Coupled Earth Surface Processes and Role of EO to Enhance Global Forecasting

A roadmap to kilometre scale simulations

Gianpaolo Balsamo
with contributions of several Colleagues acknowledged on the slides

Presented on 19th January 2018 to CNRM-Météo-France, Toulouse, France

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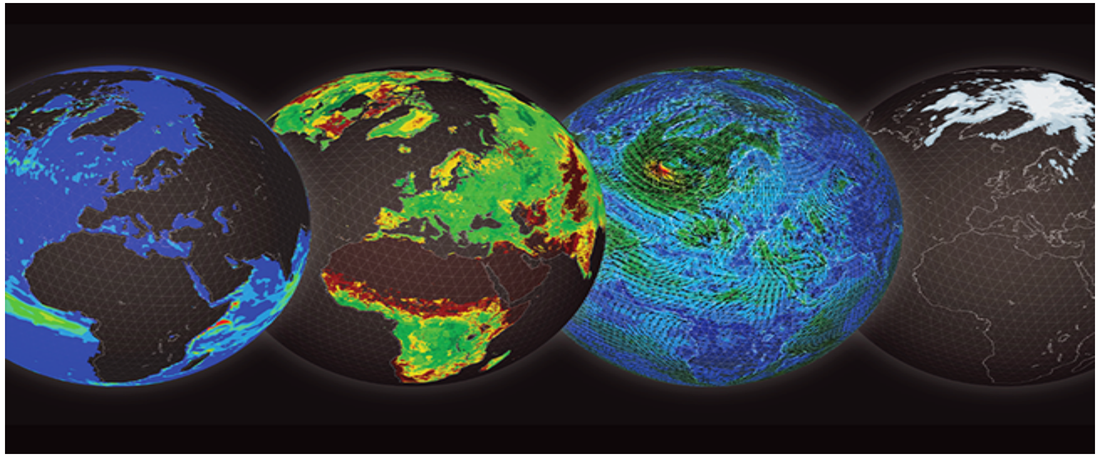
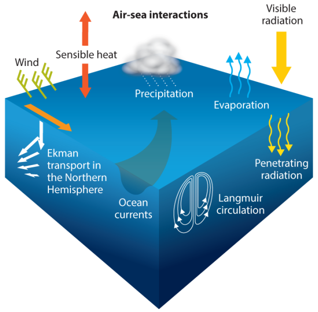
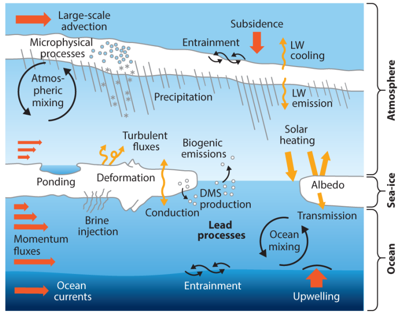
Coupled processes research @ECMWF

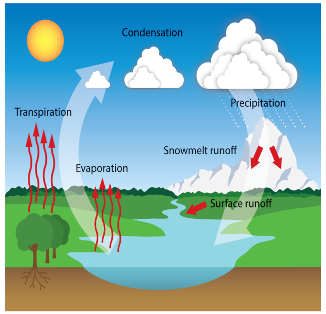


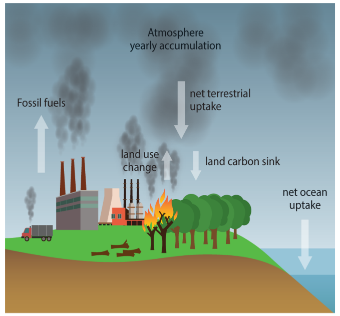
With the release of the ECMWF new 10-year strategy (2016-2025) the Earth System Ensemble approach is embraced calling for more seamless prediction & involving coupling of processes
(Weather, Environment, Climate, Human-influence)

Research topics

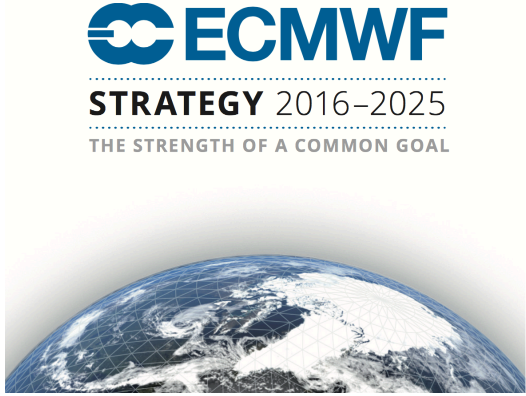








WWOSC 2014
MONTRÉAL, CANADA



J.-R. Bidlot, S. Keeley, K. Mogensen, P. Janssen, M. Choulga, G. Arduini, S. Boussetta, G. Balsamo
ECMWF coupled processes team in 2018

Outline

- Introduction: ECMWF embracing Earth System Ensemble approach
- Evolution of systematic errors: Land example
- Evolution of systematic errors: Ocean example
- Sneak peek into Future developments

Earth surface (natural) modelling components @ECMWF

- **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**

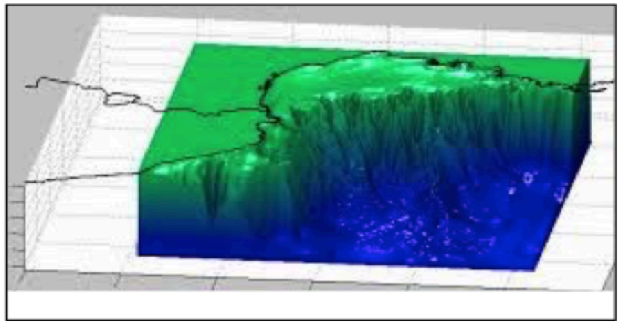
  The Louvain-la-Neuve Sea Ice Model

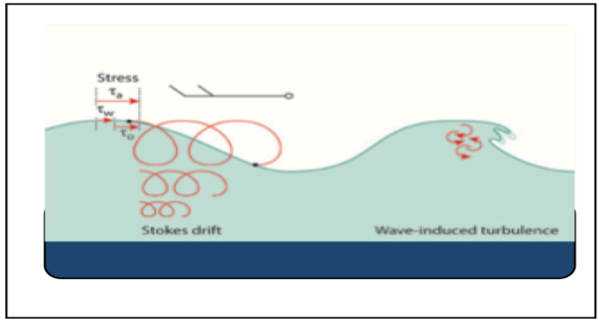
  Fichefet and Morales Maqueda (1997)

  Bouillon et al. (2009)

  Vancoppenolle et al. (2009)

  ORCA025_Z75 : 0.25° x 0.25°





Ocean 3D-Model Surface Waves and currents, Sea-ice.

- **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)

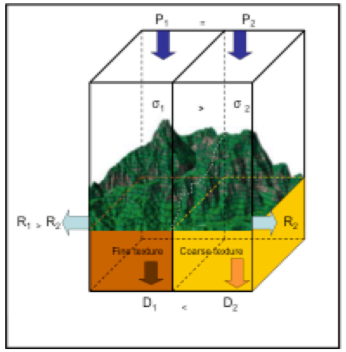
- **Enhance ML**

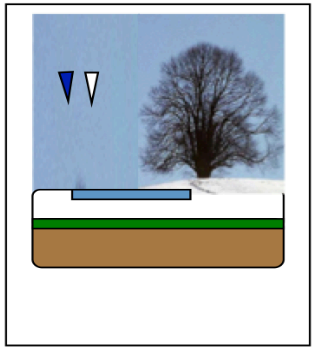
  Snow ML5

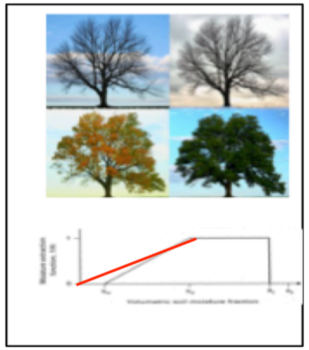
  Soil ML9

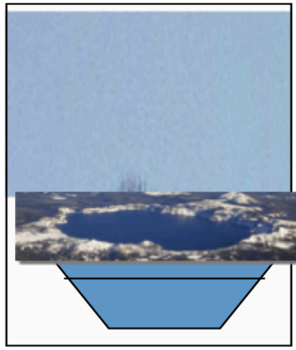
  Dutra et al. (2012, 2016)

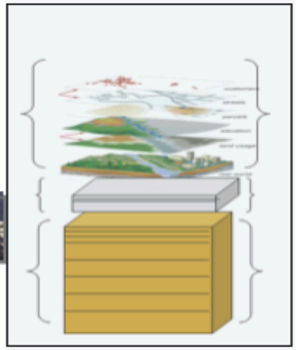
  Balsamo et al. (2016)







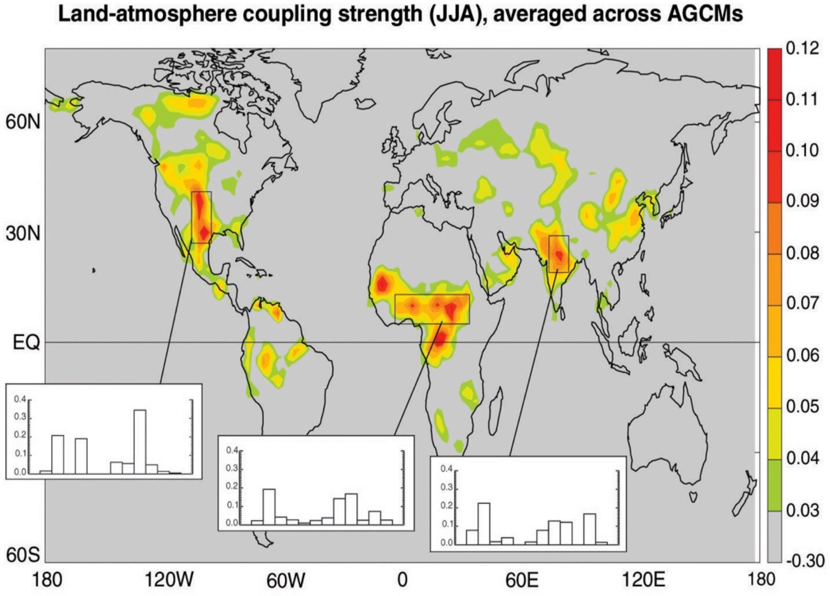




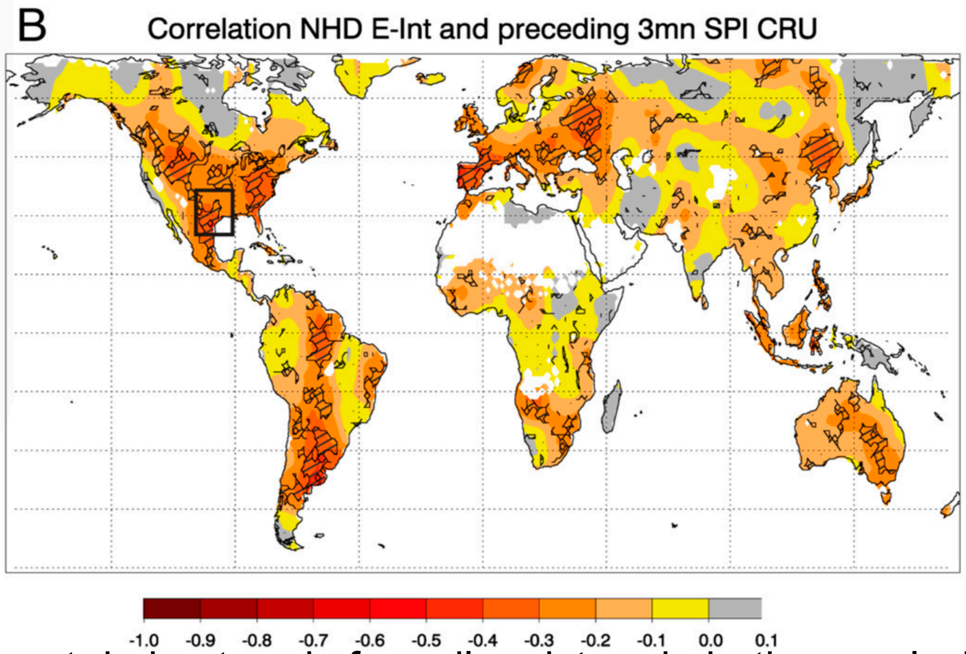
Land surface 1D-model soil, snow, vegetation, lakes and coastal water (thermodynamics only).

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

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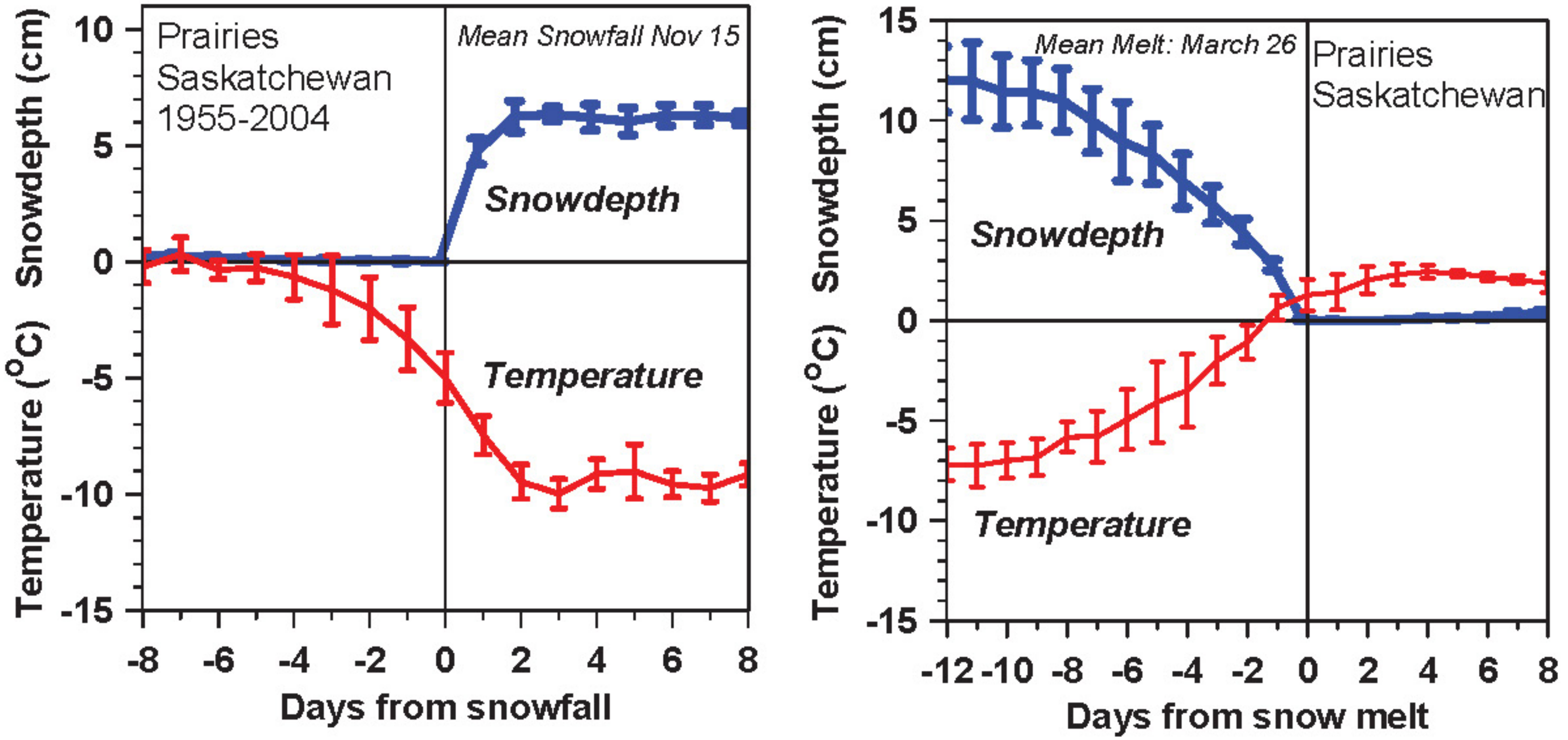
Earth surface role, observational evidence (snow)



Snow reflects sunlight; shift to cold stable BL

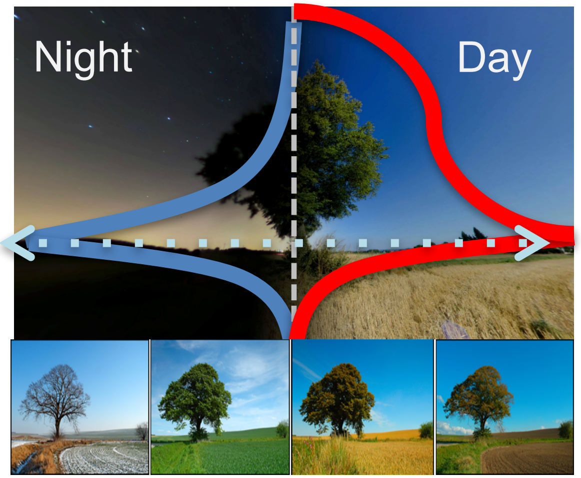
Local climate switch between warm and cold seasons

Winter comes fast with snow

Betts et al. 2014

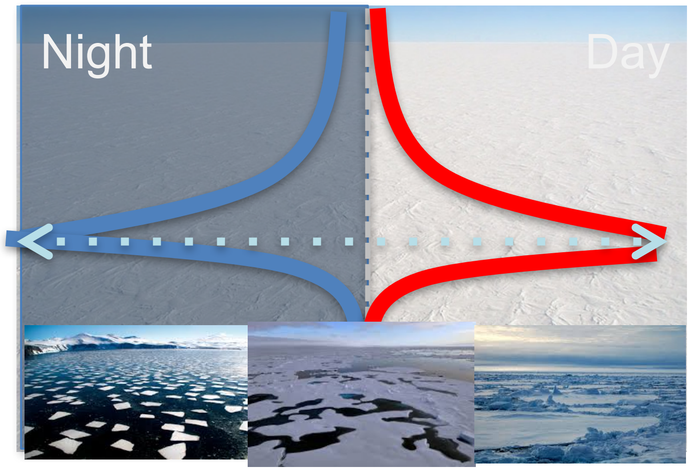
Coupled Processes at the surface interface: What are the challenges?

- The processes that are most relevant for near-surface weather prediction are also those that are most interactive and exhibit positive feedbacks or have key role in energy partitioning



Over Land

- Snow-cover, ice freezing/melting are in a positive feedback via the albedo
- Vegetation growth and variability and interaction with turbulence
- Vertical heat transport in soil/snow



Over Ocean/Cryosphere

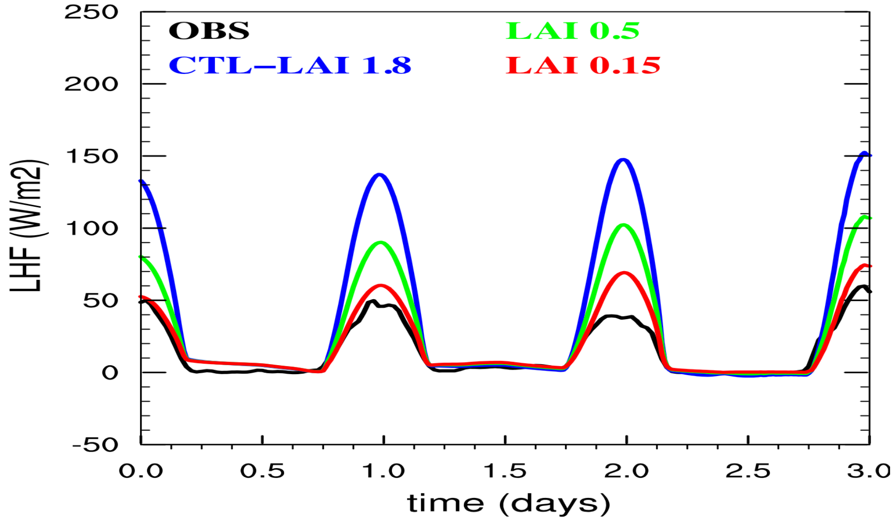
- Transition from open-sea to ice-covered conditions
- Sea-state dependent interaction wind induced mixing/waves
- Vertical transport of heat

- Studying and constraining positive feedback processes is key to advance seamless forecasting, embracing a larger amount of physical processes while still maintaining model realism

Coupling with the vegetation/soil layer with Atmosphere

Boussetta et al. 2015 (RSE) showed that albedo and vegetation state are important for accurate surface ET & weather FC during extremes.

Agusti-Panareda et al. 2014 (ACP) showed that CO_2 can be predicted using land fluxes of CHTESSEL



Sandu et al. 2014 (GEWEX Conference poster)

Diurnal cycle Couple Experiment (DICE, Lock and Best UKMO) has shown an important effect of vegetation litter shielding water extraction for evaporation processes.

Important to know vegetation state and its activity (e.g. using Sentinel satellite fluorescence data).
Vegetation cover variability is most important for NWP and linked with physiography work.
See presentation from Souhail for phenology impact

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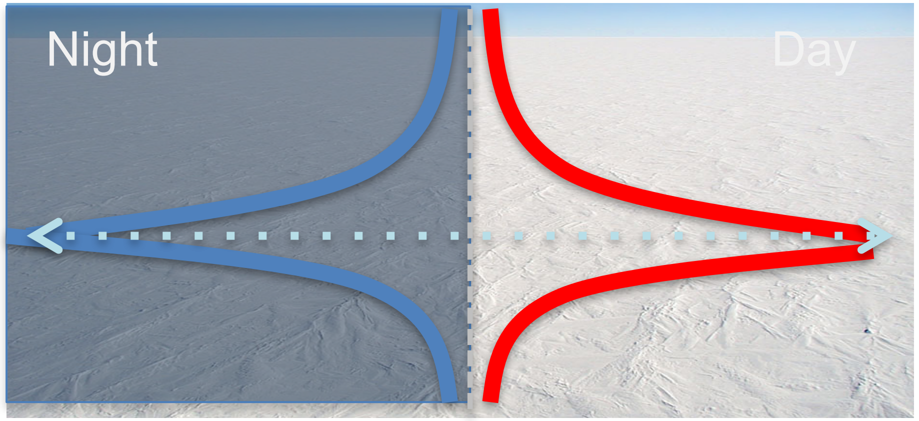
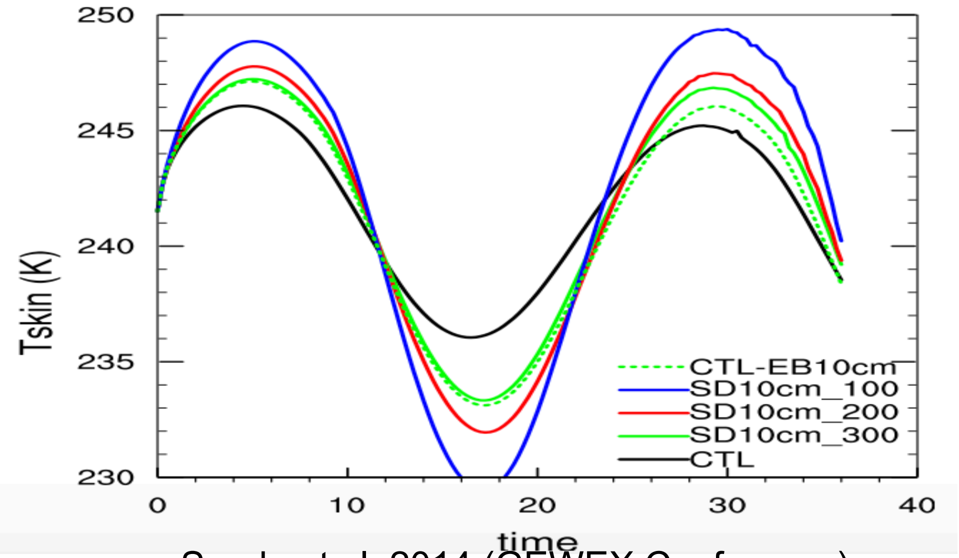
Coupling and diurnal cycle: snow and ice



GABLS experiment and interaction with CEN-MF led to a study on snow-atmosphere coupling over permanent snow area.



Sandu et al. 2014 (GEWEX Conference)

Dutra et al. 2015 (TM) show that
a shallower snow layer over Antarctica can improve the match to satellite measured skin temperature,
Supporting investment in a multi-layer snow scheme.

However there is a **sizeable technical development** to host Multi-layer surface fields in operations.

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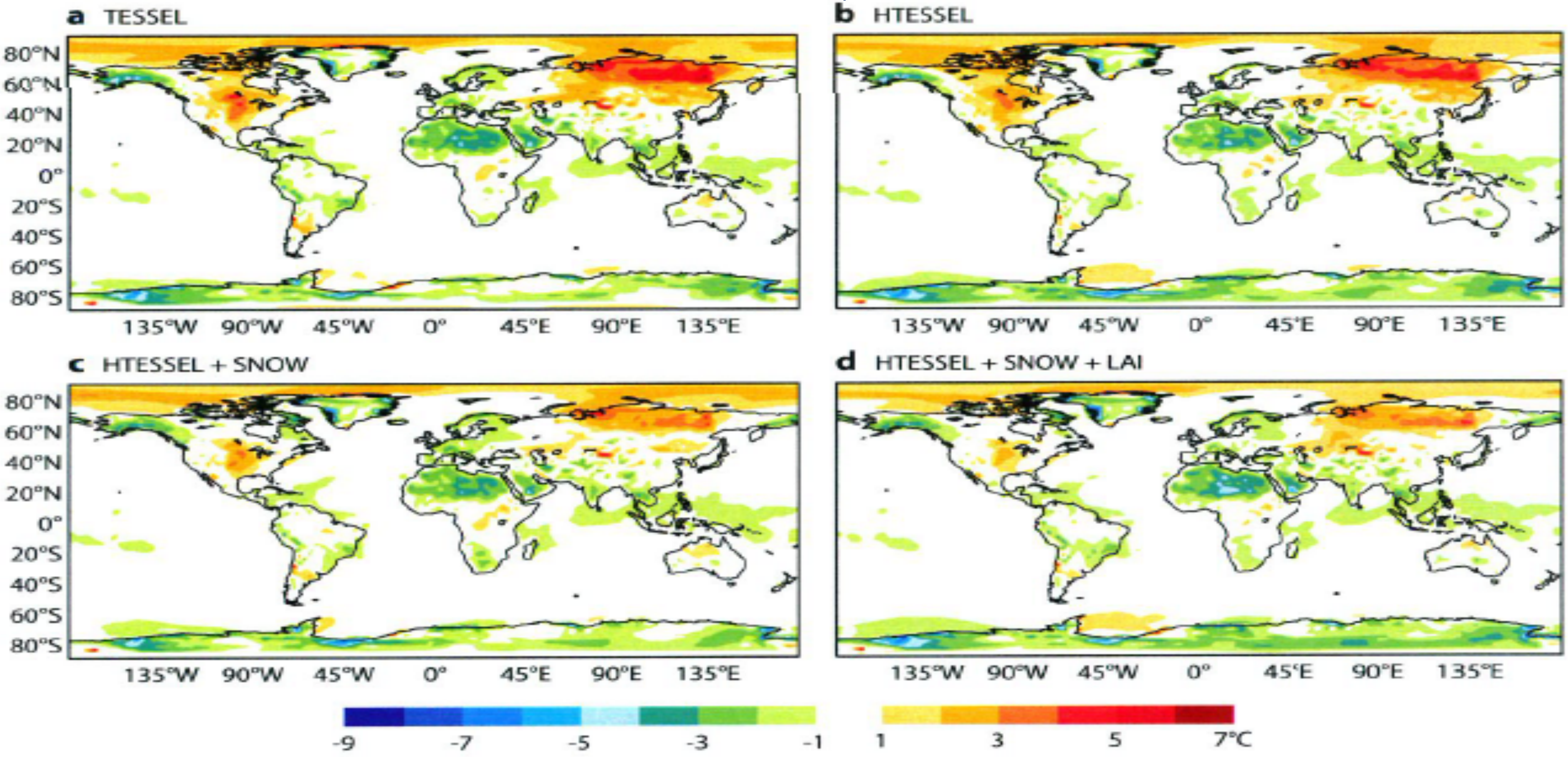
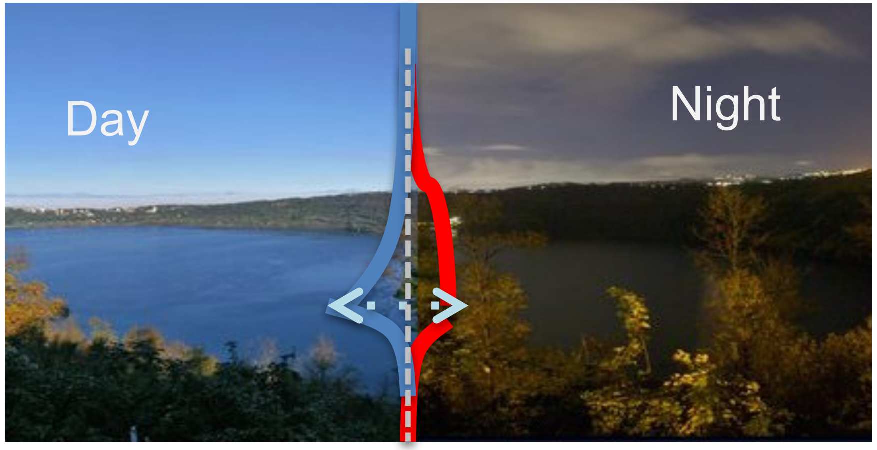
Extended-range impact (1-year) of land surface model development on model error

Impact of the soil/snow/vegetation revision in HTESSEL on 2m temperature (in 13-month long integrations (Balsamo et al. 2009, Dutra et al. 2010, Boussetta et al. 2013)

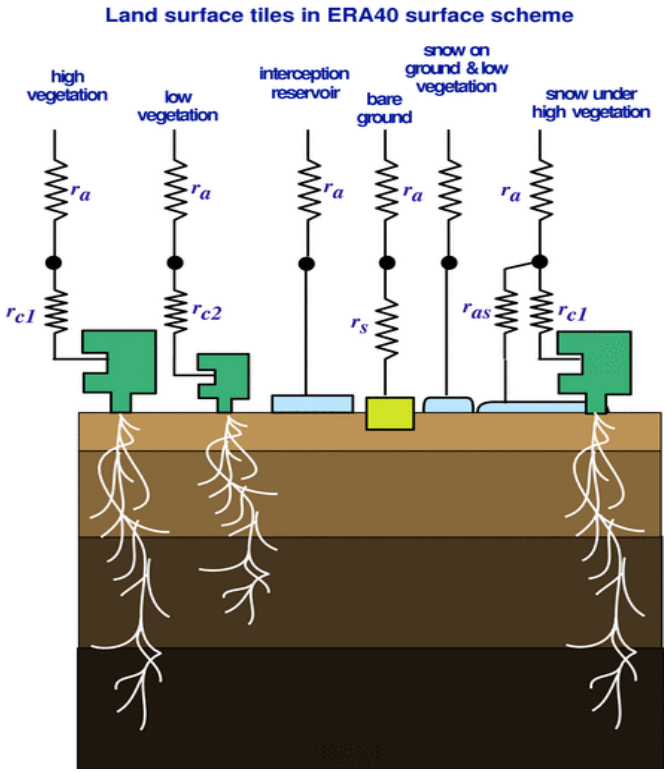


simulations colder than ERA-Interim Warmer than ERA-Interim

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 that affect fluxes and the lake heat storage



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

- **Lake tile**

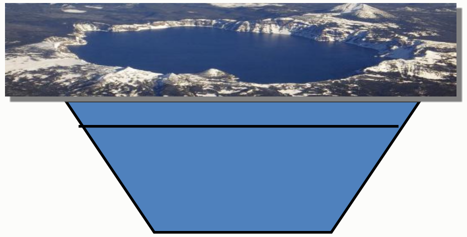
  Mironov et al (2010),

  Dutra et al. (2010),

  Balsamo et al. (2010, 2012, 2013)

- **Manrique-Sunen et al (2013)**

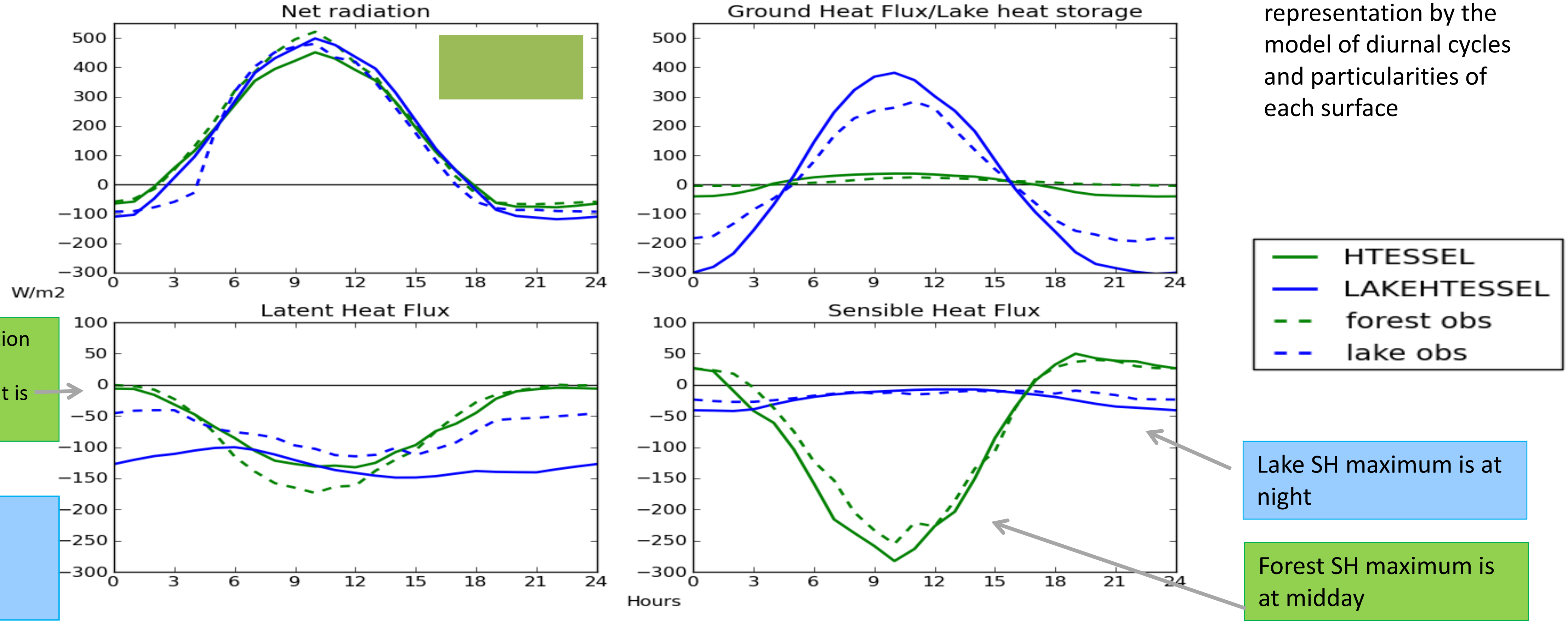
  Extra tile (9) to account for sub-grid lakes



Diurnal cycles: difference forests &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

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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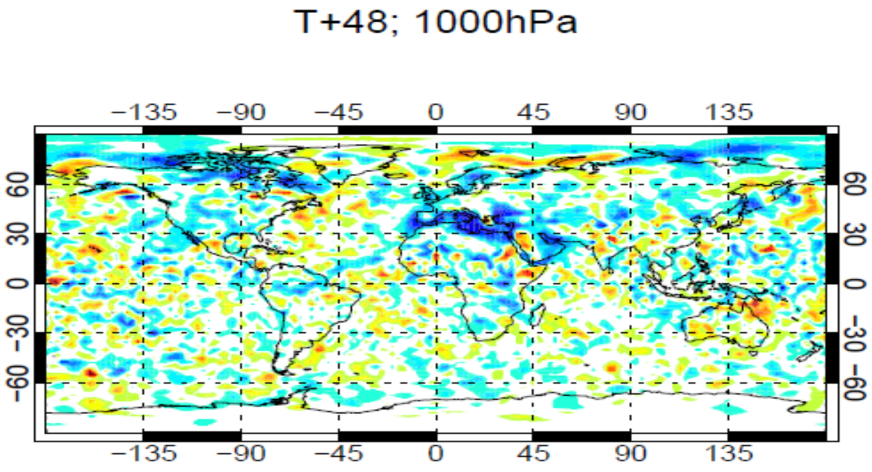
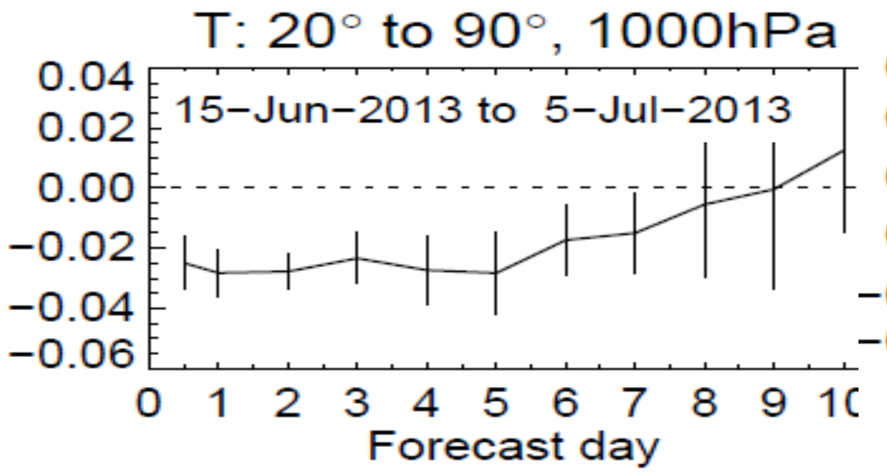
Impact of water bodies in the analysis cycles

Summer experiment

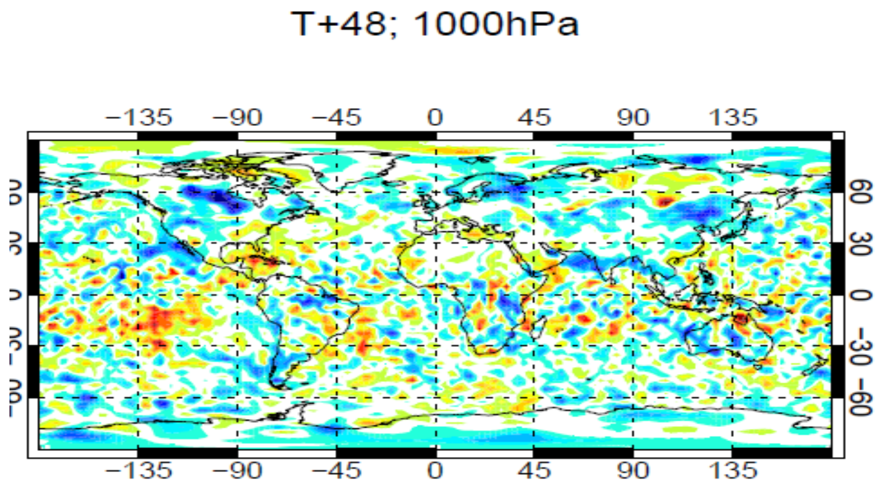
(Temperature scores)

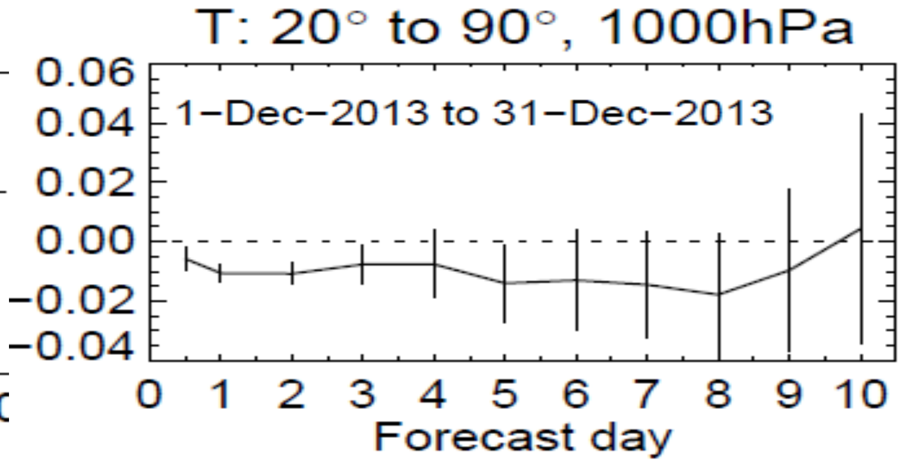




Winter experiment

(Temperature scores).



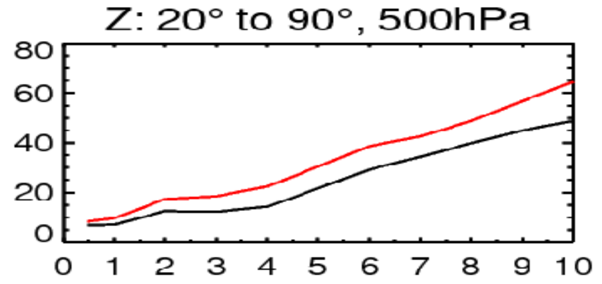


In CY40R3 forecast of 2m temperature are improved in proximity of lakes and coastal areas

Winter RMSE impact is positive as well but around 1% improvement

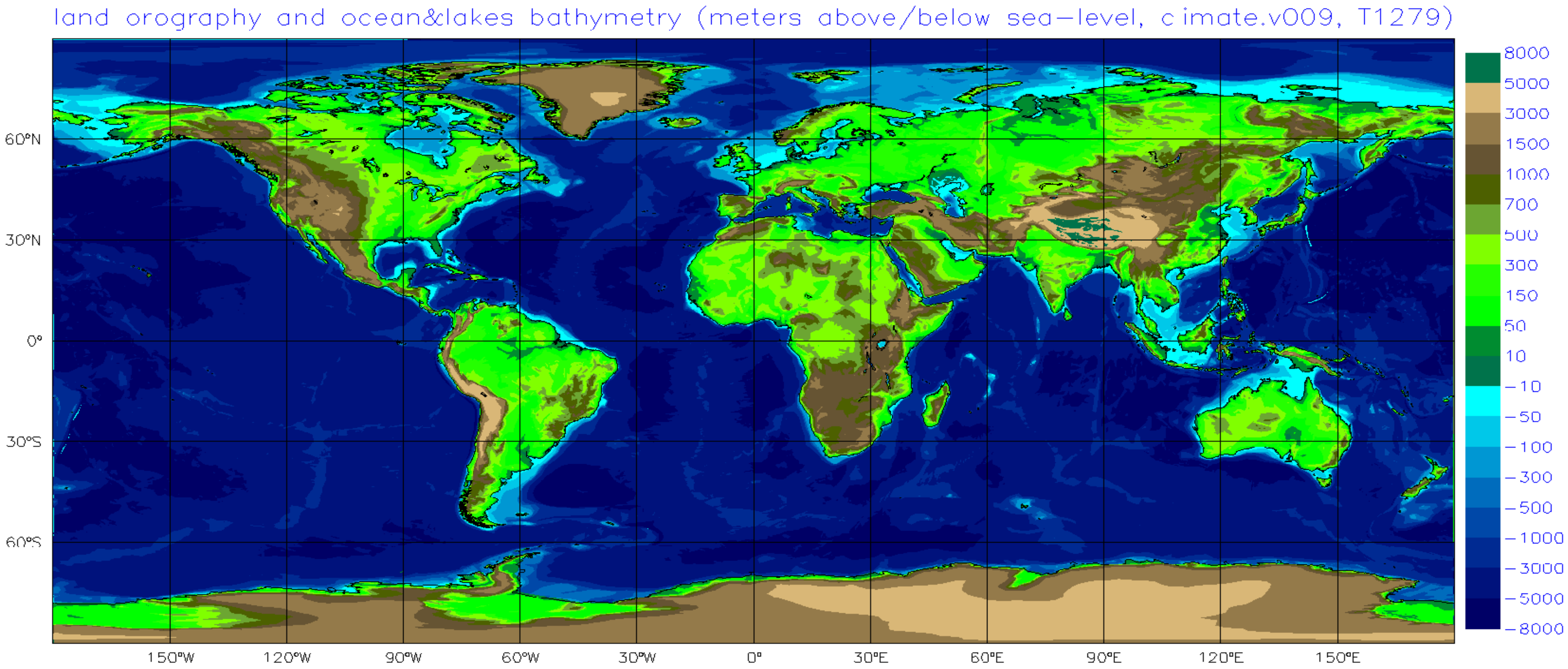
In summer the impact is estimated in 2-3% relative improvement in RMSE of T1000hPa significant up to 7 days

In summer also the Z500 mean error is reduced



Operational inland-water bodies in IFS cycle 41r1 (May 2015)

Given the large impact of including inland water bodies in forecasting near surface weather parameters investment in physyography Dataset has increased: here is shown a global Orography and Bathymetry (elevation above/below sea-level in m). Another seamless aspect!



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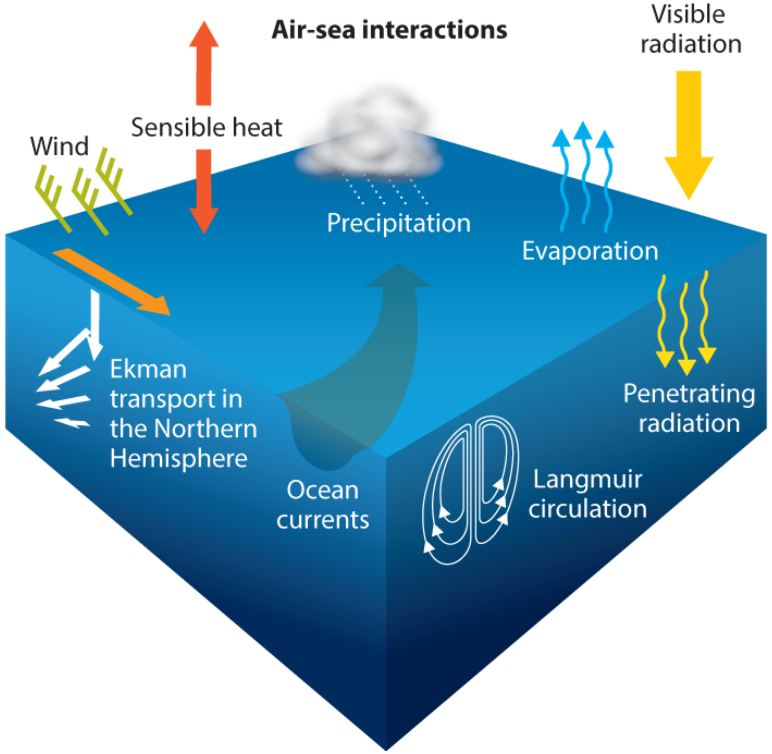
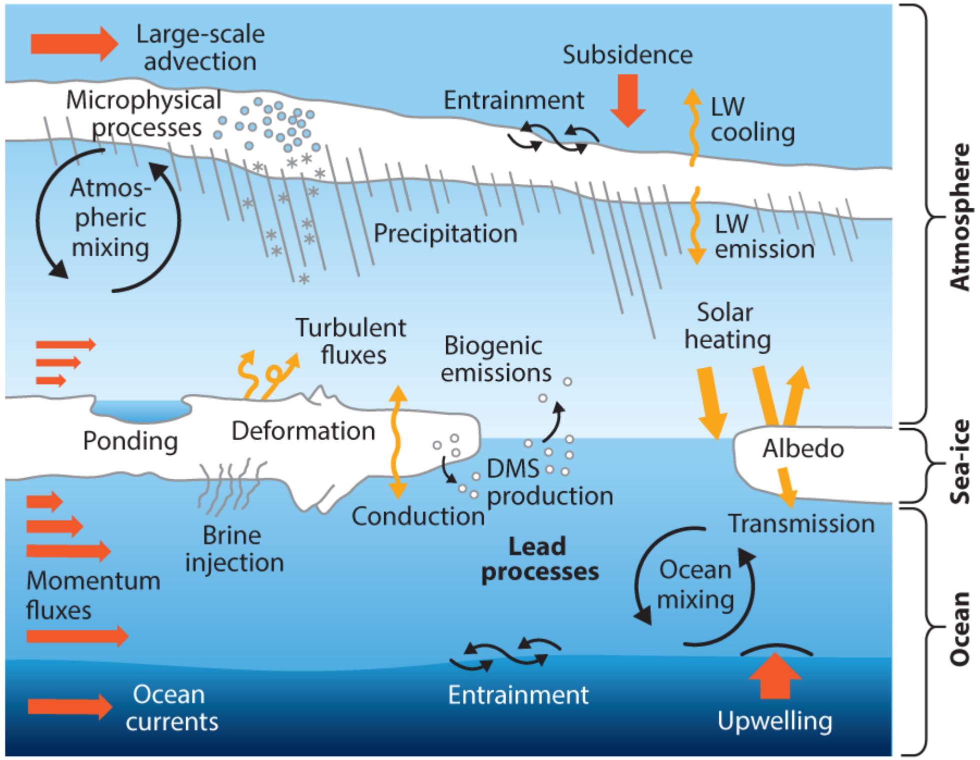
Oceans: from climate to weather





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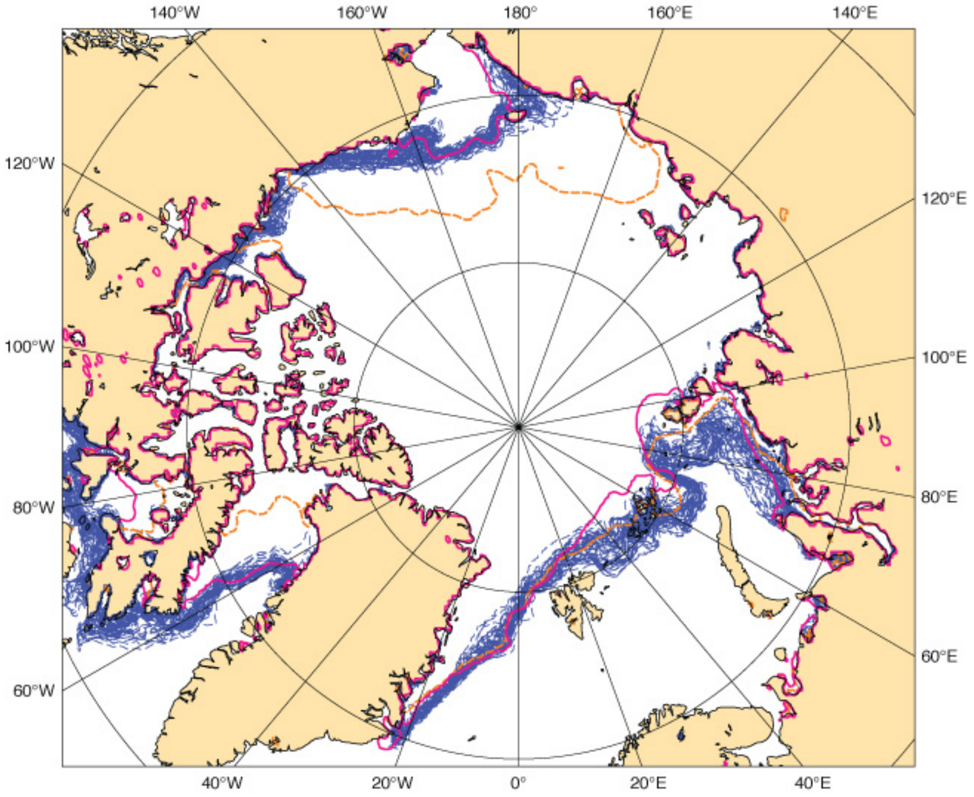
Ingredients of the ECMWF operational sea-ice model

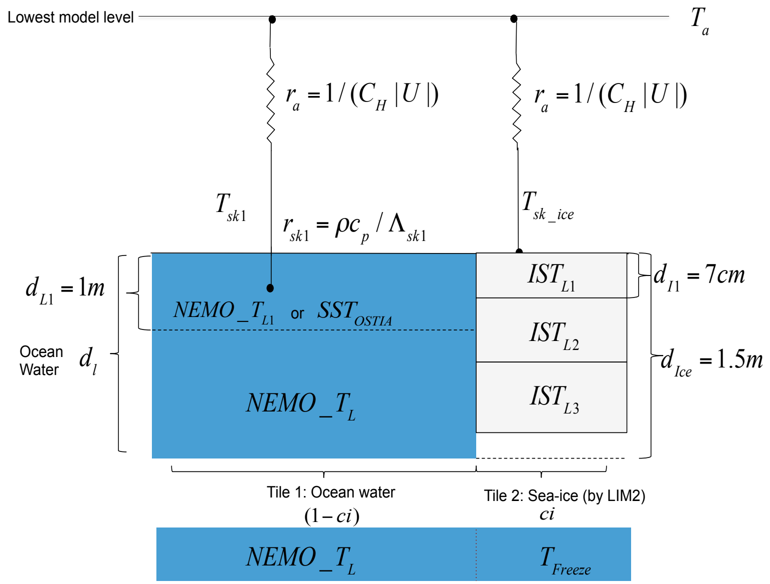
- **INTERACTIVE Dynamical SEA-ICE since NOVEMBER 2016**

For the first-time the ice is evolved along the Ensemble Forecast System

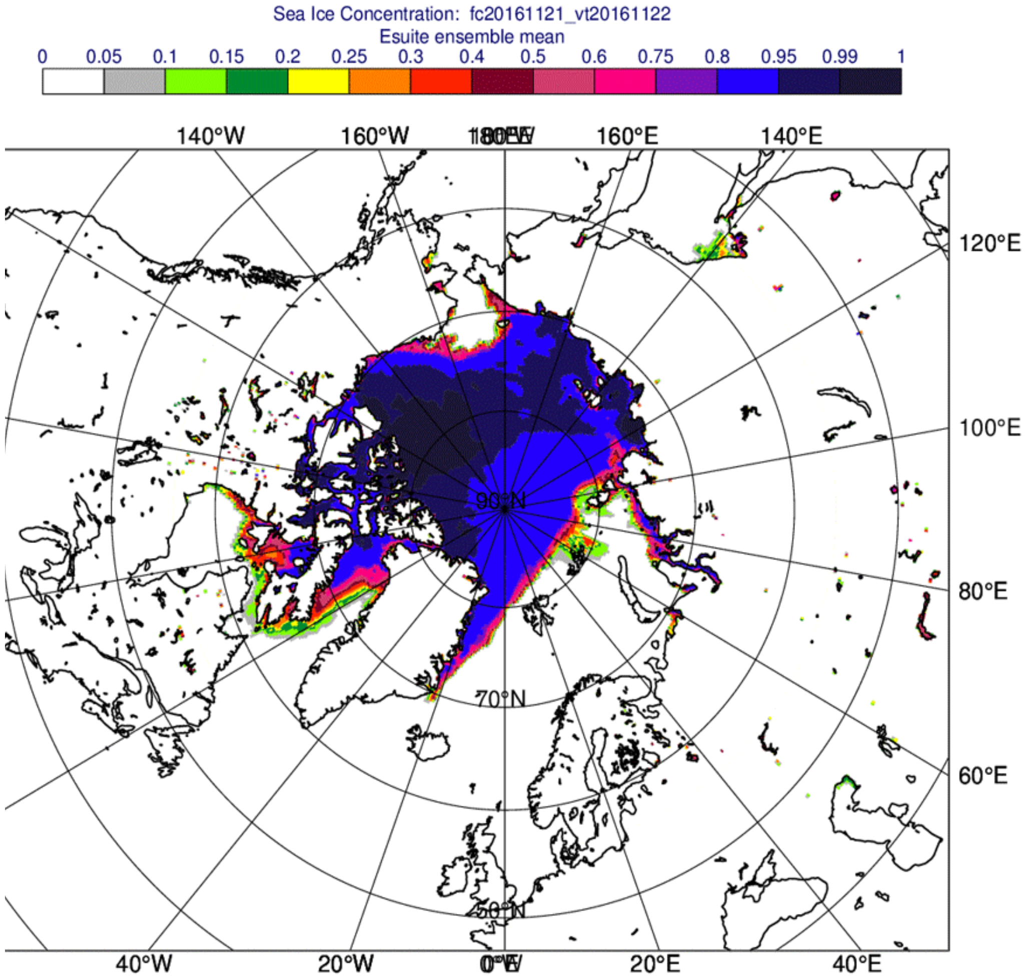


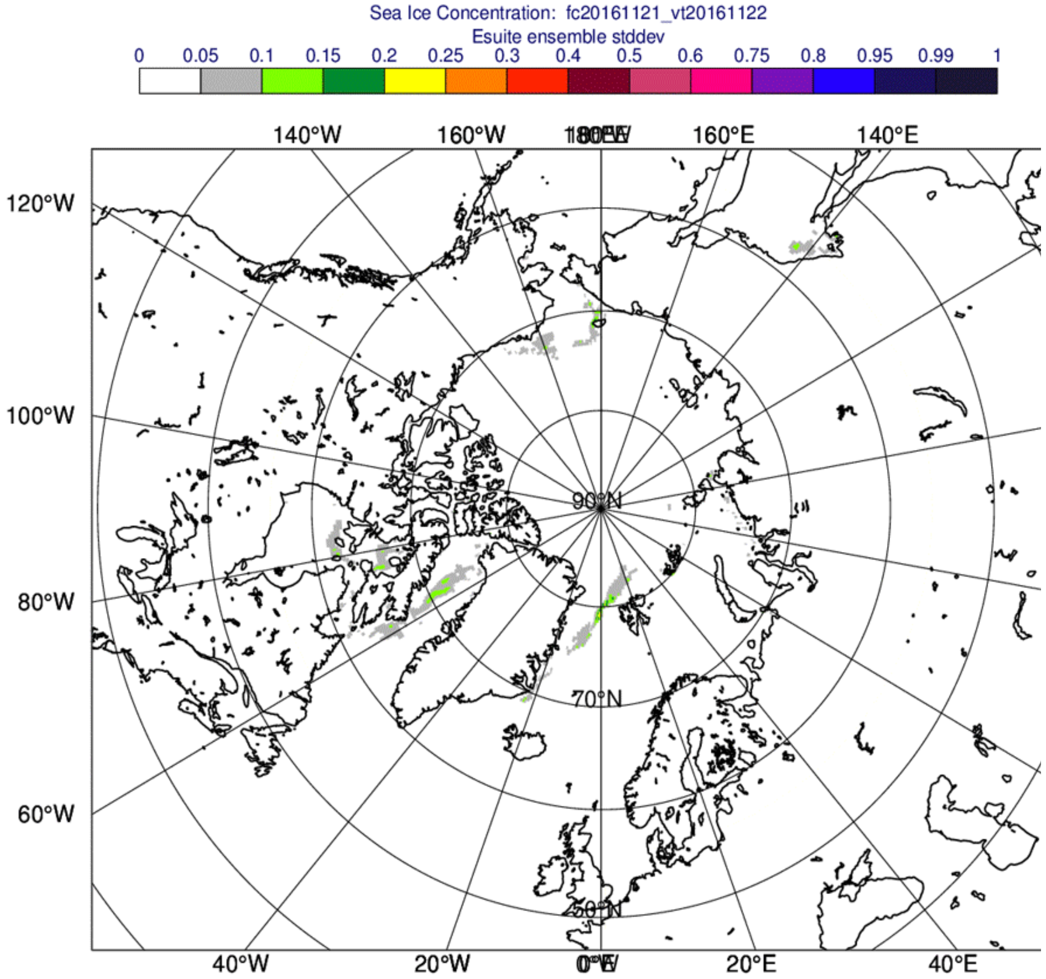
- **INTEGRATED within the TILING approach**

Fractional ice cover benefit from a tiled energy balance for water/ice



Sea-ice cover in the Ensemble Forecasting System (in HRES in 2018)





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Thanks to Sarah Keeley

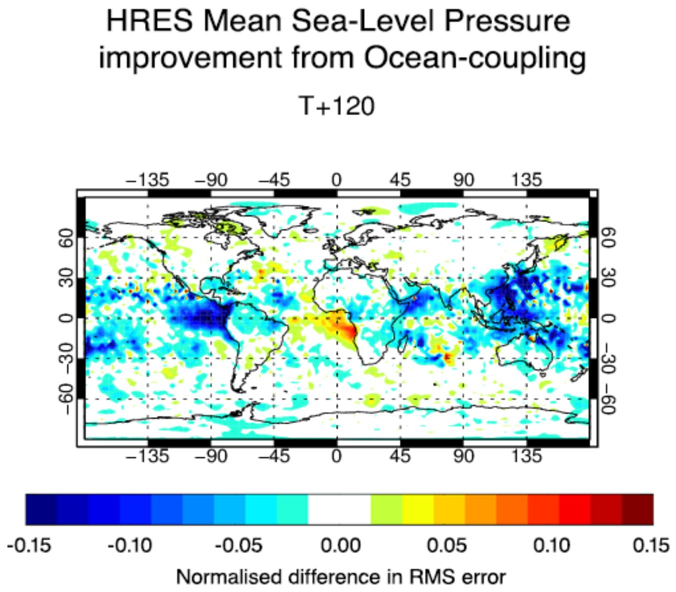
HRES-Ocean-Coupled: Impact on medium-range (operational in 2018)

Forecast improvements at Day+5 (**1 year**) (blue colors indicate RMSE reduction) due to the HRES coupling of the NEMO+LIM Ocean and sea-ice model to the atmospheric model integrations

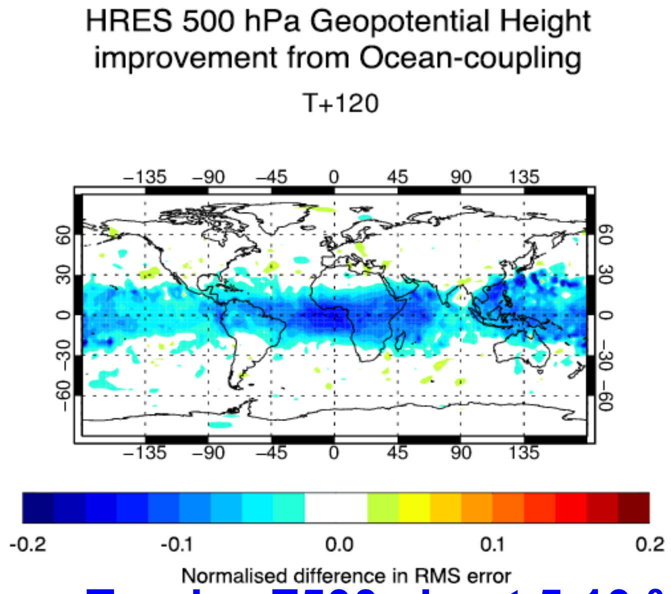
Evaluated on one full year of TCo1279 daily forecasts (April 2015-March 2016).

Largely positive in Tropical regions.
Guinea Gulf demands attention (feedback w. stratocumulus region *)

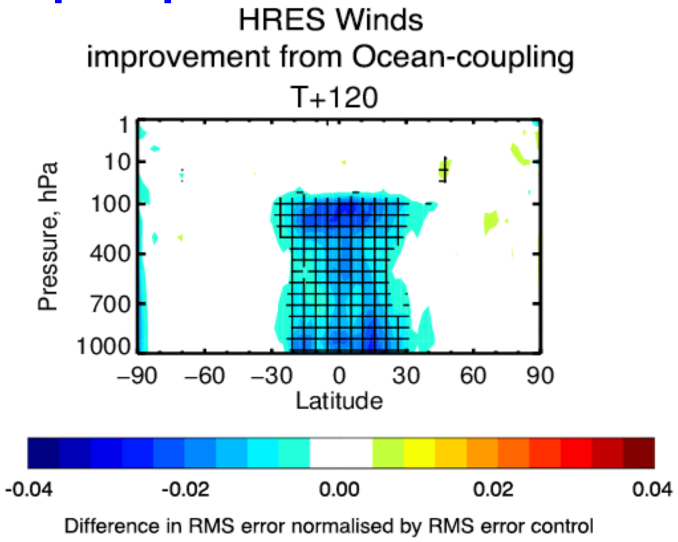
Introduced in cycle 45r1 expected to be Operational in Spring 2018



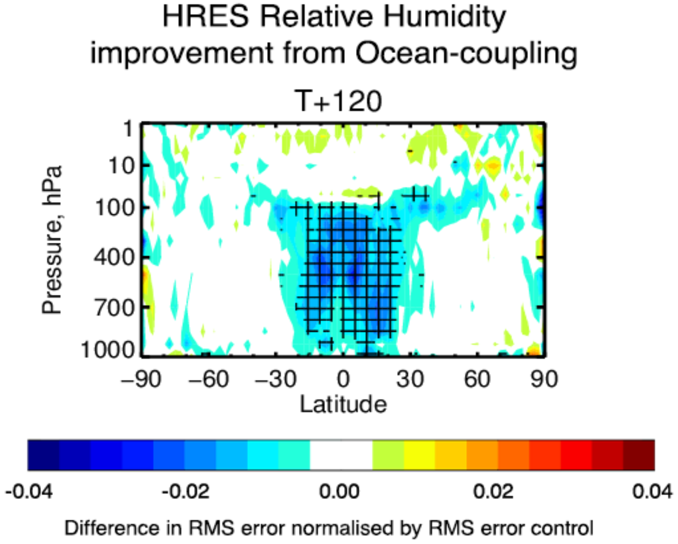
Tropics pressure about 5-10 % (*)



Tropics Z500 about 5-10 %



Tropics winds 2-4 %



Tropics humidity 2 %

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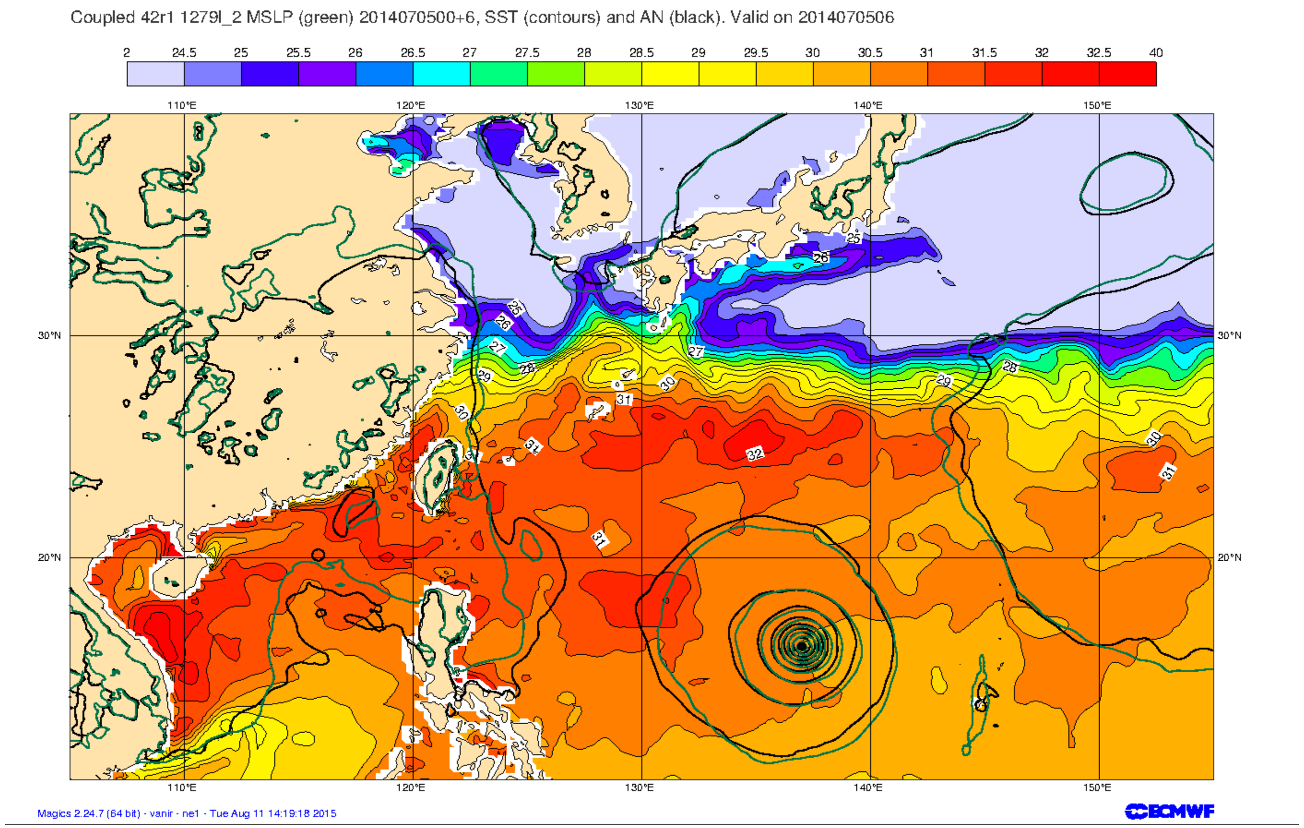
Thanks to Kristian Mogensen & CP

HRES-Ocean-Coupled and High Impact Weather: Tropical cyclone & SST interaction

ATMOSPHERE-OCEAN COUPLING EVIDENCE

A case study on Neoguri Typhoon (5-7 July 2014) The air-sea interactions are particularly evident in the case of tropical cyclones



HRES-Ocean Coupled: Impact on Extremes events

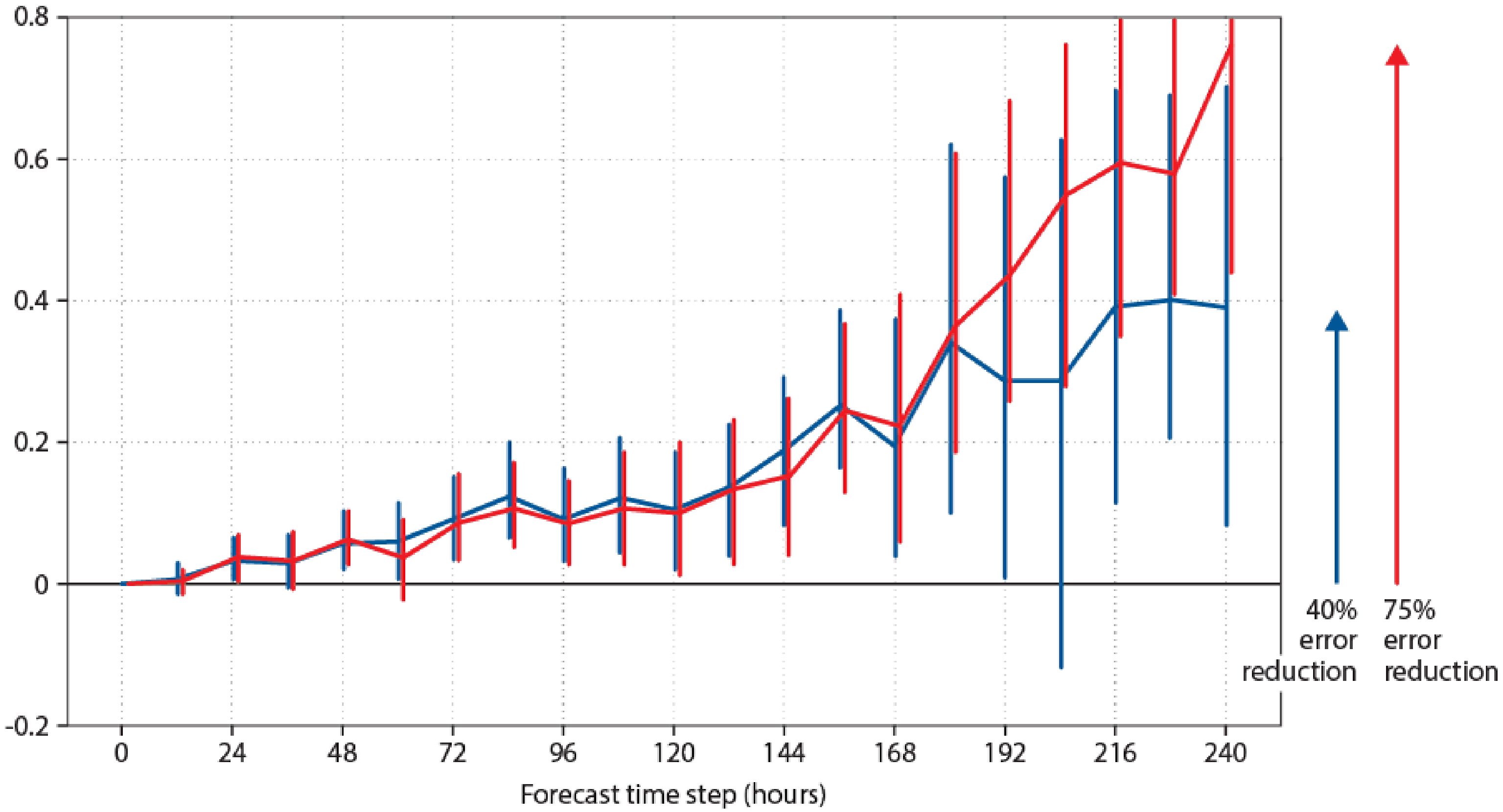
- Tropical cyclones are improved in their intensity and track

mean absolute error reduction of the tropical cyclone intensity in
Fully-Coupled & **Partially-Coupled***
(*foreseen implementation in 45r1, Q4/2017-Q1/2018)

HRES forecast of the intensity error calculated over tropical cyclones occurring during 2016-05 to 2017-01

About 100 samples at day+5 and
About 20 samples at day+10.

Bars indicate 95% confidence intervals.



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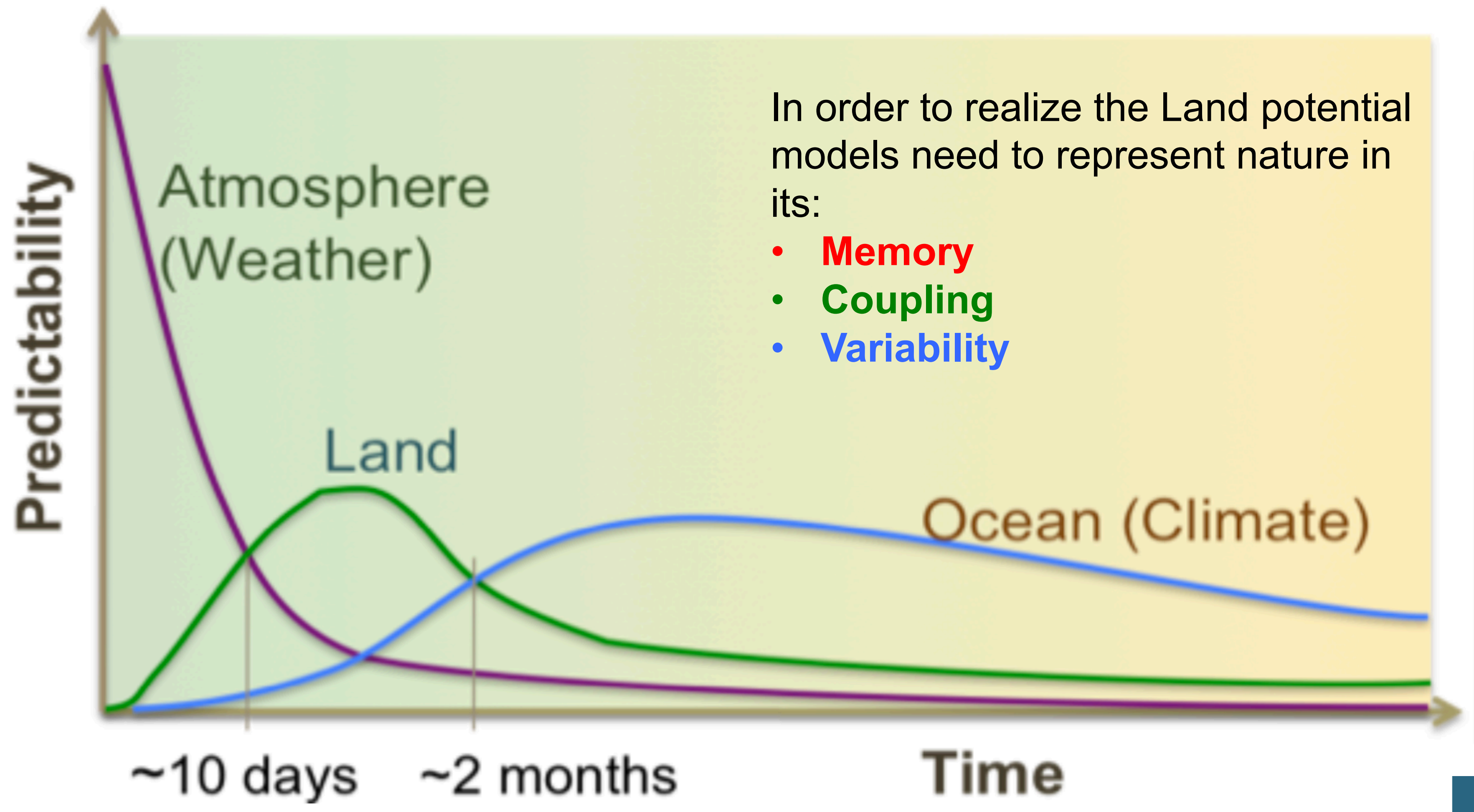
Thanks to Kristian Mogensen & Fernando Prates

Earth surface complementary role in medium-range and S2S



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

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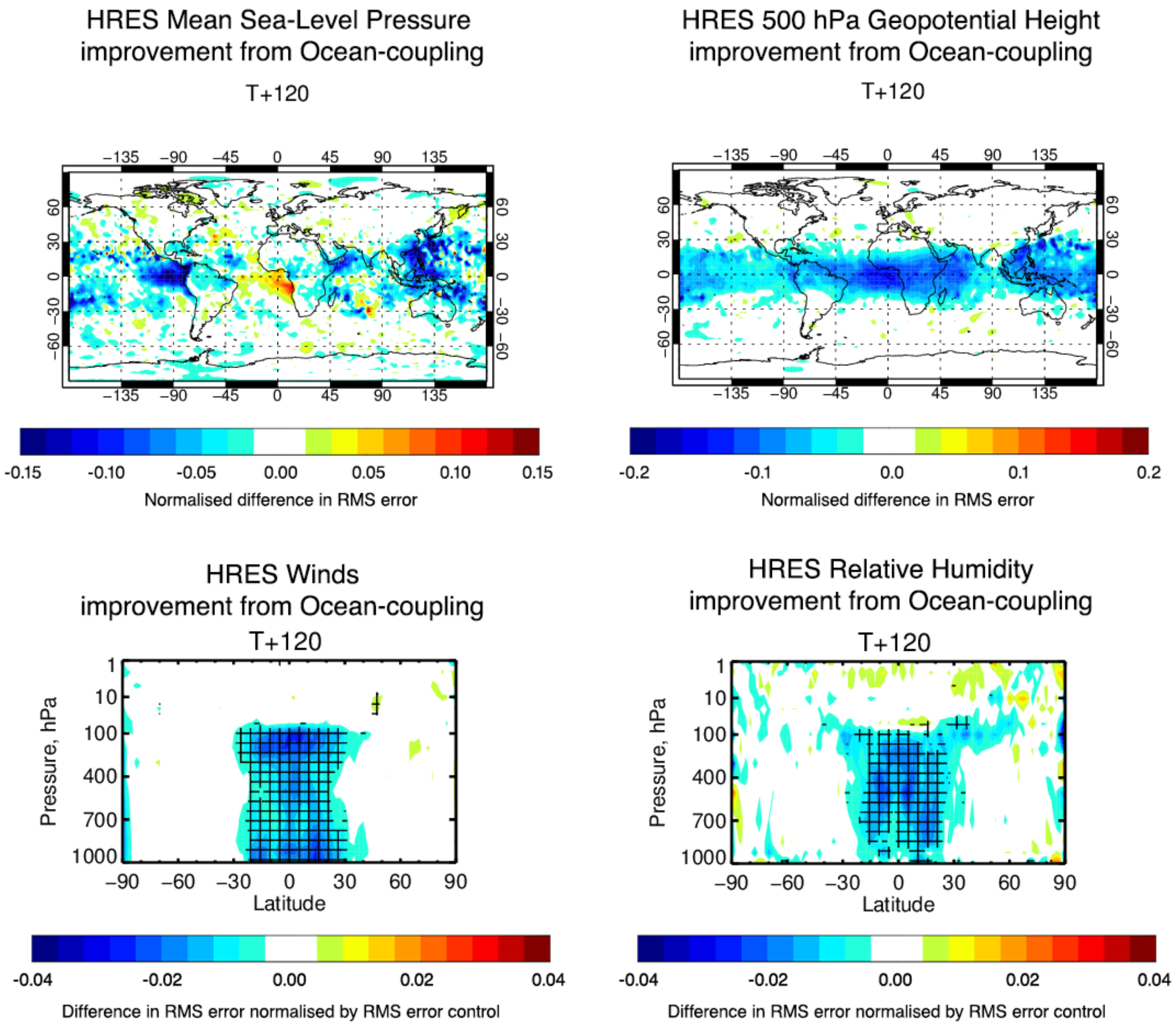
WWOSC 2014
MONTRÉAL, CANADA

On the relative contribution of land and ocean on ECMWF day-5 forecast

Forecast improvements at Day+5 (**1 year**)
Coupled-Ocean vs Uncoupled (only skin-interaction)



Forecast improvements at Day+5 (**1 year**)
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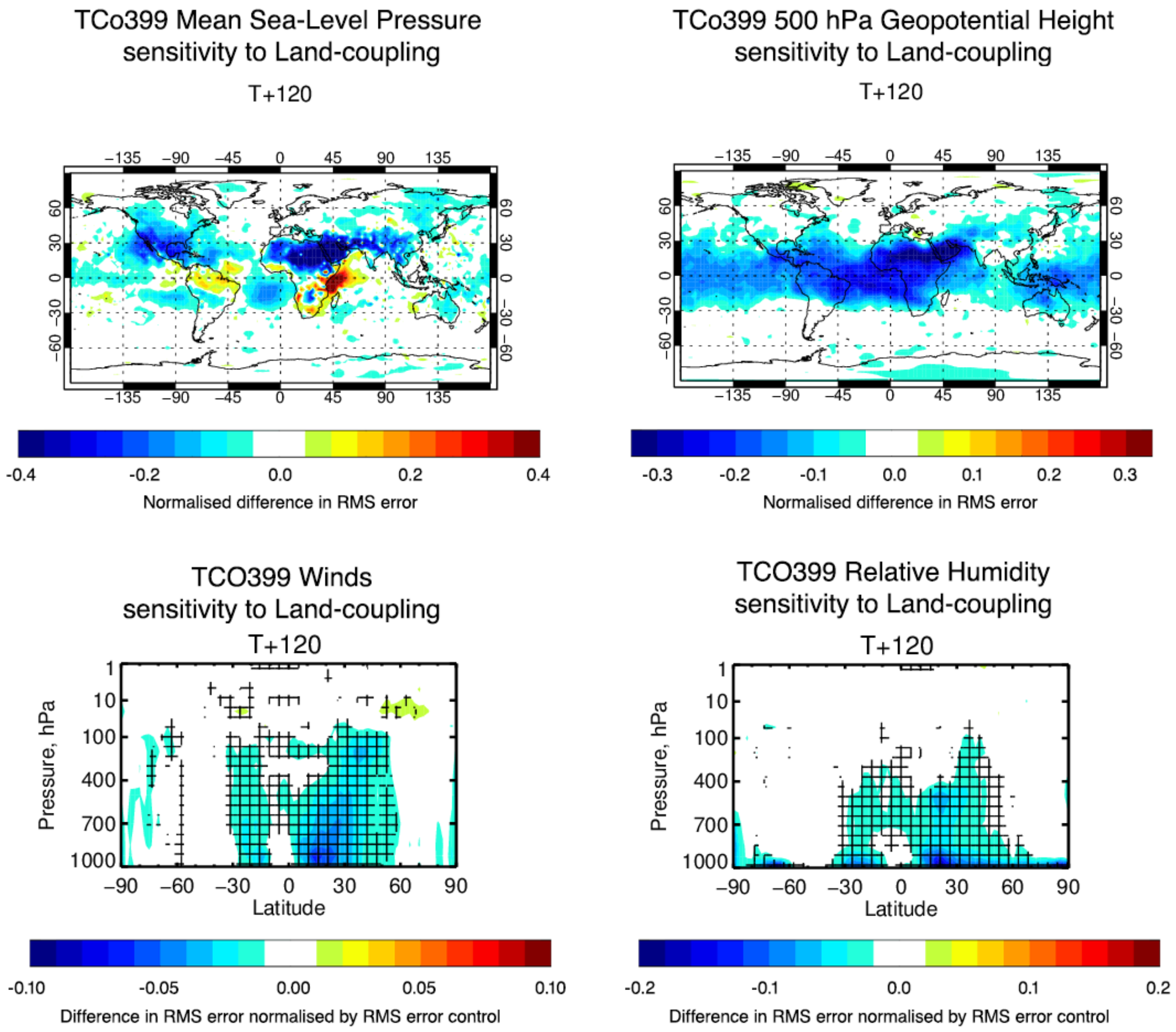


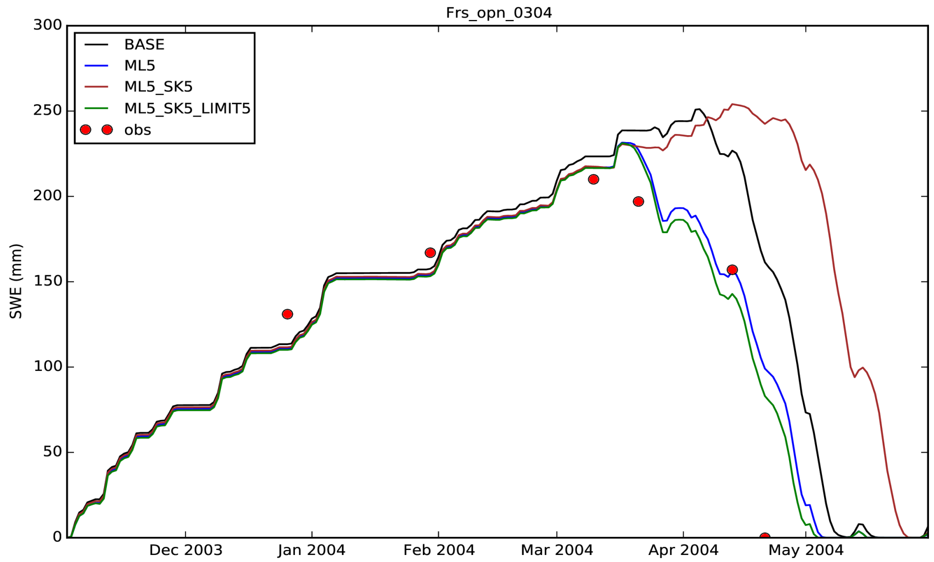
Balsamo et al. 2017 WGNE-Blue-book (submitted)

A look towards future developments

- Surface Complexity (modelling)
  - Enhanced vertical resolution in the snow
  - Enhanced vertical resolution in the soil
- Surface Information (mapping)
  - Towards 1km simulations
  - Mapping vegetation
  - Mapping water
  - Mapping anthropogenic surfaces

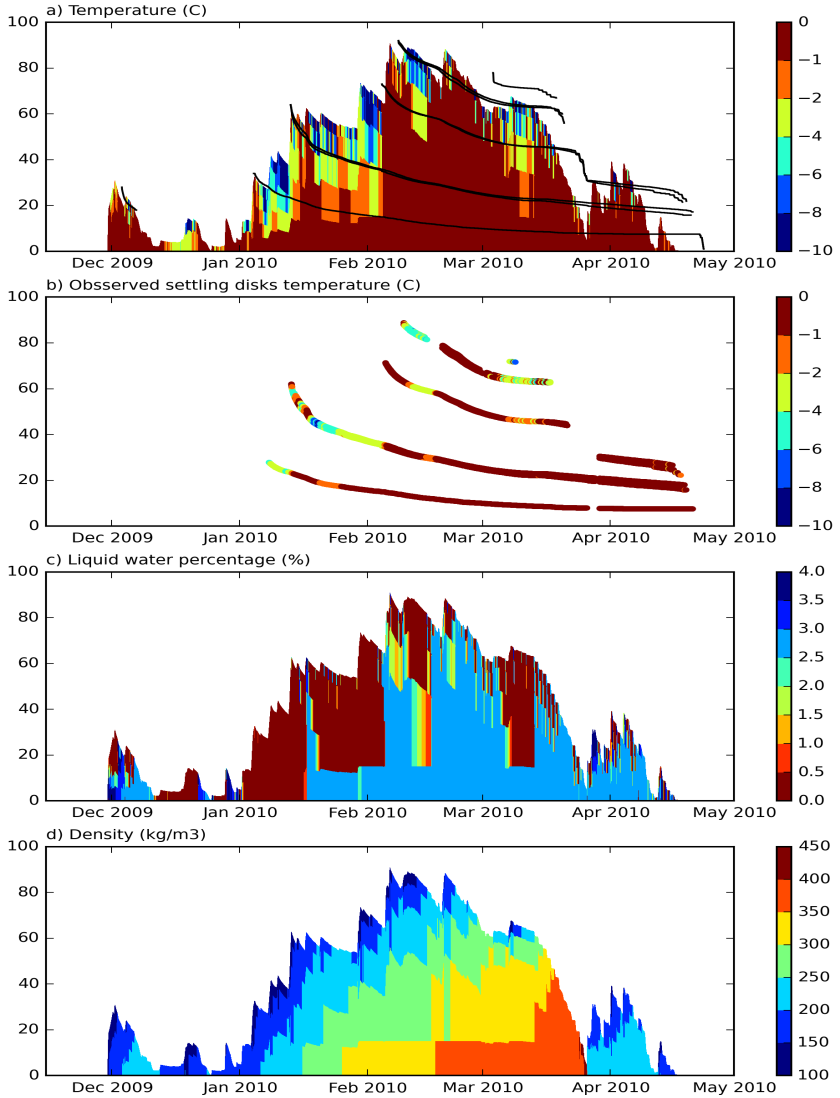
Preparing for a multi-layer snow modelling

- The operational snow model (Dutra et al. 2010) makes use of a single-layer with a diagnostic treatment of liquid water content to represent thermodynamics and mass balance.
- A refined 5-layer snow model is tested to enable representing thermal gradient observed in deep snow pack.
- This is shown to improve the simulation of snow duration as it permits a more timely representation of the melting phase.



Site simulation for Snow Water Equivalent (SWE) over Canada testing different config. of ML5

CTR L1 scheme (single layer snow)
ML5 current coupling (5-layer, fixed coupling strength)
ML5 new coupling (5-layer, diagnosed coupling strength)
ML5 new coupling (5-
layer, Energy Balance
on)*

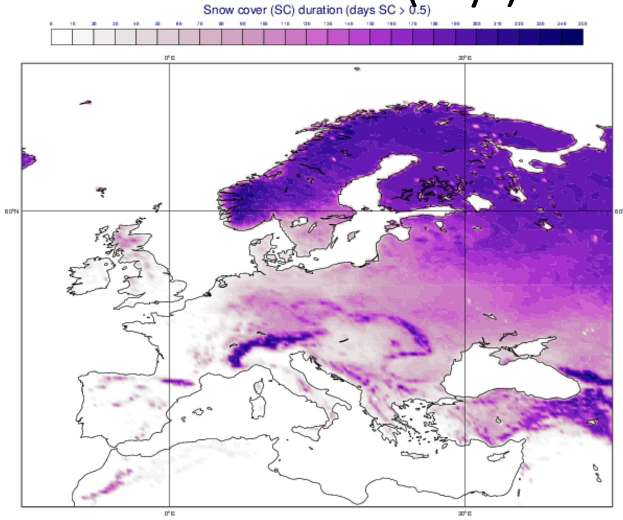


Site simulation for the ML5* for Snow Temperature, Liquid Water and Snow Density over an Alpine site.

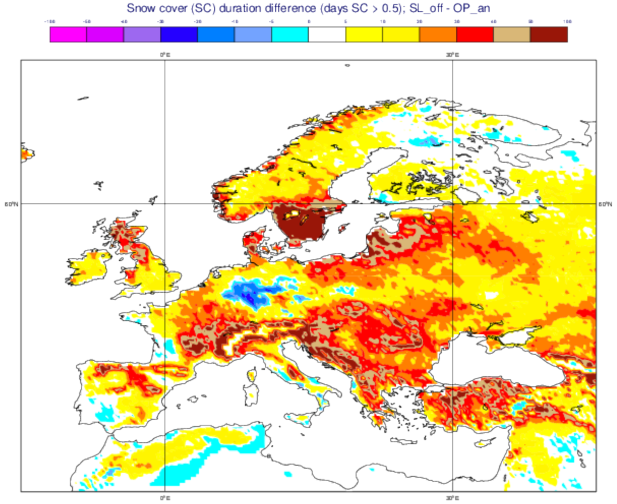
Snow modelling expected impact on weather timescale

- Testing a 5L vs 1L snow model (1-y TCo1279 forced by HRES meteorology)

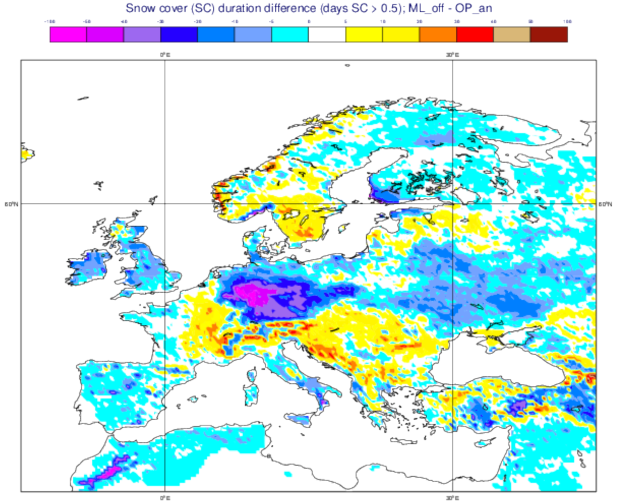
Oper Snow Analysis
Snow cover duration (days)



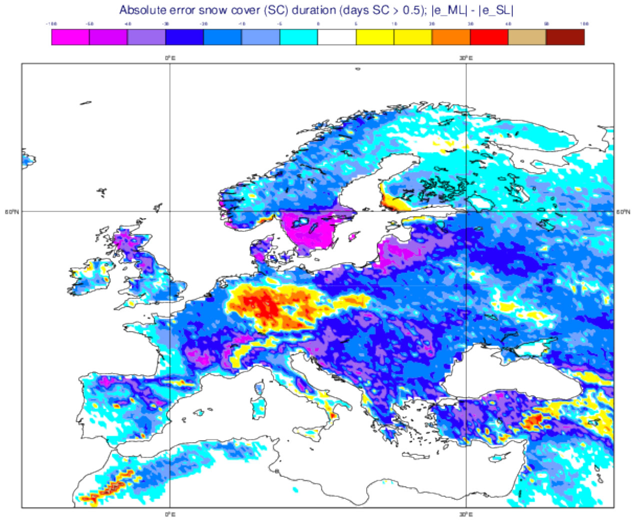
1L-Snow - Oper



5L-Snow - Oper



MAE reduction
5L vs 1L



Good
Impact on
Snow Duration
on the ground
(long outstanding
problem) to be
verified when coupled

ECMWF

Thanks to Gabriele Arduini and Emanuel Dutra

Predictability from snow model improvements evaluated in EC-Earth

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

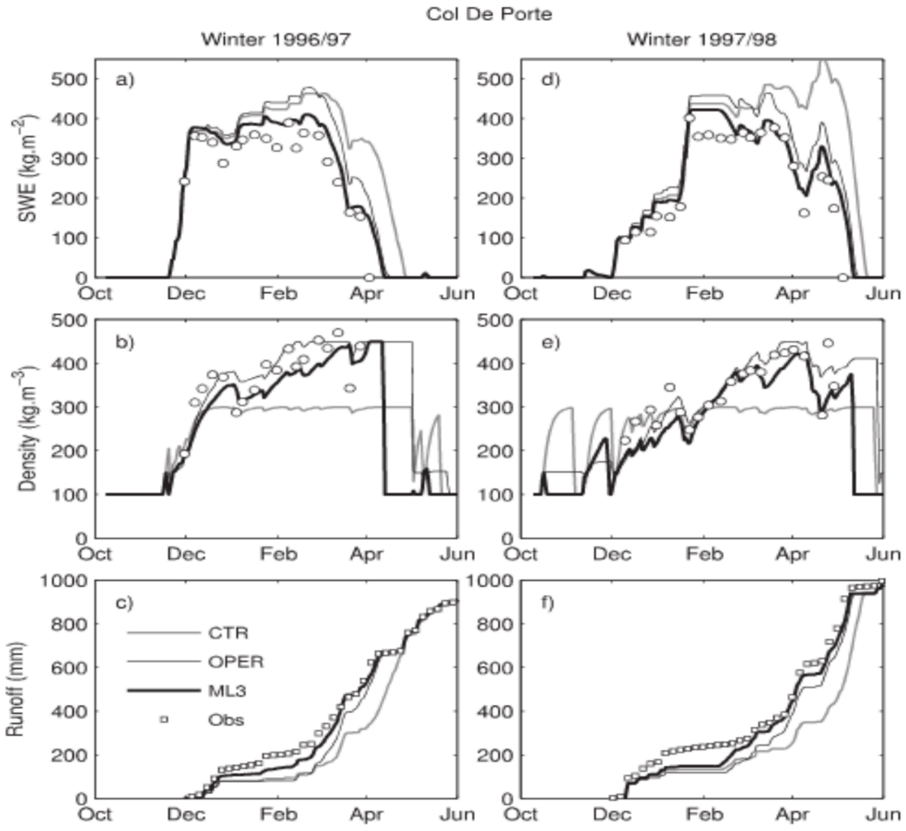


FIG. 1. Simulation results for CTR (gray), OPER (thin black), and ML3 (thick black) for the (a)–(c) 1996/97 and (d)–(f) 1997/98 winter seasons at Col de Porte site: (a),(d) snow mass, (b),(e) snow density, and (c),(f) runoff. Observations are represented by open circles. Runoff was accumulated since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

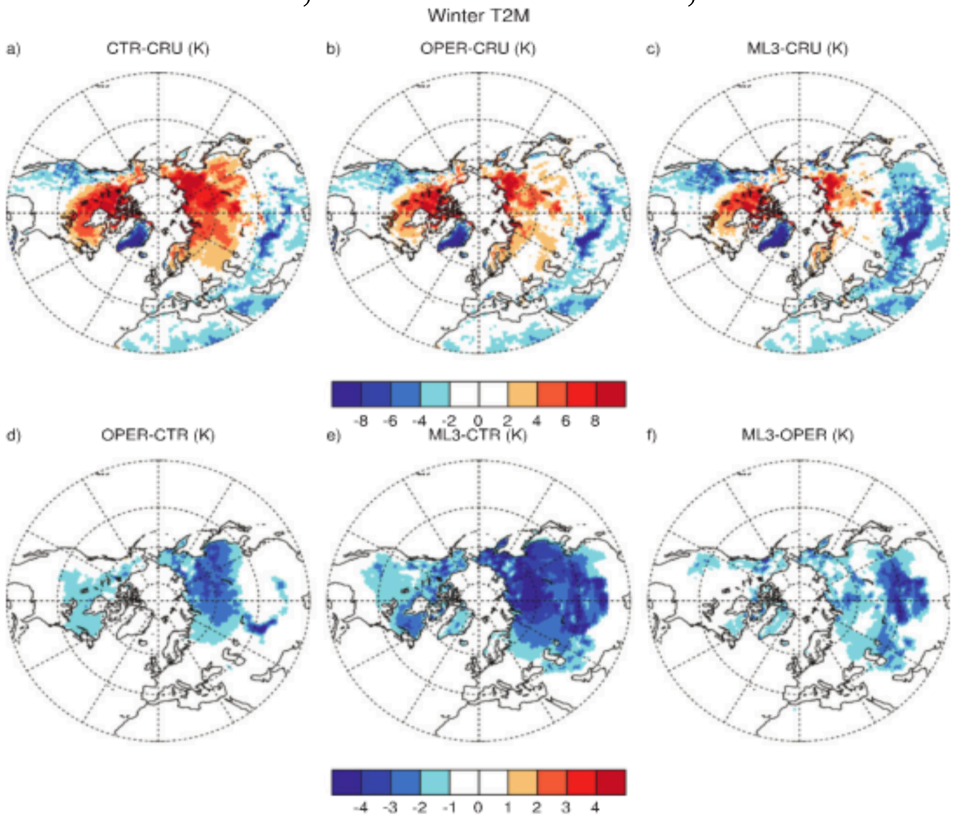


FIG. 13. Simulated winter 2-m temperature (K) biases of (a) CTR, (b) OPER, and (c) ML3 compared against CRU, and differences between (d) OPER and CTR, (e) ML3 and CTR, and (f) ML3 and OPER. Only differences significant at $p < 0.05$ are represented. Note the different color scales between (a)–(c) and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

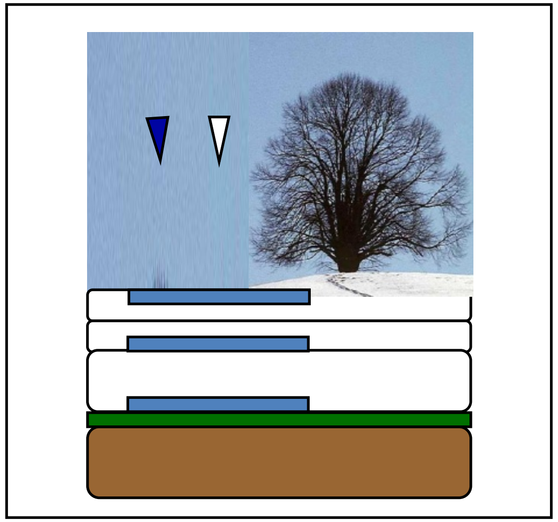
- **ML3 SNOW**

  Dutra et al. (2012)

  Up to 3 layers

  Liquid water (prognostic)

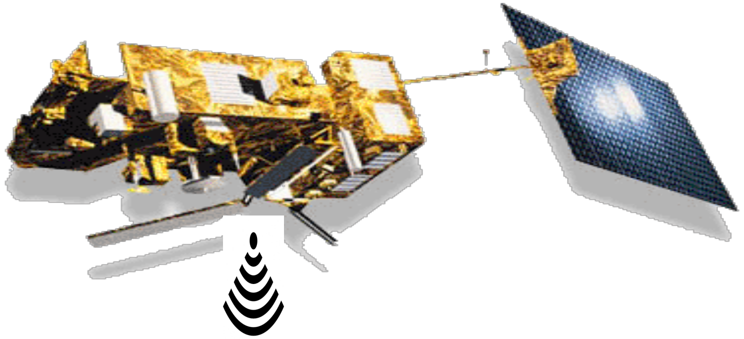
  Larger diurnal cycles (due to

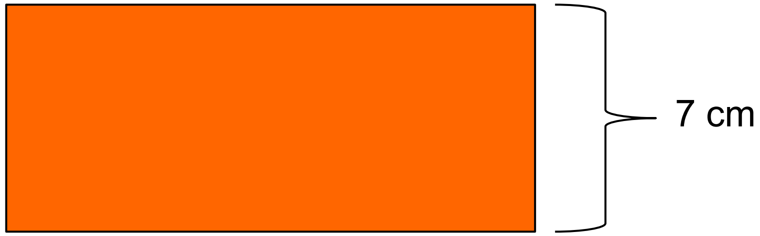


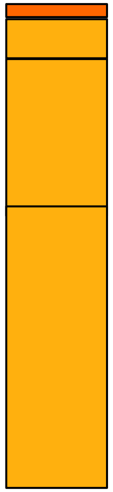
A research version multi-layer snow scheme has been developed for climate application (e.g. EC-Earth) and will be studied in EartH2Observe project. This includes up to 3 layers, an improved water cycle and further reduction of temperature bias (cooling effect in deep snow).

An enhanced soil vertical resolution

The observation of slow-drying of surface in dry areas and a 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.

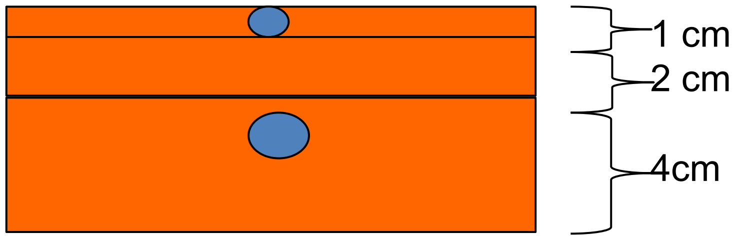






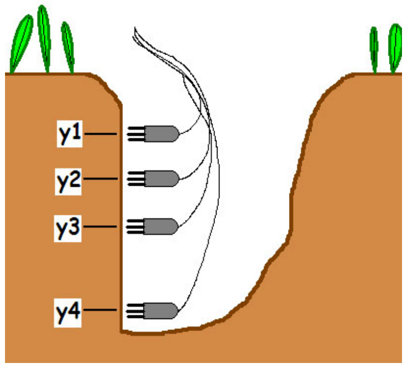
4-layers:

 # 0-7 cm
7-28 cm
28-100 cm
100-289 cm



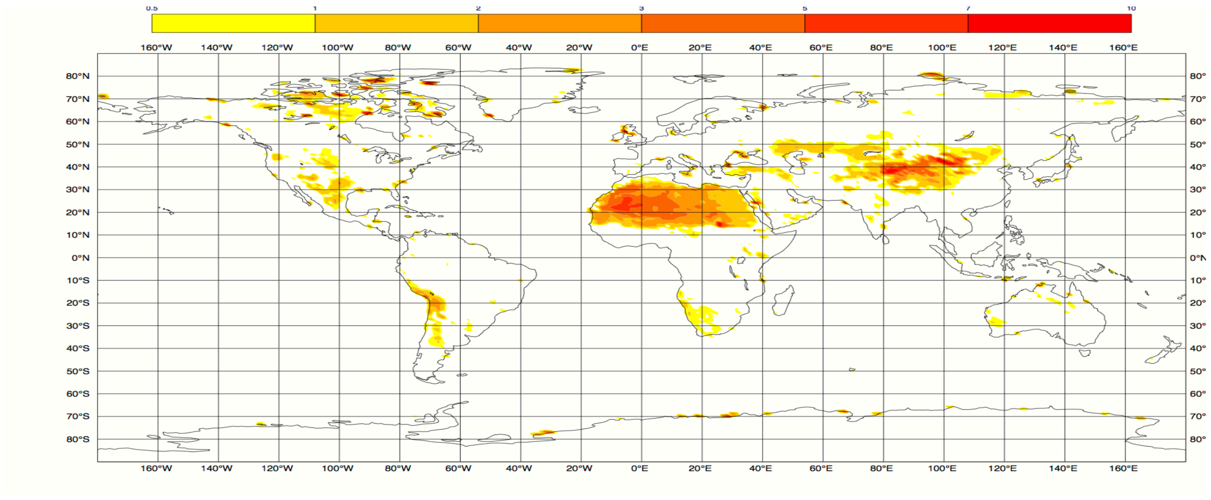
10-layers:

 # 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



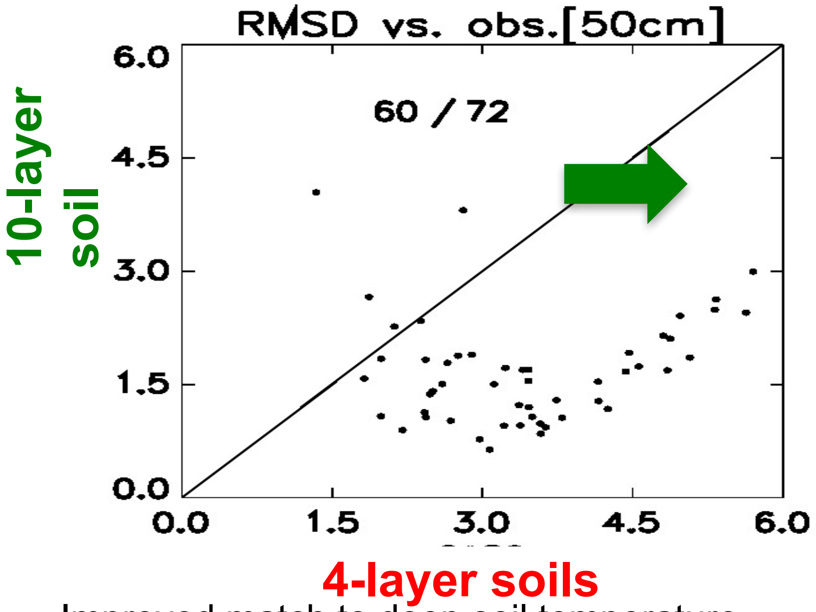
Impact of soil vertical resolution on soil temperature

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



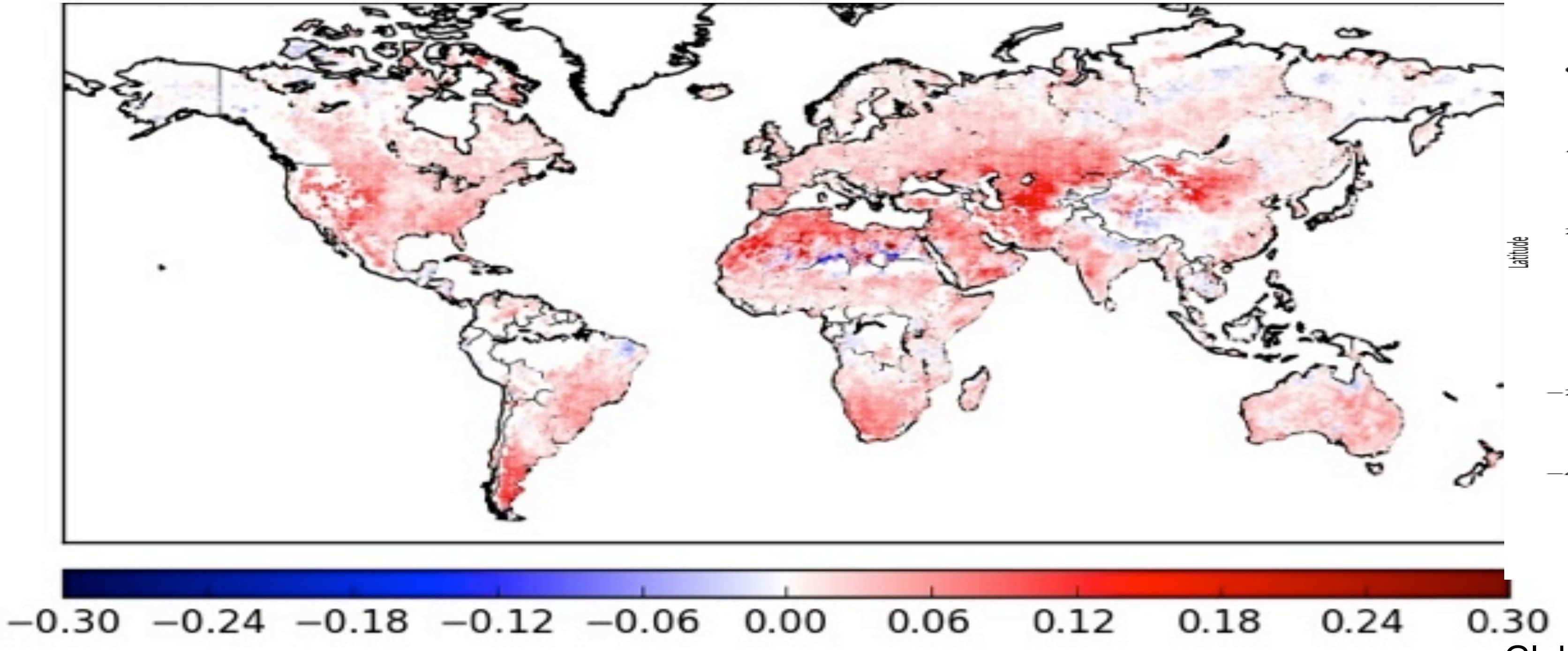
Improved match to deep soil temperature
(shown is correlation and RMSD)

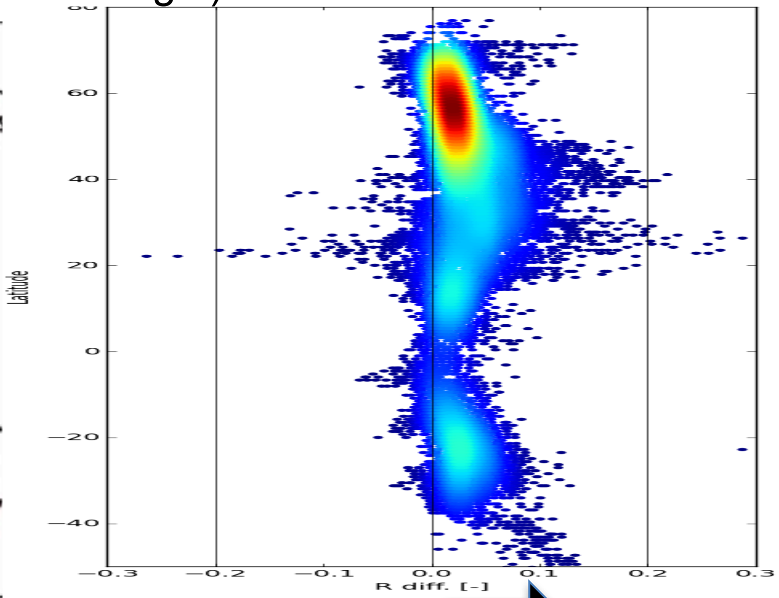
Correlation with in-situ soil temperature validate the usefulness of increase soil vertical resolution for monthly timescale (0.50 cm deep). Research work will continue using satellite skin temperature data

ECMWF

Impact of soil vertical resolution for satellite soil moisture

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





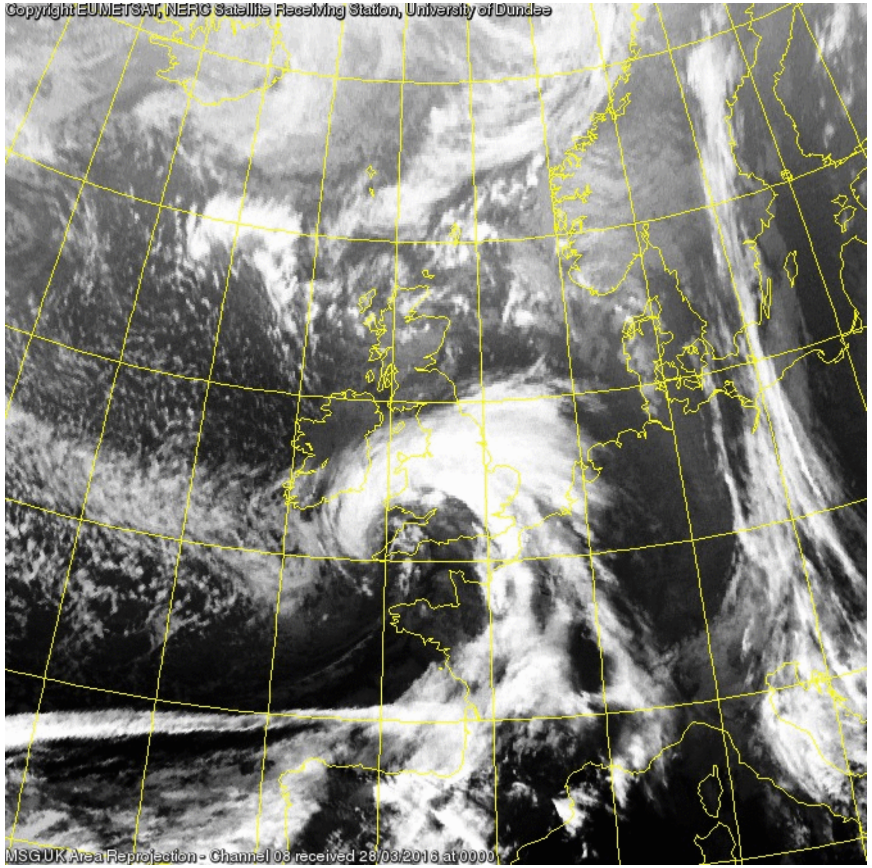
Globally Improved match to satellite soil moisture (shown is ΔACC calculate on 1-month running mean)

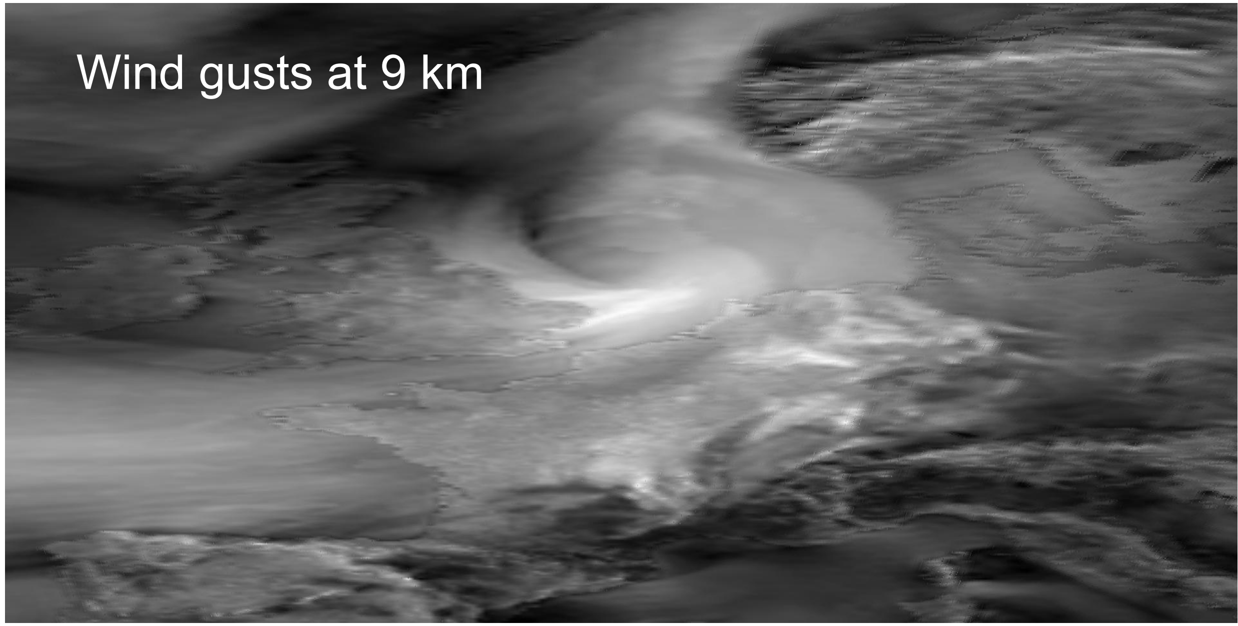
Anomaly correlation (1988-2014) measured with ESA-CCI soil moisture remote sensing (multi-sensor) product. This provide a global validation of the usefulness of increase soil vertical resolution.

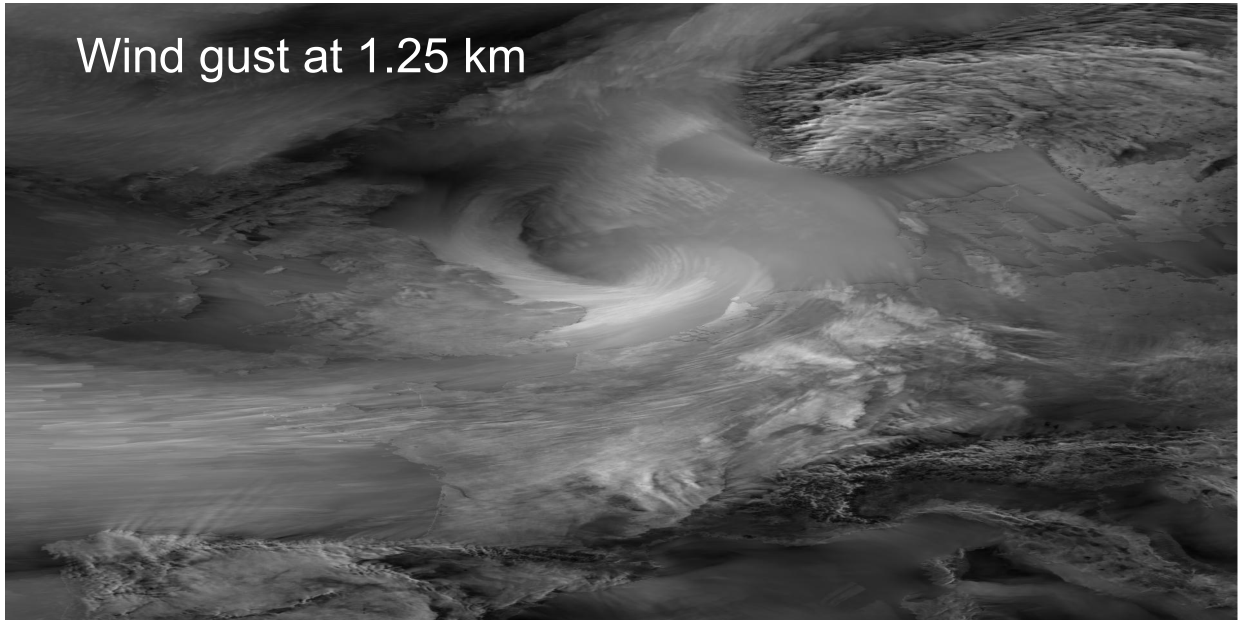
ECMWF

Pushing the boundaries of global HRES towards global kilometric scale

ECMWF's first global forecast at 1.25 km resolution





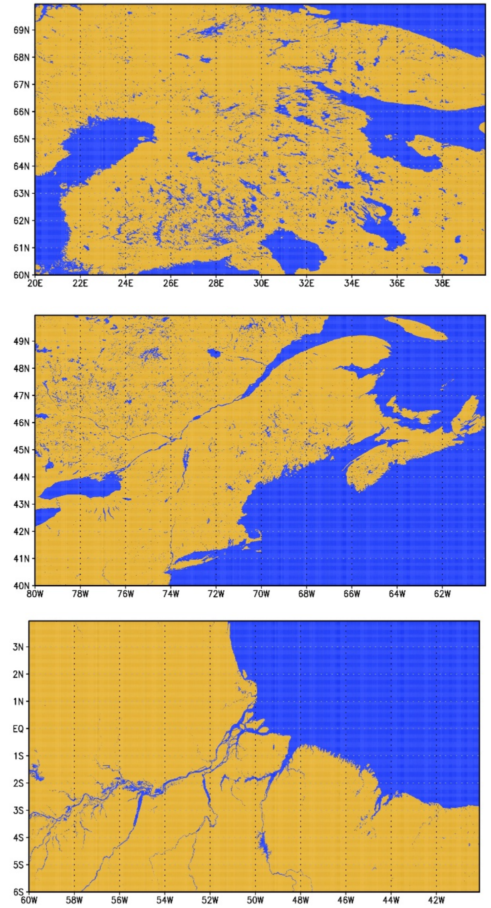


Thanks to
Nils Wedi

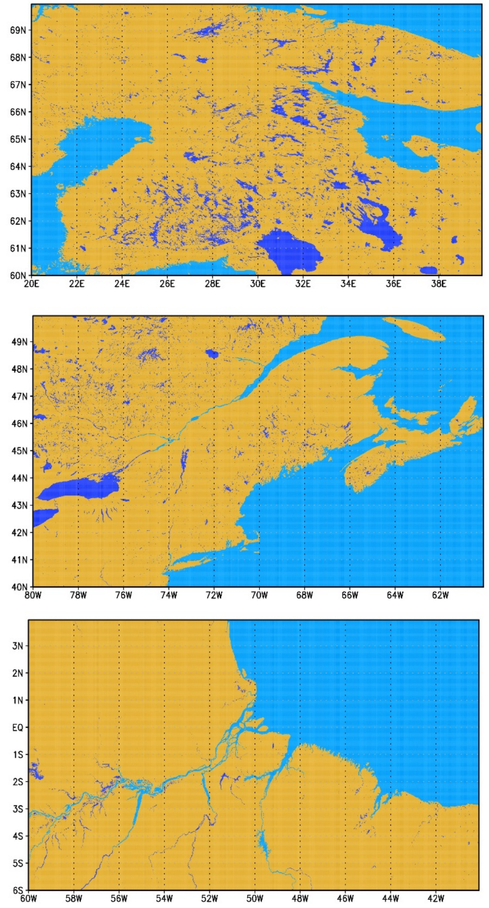
Mapping the surface at 1km: water bodies and changes over time

Classifying automatically inland water bodies is a complex task. A 1-km lake cover is a baseline for a monthly climatology

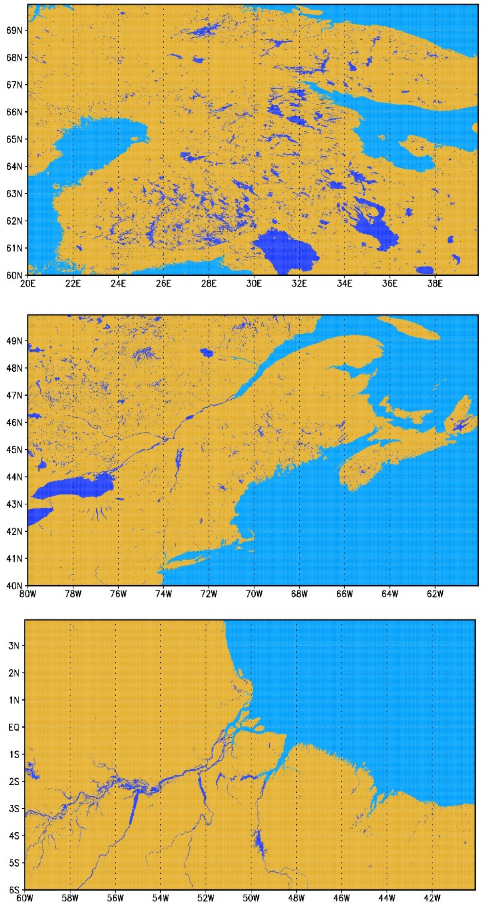
ESA GlobCOVER
has no water class

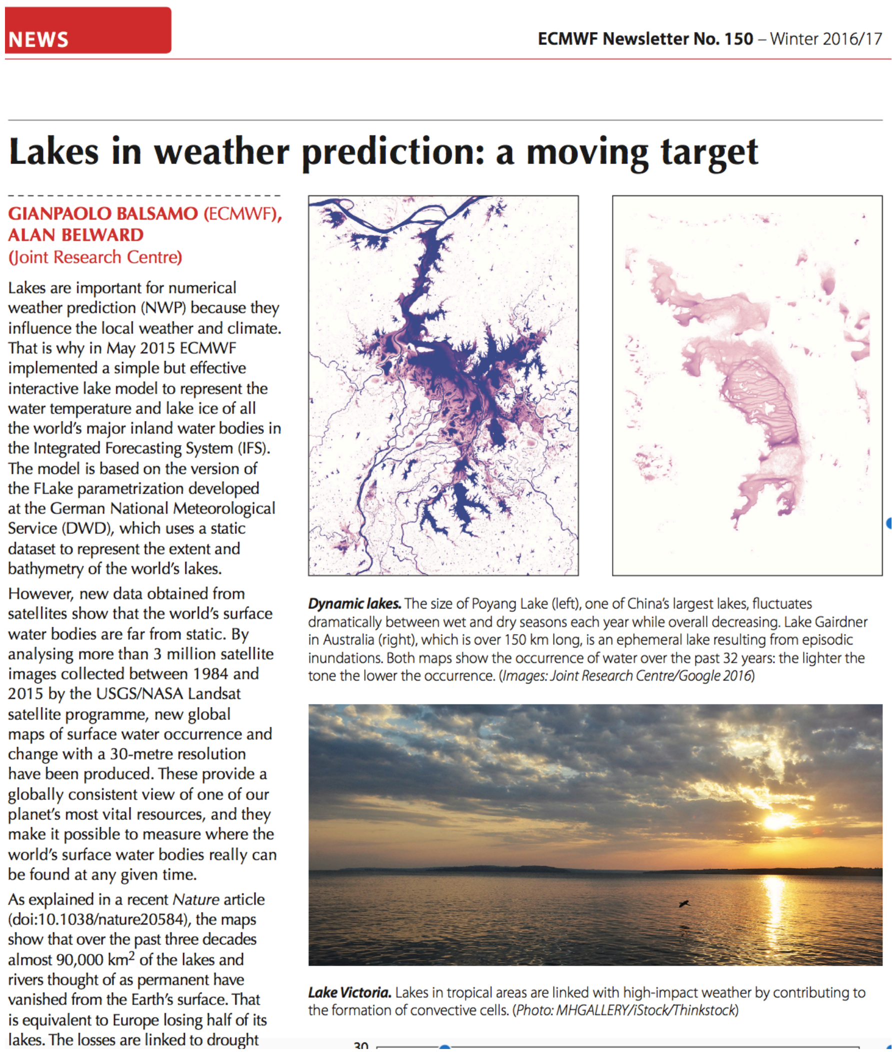


Flooding allows classify,
problems w. large rivers



New classification algo
works well at 1km




NEWS

ECMWF Newsletter No. 150 – Winter 2016/17

Lakes in weather prediction: a moving target

GIANPAOLO BALSAMO (ECMWF),
ALAN BELWARD
(Joint Research Centre)

Lakes are important for numerical weather prediction (NWP) because they influence the local weather and climate. That is why in May 2015 ECMWF implemented a simple but effective interactive lake model to represent the water temperature and lake ice of all the world's major inland water bodies in the Integrated Forecasting System (IFS). The model is based on the version of the FLake parametrization developed at the German National Meteorological Service (DWD), which uses a static dataset to represent the extent and bathymetry of the world's lakes.

However, new data obtained from satellites show that the world's surface water bodies are far from static. By analysing more than 3 million satellite images collected between 1984 and 2015 by the USGS/NASA Landsat satellite programme, new global maps of surface water occurrence and change with a 30-metre resolution have been produced. These provide a globally consistent view of one of our planet's most vital resources, and they make it possible to measure where the world's surface water bodies really can be found at any given time.

As explained in a recent *Nature* article (doi:10.1038/nature20584), the maps show that over the past three decades almost 90,000 km^2 of the lakes and rivers thought of as permanent have vanished from the Earth's surface. That is equivalent to Europe losing half of its lakes. The losses are linked to drought

Dynamic lakes. The size of Poyang Lake (left), one of China's largest lakes, fluctuates dramatically between wet and dry seasons each year while overall decreasing. Lake Gairdner in Australia (right), which is over 150 km long, is an ephemeral lake resulting from episodic inundations. Both maps show the occurrence of water over the past 32 years: the lighter the tone the lower the occurrence. (*Images: Joint Research Centre/Google 2016*)

Lake Victoria. Lakes in tropical areas are linked with high-impact weather by contributing to the formation of convective cells. (*Photo: MHGALLERY/iStock/Thinkstock*)

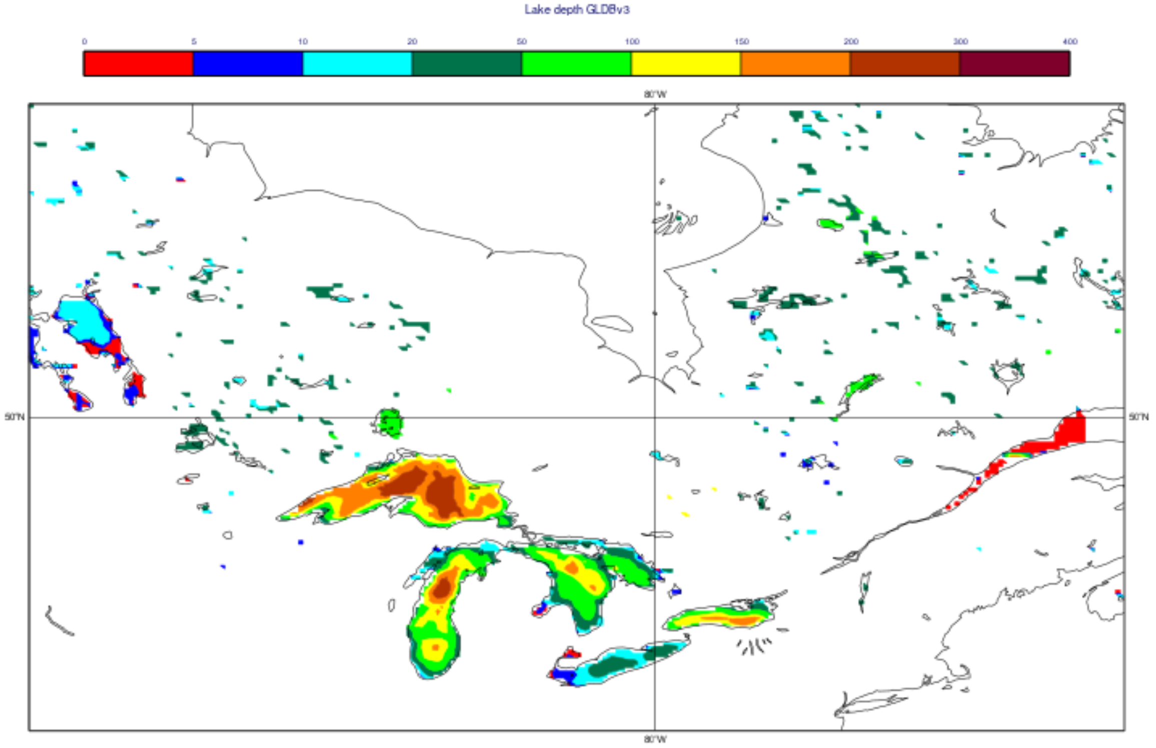
ECMWF

Thanks to Margarita Choulga and Souhail Boussetta

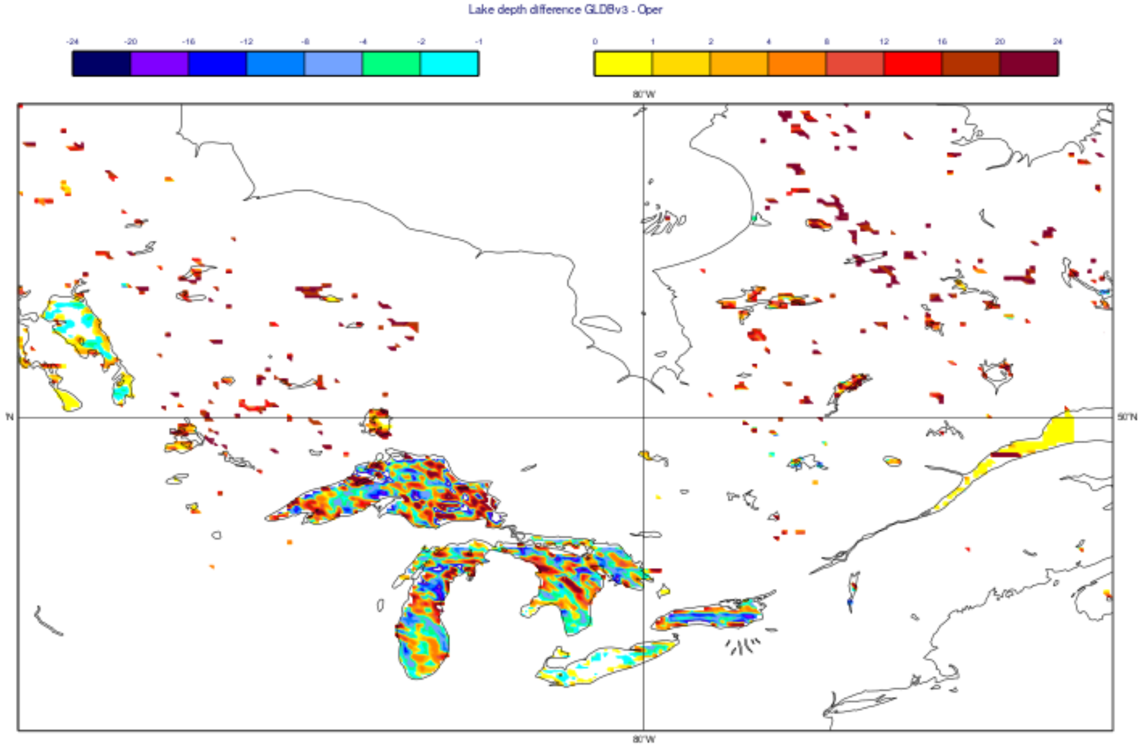
Mapping water bodies bathymetry at 1km scale: key for the heat content

A new 1-km lake (and ocean) bathymetry will be tested (GLDBv3 Choulga et al. 2014). The difference with IFS control is shown

GLDBv3 Bathymetry

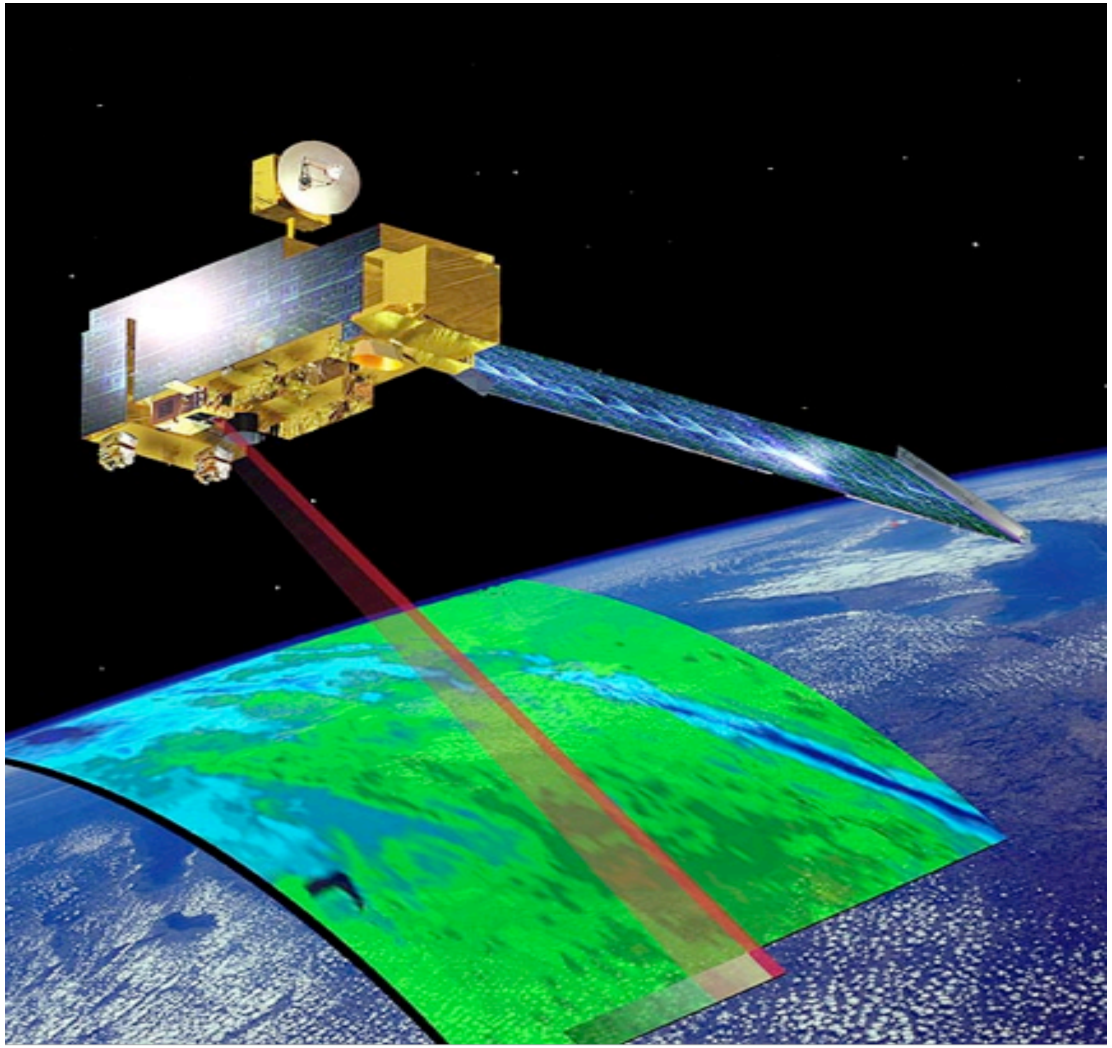


Difference GLDBv3-v1(IFS-oper) Bathymetry

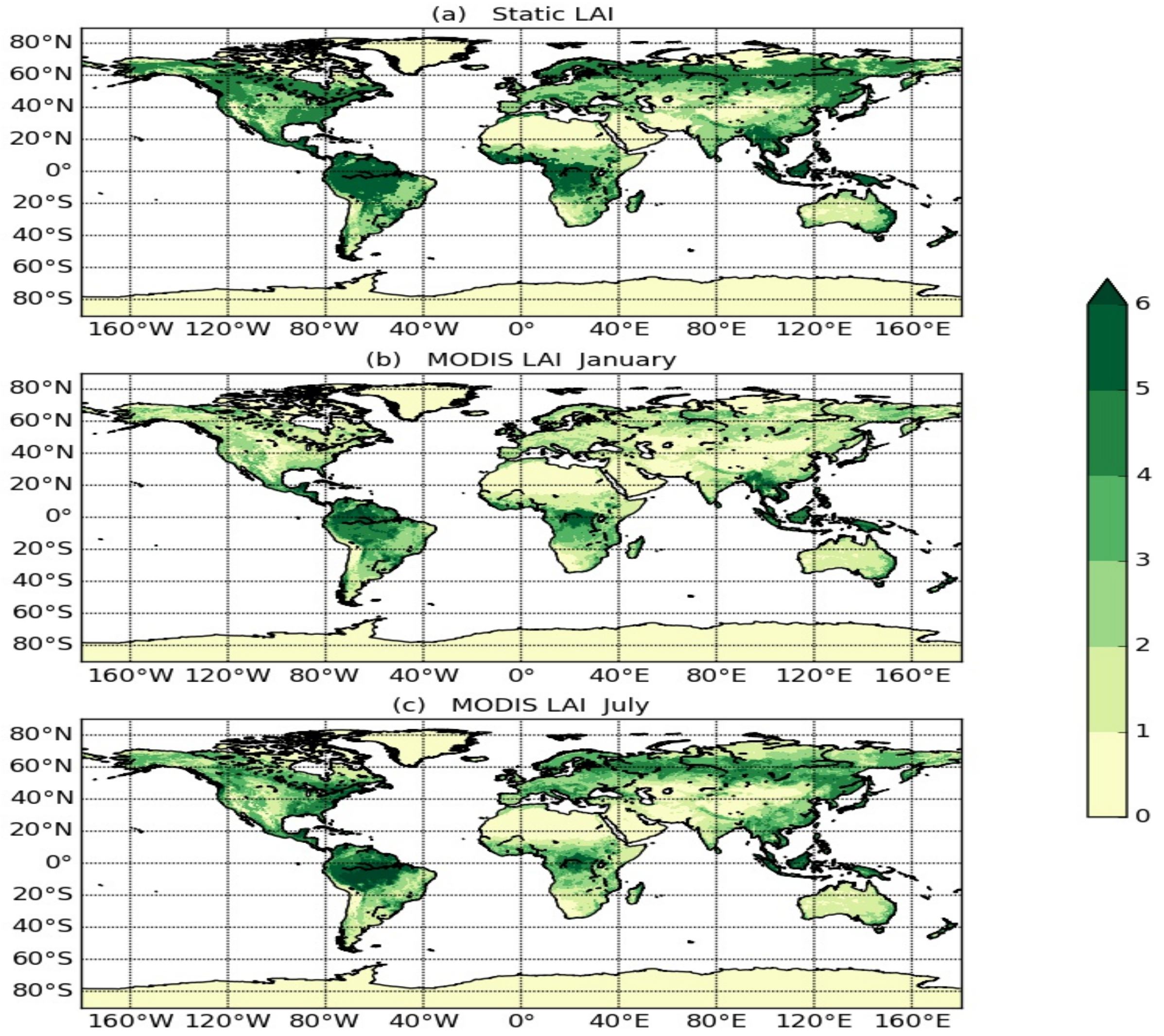


Thanks to Margarita Choulga

Mapping the vegetation state from satellite data



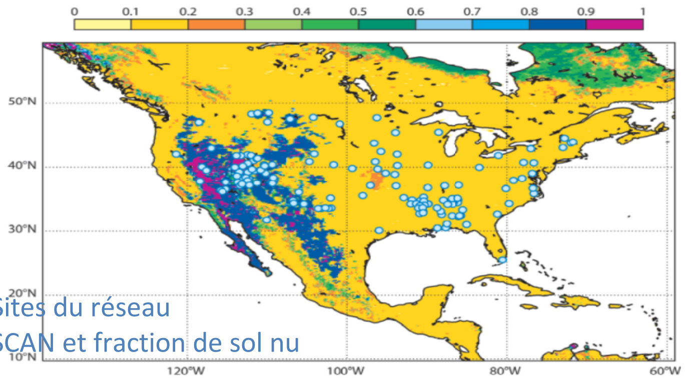
Boussetta et al. (2015, RSE)



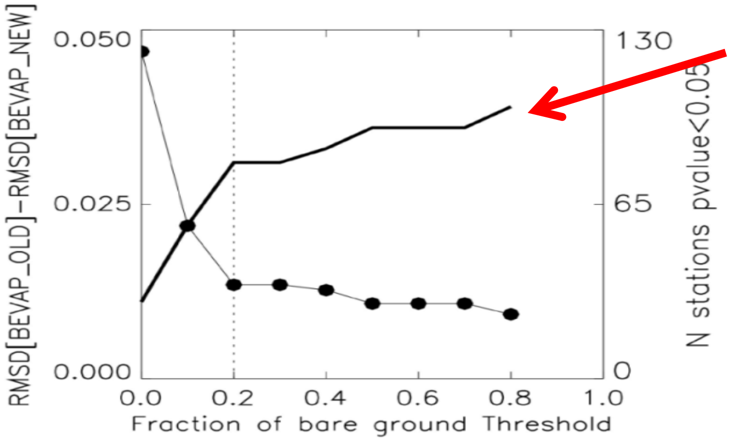
ECMWF

Arid areas and soil moisture dynamical range (via Evaporation)

Albergel et al. (2012), *HESS*

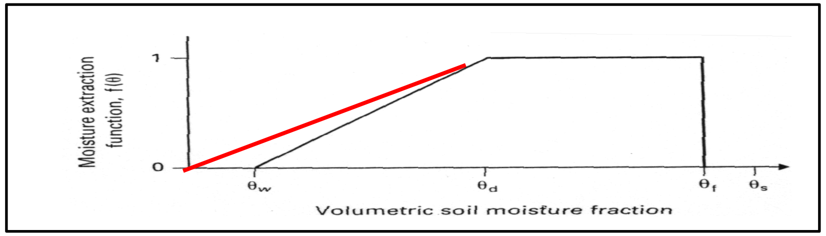


Sites du réseau SCAN et fraction de sol nu



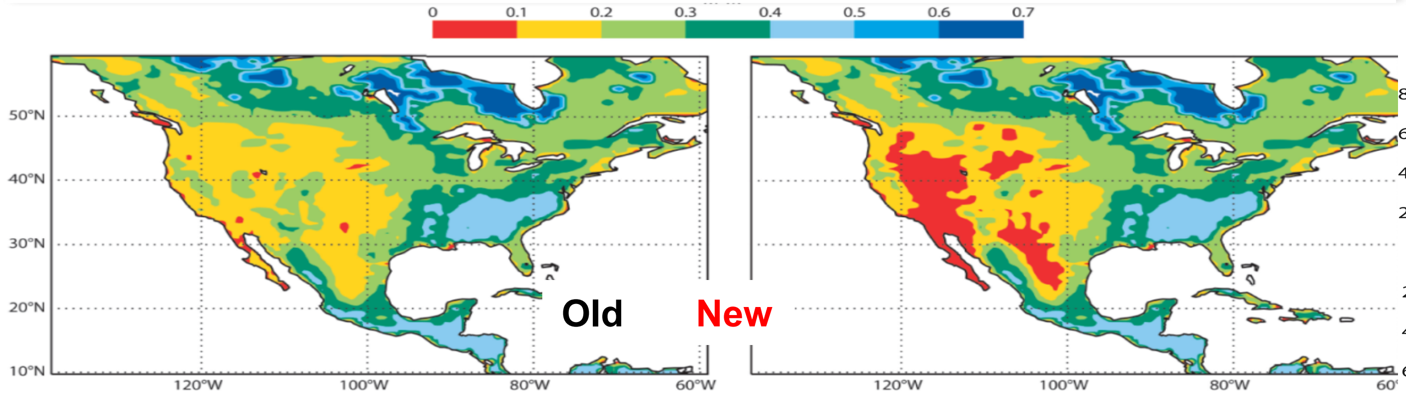
Improved fit to SCAN soil moisture data (reduced RMSE over 122 stations) as a function of bare soil.

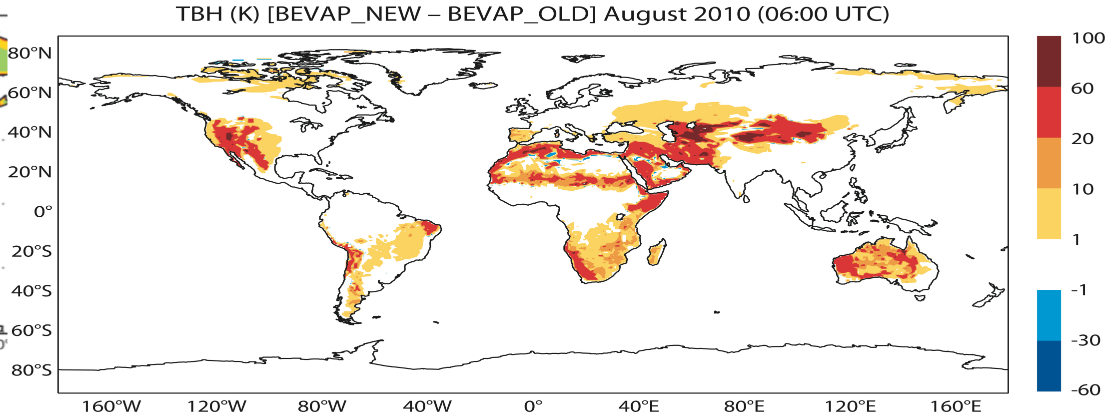
SOIL Evaporation



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

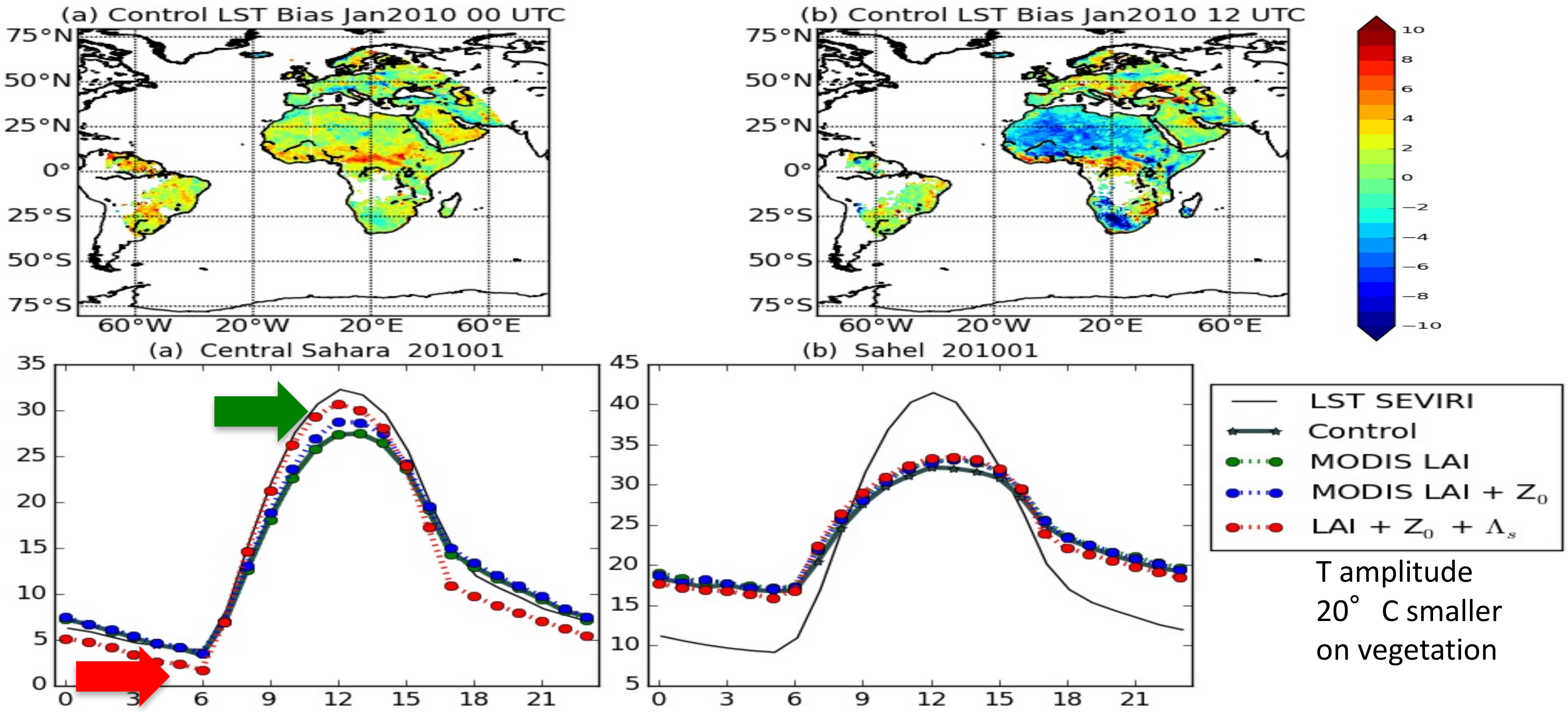
The drying effect impact enhancing SMOS/SMAP T_b (L-band) in the forward operator





Coupling and diurnal cycle: vegetation

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

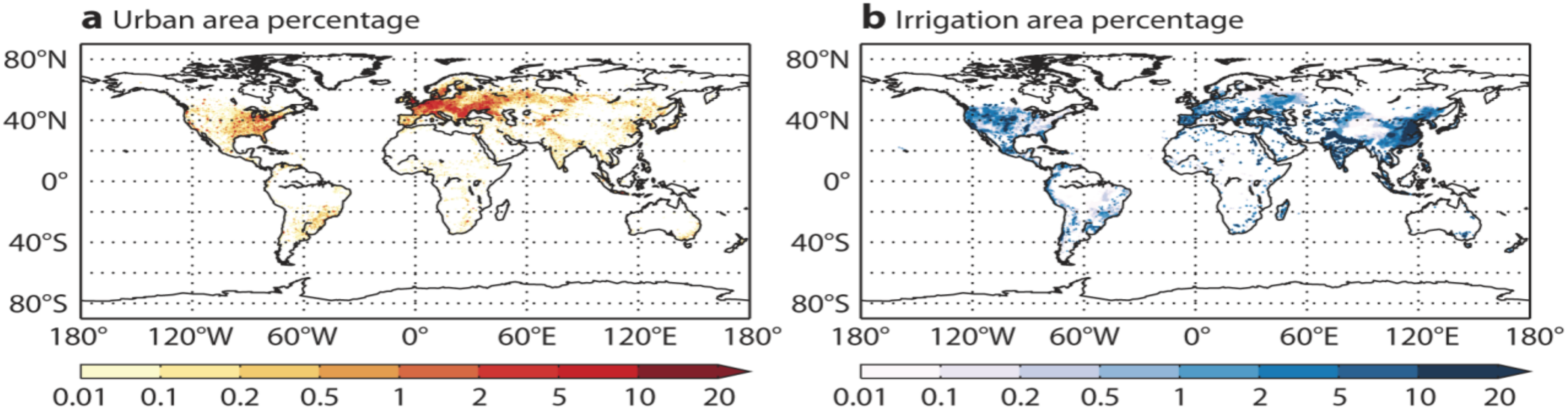


T amplitude
20° C smaller
on vegetation

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)

Mapping Human influence on land and water use

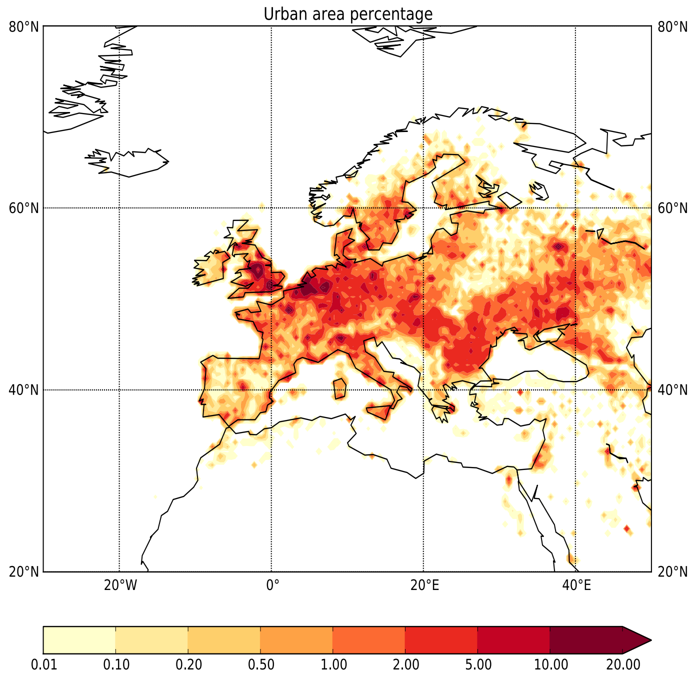
- Human action on the land and water use is currently neglected in most NWP models…



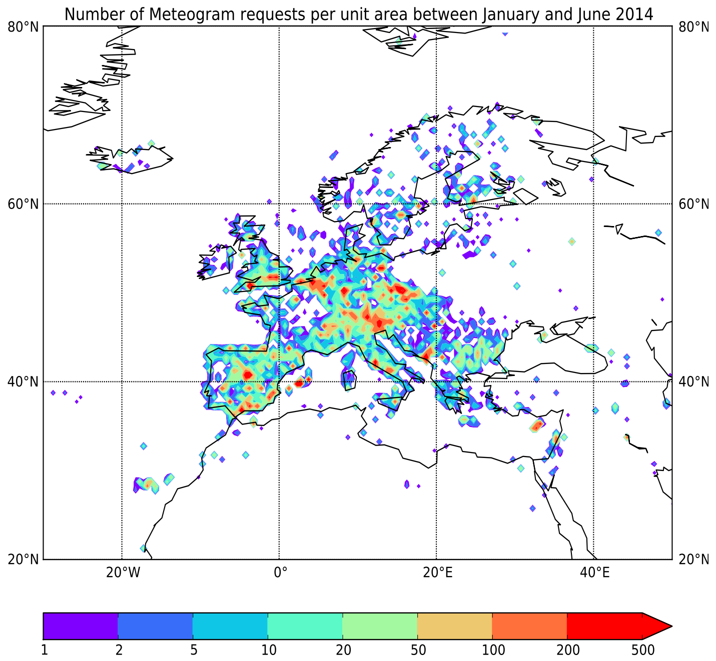
- Urban area (a, in %, from ECOCLIMAP, Masson et al., 2003) and
- Irrigated area (b, in %, from Döll and Siebert, 2002)

Towards representation of urban areas in global models

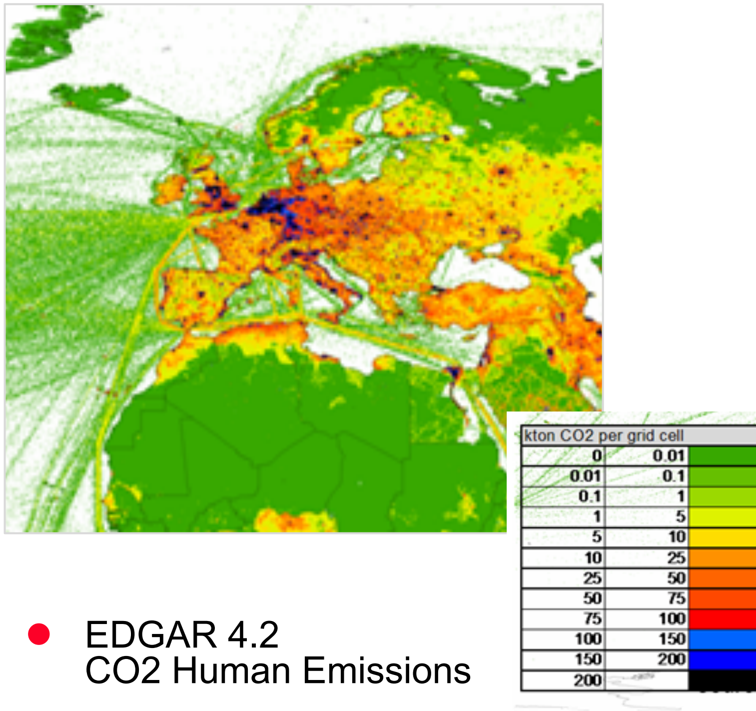
- Urban areas are important for the accurate prediction of extreme events such as heatwaves and urban flooding and need to be represented in ECMWF model.
- Best and Grimmond (2015) suggested that simple models may be well adapted to global applications
- Users lives urban areas and look at the forecast for urban locations.
- Urban maps combined with emission factors can provide first guess CO2 anthropogenic fluxes



- Urban area (a, in %, from ECOCLIMAP, Masson et al., 2003)



- Number of ECMWF Meteograms product requests from Member-States



- EDGAR 4.2 CO2 Human Emissions

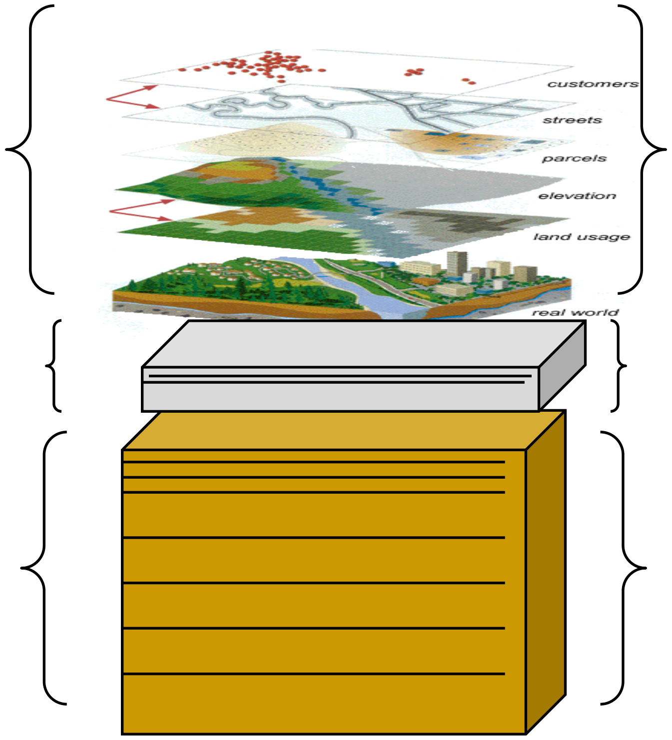
ECMWF

Summary and Outlook

- **Earth surface** moving from a necessary boundary condition to a **key predictability element**
- Efforts up to present towards representing the surface slowly-evolving processes
  - Land, Ocean and Sea-ice that carry predictability due the memory effect
- **Diurnal cycle focus** interactions provide a complexity requirement guidance
- Moving towards Earth System for **Environment prediction & Extended-range** requires:
  - An increased investment on **mapping** surface characteristics at kilometer scale
  - A **stepwise** approach to **increased complexity** (process-based verification)
  - A **better use of EO data** informative of HRES Mapping & Modelling (e.g. Tskin, MW Tb)
  - A **large collaborative efforts** (@ECMWF and within the NWP & Climate community)

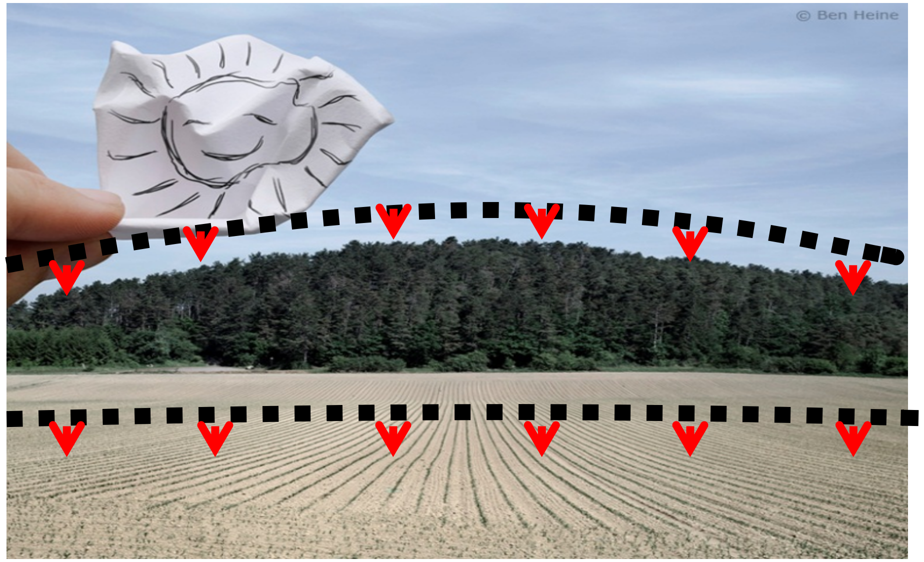
Perspectives for Earth System Prediction

Towards integrated Ecosystems modelling



- Better characterisation of the vertical profiles
- Better respresentation on heterogeneity and ecosystems interaction
- Unification of processes (cryosphere)

Modularity of the land system is a key to ESP model integrations and inter-operability of parameterizations



- Complexity needs a step-wise approach
- The assimilation methods are integral part of the model diagnostics
- A better coupling between sub-systems is the ultimate goal, achievable by enhanced knowledge on each sub-system and the mutual interactions

European Collaboration Framework

- Moving towards 1-km global simulations is a necessity driven by
  - European ambitions (e.g. Paris Climate Agreement and its implementation)
  - Value added to physical realism (e.g. Land surface, Coastal Areas, Clouds)
- Working in collaboration is a necessity driven by
  - Common goals, tools, data and needs (ISWG2018, Lisbon
  - European Financial frameworks (H2020, CES, COP)
- Outcomes of collective ambitions and efforts
  - Unifying models towards seamlessness is a drive in each single Service
  - Private initiative is a strong player that benefit from Services ahead of the Game
  - Surface Monitoring is the closest to human activity and interests (high priority)