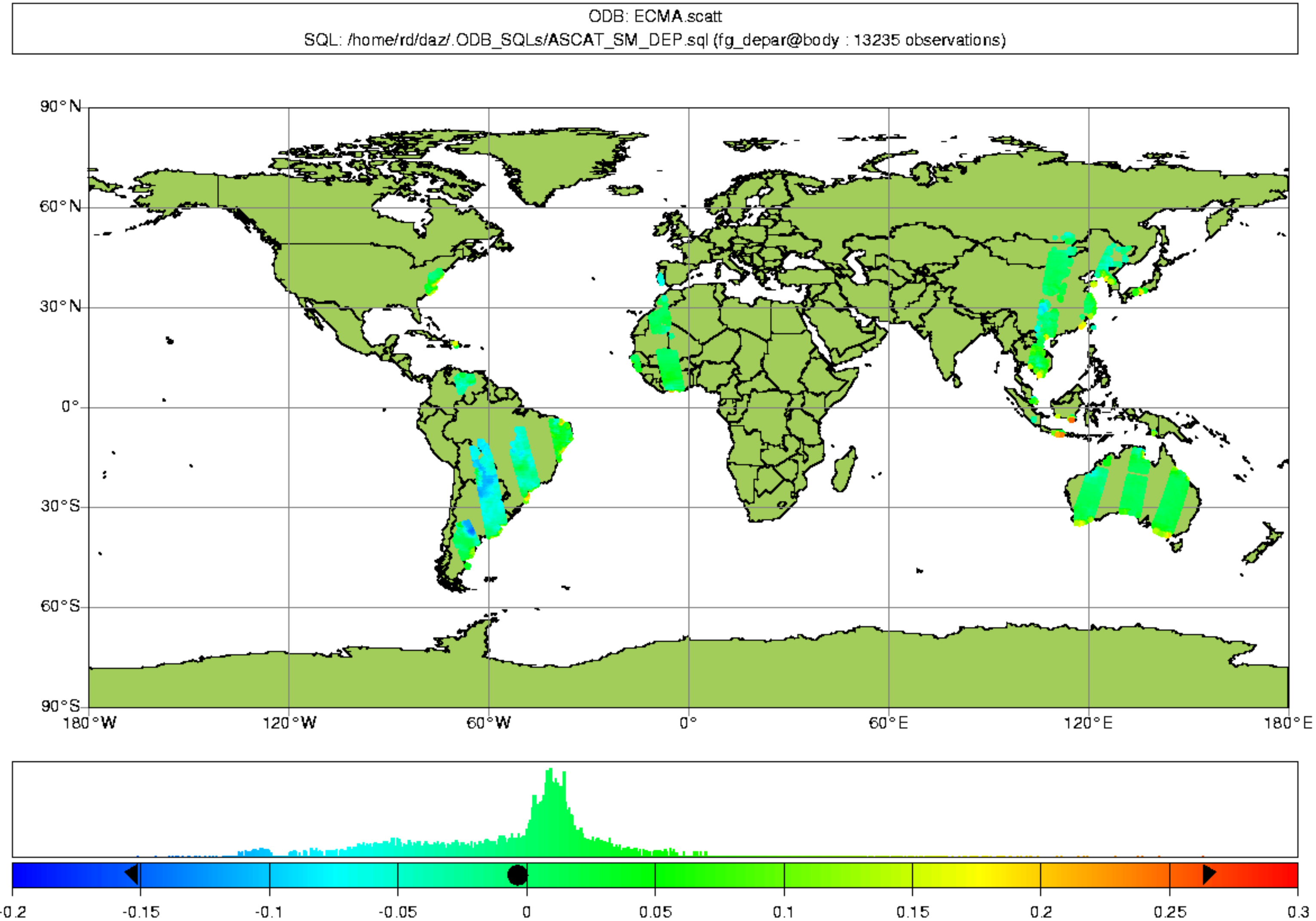
$$\Theta_{adj} = a + b \times \Theta_{Sat} \qquad a = \overline{\Theta}_M - \overline{\Theta}_{Sat} \times \frac{\sigma_{\Theta_M}}{\sigma_{\Theta_{Sat}}} \qquad b = \frac{\sigma_{\Theta_M}}{\sigma_{\Theta_{Sat}}}$$





ASCAT Monitoring

first guess departures 01/04/2007



Second Summary on Soil Moisture

- Calibrating a forward model or a retrieval algorithm is an ill-posed problem: Many parameters are unknown on the global scale, each auxiliary data set has (undefined) systematic and random errors.
- It is possible to get a ‘bias-free’ first guess using a constant value for surface roughness.
- Systematic differences remain, i.e. the modelled dynamical range is too small. => An additional ‘bias-correction’ scheme is needed.
- Vegetation is a key component: A static data set is not sufficient. Representing the annual cycle in LAI is a minimum requirement. Ideally, vegetation water content or LAI are analysed.

- Observation operator for ASCAT is in place (based on ERS / ERA-40).
- Monitoring software has been developed and tested.
- Operational monitoring should start early 2008.

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Cressman Interpolation

1. Cressman spatial interpolation:

$$S^a = S^b + \frac{\sum_{n=1}^{N} w_n \left(S_n^O - S^{b'}\right)}{\sum_{n=1}^{N} w_n}$$

with:
- S^O snow depth from synop reports,
- S^b background field estimated from the short-range forecast of snow water equivalent,
- $S^{b'}$ background field at observation location, and
- w_n weight function, which is a function of horizontal distance r and vertical displacement h (model – obs): w = H(r) v(h) with:

$$H(r) = \max\left(\frac{r_{max}^2 - r^2}{r_{max}^2 + r^2}, 0\right) \qquad r_{max} = 250 \text{ km}$$

$$v(h) = \begin{cases} 1 & \text{if } 0 < h \\ \dfrac{h_{max}^2 - h^2}{h_{max}^2 + h^2} & \text{if } -h_{max} < h < 0 \\ 0 & \text{if } h < -h_{max} \end{cases} \qquad h_{max} = 300 \text{ m}$$

Empirical Qualitity Checks

2. Quality check for every grid point

- If $T^b_{2m} < 8$ C only snow depth observations below 140 cm are accepted.
- If $T^b_{2m} > 8$ C only snow depth observations below 70 cm are accepted.
- Observations which differ by more than 50 cm from the background are rejected.
- When only one observation is available within r_{max}, the snow depth increments are set to 0.
- Snow-depth analysis is limited to 140 cm.
- Snow-depth increments are set to 0 when larger than $(160-16T^b_{2m})$ mm, where T^b_{sm} is in C.
- Snow-depth analysis is set to 0 if below 0.04 cm
- If there is no snow in the background and in more than half of the observations within a circle of radius r_{max}, the snow depth increment is kept to 0.

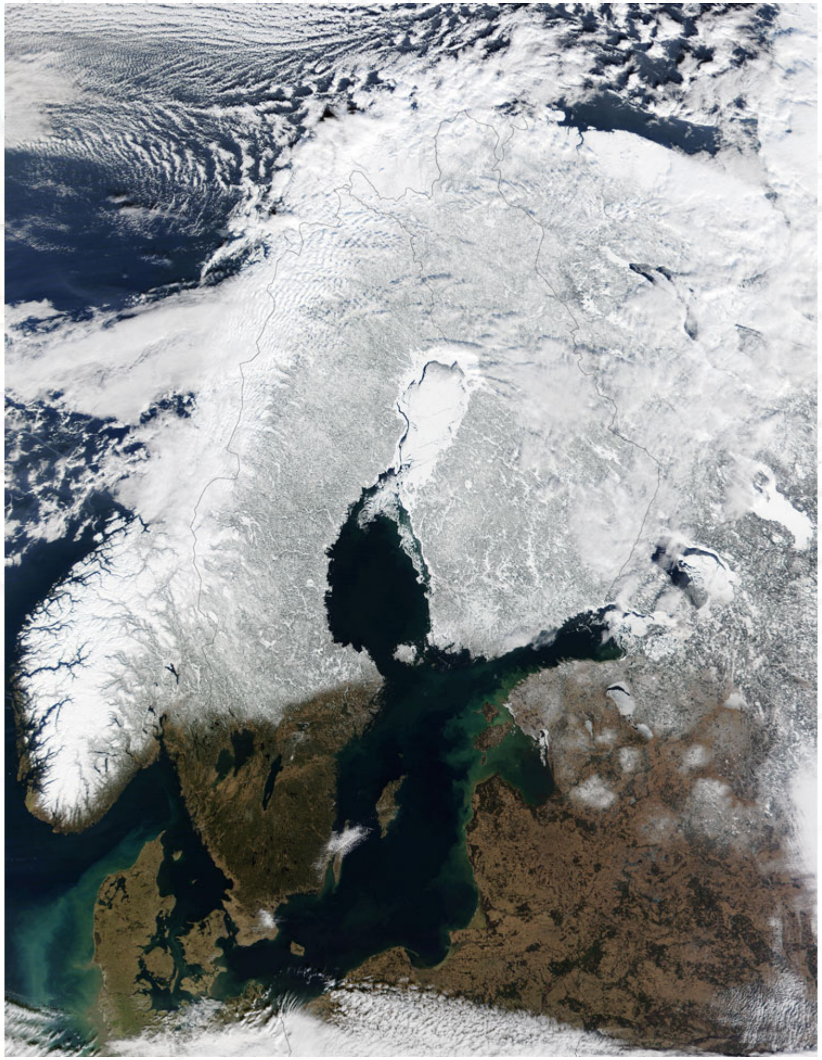
3. Final analysis using climatological values

$$S^a = (1-\alpha)S^a + \alpha S^{cli}$$

with:
- S^{cli} snow depth from climate data set (Foster and Davy 1988),
- α relaxation coefficient of 0.02

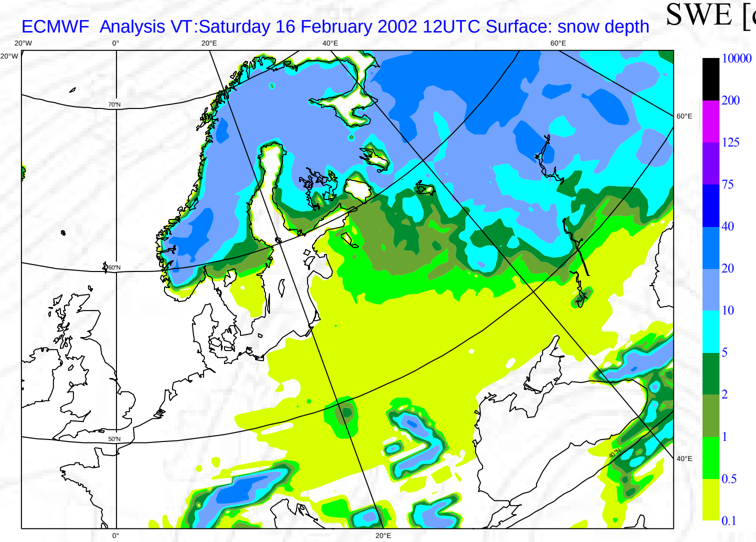
Problem I (Snow Edges)

MODIS 16/02/2002



Cressman analysis

SWE [cm]



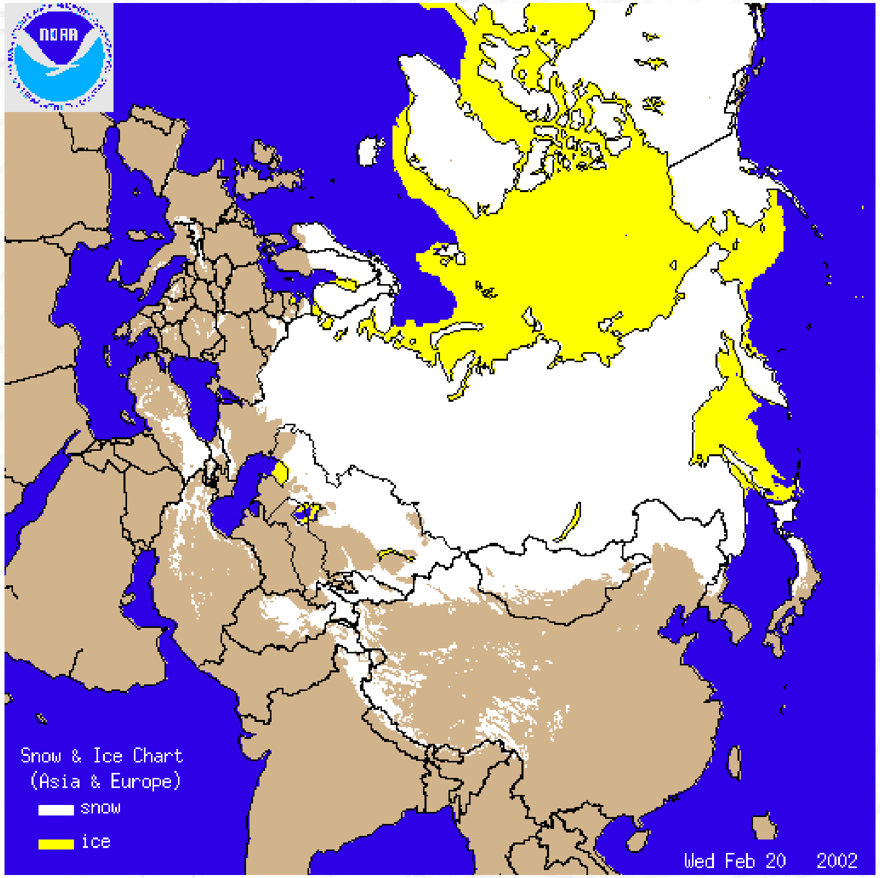
NOAA / NESDIS Snow Extent

Interactive Multisensor Snow and Ice Mapping System:

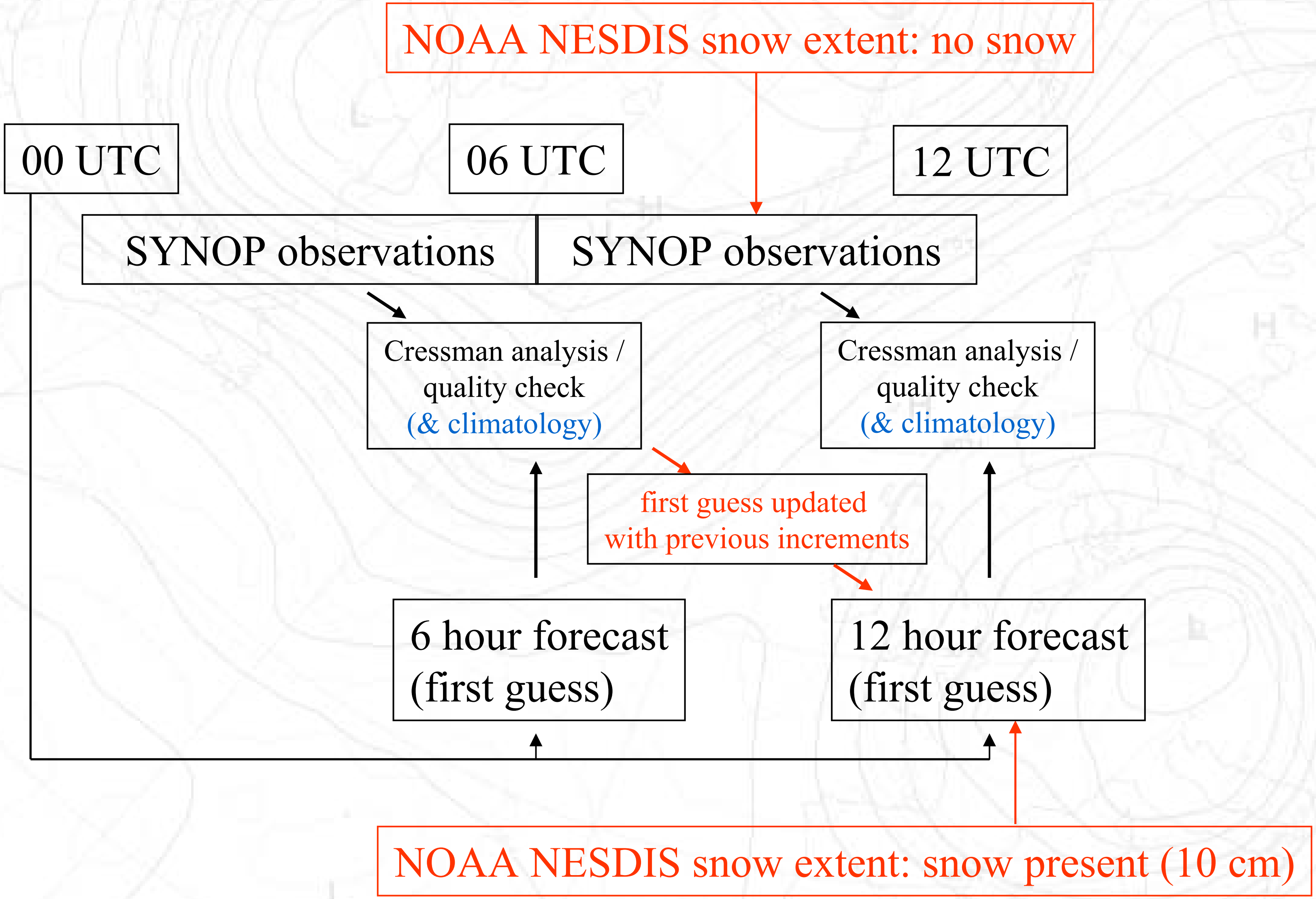
- time sequenced imagery from geostationary satellites,
- AVHRR,
- SSM/I,
- station data,
- previous day's analysis

Northern Hemisphere product

- real time
- polar stereographic projection
- 1024 × 1024 elements



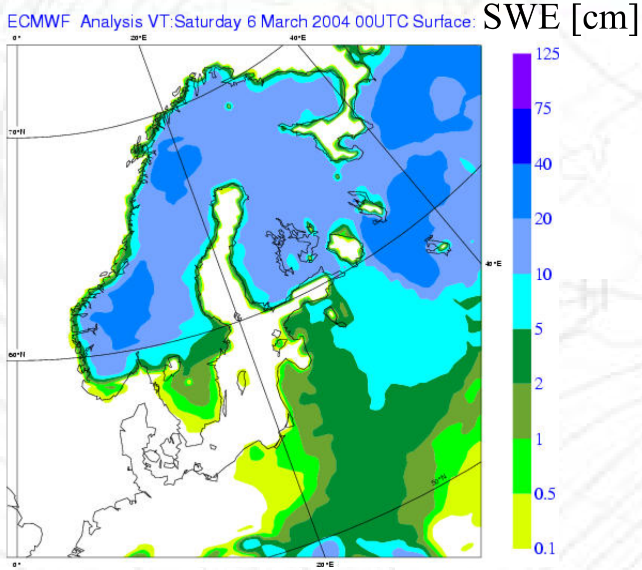
Introducing the IMS Product



6-h Cycling in 12-h 4DVar

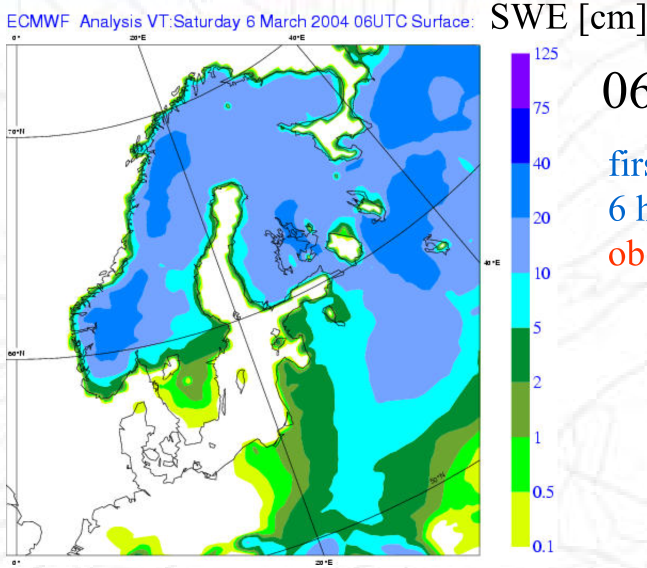
00 UTC

first guess:
12 hour fc



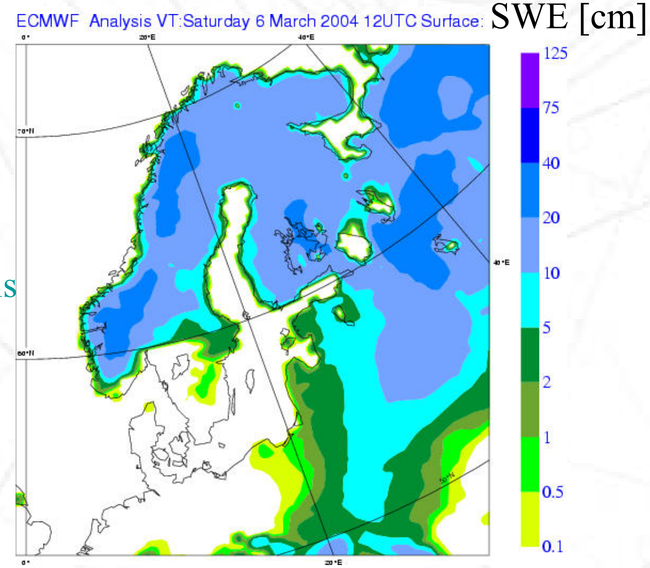
06 UTC

first guess:
6 hour fc
observations



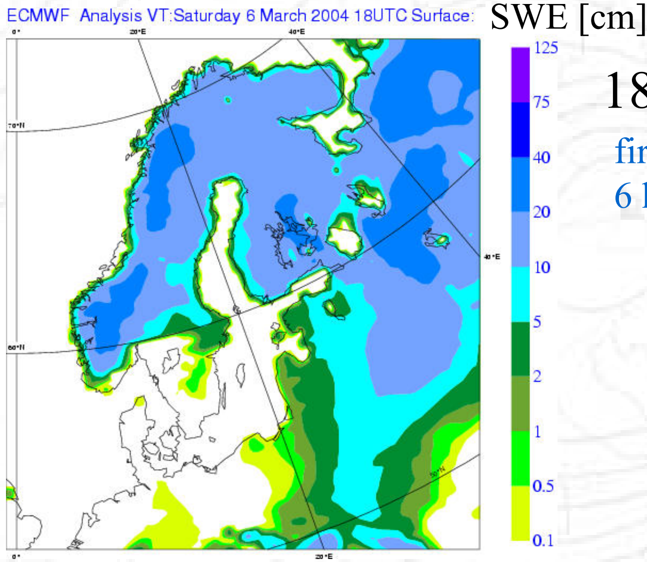
12 UTC

first guess:
12 hour fc &
update with
previous analysis
increments &
satellite data

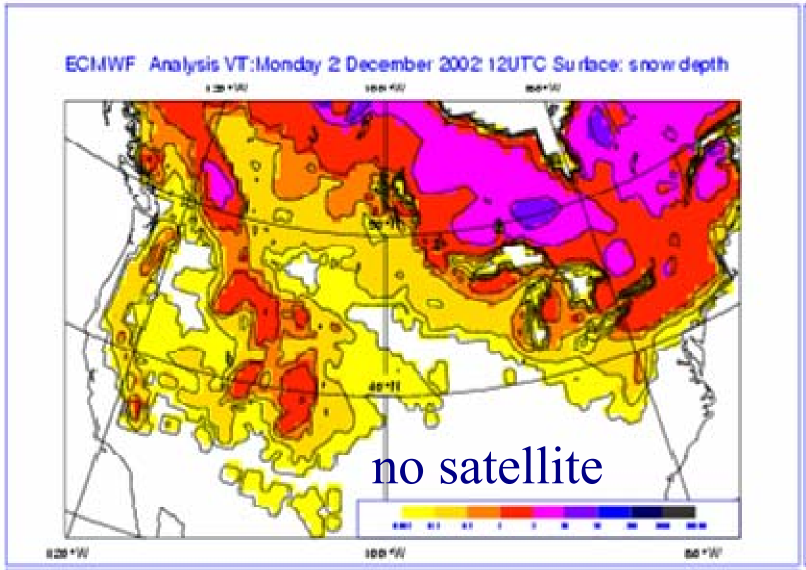


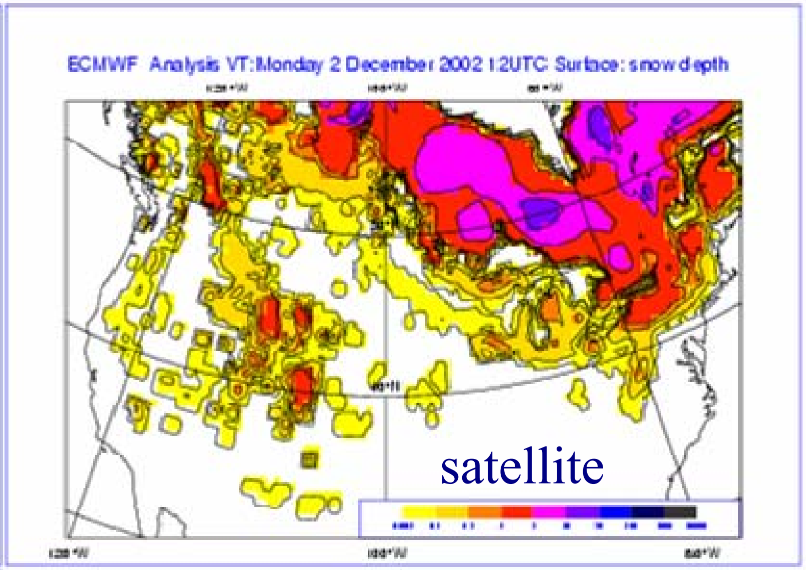
18 UTC

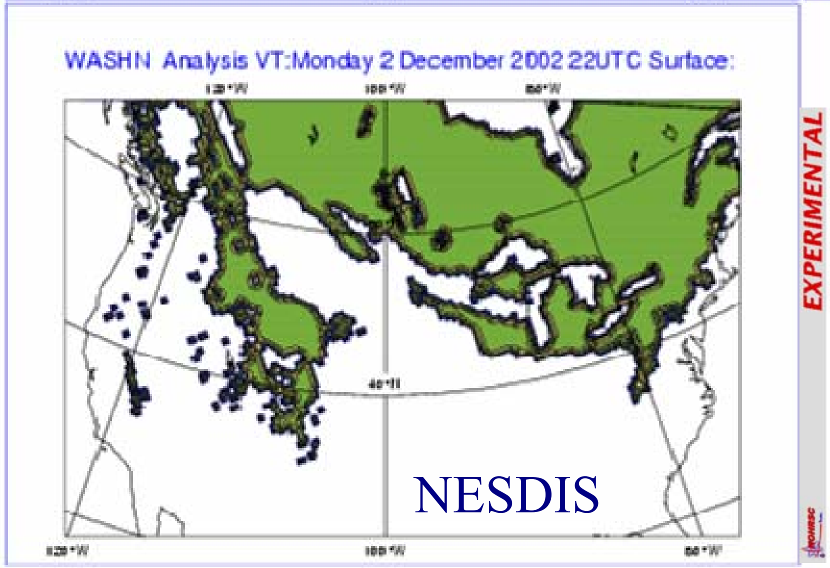
first guess:
6 hour fc



Analyses for 02/12/2002







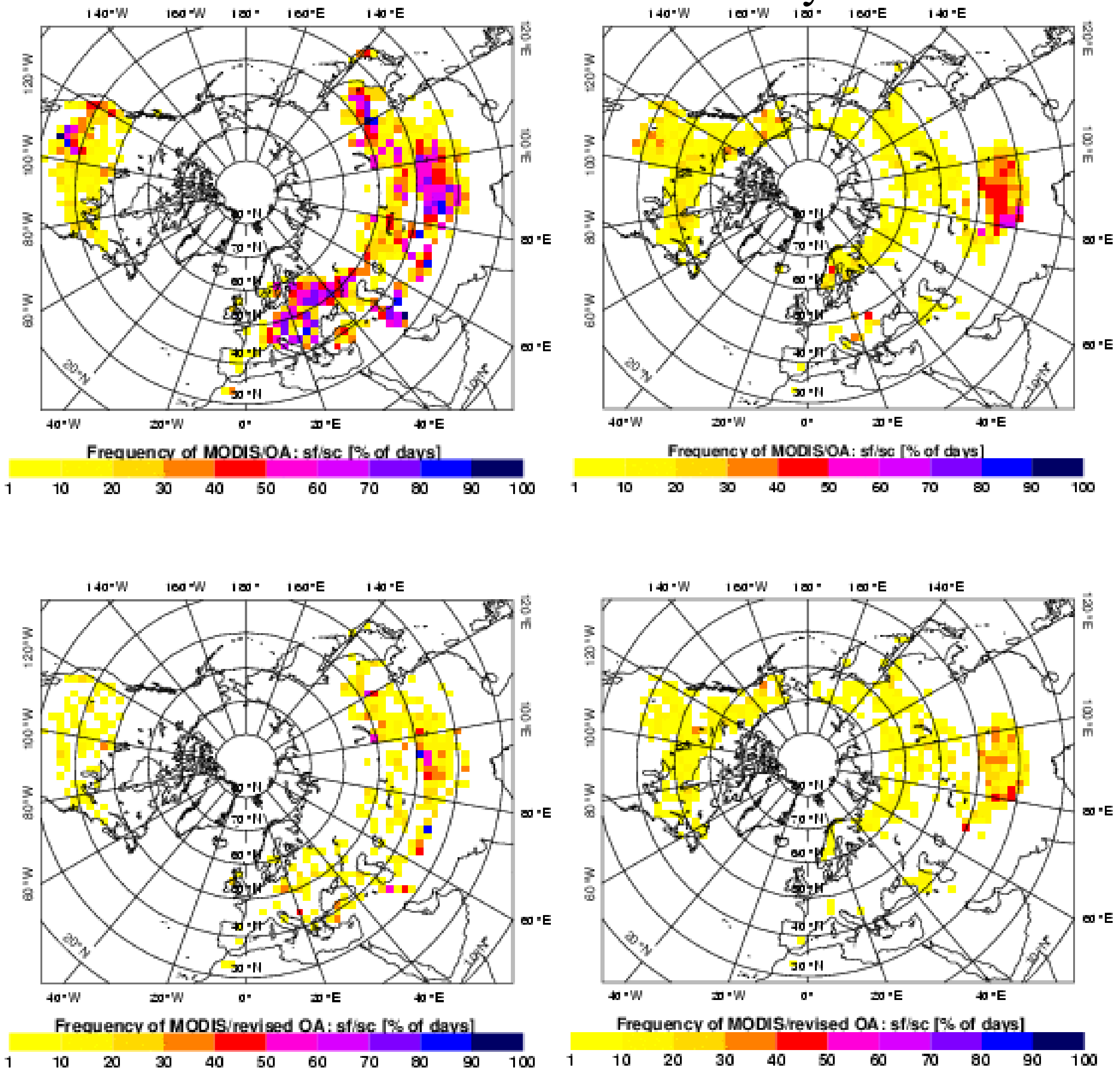
NWS National Operational
Hydrologic Remote Sensing Center

Validation against MODIS Data

March 2002 | May 2002

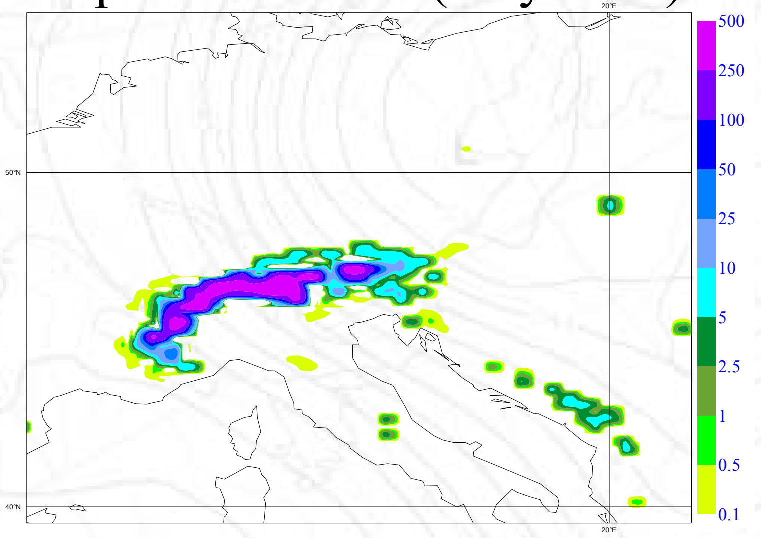
no satellite

satellite

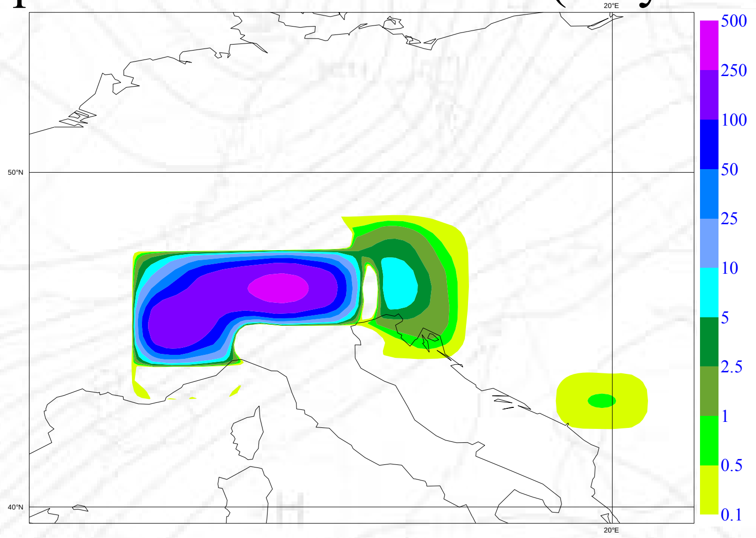


Problem II (Model Resolution)

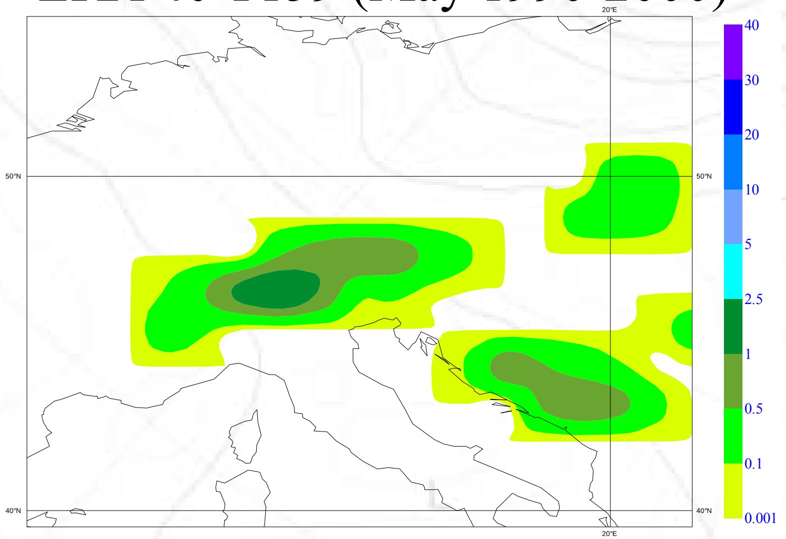
Operations T799 (May 2006)



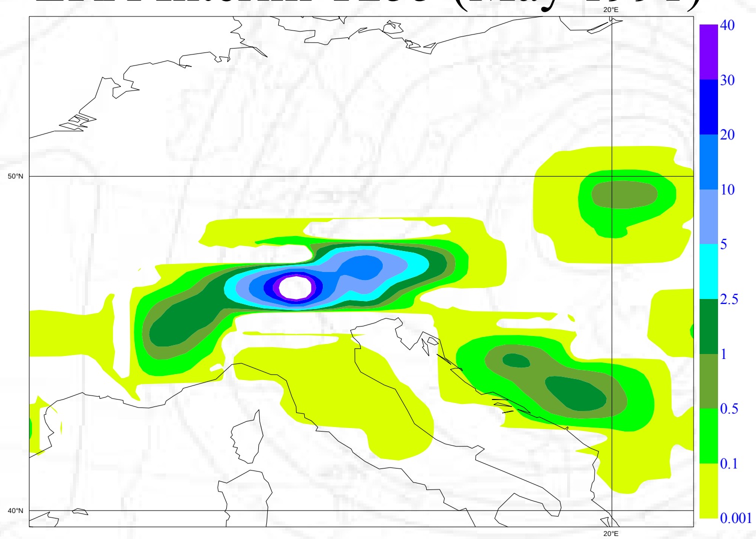
Operations scaled to T159 (May 2006)



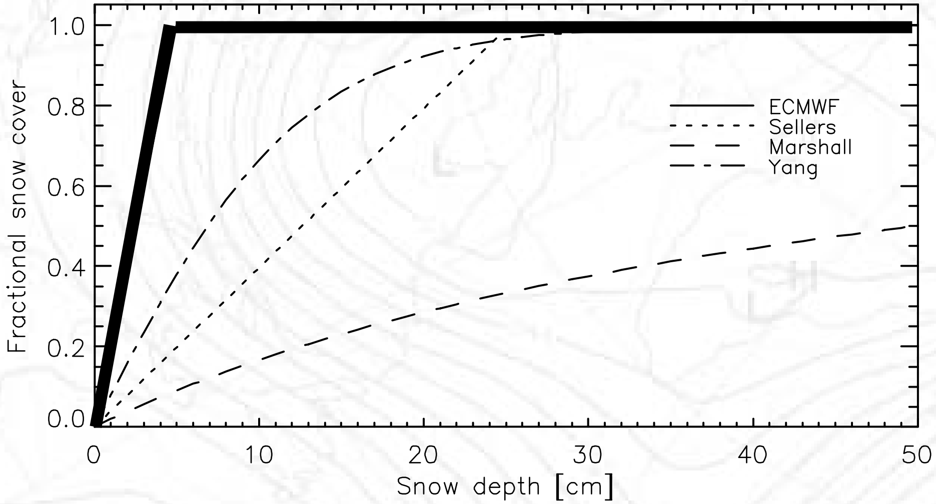
ERA 40 T159 (May 1990-2000)



ERA Interim T255 (May 1991)

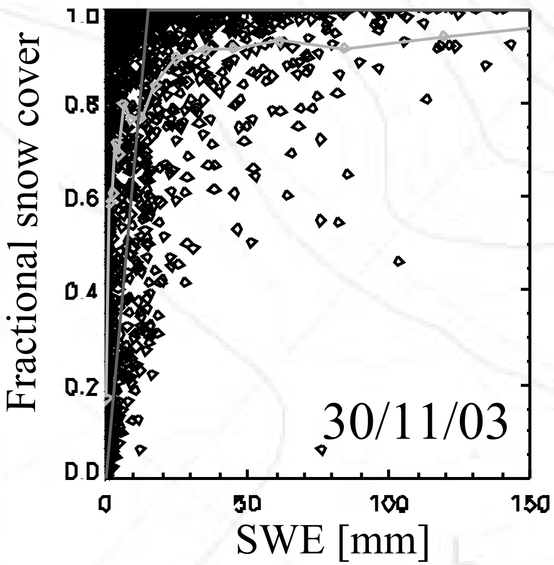


Fractional Snow Coverage

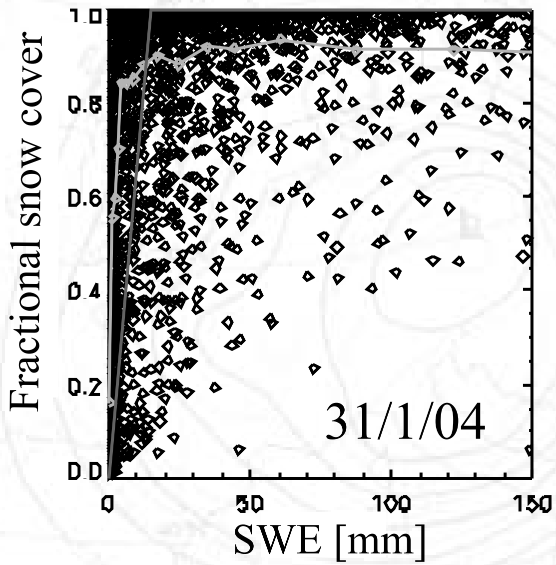


Sellers et al. 1996: SiB2
Marshall et al. 1994: CCM2 (NCAR)
Yang et al. 1997

z_0 : 2 cm; ρ = 300 kg m^{-3}



SNODAS
at T511

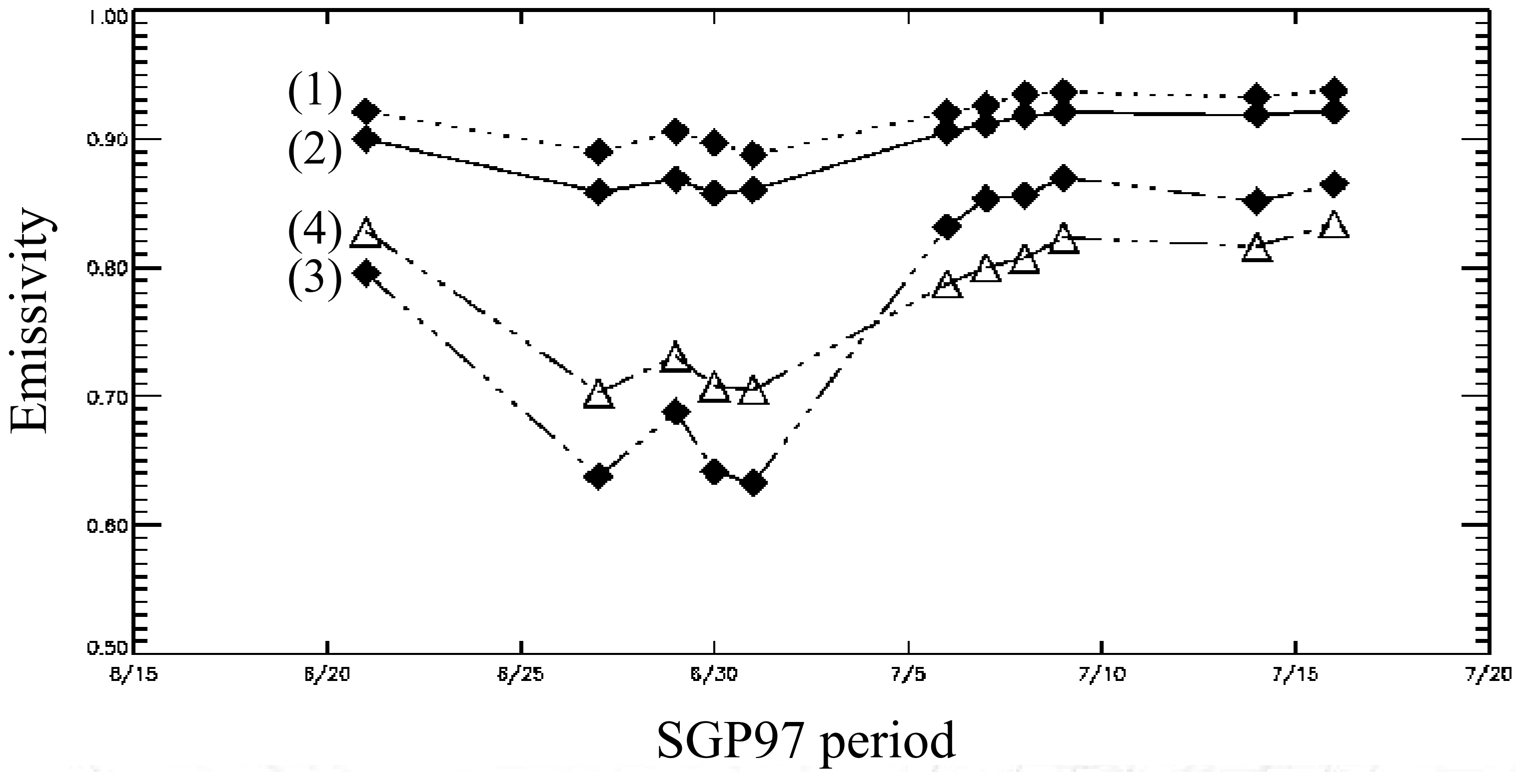


Summary on Snow

- Satellite observations (snow coverage) improve the SWE analysis.
- The ECMWF system is relatively insensitive to SWE and the impact on the forecast skill is neutral.
- The description of fractional snow coverage and sub-grid snow variability are key components for the energy exchange between the surface and the atmosphere, which are poorly represented in the model.
- SWE and fractional snow coverage should be analysed separately including microwave observations and visible / infra red data, respectively.
- Missing components:
  - multi-layer snow model (including grain size distributions)
  - snow microwave emission model
  - sub-grid snow distribution model
  - (advanced data assimilation system, e.g. KF from the soil moisture analysis)

Synergies with the Atmospheric Analysis

Emissivities for 19 GHz H-Pol at the Central Facility Site in OK.



(1) measured SSM/I brightness temperature / measured surface temperature
(2) with atmospheric corrections
(3) with vegetative corrections
(4) surface emission model with measured soil moisture

Summary (I)

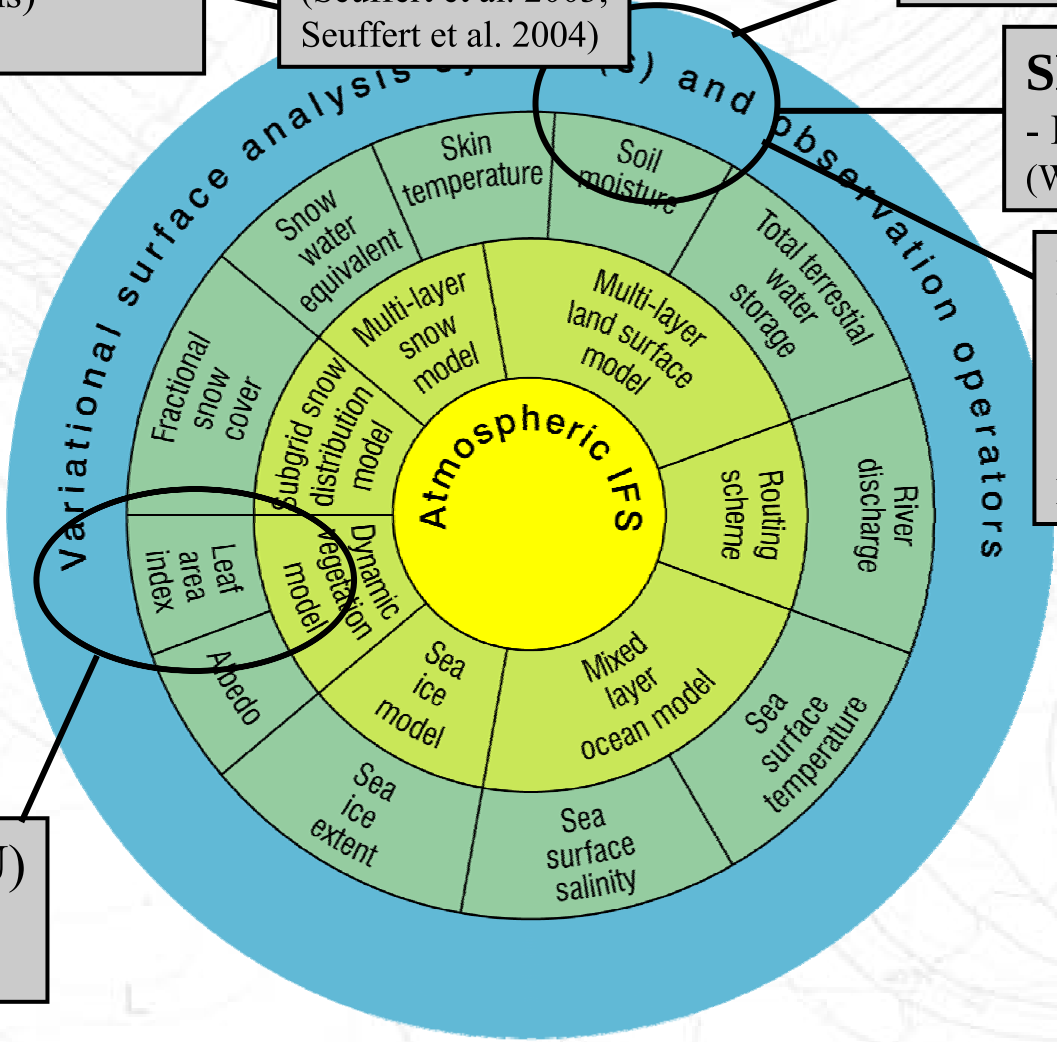
H-SAF (EUMETSAT)
-ERS scat (demo, re-analyses)
-ASCAT (operations)
(Scipal et al. 2007)

ELDAS (EU)
-MW TB
(Seuffert et al. 2003,
Seuffert et al. 2004)

SMOS DA I (ESA)
- SMOS TB

SMASS (DFG)
- MW TB
(Wilker et al. 2007)

NWP-SAF
(EUMETSAT)
- SMOS TB
(Holmes et al. 2007,
Drusch et al. 2007)



Geoland I (EU)
- MODIS LAI
(Jarlan et al. 2007)

Summary (II)

- Revising the surface analysis and including satellite observations is a mandatory step to improve weather forecasts and to meet our complimentary goals.

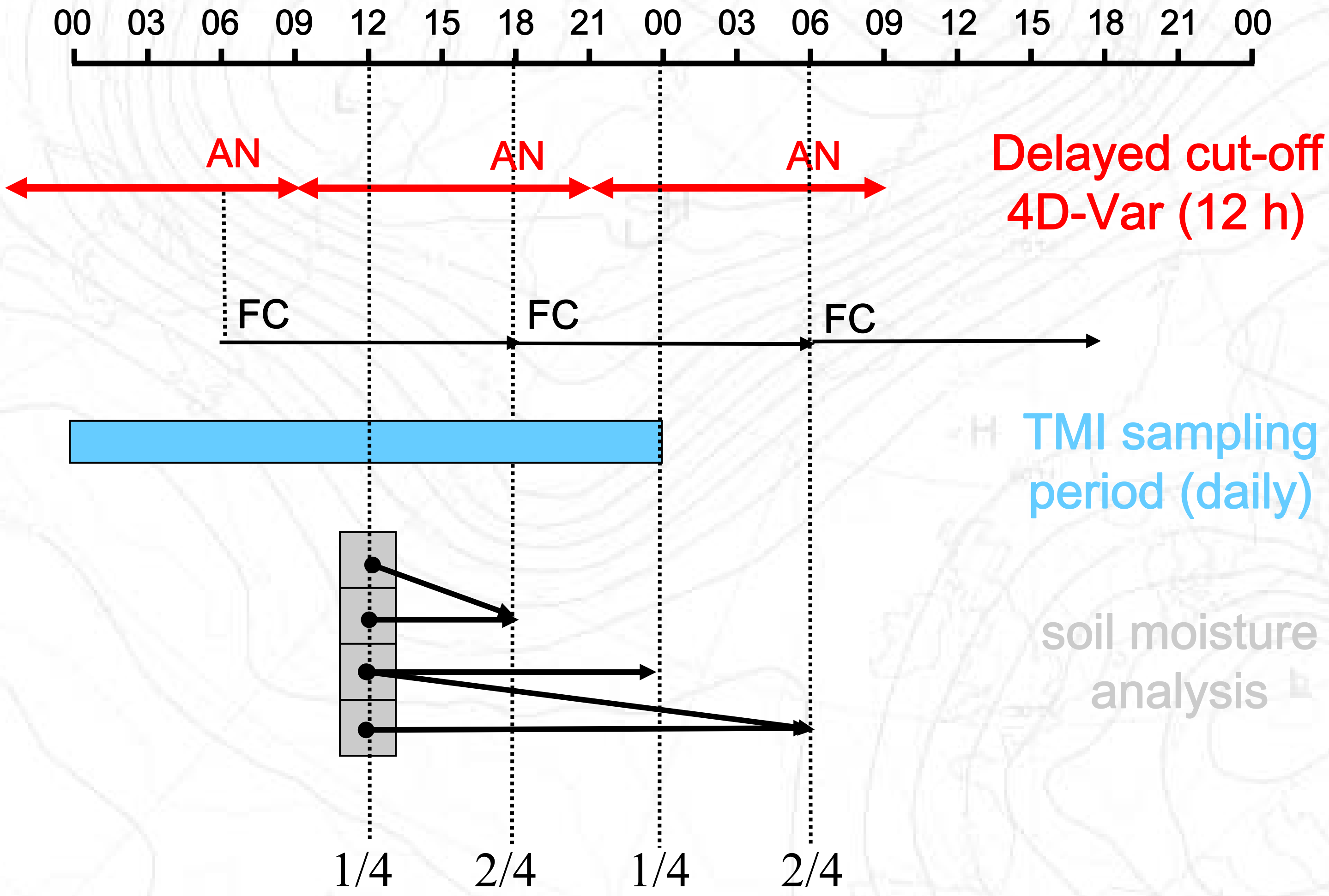
- Conceptually, we move from weakly constrained 'sink variables' (e.g. surface temperature, soil moisture) and / or simplified data sets and parameterizations (e.g. snow density, fractional snow cover) to physical variables.

- Introducing and monitoring new satellite observations is the first step. However, subsequently the model and data assimilation system will need modifications to obtain a positive impact on the forecast.

- ECMWF will focus on soil moisture and vegetation, snow could be addressed at a later stage. The first satellite data set used could be ASCAT derived soil moisture. Revising the system is a multi-year project.

- One 'milestone' for the NWP community would be a land surface emission model for RTTOV. Collaboration with the SMOS VRT is the most obvious way forward.

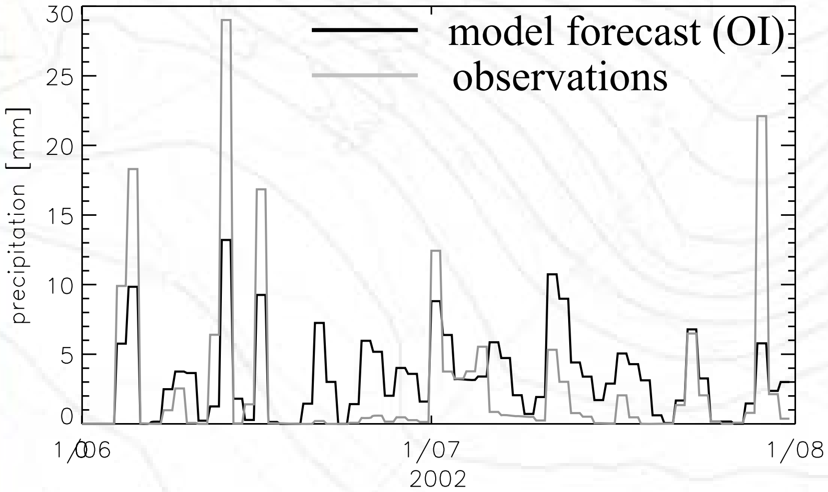
Nudging set up



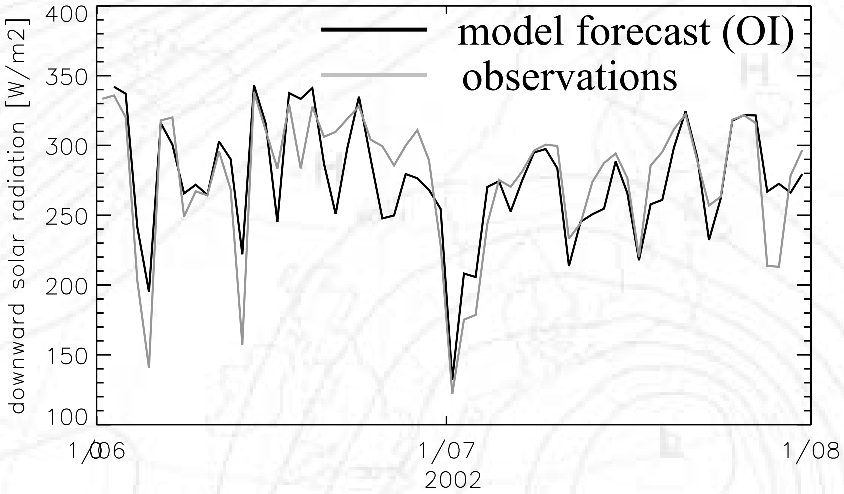
Validation of Forcing Data

area averages for Oklahoma
(72 stations, equally distributed)

daily precipitation



daily downward shortwave radiation



total amount of rainfall:

June	87.3 mm model	on	19 days
	87.8 mm observations	on	9 days
July	110. mm model	on	26 days
	79. mm observations	on	20 days

Correlation : 0.85
Bias : - 0.7 Wm^{-2}