Introduction to the parameterization of Land Surfaces processes in coupled Earth System Modelling

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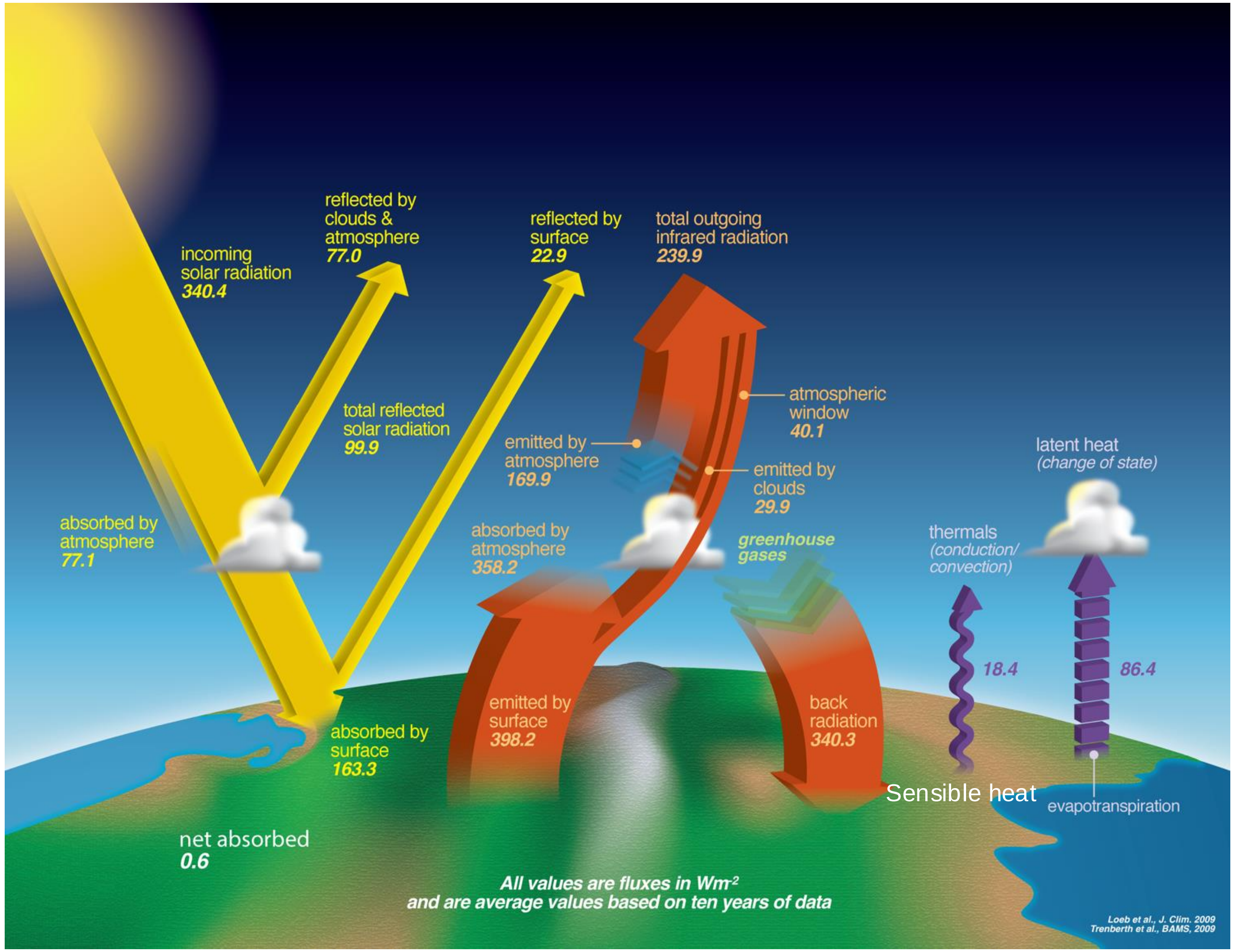
Thanks to Gabriele Arduini and all the land modelling team,
and all previous contributors to the land modeling processes

Outline

- Land-surface processes in the earth system:
  why is this important for Numerical Weather Predications?
- Representing land-surface heterogeneities for NWP applications:
  - Coupling with the atmosphere
  - Surface energy balance and surface (skin) temperature
  - Energy and water budgets in the soil
  - Inland water bodies (lakes)
- Perspectives

The land surface in the earth energy budget



- The surface is a physical boundary for atmospheric processes
- amount of energy reflected: surface albedo
- Conduction into the soil: amount of energy conducted and absorbed in the soil
- Emitted by the surface: surface temperature and surface emissivity
- Surface sensible heat flux
- Evapotranspiration (latent heat) flux

The land-surface in the earth global water cycle

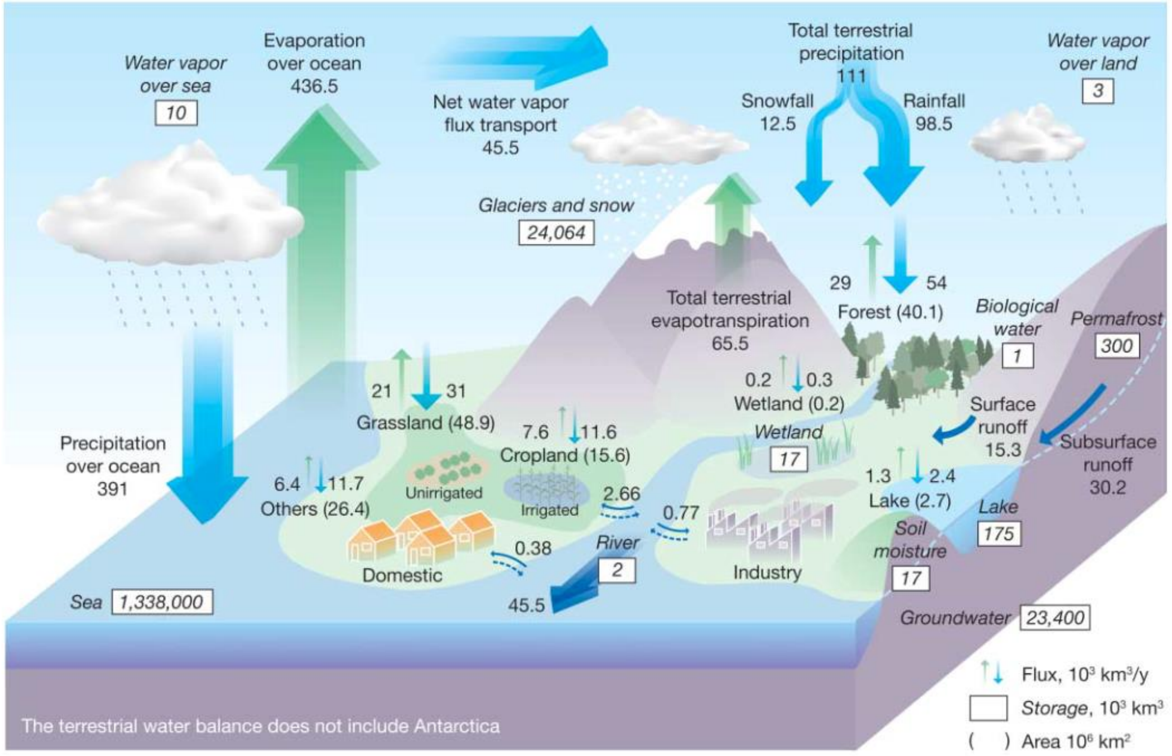


Fig. 1. Global hydrological fluxes (1000 km^3/year) and storages (1000 km^3) with natural and anthropogenic cycles are synthesized from various sources (*1*, *3*–*5*). Big vertical arrows show total annual precipitation and evapotranspiration over land and ocean (1000 km^3/year), which include annual precipitation and evapotranspiration in major landscapes (1000 km^3/year) presented by small vertical arrows; parentheses indicate area (million km^2). The direct groundwater discharge, which is estimated to be about 10% of total river discharge globally (*6*), is included in river discharge.

Total land precipitation:
60% evapotranspiration
40% runoff

Total land evapotranspiration:
44% Forests
32% Grassland
12% Cropland
12% Others

88% via vegetation !

Oki and Kanae, Science 2006. Fluxes / Storage are estimates from different sources
https://www.researchgate.net/publication/6856186_Global_Hydrological_Cycles_and_World_Water_Resources

Earth Global Water Cycle – Reservoirs and timescales

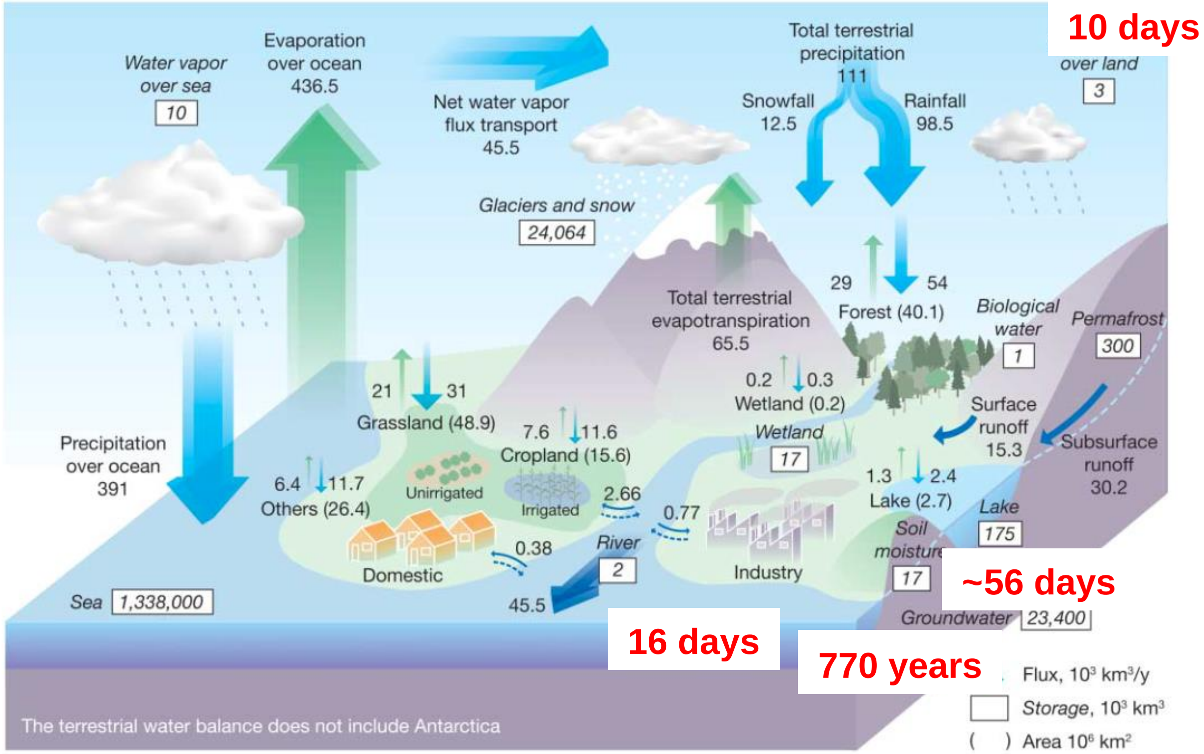


Fig. 1. Global hydrological fluxes (1000 km³/year) and storages (1000 km³) with natural and anthropogenic cycles are synthesized from various sources (*1, 3–5*). Big vertical arrows show total annual precipitation and evapotranspiration over land and ocean (1000 km³/year), which include annual precipitation and evapotranspiration in major landscapes (1000 km³/year) presented by small vertical arrows; parentheses indicate area (million km²). The direct groundwater discharge, which is estimated to be about 10% of total river discharge globally (*6*), is included in river discharge.

Total land precipitation:
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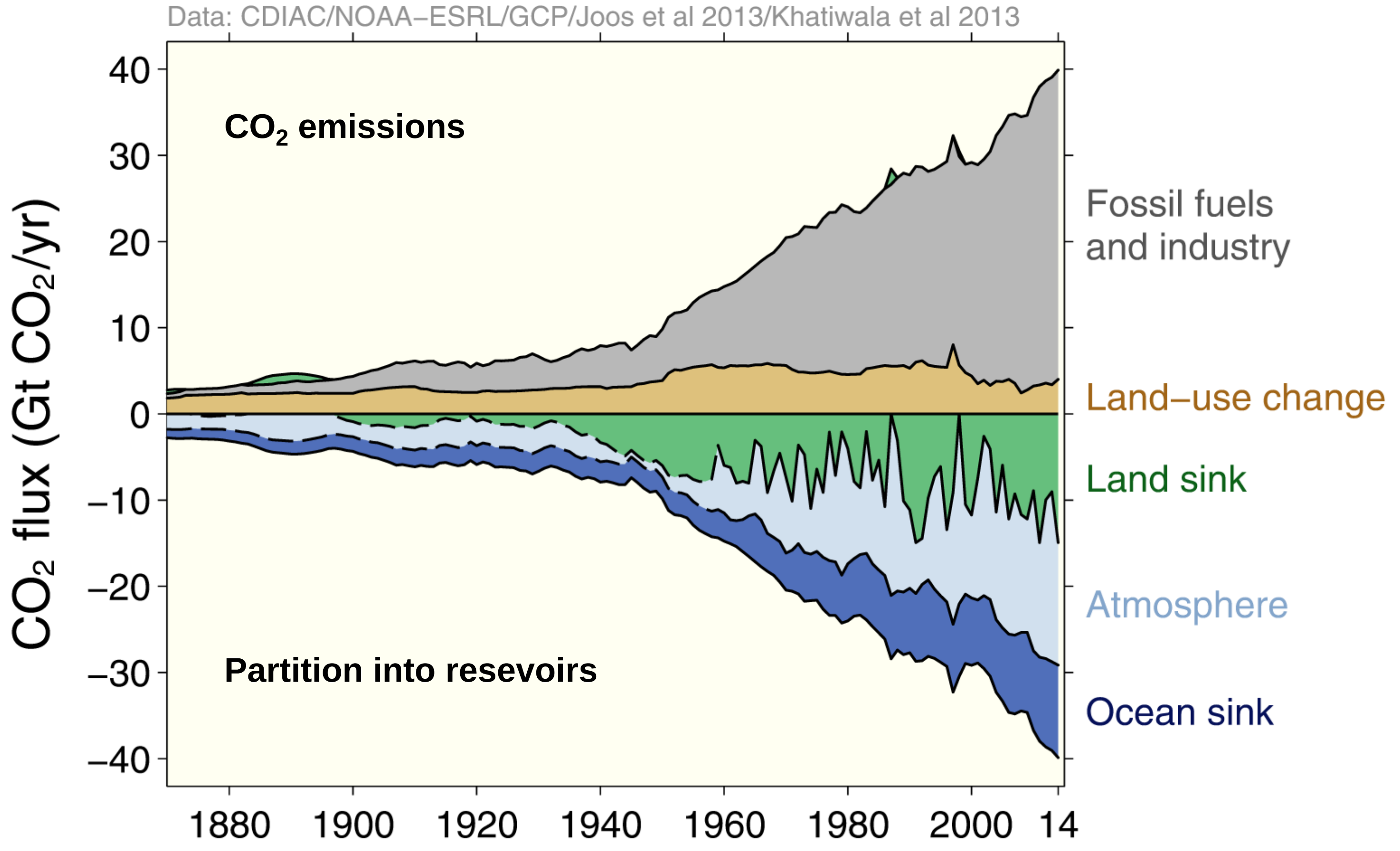
40% runoff

Total land evapotranspiration:
44% Forests
32% Grassland } **88% via vegetation !**
12% Cropland
12% Others

Residence time = Reservoir size / flux
Atmosphere : 10 days
Rivers : 16 days
Soil moisture : 56 days
Groundwater: 770 years

Oki and Kanae, Science 2006. Fluxes / Storage are estimates from different sources
https://www.researchgate.net/publication/6856186_Global_Hydrological_Cycles_and_World_Water_Resources

Earth Global Carbon Cycle - Reservoirs

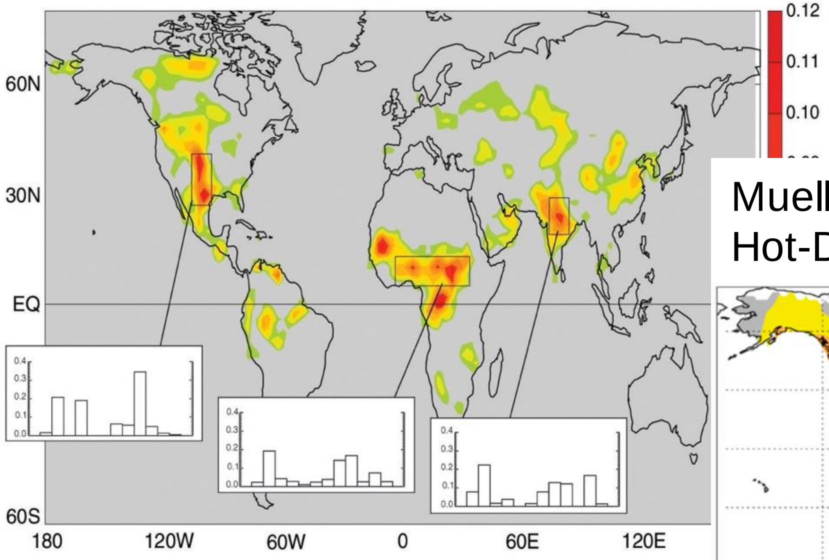


Global Carbon Budget 2015, LeQuere et al., 2015

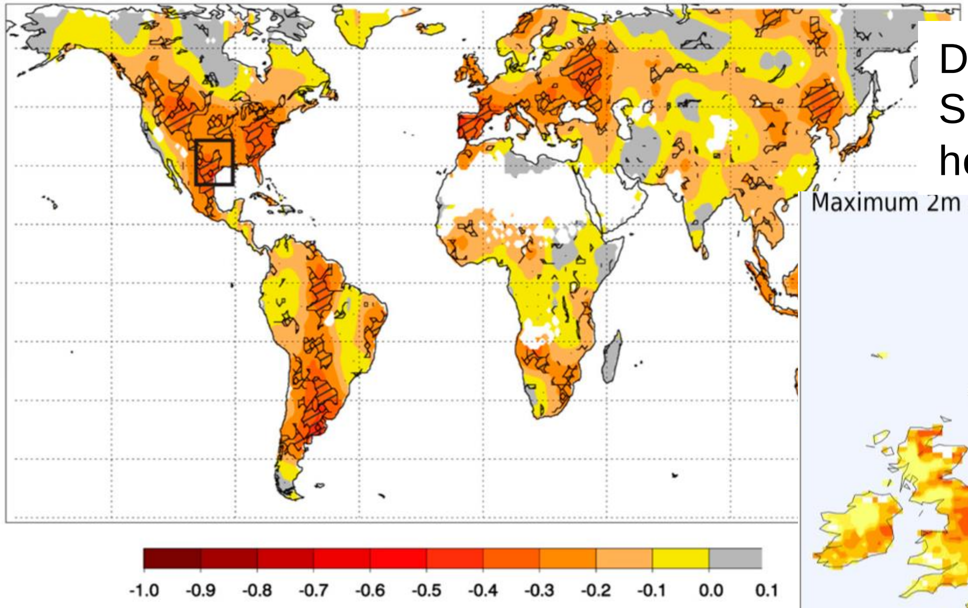
Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2015; Global Carbon Budget 2015

Earth surface role, experimental evidence (soil moisture)

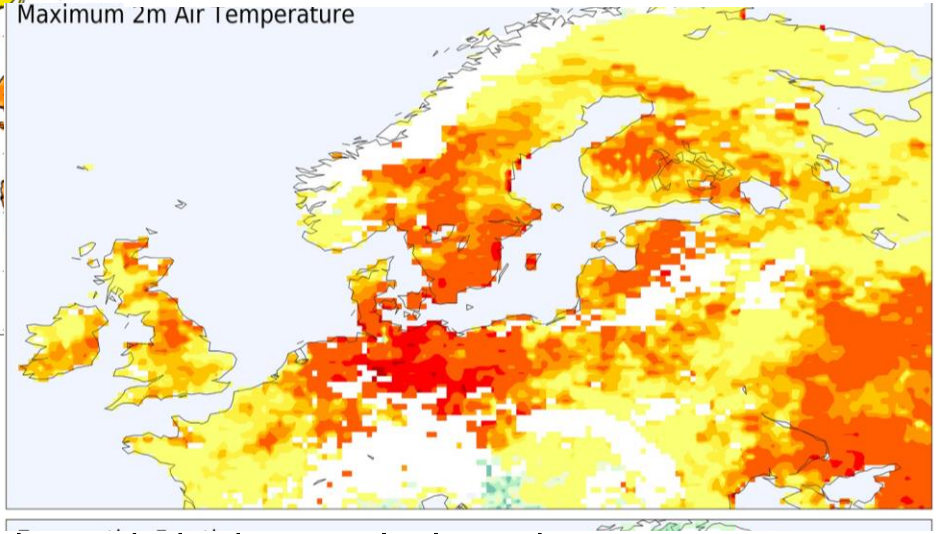
Koster et al. 2004 Science
Land-atmosphere coupling (SoilMoist-Precip feedback), JJA



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

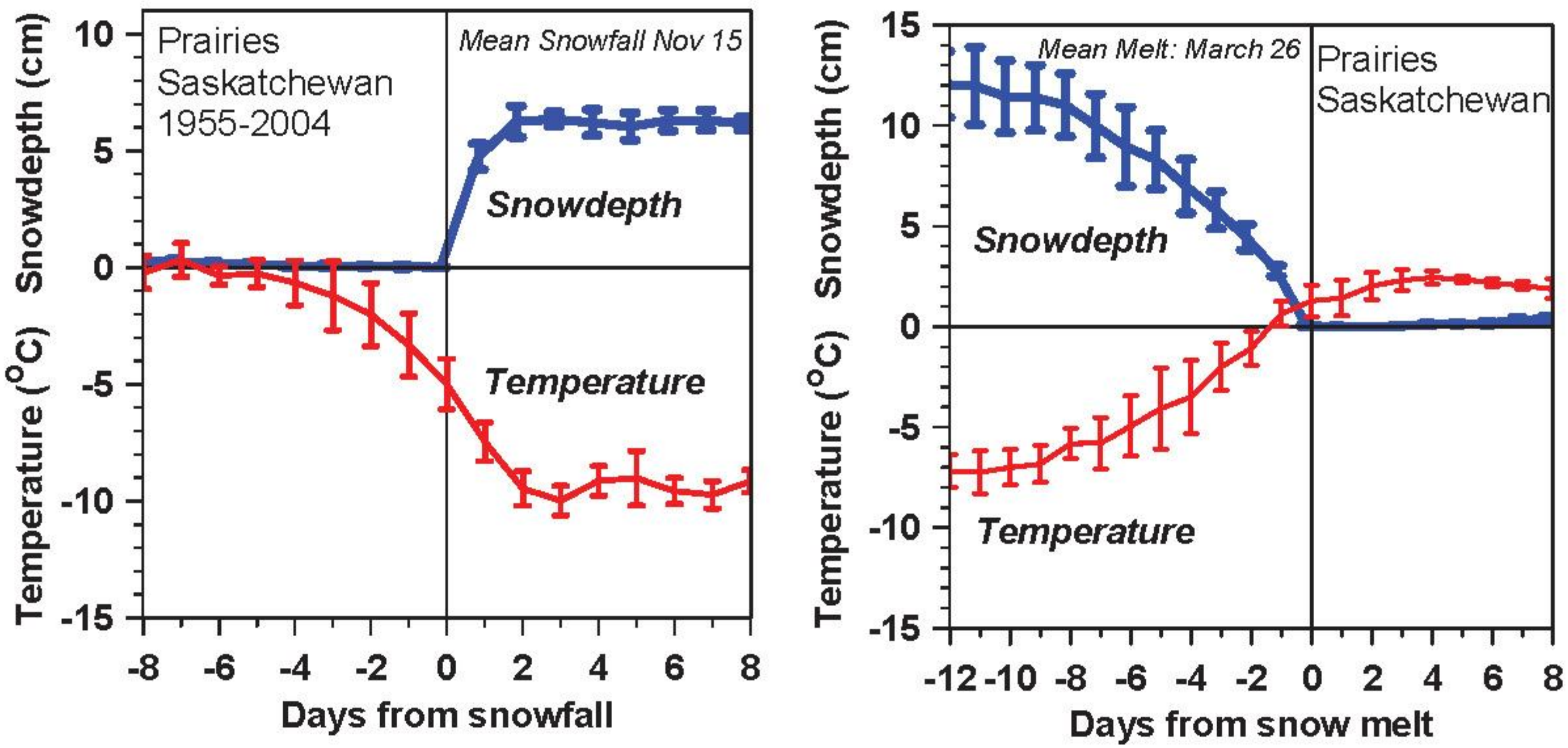


Dirmeyer et al. 2018
SM-Tmax coupling during North Europe heat wave in summer 2018



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

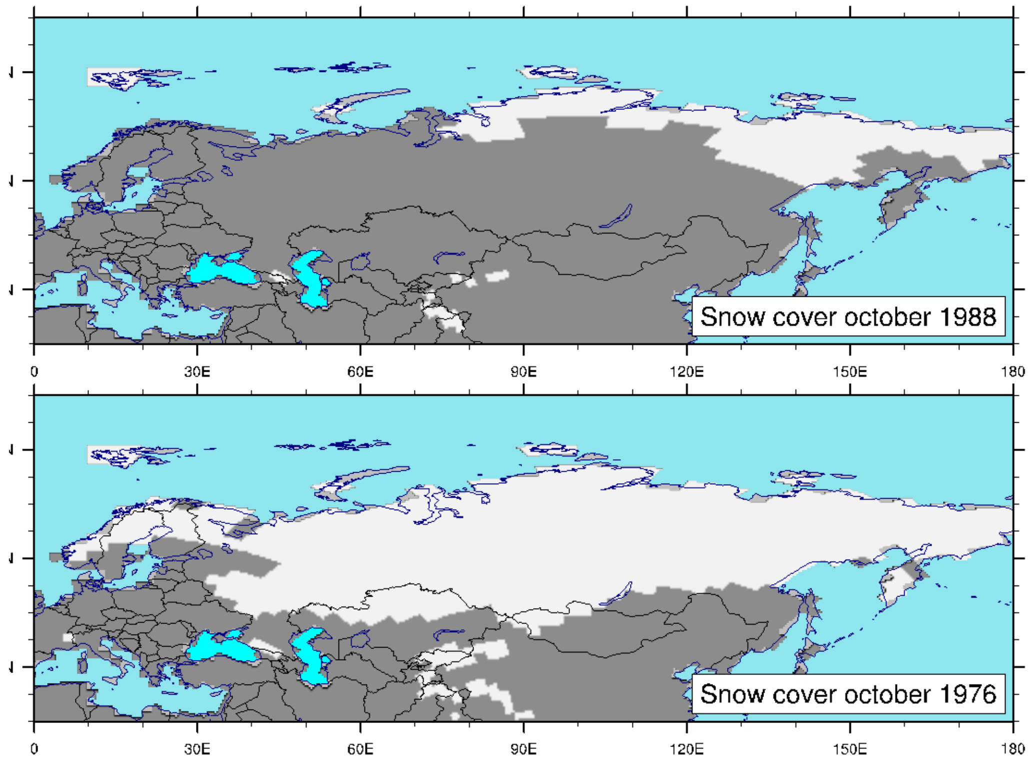
<u>Local climate switch</u> between warm and cold seasons

Winter comes fast with snow

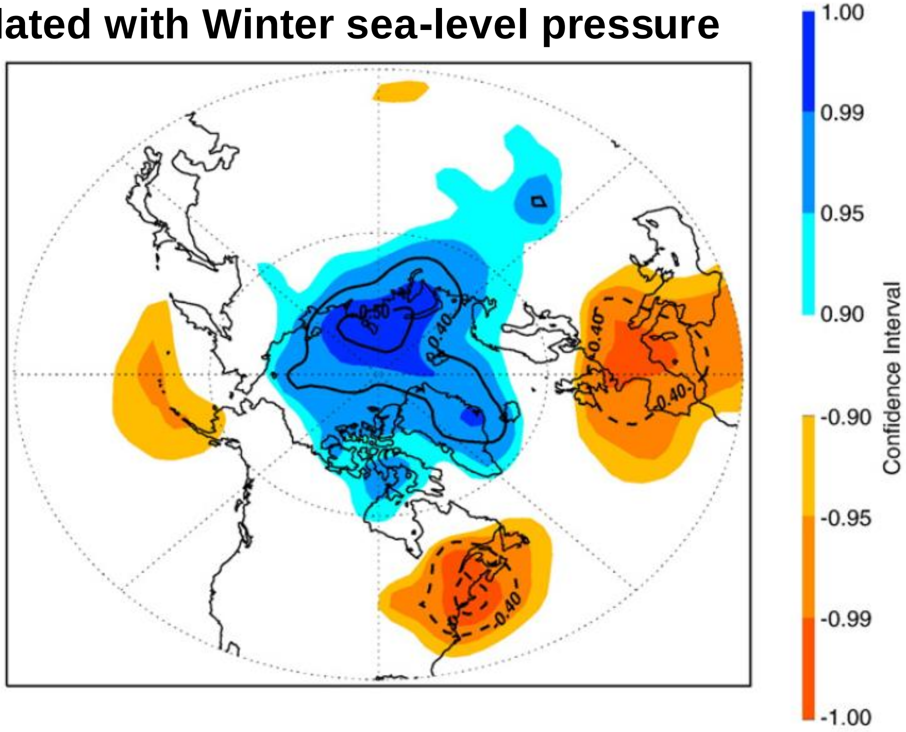
Betts et al. 2014

Earth surface role, snow cover variability

Snow cover shows large interannual variability



October snow cover anomalies (Eurasia) correlated with Winter sea-level pressure



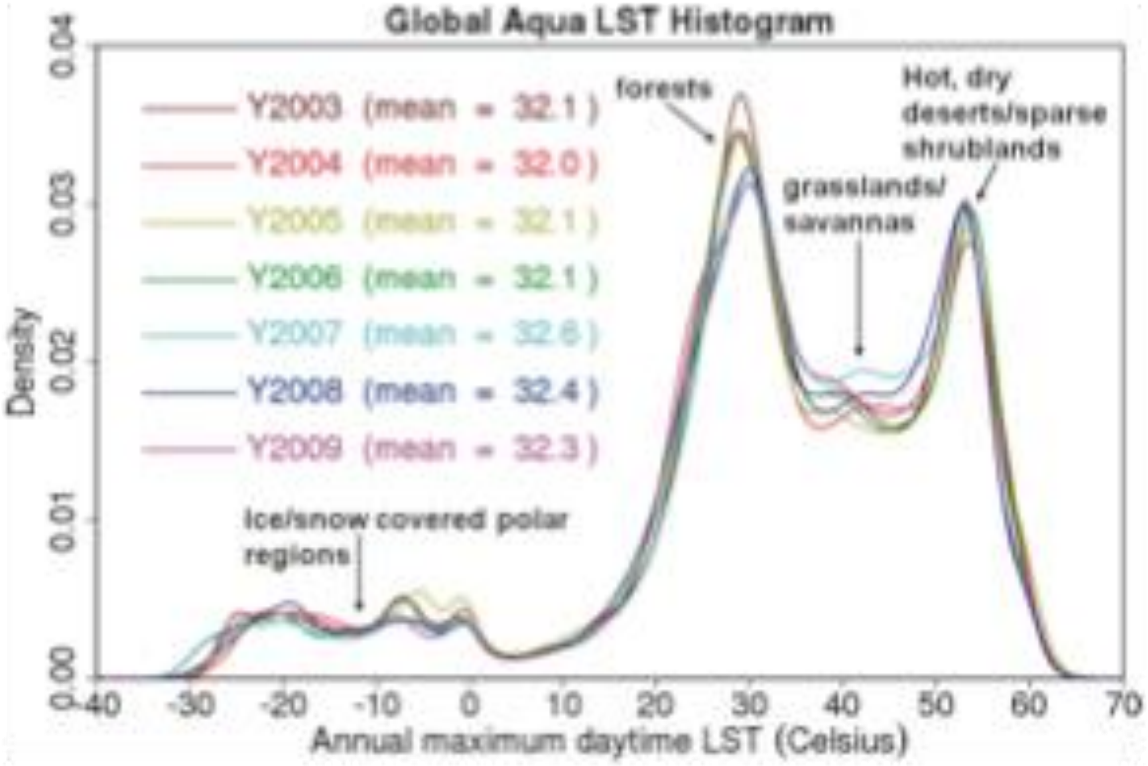
(Cohen and Saito 2003, Gong et al. 2007)

The spatial anomaly patterns resemble the Artic Oscillation pattern of variability

Modelling surface heterogeneity and coupling with the atmosphere

Different surfaces has different surface properties, leading to large differences on surface temperature, energy and water fluxes and their diurnal cycle

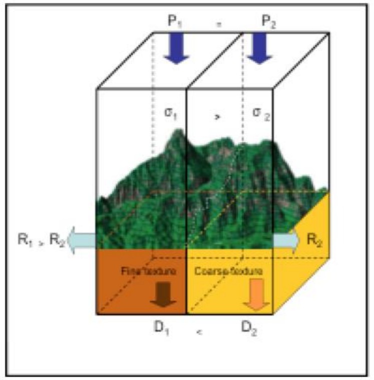
Histogram of maximum surface temperature from satellite captures the influence of land-cover types



Earth surface modelling components @ECMWF

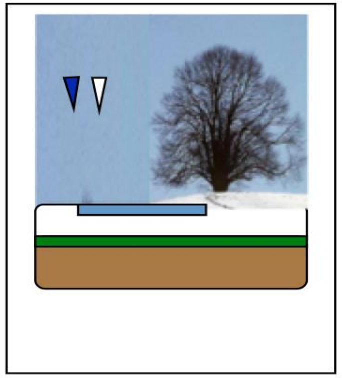
- **Hydrology-TESSEL**

Balsamo et al. 2009
- tiling scheme
- 4-layer soil heat and water budget
- 7 soil texture/type
- Variable infiltration and runoff



- **Snow module**

- snow multi-layer (5 layers, Arduini et al. 2019)
- single layer (Dutra et al. 2009)



- **Vegetation & LAI**

Boussetta et al. (2013)

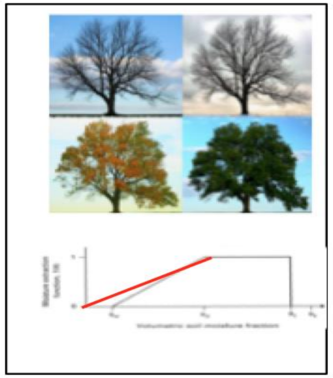
New satellite-based

Leaf-Area-Index

- **SOIL Evaporation**

Balsamo et al. (2011),

Albergel et al. (2012)



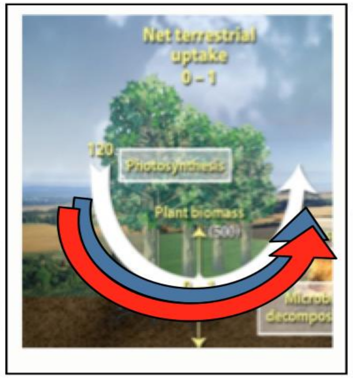
- **Carbon**

Integration of

Carbon/Energy/Water

Boussetta et al. 2013

Agusti-Panareda et al. 2015



- **Lake & Coastal area**

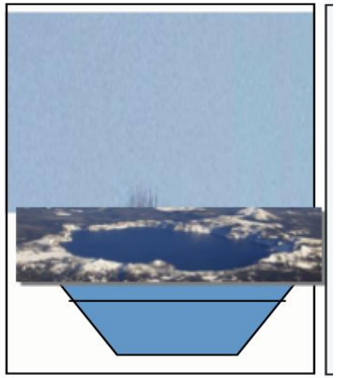
Mironov et al (2010),

Dutra et al. (2010),

Balsamo et al. (2012, 2010)

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

LW tiling (Dutra)



Sea-ice module

4-layer Ice thermodynamic model
Fixed sea-ice depth, 1.5m

ECMWF land-surface, ”ecLand”

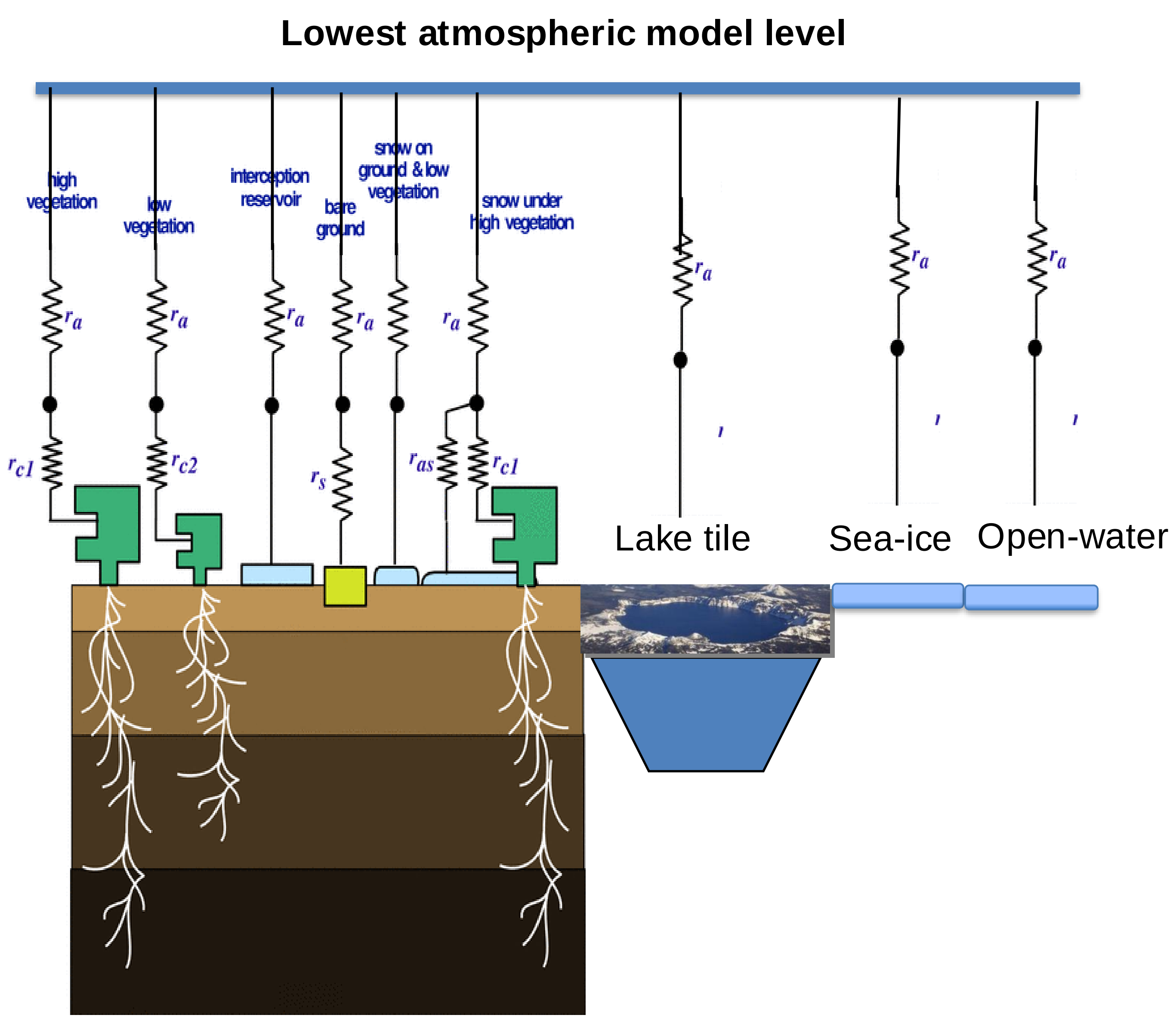
Land surface 1D-model: soil, snow, vegetation, lakes and coastal water. Same horizontal resolution as atmosphere.

Ocean, waves and sea-ice* : NEMO3.4, ecWAM, LIM2

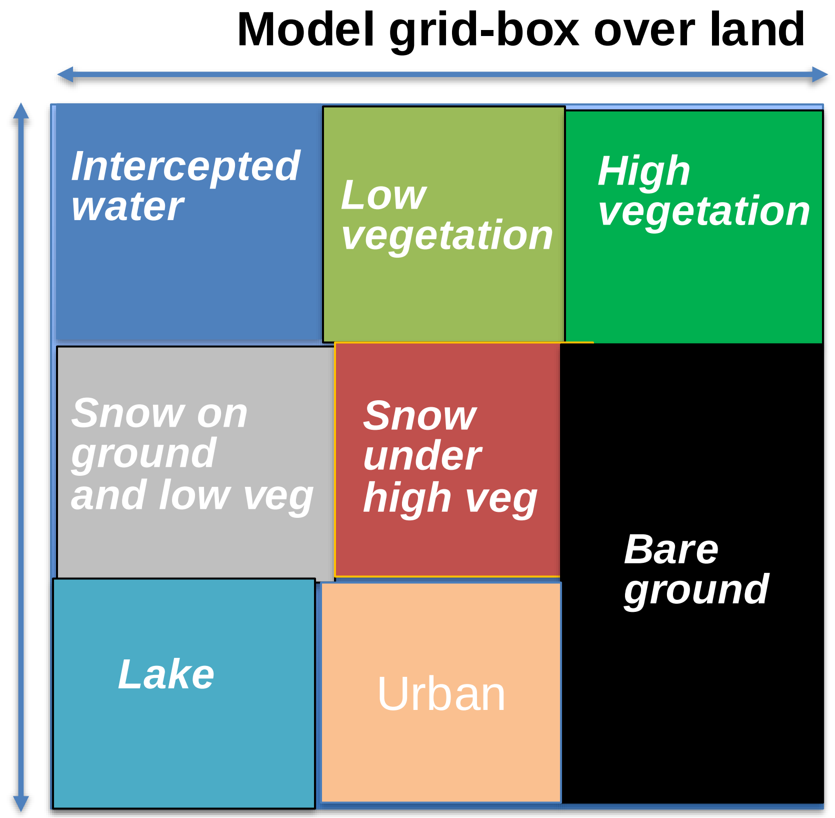
*only sea-ice fraction

Atm/Land resol.	**ECMWF Config, 2023**
80 km	ERAI
32 km	ERA5 SEAS5
9 km	ENS
9 km	HRES

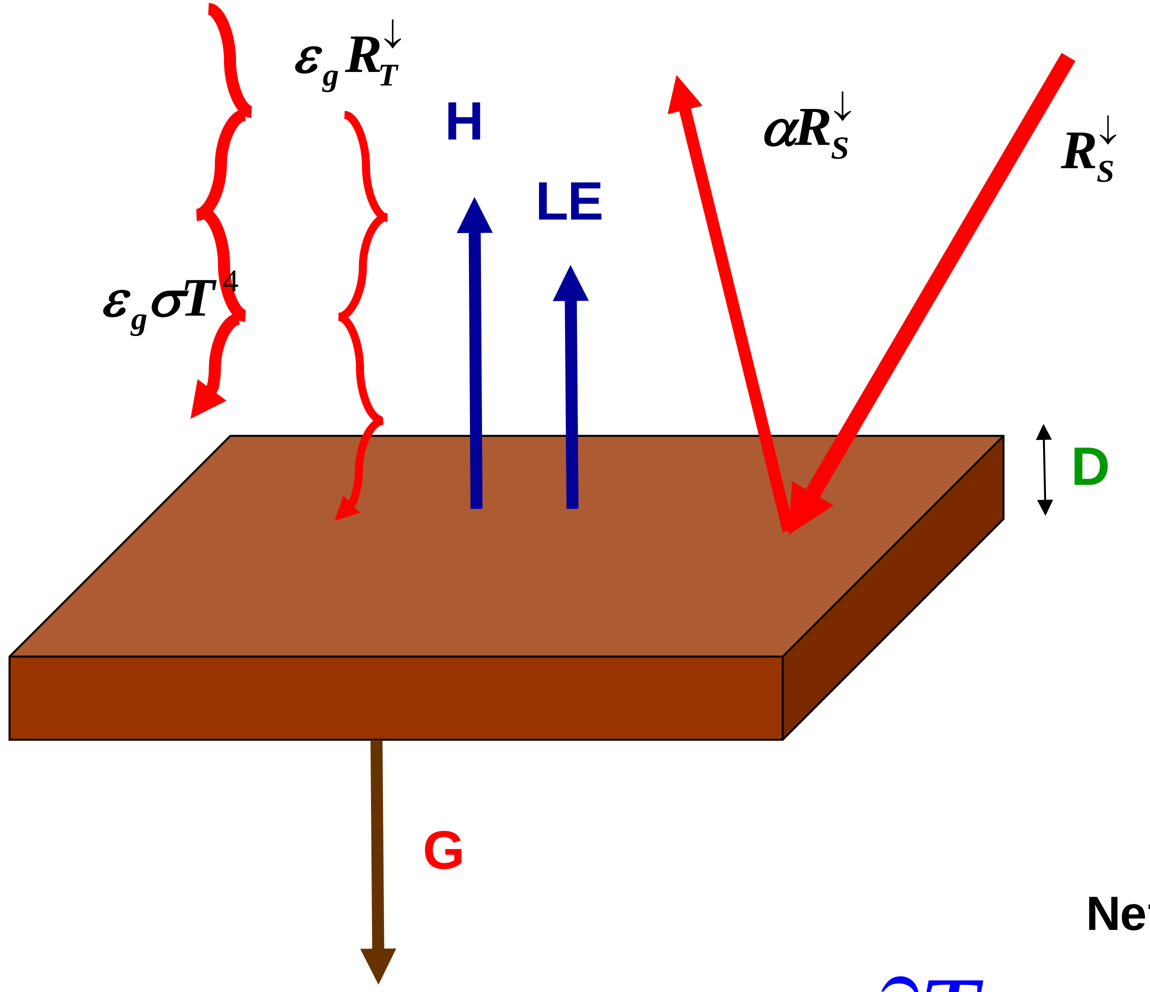
Modelling surface heterogeneity: ecLand tiling approach

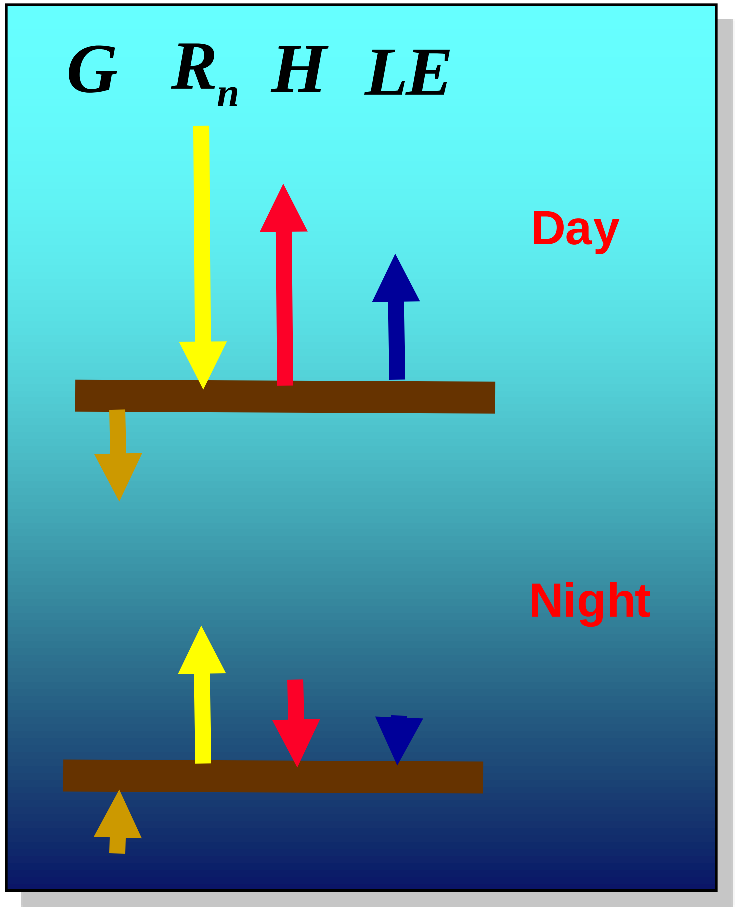


- Atmospheric resolution is too coarse to represent surface heterogeneities
- The surface energy balance and heat fluxes are computed for each tile
- Each tile communicates with the lowest model level above and snow/soil underneath



Schematic for the energy balance at the surface





Net radiation, Sensible heat, Latent heat, Conducted heat

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

ECMWF

ecLand skin temperature equation, aerodynamic perspective

For each tile:

$$(1-\alpha_i)R_S^{\downarrow} + \varepsilon_g R_T^{\downarrow} - \varepsilon_g \sigma T_{sk,i}^4 +$$ ← **Net radiation** (Shortwave and longwave)

$$\rho C_{h,i} u_L (C_p T_L + gz - C_p T_{sk,i}) +$$ ← Turbulent **Sensible** heat flux

$$\rho C_{h,i} u_L \left[a_{L,i} q_L - a_{s,i} q_{sat}(T_{sk,i}, p_s) \right] +$$ ← Turbulent **latent** heat flux

$$\Lambda_{sk,i}(T_s - T_{sk,i}) =$$ ← **Ground (basal)** heat flux

$$= 0$$ ← **no storage term!**

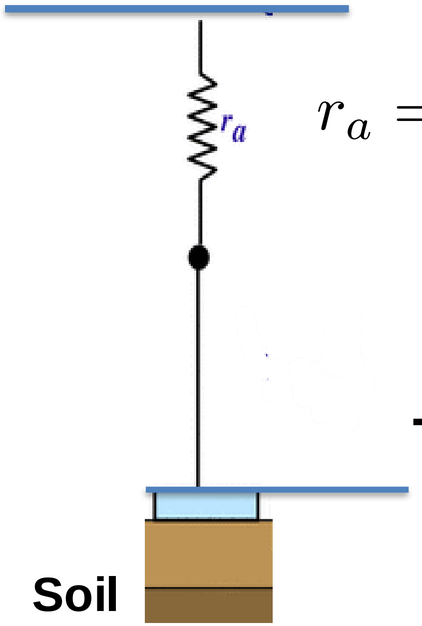
Grid-box quantities

$$H = \sum_i C_i H_i$$

$$E = \sum_i C_i E_i$$

$$T_{sk} = \sum_i C_i T_{sk,i}$$

C_i Tile fraction



ecLand heat transfer

Soil temperature equation, no phase changes

$$(\rho C)_g \frac{\partial T_s}{\partial t} = -\frac{\partial G}{\partial z} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z}$$

$(\rho C)_g$ **Soil volumetric heat capacity**

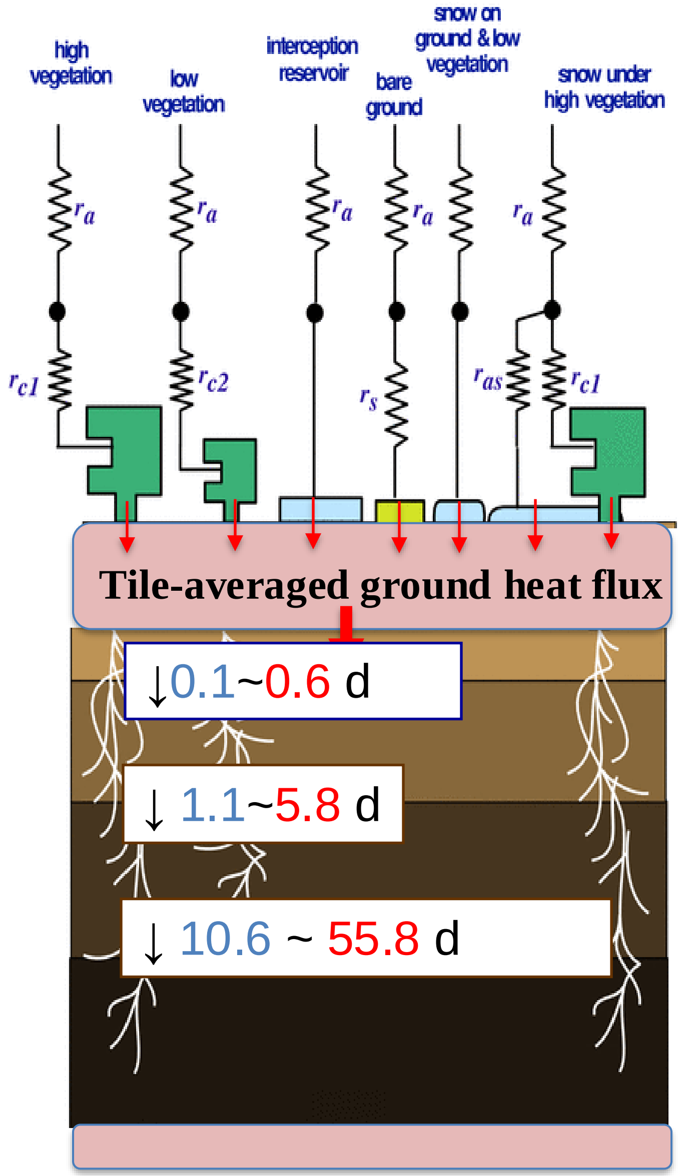
λ_T **Thermal conductivity**

$k = \frac{\lambda_T}{(\rho C)_g}$ **Thermal diffusivity**

For an homogeneous soil,

$$\frac{\partial T_s}{\partial t} = k \frac{\partial^2 T}{\partial z^2}$$

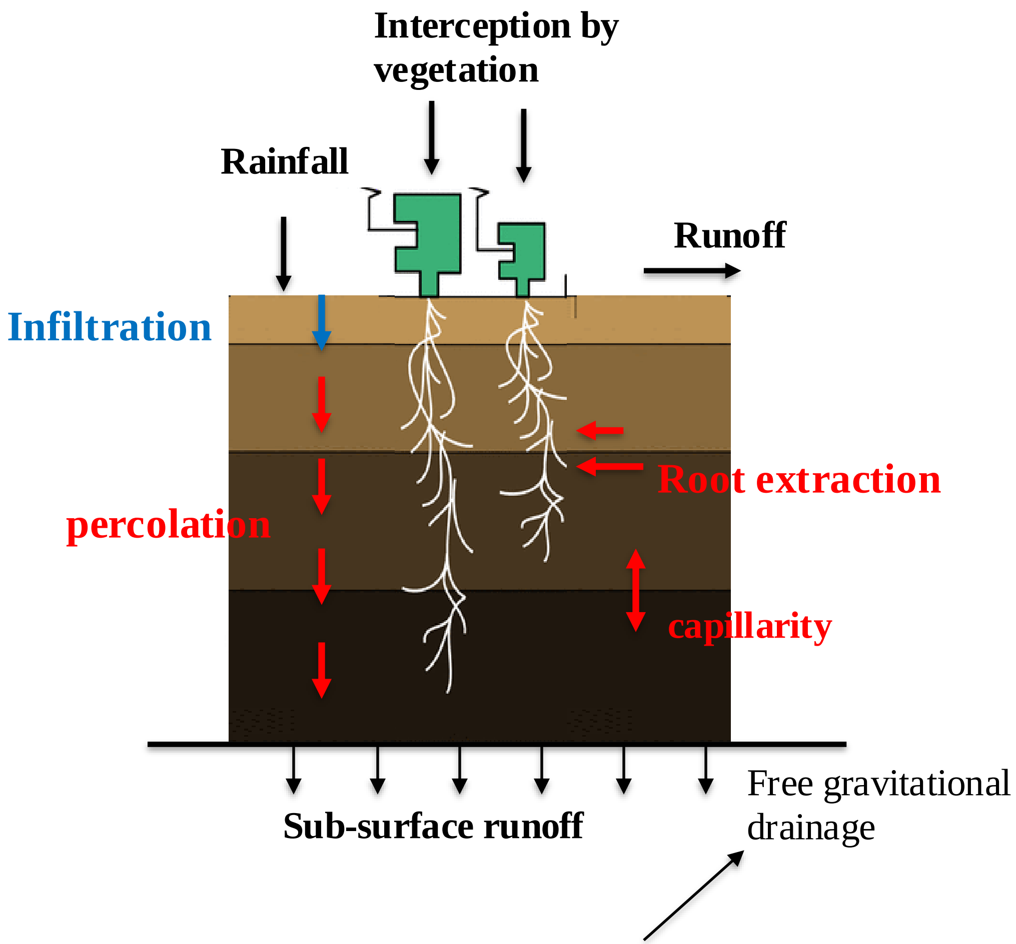
- Solution of heat transfer equation with the soil discretized in 4 layers of depths 7, 21, 72, and 189 cm.
- No-flux bottom boundary condition
- Heat conductivity dependent on soil water content
- Thermal effects of soil water phase change



Time-scale for downward heat transfers in wet/dry soil

ECMWF

Soil water budget



No groundwater or bedrock representation

$$\rho_w \frac{\partial \theta}{\partial t} = -\frac{\partial F}{\partial z} + \rho_w S_\theta$$

θ soil water $[\ ] = m^3 m^{-3}$

F Soil water flux $[\ ] = kg m^{-2} s^{-1}$

S_θ Soil water source/sin k, ie root extraction

Boundary conditions

Top: **Infiltration = precip – interception – runoff**

Bottom: **Free drainage**

Root extraction

The amount of water transported from the root system up to the stomata and then available for transpiration

Coupling with the soil temperature

In frozen soil, infiltration and percolation are minimum → most of water goes into runoff

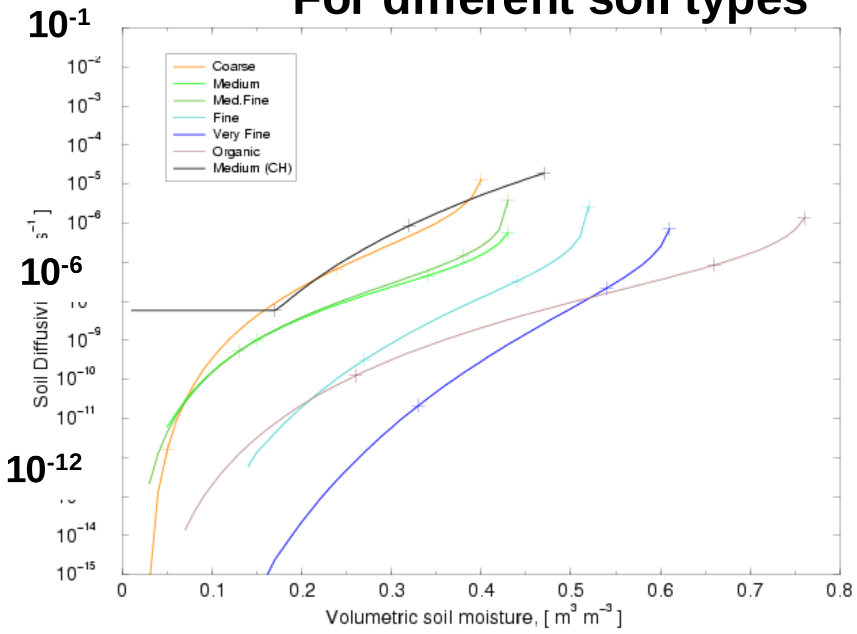
Soil water flux

$$F = -\rho_w\left(\lambda \frac{\partial \theta}{\partial z} - \gamma\right) \qquad \textbf{Darcy's law}$$

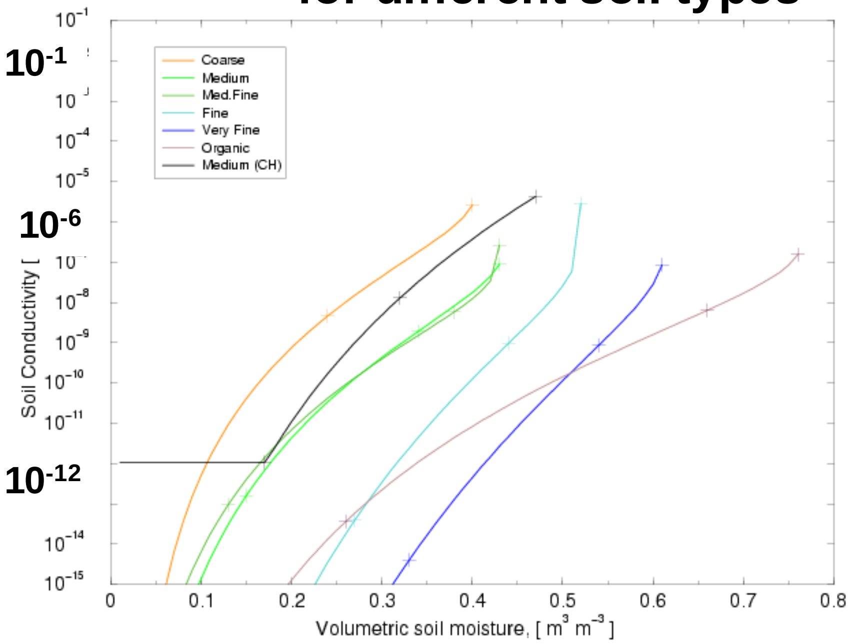
λ hydraulic diffusivity $\quad [\lambda] = m^2 s^{-1}$

γ hydraulic conductivity $\quad [\gamma] = m s^{-1}$

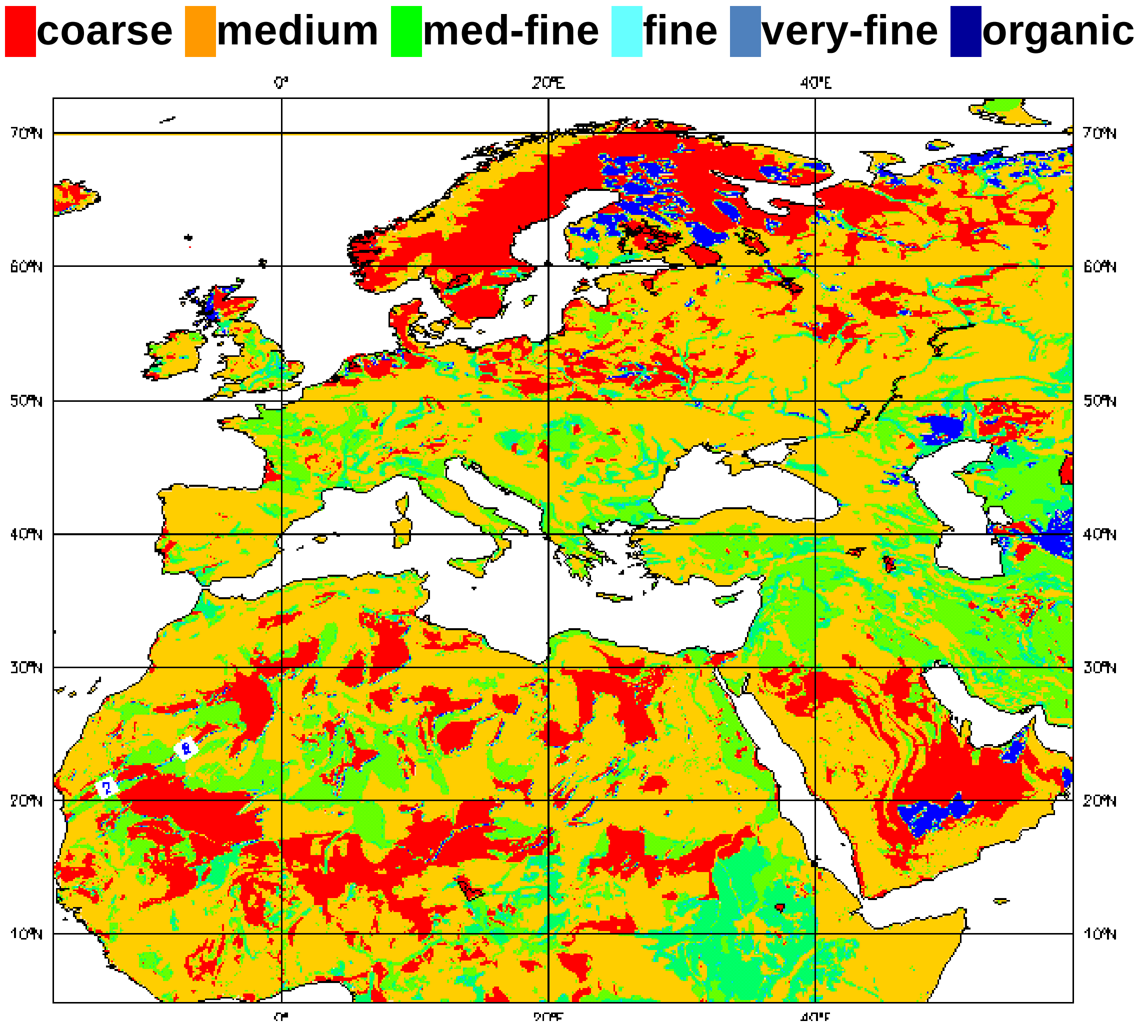
Hydraulic Diffusivity, For different soil types



Hydraulic conductivity, for different soil types

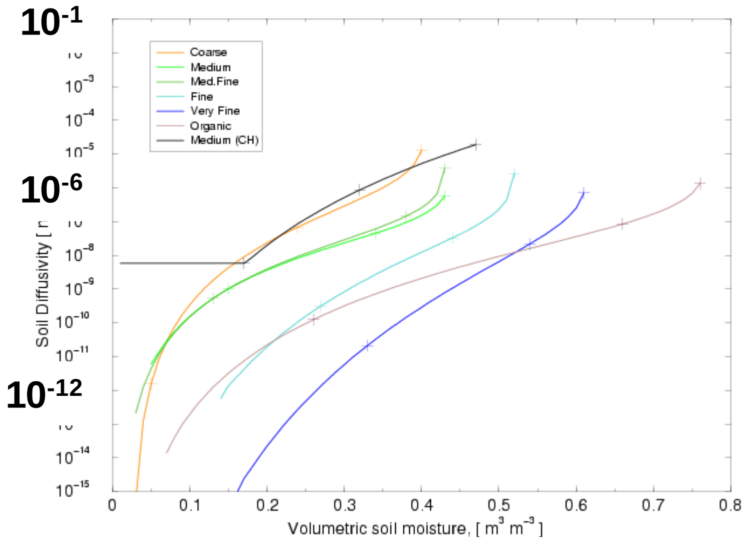


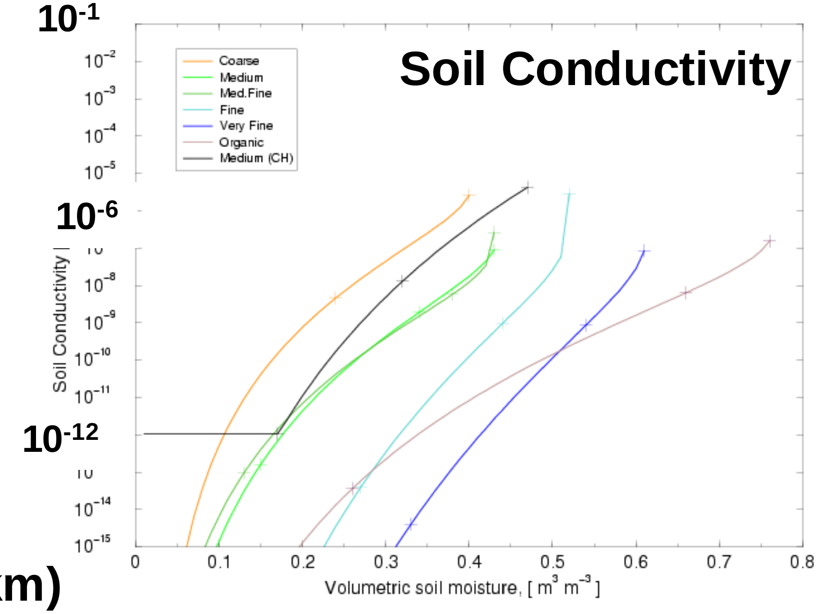
ecLand hydrology scheme(1)



Dominant soil type from FAO2003 (at native resolution of ~ 10 km)

Soil Diffusivity



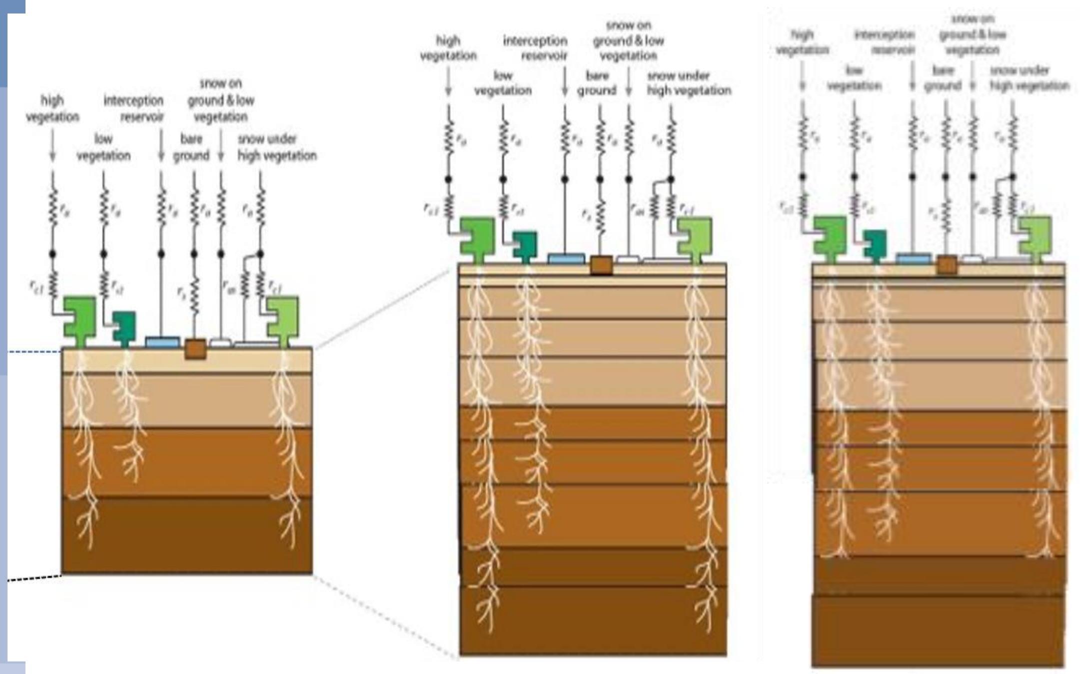


ECMWF

Water transfer, considerations on vertical discretization

- The number of vertical layers and the thickness of the topmost layer is important to correctly represent water fluxes like bare soil evaporation, transpiration and runoff

Best solution is to have a large number of layers, a deep column, and very fine layer close to the surface interface

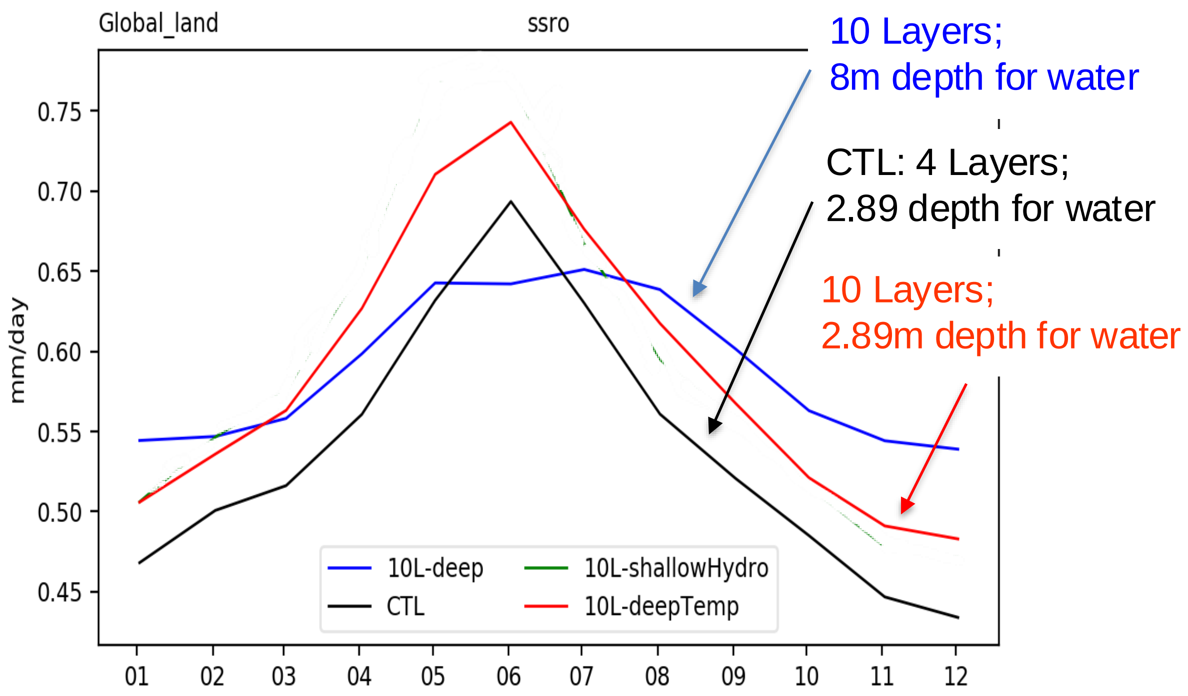


4 Layers (2.89m)

10 Layers (8m)

10 Layers (8m,2.89m for water)

Global sub-surface runoff from simulation with different number of layers and total column depth



ECMWF

Modelling of 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, FLake, was introduced as part of ecLand.

FLake (Mironov et al. 2010, BER) is a two-layer bulk model based on a self-similar parametric representation of the evolving temperature profile within lake water and ice.

ecLand - HTESSEL

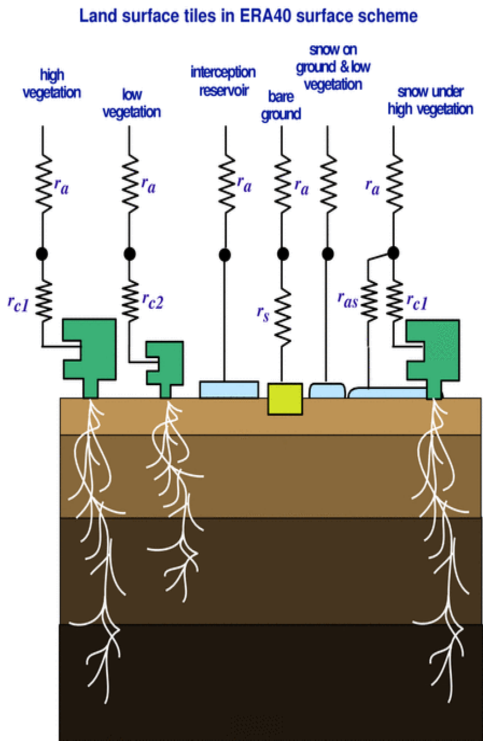
Hydrology - Tiled ECMWF

Scheme for Surface Exchanges over Land

+

FLake

Fresh water Lake scheme



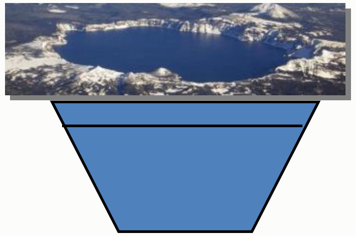
- **Lake tile**

Mironov et al (2010),

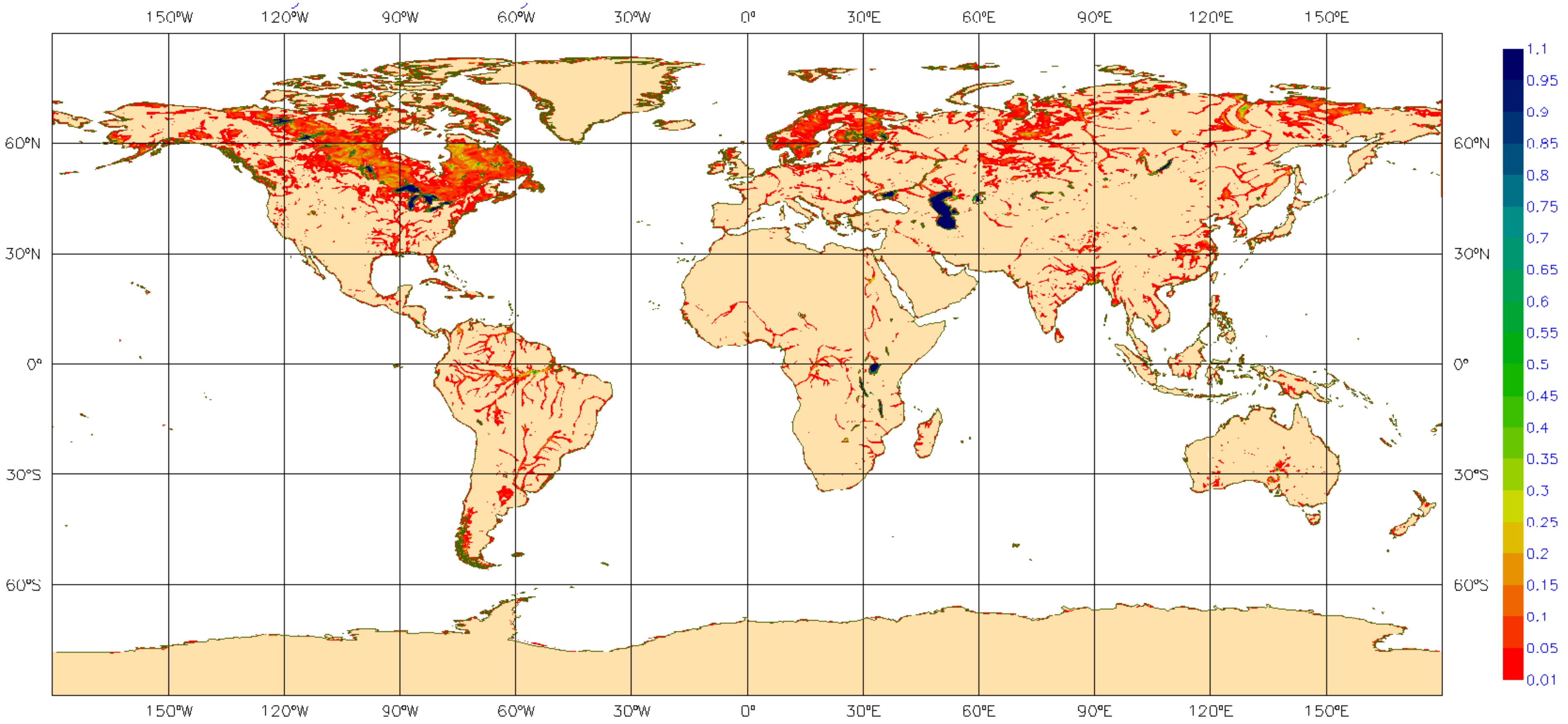
Dutra et al. (2010),

Balsamo et al. (2010, 2012, 2013)

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



Inland water bodies fraction



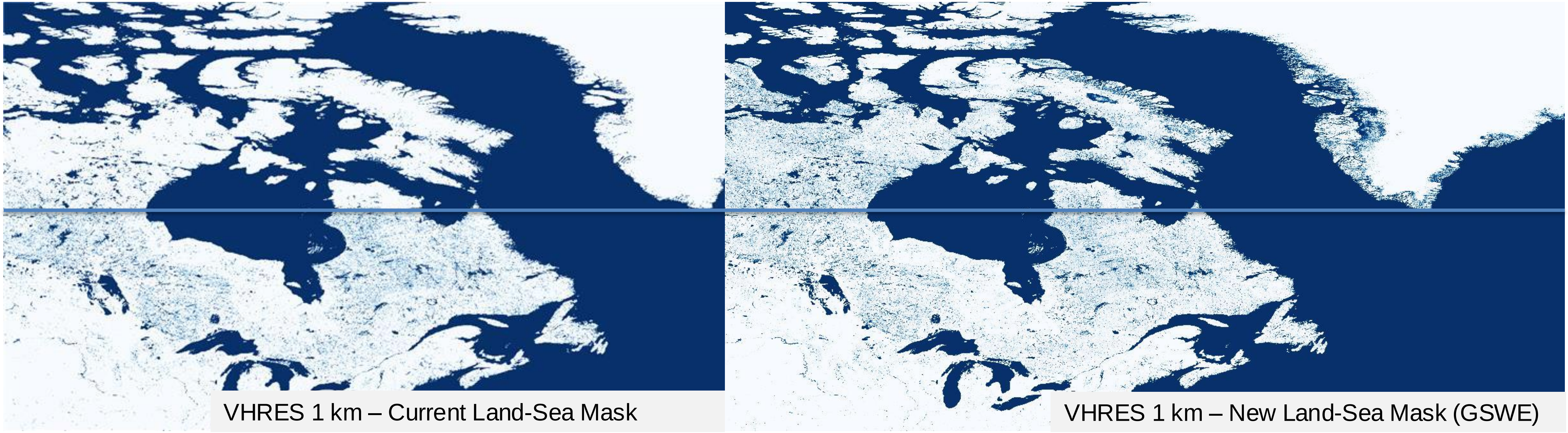
Aggregated from GLOBCOVER 300m

Towards representing inland water surfaces at km-scale resolution

Margarita Choulga, Souhail Boussetta et al.

Moving towards global 1km enable resolving more of the inland water surfaces affecting the surface temperature

Mapping water surfaces correctly is essential to have an inter-consistent treatment of land surface



Choulga et al. 2021. Example of land sea mask obtained by the global 30m resolution GSWE aggregated to 1km on Google Earth Engine.
https://hess.copernicus.org/articles/23/4051/2019/

Energy fluxes: diurnal cycle impact of lakes

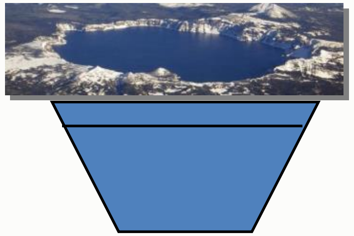
- **Lake tile**

  Mironov et al (2010),

  Dutra et al. (2010),

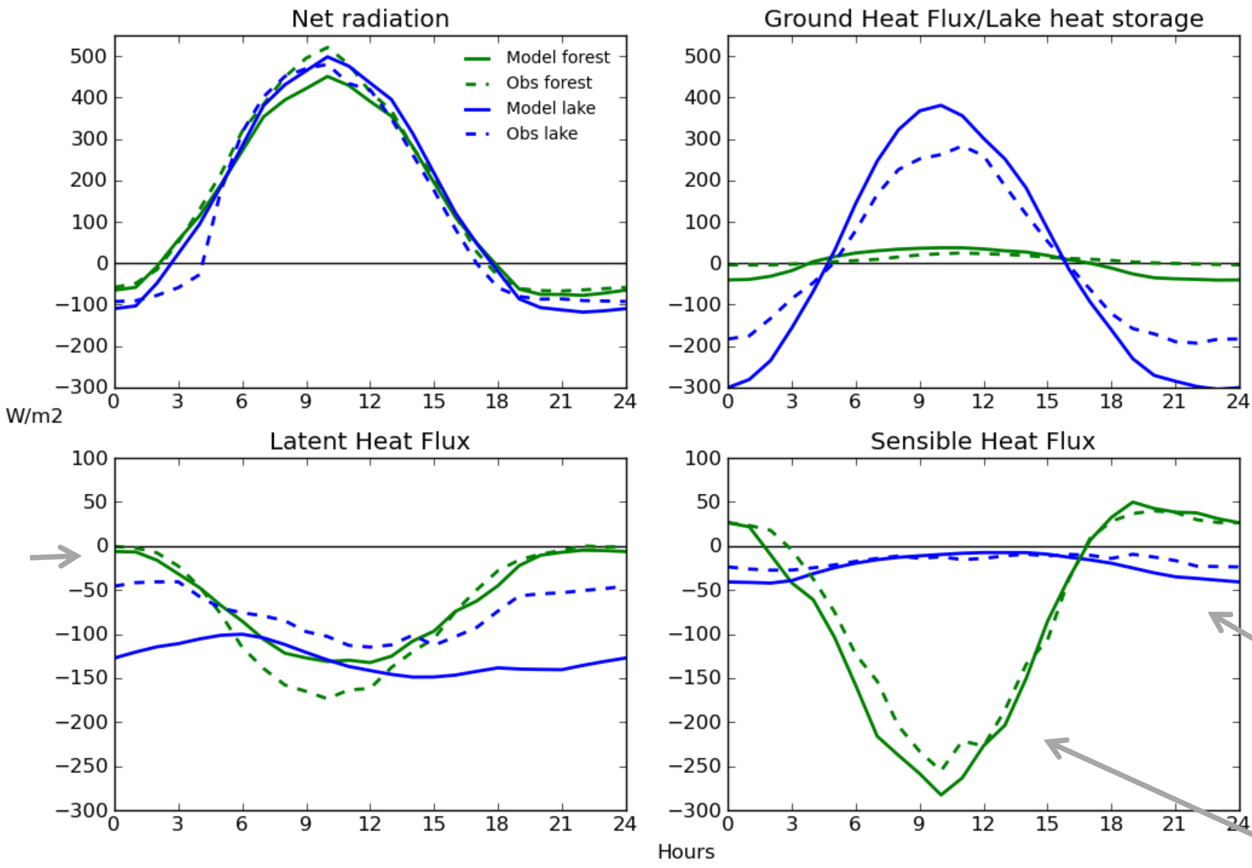
  Balsamo et al. (2010, 2012, 2013)

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



Manrique-Suñén et al. (2013, JHM)

Monthly diurnal cycle of energy fluxes for July



HTESSEL
LAKEHTESSEL
forest obs
lake obs

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

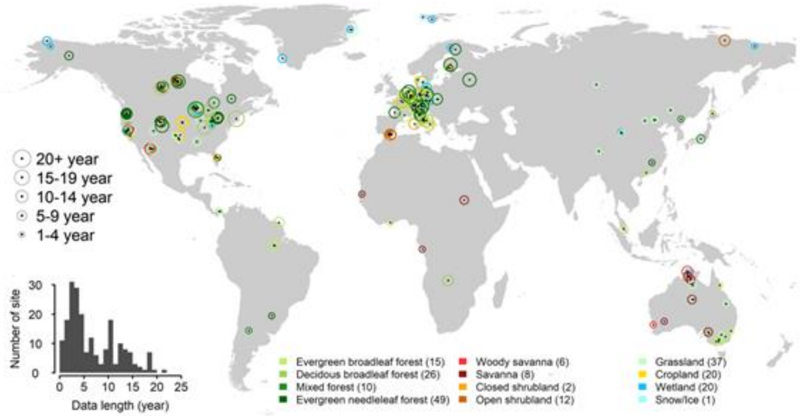
Main difference between lake & forest sites is found in energy partitioning

ECMWF

Process evaluation using in-situ observations

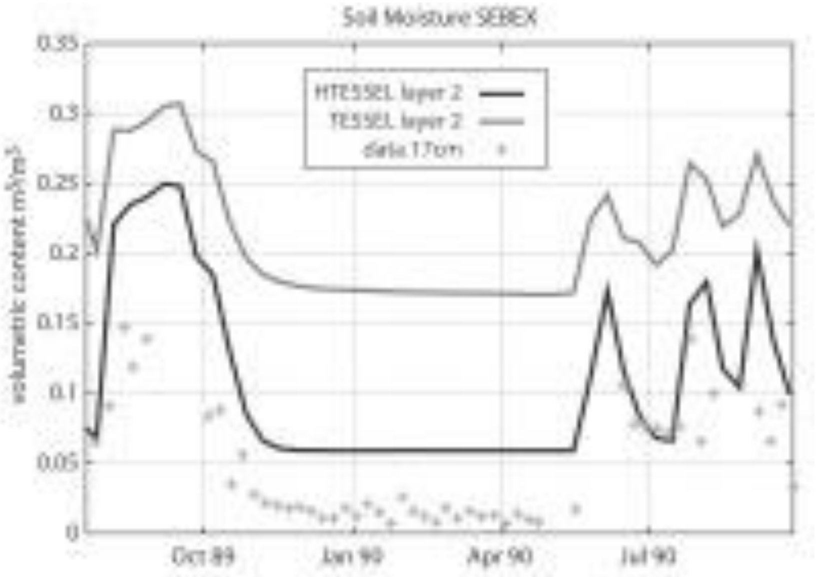
Balsamo et al 2009 JHM, Dutra et al. 2010 JHM, Arduini et al. 2019, ….

FLUXNET 2015 sites

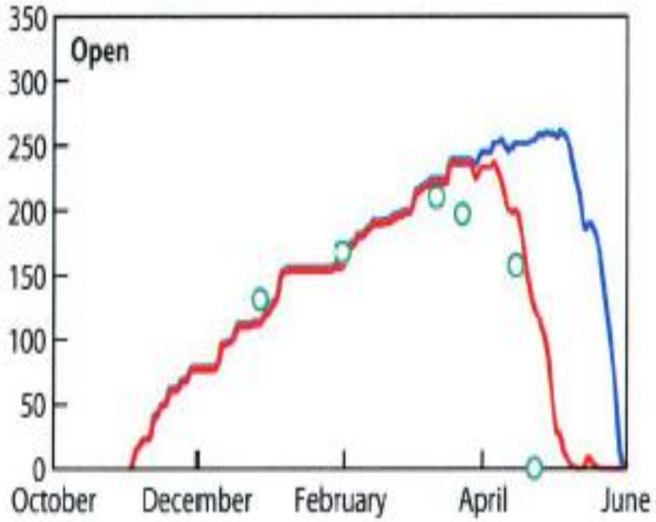


Evaluation of land-surface process improvements at instrumented sites is fundamental for assessing that forecasts are improved for the right reason

Evolution of soil moisture for a site at SEBEX site. Observations (dot), TESSEL(Grey), and HTESSEL(black) schemes.



Evolution of snow mass at SNOWMIP 2 site in the **2010** and **old** snow scheme



Col de Porte, snow site in French Alps

ECMWF

Weather forecasts impact of improved representation of soil/snow processes

- **H**ydrology-**TESSEL**

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

  Global Soil Texture (FAO)

  New hydraulic properties

  Variable Infiltration capacity & surface runoff revision

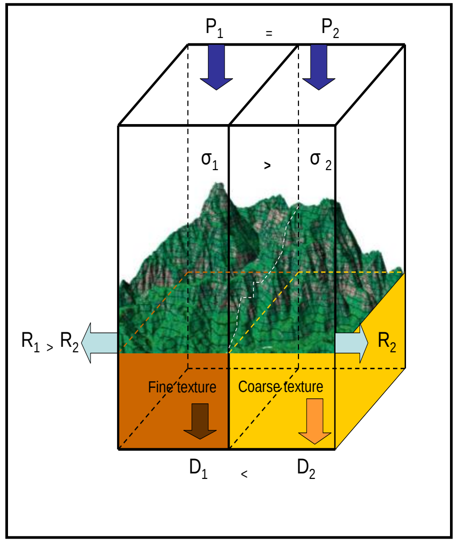
- Snow update

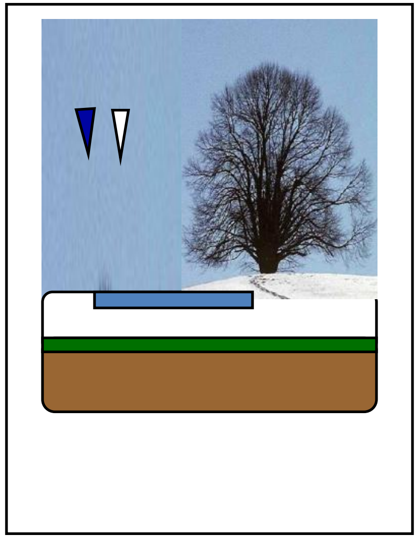
  Dutra et al. (2010)

  Revised snow density

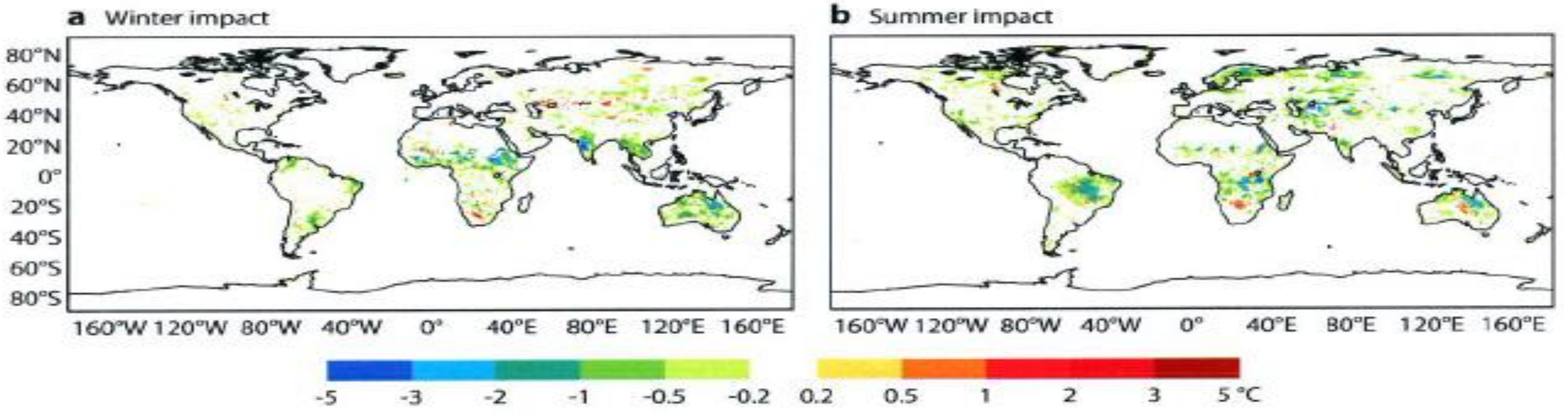
  Liquid water reservoir

  Revision of Albedo and sub-grid snow cover



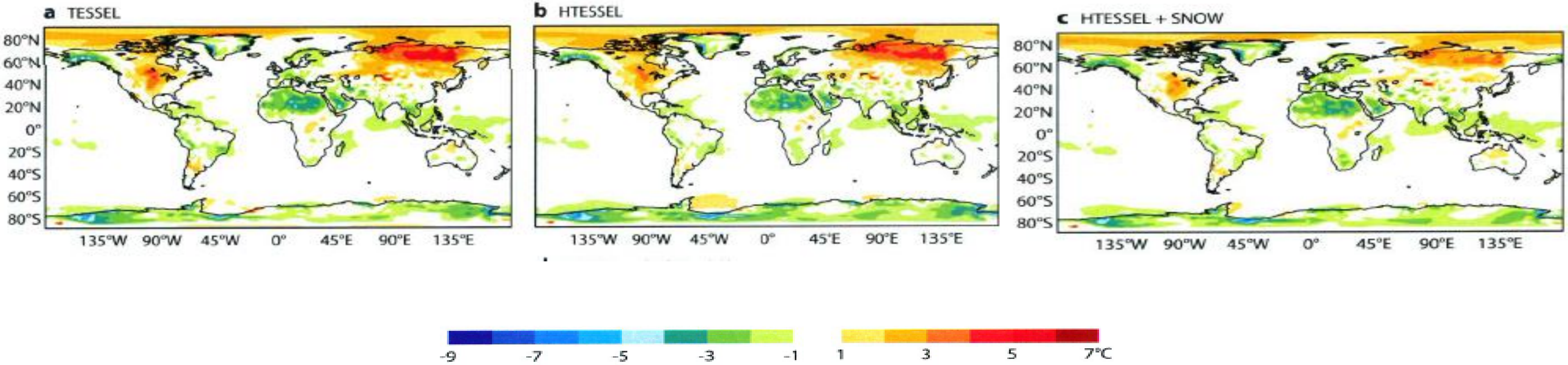


Forecast Impact (+36-hour forecast, mean error at 2m temperature)



Improving 2m temperature **Degrade 2m temperature**

Climate improvements from land developments (soil, snow)

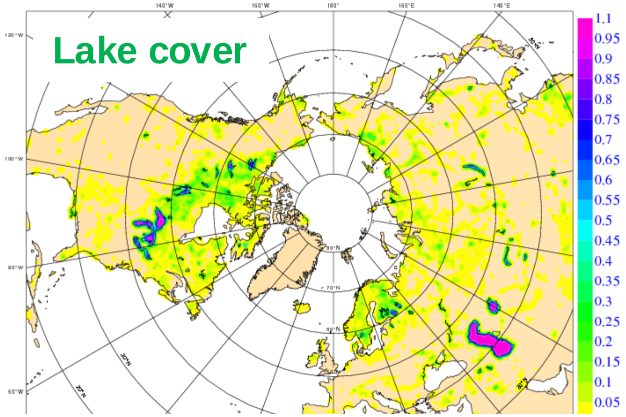


simulations colder than ERA-Interim

Warmer than ERA-Interim

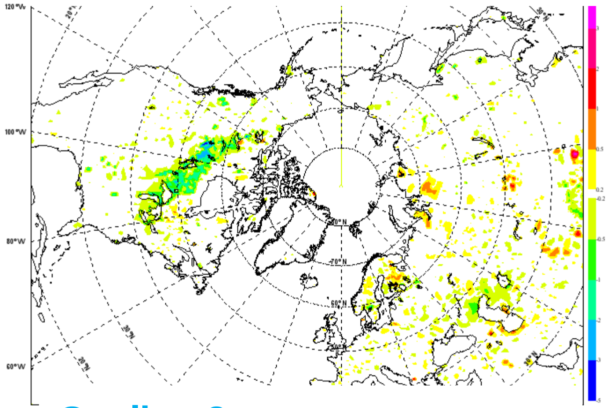
Impact of lakes in NWP forecasts

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



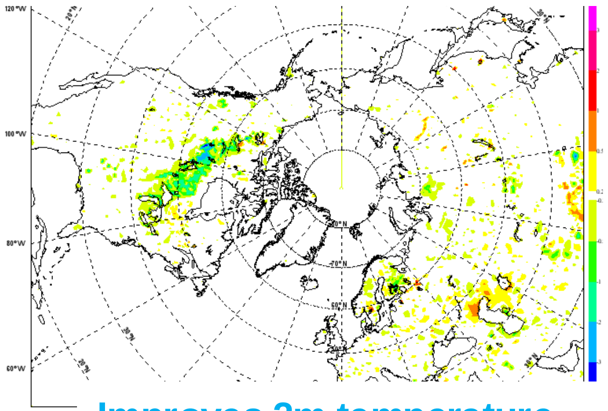
- **Forecasts sensitivity and impact of lakes is shown to produce a spring-cooling on lake areas with benefit on the temperatures forecasts (day-2 (48-hour forecast) at 2m.**
- **The lake surface temperatures are verified with MODIS LSTs as indicative of the heat-storage accuracy of the lake model**

Forecast sensitivity

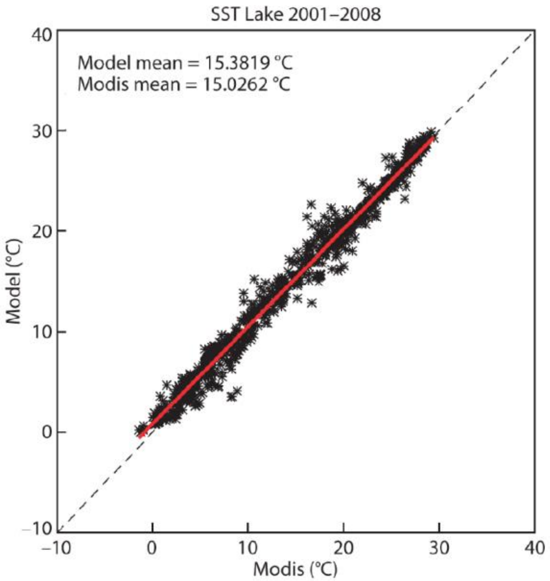


Cooling 2m temperature
Warming 2m temperature

Forecast impact



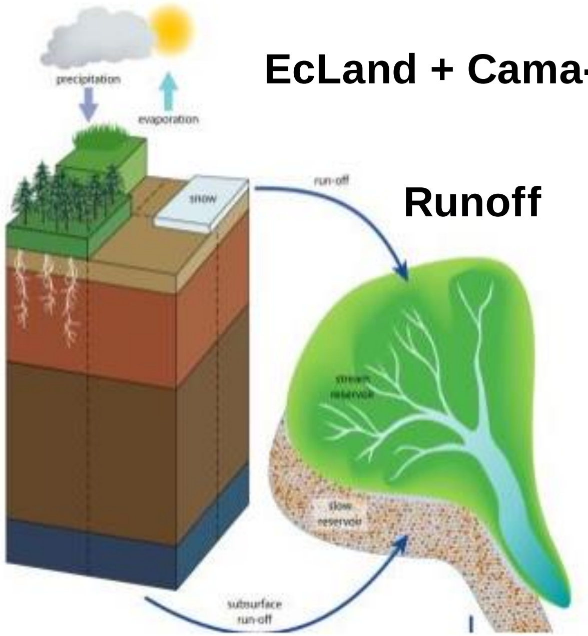
Improves 2m temperature
Degrades 2m temperature



ECMWF

Toward simulating floods & inundations in ecLand and in the IFS

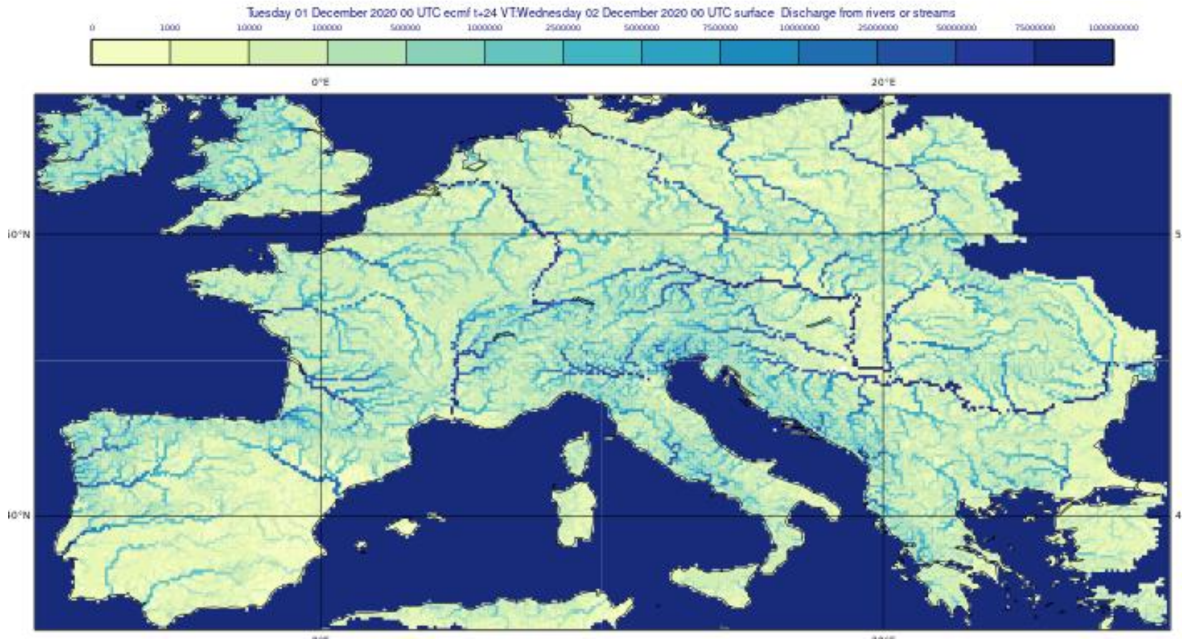
EcLand + Cama-flood



Runoff

Sub-surface Runoff

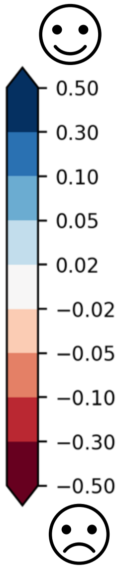
- Coupling river discharge to ecLand in future high resolution land reanalysis (running since 2023 in Destination Earth project)
- Coupling within the IFS is ongoing to permit forecasting river floods



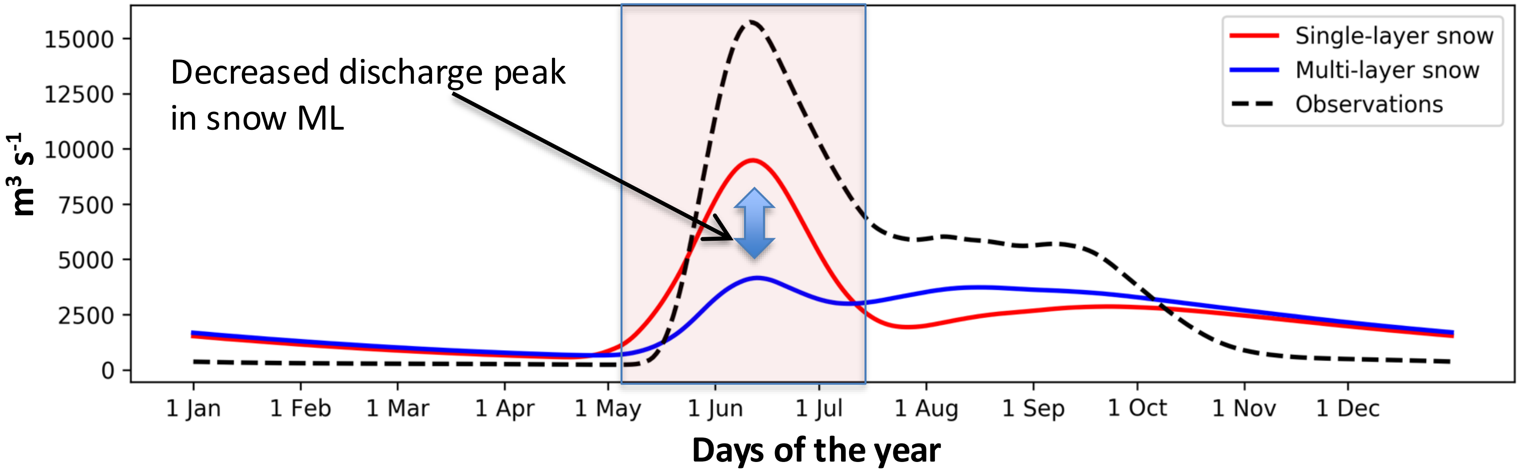
River discharge from EcLand coupled with Cama-flood over the European domain at 3arc/min resolution (~5km)

Hydrology to evaluate land-surface model developments – multi-layer snow example

KGE skill score of river discharge, snow ML – old scheme



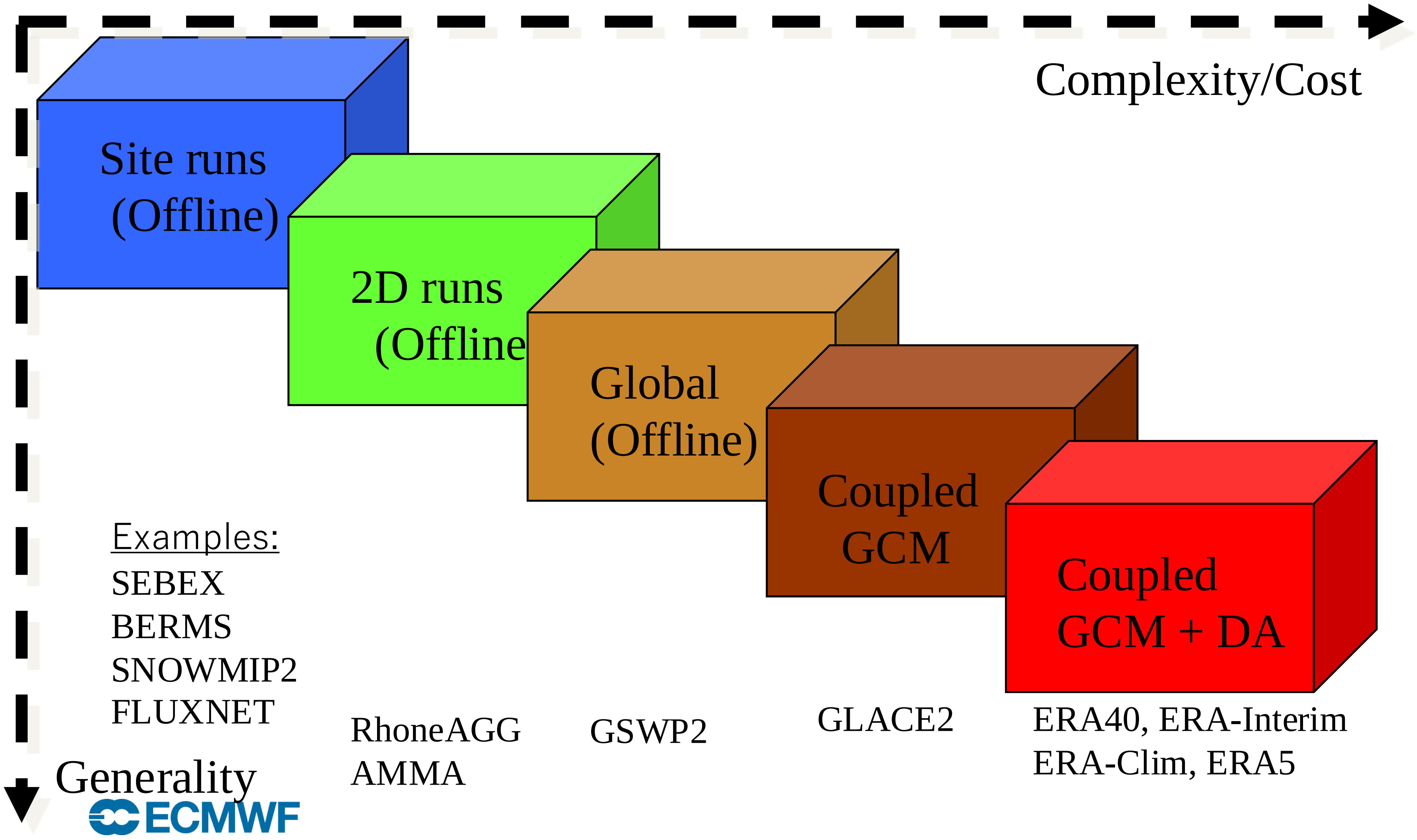
Daily mean annual cycle of river discharge for Kolyma river, lat=68.72; lon=158.71



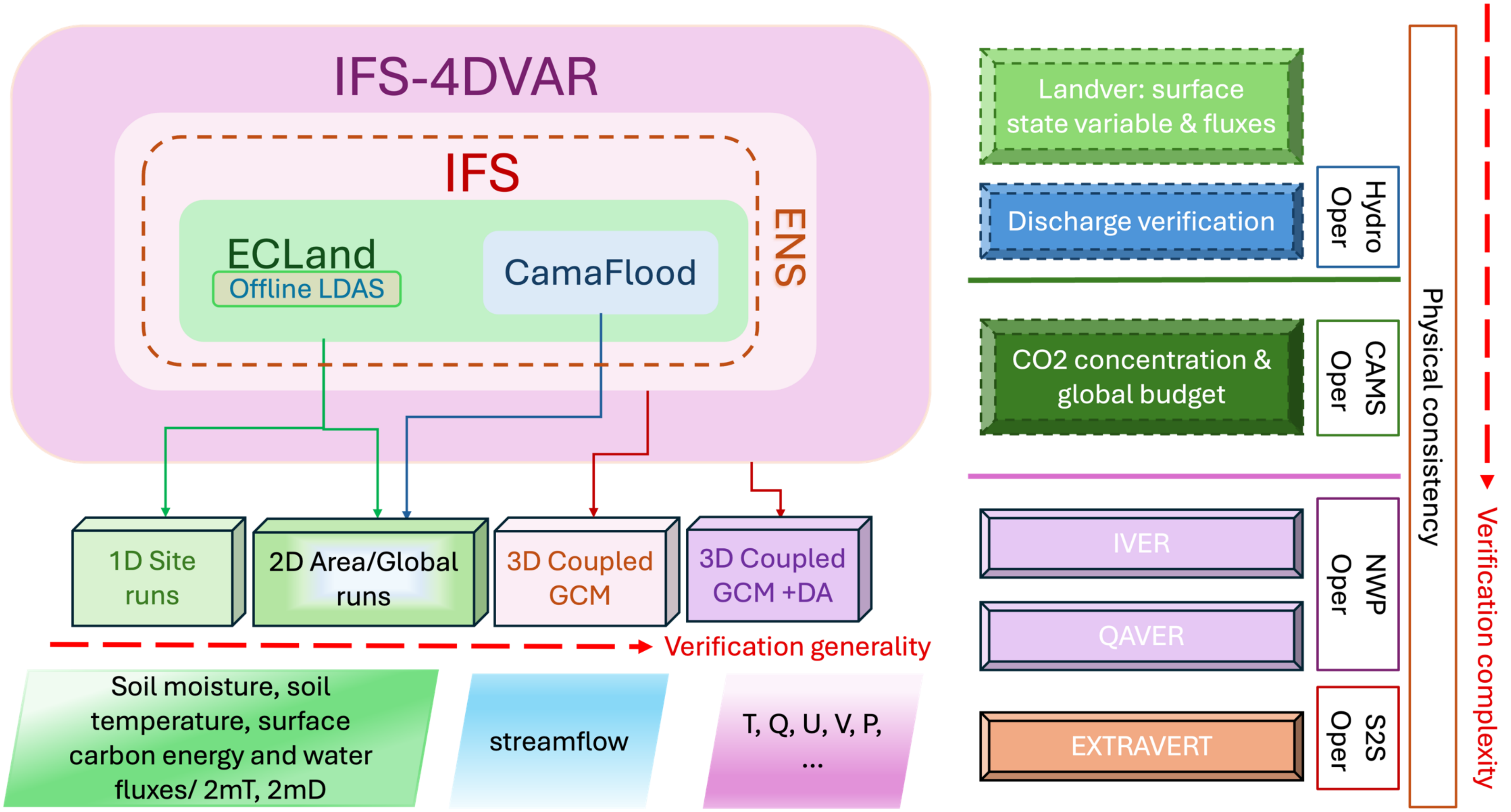
- More catchments show improvements, in particular over Rockies and mid-latitude Eurasia
- Many catchments in cold climates show lower skills (permafrost regions)
- In permafrost areas, excess of water infiltrating into the soil amplifies river discharge biases. Main causes:
  - warmer soil temperature in snowML
  - Frozen soil thawing for sub-zero temperatures

Zsoter et al. 2022

Strategy for surface model development at ECMWF (applied)

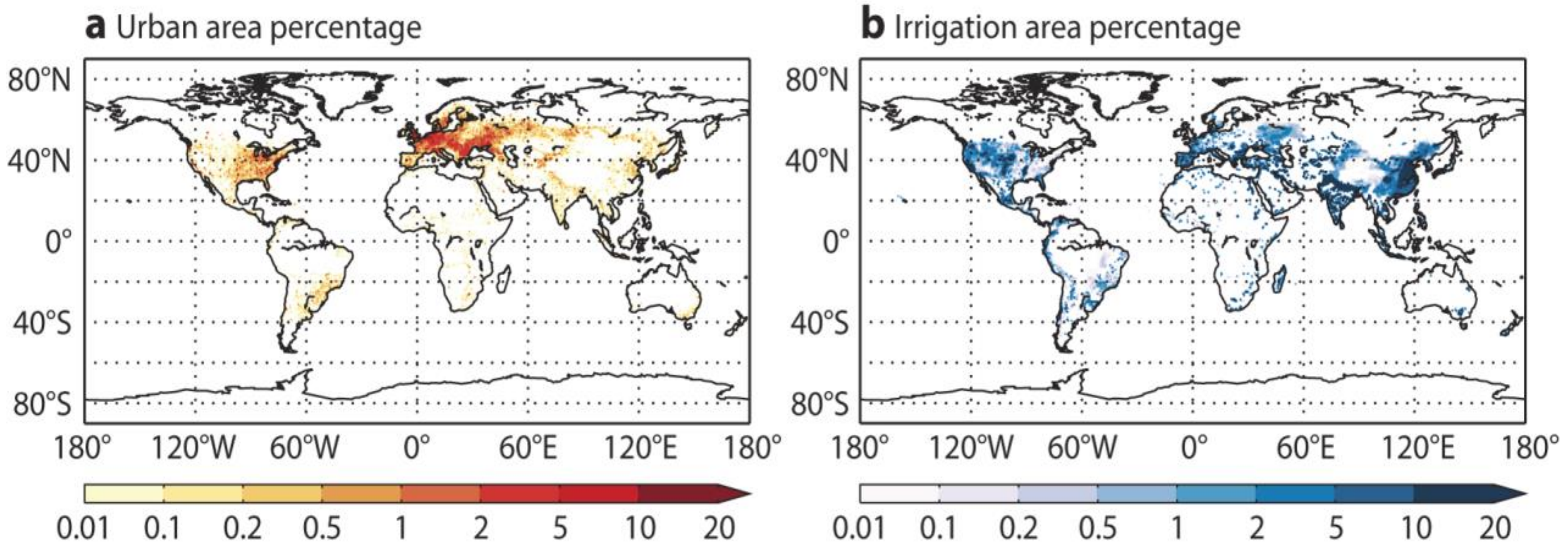


Strategy for surface model development at ECMWF (applied 2)



Missing surface components: An example

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

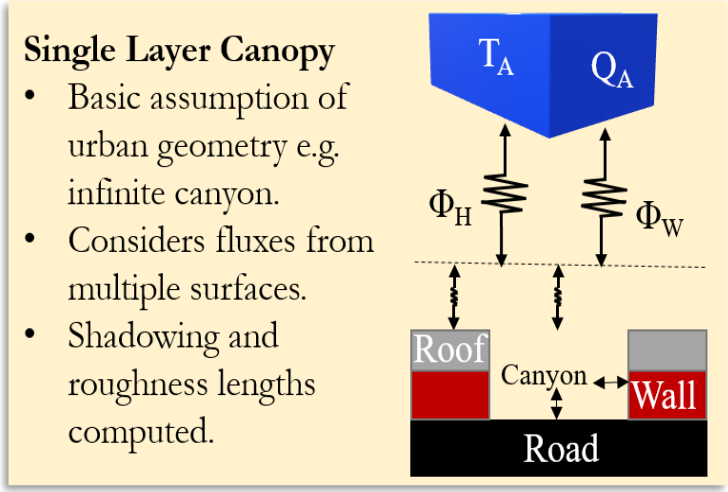


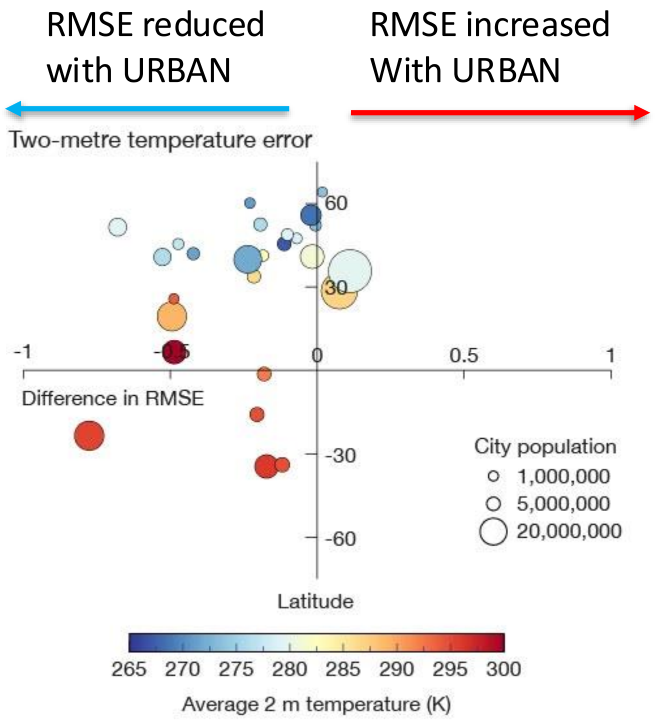
- Urban area (a, in %, from ECOCLIMAP, Masson et al., 2003) ←Operational in 2024
- Irrigated area (b, in %, from Döll and Siebert, 2002)
- Also water bodies are changing over time
- Glacier mass dynamics is missing

ECMWF

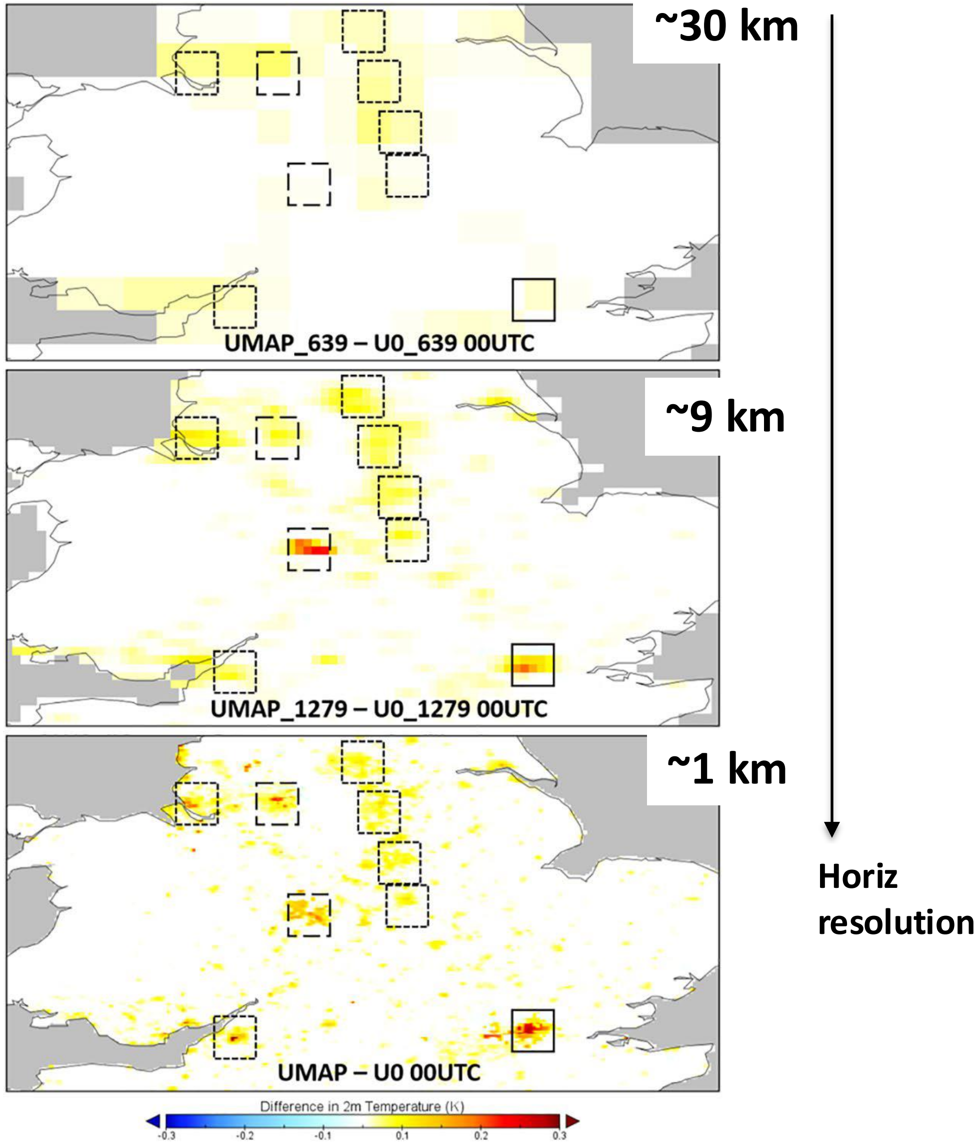
Increase in horizontal resolution calls for more complexity at the surface

- As horizontal resolution of forecast model increases, urban environments get more and more resolved.
- Urban heat island effects can affect temperature by several Celsius
- A urban module and dedicated tile under testing for future IFS cycles





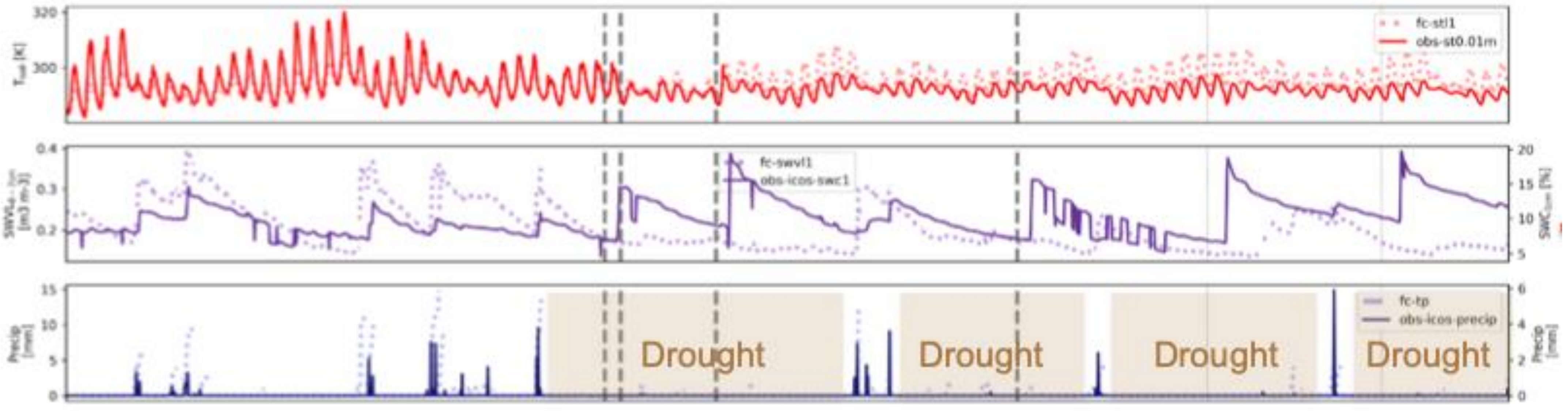
2-metre temperature difference between two simulation with and without an urban scheme



Thanks Joe McNorton

Missing surface components: An example for irrigation

Soil temperature, Soil moisture and precipitation for an irrigated site in Germany.
Observations compared to forecasts.



- Irrigation increases soil moisture, with a direct impact on temperature (and plant growth)
- Operationally, this is currently accounted for by the soil moisture data assimilation scheme

Thanks to Florentine Weber

ECMWF

Emulation of the Land Surface

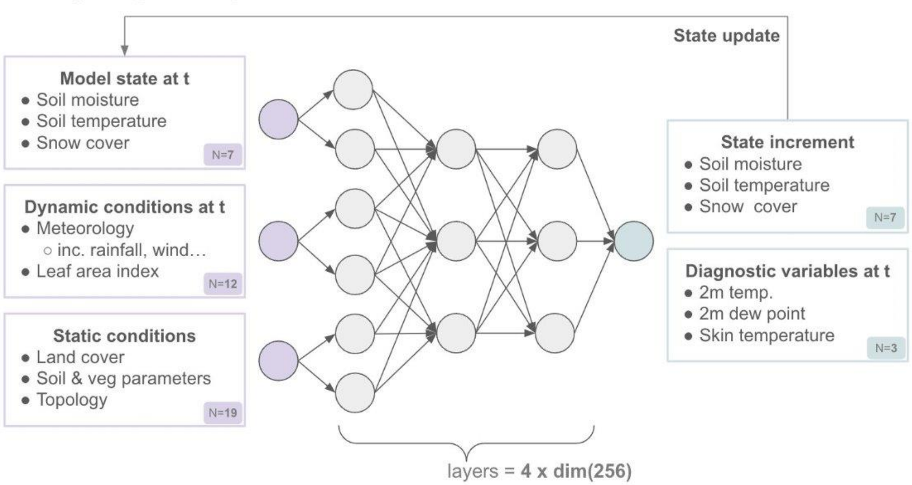
ML has already successfully been used to emulate different parts of the land surface at ECMWF

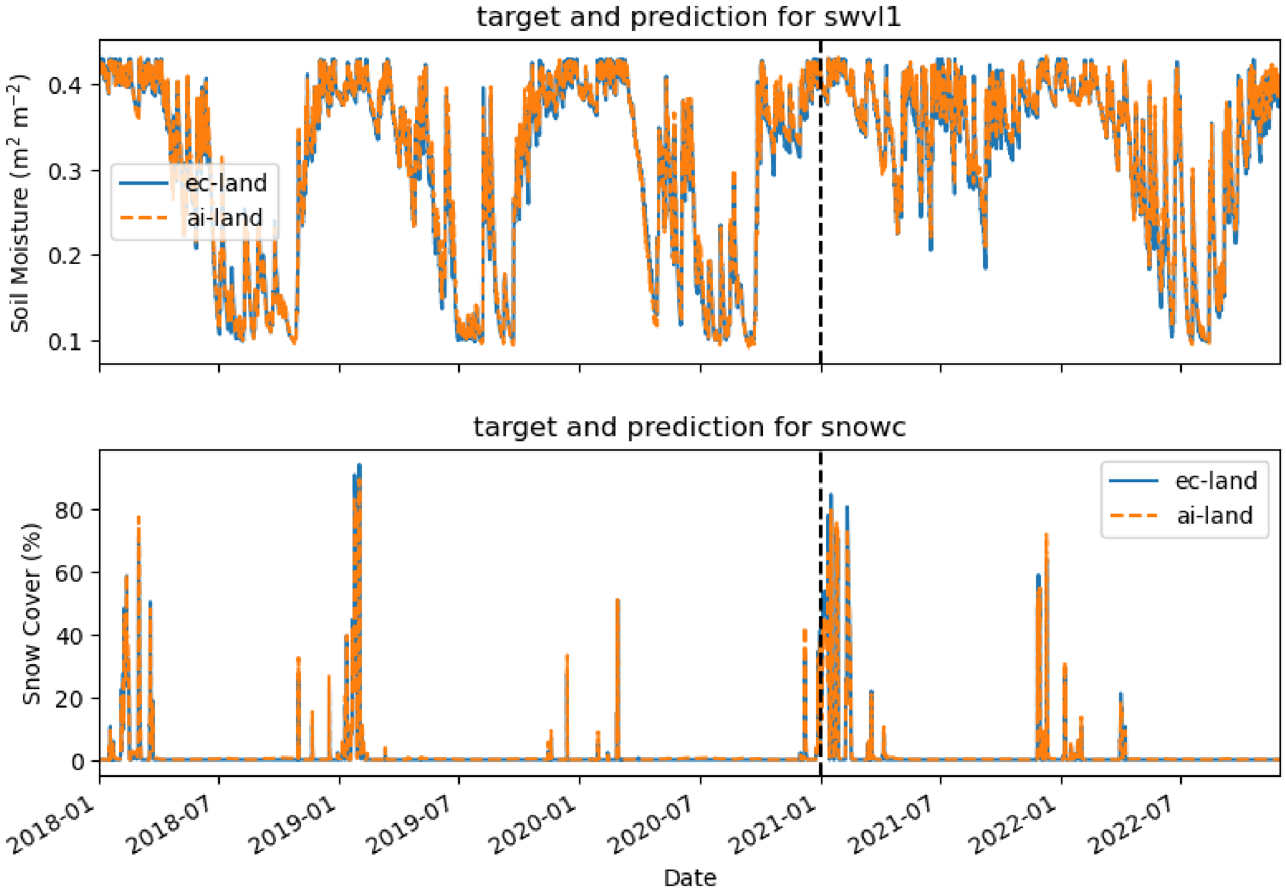
ecLand	Land & hydrology variables in the AIFS	EFAS/LISFLOOD	Probability of Fire	Orography parameters
Multilayer perceptron	Graph neural network encoder + decoder Transformer processor	Long-Short Term Memory	XGBoost	Gaussian process

Thanks to N. Raoult and E. Pinnington

Emulating the land surface: aiLand

- Standalone land emulator trained taking atmospheric forcing
- Simple column model MLP, stable for multiple year rollouts
- Will be used in Land Data Assimilation and Parameter Estimation routines to improve the physical model
- Looking into coupling strategies with the other Earth System components



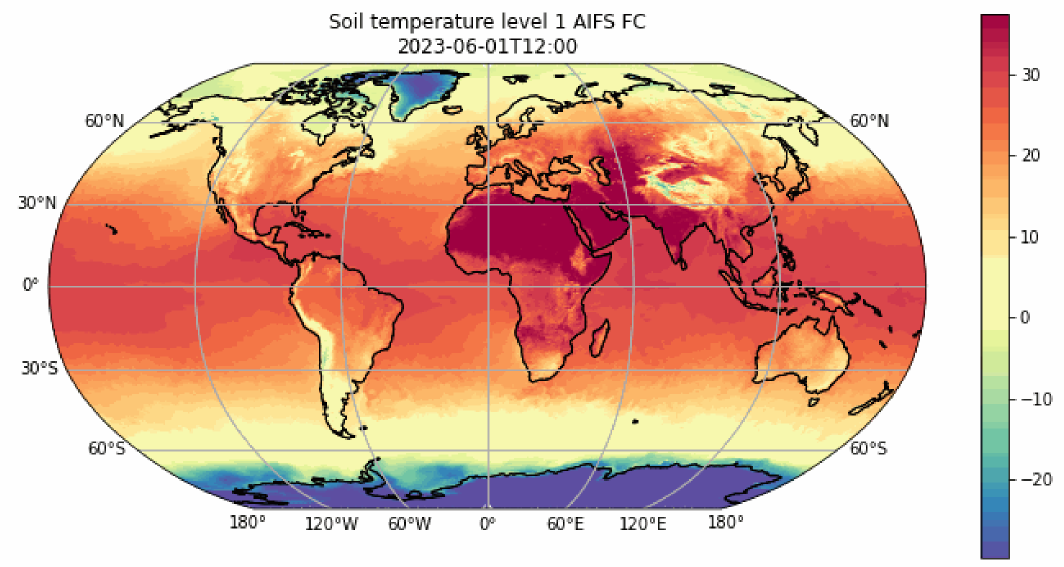


Thanks to N. Raoult and E. Pinnington

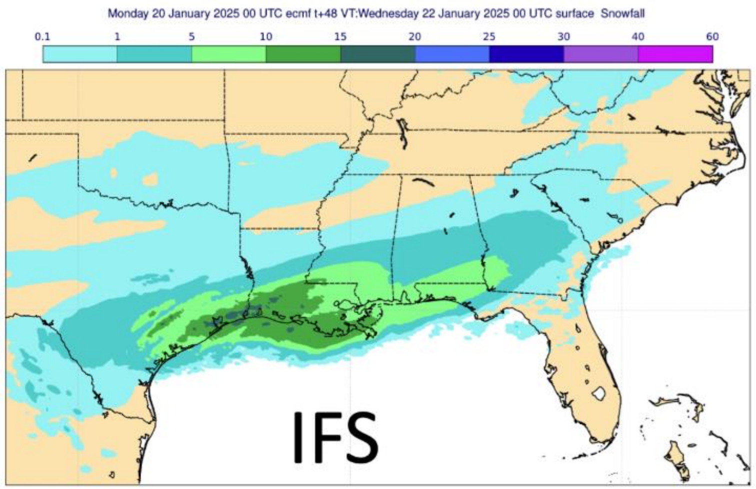
Emulating the land surface: AIFS v1

- Variables of **soil moisture, soil temperature, runoff, solar radiations, cloud covers, 100m winds, snow fall** have been directly trained as part of the newly operational AIFS v1

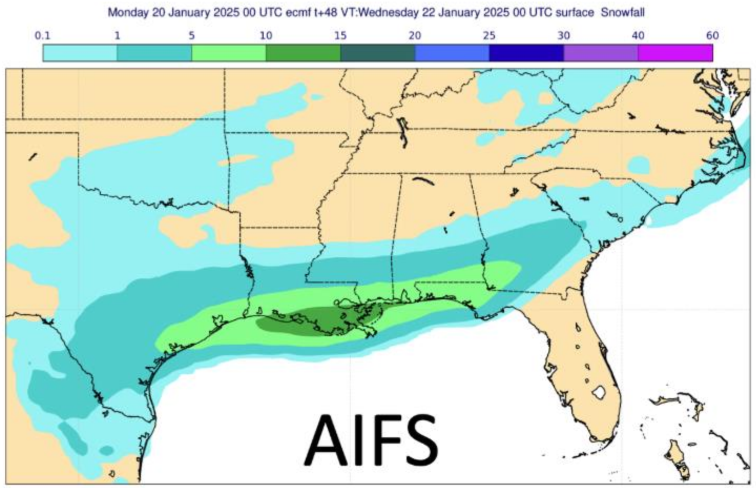
- Rare snow event capture in the ML model, even though it was out of sample



Pinnington



24h snowfall; T+24-48h
VT: 21 January 2025



Rare snow along the Gulf Coast

"AIFS snowfall forecast looks consistent with the IFS snowfall forecasts globally and for this specific snow event near the Gulf of Mexico."

22/01/2025 Weather report
Ivan & Linus

Thanks to N. Raoult and E. Pinnington

Perspectives

- Efforts to improve diurnal and seasonal cycles of surface state variables has transferred into weather and climate improvements and this 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.
- Foreseen benefits from using ML (and hybrid system) for surface modeling in different aspects (from parameters estimation and uncertainty quantification to process emulation)

ECMWF surface model milestones

Vegetation based evaporation	1989
ML-soil (4 layers + …)	1993 / ERA15
Initial conditions for soil water	1994
Stable BL/soil water freezing	1996
Albedo of snow forests	1996
OI increments of soil water	1999
TESSEL, new snow and sea ice	2000 / ERA40
HTESSEL, revised soil hydrology	2007
HTESSEL+SNOW, revised snow	2009
HTESSEL+SNOW+LAI, seasonal vegetation	2010
CHTESSEL (carbon-land surface)	2012
LAKETESSEL (addition of lake tile)	2015
SEAMLESS Coupling Ocean-Sea-Ice	2018
ecLand modelling platform.	2021
Multi-layer snow model	2023
Coupling with Cama Flood	2023
Urban parametrisation in IFS	2024