Land-surface data assimilation systems

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Agradecimentos: Alan Betts, Emanuel Dutra (CGUL), Matthias Drusch (ECMWF), Laura Ferranti (ECMWF)

ECMWF Workshop on atmospheric reanalysis, 19 - 22 June 2006

Layout

- Introduction: Imperfect models and inaccurate data
- Land surface in ERA-40: Strengths and weaknesses
- Soil moisture
- Snow
- Conclusions

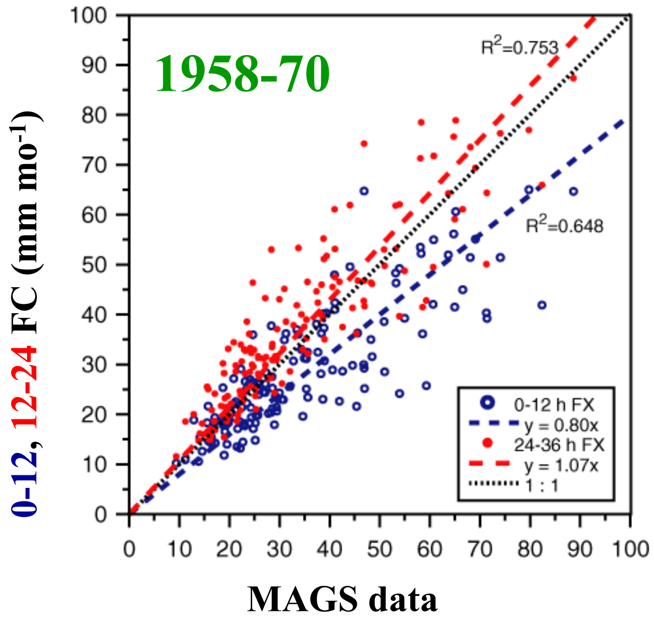
Layout

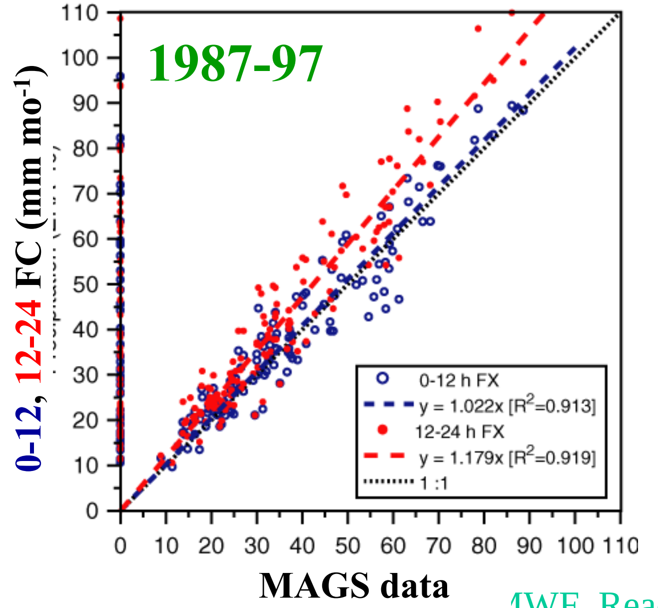
- **Introduction: Imperfect models and inaccurate data**
  - **Model drift**
  - **State variables**
  - **Observations**
  - **Reanalyses practice**
- **Land surface in ERA-40: Strengths and weaknesses**
- **Soil moisture**
- **Snow**
- **Conclusions**

The need for data assimilation

- Long time scales in land state variables (deeper soil water and temperature, snow): Forecast drifts are possible. A way of controlling model drift (initialisation of soil variables) is needed
- Drifts due to errors in forcing (precipitation, radiation, BL humidity) or in the land-surface model/model fluxes

Mackenzie river basin precipitation: era40 vs. observations





What to initialise and how?

- There are no routine direct observations of soil state variables
- For an effective data assimilation, the state variables with longer timescales need to be initialised:

STATE VARIABLES	OBSERVABLES
– Root zone soil moisture	No direct observations globally (see below)
– Snow mass	Snow depth
	Snow cover from remote sensing
	Snow mass from AMSR-E (saturates at higher values; does not work in forest areas)
– Above ground biomass	(Indirectly) from remote sensing: vegetation indices, LAI/fAPAR

- Proxy observations for root zone soil water
  - Screen level T and RH: Linked to Bowen ratio
  - Rainfall rates
  - Window channel brightness temperature: Early morning evolution is linked to evaporation
  - Microwave (L-band, 1.4 GHz) radiances: Top soil moisture
  - C-band passive and active systems: Top soil moisture
- State variables are non-linearly related (via the equations of the land-surface scheme) to observations: Complex observation operators

Current practice at global centres

	Soil water	Snow mass	Biomass
JRA-25	???	Use of snow depth obs Snow cover	Monthly climate LAI
ERA-40	OI for root zone, based on 2T/RH	Use of snow depth obs, Cressman	Constant LAI
NCEP/NCAR R1	Relaxation to climate	Climate	Monthly climate LAI
NCEP/NCAR R2	(Observed precipitation "ingestion")	???	Monthly climate LAI

Land surface analysis lies, in terms of methods and data usage, far behind its atmospheric counterpart

G(N/E)LDAS

- **Global/North-American/European Land Data Assimilation Systems**
  - Running offline a land surface scheme, forced by near-surface meteorology, downwelling radiative fluxes and precipitation
  - Best possible forcing, very often observation-based estimates hybridized with reanalysis
  - Inexpensive, often run with several models and several versions of the forcing. Ideal tool to have a land-surface model climate
- **In most cases (GLDAS, NLDAS) LDAS is a misleading name, because there is no data assimilation involved: It assumes that the forcing is correct.**
- **Global Soil Water Project (GSWP) is one version of "LDAS", using best available forcing for 1986-1995**

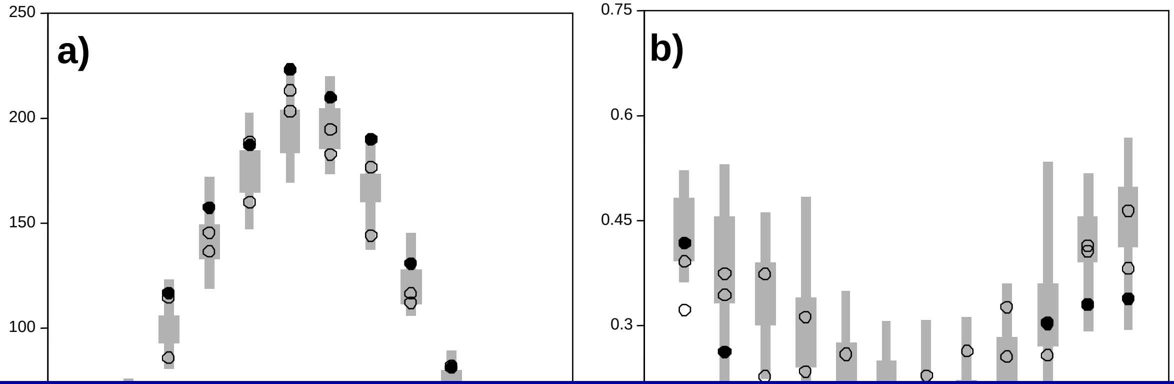
Layout

- Introduction: Imperfect models and inaccurate data
- **Land surface in ERA-40: Strengths and weaknesses**
  - Surface fluxes
  - Soil water
  - Don’t throw the baby with the bath water
- Soil moisture
- Snow
- Conclusions

Surface energy balance (41º-50ºN 2ºW-16ºE)

•ERA-40: Boxes and whiskers; 2001 e 2002 ¤; 2003 •

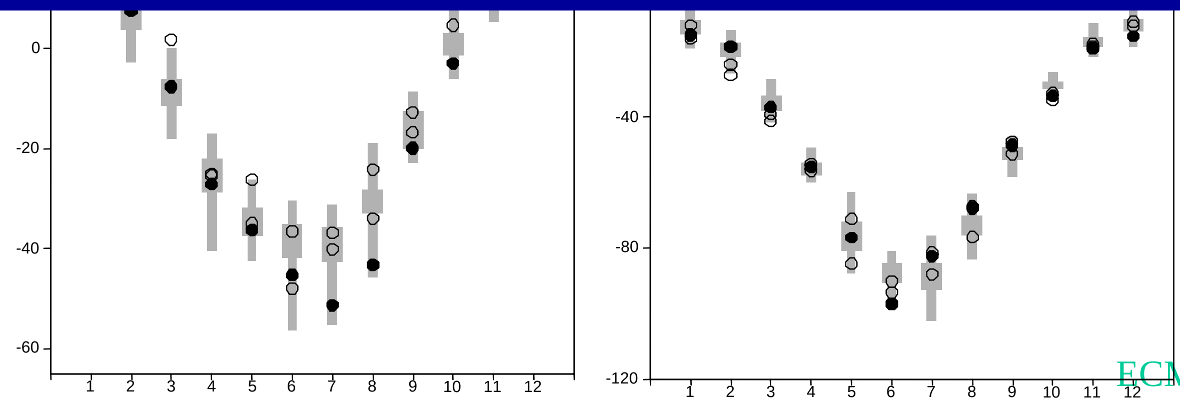
SW_{net} (Wm^{-2})



cloudiness

- **Positive surface solar radiation anomalies since March, associated to anomalously low cloud**
- **The surface starts responding in June, with an increase in sensible heat flux followed by a decrease in evaporation in July**

H (Wm^{-2})



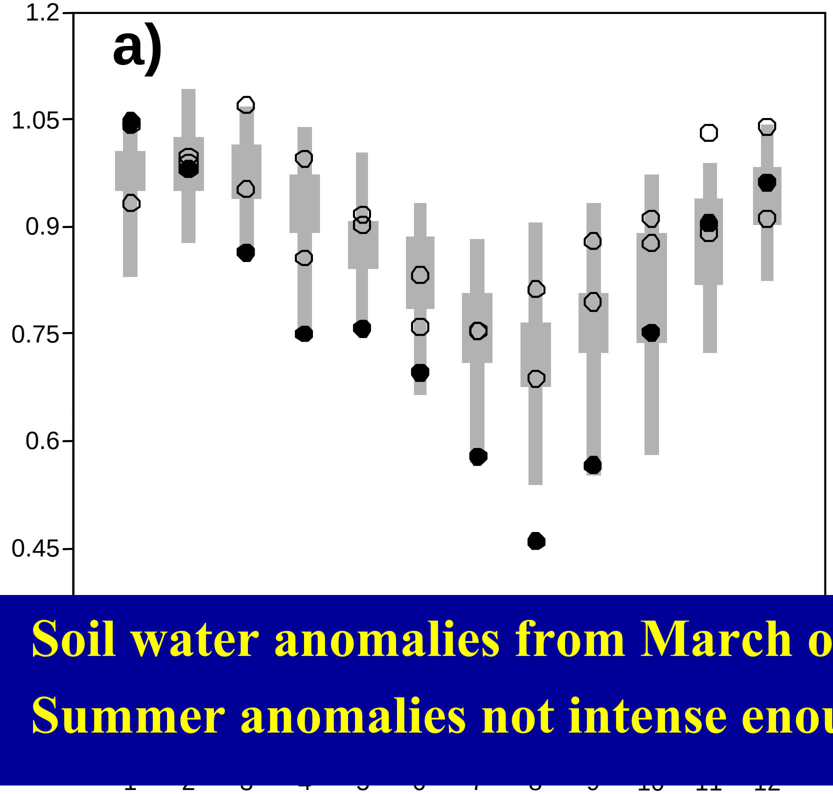
LE (Wm^{-2})

Soil water index (SWI)

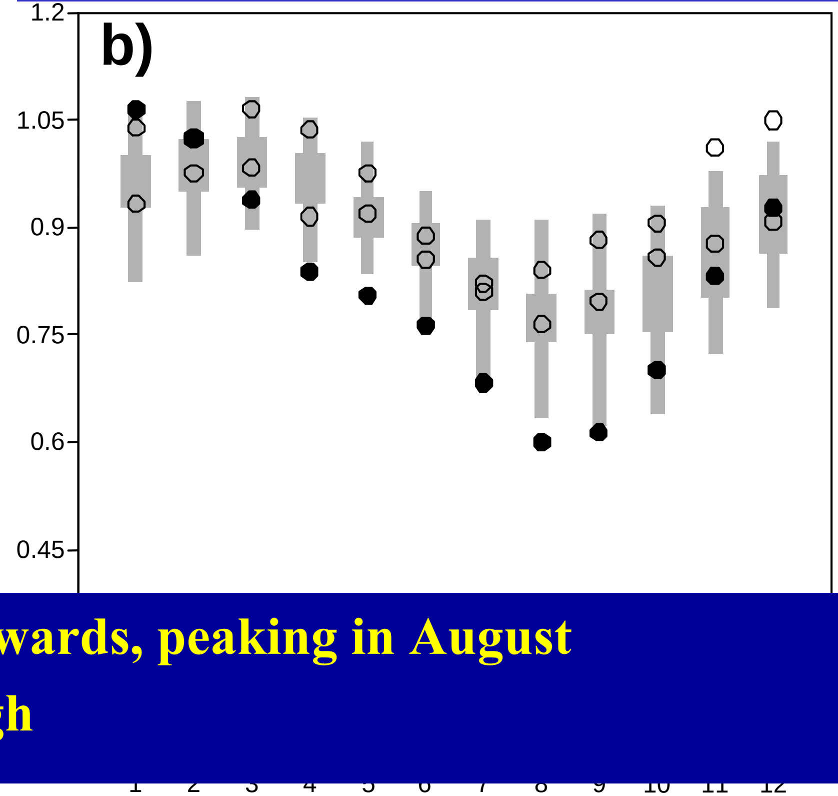
•SWI=1: No restrictions to evapotranspiration due to soil water

•SWI=0: Evapotranspirations shuts

Root zone

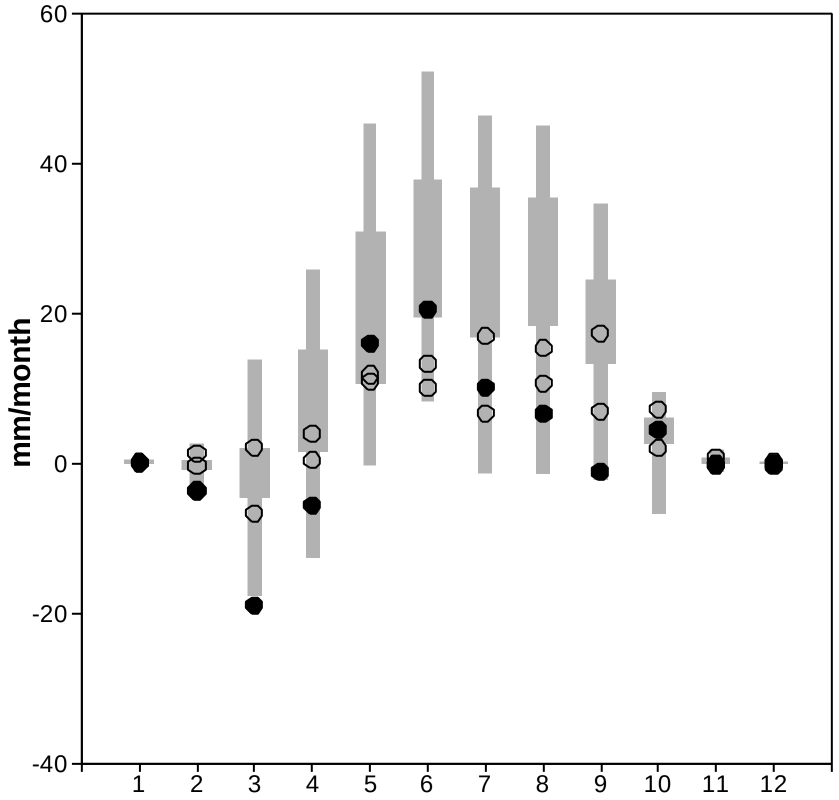


Total water reservoir



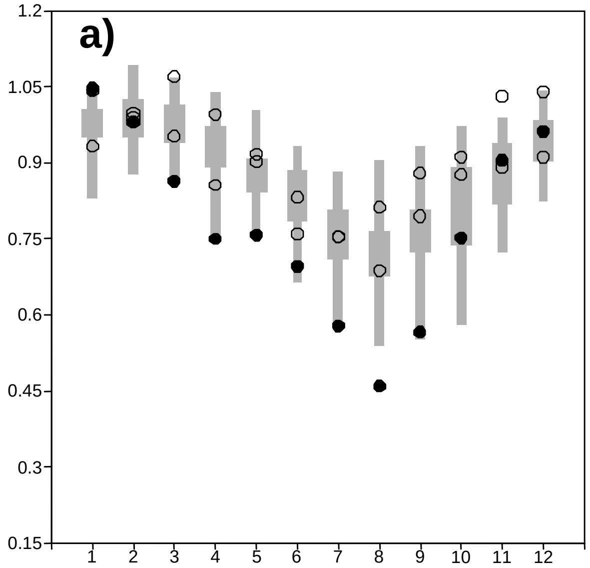
- **Soil water anomalies from March onwards, peaking in August**
- **Summer anomalies not intense enough**

Soil water analysis increments



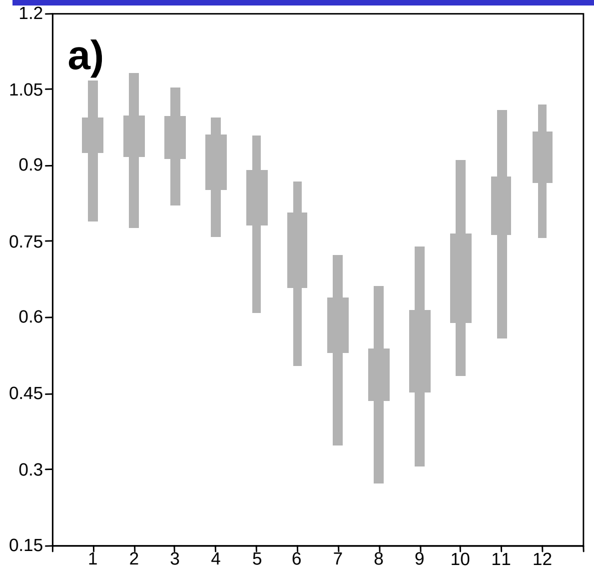
Soil water: 2003 and climate

2001-2003 and ERA-40



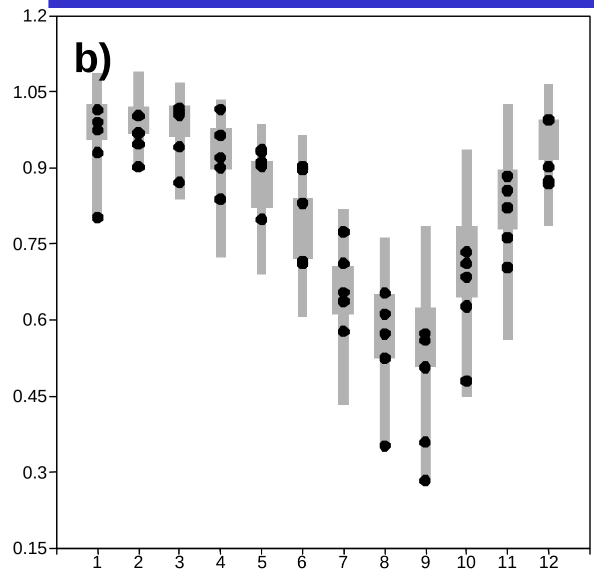
Model climate:

40 year AMIP run



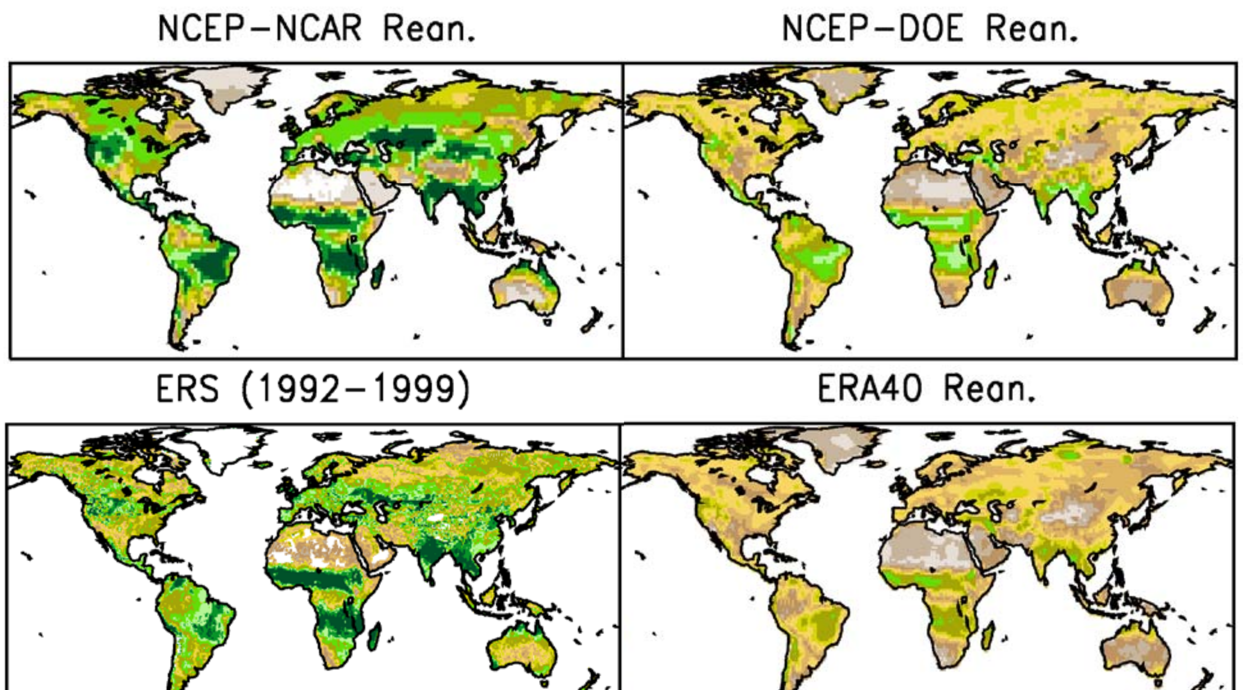
Model climate: 6 months ocean coupled

Hindcasts+2003

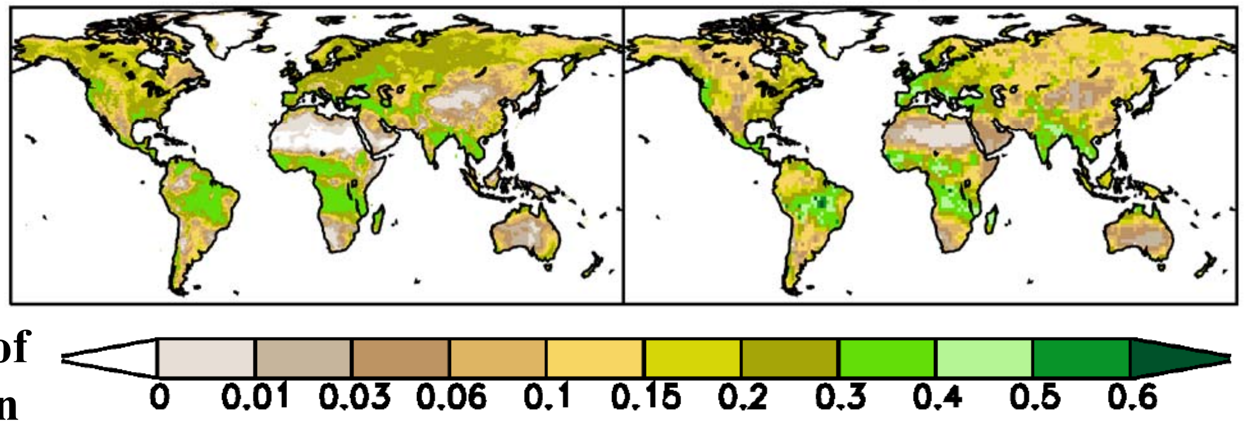


Soil water assimilation reduces seasonal soil water amplitude

Mean annual range of soil water (Dirmeyer et al 1994, JHM)

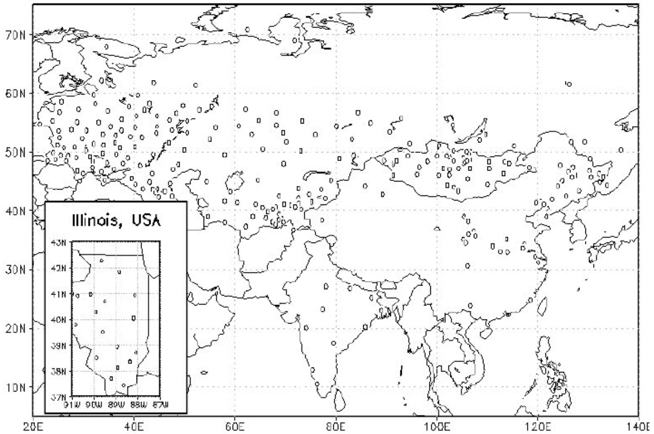


- **ERA-40 has the smallest mean seasonal amplitude**



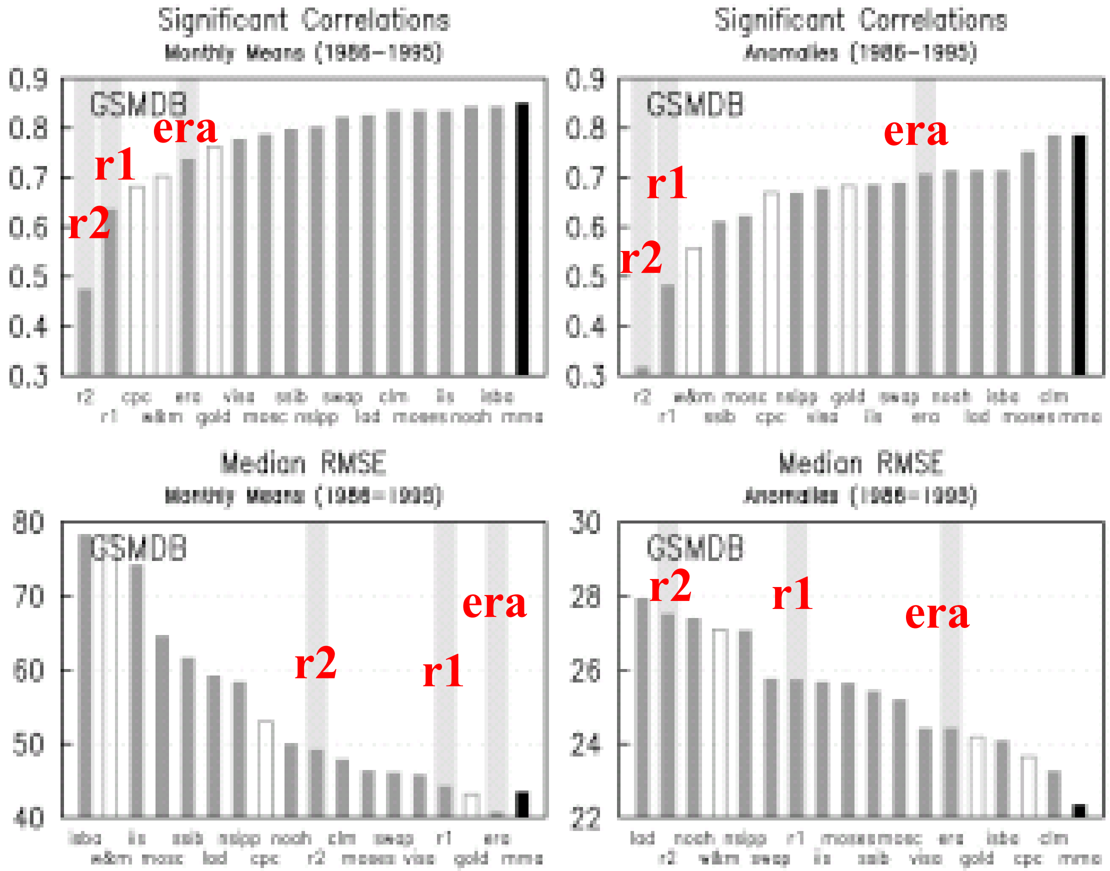
Fraction of saturation

Reanalyses soil water (shaded) and GSWP: ranked validation against obs



Guo et al., 2006: QJRMS, accepted

Monthly means **Anomalies**



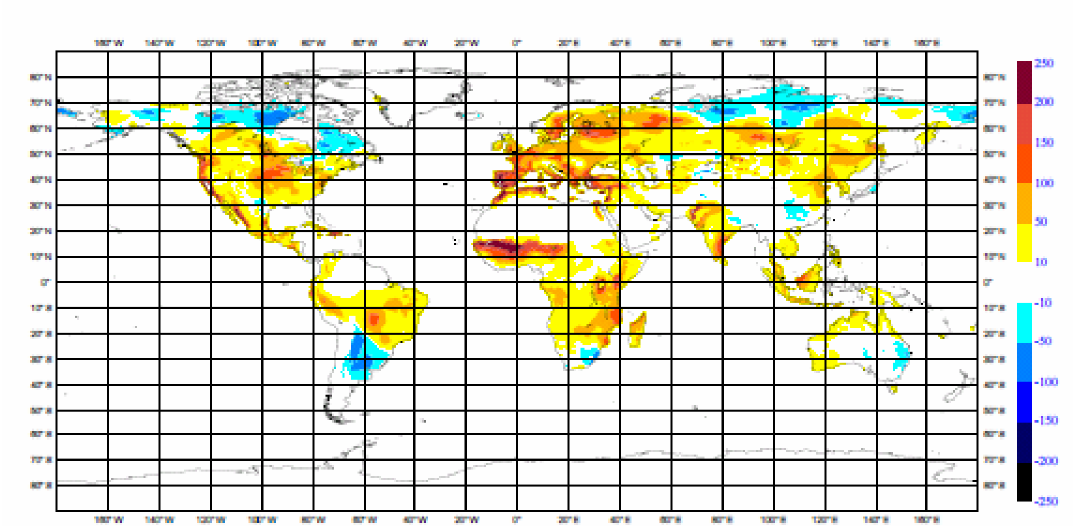
- **ERA-40 is the best reanalysis product, and better than many GSWP models**

Layout

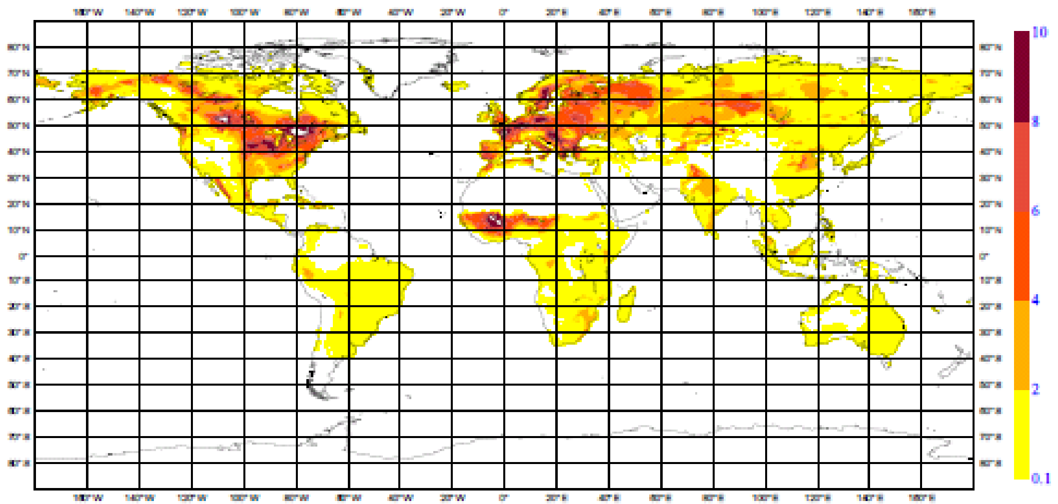
- Introduction: Imperfect models and inaccurate data
- Land surface in ERA-40; Strengths and weaknesses
- **Soil moisture**
  - What we do now: Assimilation based on two-metre temperature/humidity
  - What we should do: Sample the entire physical space, to avoid overfitting or aliasing
  - What we can do: Use LDAS as a weak constraint
- Snow
- Conclusions

Soil water increments: June-July 2002

Accumulated increments

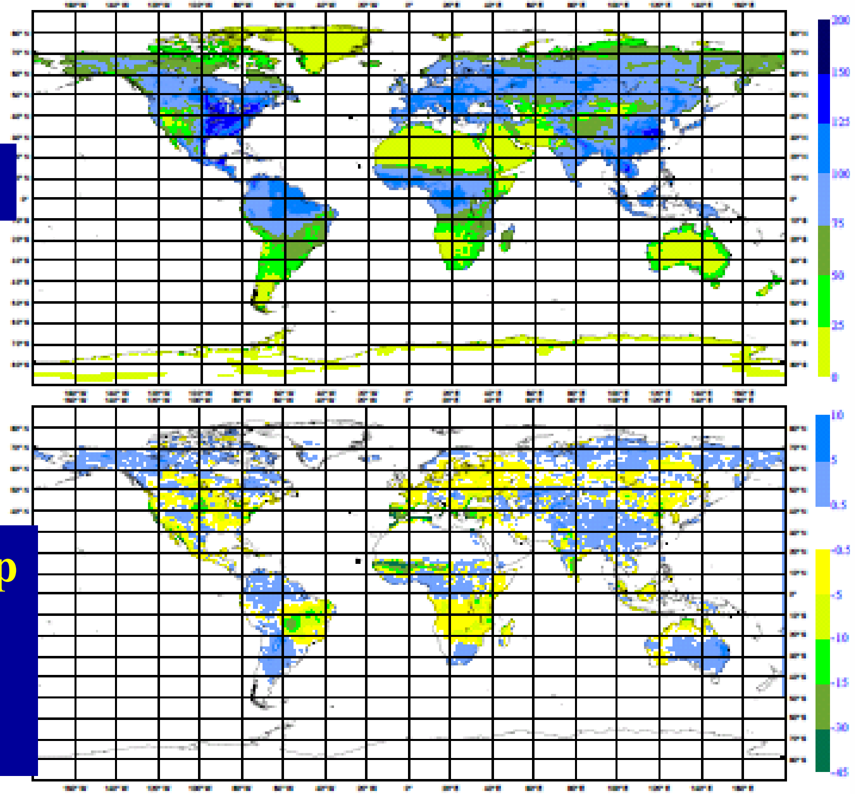


Variance of daily increments

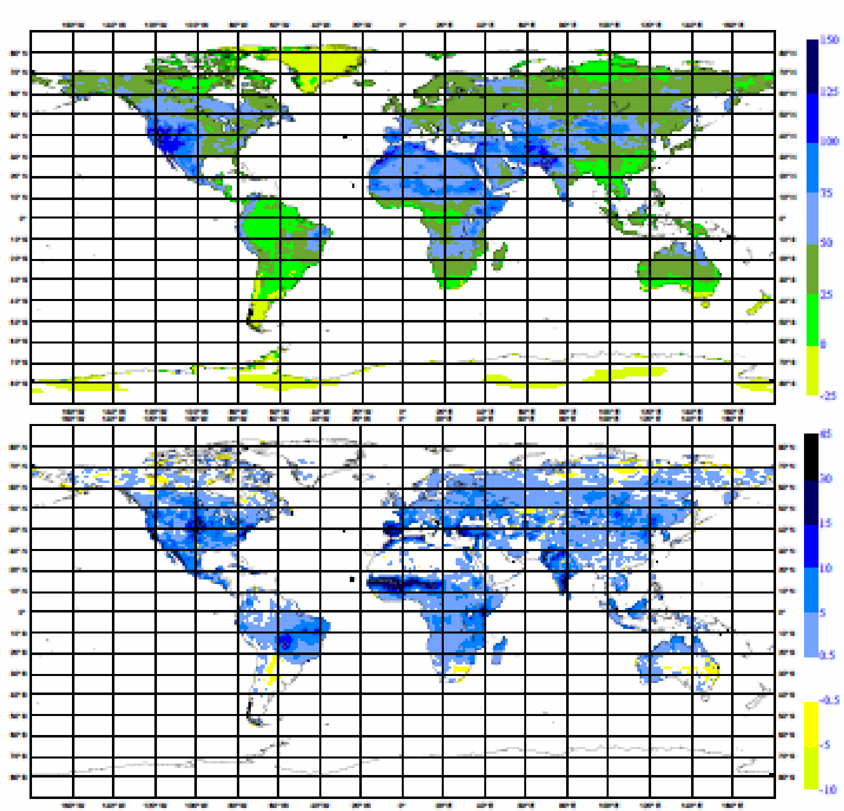


Impact of analysis increments on surface fluxes

Latent heat flux



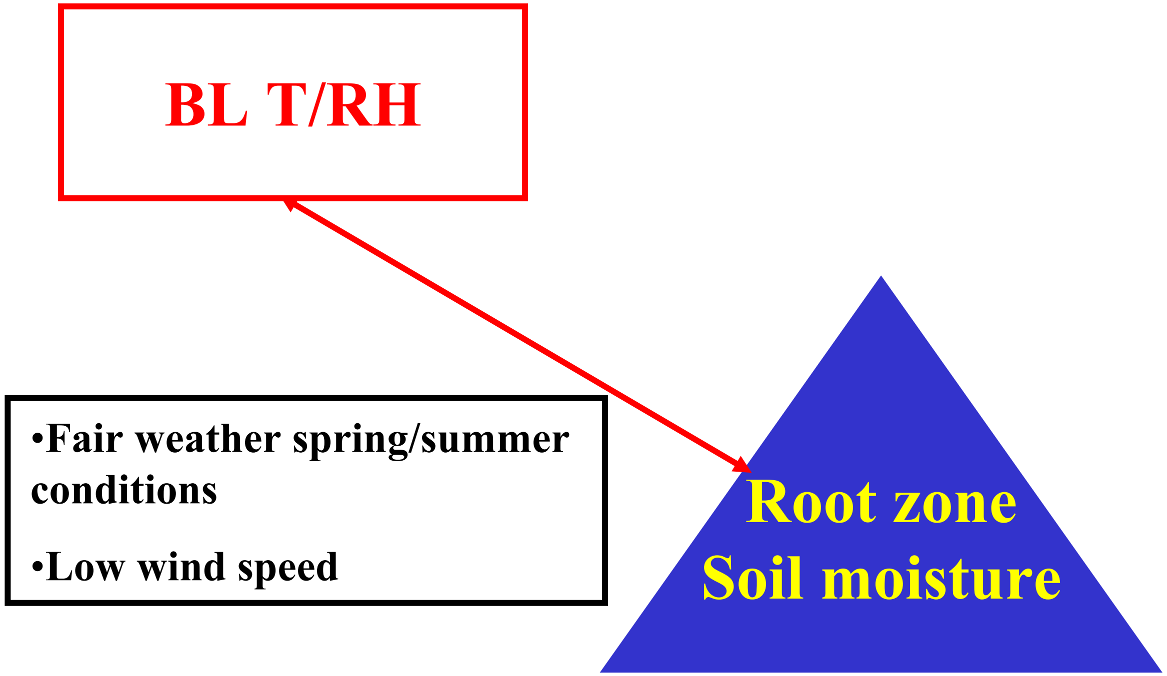
Sensible heat flux



Control

Open loop - Control

Root zone soil moisture: observables and caveats



What we do now

Synergy of observations

- **Screen level temperature and humidity are indirect linked to soil moisture through evaporative cooling.**
- **Microwave brightness temperature contains more direct information of near surface soil moisture and is less dependent on atmospheric conditions.**
  - **Penetration depth of µw Tb depends on:**
    - **Soil texture**
    - **Soil temperature profile**
    - **Vegetation fraction**
    - **Vegetation water content**
    - **Surface roughness**
    - **LSMEM (Land Surface Microwave Emissivity Model) for model equivalent of Tb**
- **Rate of change of thermal infrared brightness temperature contains information on soil moisture, but**
  - **Clear sky data only;**
  - **Model Tskin is very sensitive to aerodynamical resistance (surface roughness)**

Root zone soil moisture: observables and caveats

BL T/RH

What we should do

Vegetation state (NDVI)

- Fair weather spring/summer conditions
- Low wind speed

Root zone Soil moisture

- Clear-sky data
- Saturation of LAI=f(NDVI)

- Low water on vegetation
- C-band limited to non-forest areas

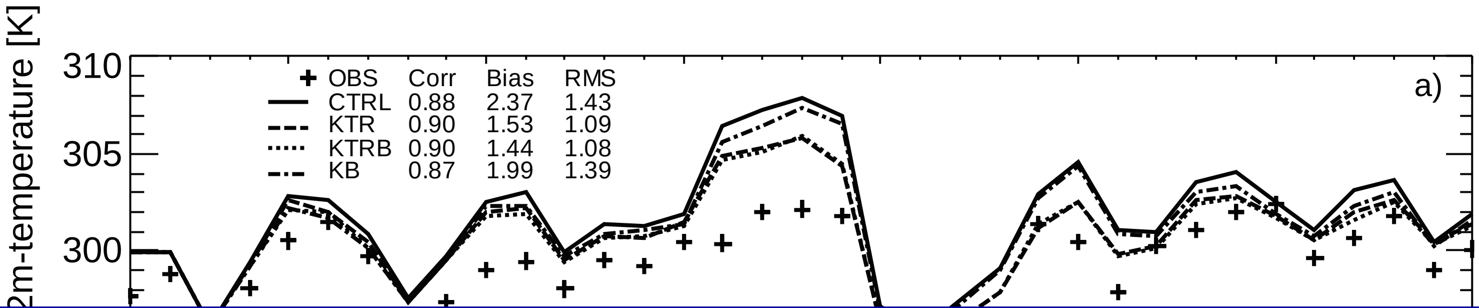
μw Tb
L- and C- band
(d=1-5 cm)

ECMWF experimental soil moisture analysis system

- Extended Kalman filter
- Assimilation of two-metre temperature and relative humidity and microwaveTb
- Updated forecast errors
- System is forced with observed estimates of precipitation and downward SW and LW surface radiation, where available

Assimilation of mw Tb: Performance of 2T/RH

2T

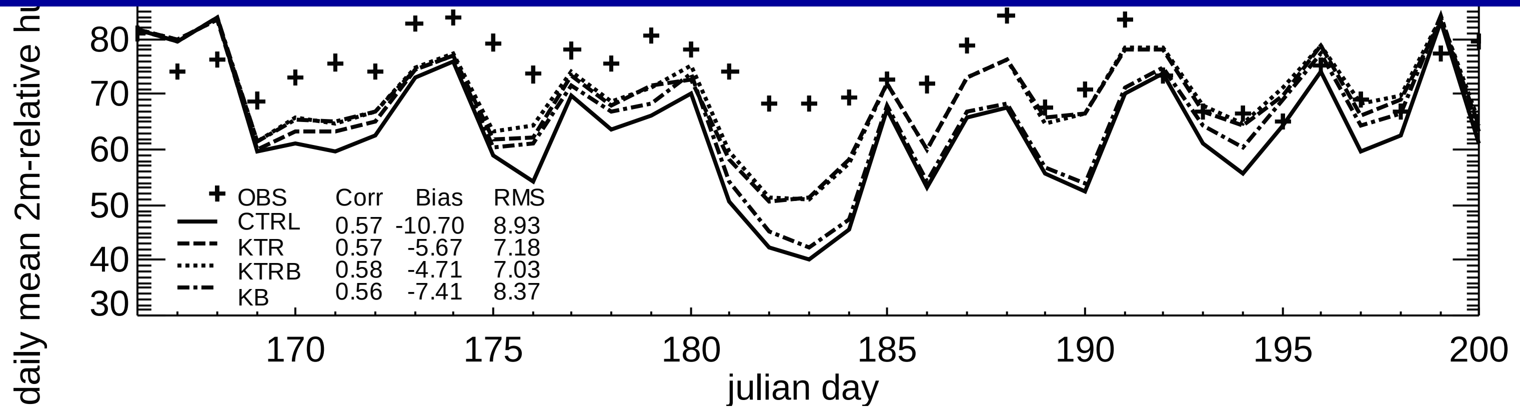


•The control simulation (indeed, all simulations) are too warm and too dry. Model day-to-day variability of humidity exceeds observations.

•Assimilation of screen-level parameters decrease the warm/dry bias by 30-40%.

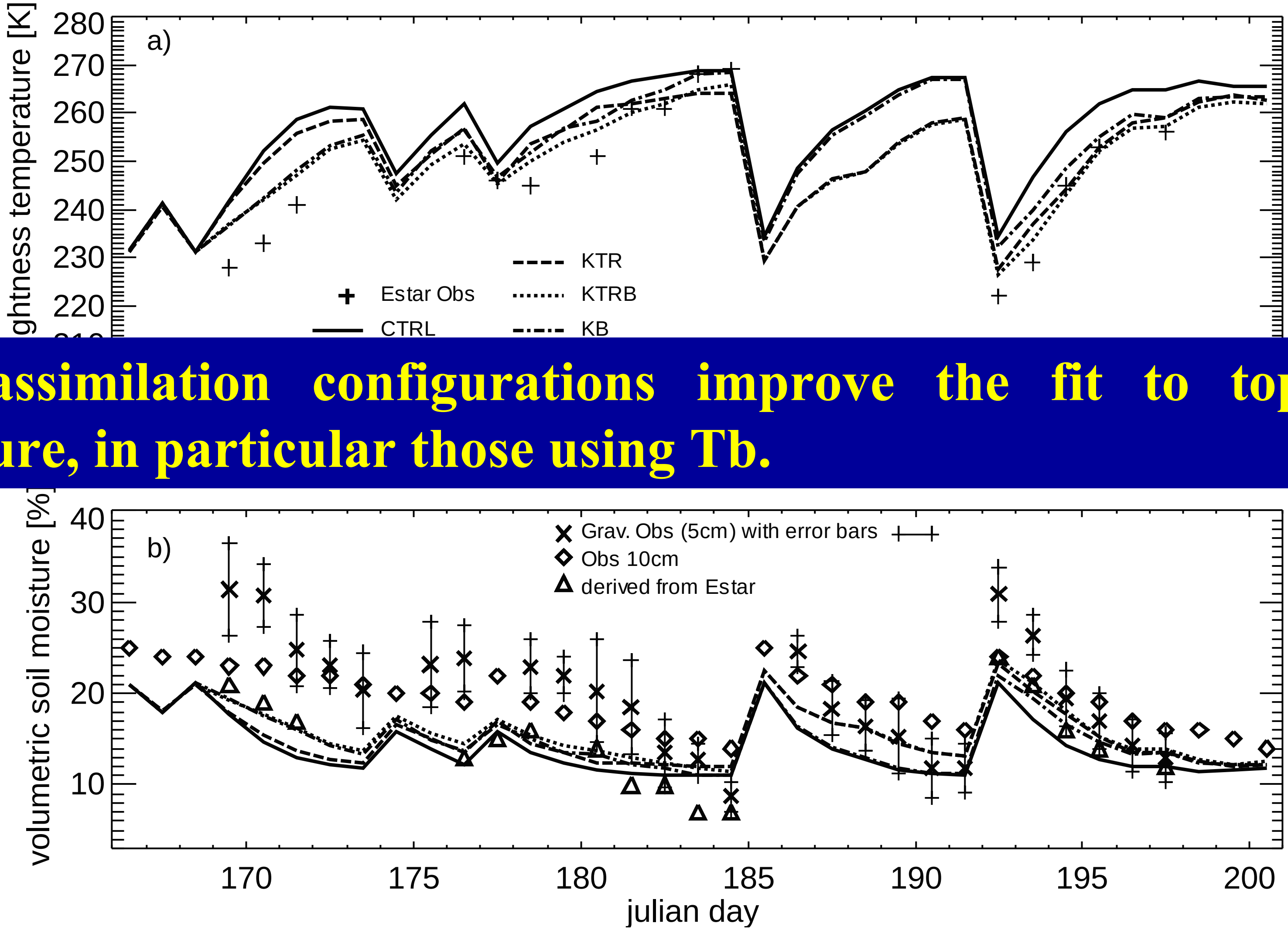
•Assimilation of mw Tb, on top of screen-level parameters, slightly deteriorates the fit to screen-level observations.

2RH



Surface soil moisture and Tb (SGP97)

Tb

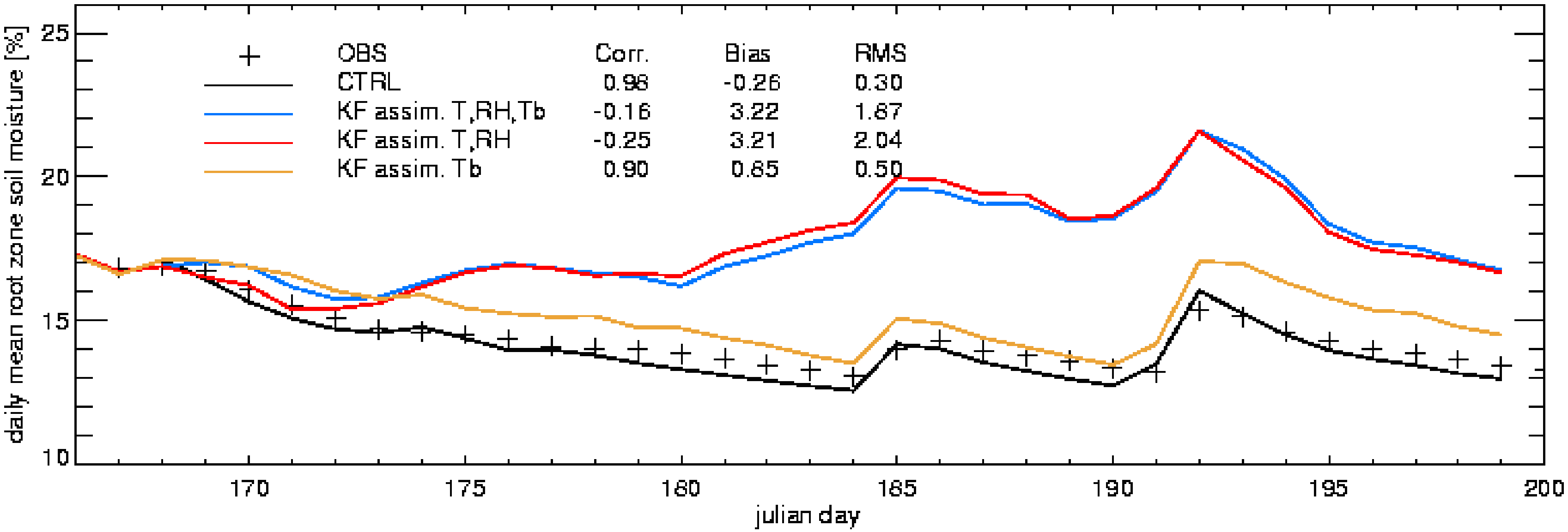


Top soil moisture

•All assimilation configurations improve the fit to top soil moisture, in particular those using Tb.

Root zone soil moisture (SGP97)

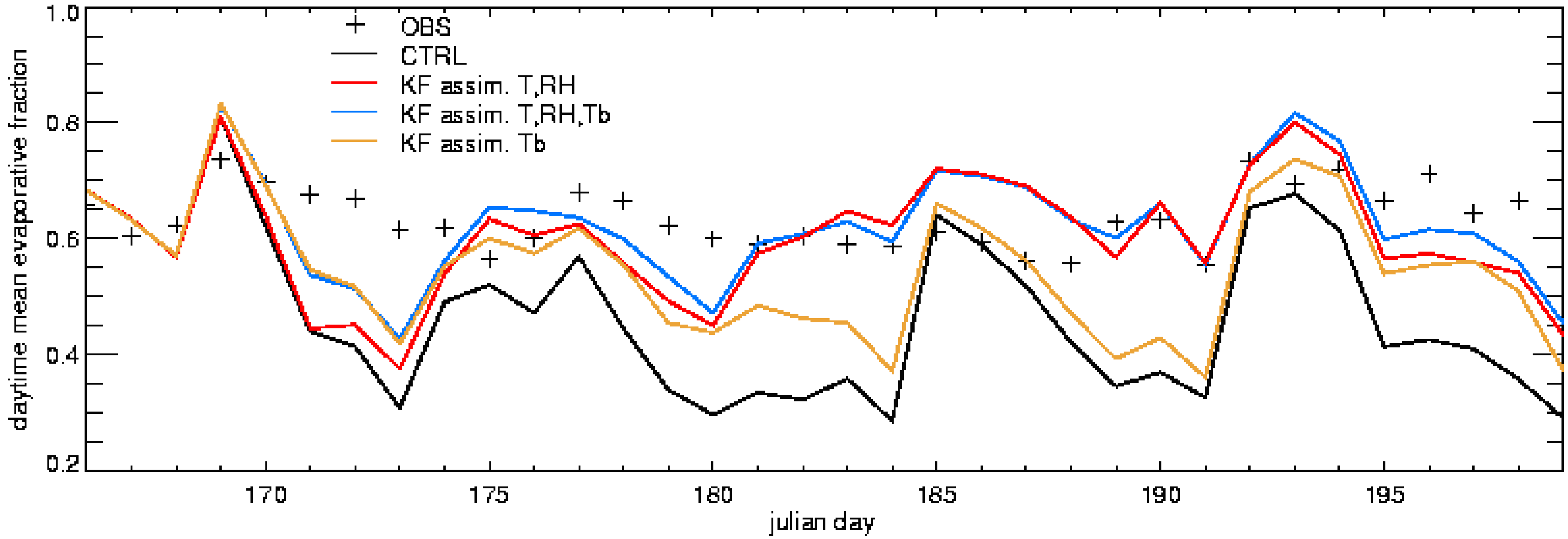
Soil moisture



- On its own, Tb gives a very good simulation for the root layer.
- The use of screen-level parameters, w/ or w/o Tb, brings the simulation away from observations

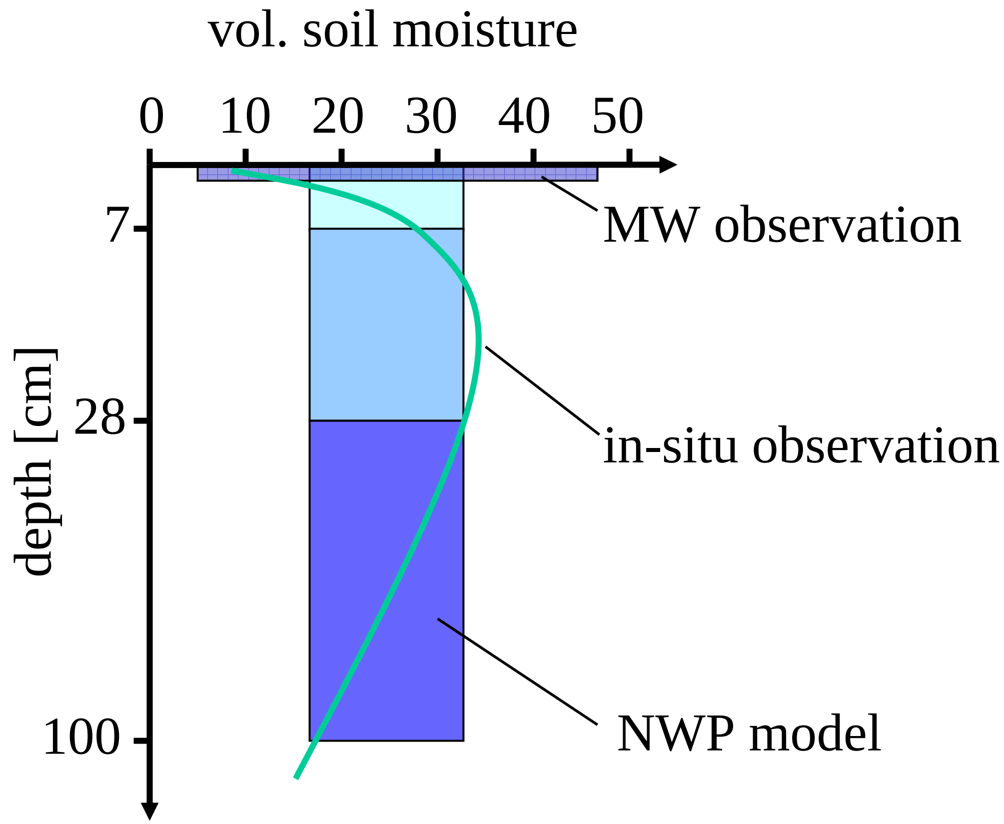
Evaporative fraction (SGP97)

Evapor. fraction

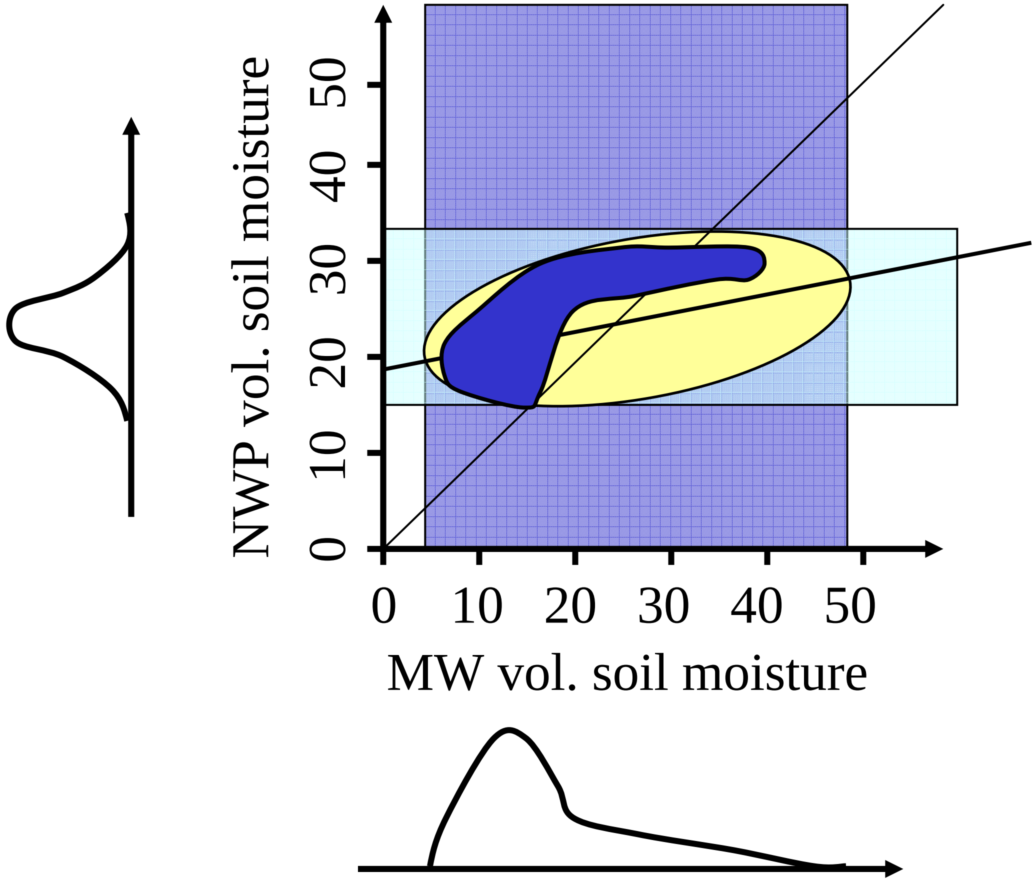


- Evaporative fraction [EF=LE/(H+LE)], the relevant quantity for the surface impact on the atmosphere, is underestimated by the control simulation (cf. dry/warm bias).
- µw Tb, on its own, is not effective enough to change EF.
- EF is clearly improved when screen-level parameters are used.
- The synergy of all 3 observations is again visible.

Problem 1: Matching vertical resolution of in-situ, remote sensing, and model soil moisture

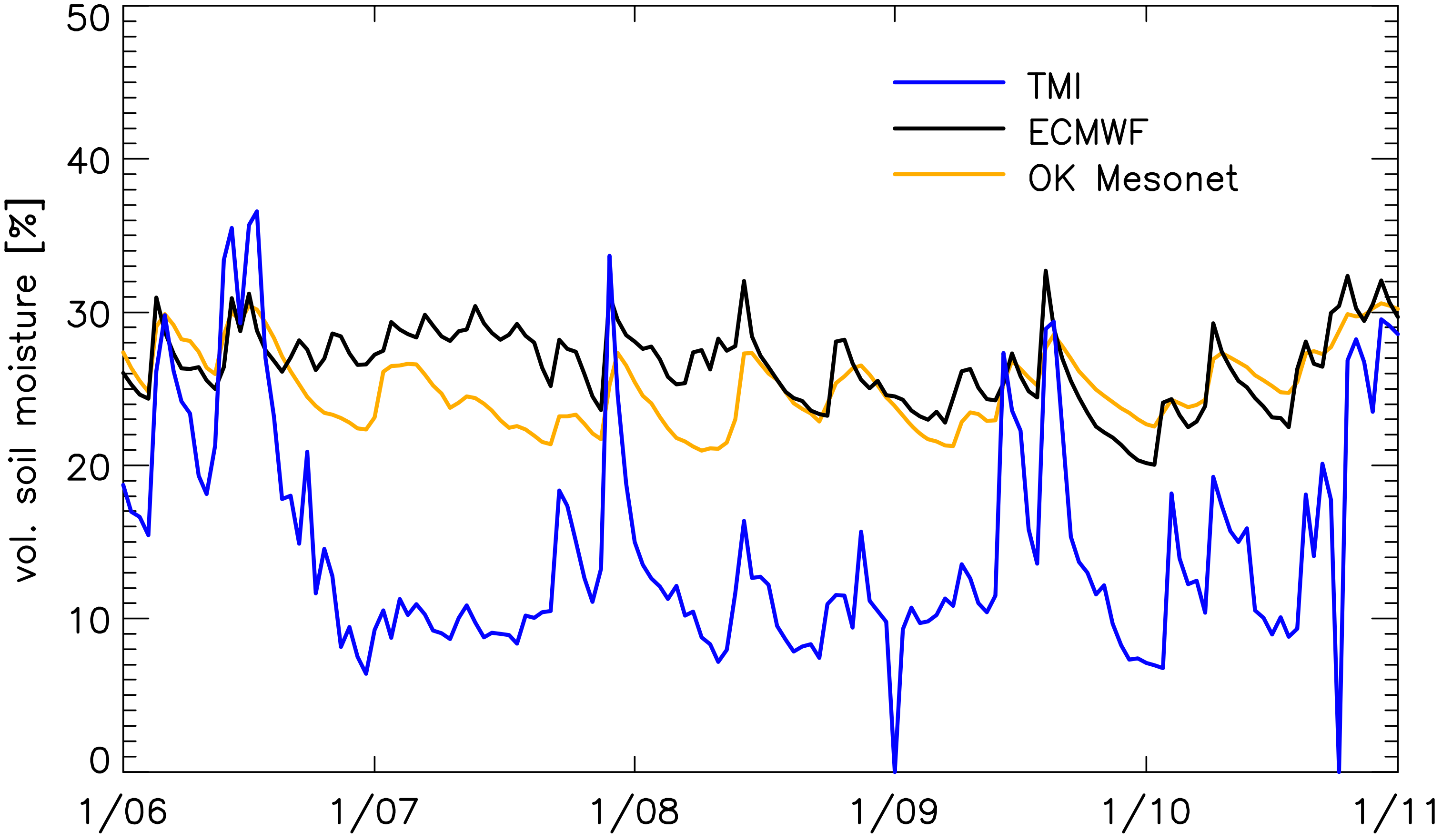


Joint and marginal pdf



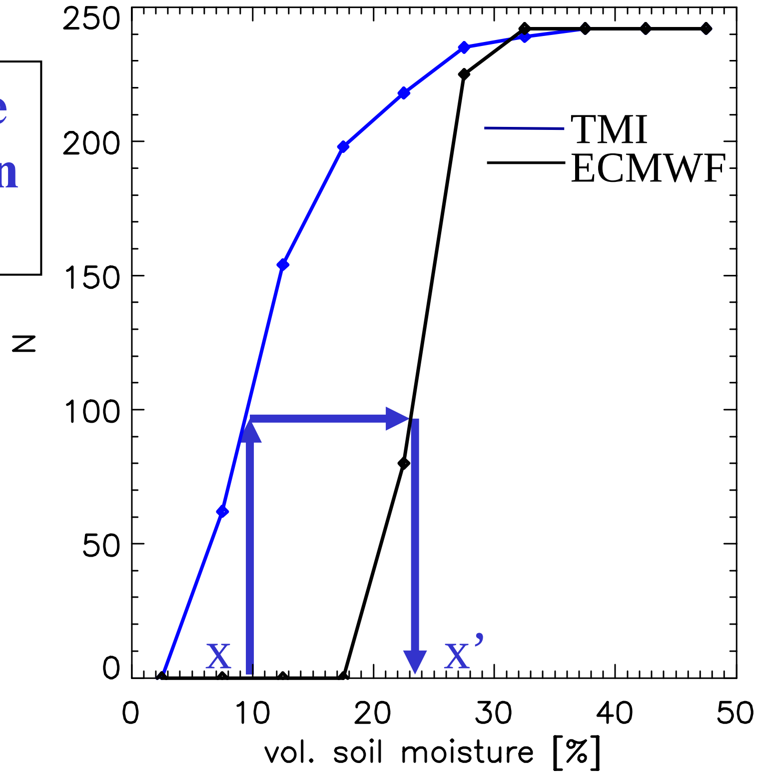
Problem 2: Bias corrections of remote sensing data

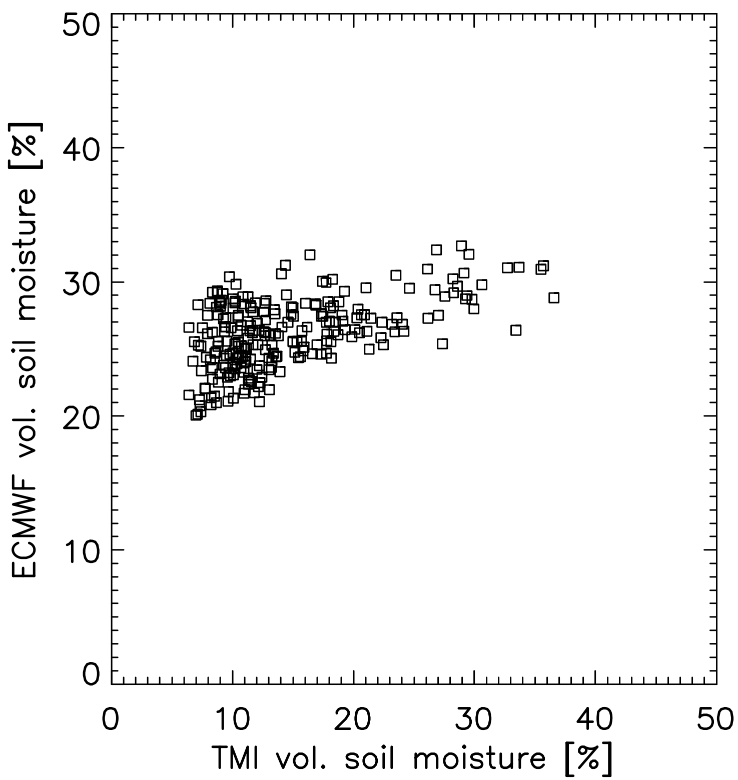
Oklahoma data sets 2002



CDF matching

Cumulative Distribution Function



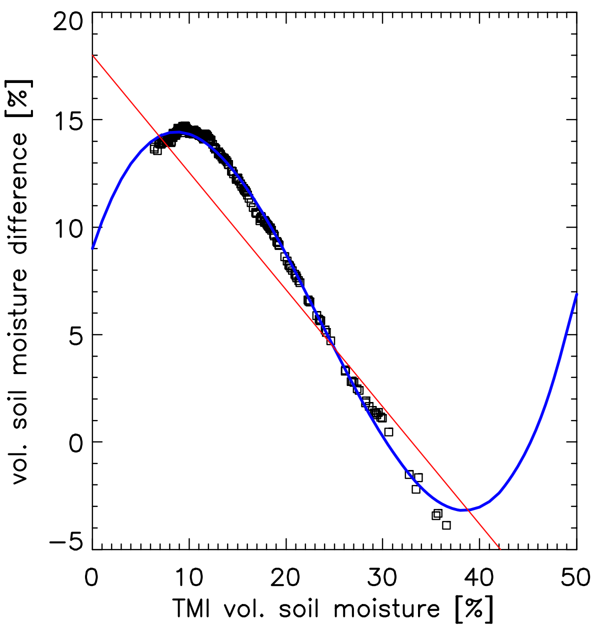


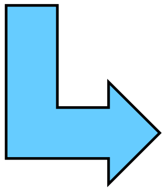
$$\mathrm{CDF}_{ECM}(x') = \mathrm{CDF}_{TMI}(x)$$

(Reichle and Koster, 2004)

TMI soil moisture transformation

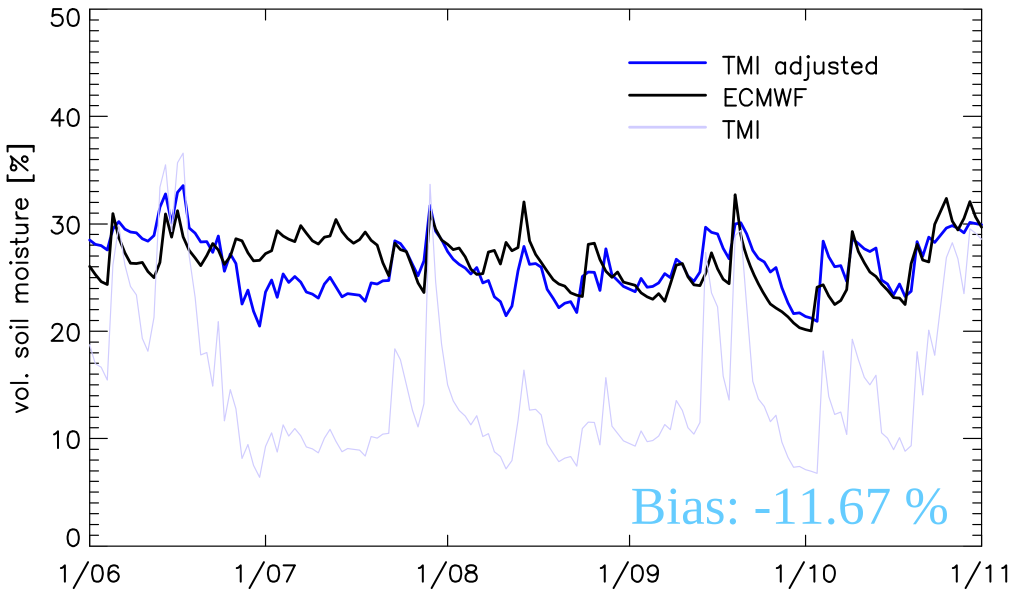
transfer funcion
03/2002-10/2002





- CDF matching reduces systematic errors: The bias has been removed and the dynamic range has been adjusted.

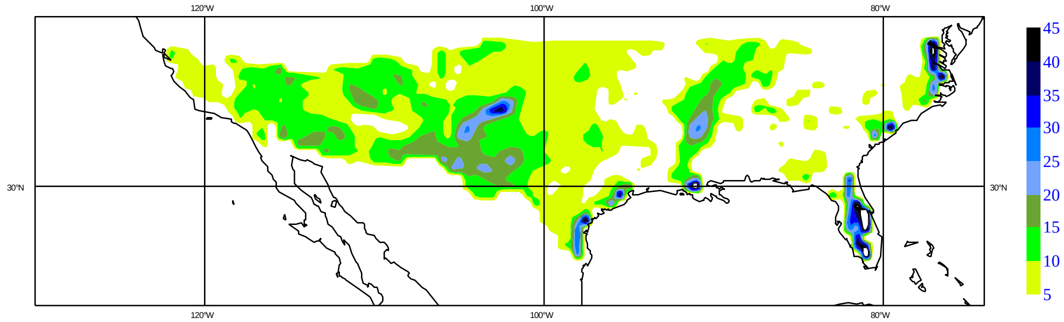
$r^2 = 0.18$ → $r^2 = 0.69$



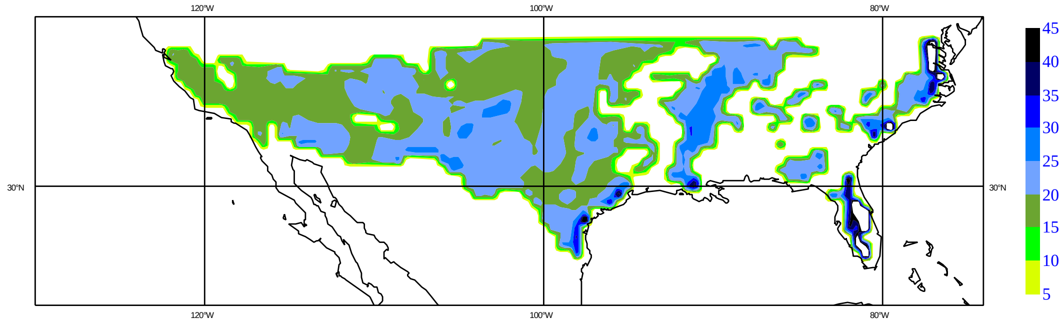
Matthias Drusch

Transferred TMI images

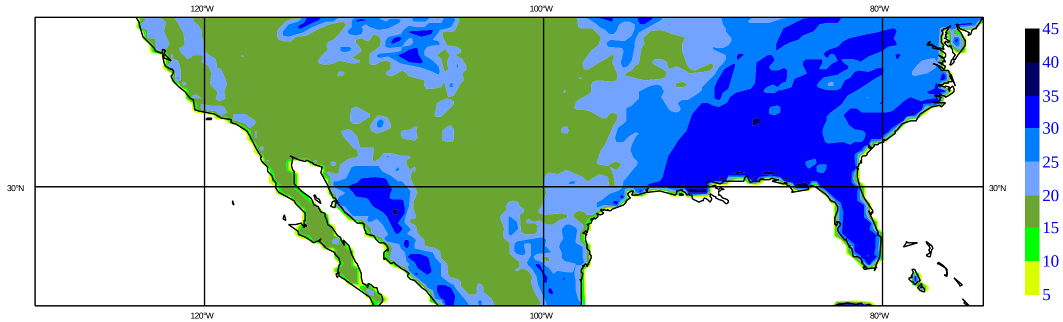
Volumetric soil moisture 01/10/2002



TMI Pathfinder Data Set



Transferred TMI data (2002 regional transfer functions)

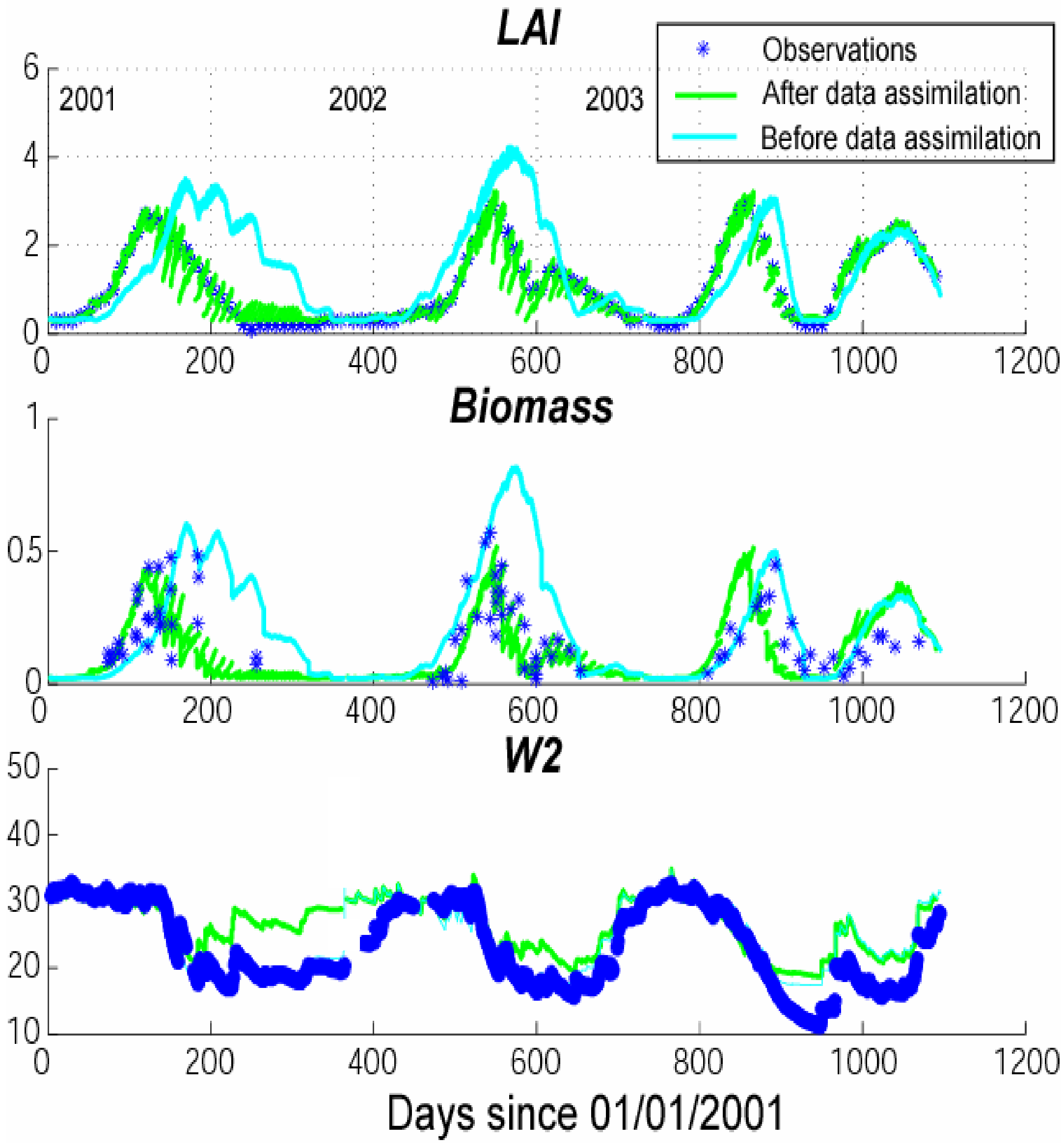


ECMWF

Model development at ECMWF

- **The use of LAI information requires model developments**
  - **In order to perform data assimilation the model has to look like the observations**
- **At present, LAI is time-invariant in the ECMWF**
- **Current development (monthly LAI climatology)**
- **In preparation (carbon/biomass) (w/ KNMI)**
  - **Photosynthesis-based evaporation formulation (from ISBA-Ags), linking water and carbon cycles**
  - **Spin-off: (natural) Land carbon fluxes**
  - **Vegetation: Biomass evolves according to parameterized growth and mortality functions**
- **Data assimilation of biomass using LAI retrievals (at Meteo-France)**
  - **Biomass to LAI observation operator**
  - **Variational approach minimizing the difference to background and observations**
  - **State variables: Biomass and soil moisture**

SMOSREX (Toulouse) site: Biomass only



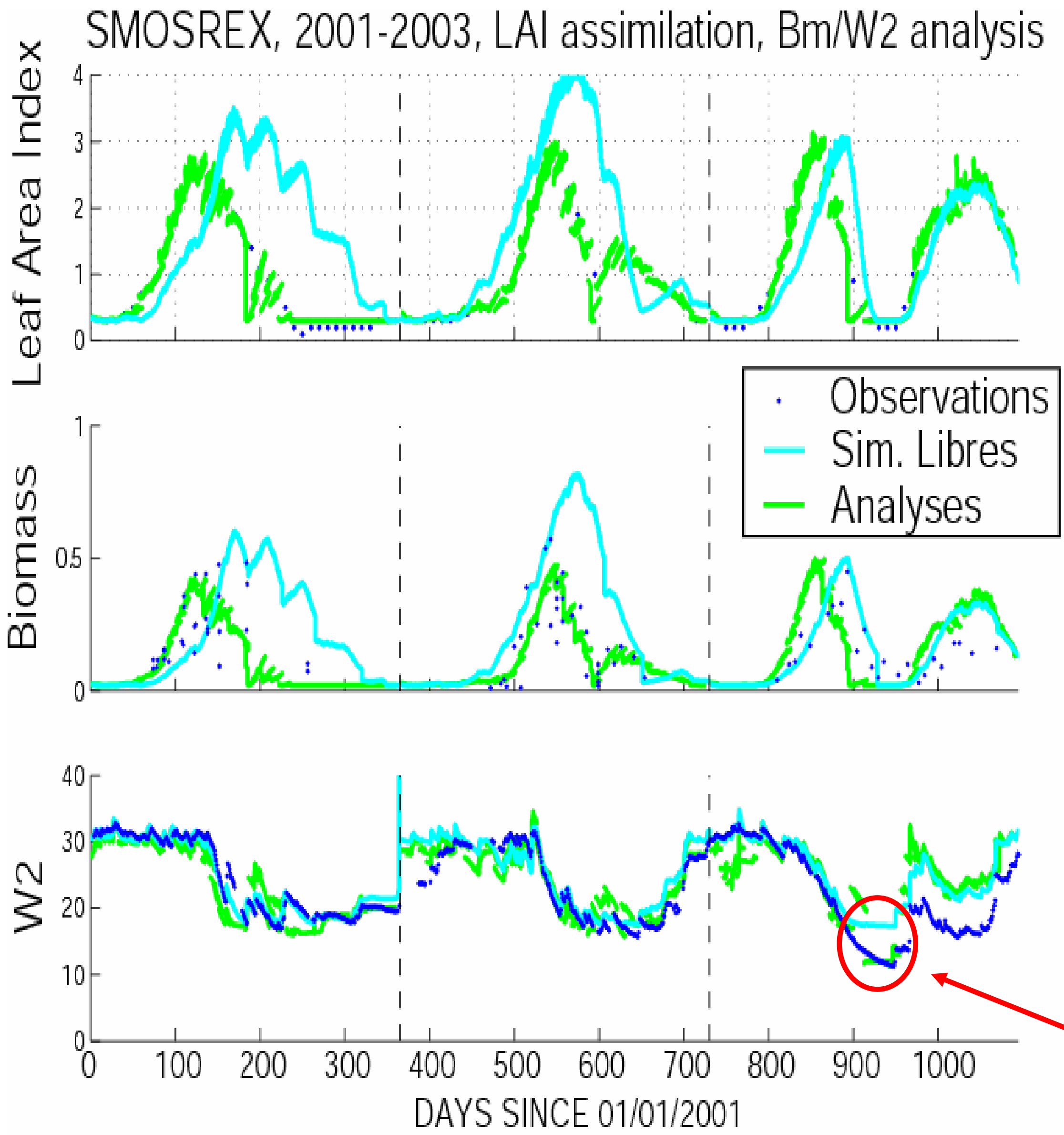
- **Analysis of Biomass using LAI observations (10 days analysis period)**

- **Good LAI correction**

- **Overall good Biomass analysis (particularly in 2002)**

- **Strong (negative) impact of root zone soil moisture, w2, (different LAI → different root water extraction and transpiration rates)**

SMOSREX site: Biomass and soil moisture

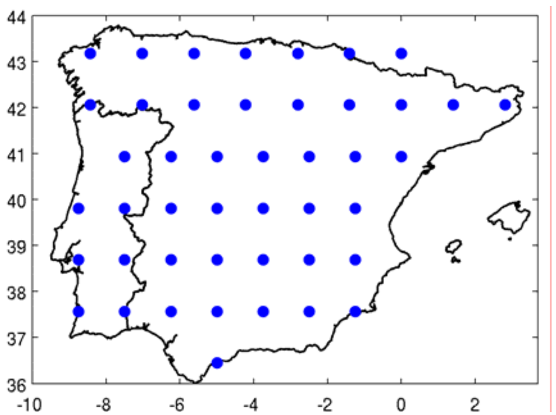


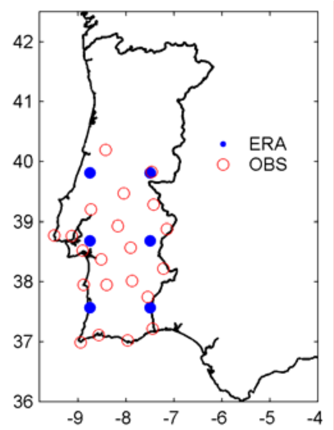
- **Analysis of Biomass and w2 using LAI observations (10 day analysis period) + non stationary covariance matrix**
- **Good LAI correction**
- **Overall good Biomass analysis**
- **… but w2 better in agreement with observations during high water stress period**

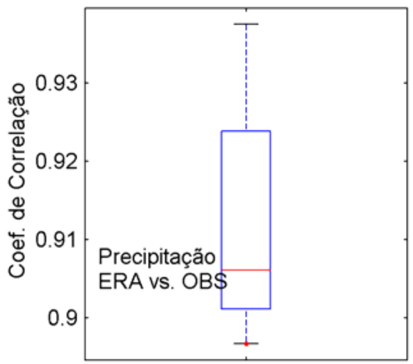
Lionel Jarlan

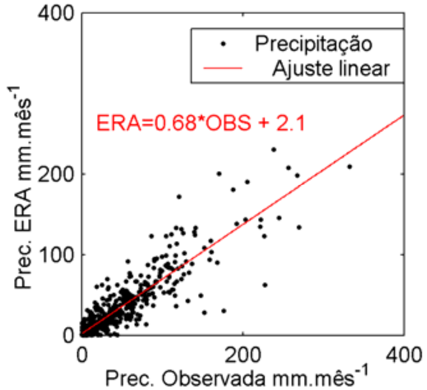
Iberian LDAS

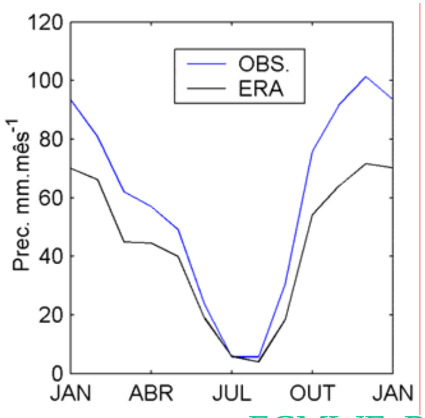
- **Running TESSEL (land surface model of ERA-40) offline, forced by ERA-40**
  - **TESSEL results without land assimilation**





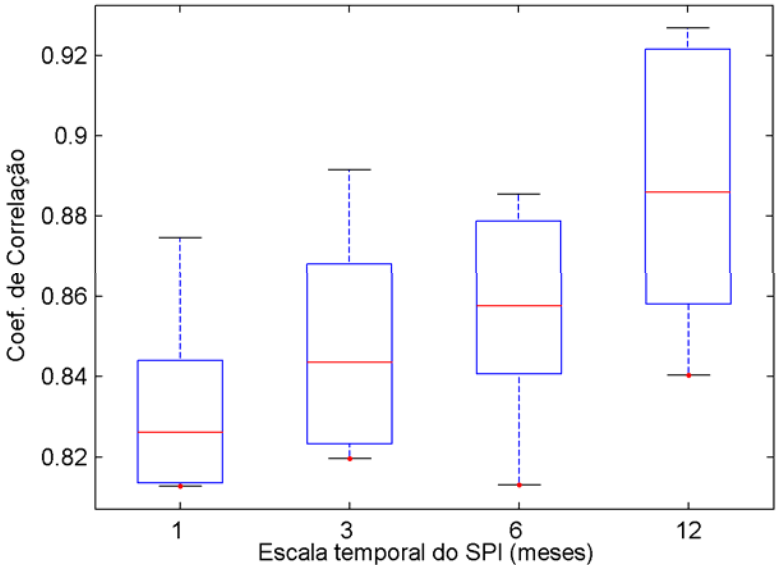






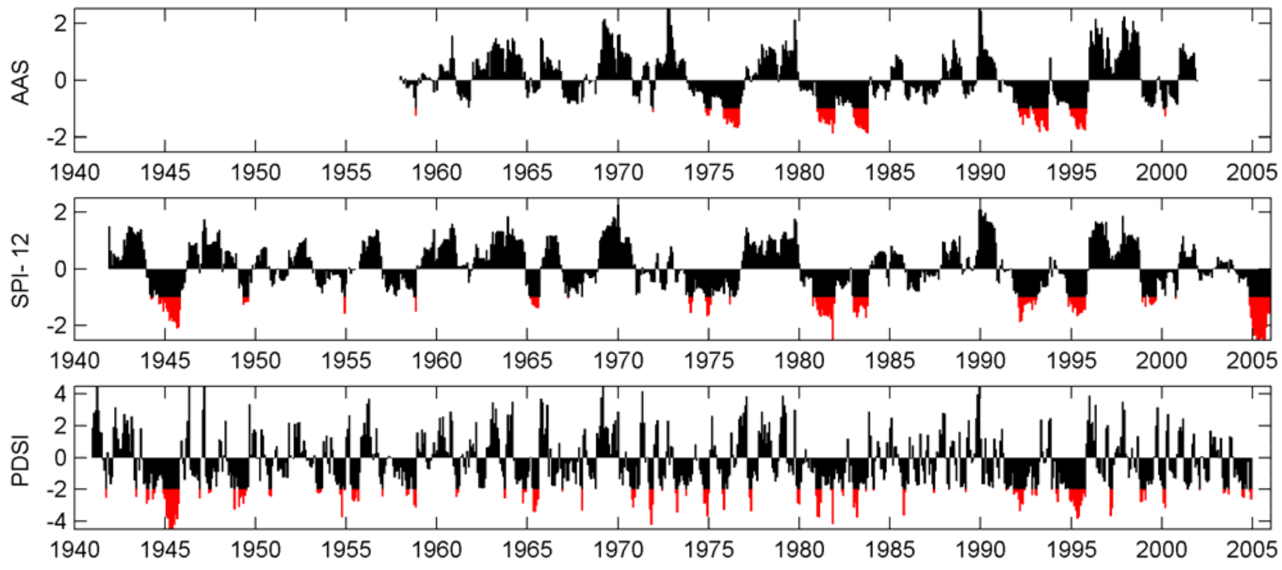
Emanuel Dutra

Standardized Precipitation Index (SPI): ERA-40 vs observations



Drought indicators

- **AAS – Normalized soil water anomaly**
- **SPI: Standardized precipitation index**
- **PDSI: Palmer Drought Stress Index (Official drought indicator in Portugal)**



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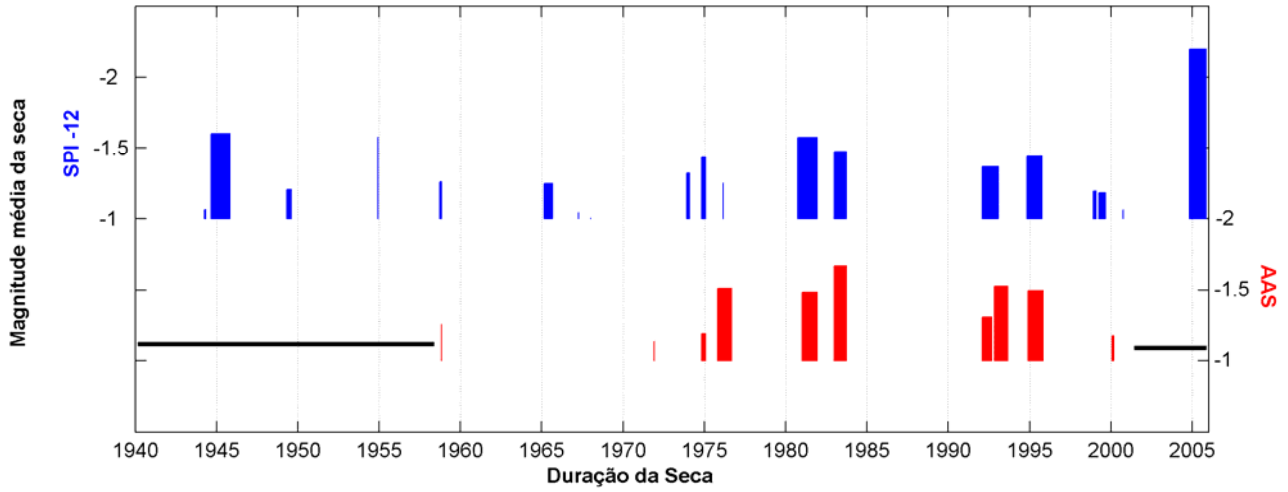
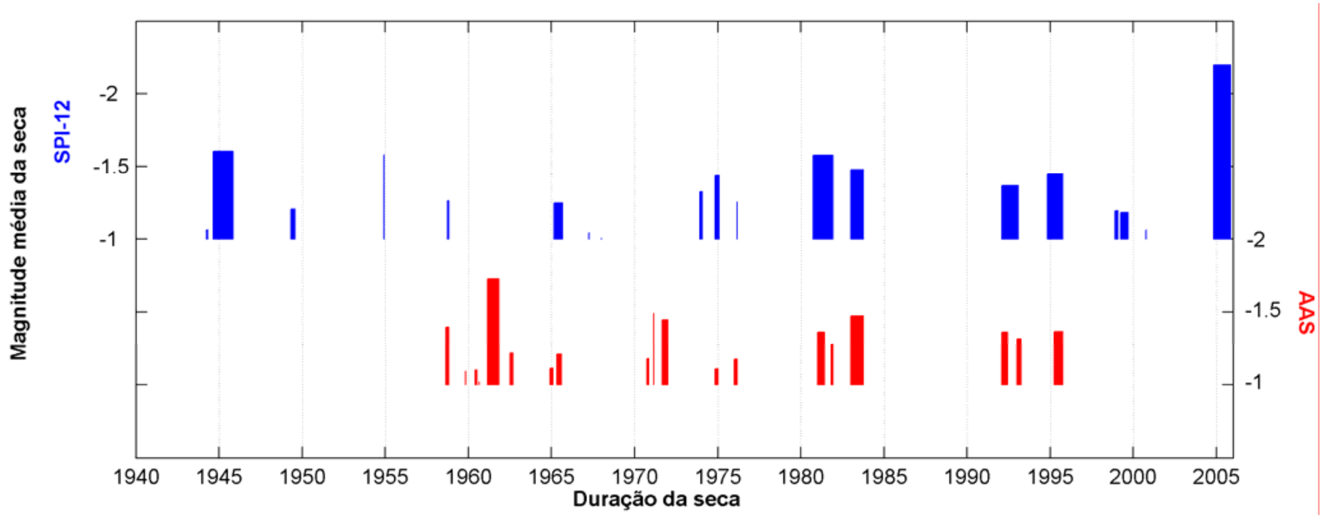
SPI and normalized soil water anomaly

Offline TESSEL

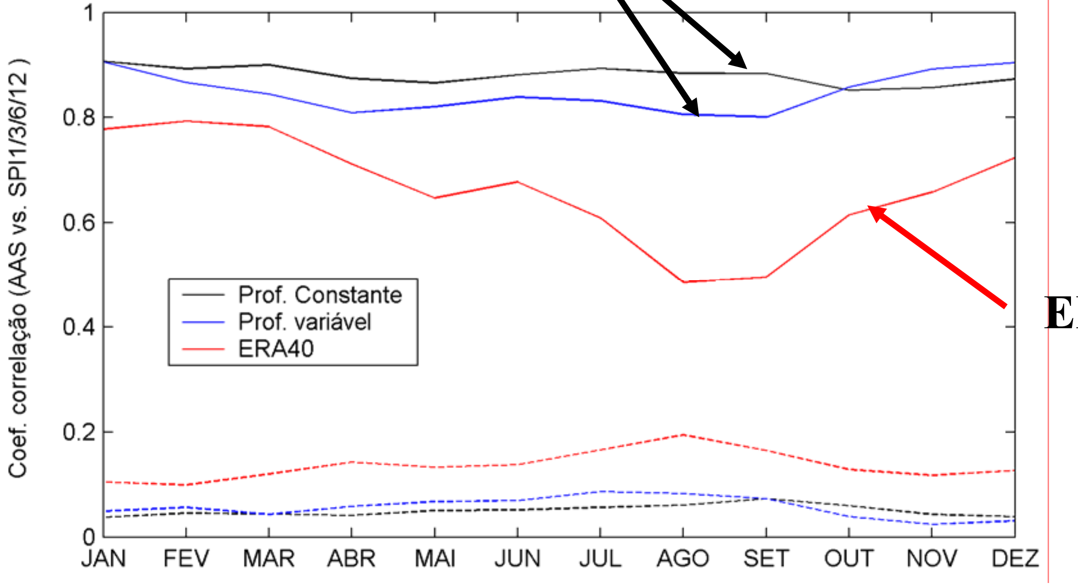


ERA-40 soil water



Correlation of SPI and normalized soil water anomaly

Offline TESSEL



ERA-40 soil water

Emanuel Dutra

Root zone soil moisture: observables and caveats

BL T/RH

What we can do

•Fair weather spring/summer conditions

•Low wind speed

Root zone
Soil moisture

•Run the surface model offline, forced by 24-48 hour precipitation

•Use output soil water as a weak constraint to OI soil water analysis

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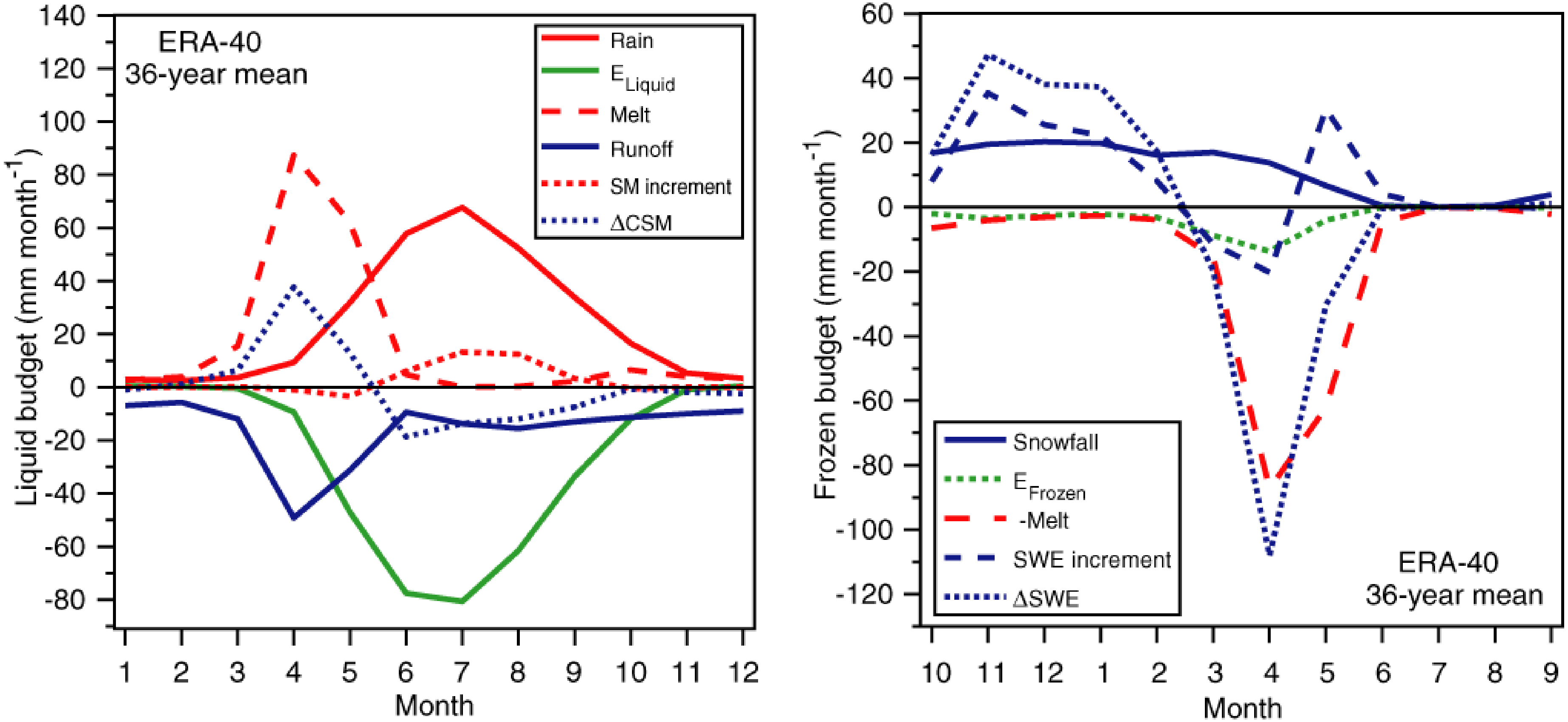
- Introduction: Imperfect models and inaccurate data
- Land surface in ERA-40; Strengths and weaknesses
- Soil moisture
- **Snow**
  - Large analysis increments
  - Snow cover vs. snow depth
  - Model problems: Density and melting
- Conclusions

Mackenzie river basin era40: Surface water and snow budget

$$\eta^{a}_{n+1} = \eta^{a}_{n} + \sum [P + M - E_l - Y + \Delta\eta] \qquad S^{a}_{n+1} = S^{a}_{n} + \sum [F - E_s - M + \Delta S]$$



- **Surface analysis increments are of the same order of the seasonal evolution of the soil water and snow mass budget**

ECMWF snow depth and snow cover analysis

- Background (modified short term forecast)
- Observation operator uses model snow density to go from model snow mass to snow depth
- Snow depth (conventional observations)
- NOAA/NESDIS snow cover, ScNESDIS product is used
  - ScNESDIS=0 is unambiguous information
    - This information is presented as an observation
  - ScNESDIS > 0 and Scbackground=0 is ambiguous information
    - This information is used to modify the short term forecast, assigning a small value to these points
- In the following, we will compare analysed snow mass with MODIS snow extent and a high-resolution (1 km), high-quality US snow analysis product (SNODAS); both fields are upscaled to model resolution

Comparison with MODIS

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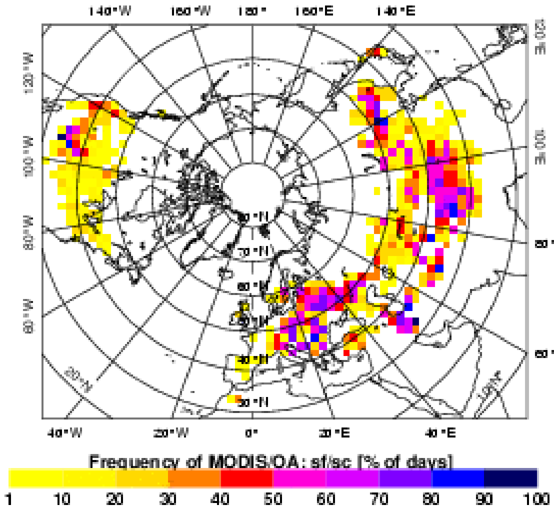
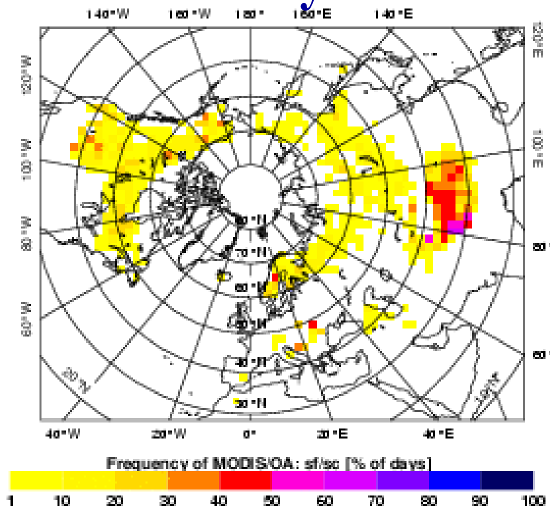
Frequency of days where $Sc_{MODIS}=0$ and $snow\_mass_{analysis} > 0$

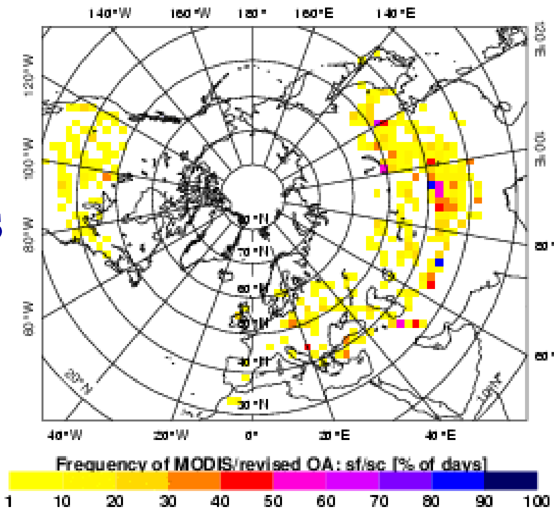
March 2002 | **May 2002**

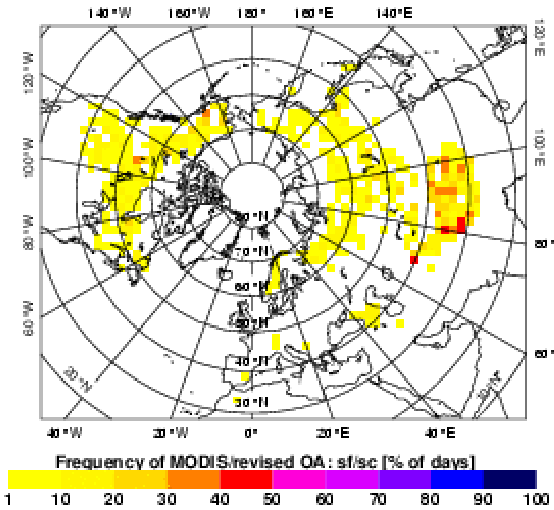
Analysis w/o Sc_{NESDIS}





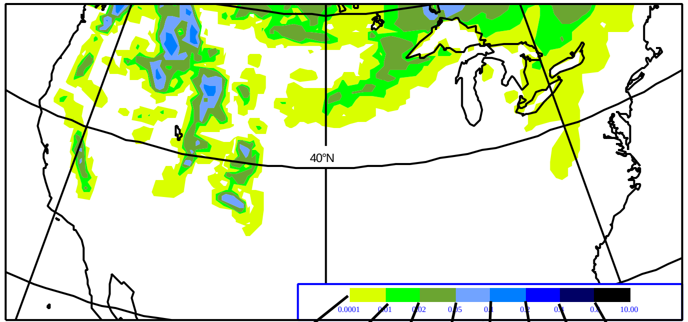
Full analysis





Comparison with SNODAS: snow mass

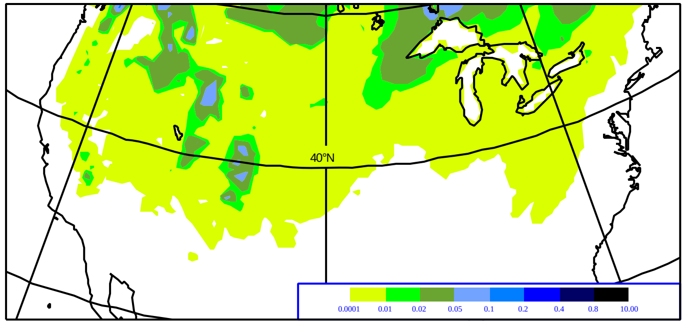
SNODAS 30/11/04



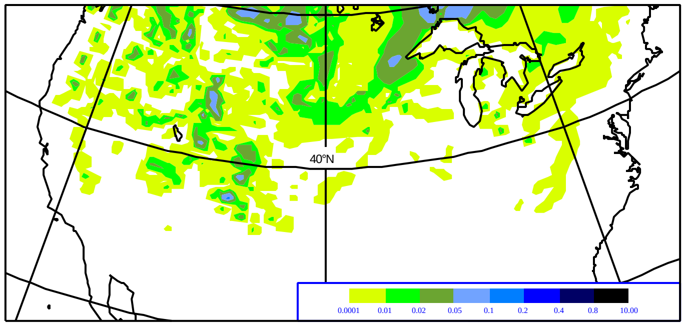
0.0001 0.01 0.02 0.05 0.1 0.2 0.4 0.8

Snow mass [10^{-3} kgm^{-2}]

Analysis w/o Sc_{NESDIS} 30/11/04



Full analysis 30/11/04



Layout

- Introduction: Imperfect models and inaccurate data
- Land surface in ERA-40; Strengths and weaknesses
- Soil moisture
- Snow
- **Conclusions**

Conclusions

- **Land surface data assimilation is necessary to correct drifts in slow components of the land system, caused by deficiencies in the forcing or inaccurate (surface) model physics**
- **Surface analysis still lags behind its atmospheric counterpart**
- **New methods allow the use of more observations**
  - **A more complete sampling of soil water in physical space: Evaporative feedback to the atmosphere (two-metre temperature and humidity), hydrology (1.4 and 6.4 GHz microwave Tb), and vegetation state (vegetation indices, lead area index, …)**
  - **Sinergy of 3 observation types reduces the risk of overfitting and/or aliasing**
- **Non-linear transfer functions to match model and observation space**
  - **Bias correction will always be necessary**
- **In case of contradictory information between screen-level parameters and mw Tb on soil moisture, NWP centres will tend to tune the assimilation to fit the evaporative fraction, since that is the quantity impacting on the atmosphere.**
- **In practice, the output of LDAS can be used to provide a penalty term to soil assimilation**
- **Snow**
  - **Check the observations beforehand (snow)**
  - **Need snow cover for whole reanalysis period (it exists since 1966)**
  - **Optimal ingestion of special observations (Russia and Canada)?**