Earth Surface Modelling Advances at ECMWF and their connection with Extreme Events

presented by

Gianpaolo Balsamo

Thanks to contributions from several colleagues from ECMWF Research & Forecast departments, acknowledged on the slides

Catchment-based Hydrological Model Data Assimilation (CAHMDA VI)
and
Hydrologic Ensemble Prediction Experiment (HEPEX-DAFOH III)
Joint workshop

8–12 September, 2014, Austin, Texas, USA

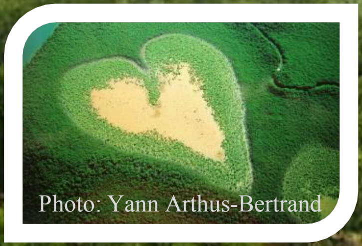


Photo: Yann Arthus-Bertrand

ECMWF

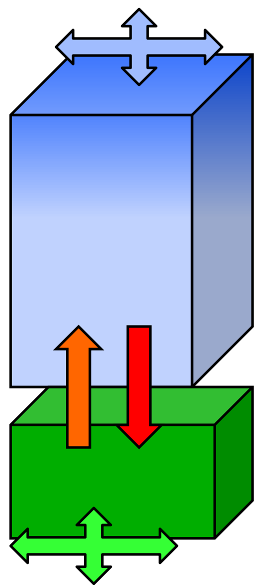
Outline

- Surface role in NWP in normal conditions & extreme events
- Earth surface components represented in ECMWF model & data assimilation
- Predictability of extremes associated with land surface
- Weather & Climate interaction with land surfaces: what do we miss?
- Summary & outlook

Earth Surface Modelling Advances at ECMWF and their connection with Extreme Events

Improving the realism of soil, snow, vegetation and lakes parameterisations has been subject of several recent research efforts at ECMWF. These Earth surface components work effectively as **energy and water storage** terms with **memory** considerably longer than the atmosphere counterpart.

Their role regulating land-atmosphere **fluxes** is particularly relevant in presence of large weather and climate anomalies



$$(\rho C)D\frac{\partial T_s}{\partial t} = R_n + LE + H + G$$

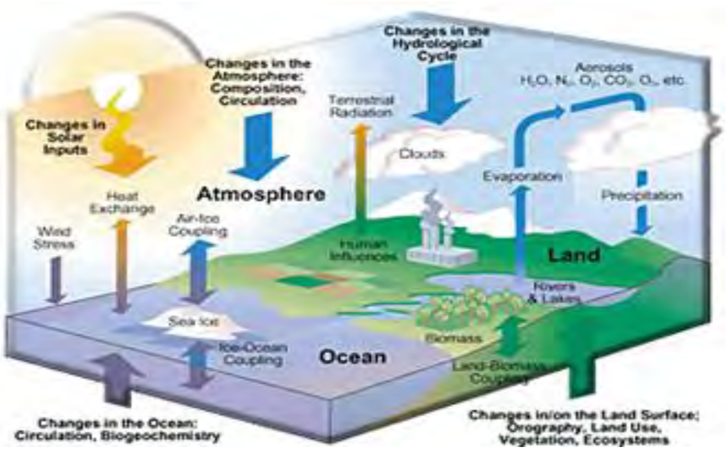
$$\frac{\P TWS}{\P t} = P - E - R$$

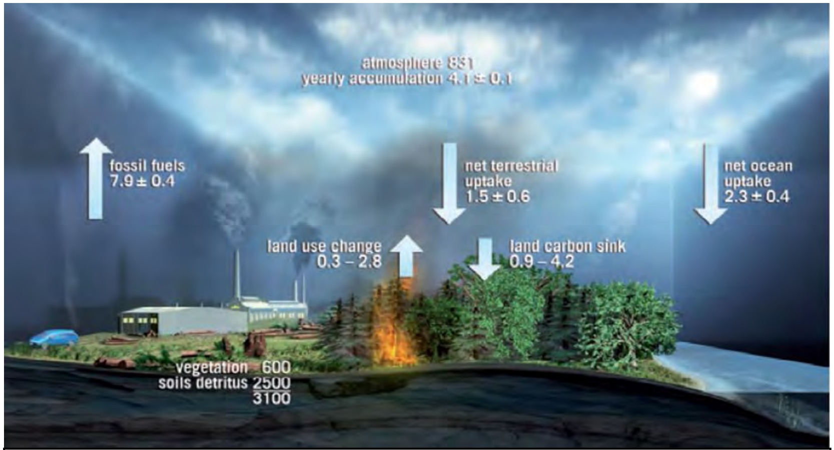
$$\frac{\P CO2}{\P t} = GPP + \mathrm{Re} + A$$

Validity for H_2O / E / CO_2 cycles: surface R&D directed towards improved **storages** and **fluxes**

The water and Carbon cycle

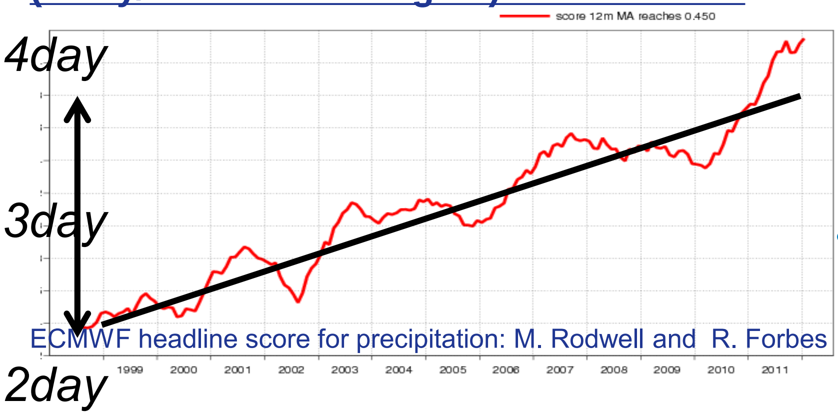
- Numerical Weather Prediction models have considerably evolved over time with respect to how the represent the land surface and its interaction with the atmosphere





CO2 budget (from ESA – BIOMASS mission report)

Precipitation forecasts improvements support (1 day/decade in skill gain) refined LSMs



ECMWF headline score for precipitation: M. Rodwell and R. Forbes

- The needs of unification of NWP and Climate model are a driver to develop land surface schemes with increased realism

Evolving towards Earth System Models

- However surface remains a severely ill-posed problem (lack of obs to represent complexity)

ECMWF

Predicting land fluxes & storages: a cure for ill-posed?

Observations

SYNOPs 2m T/RH
Snow depth

FLUXNET LE/H/C

ISMN soil moisture

GRDC rivers

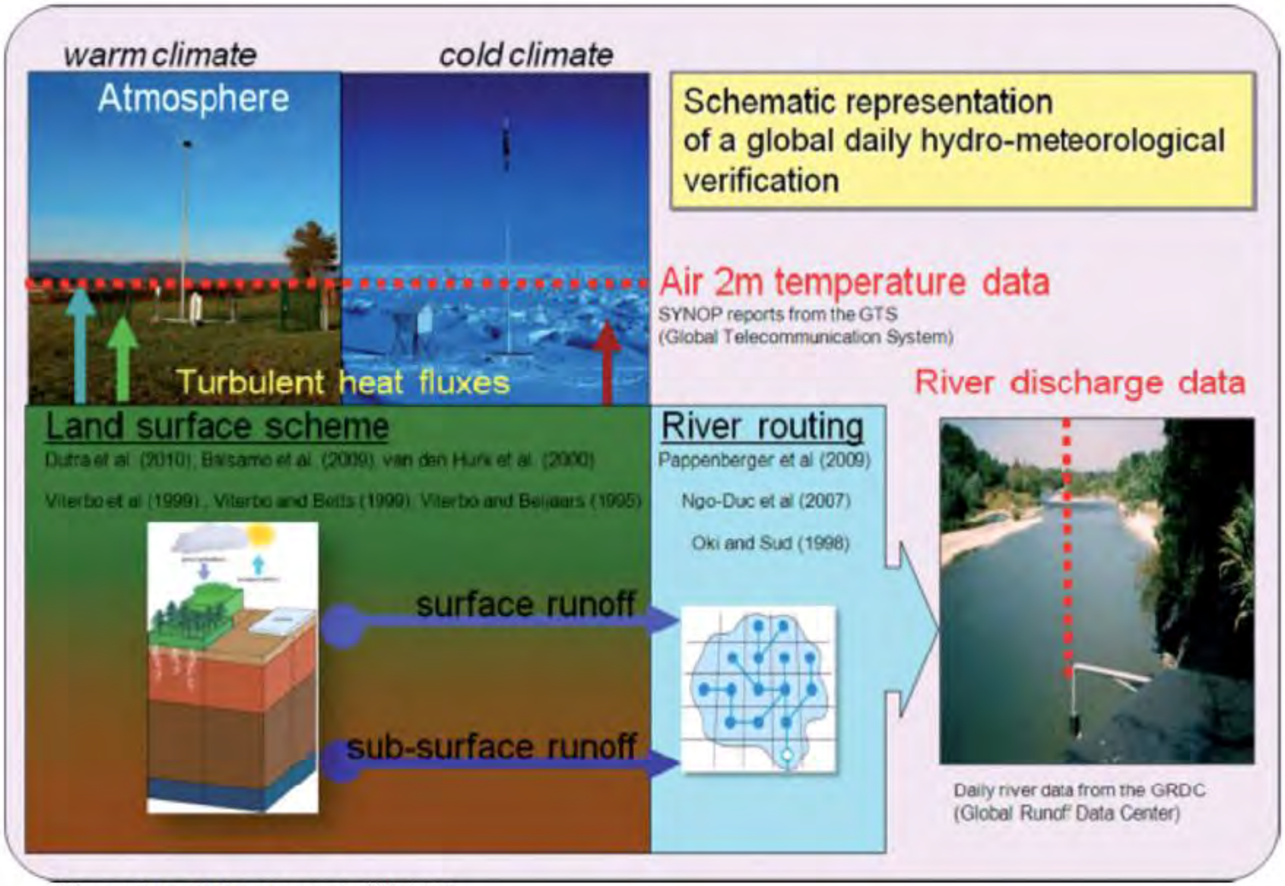


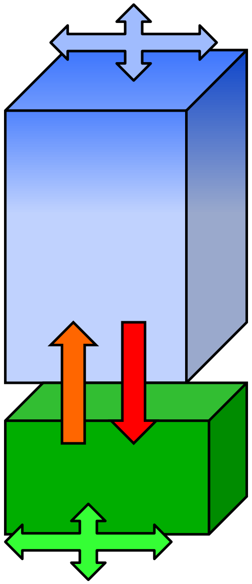
Figure from Balsamo et al. 2010 HP

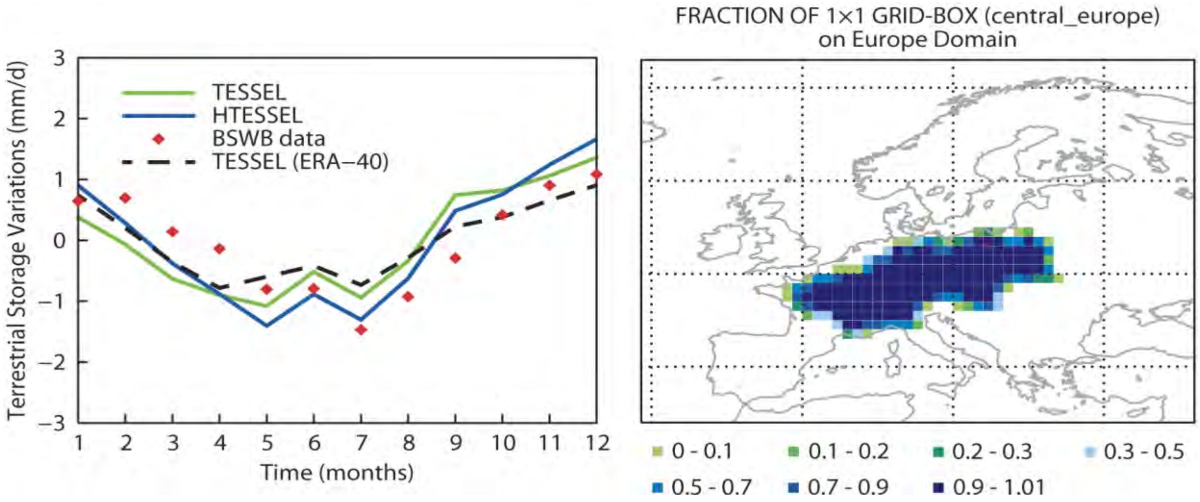
A combined verification of models reduced the chances of overfitting to a particular variable/purpose (e.g. NWP model tend to use soil moisture as sink variable to optimize evaporative fluxes.

Land water storage and its link to soil hydrology

$$\frac{\partial TWS}{\partial t} = -\nabla Q + \frac{\partial TCWV}{\partial t} - R$$

$$\frac{\P TWS}{\P t} = P - E - R$$

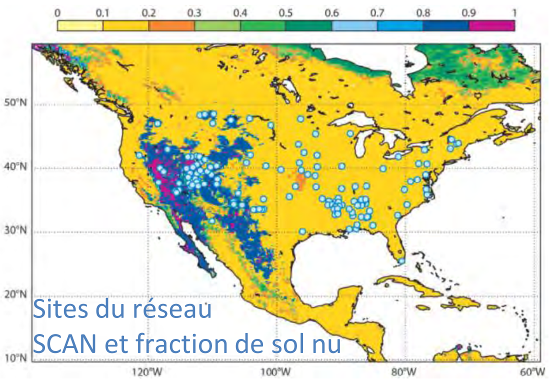


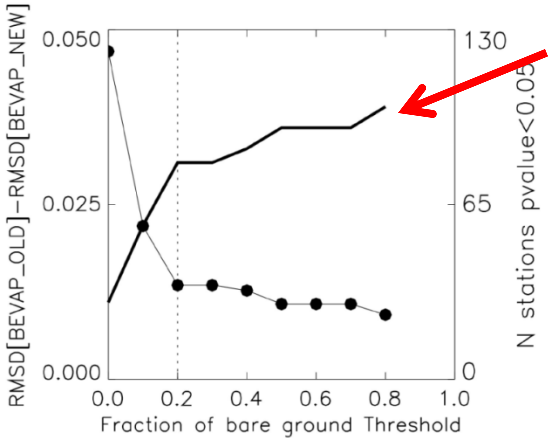


Monthly Terrestrial Water Storage (TWS) changes (left panel) for the Central European catchments Wisla, Odra, Elbe, Weser, Rhine, Seine, Rhone, Po, North-Danube (the coverage is shown in the right panel). The curves are for TESSEL (GSWP-2-driven, green line), H-TESSEL (GSWP-2-driven, blue line), TESSEL in ERA-40 (black dashed line). The red diamonds are the Hirschi et al. (2006) monthly values derived from atmospheric moisture convergence and runoff for the years 1986–1995.

Arid areas and impact of bare soil dynamical range (via Evaporation)

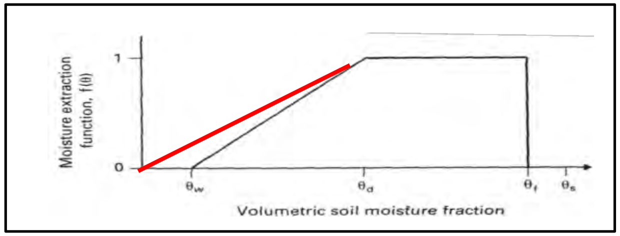
Albergel et al. (2012), *HESS*





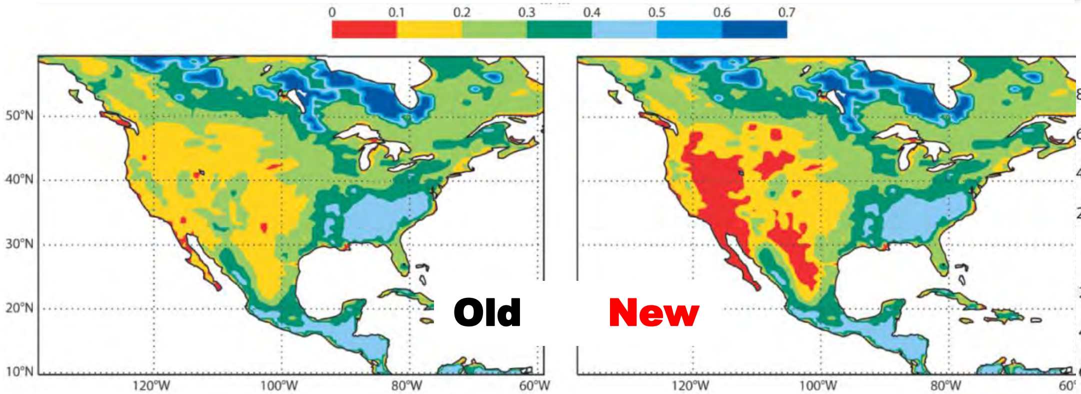
Improved fit to SCAN soil moisture data (reduced RMSE over 122 stations) as a function of bare soil.

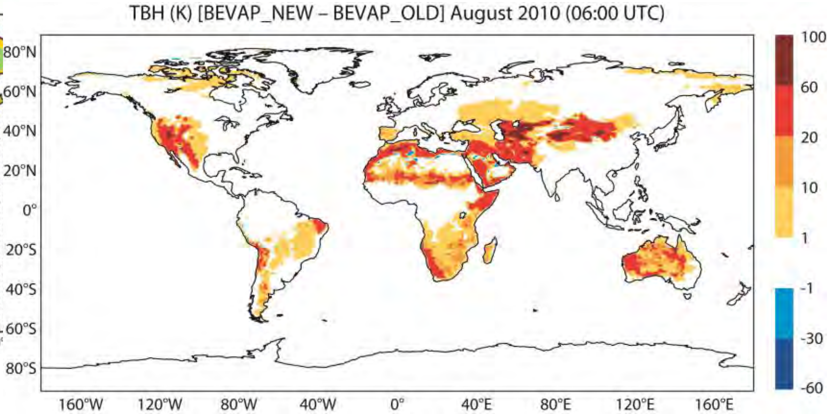
SOIL Evaporation



A revision of the bare soil evaporation which is allowed to extract water below the wilting point in arid regions produces a soil moisture drying

The drying effect impact enhancing SMOS/SMAP T_b (L-band) in the forward operator





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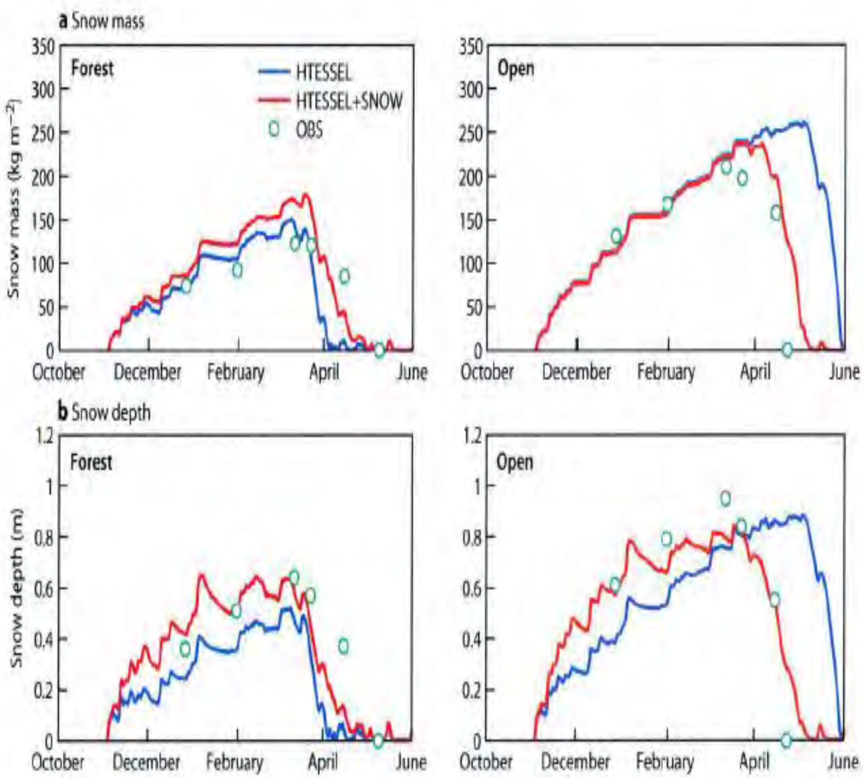
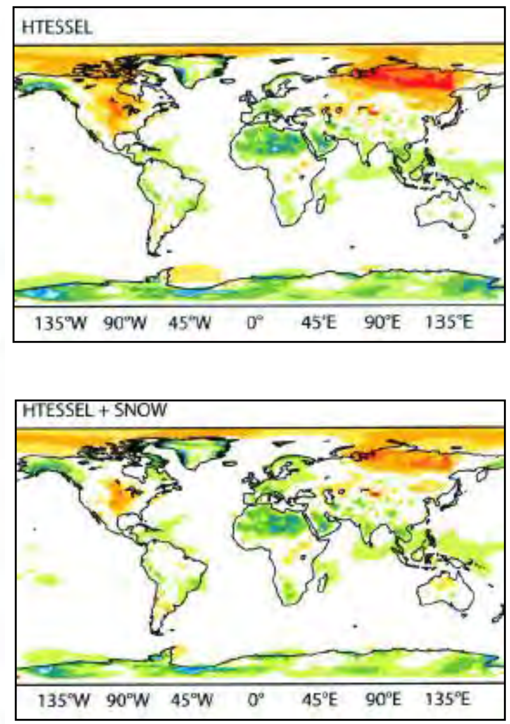
Snow modelling (current version)

Dutra et al. 2010 JHM, Balsamo et al. 2011 EC-NL





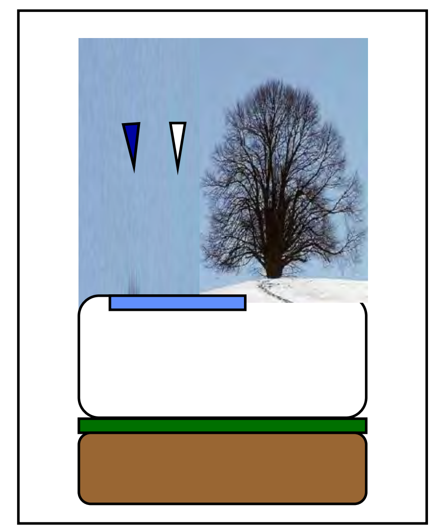
- **SL1 SNOW**

  Dutra et al. (2010)

  Improved snow density

  Liquid water (diagnostic)

  Revision of Albedo and sub-grid snow cover



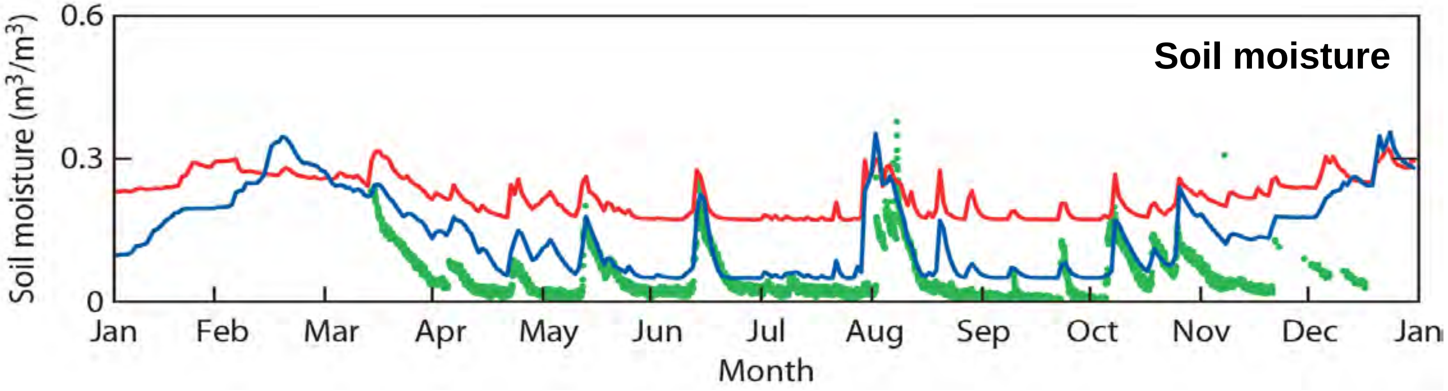
The key elements of the current ECMWF snow schemes are in the treatment of snow density (including the capacity to hold liquid water content in the snowpack). The SNOWMIP 1&2 projects with their observational sites have been essential for the calibration/validation of the new scheme which was improved with respect to the ERA-Interim snow scheme.

ECMWF

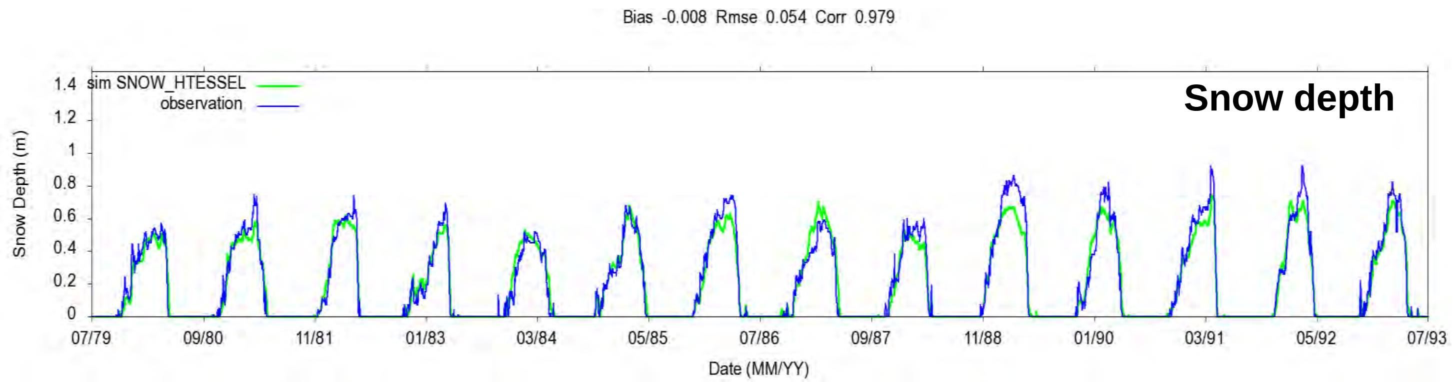
ERA-Interim/Land: Storages verification

Albergel et al. (2013 JHM), Balsamo et al. (2013 HESSD)

ERA-Interim/Land integrates land surface modelling improvements with respect to ERA-Interim surface scheme.



Evolution of soil moisture for a site in Utah in2010. Observations, ERA-Interim, and ERA-Interim/Land.



Evolution of snow depth for a site in Perm Siberia (58.0N, 56.5E) ERA-Interim/Land and in-situ observation between 1979 and 1993.

ERA-Interim/Land: Fluxes verification

Balsamo et al. (2012), BAMS July (AMS conference summary).

The ERA-Interim/Land fluxes are validated with independent datasets used as benchmarking.

E

CO_2

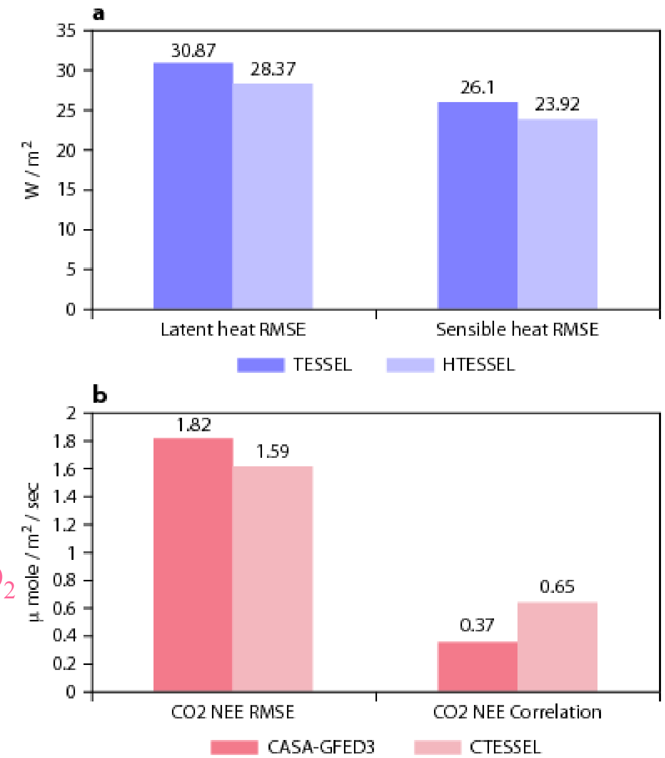
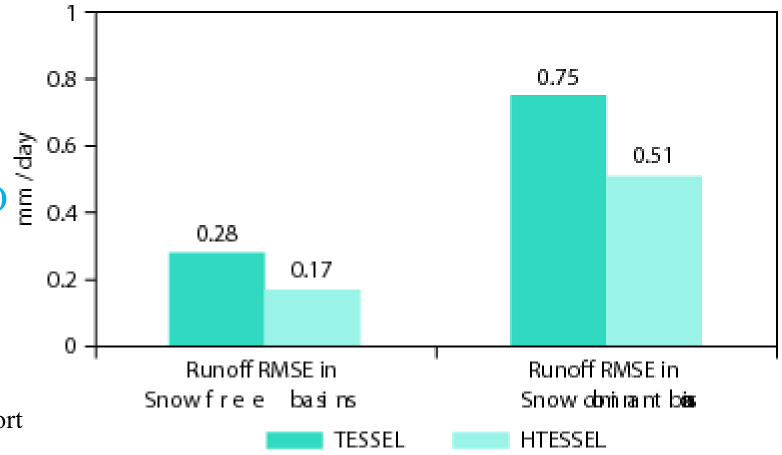


Figure 1: Mean errors over 36 stations with hourly data from FLUXNET & CEOP networks (decadal-averages) in 2006 for HTESSEL, TESSEL scheme versions (with latent and sensible heat fluxes RMSE shown in (a)) and HTESSEL and CHTESSEL (with Net Ecosystem Exchange RMSE and Correlation in (b)).

Validation of H_2O / E / CO_2 cycles

H_2O



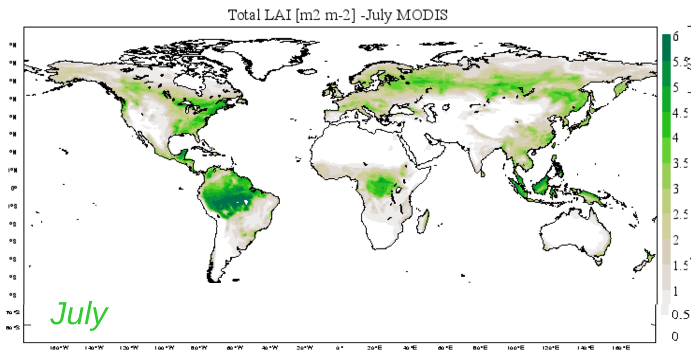
GEOLAND-2 R&D support

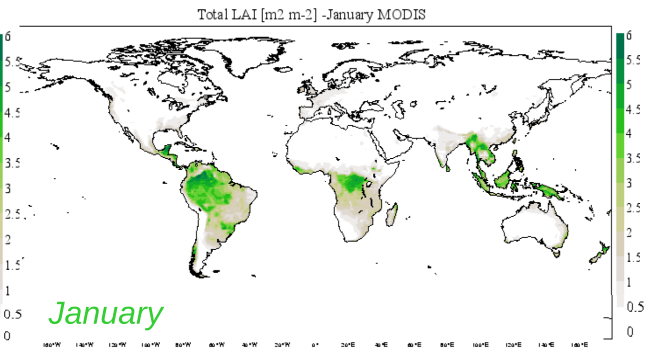
Figure 2: Runoff root-mean-square error (RMSE) for GSWP2 global offline land simulations (1986–1995) verified with GRDC monthly river discharge observations on mainly snow-free basins (North-East and Central Europe) and snow-dominated basins (Yukon, Podka, Lena, Tom, Ob, Yenisei, Mackenzie, Volga, Irtish and Neva).
The mean RMSEs are area-weighted and show the TESSEL and HTESSEL scheme versions.

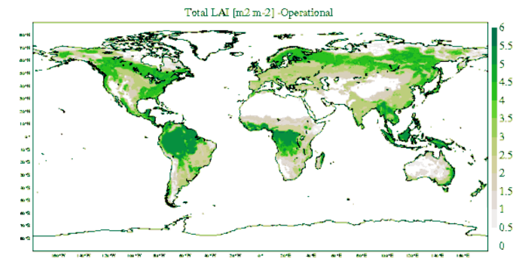
Vegetation seasonal cycle

Boussetta et al. (2013, IJRS)

MODIS LAI (c5) Myneni et al., 2002, Jarlan et al. 2008



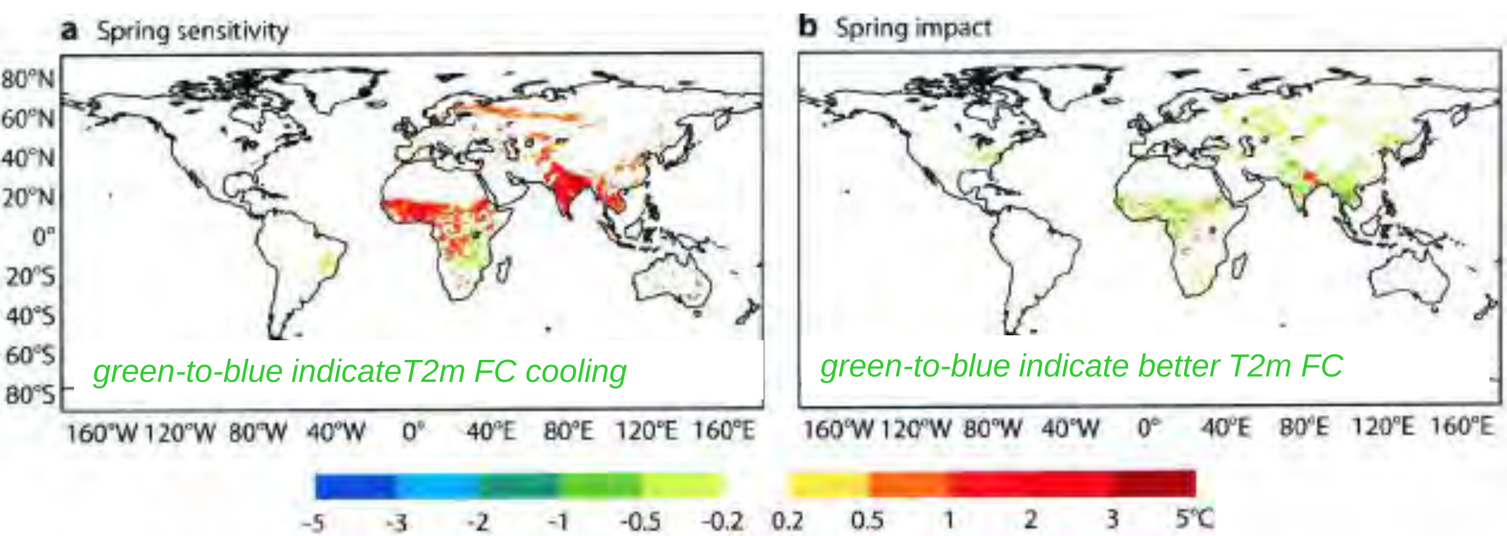




Previously fixed LAI
(van den Hurk et al. 2000)

The MODIS LAI introduces a consistent warming seen in FC36h (12UTC) due to reduction of LAI in spring, (increasing vegetation resistance to ET).

This has beneficial impact on near surface temperature forecast (green being positive impact in reducing t2m bias by ~0.5degree)



- **NEW LAI**

  Boussetta et al. (2011)

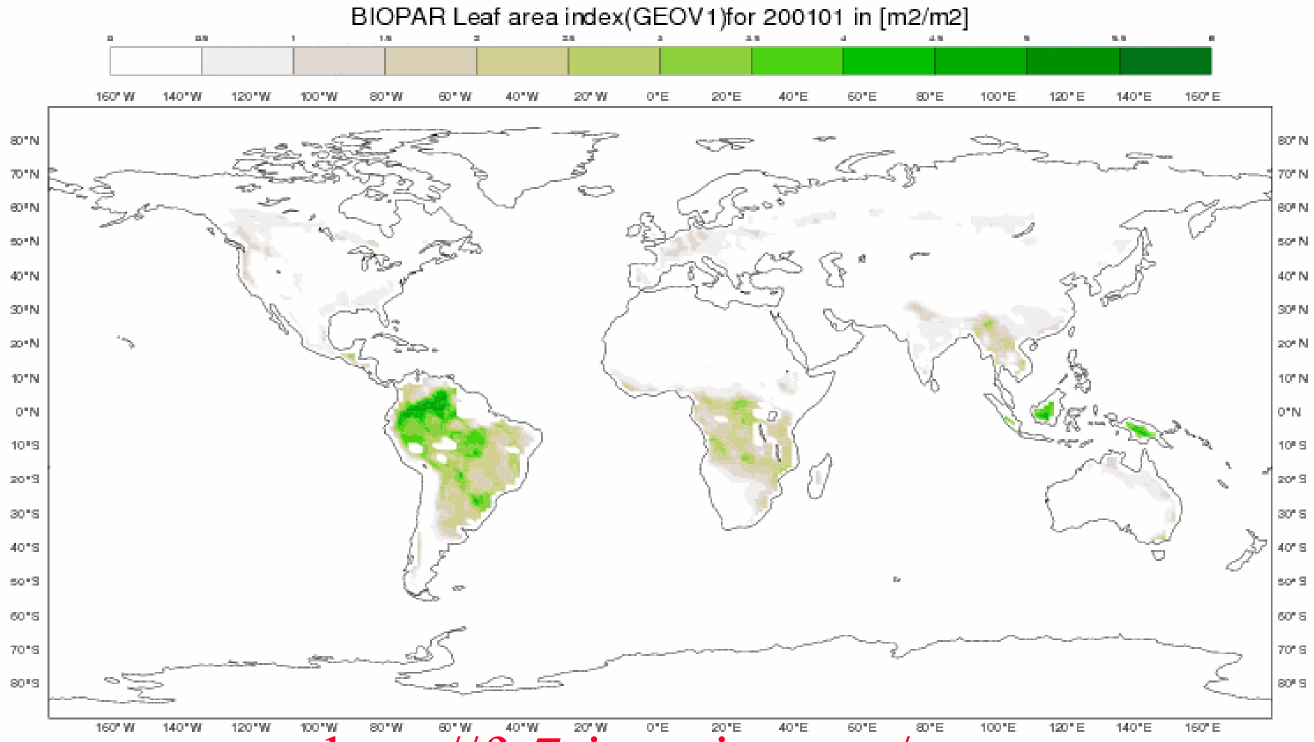
  New satellite-based

  Leaf-Area-Index

Vegetation inter-annual variability

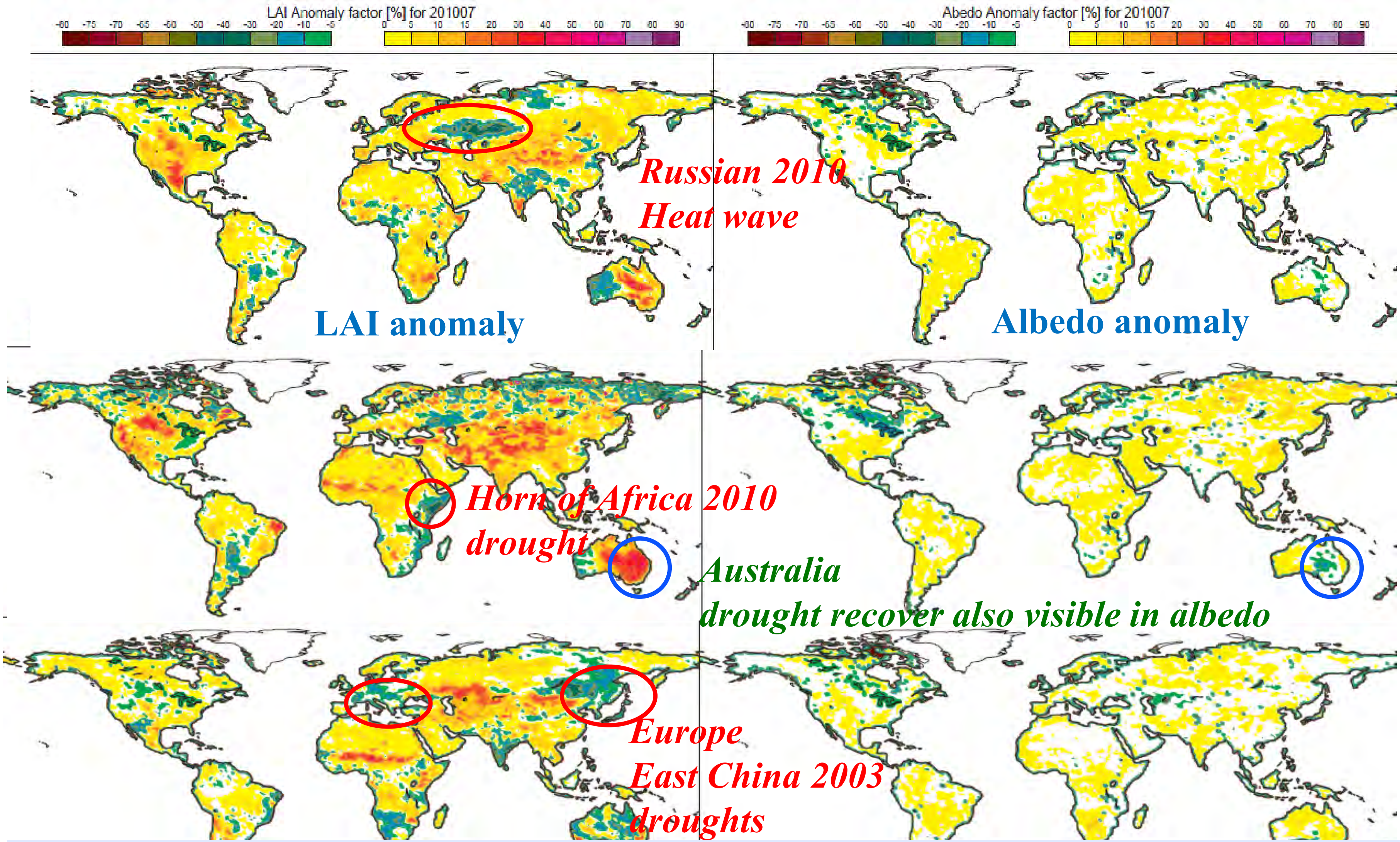
geoland 2 | Imagines

A 10-year global LAI (and Albedo) product (10-day frequency) has been provided by the geoland2 BIOPAR (GEOV1 product) and continues in IMAGINES project. Our plan is to assimilate in the ECMWF system to test the impact fluxes and forecasts. Preparing for SENTINEL ESA satellites.



http://fp7-imagines.eu/

Vegetation anomalies linked with droughts

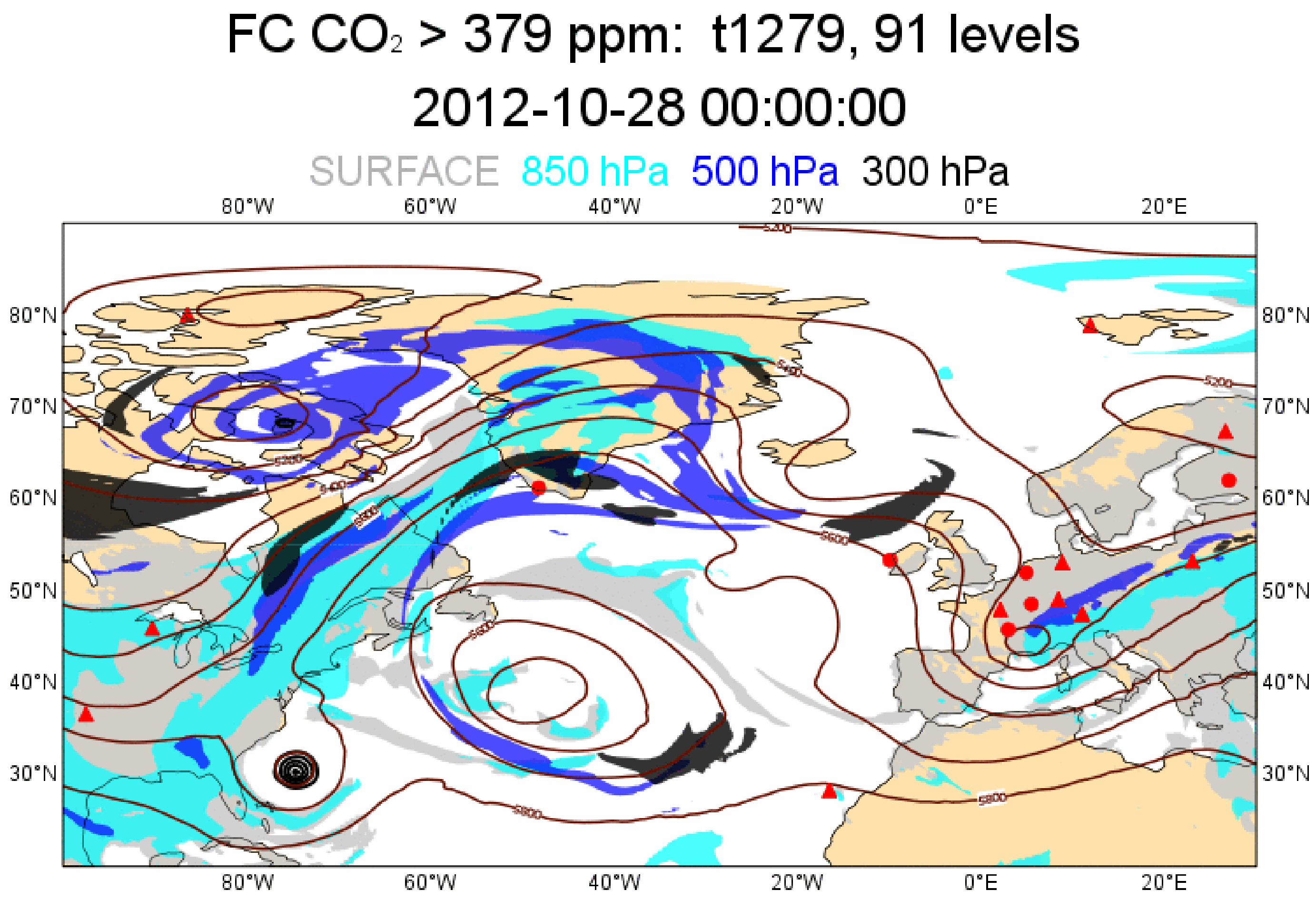


- ➔ NRT analysed LAI seems able to detect/monitor anomalous year
- ➔ The analysed LAI and albedo signal appear to be covariant mainly during wet year.
- ➔ NWP forecasts respond mildly to vegetation anomalies and seem neutral to albedo changes (not shown)
- ➔ Vegetation state is instead very important for CO_2

Near Real Time CO_2 concentration & meteorology

Agusti-Panareda et al. (2013, ACP), Boussetta et al. (2013 JGR)

Hurricane Sandy (2012) from a different perspective



ECMWF

Modelling inland water bodies

A representation of **inland water bodies and coastal areas** in NWP models is essential to simulate large contrasts of albedo, roughness and heat storage

A lake and shallow coastal waters parametrization scheme has been introduced in the ECMWF Integrated Forecasting System combining

HTESSEL

Hydrology - Tiled ECMWF

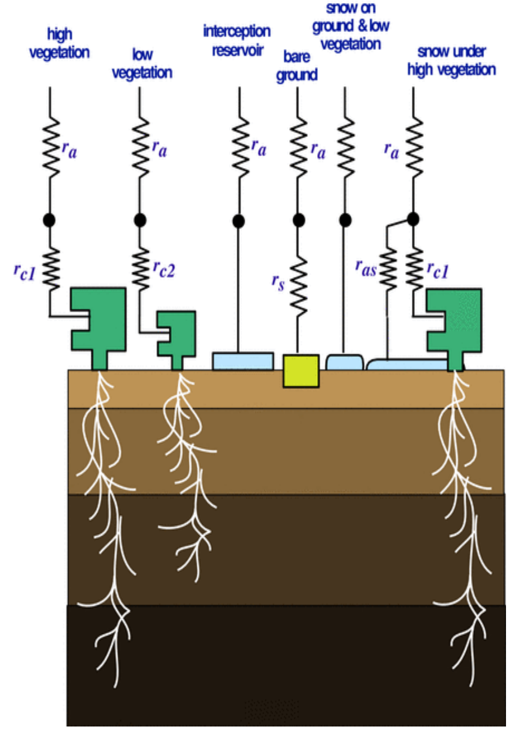
Scheme for Surface Exchanges over Land

+

FLake

Fresh water Lake scheme

Land surface tiles in ERA40 surface scheme



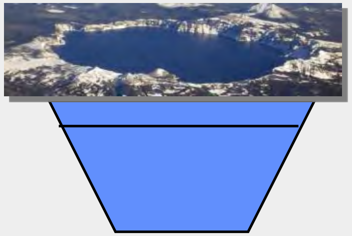
- **Lake tile**

Mironov et al (2010),

Dutra et al. (2010),

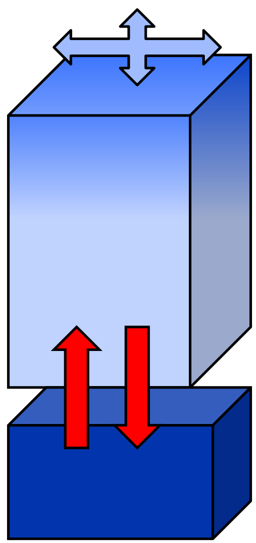
Balsamo et al. (2010, 2012, 2013)

Extra tile (9) to account for sub-grid lakes

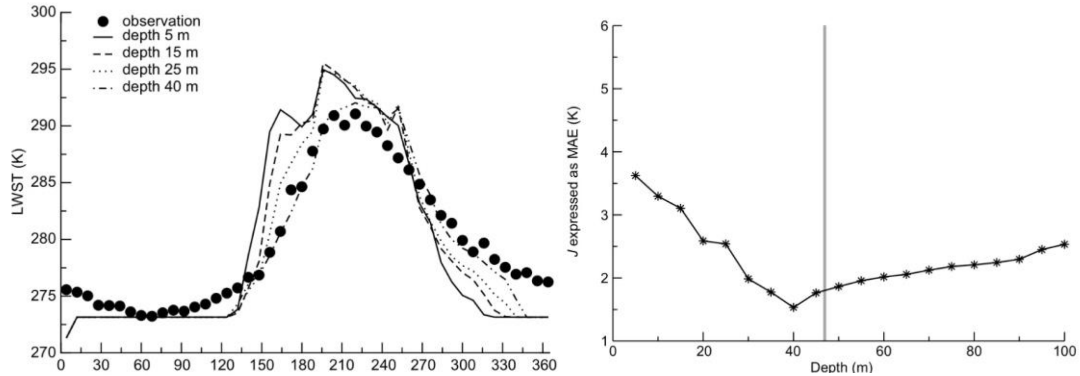


Water bodies heat storage

- All inland water bodies are important energy storage drastically changing sensible heat flux
- FLake (Mironov et al. 2010, BER) http://lakemodel.net a two-layer bulk model based on a **self-similar** parametric representation of the evolving temperature profile within lake water and ice
- Introduced in the IFS by Dutra et al. (2010,BER), Balsamo et al. (2010,BER; 2012,TELLUS)



Lake depth is a scalar for lake temperature annual cycle



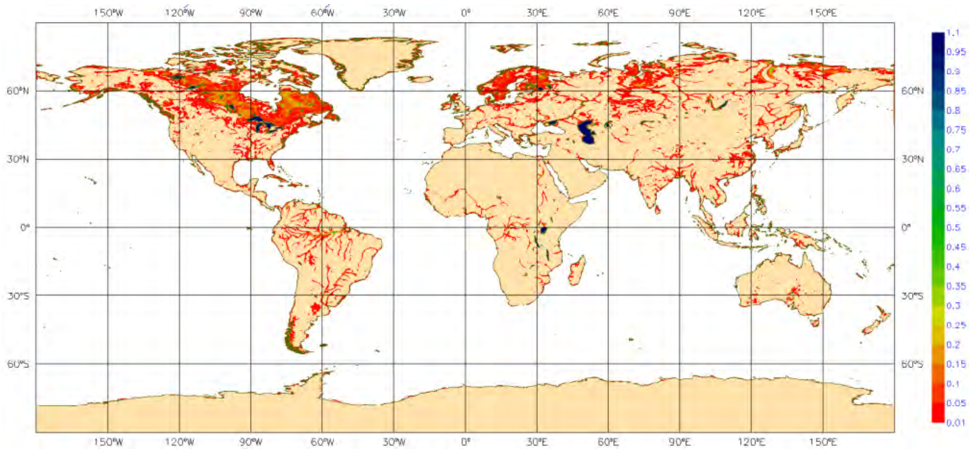
The relationship between the lake temperature (as observed by MODIS) and the lake depth can be used to infer the lake depth in an inversion procedure (Balsamo et al. 2010 BER)

Lake cover and lake depth at global scale

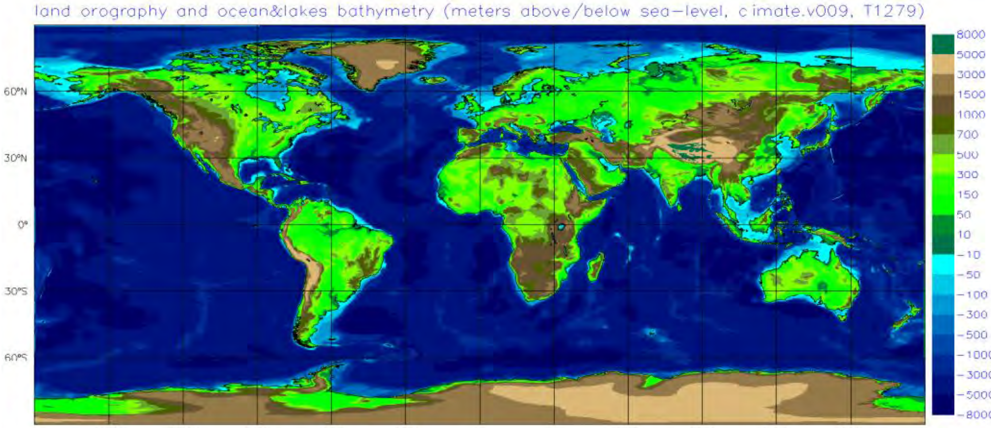
Dutra, 2010 (BER), Balsamo et al. 2010 (BER)

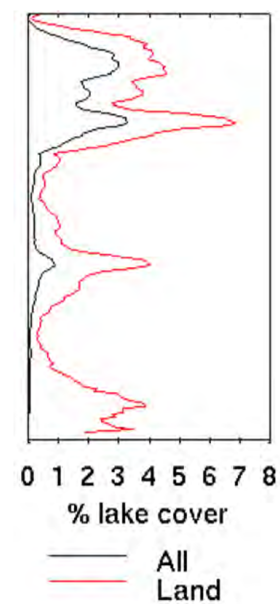
A sizeable fraction of land surface has sub-grid lakes: different radiative, thermal roughness characteristics compare to land → affect surface fluxes to the atmosphere

LAKE COVER FRACTION



LAKE & SEA BATHYMETRY





Nº Points 0.05< Clake<0.5

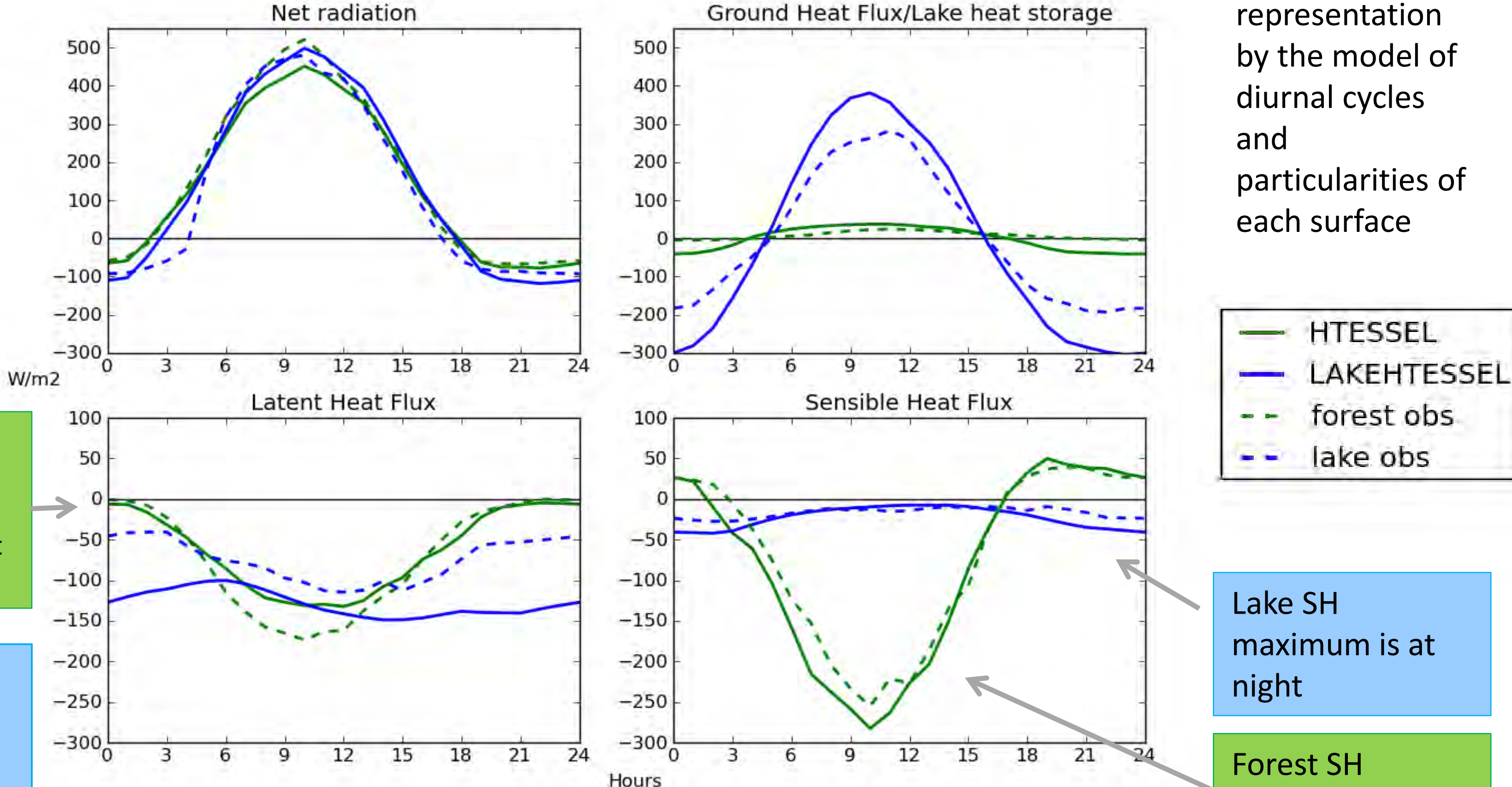
Canada	309/754 **41%**
USA	175/482 **36%**
Europe	170/385 **44%**
Siberia	104/467 **22%**
Amazon	81/629 **13%**
Africa	74/584 **13%**

- Lake cover and lake bathymetry are important fields to describe size and volume of the water bodies that are associated to thermal inertia
- source: ESA-GlobCover/GLDBv1

Energy fluxes: Diurnal cycles

Manrique-Suñén et al. (2013, JHM)

Monthly diurnal cycle of energy fluxes for July



Very good representation by the model of diurnal cycles and particularities of each surface

Forest evaporation is driven by vegetation, so it is zero at night

Lake LH diurnal cycle: overestimation in evaporation

Lake SH maximum is at night

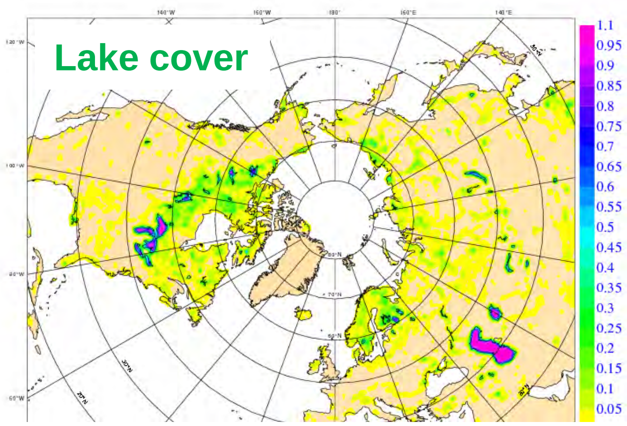
Forest SH maximum is at midday

Main difference between both sites is found in the energy partitioning into SH and G

ECMWF

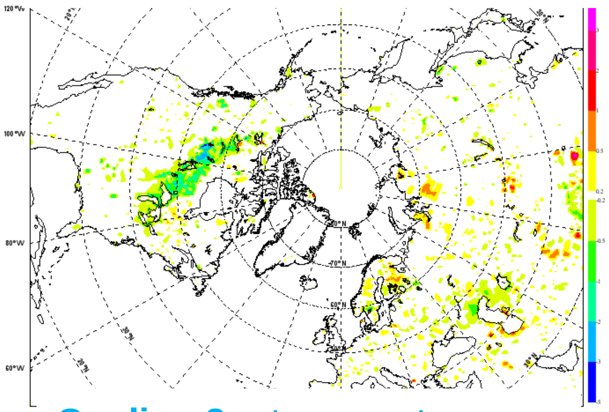
Impact of lakes in NWP forecasts

Balsamo et al. (2012, TELLUS-A) and ECMWF TM 648



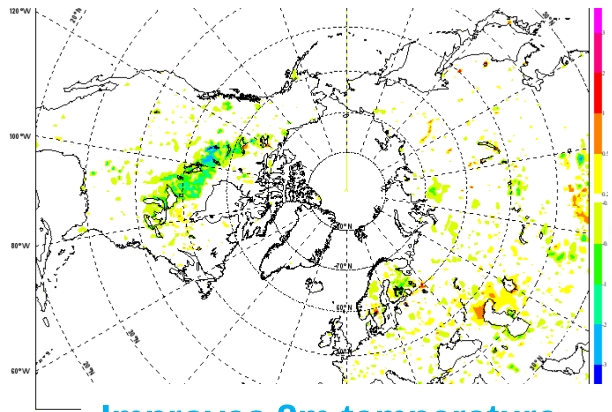
- **Forecasts sensitivity and impact of lakes is shown to produce a spring-cooling on lake areas with benefit on the temperatures forecasts (day-2 (48-hour forecast) at 2m.**
- **The lake surface temperatures are verified with MODIS LSTs as indicative of the heat-storage accuracy of the lake model**

Forecast sensitivity

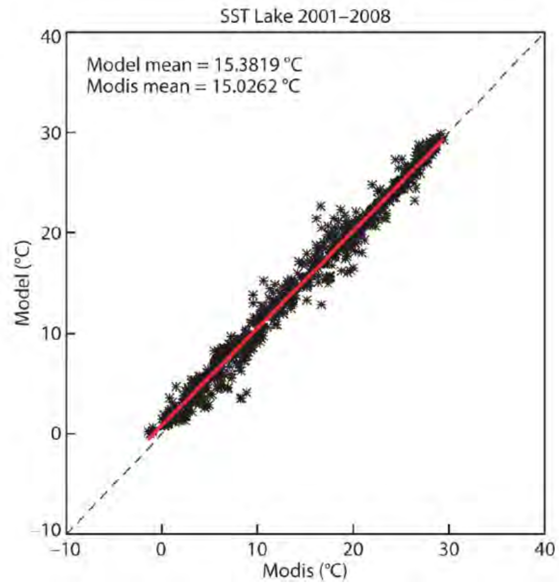


Cooling 2m temperature
Warming 2m temperature

Forecast impact



Improves 2m temperature
Degrades 2m temperature

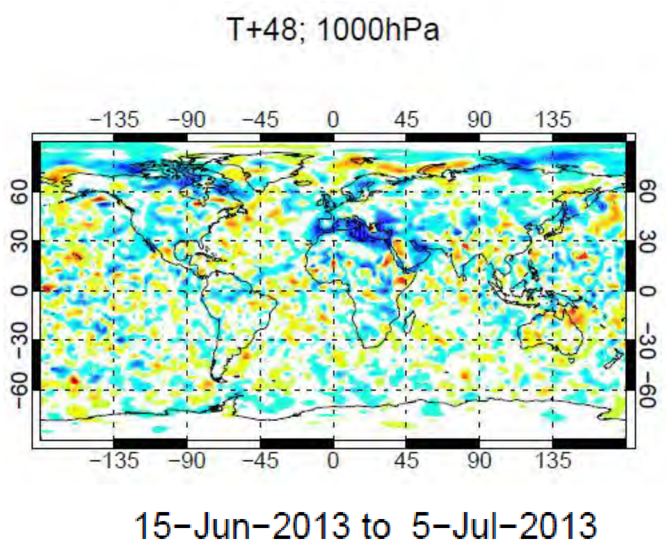


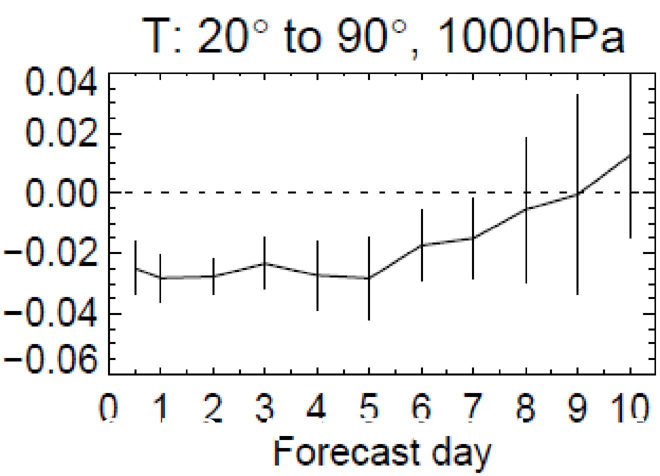
ECMWF

Impact of lakes in NWP analysis cycles

Summer experiment

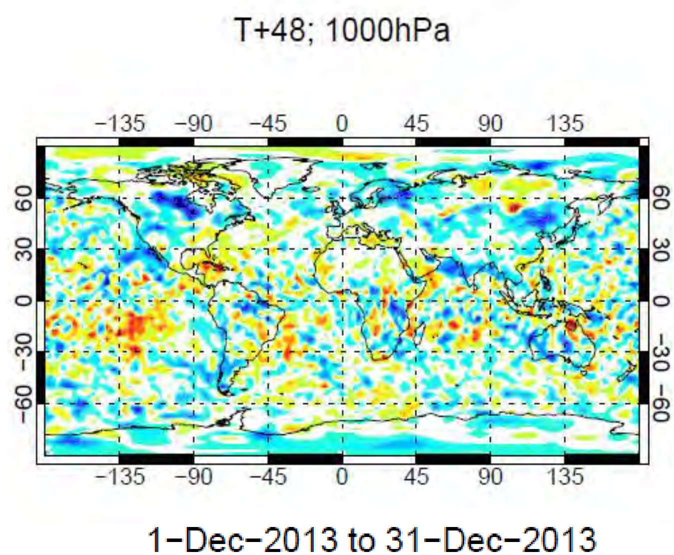
(Temperature scores)

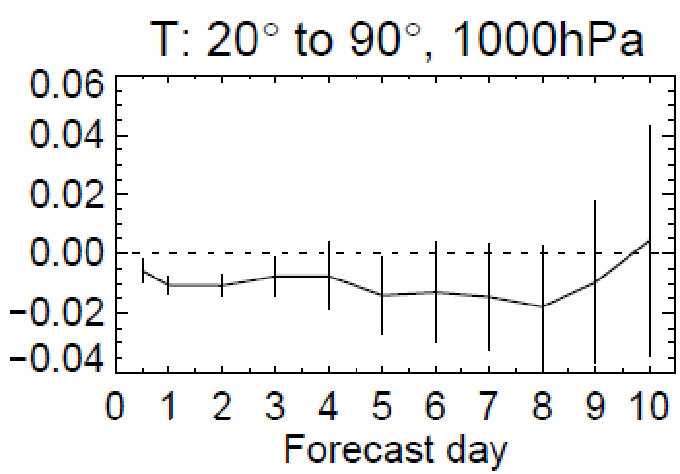




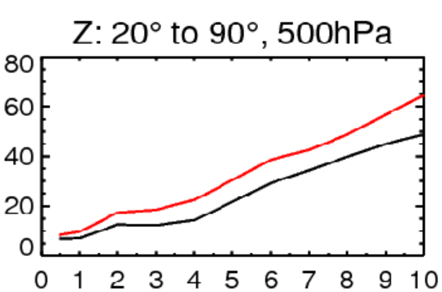
Winter experiment

(Temperature scores).





- Forecast of 2m temperature are improved in proximity of lakes and coastal areas
- Winter RMSE impact is positive as well but of around 1%
- In summer The impact is estimated in 2-3% relative improvement in RMSE of T1000hPa significant up to 7 days
- In summer Z500 mean error is reduced



ECMWF

Land Data Assimilation System

Patricia de Rosnay, Clément Albergel, Joaquin Munoz-Sabater
page:https://software.ecmwf.int/wiki/display/LDAS/LDAS+Home

LDAS exploits multi-sensors **satellite** remote sensing combined with ***in-situ*** for spatially integrated land water reservoirs monitoring & analyses (e.g. NWP/Climate applications)

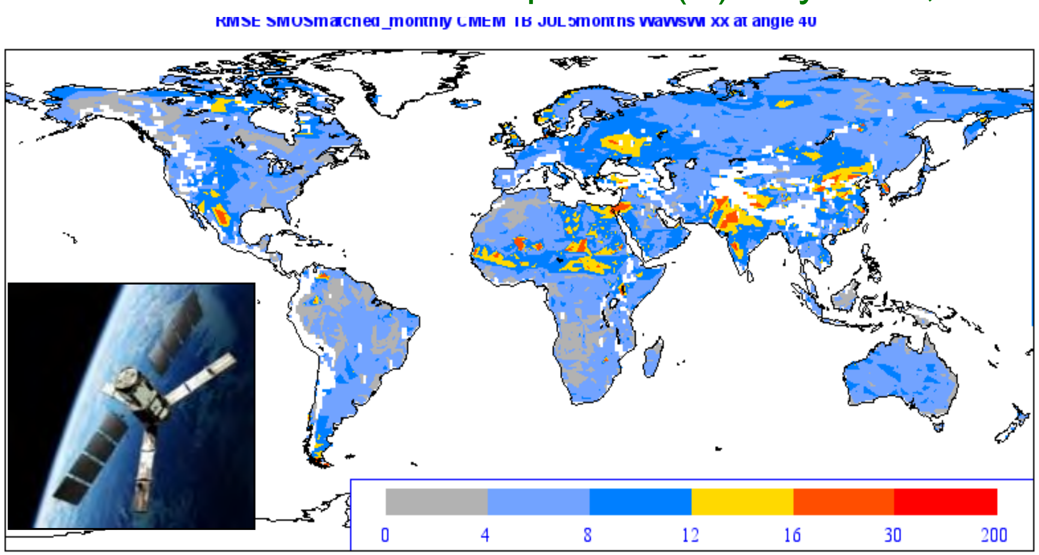
For soil moisture

- SYNOP *In-situ* T2m and RH2m; Satellite Scatterometer data (ERS/SCAT, MetOp/ASCAT), Passive microwave SMOS.

For snow

- SYNOP in-situ depth and multi-sensor NOAA NESDIS/IMS product on cover

SMOS TB First Guess Departure (K) July 2012, RMSD=6.7K



Future missions relevant for Land

Water cycle

- SMAP Active-passive MW (2014) and SWOT altimetry (NASA/CNES - 2020) highly relevant for Soil moisture and Sentinel-3 snow cover

Energy cycle

- METOP and MTG LSTs

Carbon cycle

- Sentinel 2 (LAI/Albedo), BIOMASS

In-situ networks for snow, temperature, soil moisture, and fluxes important also for verification

ASCAT SSM data assimilation

The EUMETSAT Network of Satellite Application Facilities

H SAF Support to Operational Hydrology and Water Management

- Satellite data: surface soil moisture (top cm of soil)
- Data Assimilation (DA) to retrieve root zone soil moisture
- Started in 2008 (H-SAF DVPT), operational since 2012 (H-SAF CDOP2)

ECMWF Atmospheric conditions

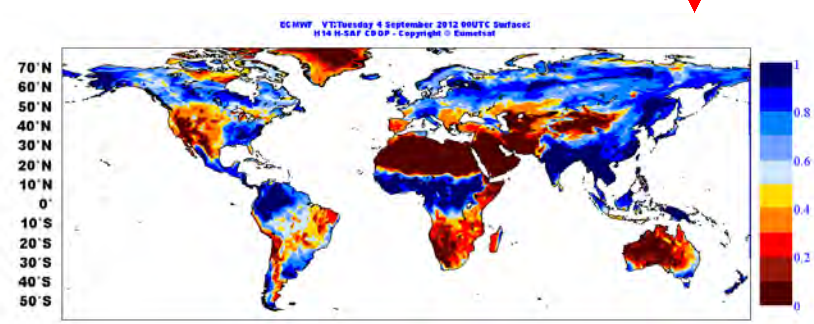
SYNOP
T2m RH2m

ASCAT
Surface SM
MetOp A&B

EKF
Soil Moisture
Analysis

SM-DAS-2/H14:
Root zone
Soil Moisture
Profile

~25km



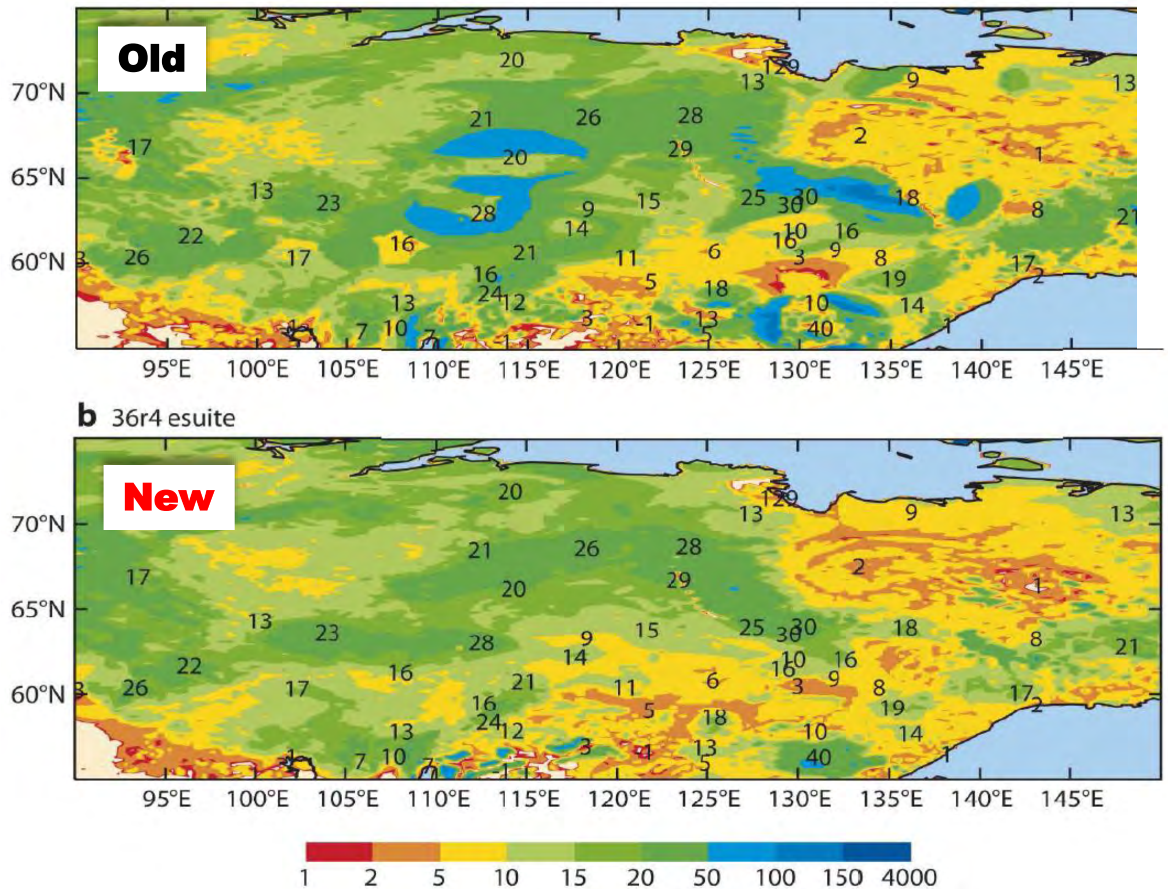
ASCAT seasonal Bias correction
based on CDF-matching **(de Rosnay et al., 2011)**

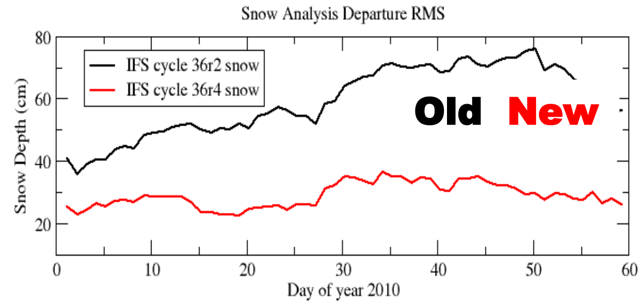
http://hsaf.meteoam.it/soil-moisture.php

ECMWF

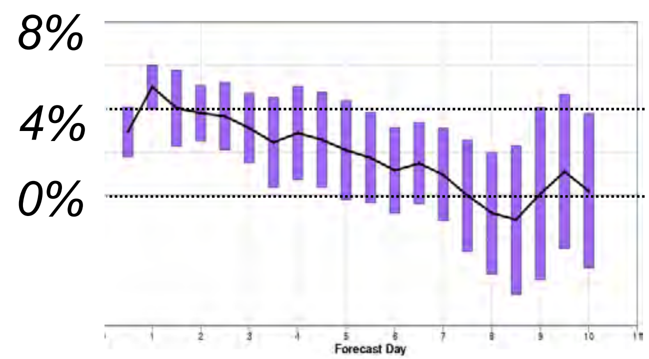
Snow Optimal Interpolation Analysis

de Rosnay et al (2012, *Surveys in Geophysics*)





Better match to observed snow depth (SYNOPs)



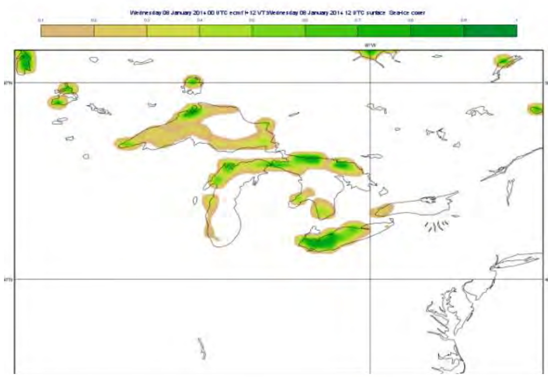
Comparison of OI and Cressman snow analyses on the 30 October 2010 (from de de Rosnay et al. 2012). SYNOP observations values in black.

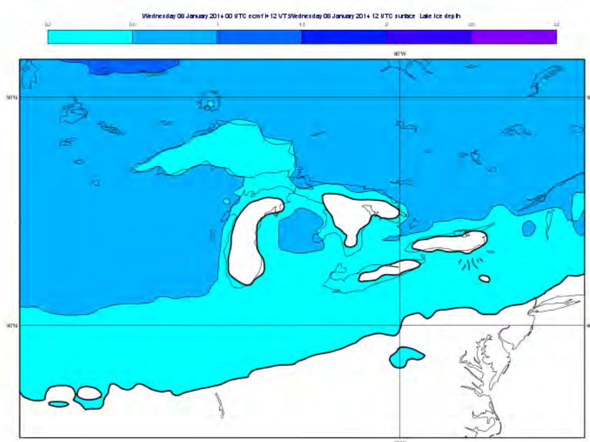
An improvement of up to 3-4% on Z500 hPa over Est Asia (in first 5 days of forecast range)

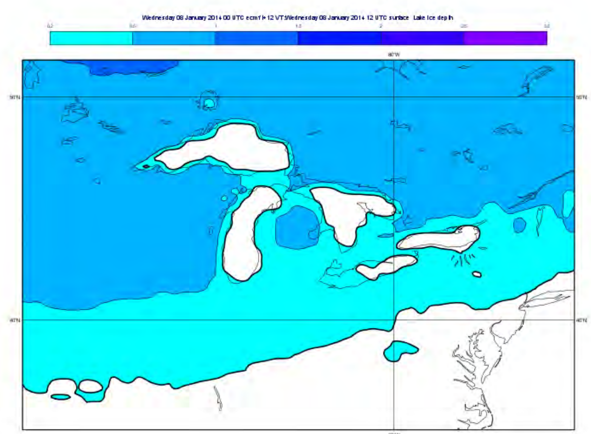
ECMWF

Initialization of inland water bodies (a first steps towards data assimilation)

- **Initialization of lakes and coastal waters using satellite SST/LST and ice conditions is crucial for atmospheric forecast performance (lake forecast is a initial value problem) and constrain modelling errors**





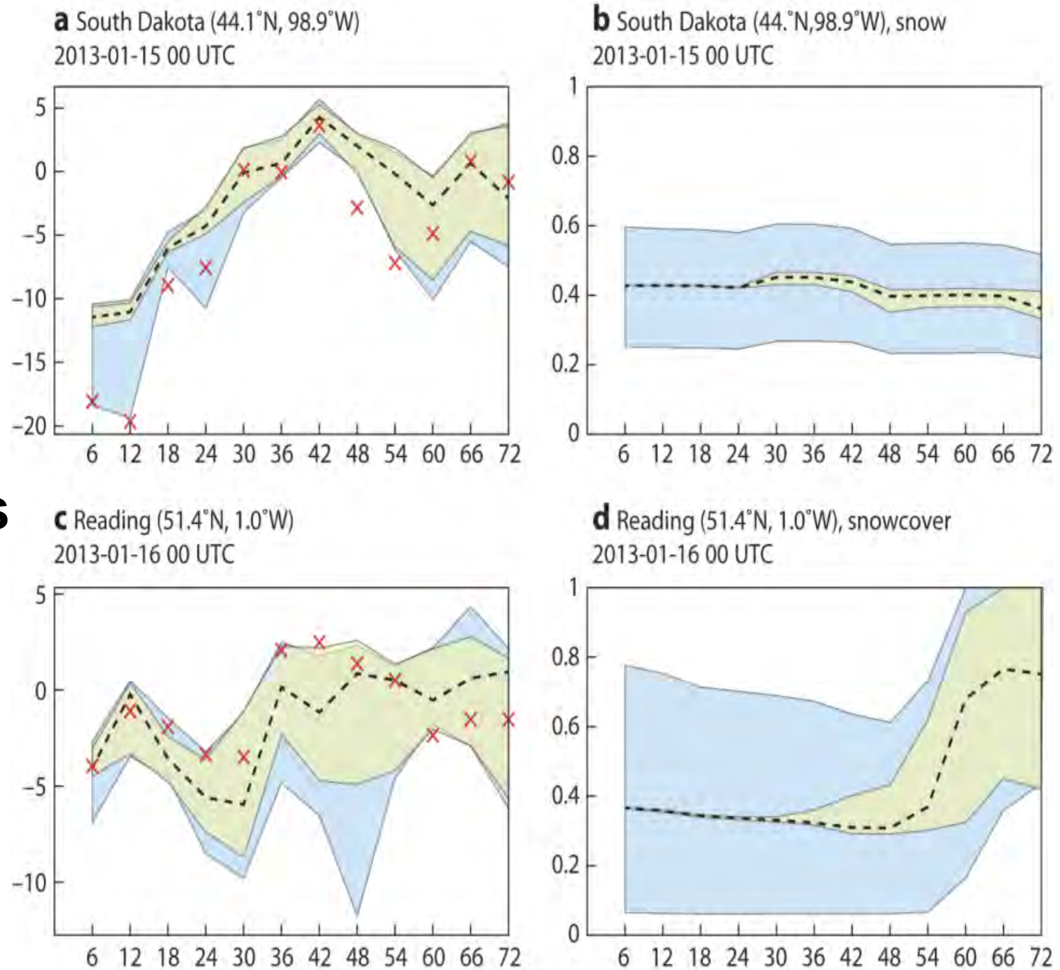


- The model error are attributed to lack of fractional lake ice.
- The lake model freeze entire grid-box.
- Effective initialization of water (add a mix layer and an inertial heat) together with the ice cover was implemented.
- This led to a further improve in winter forecasts scores

Representing land uncertainties

Lang et al. (2013, RM), Balsamo et al. (2014)

- **Forecasting is a probability problem at all forecast-range**
- **Ensemble are used to represent uncertainties and permit to extract probabilities of occurrence of extremes**
- **Accounting for uncertainties in soil moisture and snow enhances the ensemble spread**

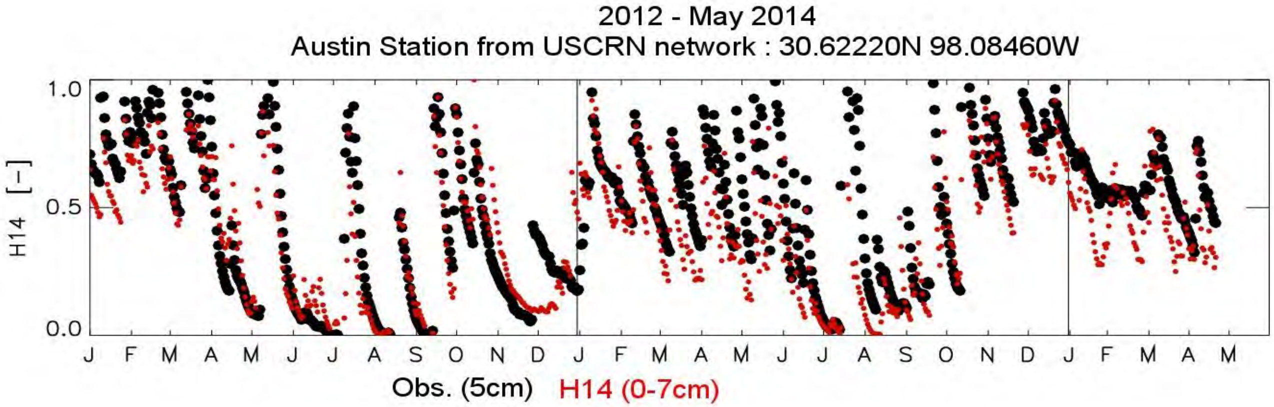


ECMWF

Verifying land moisture and temperature with in-situ

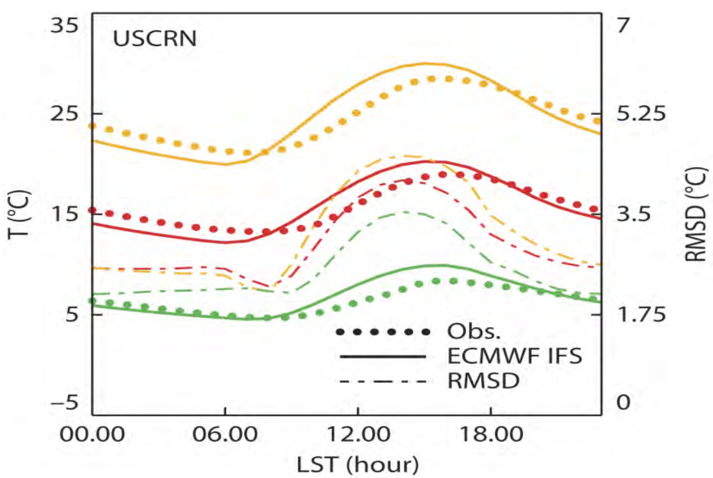
Albergel et al. (2014JHM, 2014JGR submitted)

- **Soil moisture**



H-SAF SM-DAS2 analysed soil moisture verification in the framework of EUMETSAT H-SAF. Site at Austin, Tx

- **Soil temperature**

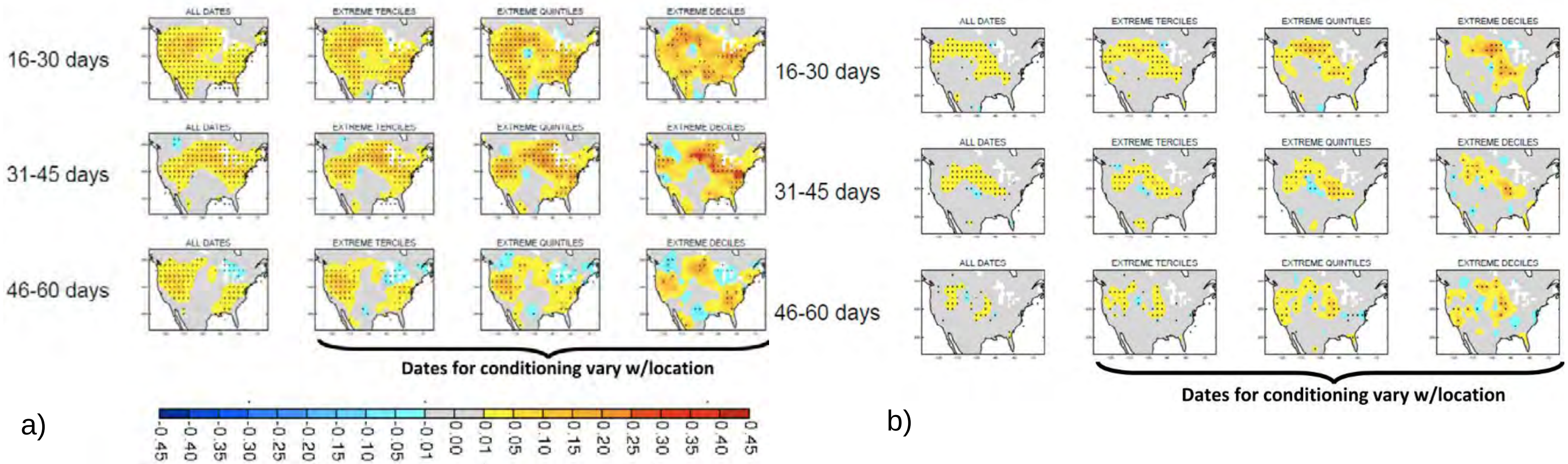


Mean diurnal soil temperature cycle for the USCRN spanning the entire USA for the year of 2012 (red), January to March (JFM in green) and July to September (JAS in orange). Dashed lines represent the mean diurnal RMS error between ECMWF 0 to 24 hour forecasts and observations.

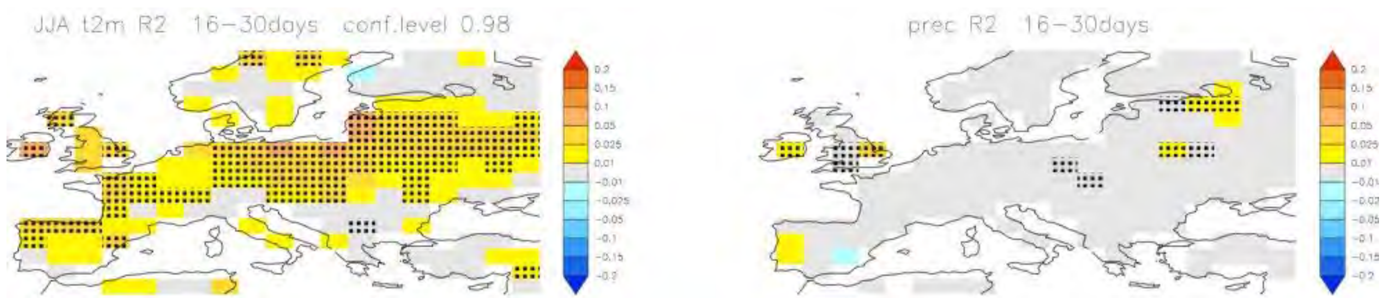
ECMWF

Predictability from soil moisture initialization

Koster et al. (2010), van den Hurk et al. (2012)



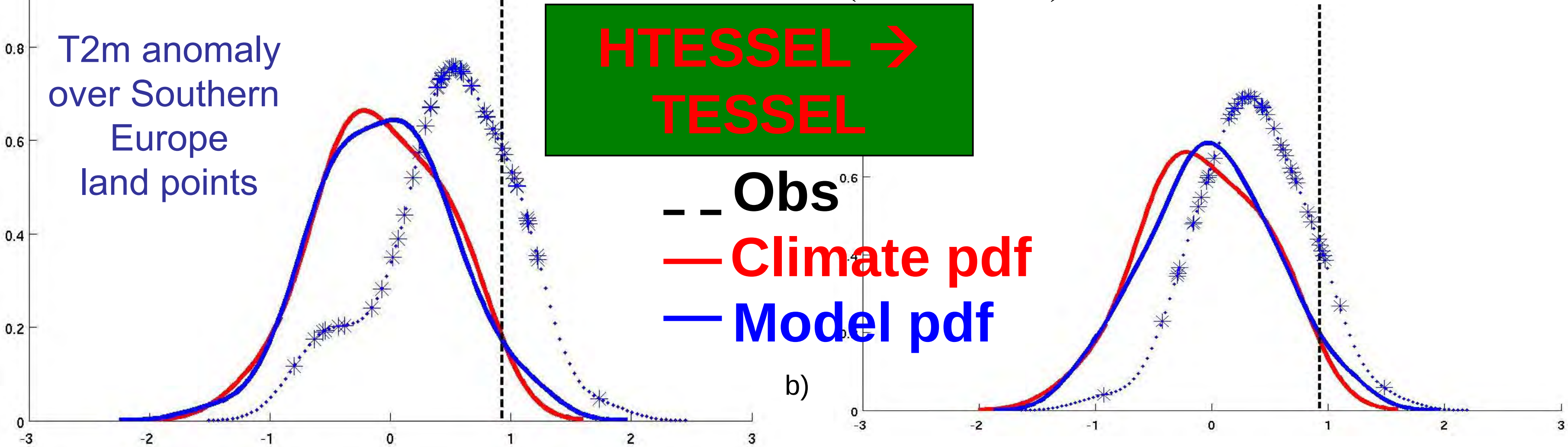
Predictability gain (mesured in r²) for (a) 2m temperature (b) precipitation when initializing with realistic soil moisture (following GLACE2 Koster et al. 2010). Columns refer to (i) all dates, (ii) dates upper terciles, (iii) quintile (iv) decile, according to soil moisture anomaly.



Predictability gain (mesured in r²) for Europe for 2m temperature (left) and precipitation (right) from van den Hurk et al., (2012) for the 16-30 days of the forecast range.

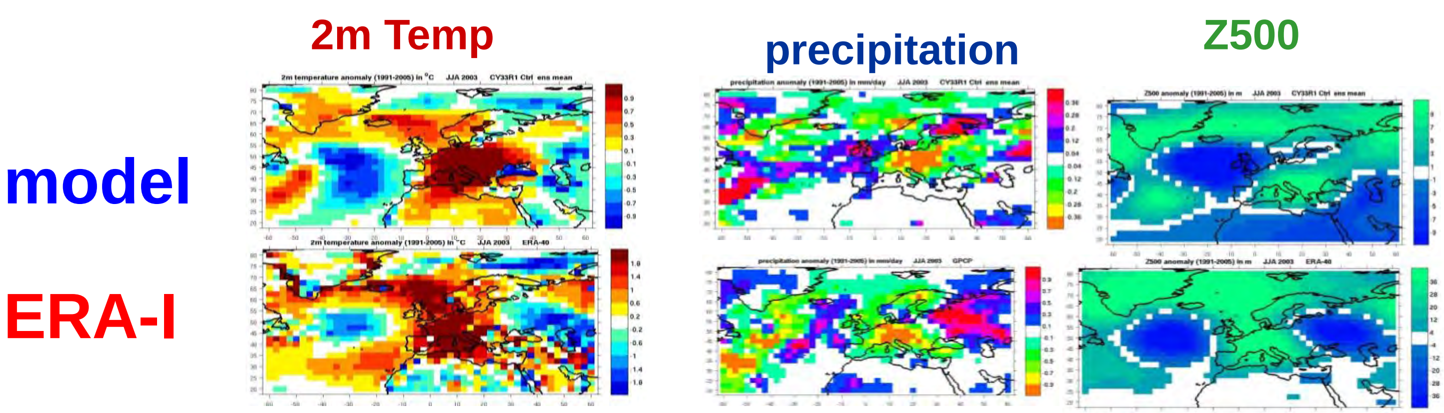
Predictability from soil model improvements

Weisheimer et al. (GRL 2011)



Forecast (50 ensemble members) *******
observed anomaly, analysis climate, model climate

hindcast period: 1991-2005



*Soil moisture was only one component leading to a fair forecast (**Convection** and **Radiation** also played an important role on large scale dynamical forcing*

ECMWF

Predictability from snow model improvements

Dutra et al. 2011 JGR, Dutra et al. 2012, JHM

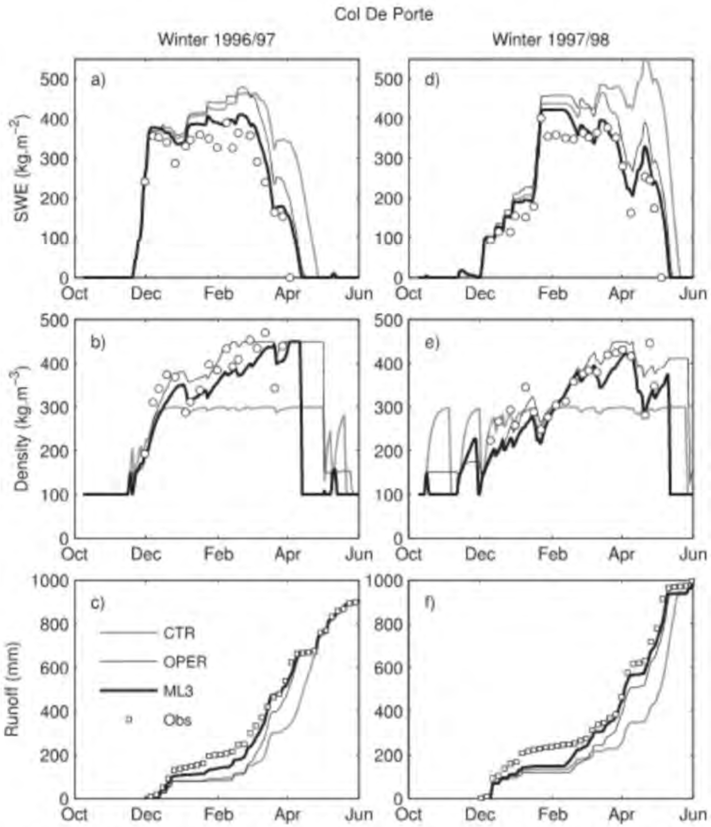


FIG. 1. Simulation results for CTR (gray), OPER (thin black), and ML3 (thick black) for the (a)–(c) 1996/97 and (d)–(f) 1997/98 winter seasons at Col de Porte site: (a),(d) snow mass, (b),(e) snow density, and (c),(f) runoff. Observations are represented by open circles. Runoff was accumulated since 1 Dec of each year and is defined as liquid precipitation and snowmelt that is in excess of the snow-cover holding capacity.

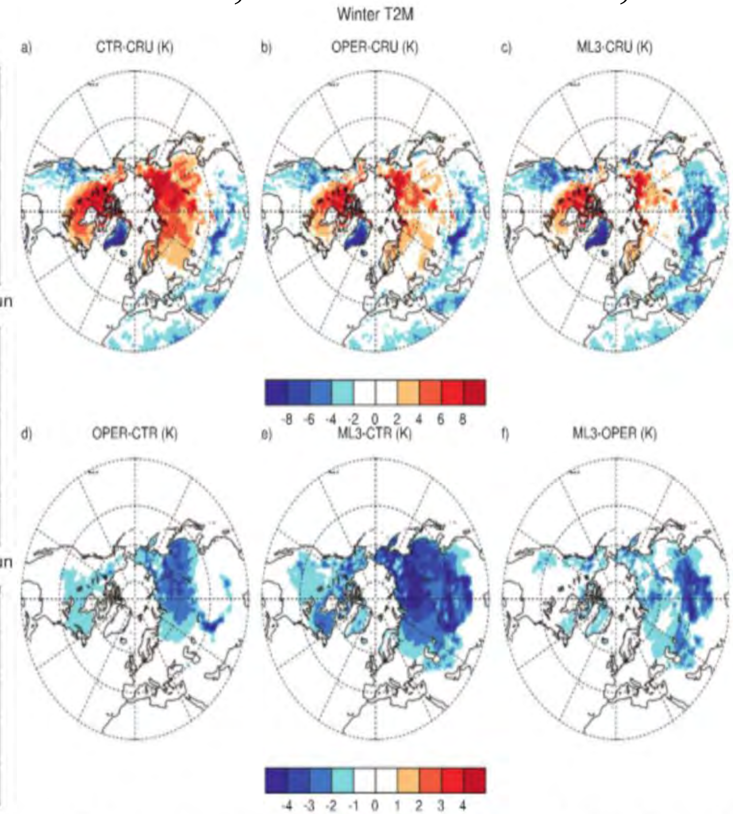


FIG. 13. Simulated winter 2-m temperature (K) biases of (a) CTR, (b) OPER, and (c) ML3 compared against CRU, and differences between (d) OPER and CTR, (e) ML3 and CTR, and (f) ML3 and OPER. Only differences significant at $p < 0.05$ are represented. Note the different color scales between (a)–(c) and (d)–(f).

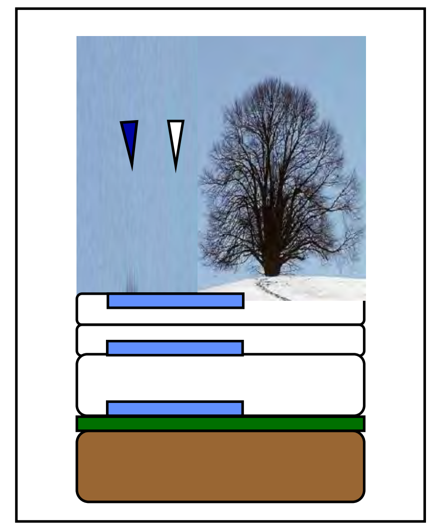
- **ML3 SNOW**

  Dutra et al. (2012)

  Up to 3 layers

  Liquid water (prognostic)

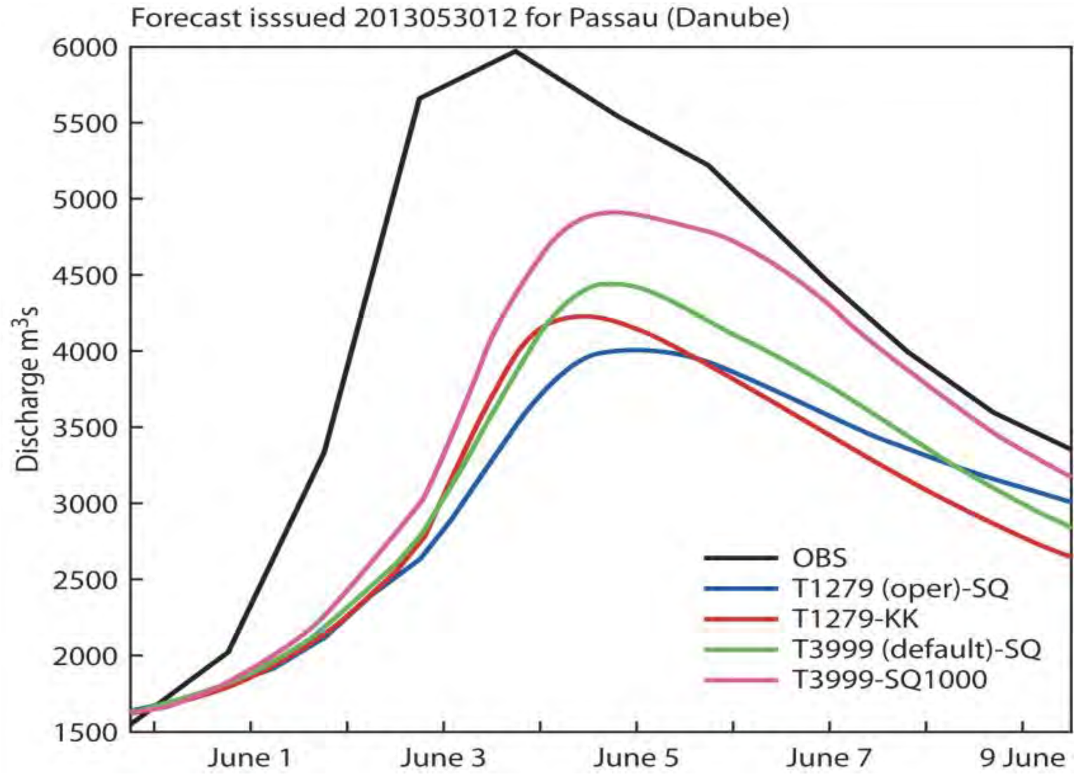
  Larger diurnal cycles (due to



A research version multi-layer snow scheme has been developed for climate application (e.g. EC-Earth) and will be studied in EartH2Observe project. This includes up to 3 layers, an improved water cycle and further reduction of temperature bias (cooling effect in deep snow).

Predictability from resolution increase

Haiden et al. (2014, TM723) and EFAS team



European flood event May 2013: Forecast discharge levels with two different model resolutions (T1279, 16km in blue and T3999 at 5 km in green) for the station Passau at the river Danube. The black line denotes the EFAS simulated discharge using observed precipitation, interpreted as the forecast potential. The red and magenta lines indicate the improvement in river discharge forecasts with improved cloud physics for the T1279 and T3999 resolution respectively

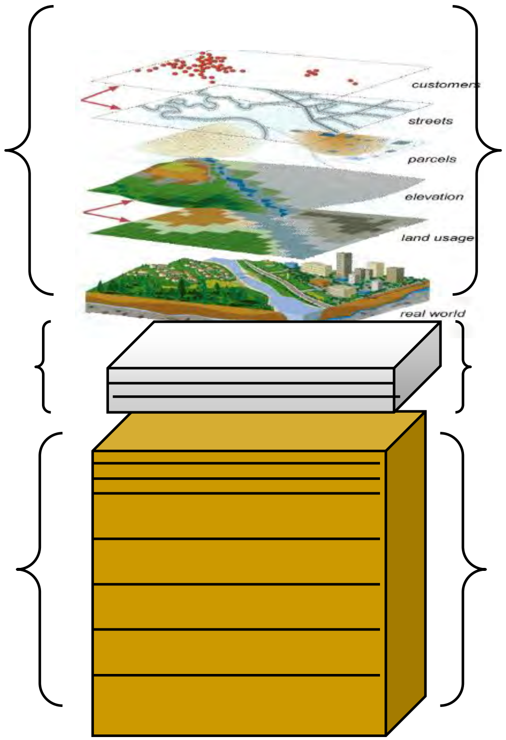
- Higher resolution and improved physics holds promise to enhance the realism of precipitation in extreme events
- Ensemble Data Assimilation will play a crucial role right from the start of th forecast up to monthly range

Conclusions

- Soil, vegetation, snow and inland water bodies act as reservoirs and modulate the energy, water and carbon cycle
- Representing the size of the reservoir and the main fluxes at the interface with the atmosphere has received considerable research attention and lead to operational forecasting improvements
- Those earth surface components are slow and present predictability potential al longer lead time, but require accurate initial condition
- Land Data Assimilation and modelling components have evolved in synergy to face the challenge of a more realistic representation
- Land surface model error is evaluated and represented in ENS, but still subject under-dispersion (missing processes?)

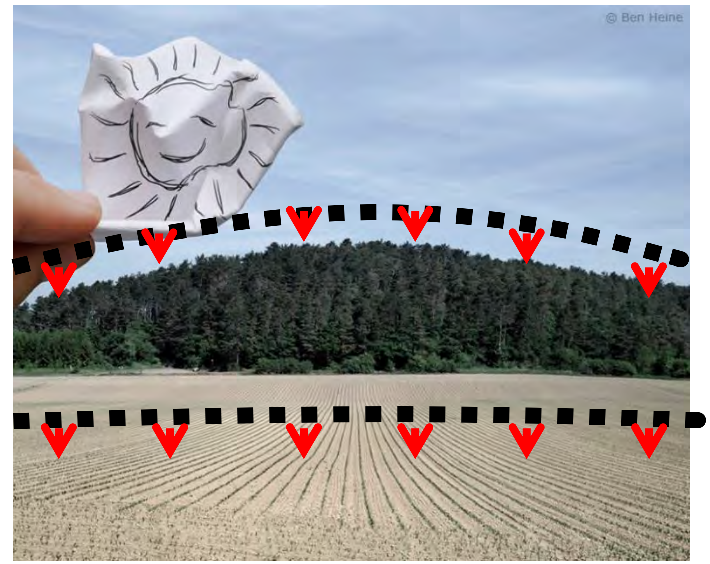
Perspectives for surface modelling & DA

Moving towards a more integrated modelling of the earth ecosystems



- Better vertical discretisation
- Better account of sub-grid variability
- Reconciliation of processes and schemes (eg.cryosphere)

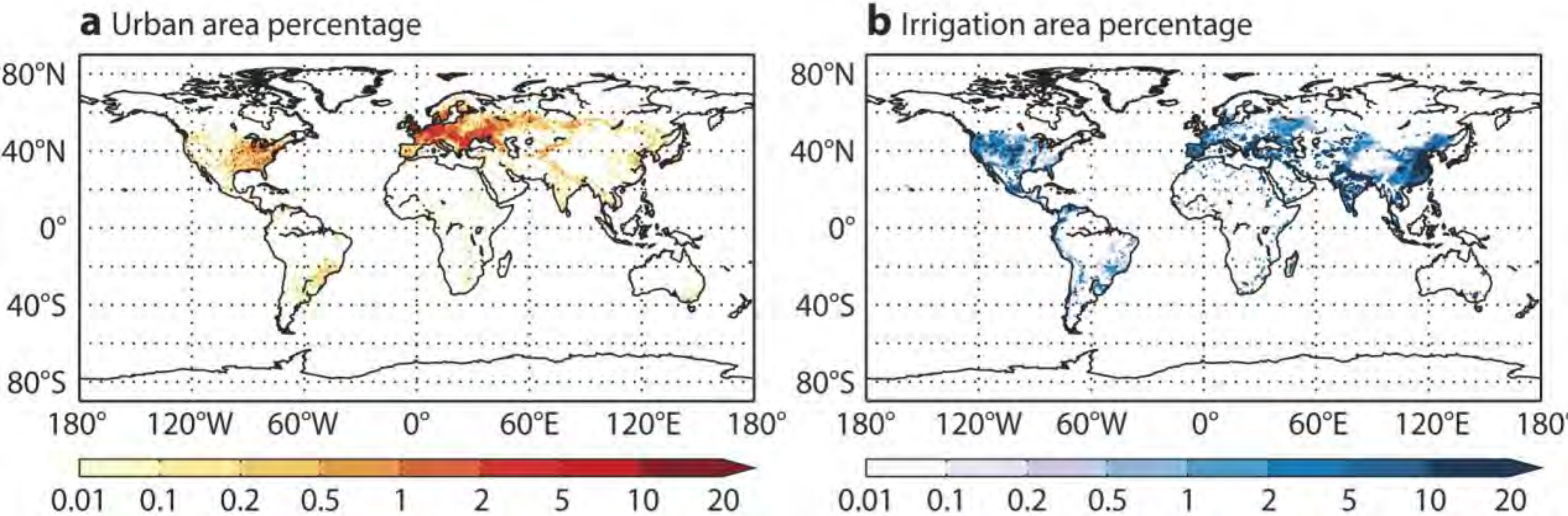
Moving towards a modular, stand-alone, adaptative, data assimilation system that can be used for both parameters and state variables



- Towards greater use optimality diagnostics
- Methods better adapted to non-linearity
- Integration in couple reanalysis

Missing surface components

- Human action on the land and water use is currently neglected in most NWP models…

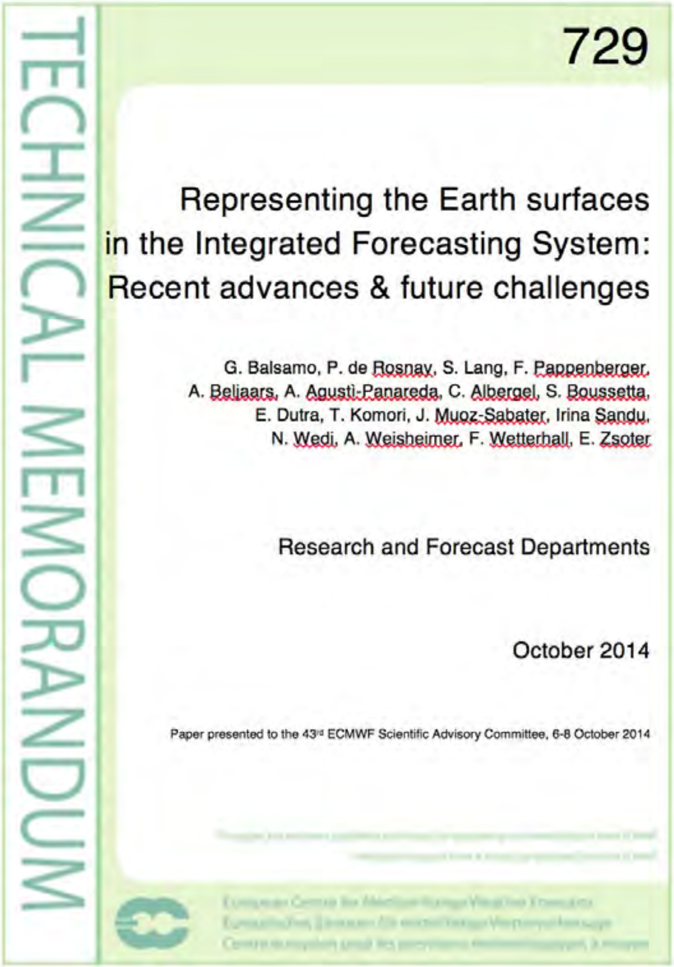


- Urban area (a, in %, from ECOCLIMAP, Masson et al., 2003) and
- Irrigated area (b, in %, from Döll and Siebert, 2002)

- **Thanks for your attention, questions, remarks**

- **Further reading:**

Balsamo, G., P. de Rosnay, S. Lang, F. Pappenberger, A. Agustì-Panareda, C. Albergel, A. Beljaars, S. Boussetta, E. Dutra, T. Komori, J. Munoz-Sabater, Irina Sandu, N. Wedi, A. Weisheimer, F. Wetterhall, E. Zsoter, 2014: Representing the Earth surfaces in the Integrated Forecasting System: Recent advances and future challenges, ECMWF Tech. Memo. 729, available from www.ecmwf.int. (in October 2014)


TECHNICAL MEMORANDUM

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Representing the Earth surfaces in the Integrated Forecasting System: Recent advances & future challenges

G. Balsamo, P. de Rosnay, S. Lang, F. Pappenberger, A. Beljaars, A. Agusti-Panareda, C. Albergel, S. Boussetta, E. Dutra, T. Komori, J. Muoz-Sabater, Irina Sandu, N. Wedi, A. Weisheimer, F. Wetterhall, E. Zsoter

Research and Forecast Departments

October 2014

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H-SAF & HEPEX workshop, 3-6 November 2014

http://ecmwf.int/en/h-saf-and-hepex-workshops-coupled-hydrology

Co-organized by
Patricia de Rosnay &
Florian Pappenberger