On the relative importance of continental surfaces in coupled Earth System Modelling

Which surface processes influence Earth System predictability?

Gianpaolo Balsamo

Coupling Processes Team, Earth System Model Section

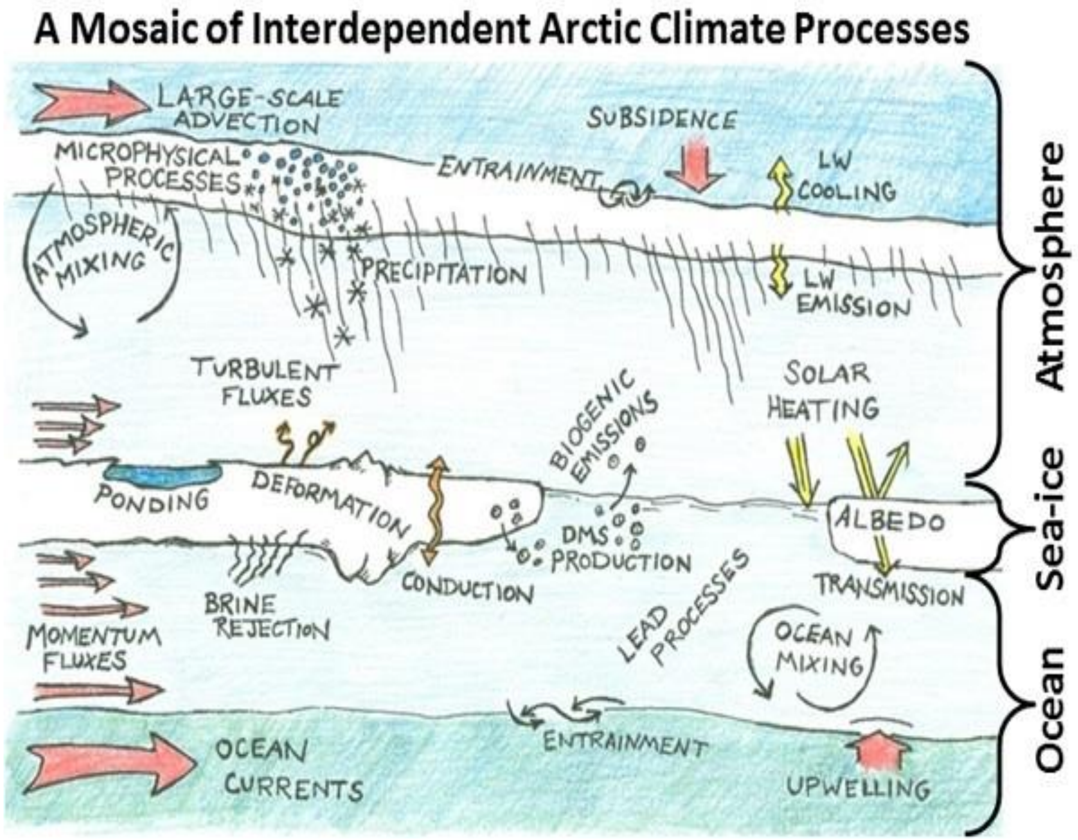
gianpaolo.balsamo@ecmwf.int

ECMWF

Rationale of talk

- Why Numerical Weather Prediction had to embrace Earth System Modelling?
  - It is much nicer and represent nature better? Do we gain?
- Biosphere, Hydrosphere, Cryosphere, and Atmosphere: Do they all matter the same?
  - Can we attempt a quantitative evaluation? What are the caveats?
- Diurnal and Seasonal amplitude improvements
  - How much are they drivers to accurate predictions?
- What else is in the “hat” and where do we need (r)evolutionary ideas?
  - Bridging gaps between modelling communities
  - Bringing new EO data to guide model development
- Roadmap to Global Environmental Monitoring and Prediction
  - If we can imagine it, probably we can do it?

How complex are the coupled Processes over land and ocean/sea-ice?



Source: Mosaic project

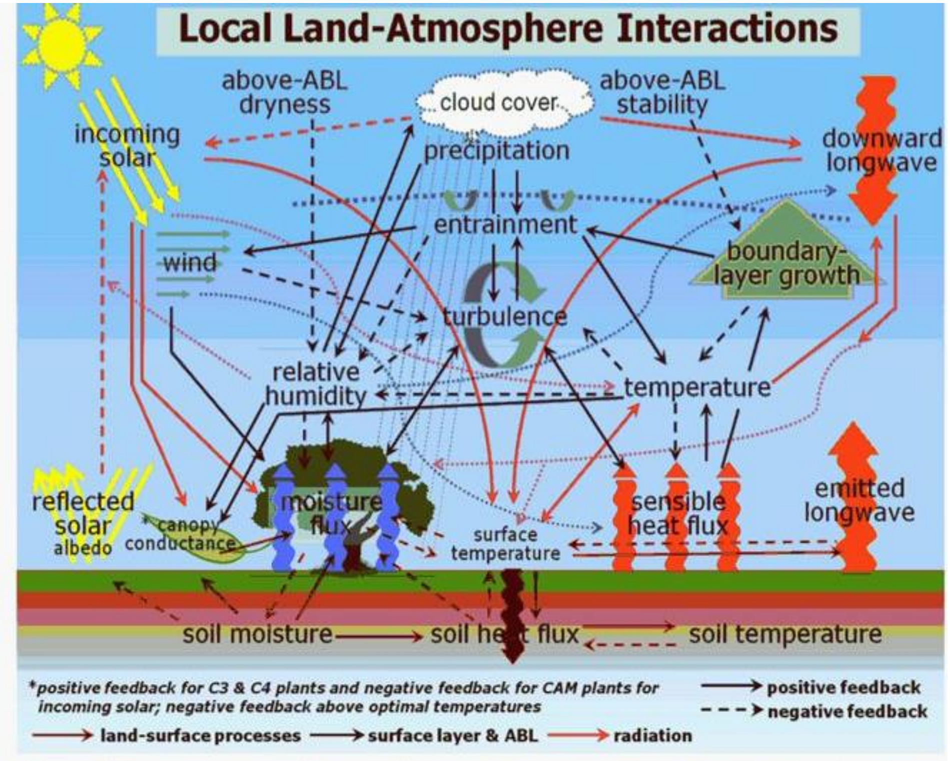


Fig. 3.1. Schematic of the complex interactions between the land surface, atmospheric boundary layer (ABL), and radiation via many variables (temperature, relative humidity, wind and associated turbulence, cloud cover, etc). Adapted from Ek and Holtslag (2004 *J. Hydromet.*, 5, 86-99), courtesy Mike Ek and Kevin Trenberth. 6

Source: GEWEX imperatives

Ocean, waves, sea-ice in ECMWF model (2016-2017)

- **NEMO3.4**

  NEMO3.4 (Nucleus for European Modelling of the Ocean)

  Madec et al. (2008)

  Mogensen et al. (2012)

  ORCA1_Z42: 1.0° x 1.0°

  ORCA025_Z75 : 0.25° x 0.25°

- **EC-WAM**

  ECMWF Wave Model

  Janssen, (2004)

  Janssen et al. (2013)

  ENS-WAM : 0.25° x 0.25°

  HRES-WAM: 0.125° x 0.125°

- **LIM2**

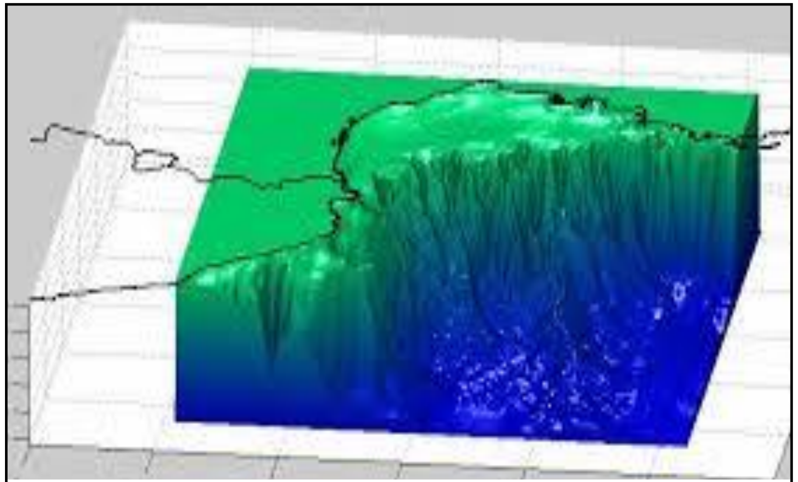
  The Louvain-la-Neuve Sea Ice Model

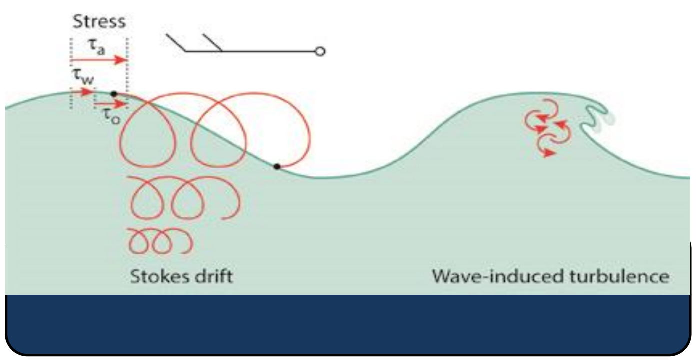
  Fichefet and Morales Maqueda (1997)

  Bouillon et al. (2009)

  Vancoppenolle et al. (2009)

  ORCA025_Z75 : 0.25° x 0.25°





Land surface model at ECMWF (2016-2017)

- **Hydrology-TESSEL**

  Balsamo et al. (2009)
  van den Hurk and Viterbo (2003)

  Global Soil Texture (FAO)

  New hydraulic properties

  Variable Infiltration capacity & surface runoff revision

- **NEW SNOW**

  Dutra et al. (2010)

  Revised snow density

  Liquid water reservoir

  Revision of Albedo and sub-grid snow cover

- **NEW LAI**

  Boussetta et al. (2013)

  New satellite-based

  Leaf-Area-Index

- **SOIL Evaporation**

  Balsamo et al. (2011),

  Albergel et al. (2012)

- **H_2O / E / CO_2**

  Integration of

  Carbon/Energy/Water

  Boussetta et al. 2013

  Agusti-Panareda et al. 2015

- **Lake & Coastal area**

  Mironov et al (2010),

  Dutra et al. (2010),

  Balsamo et al. (2012, 2010)

  Extra tile (9) to for sub-grid lakes and ice

  LW tiling (Dutra)

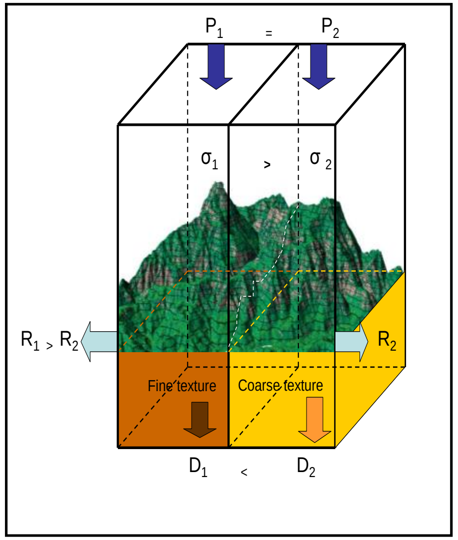
- **Enhance ML**

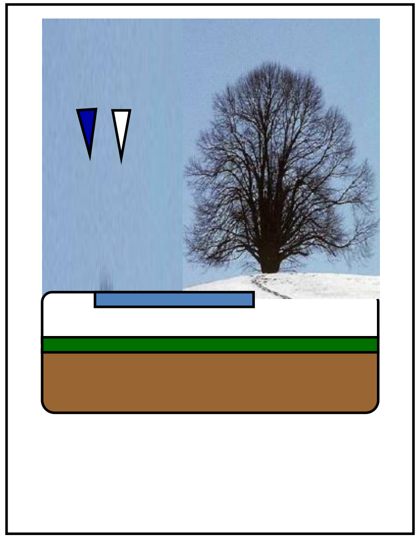
  Snow ML5

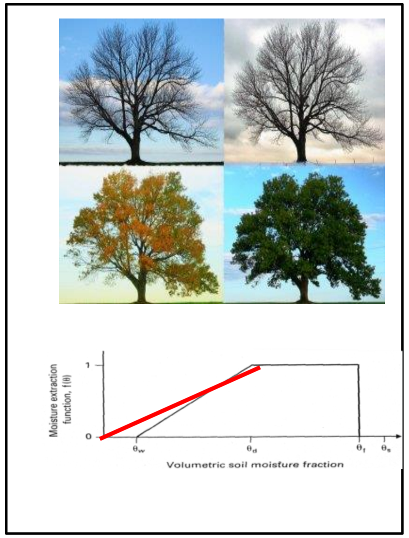
  Soil ML9

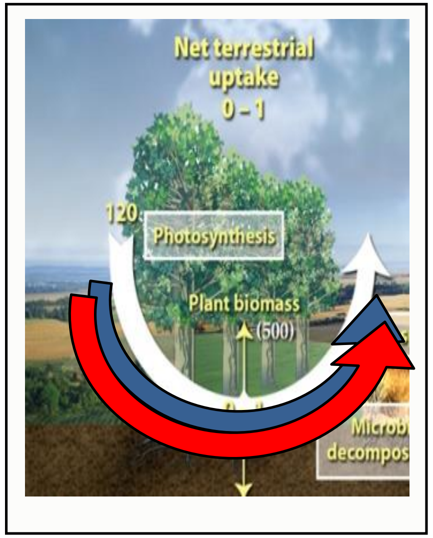
  Dutra et al. (2012, 2016)

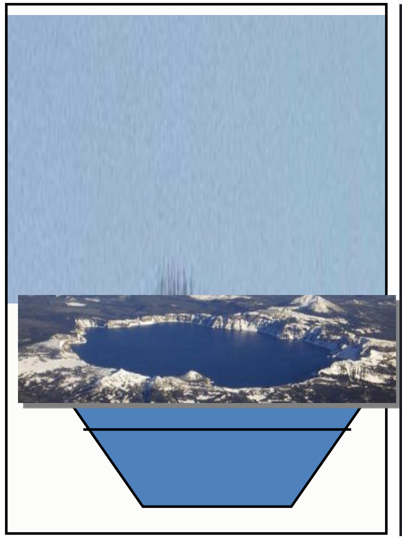
  Balsamo et al. (2016)

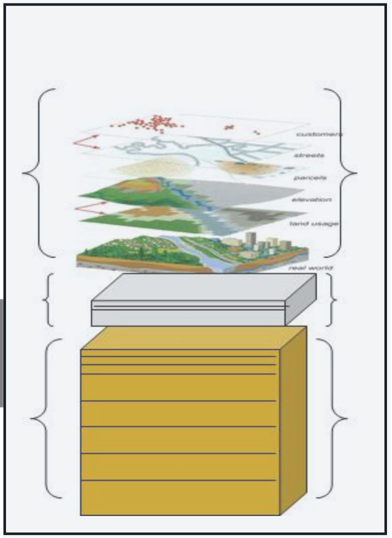






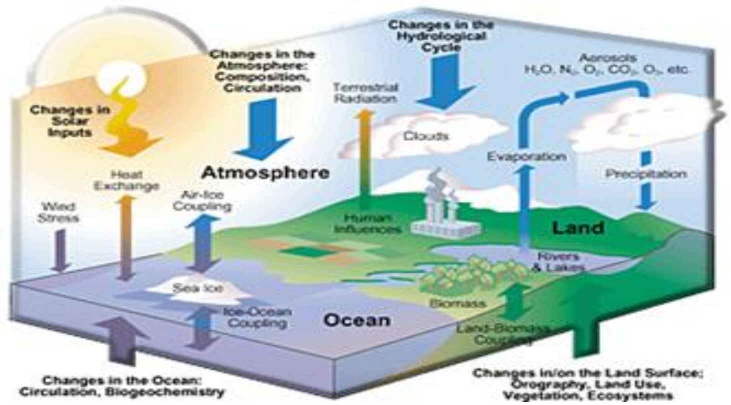


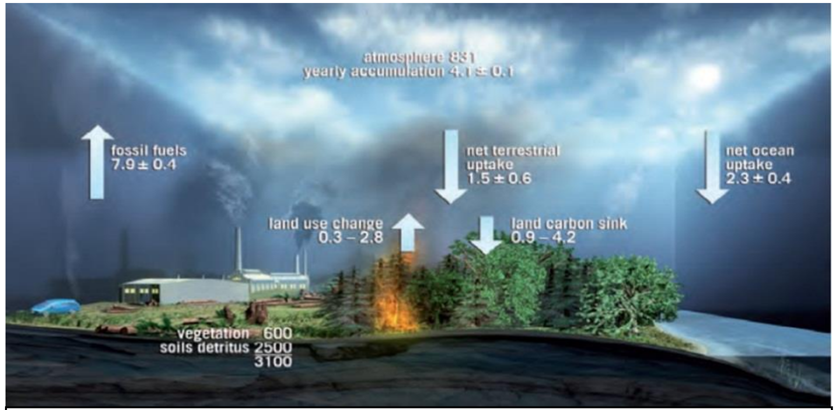




The water and Carbon cycle

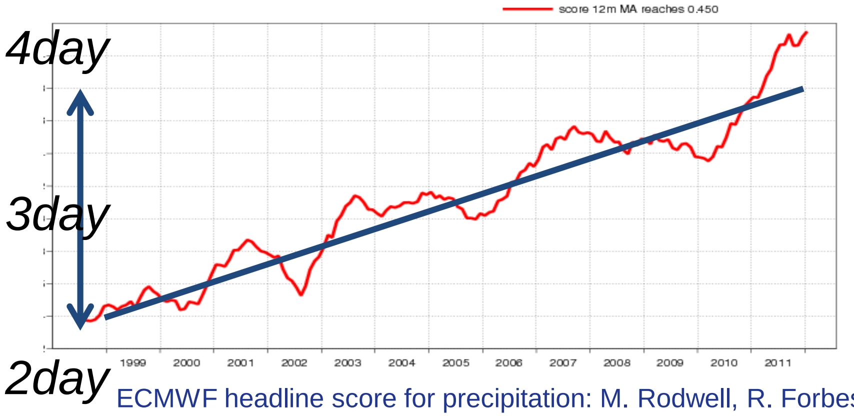
- **Numerical Weather Prediction models have considerably evolved over time with respect to how they represent the land surface and its interaction with the atmosphere**





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, 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

- **Enhanced Earth surface complexity is supported by quality of atmospheric forcing**

ECMWF

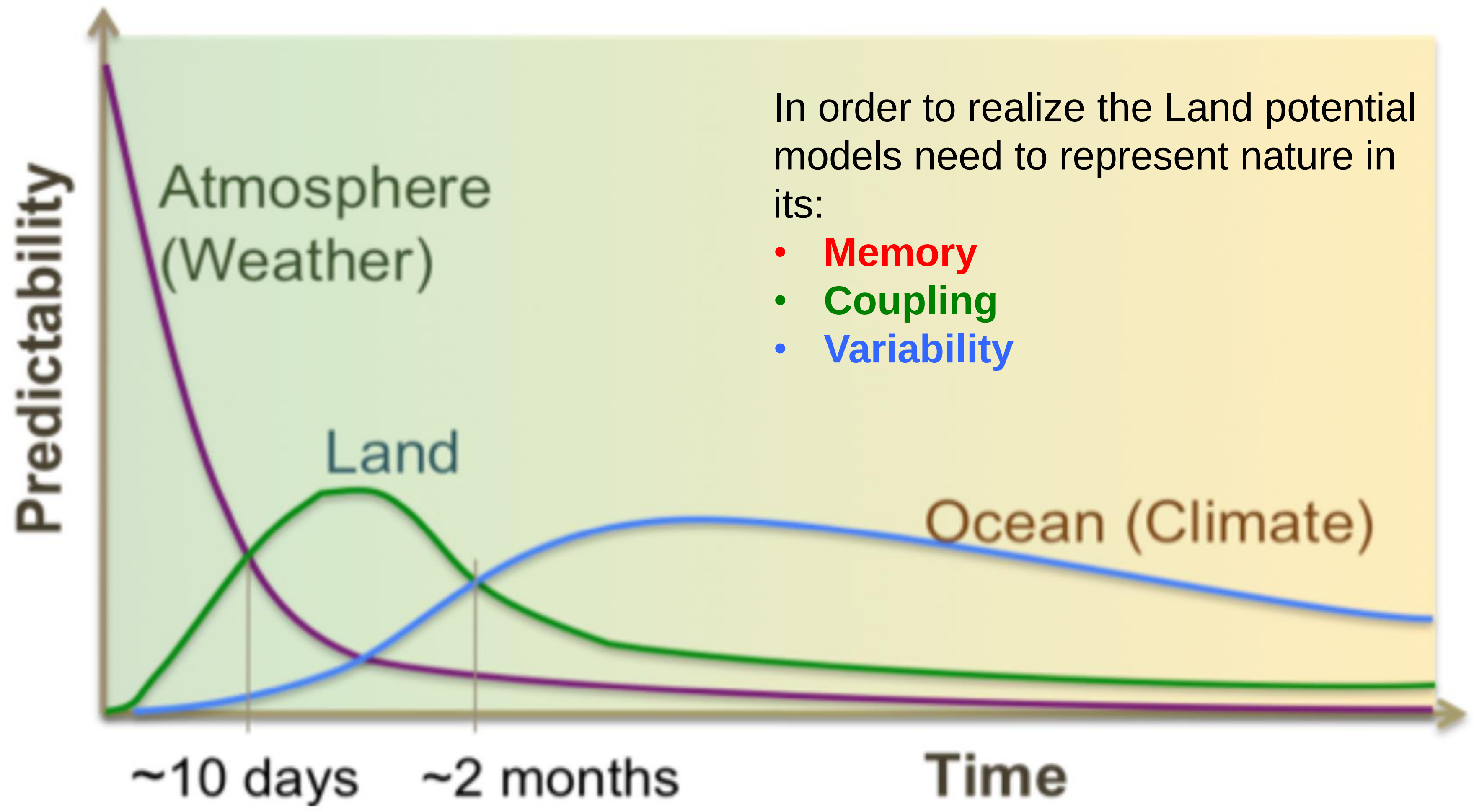
Impact of Earth Surface in Global Environmental prediction

- The surface is characterized by many slow processes
- A slow process makes initial condition a priority: they need to be accurate to extract predictability from the modelling components
- Can we say all surface predictability rely on initial condition accuracy?
- What is the value of surface process representation in models?

Value of Earth Surface Global Environmental prediction

- The surface is where we live and it sustains all human activities.
- Forecasting the surface state has value per se (e.g. floods, droughts, biomass-anomalies, sea-state, ice & snow conditions all matters for users).
- Most importantly better surface can sustain medium/extended range skill.
- But can we prove it experimentally? And which surface process does what?

Earth surface role in medium-range and S2S



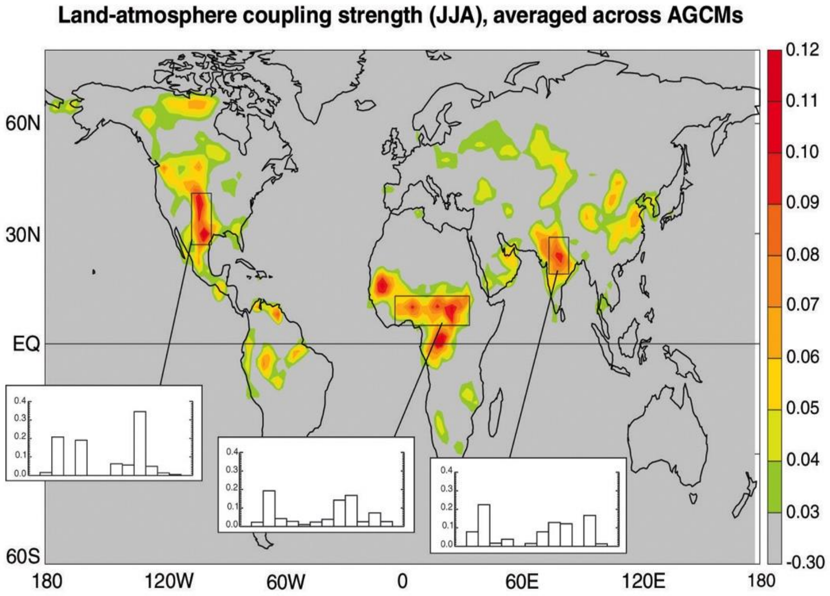
In order to realize the Land potential models need to represent nature in its:

- **Memory**
- **Coupling**
- **Variability**

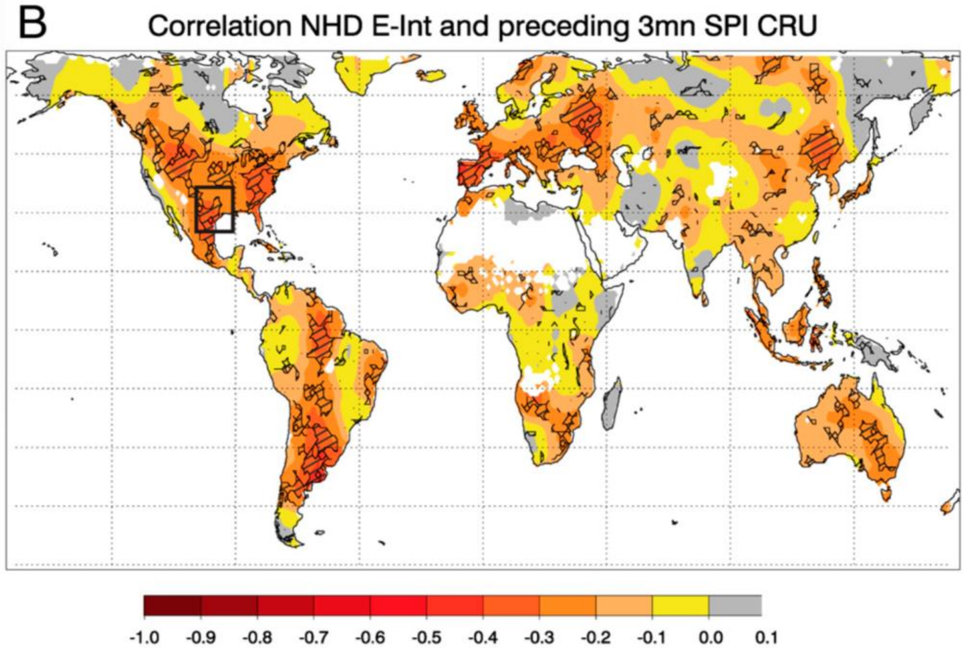
Dirmeyer et al. 2015: http://library.wmo.int/pmb_ged/wmo_1156_en.pdf

Earth surface role, experimental evidence (soil moisture)

Koster et al. 2004 Science
Land-coupling (SM-T) in Northern Hemisphere JJA

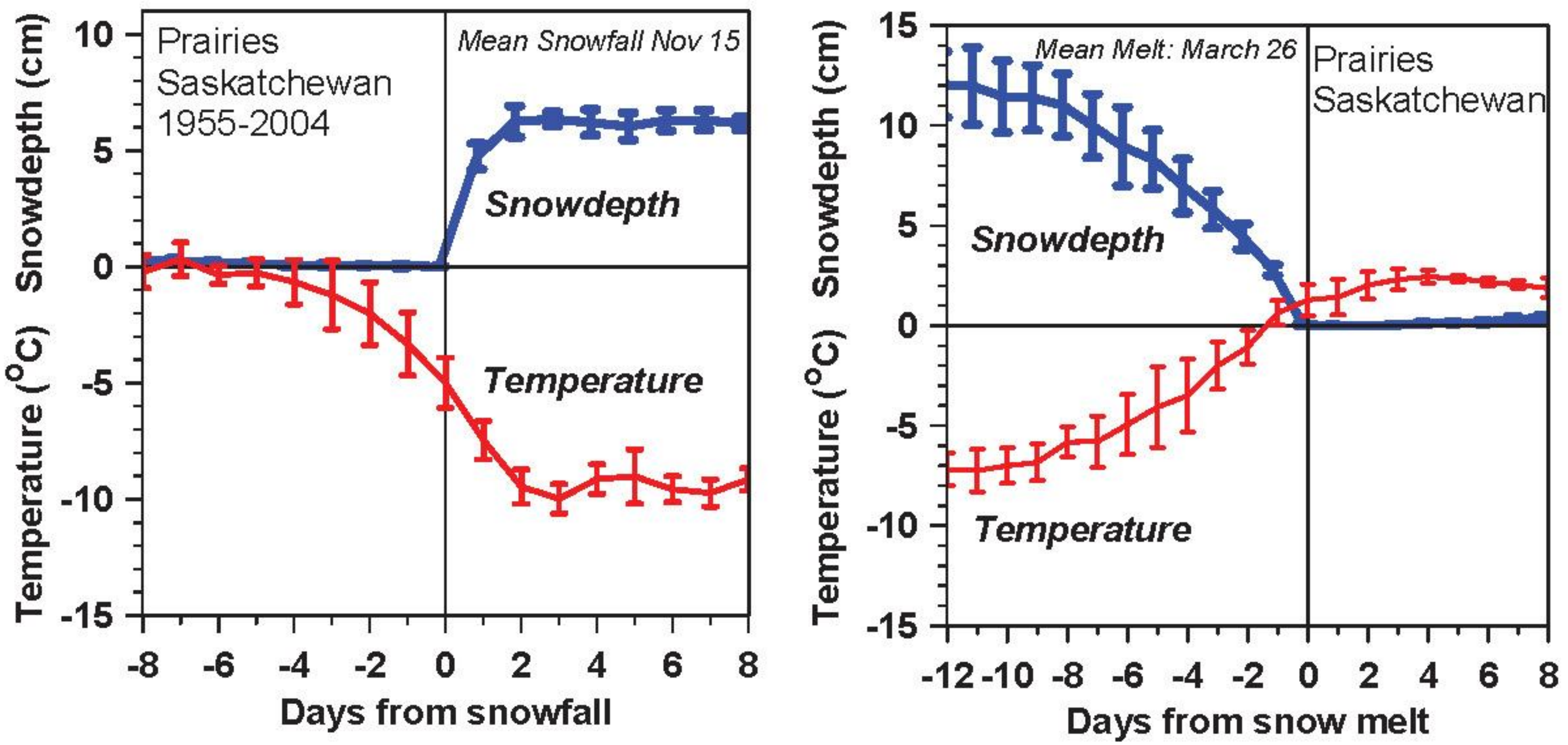


Mueller and Seneviratne 2012 PNAS
Hot-Days correlation with 3-month antecedent P deficit



Albergel et al. 2013JHM show dominance of significant drying trends for soil moisture in both reanalysis and satellite-based soil moisture dataset, with possibly larger areas of land surface predictability

Earth surface role, observational evidence (snow)



Snow reflects sunlight; shift to cold stable BL

<u>Local climate switch</u> between warm and cold seasons

Winter comes fast with snow

Betts et al. 2014

Earth surface role, literature (sea-ice)

“Arctic sea ice …has strong feedback effects on the other components of the climate system”

Vihma 2014, Survey in Geophysics

“Arctic sea ice change includes global scale impacts, as well as regionally changing interaction mechanisms and Trends”

Doscher et al. 2014, ACP

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Designing a “Process-denial” experiment for the ECMWF Earth-System

- With the scope of trying to answer to the proposed seminar question on process relevance for NWP & Climate timescales independently from initial conditions skill.
- A surface “process-denial protocol” (persistence) in a given set processes applied:

(1) **Soil processes** (2) **Snow processes** (3) **Sea-ice processes** (4) **Lakes processes**

(5) **All the above processes**

PROTOCOL:

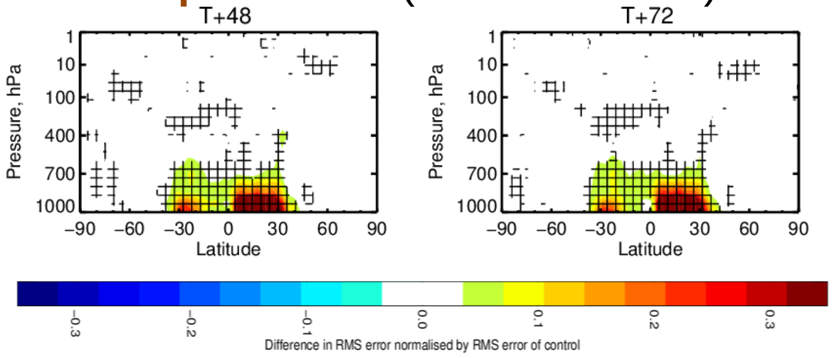
- Using the 43r1 ECMWF model cycle due to become operational later in 2016
  - Latest atmospheric and land physics package (run at Tco399L137, about ¼ of degree)
  - New ¼ degree ocean 75-layer with a top 1m slab (NEMO3.4)
  - New ¼ degree sea-ice model (LIM2)
- 1 full year of daily forecast (tendency=0 for each process) (June2015-June 2016, 10-day FC)
- 4-year climate integration (August 2000-2004, 13-month prediction, at 0.7 degree resolution)

CAVEAT & ADVANTAGE:

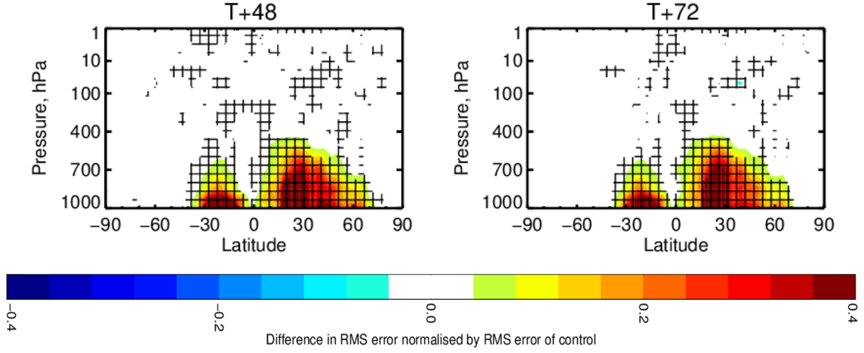
- Model dependent results! A single quantitative evaluation allows a comparative discussion!

Soil and Snow forecast impact

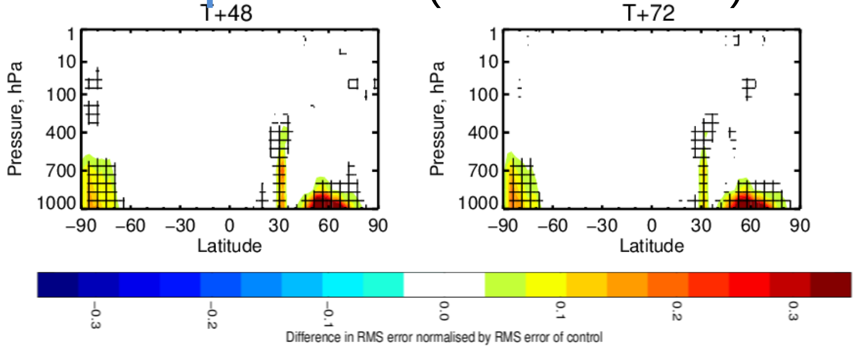
Soil processes (winter 2015-16)



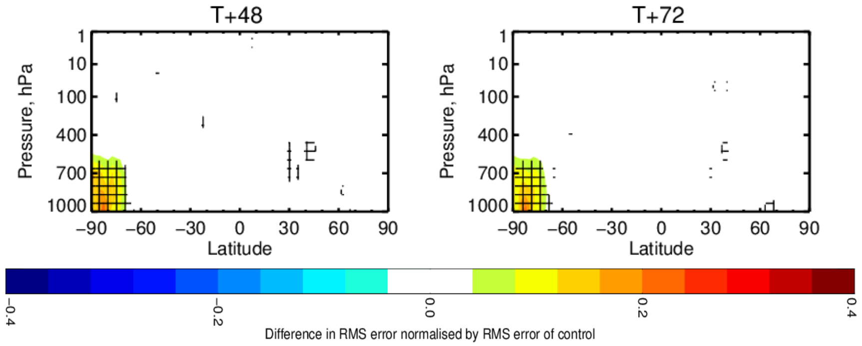
Soil processes (summer 2015)



Snow processes (winter 2015-16)



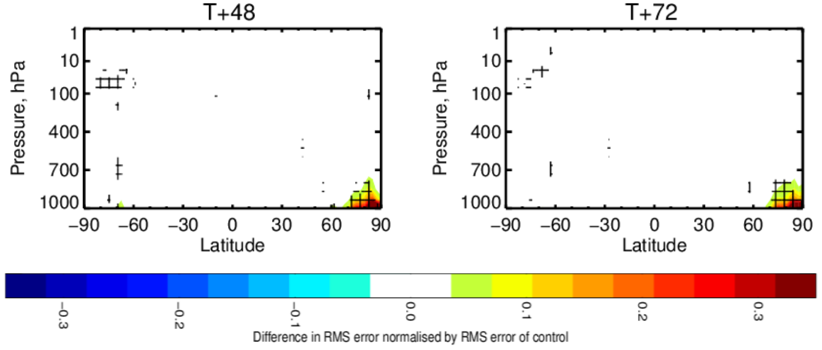
Snow processes (summer 2015)



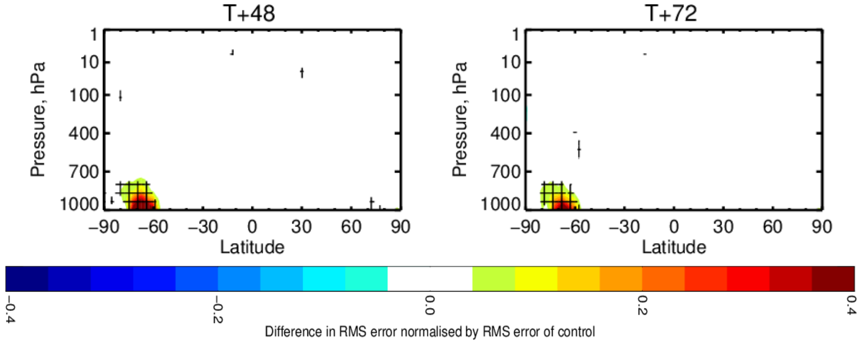
- Soil/Biosphere has major impact (20-30%) propagating, throughout the troposphere
- Snow has both NH/SH impact (20-30% winter, 10-20% summer) lower troposphere

Sea-ice and Lakes forecast impact

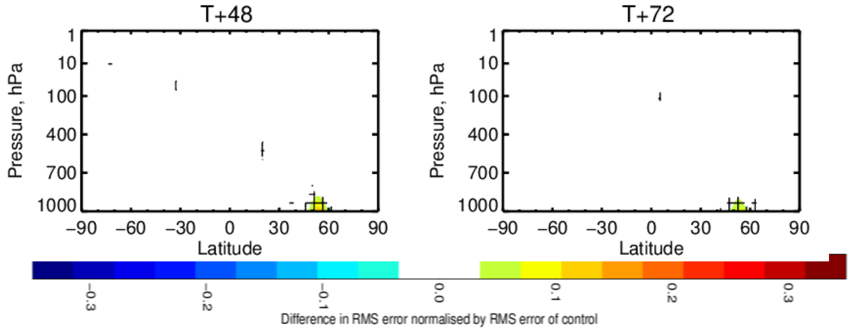
Sea-ice processes (winter 2015-16)



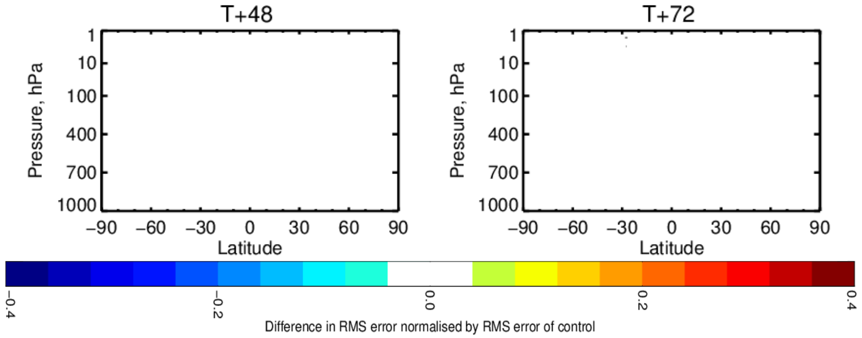
Sea-ice processes (summer 2015)



Lakes processes (winter 2015-16)



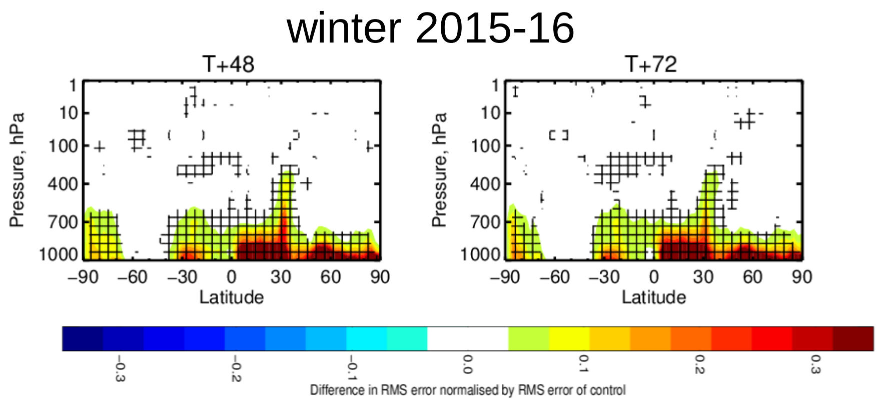
Lakes processes(summer 2015)

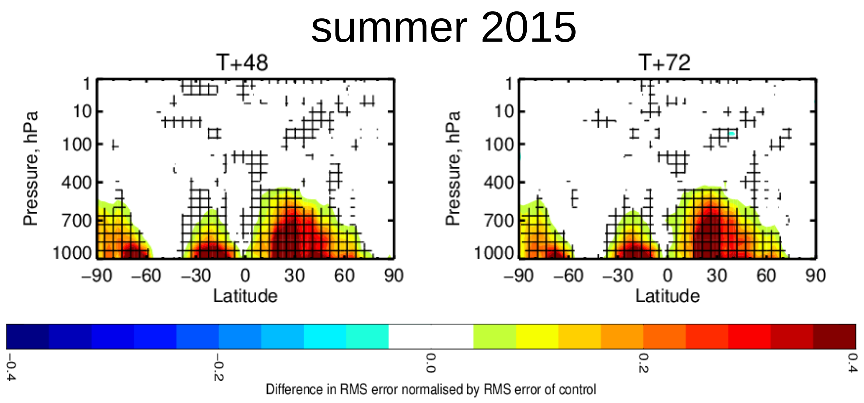


- Sea-ice has major surface impact (20-30%) lower troposphere
- Lakes have surface impact (5-10% winter, ~0% summer), initial condition dominate!

Surface (all the above) temperature forecast impact

All the above surface processes





- The surface elements do add up to when all processes are disabled (30-40%).
- Temperature deterioration extend up to 700hPa both in winter and in summer.
- There is no apparent compensation.

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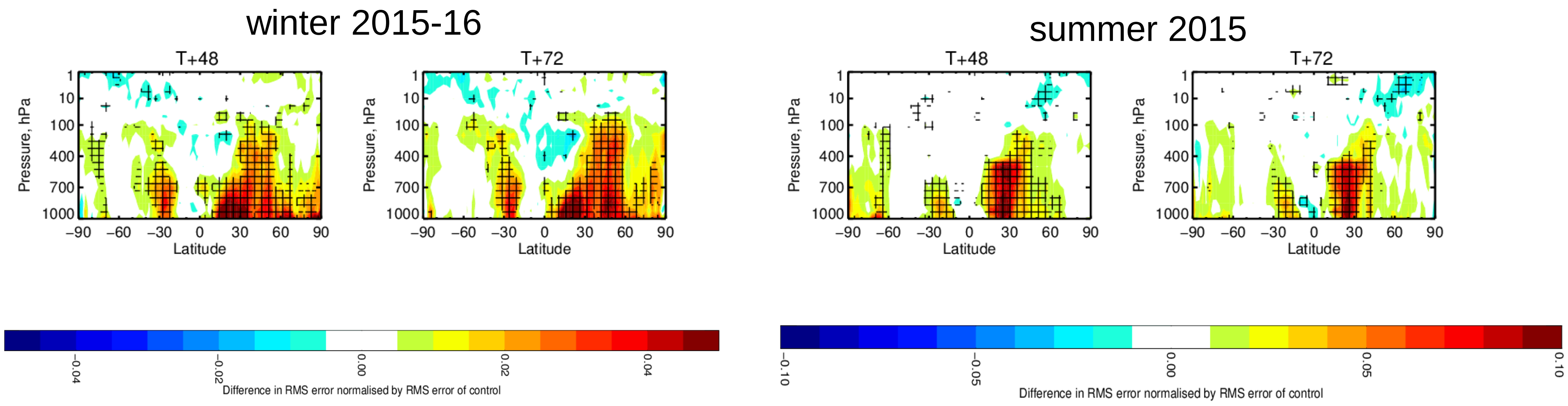
Surface (all the above) wind forecast impact

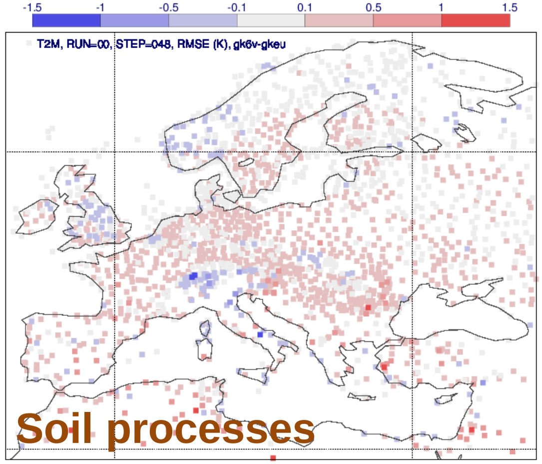
All the above surface processes

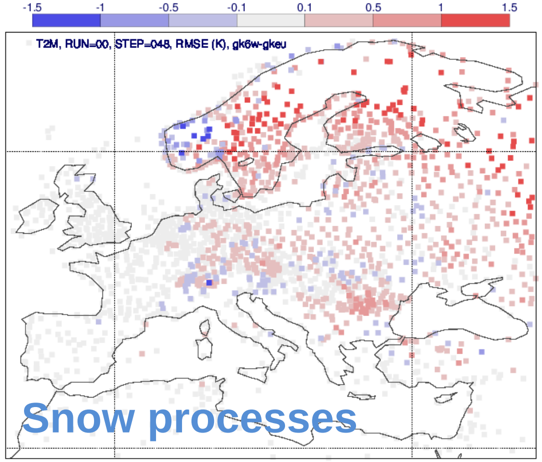


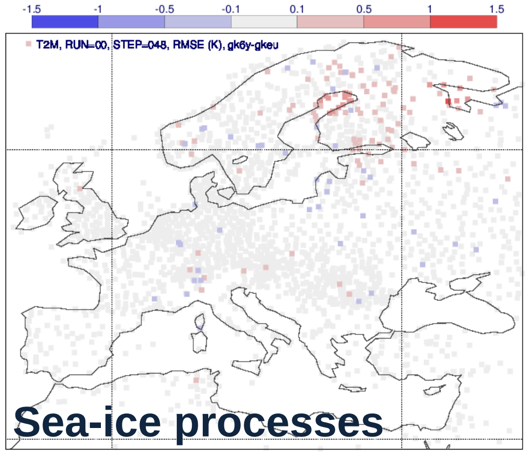
- Wind deterioration (5-10%) propagates up to 100hPa in winter and in summer.
- This is consistent with large scale thermal gradients deterioration.
- Note that these errors are large as they are zonal averages!

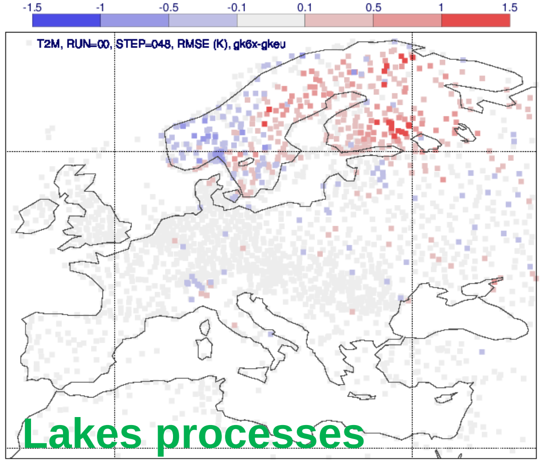
Surface processes forecast impact (locally vs in-situ data)

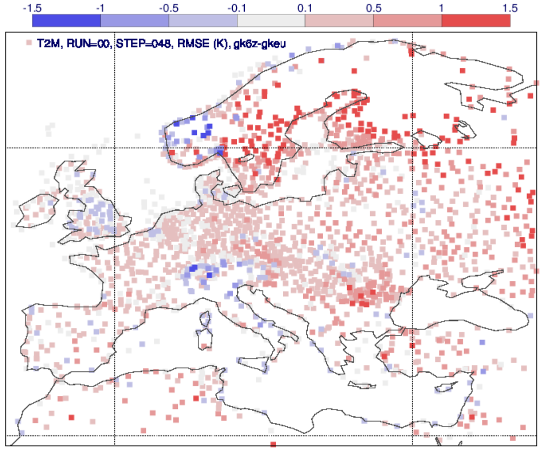
European winter 2015-16









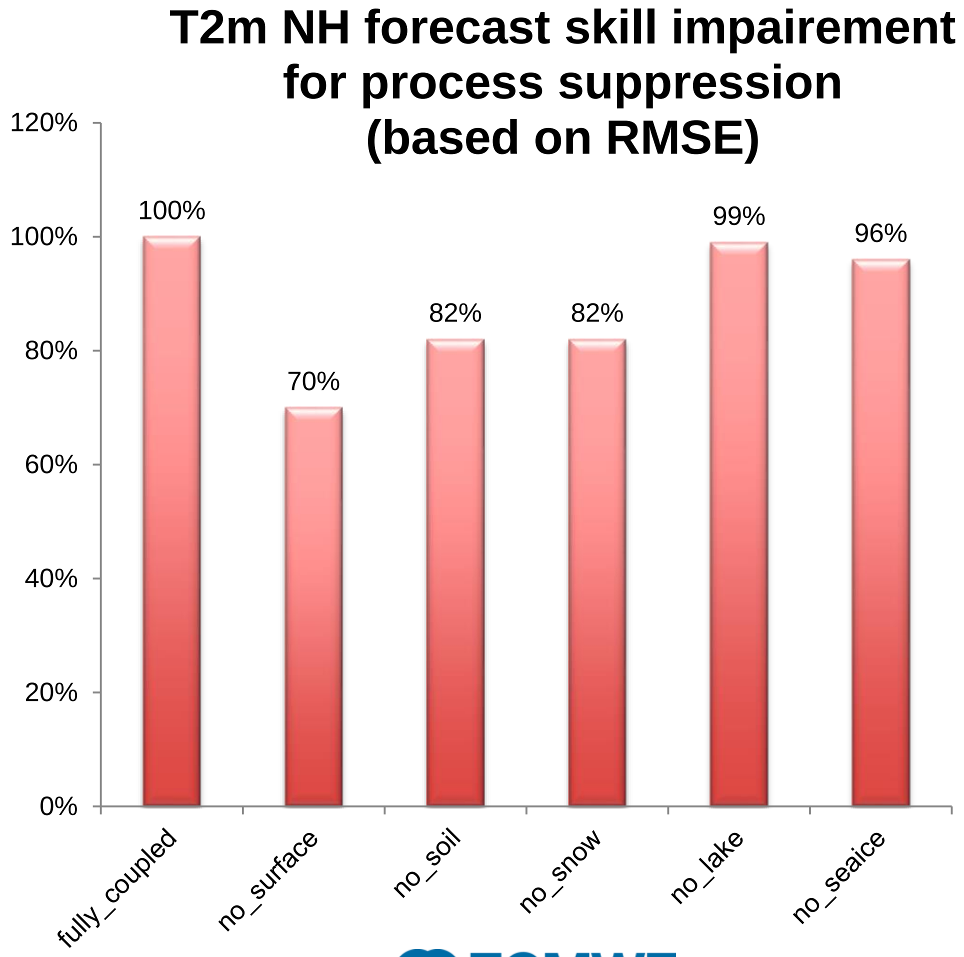


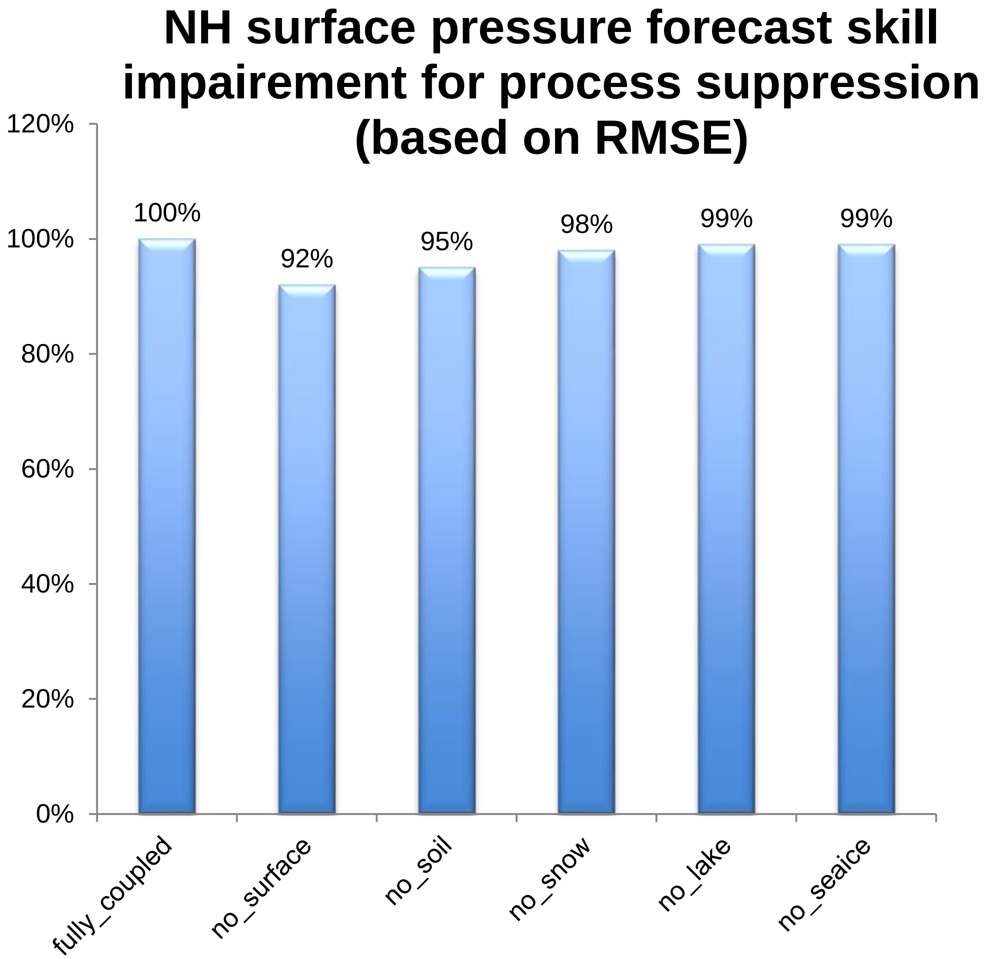
- Evaluated for 48-h forecast vs SYNOP 2m temperature
- Local deterioration can be large for a missing process (red-colors)
- Global diagnostics cannot be the only guidance

All the above surface processes

Weather impact of surface processes

- Evaluating the 3-day forecast-range skill deterioration induced by the surface process being deactivated (366 forecasts 1st June 2015 to 1st June 2016)





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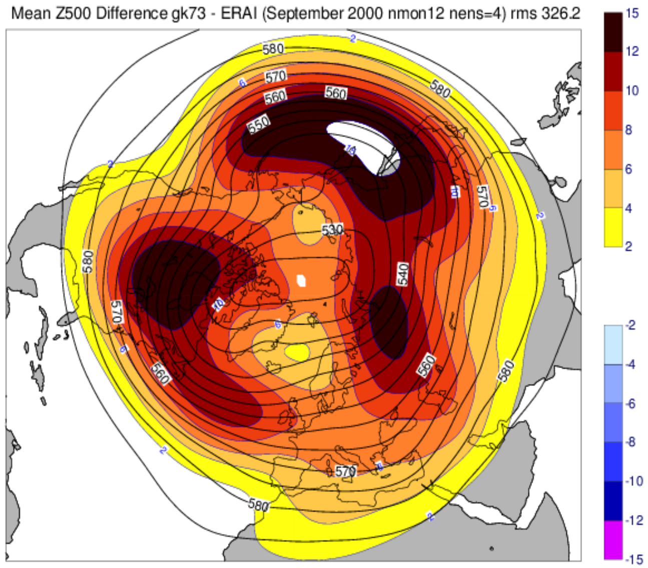
Climate impact of surface processes

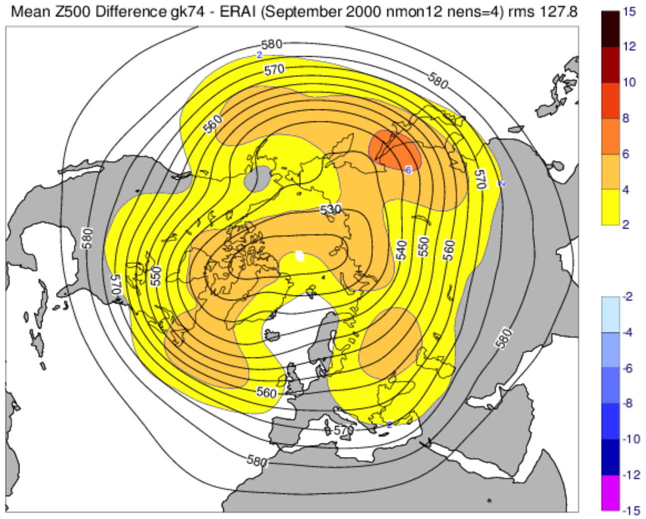
- 4-year climate integrations (August 2000-2004, 13-month prediction) average to look at 4-member ensemble mean climate
- Scored against a variety of climate observing datasets

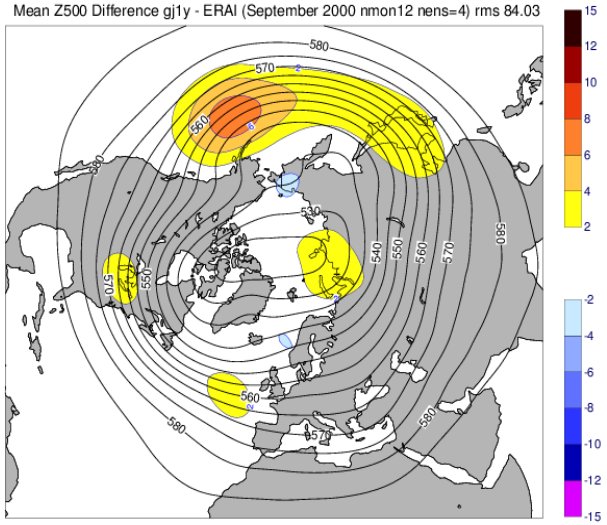
Soil and Snow climate circulation (Z500) impact

Soil processes
disabled



Snow processes
disabled

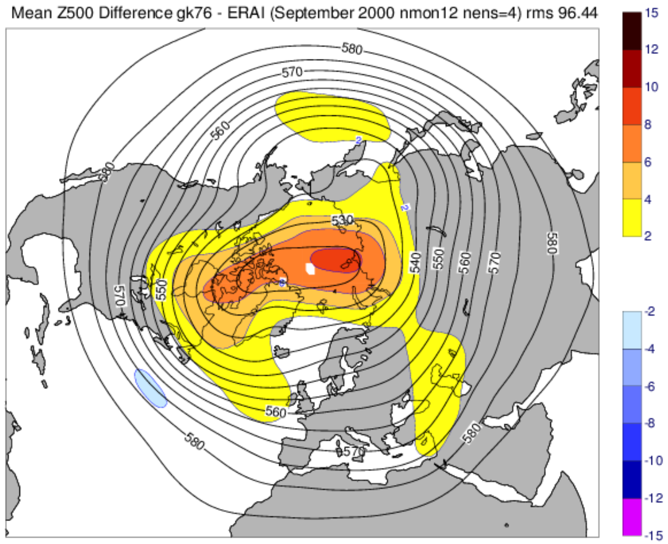




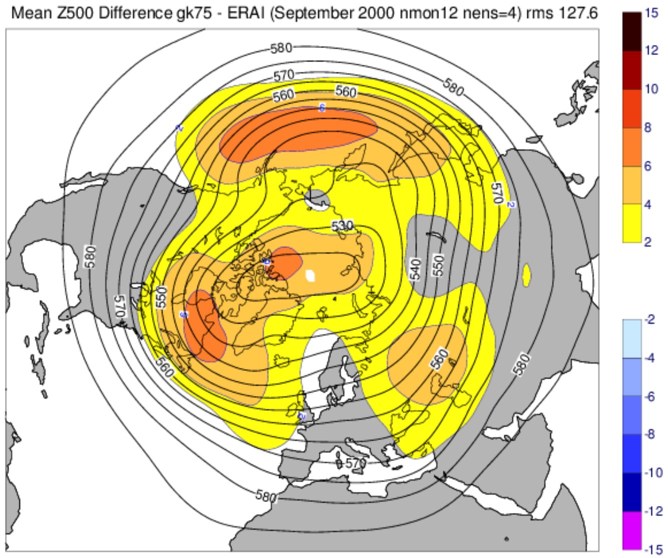
Control Climate
Mean Z500 RMS error 2000-2004
of a 13-month coupled forecast
Initialized in August.
First month integration excluded.
Evaluated vs. ERA-Interim.

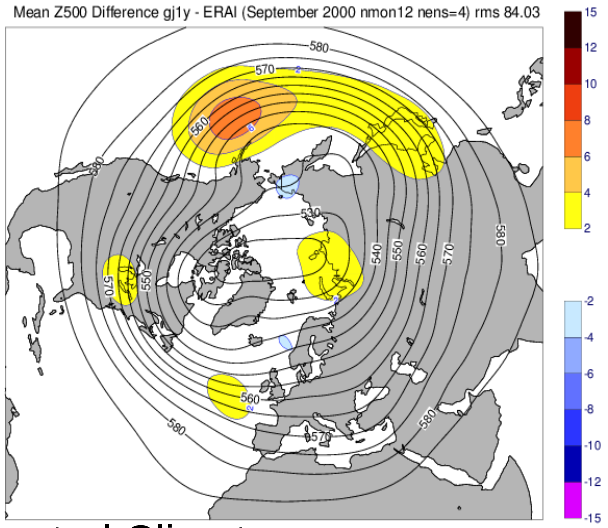
Sea-ice and Lakes climate circulation (Z500) impact

Sea-ice processes disabled



Lakes processes disabled





Control Climate
Mean Z500 RMS error 2000-2004
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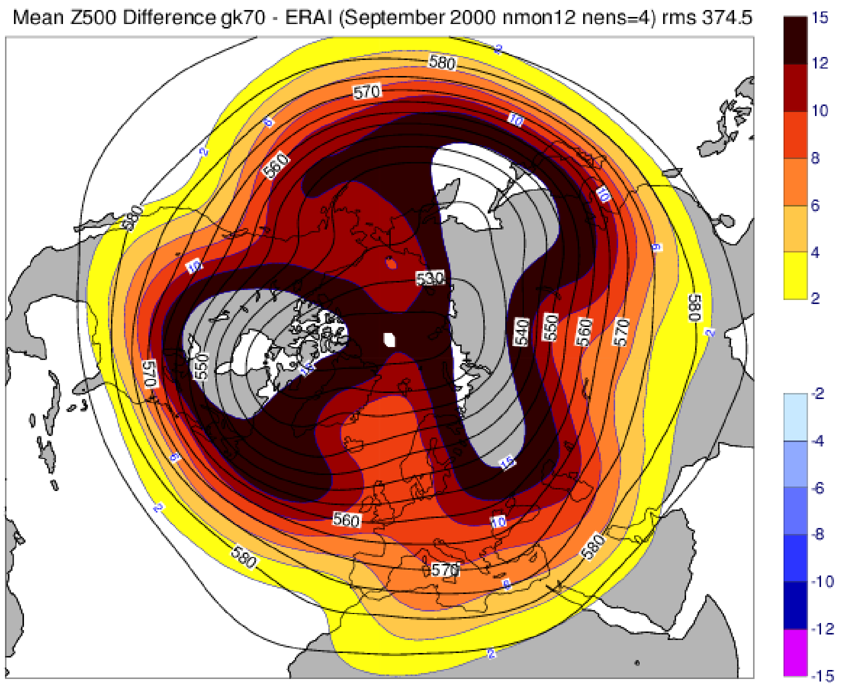
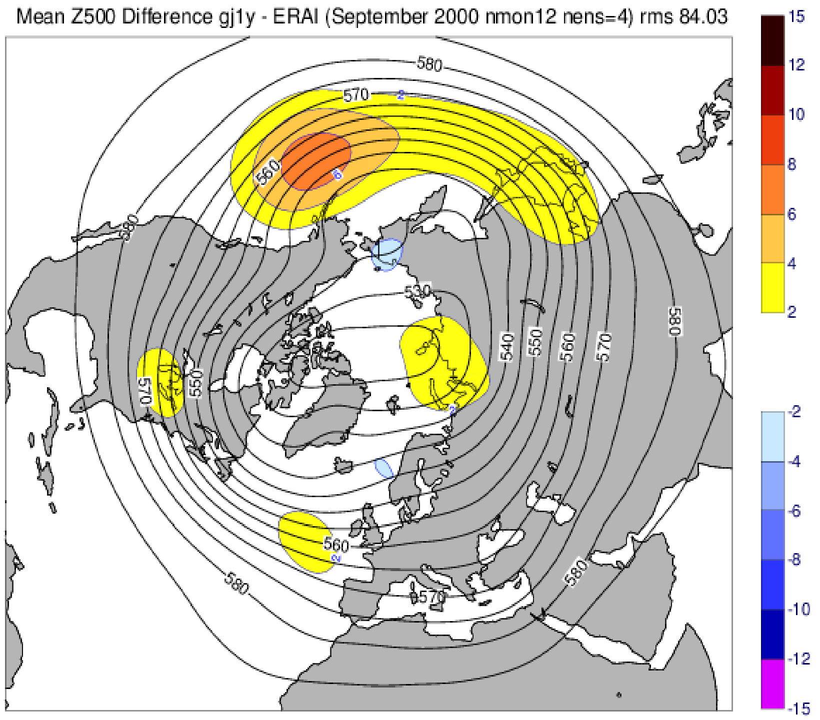
Surface (all above) Geopotential (Z500) climate impact

All surface processes disabled (except ocean)





Control Climate
Mean Z500 RMS error 2000-2004 of a 13-month coupled forecast Initialized in August.
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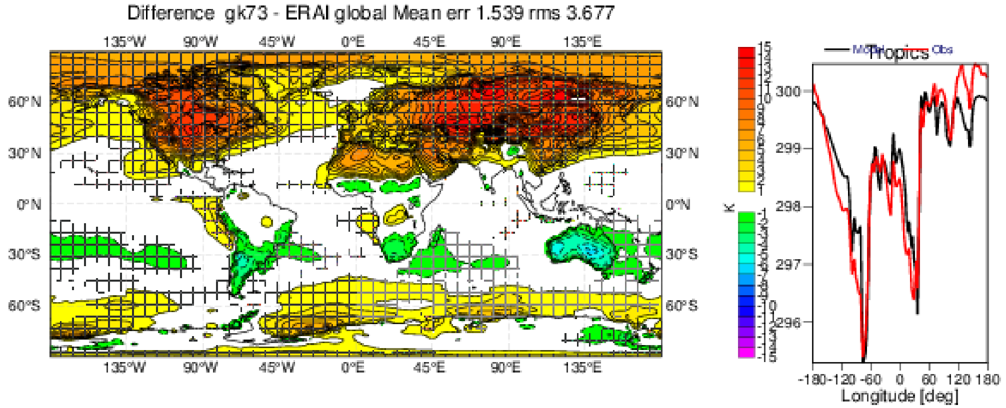
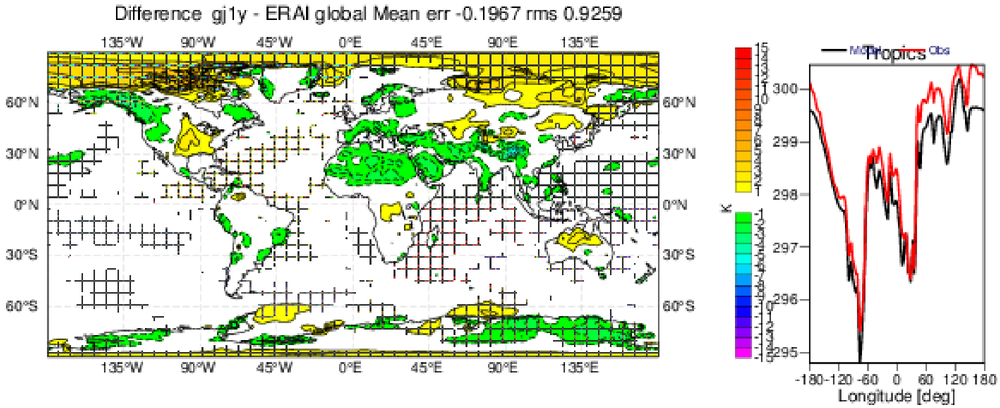
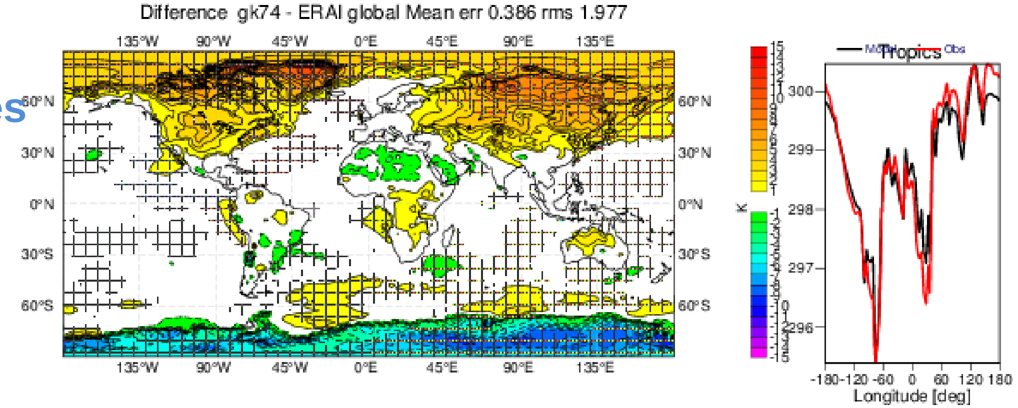
Soil and Snow climate surface temperature (T2m) impact

Soil processes disabled





Snow processes disabled



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Mean T2m RMS error 2000-2004 of a 13-month coupled forecast
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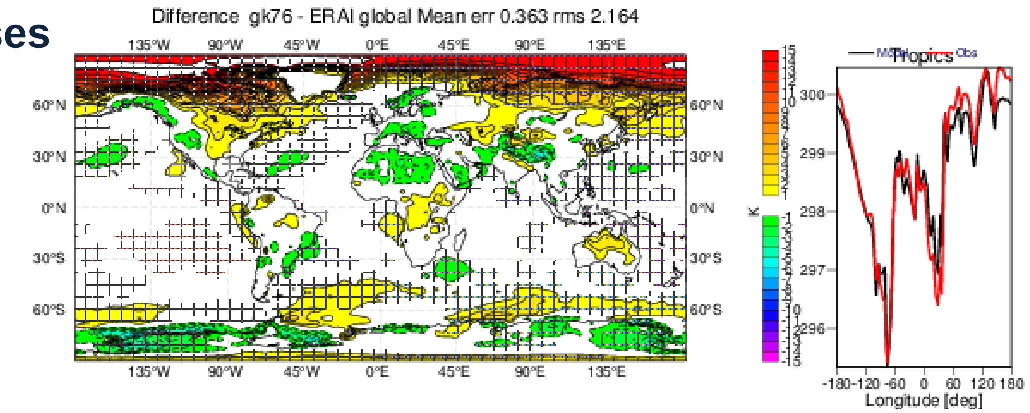
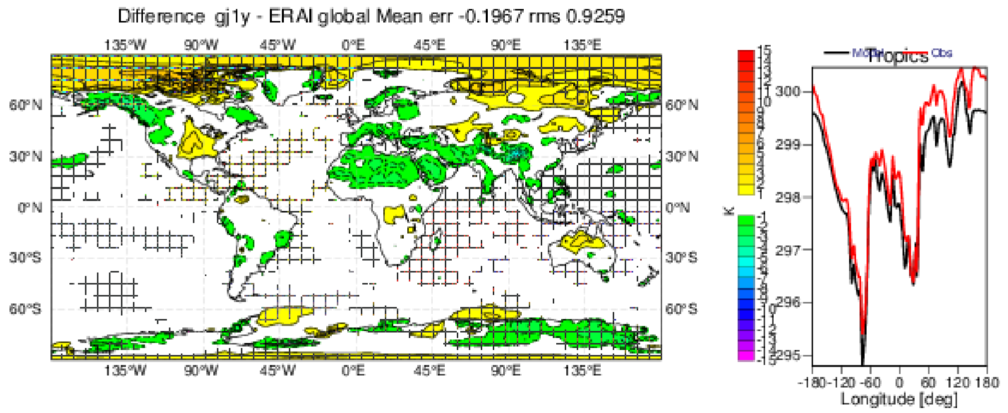
Evaluated vs. ERA-Interim

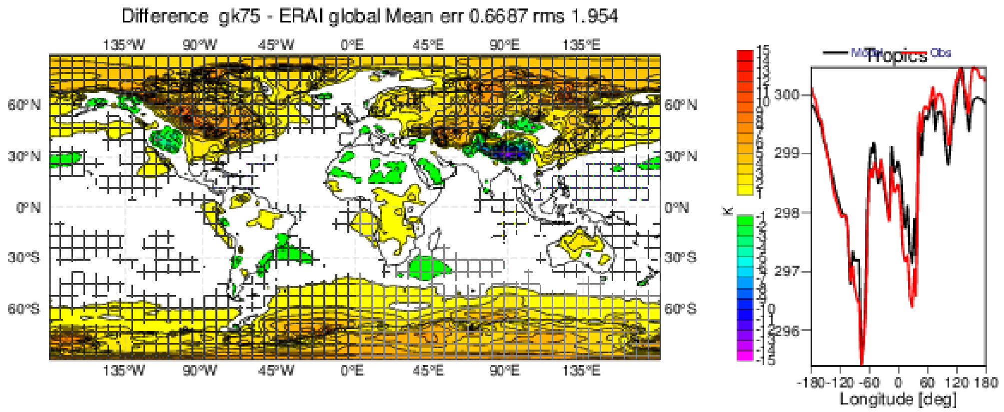
Sea-ice and Lakes climate surface temperature (T2m) impact

Sea-ice processes disabled





Lakes processes disabled



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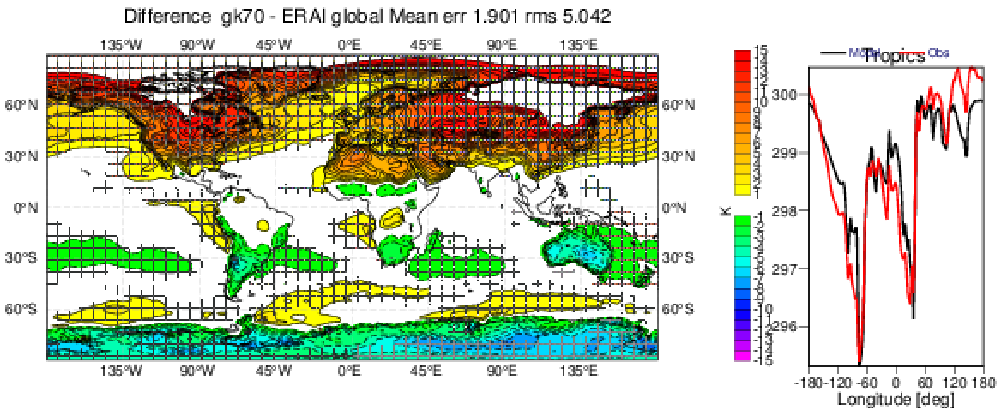
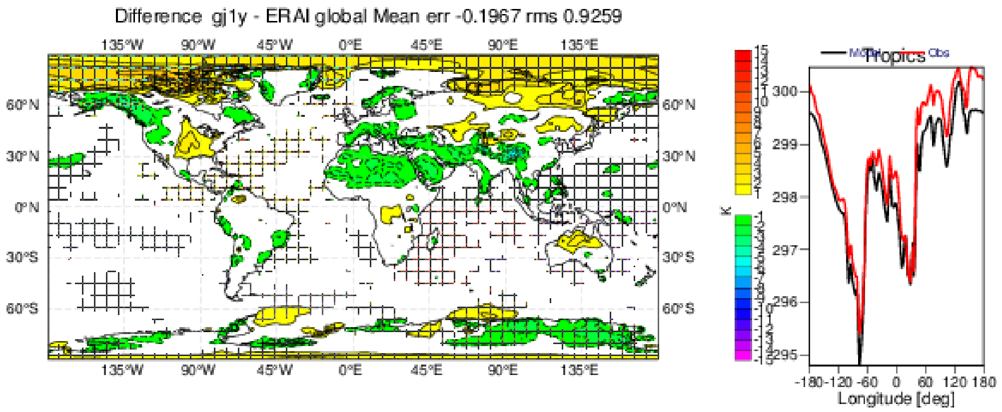
ECMWF

Surface (all above) climate surface temperature (T2m) impact

All surface processes disabled (except ocean)

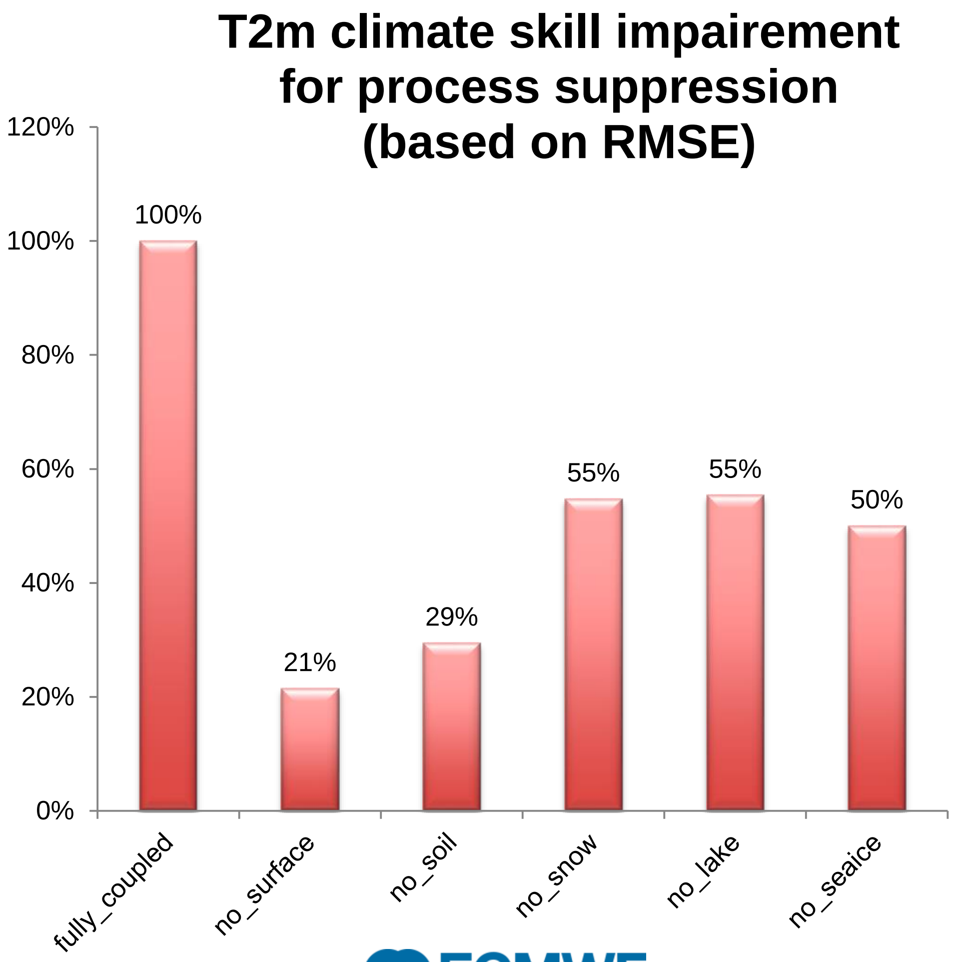


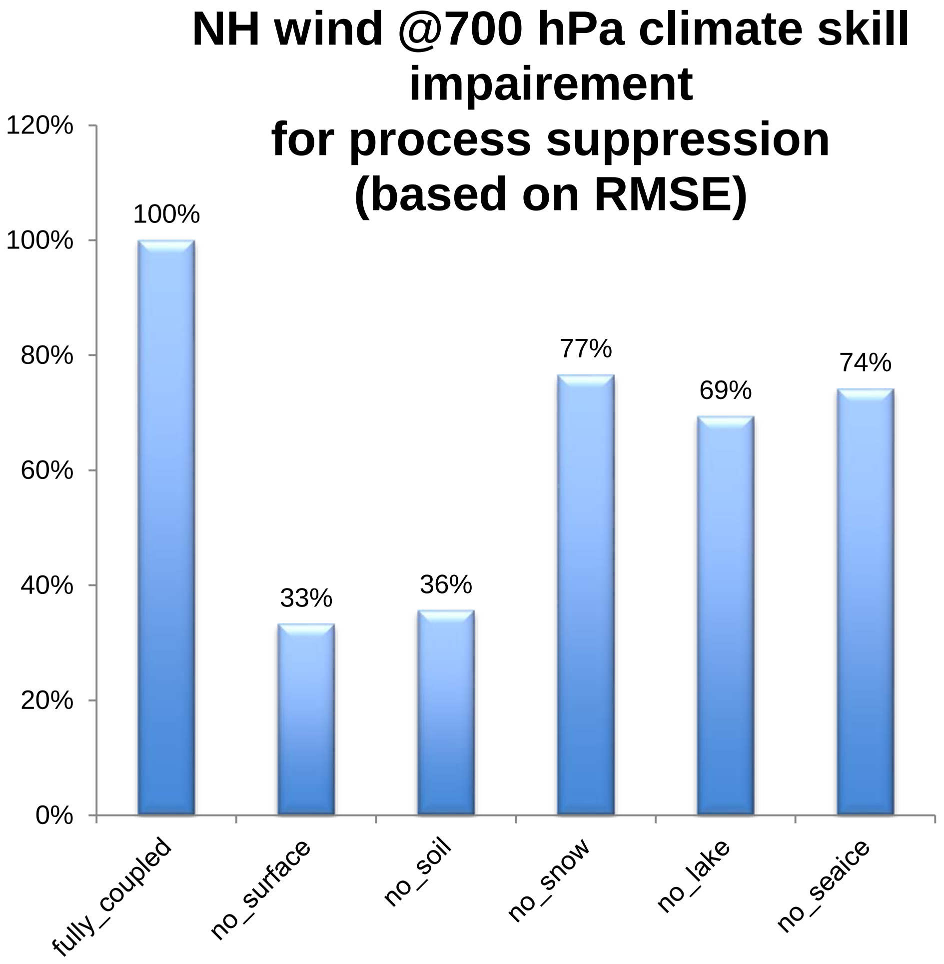


Control Climate
Mean T2m RMS error 2000-2004 of a 13-month coupled forecast Initialized in August.
First month integration excluded.
Evaluated vs. ERA-Interim

Climate impact of surface processes

- Evaluated for the 1-year forecast range (annual mean) based on the skill deterioration induced by the surface process being deactivated





ECMWF

Rationale of talk

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Weather forecasts impact of soil/snow processes improved representation

- **Hydrology-TESSEL**

  Balsamo et al. (2009)
  van den Hurk and Viterbo (2003)

  Global Soil Texture (FAO)

  New hydraulic properties

  Variable Infiltration capacity & surface runoff revision

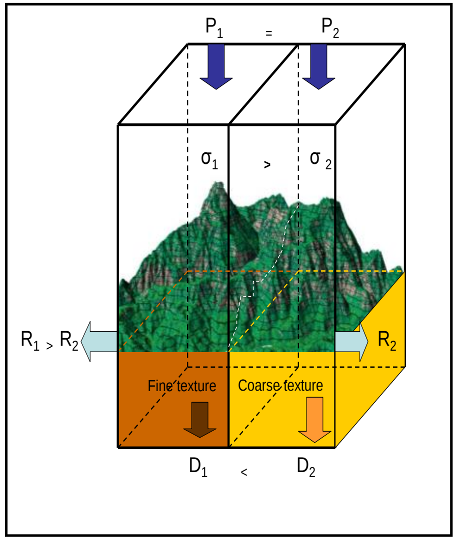
- **NEW SNOW**

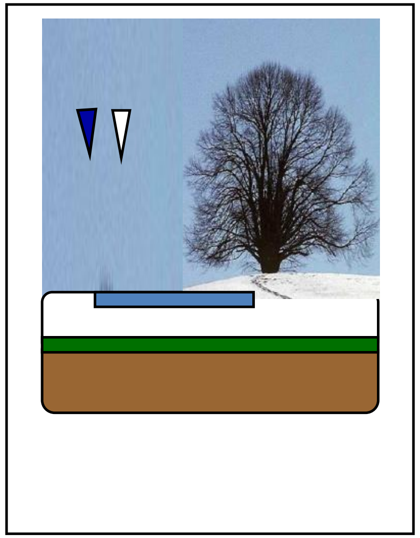
  Dutra et al. (2010)

  Revised snow density

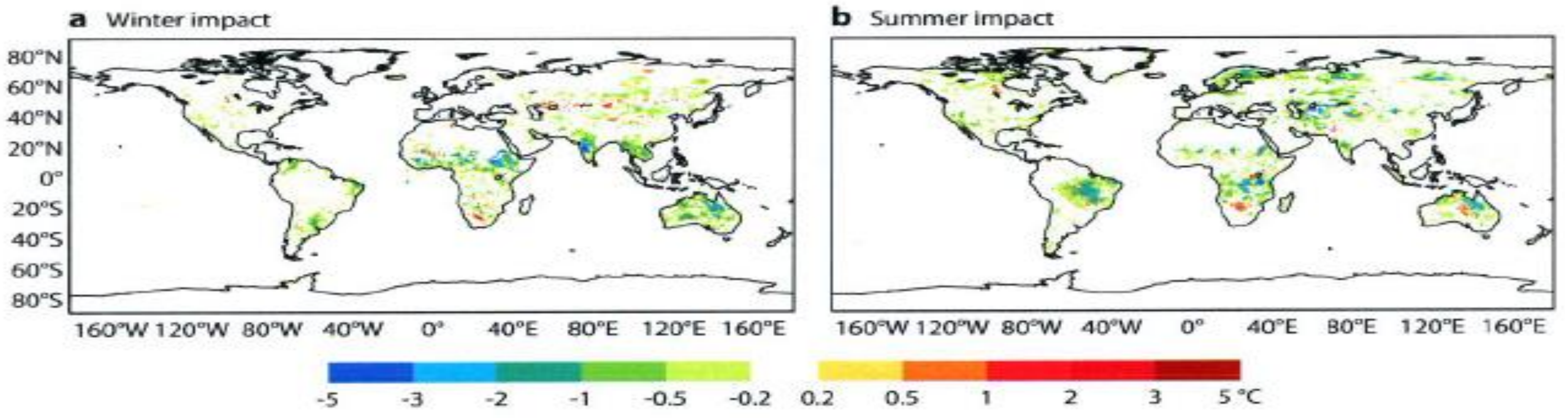
  Liquid water reservoir

  Revision of Albedo and sub-grid snow cover





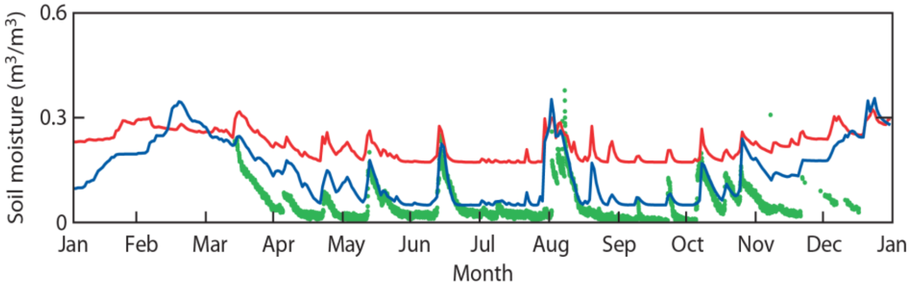
Forecast Impact (+36-hour forecast, mean error at 2m temperature)



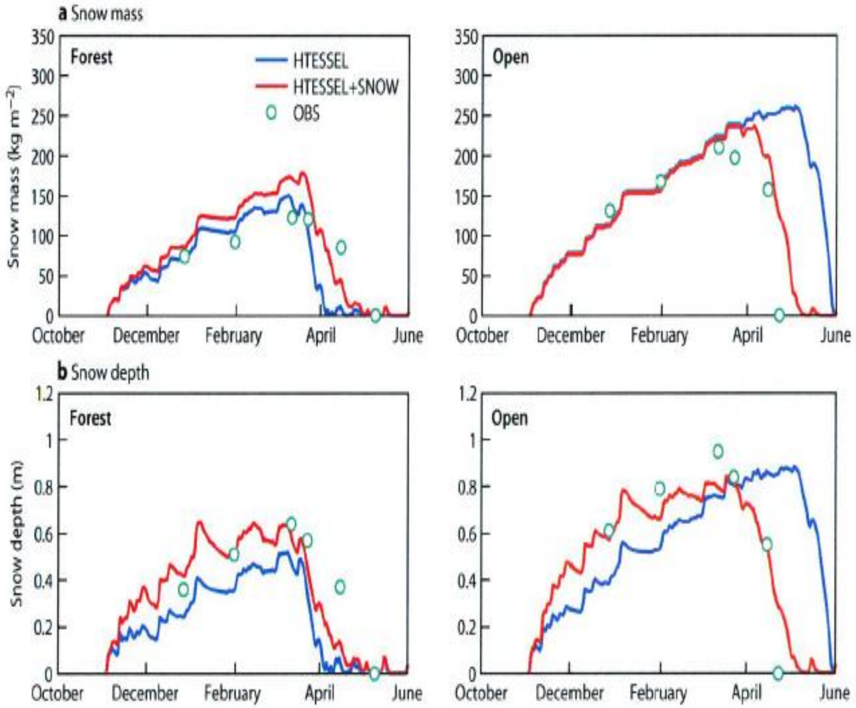
Improving 2m temperature   Degrade 2m temperature

Soil moisture and Snow-pack modelling evaluated in-situ

Balsamo et al 2009 JHM, Dutra et al. 2010 JHM



Evolution of soil moisture for a site in Utah in2010.
Observations, **old**, and **new** schemes.



Evolution of snow mass and depth at SNOWMIP 2 observational sites in the new and old scheme

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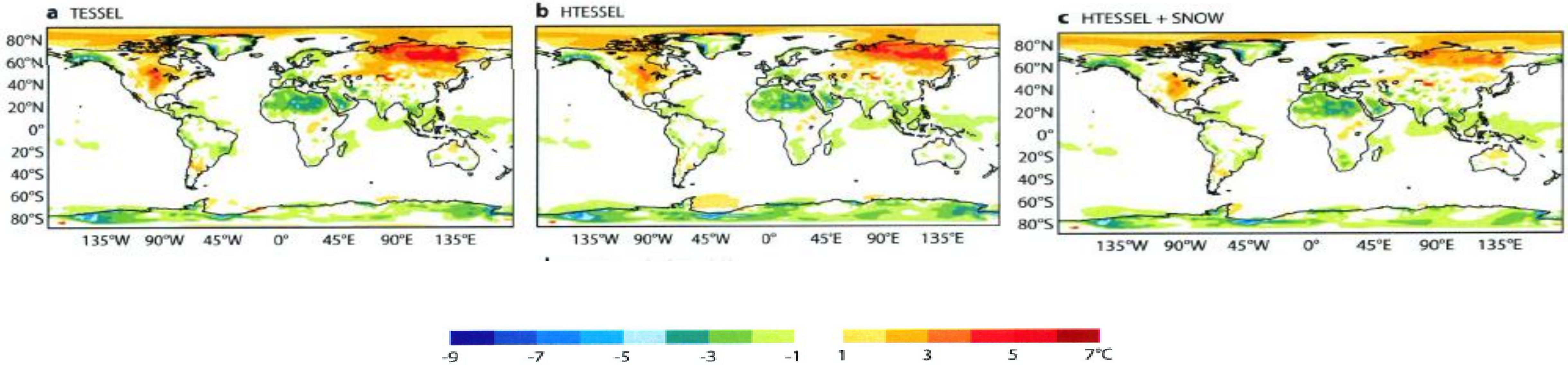
Climate improvements from land developments (soil, snow, vegetation)

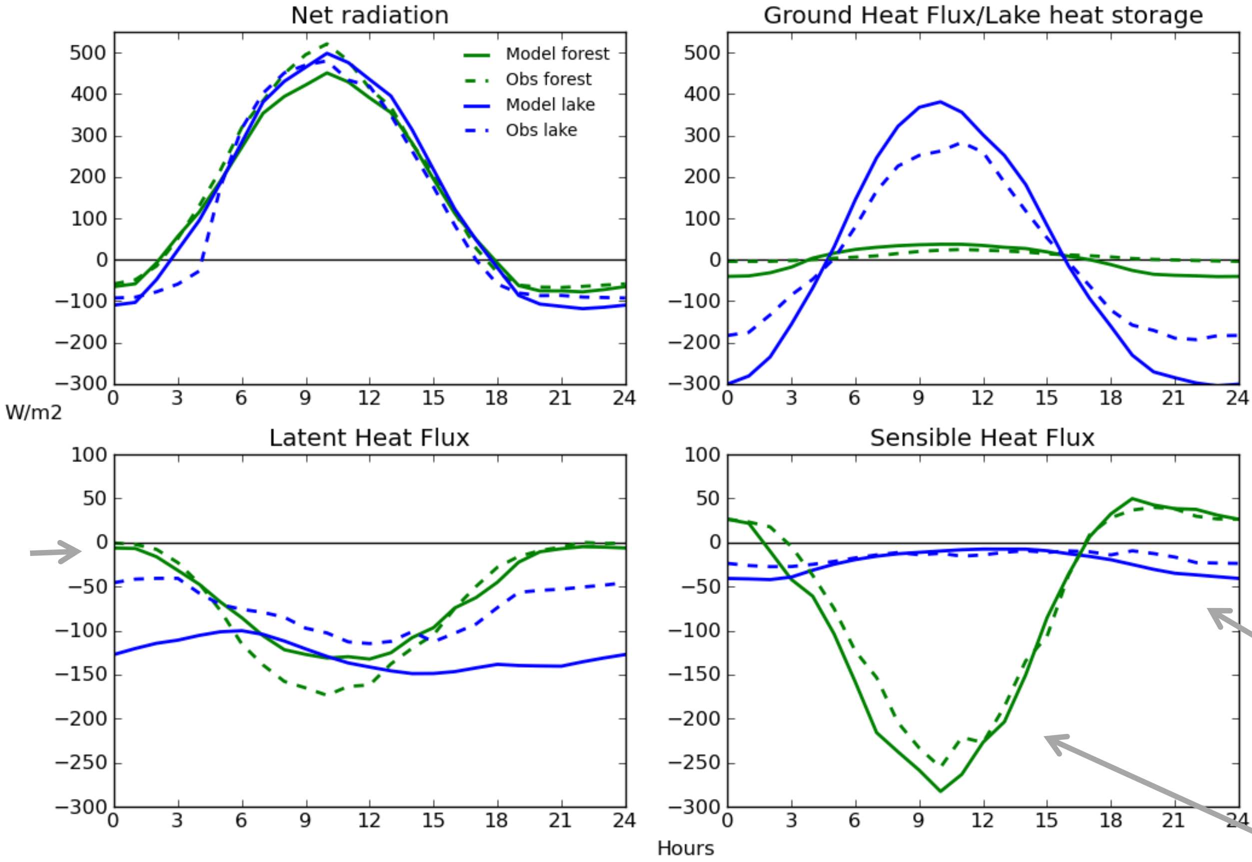


simulations colder than ERA-Interim Warmer than ERA-Interim

Energy fluxes: diurnal cycle impact of lakes

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

- HTESSEL
- LAKEHTESSEL
- forest obs
- lake obs

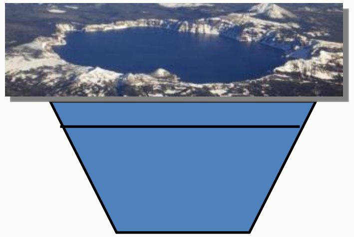
- **Lake tile**

Mironov et al (2010),

Dutra et al. (2010),

Balsamo et al. (2010, 2012, 2013)

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



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

Lake LH diurnal cycle: over-estimation in evaporation

Lake SH maximum is at night

Forest SH maximum is at midday

Main difference between lake & forest sites is found in energy partitioning

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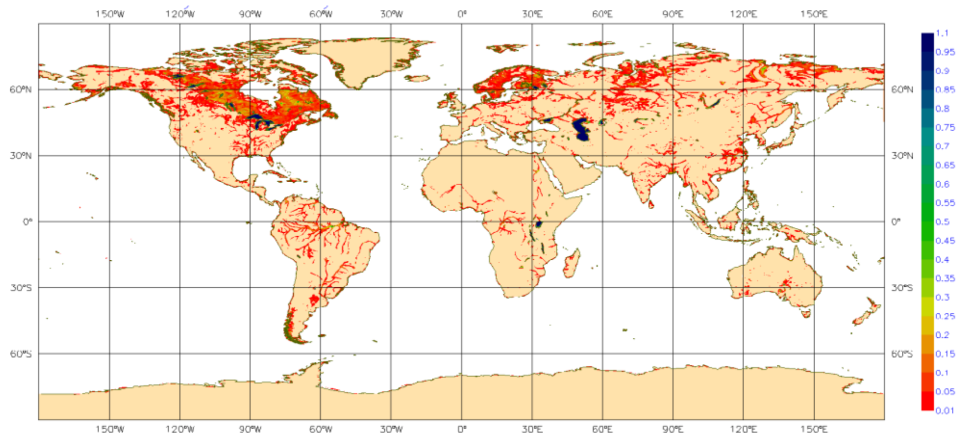
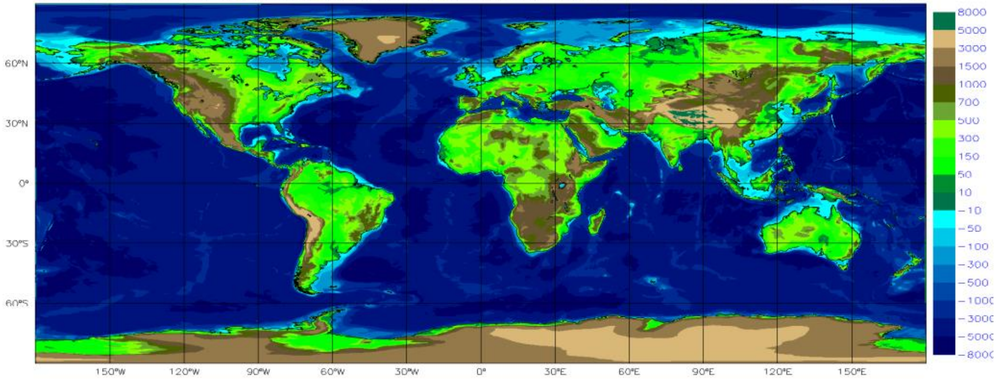
Global surface physiography description: e.g. Lake cover/depth

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

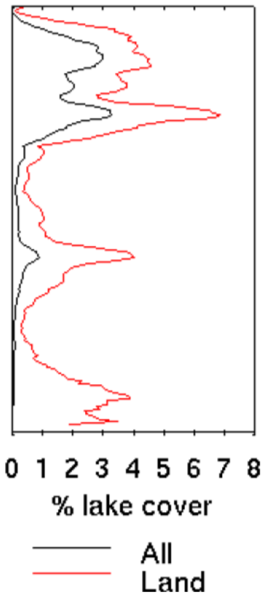
LAKE COVER FRACTION



LAKE & SEA BATHYMETRY / NEW OROGRAPHY



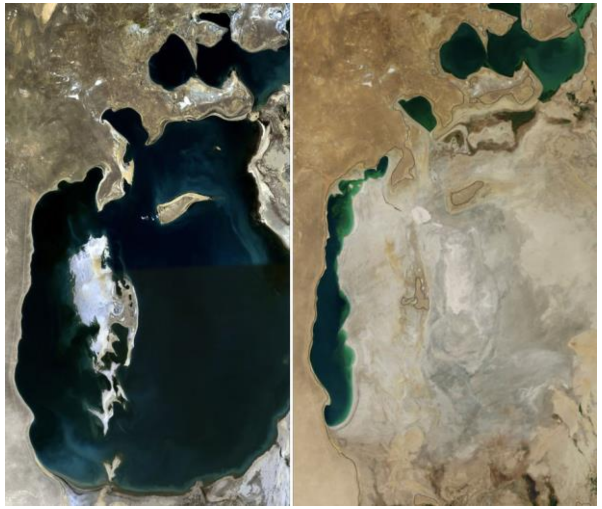
Nº Points 0.05< lake fraction<0.5



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

- Lake cover & lake bathymetry are among the surface important fields to describe size and volume of the water bodies that are associated to thermal inertia. Physiography has been completely revised in 40R3
- source: ESA-GlobCover/GLDBv1

But is it correct to assume LAKE COVER as constant?



- Lake Aral in 1989 and 2014 (source: NASA)

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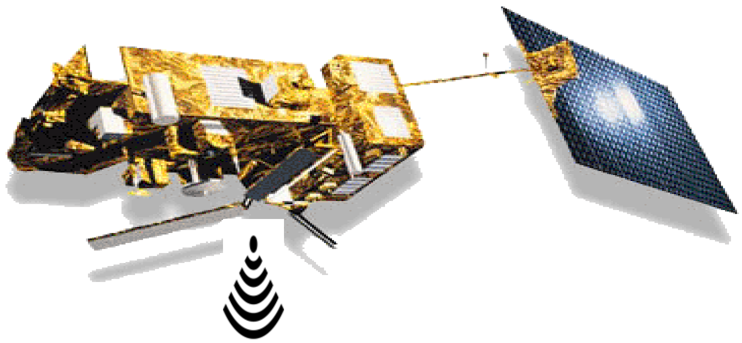
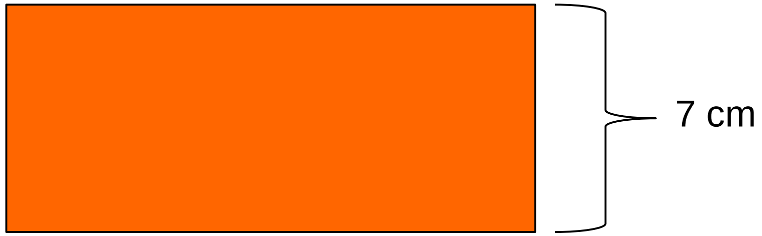
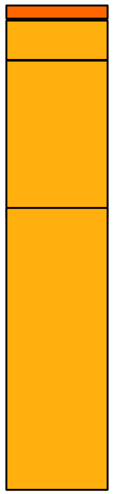
An enhanced soil vertical resolution

The model bias in Tskin amplitude shown by *Trigo et al. (2015)* motivated the development of an enhanced soil vertical discretisation to improve the match with satellite products.







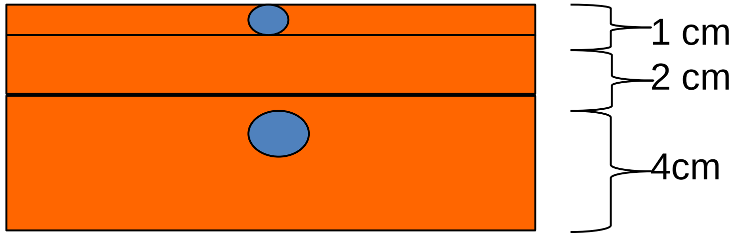
4-layers:

 # 0-7 cm

7-28 cm

28-100 cm

100-289 cm



10-layers:

 # 0-1 cm

 # 1-3 cm

 # 3-7 cm

7-15 cm

15-25 cm

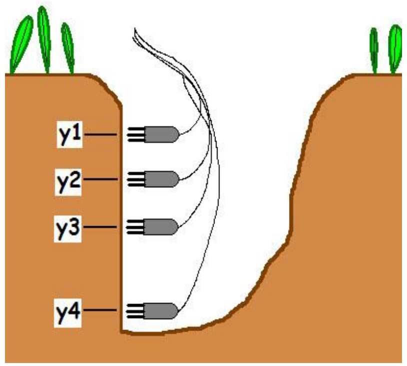
25-50 cm

50-100 cm

100-200 cm

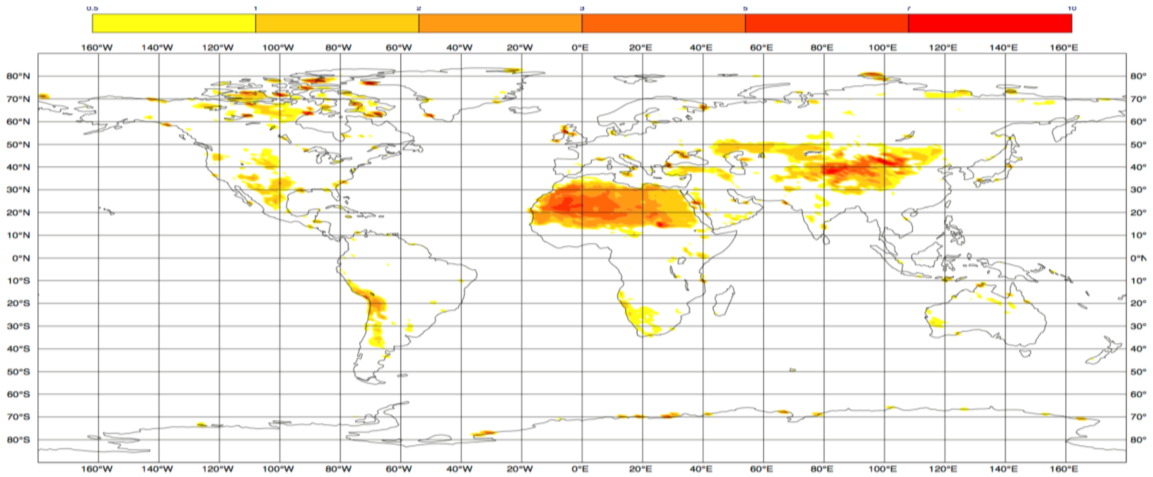
200-400 cm

 # 400-800 cm



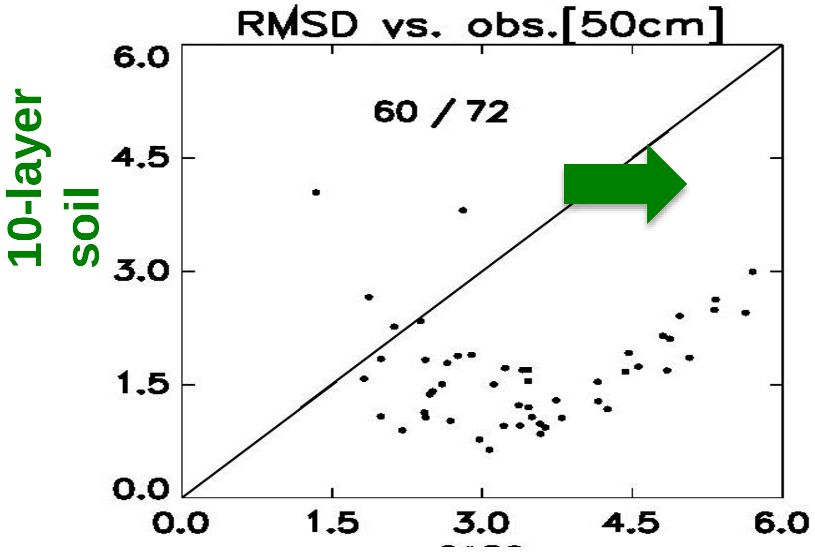
Impact of soil vertical resolution on soil temperature

Sensitivity Max Tskin for July 2014



Higher T-max at the L-A interface
up to 3 degrees warmer on bare soil
(without symmetric effect on Tmin!)
Offline simulations with **10-layer soil**
Compared to **4-layer soils**

In-situ validation at 50cm depth
(on 2014, 64 stations)
Results by Clément Albergel



4-layer soils

Improved match to deep soil temperature
(shown is correlation and RMSD)

Correlation with in-situ soil temperature validate the usefulness of increase soil vertical resolution for monthly timescale (0.50 cm deep). Research work will continue using satellite skin temperature data (2nd visit of René Orth ETH).

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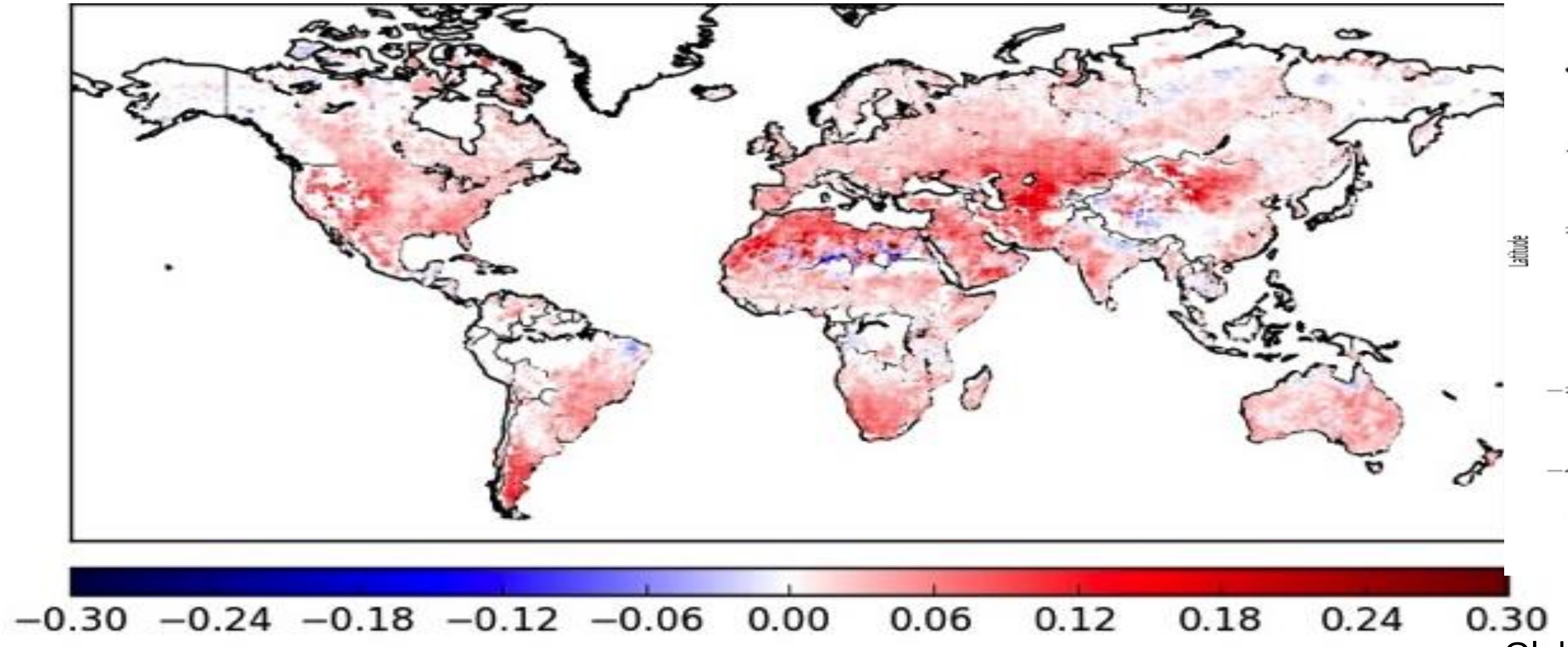
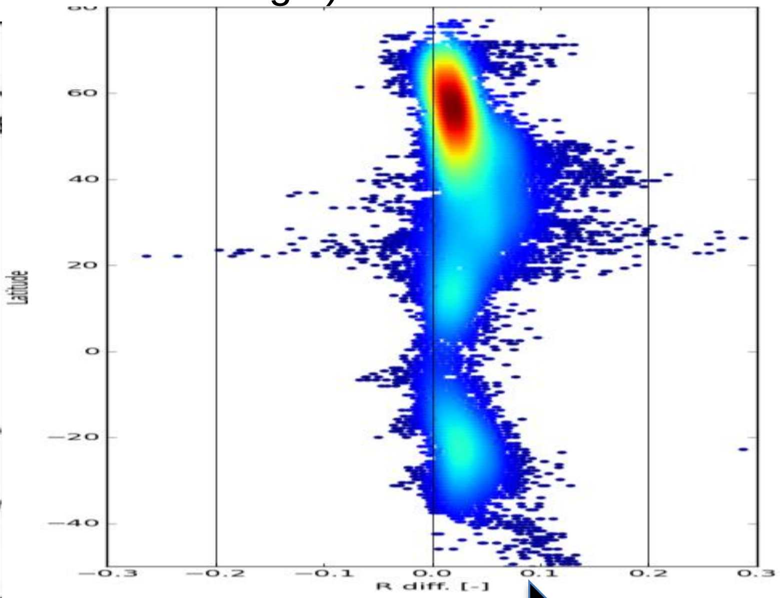
Impact of soil vertical resolution for satellite soil moisture

Impact on Anomaly Correlation with ESA-CCI satellite soil moisture (courtesy of Clément Albergel)





Globally Improved match to satellite soil moisture (shown is ΔACC calculate on 1-month running mean)

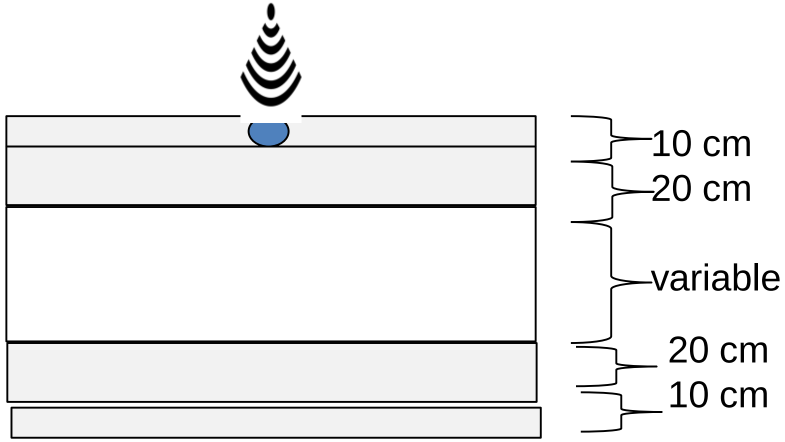
Anomaly correlation (1988-2014) measured with ESA-CCI soil moisture remote sensing (multi-sensor) product. This provide a global validation of the usefulness of increase soil vertical resolution.

ECMWF

An enhanced snow vertical resolution

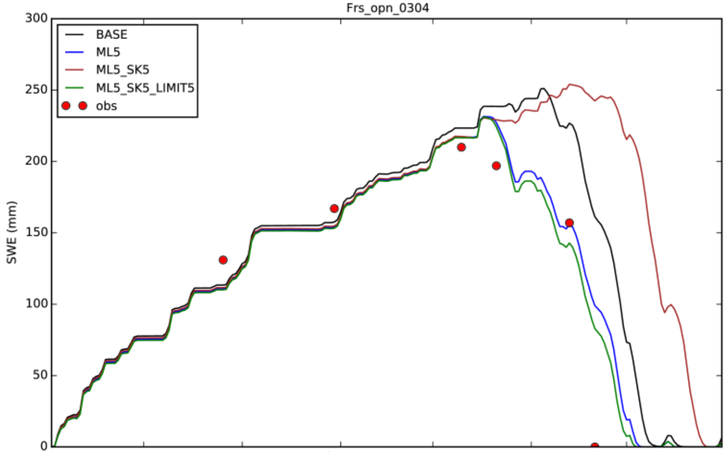
The snow temperature representation in a 5-layer scheme can take into account the coupling to the atmosphere and to the underlying soils with dedicated timescale that can better represent accumulation and melting.

1-layers:
 # 0-X cm



5-layers:

from Emanuel Dutra



Simulations of Snow Water Equivalent (SWE- mm) for the 2003/04 winter season at the Fraser open site (USA Rocky mountains) comparing observations (red circles) with **current** 1-layer model (BASE-black), 5-layers **new** snow model (ML5-green).

Looking to a future of Earth surface forecasts relevant to users

- Wind energy forecast (require very accurate surface drag)
- Water availability forecast (require very accurate soil hydrology)
- Biomass and crops forecasts (require skilful vegetation dynamics)
- Urban-areas T/RH forecasts (require representation of roads/buildings)

Will global weather forecasts benefit from those high level requirements?

Extreme weather effects on surface state are evident and globally observable (e.g. fires, floods, vegetation disturbances, extreme surface temperatures,…)

Induced surface modifications are relevant for weather sensitive parameters (albedo, surface water coverage, flux partitioning, drag, land-use).

PROPOSED REFLECTION:

Can we ***imagine*** *what Global Environmental Monitoring / Prediction will bring as societal impact and its potential for improved forecasts?*

…nowadays we all carry a device that was first just imagination…

Conclusions

- Earth surface matters! Further evidence via dedicated experiments (in a single ESM).
- Skill enhancement from surface processes range from 1 day to 1 year:
- 1-DAY and MEDIUM-RANGE
  – Land biosphere, snow, sea-ice, lakes contribute to weather forecast skill 1-to-30 % T2m (1-8% SP)
  – Tropics is all about Land & biosphere both in summer and in winter (not shown).
  – Northern hemisphere winter: Snow and Sea-ice dominate, Lake have small impact (large locally).
  – Southern hemisphere winter: Sea-ice dominates, followed by Snow and Soil
  – Northern hemisphere summer: Soil dominates and signal propagates throughout the troposphere
  – Southern hemisphere summer: Snow (Antarctica) followed by Soil and Sea-ice
- 1-YEAR and SEASONAL-RANGE
  – Surface elements such lakes occupying small cover of Earth surface can have large impact on climate.
  – All the surface elements combined can modify the model climate and account for
    - 80% of surface temperature skill (measured on T2m RMSE)
    - 66% of skill in the northern hemisphere circulation (measured on 700 hPa winds)

Perspectives

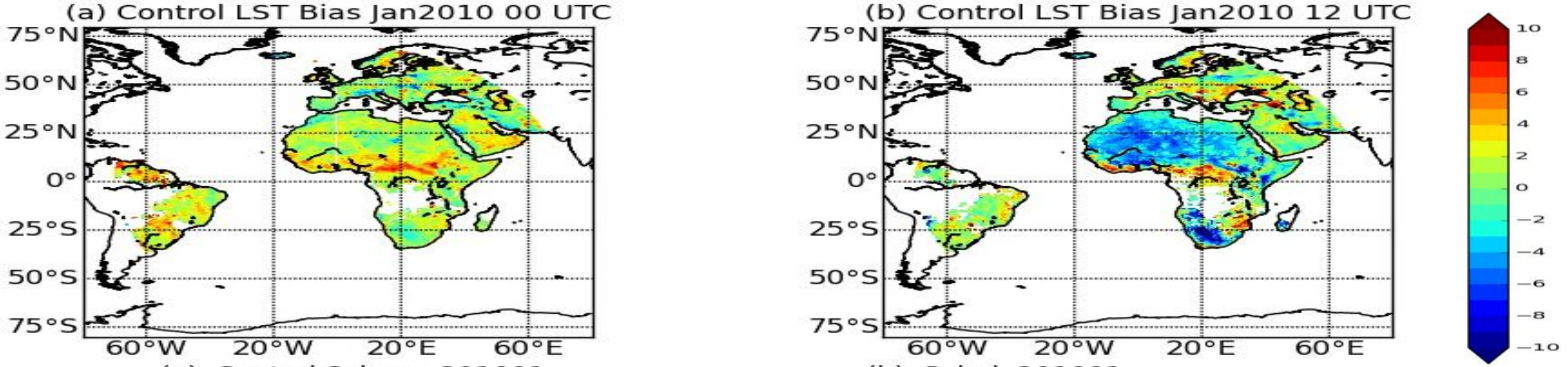
- Efforts to improve diurnal and seasonal cycles of surface state variables has transferred into weather and climate improvements and this it will continue (doing things better may not sound attractive but it pays off!)
- Surface complexity is needed and permitted by the overall skill of the atmospheric processes.
- Surface representation requirements for higher resolution will not saturate at a given scale.
- Earth-Observation from Satellites provide guidance for improving processes (not only useful in the data assimilation step, but also in the model development phase) and justify complexity.
- In-situ data will provide guidance on process-level fidelity of a scheme. That cannot be expected at global scale and therefore in-situ data will always be a crucial part of verification.
- Human influence on the surface (such as urbanization, irrigation) is yet to be represented in many models that can no longer assume natural surfaces to be static (priority not only at ECMWF).
- Surface-state (in the Biosphere, Cryosphere and Hydrosphere compartments) and near-surface atmospheric variables are likely to gain importance as forecasts products per-se.

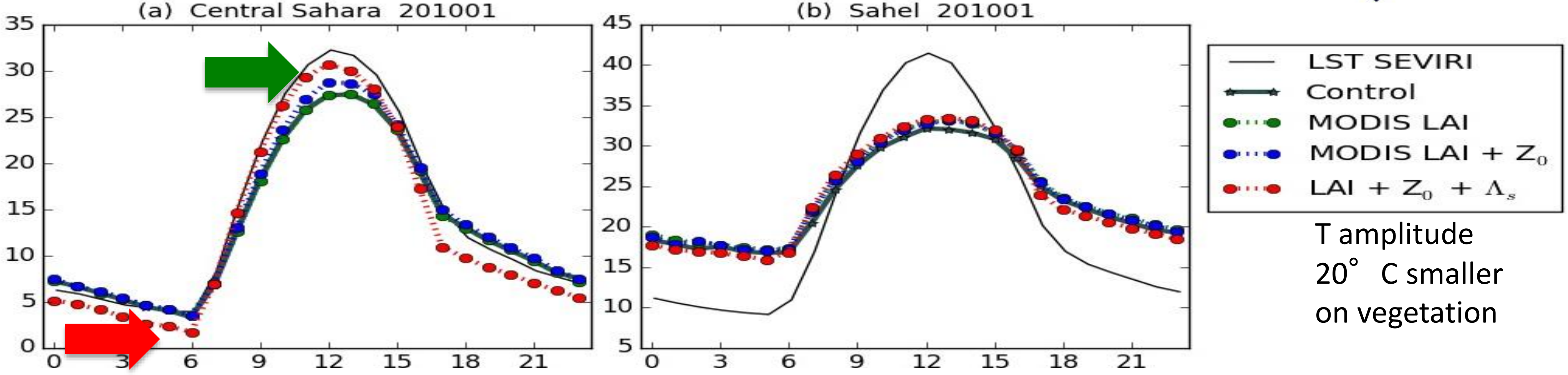
Thank you for your attention

Extra slides for Q&A

Coupling and diurnal cycle: the impact of vegetation

Trigo et al. (2015, JGR in rev.), Boussetta et al. (2015, RSE)





T amplitude
20° C smaller
on vegetation

Findings of large biases in the diurnal temperature reposed on the use of MSG Skin Temperature. However with the current model version we are limited (both over bare soil and vegetation)

ECMWF

Lake surface temperature verification using satellites

JJA 2015 (91-days AN vs OSTIA-lake)

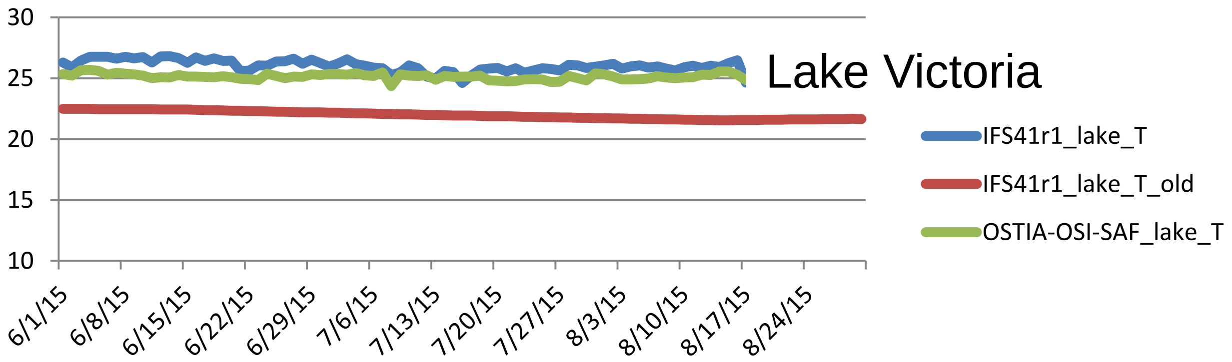
Lake AFRICA	RMSE	BIAS	Correlation	Mean Model	Mean Obs	Stdev Model	Stdev Obs
Victoria_IFS41R1	0.957	0.826	0.491	25.665	24.849	0.554415	0.230933
Victoria_IFS40R1	3.157	-3.14	0.328	21.743	24.849	0.322463	0.230933

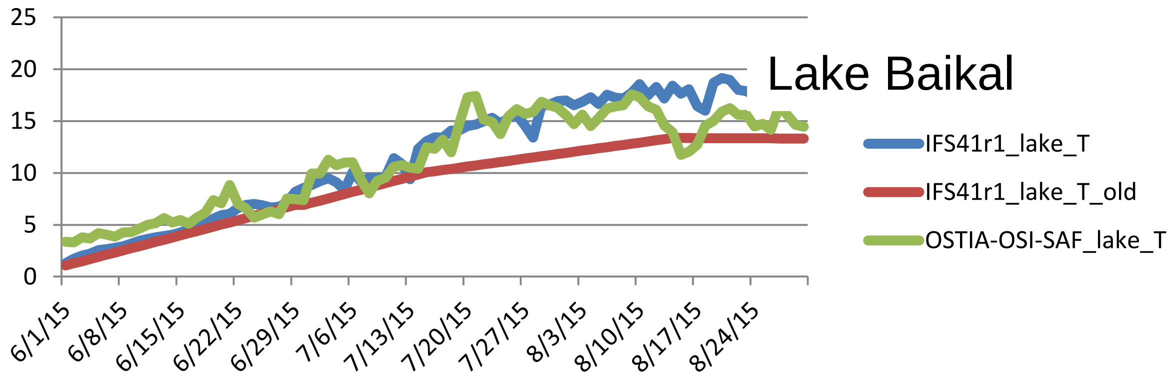
Lake CANADA	RMSE	BIAS	CORR	Mean Model	Mean Obs	Stdev Model	Stdev Obs
Great_Bear_IFS41R1	2.875	1.877	0.927	5.225	3.368	3.87317	1.96852
Great_Bear_IFS40R1	5.401	4.598	0.894	7.916	3.368	4.45394	1.96852

Lake S. AMERICA	RMSE	BIAS	CORR	Mean Model	Mean Obs	Stdev Model	Stdev Obs
Titicaca_IFS41R1	0.611	-0.425	0.822	12.322	12.742	0.739826	0.482809
Titicaca_IFS40R1	3.804	-3.789	0.752	8.995	12.742	0.463688	0.482809

Lake EU	RMSE	BIAS	CORR	Mean Model	Mean Obs	Stdev Model	Stdev Obs
Ladoga_IFS41R1	2.45	2.051	0.958	14.207	12.178	4.22985	4.60613
Ladoga_IFS40R1	1.443	-0.295	0.984	11.886	12.178	3.3881	4.60613

Lake sub-grid EU	RMSE	BIAS	CORR	Mean Model	Mean Obs	Stdev Model	Stdev Obs
Haukivesi_IFS41R1	1.706	-0.02	0.807	15.188	15.207	2.24239	2.88615
Haukivesi_IFS40R1	2.915	-2.733	0.964	12.504	15.207	3.44774	2.88615

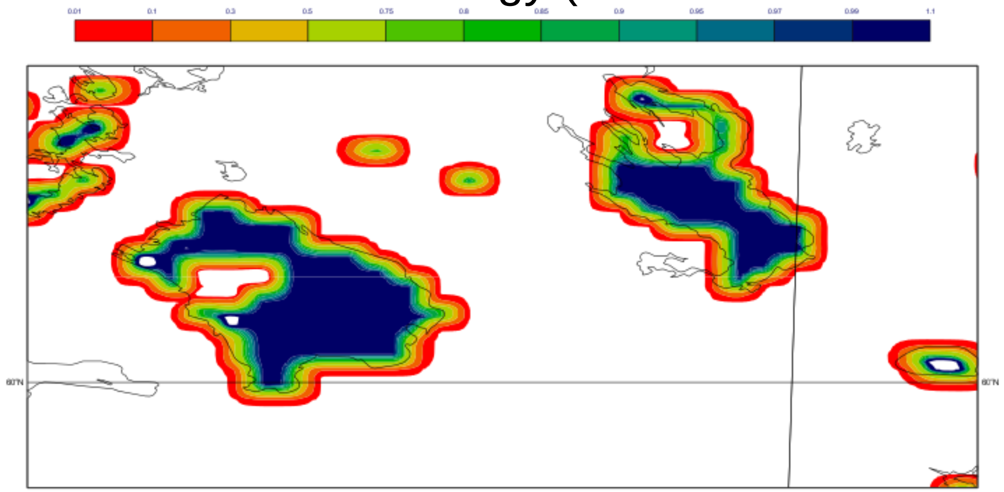




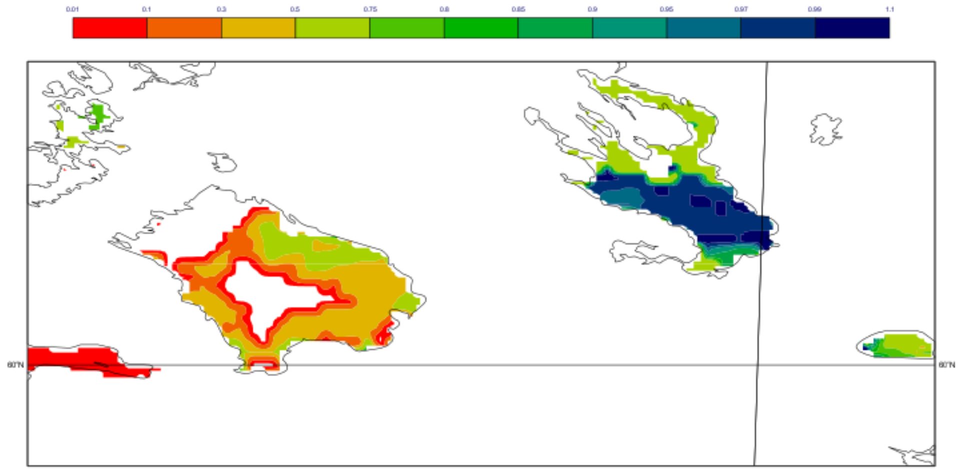
Improved representation of lake ice melting: Lakes Ladoga and Onega

Case Study of 18 April 2016:
The Largest European Lakes:
Lake Lagoda & Lake Onega
started to melt lake ice, with
Faster melting occurring in Ladoga

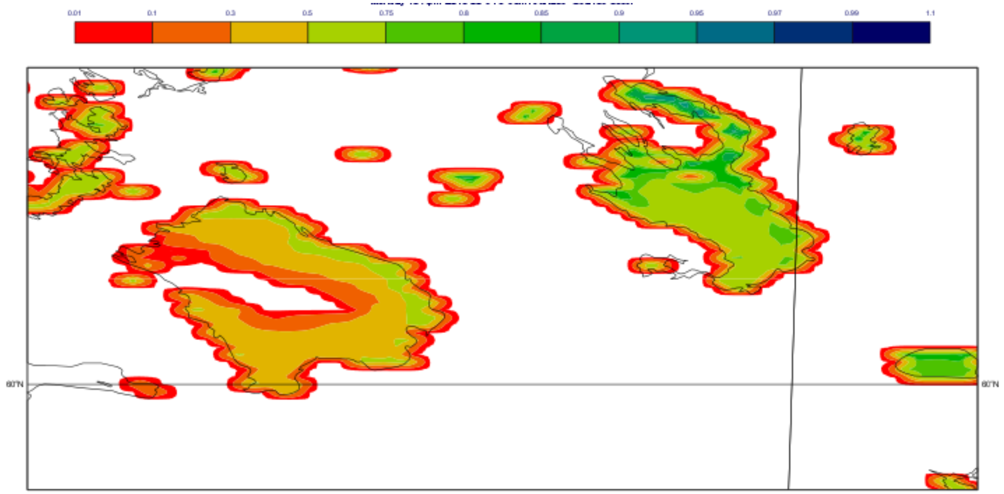
ECMWF Old model climatology (no difference in melting)



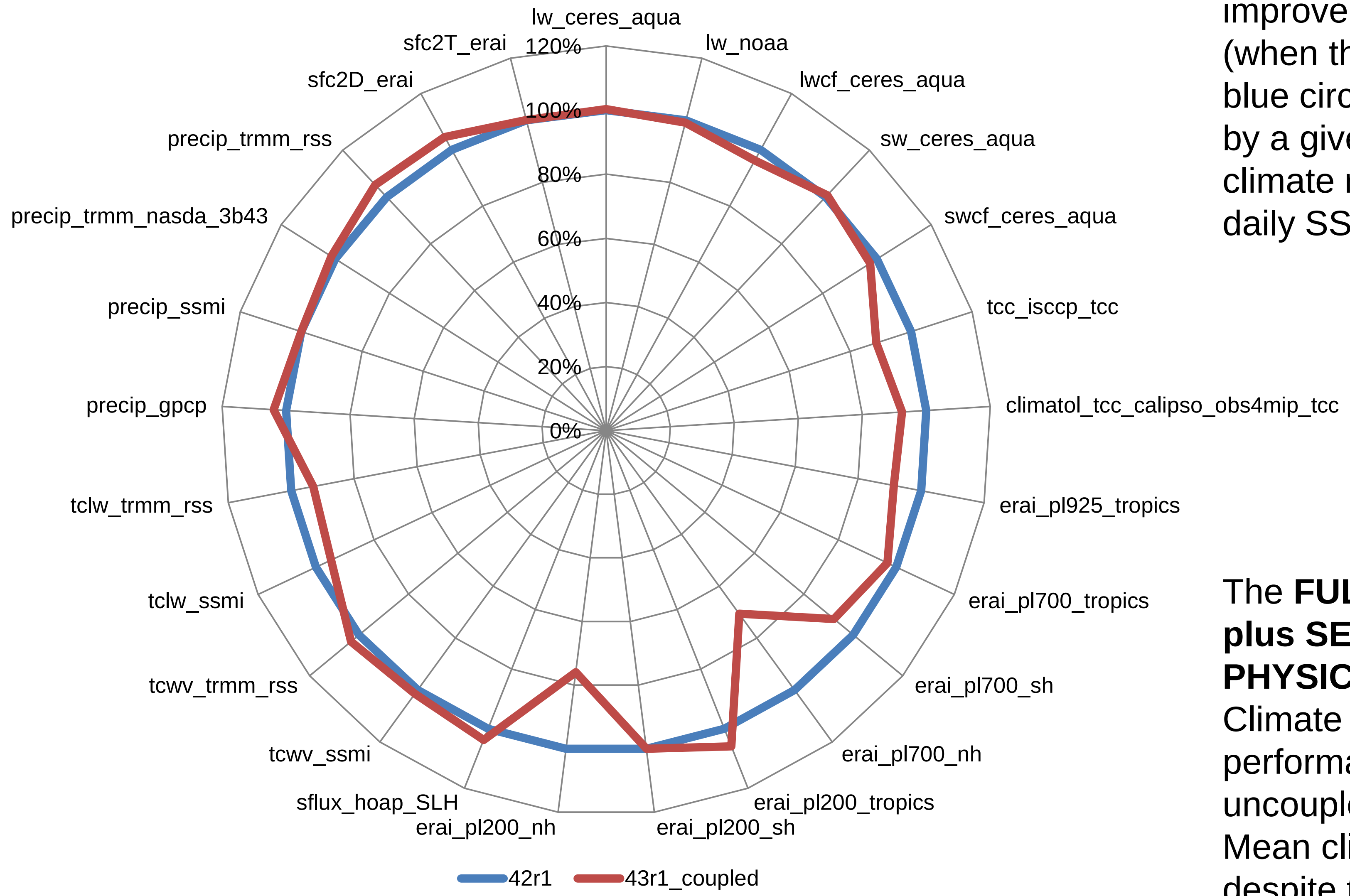
OSI-SAF Satellite Ice cover 18 April 2016:



ECMWF IFS Lake Ice Cover (Ladoga melting faster)



Climate behavior of the new ECMWF coupled system

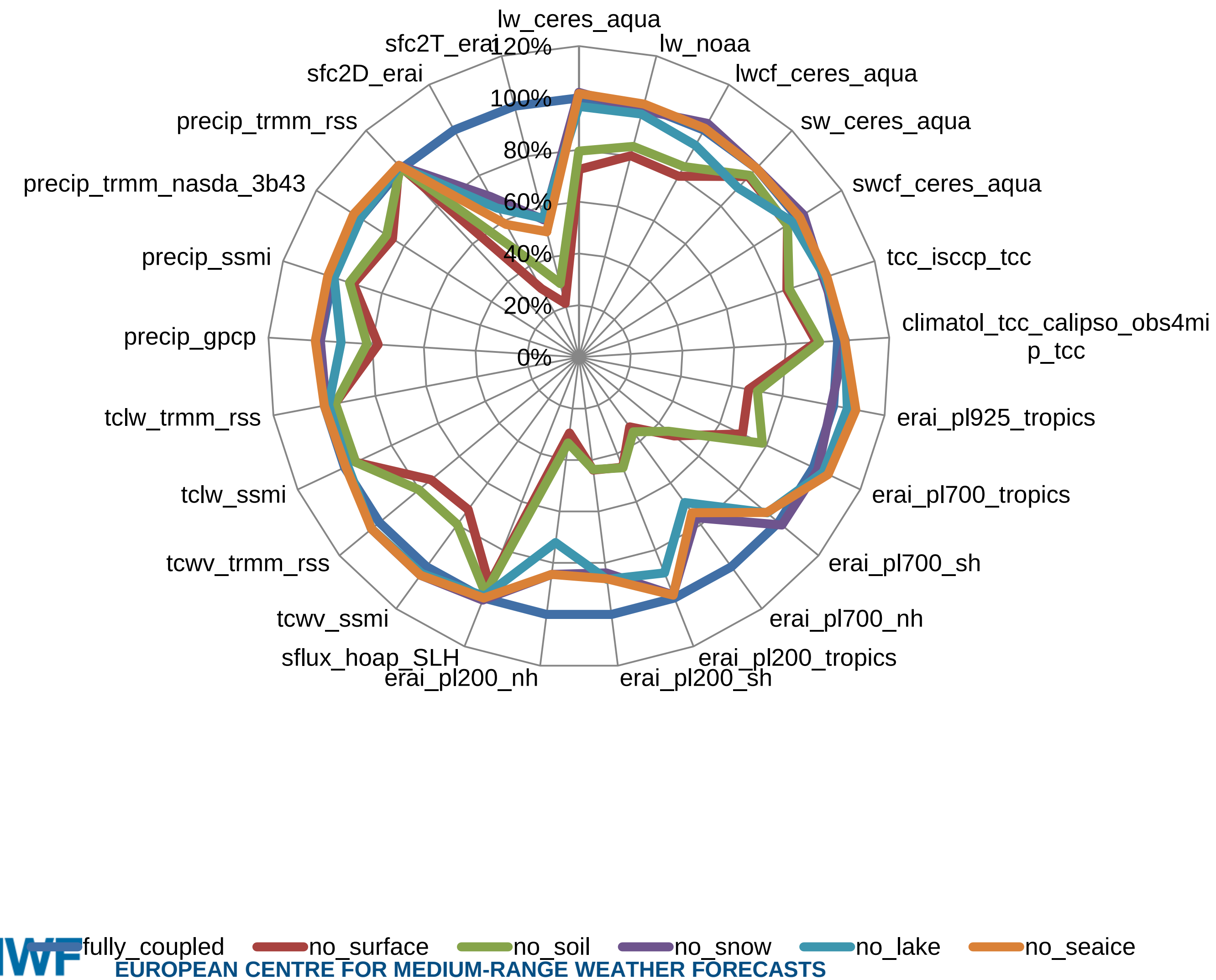


The **4-y climate** radial plot show improvements in the climate (when the red curve is inside the blue circle the RMSE is reduced by a given % with respect to 41r2 climate run (uncoupled and with daily SST/Sea-Ice from ERAI).

The FULL-OCEAN-COUPLING plus SEA-ICE and NEW PHYSICS PACKAGE
Climate run is stable and it has performance similar to the uncoupled AMIP runs!
Mean climate is slightly improved despite the large amount of degrees of freedom introduced by having coupled ocean and

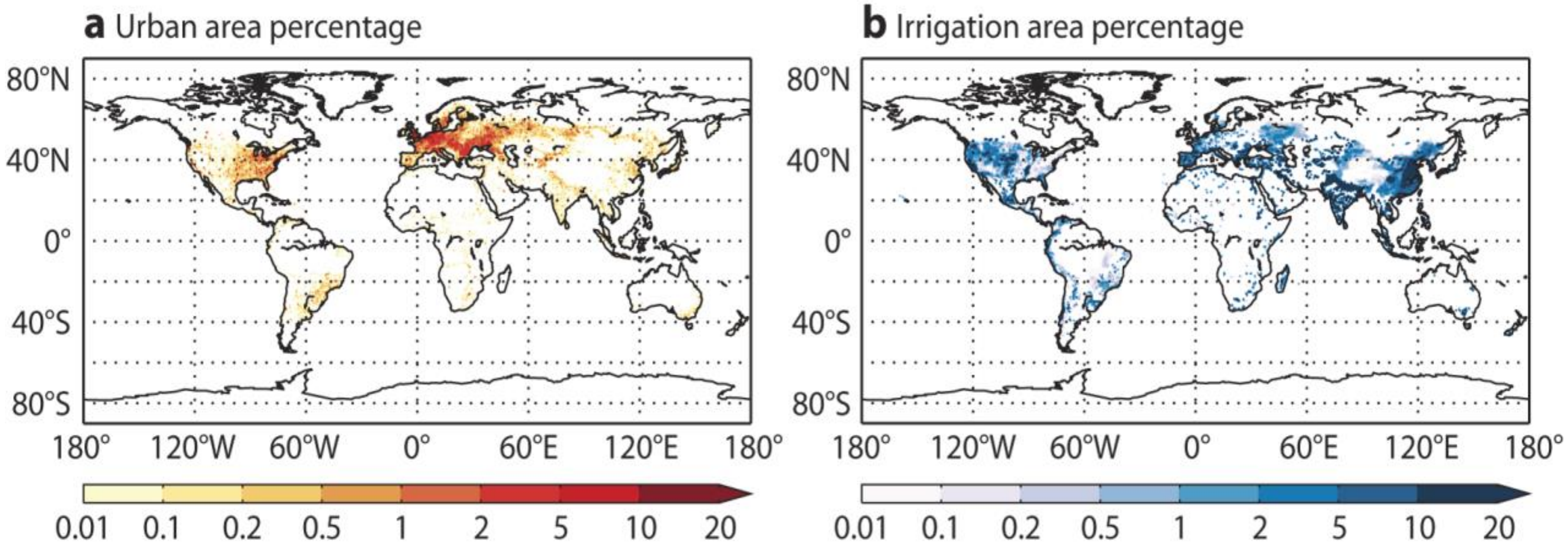
ECMWF EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

Quantitative impact of surface processes on the climate (II)



Missing surface components: An example

- 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)

Representing land-related forecast uncertainties

- EDA/ENS system includes land surface components (CY40R1) and perturbation also to the assimilated observations (CY40R3)
- Accounting for land surface uncertainties (particularly for snow) enhances the ensemble spread of 2m temperature prediction and its usefulness for forecasters
- The uncertainty is situation dependent and perturbations permit to capture the occurrence of extremes (e.g. clear sky nights combined with snow covered surface can generate very cold temperatures)
- Small snow cover errors → large temperature impact