Parameterization of continental surfaces in coupled Earth System Modelling: Introduction

Which surface processes influence Earth System predictability?

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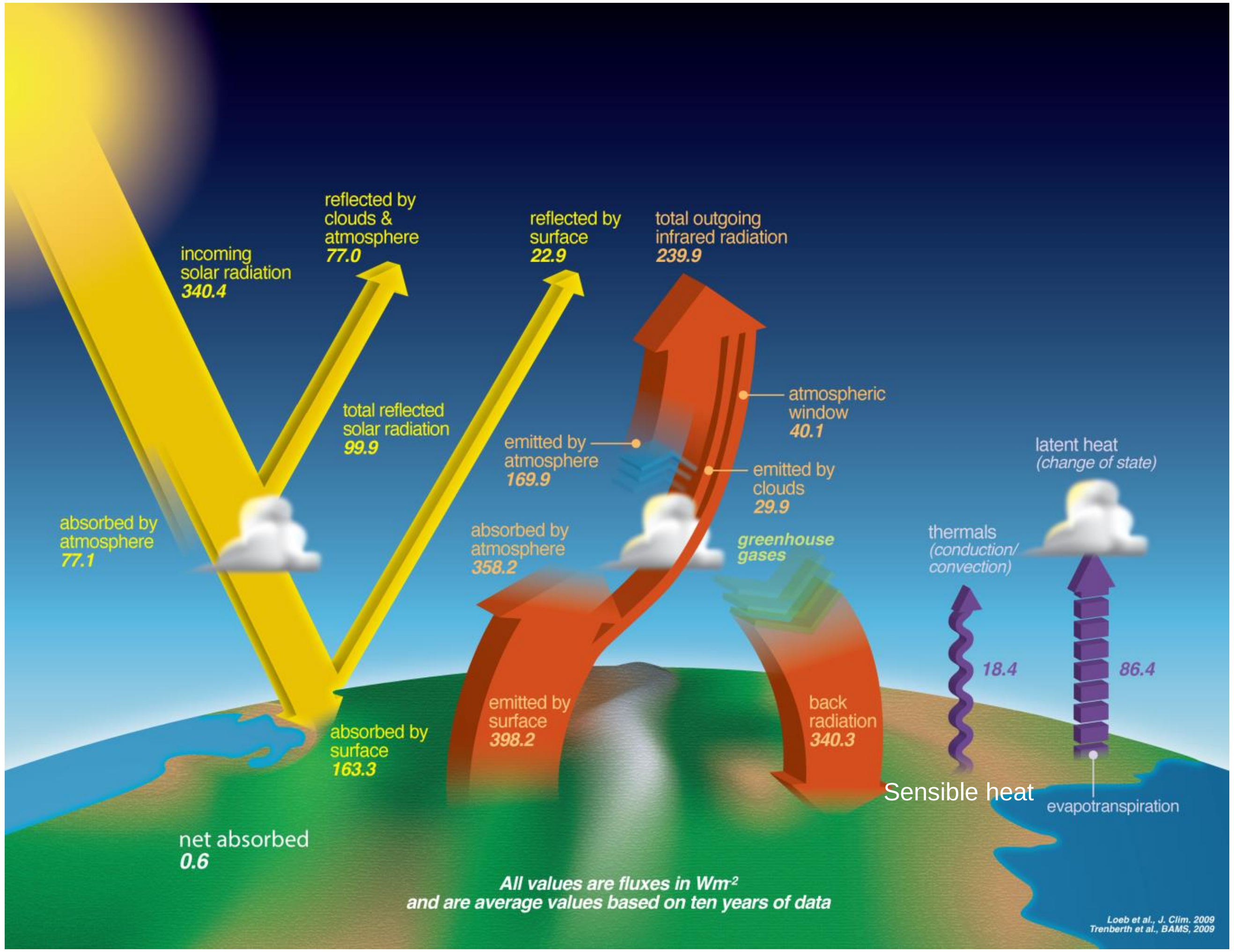
Outline

- 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)

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

Adapted from myNASA data: https://mynasadata.larc.nasa.gov/basic-page/earths-energy-budget

The land-surface in the earth global water cycle

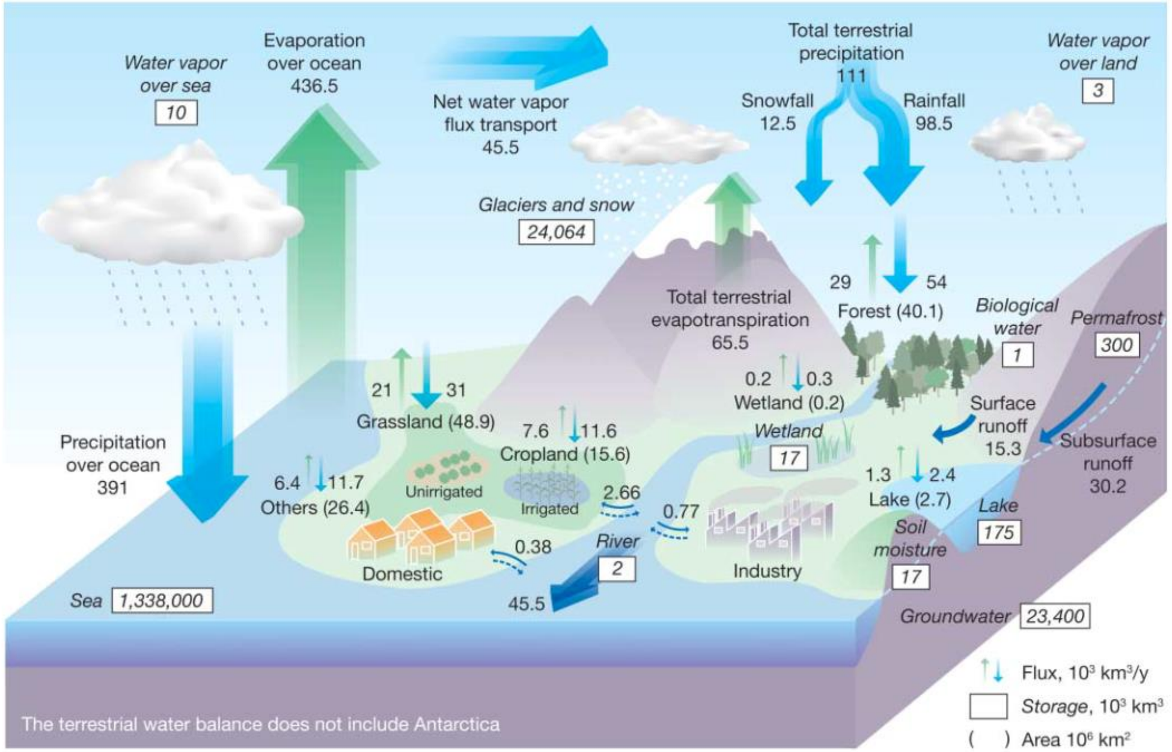


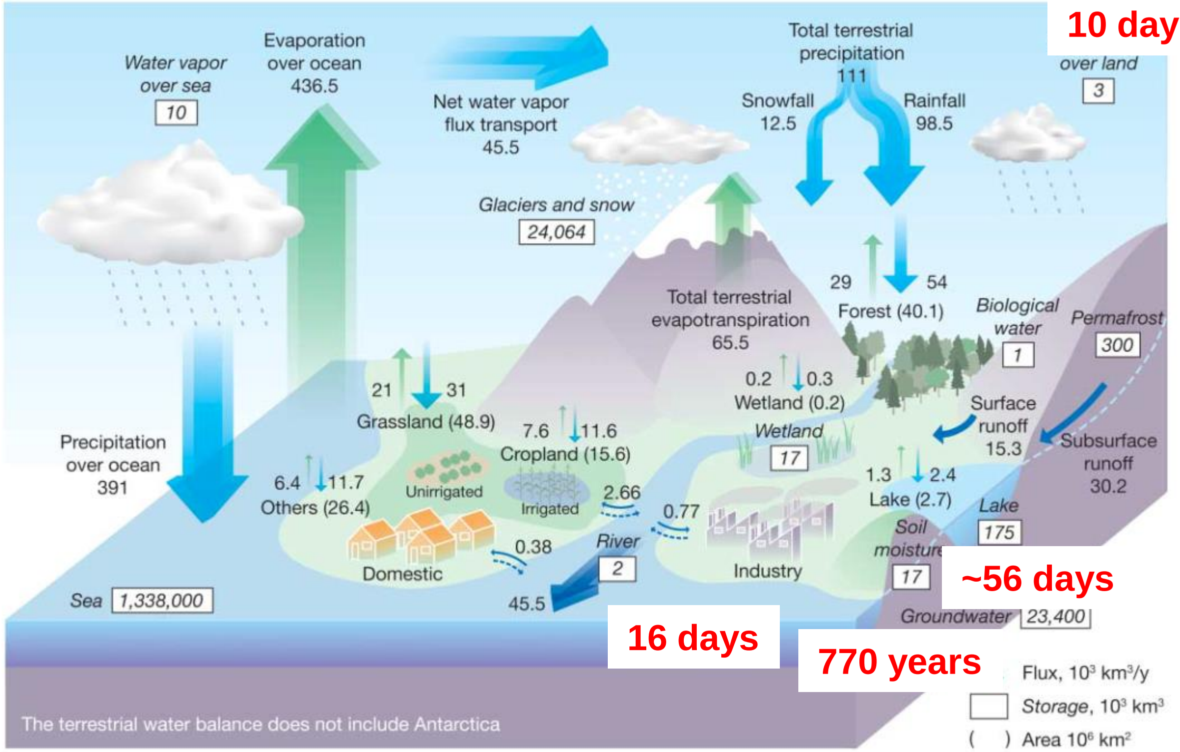
Fig. 1. Global hydrological fluxes (1000 km³/year) and storages (1000 km³) with natural and anthropogenic cycles are synthesized from various sources (*1*, *3–5*). Big vertical arrows show total annual precipitation and evapotranspiration over land and ocean (1000 km³/year), which include annual precipitation 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.

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

Total land precipitation:
60% evapotranspiration
40% runoff

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

Earth Global Water Cycle – Reservoirs and timescales



10 days

~56 days

16 days

770 years

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.

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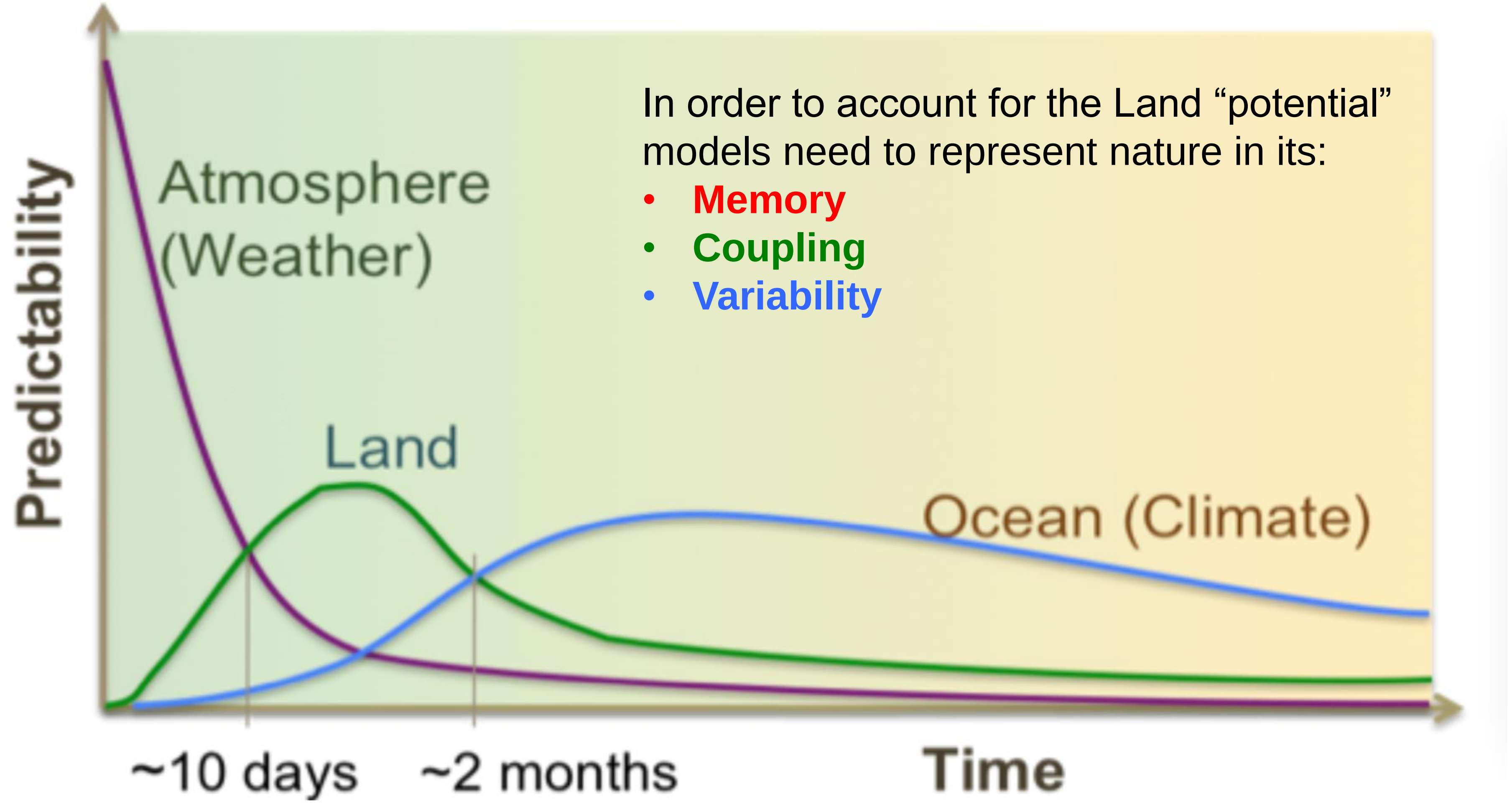
Total land precipitation:
60% evapotranspiration
40% runoff

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

88% via vegetation !

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

Earth surface role in medium-range and S2S



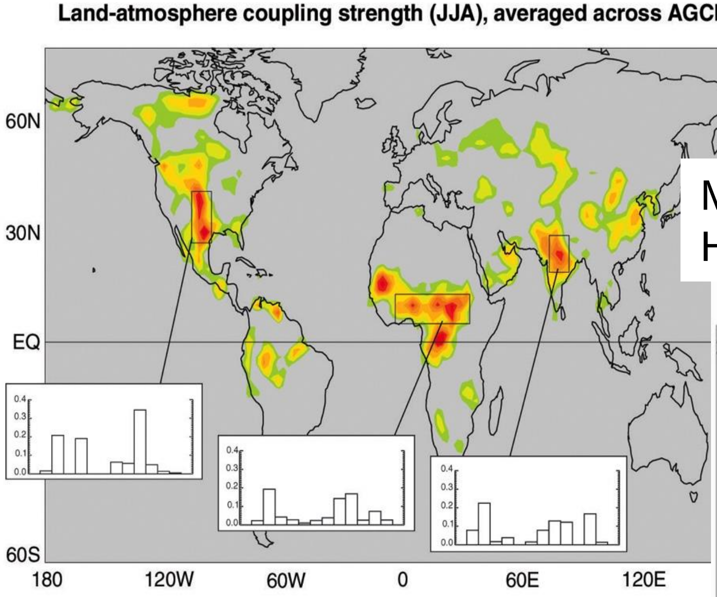
In order to account for the Land “potential” models need to represent nature in its:

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

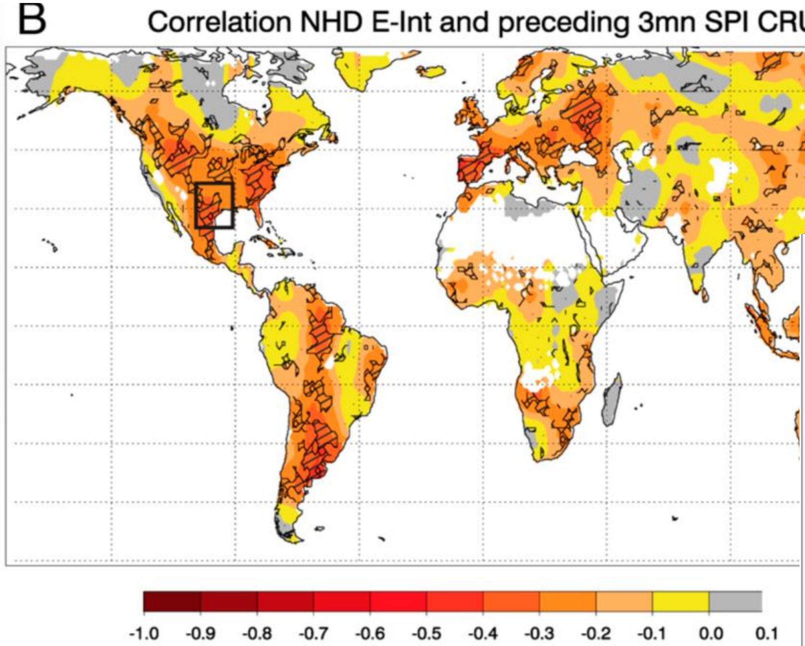
Dirmeyer et al. 2015: http://library.wmo.int/pmb_ged/wmo_1156_en.pdf

Earth surface role, experimental evidence (soil moisture)

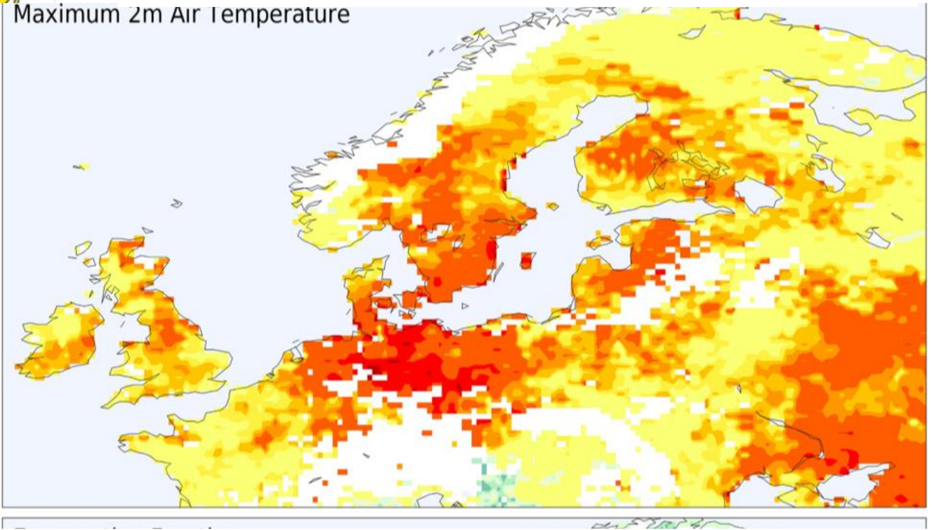
Koster et al. 2004 Science
Land-atmosphere coupling strength (SoilMoist-Precip feedback), JJA



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

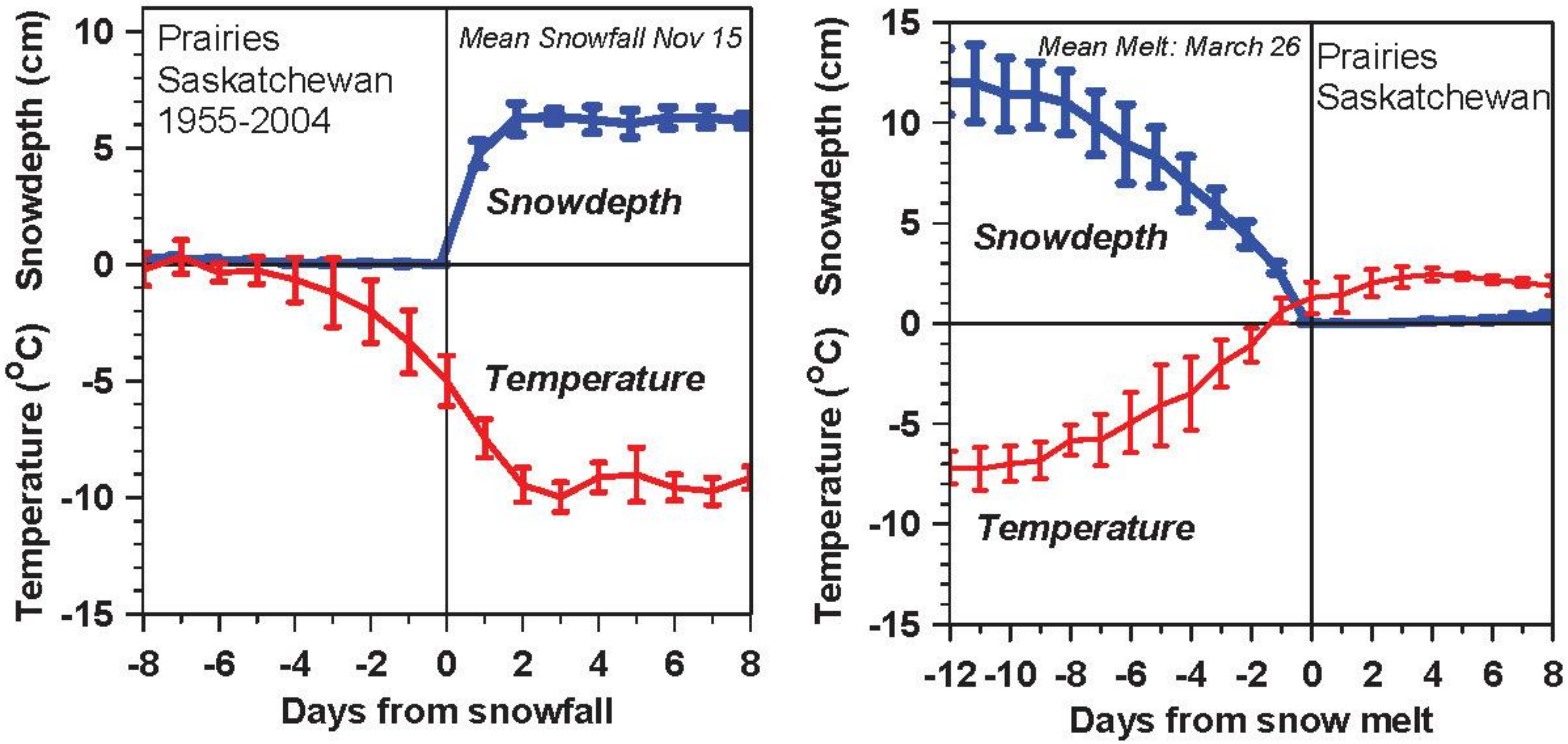


Dirmeyer et al. 2018
SM-Tmax coupling during North Europe heat wave in summer 2018



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

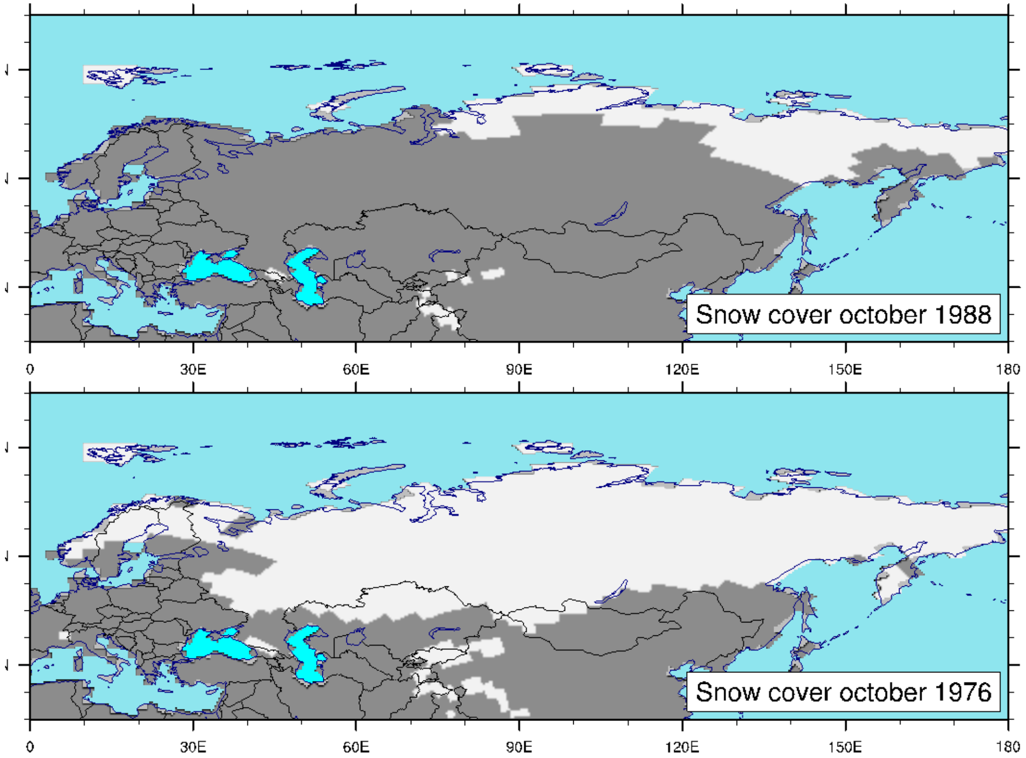
Local climate switch between warm and cold seasons

Winter comes fast with snow

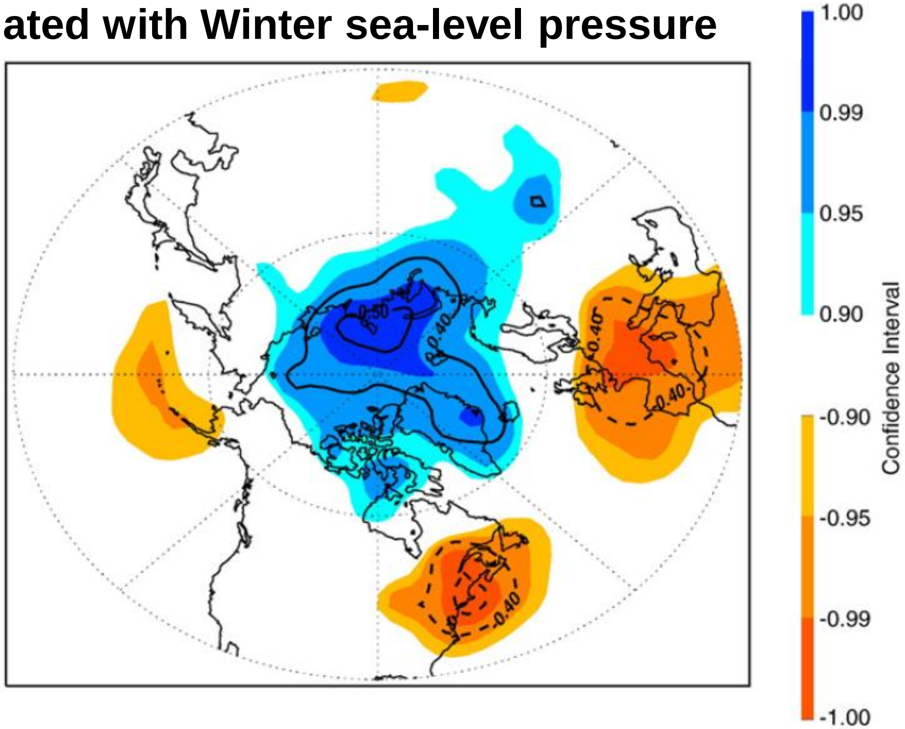
Betts et al. 2014

Earth surface role, snow cover variability

Snow cover shows large interannual variability



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



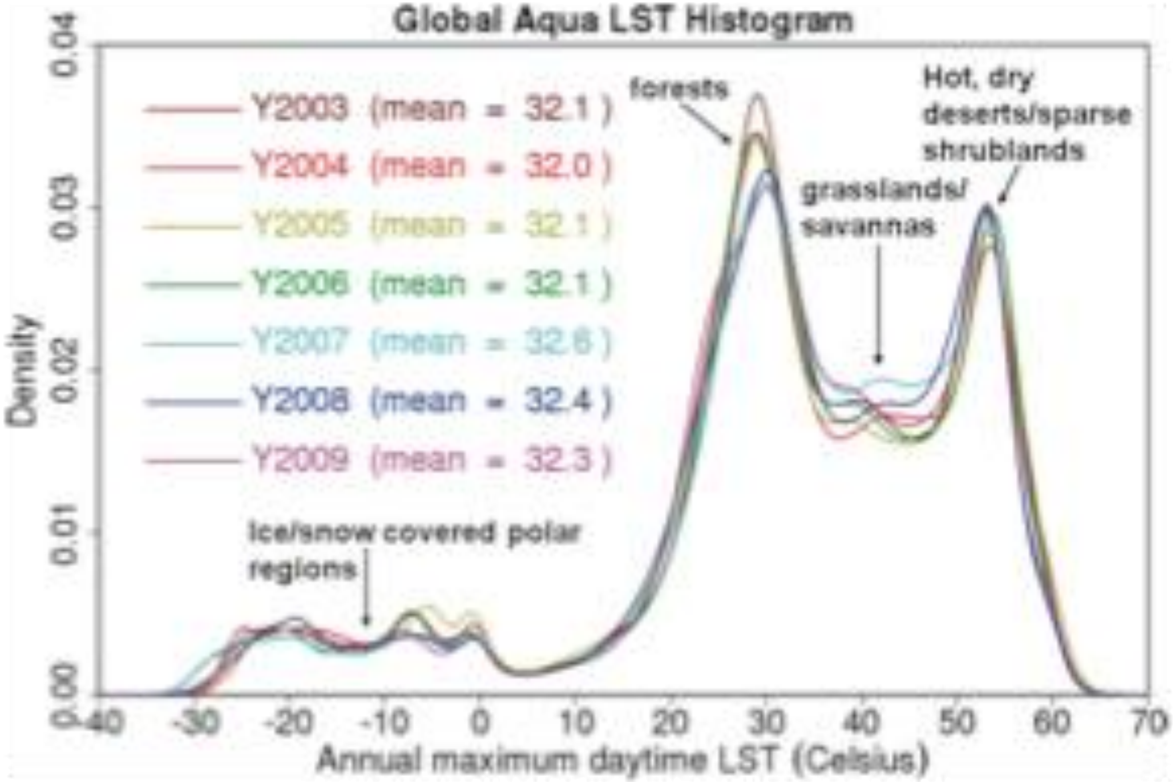
(Cohen and Saito 2003, Gong et al. 2007)

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

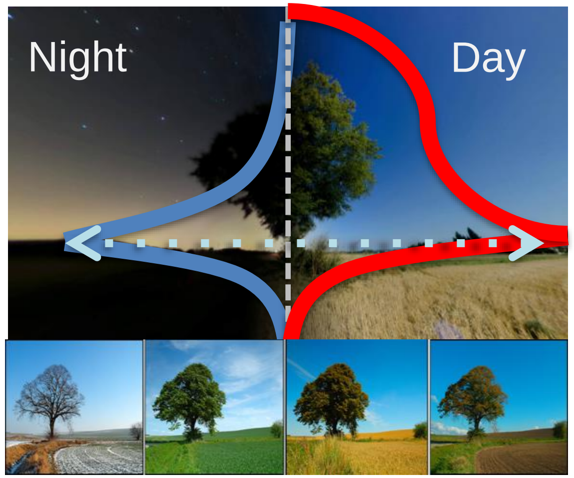
Histogram of maximum surface temperature from satellite captures the influence of land-cover types



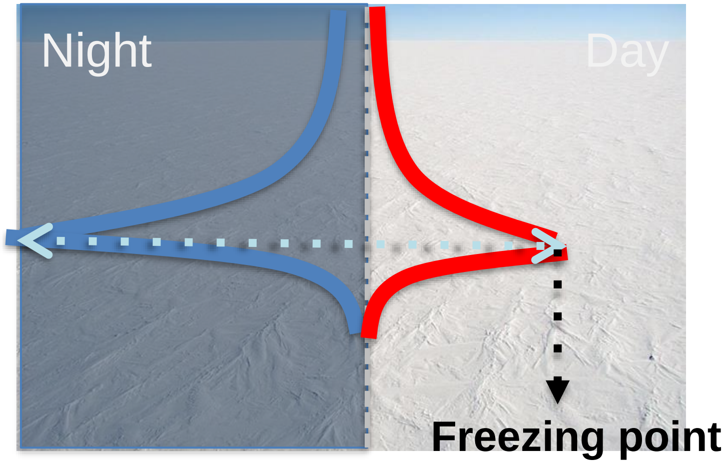
Modelling surface heterogeneity and coupling with the atmosphere

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

Idealised diurnal cycle of temperature over vegetated surfaces



Idealised diurnal cycle of temperature over snow/ice



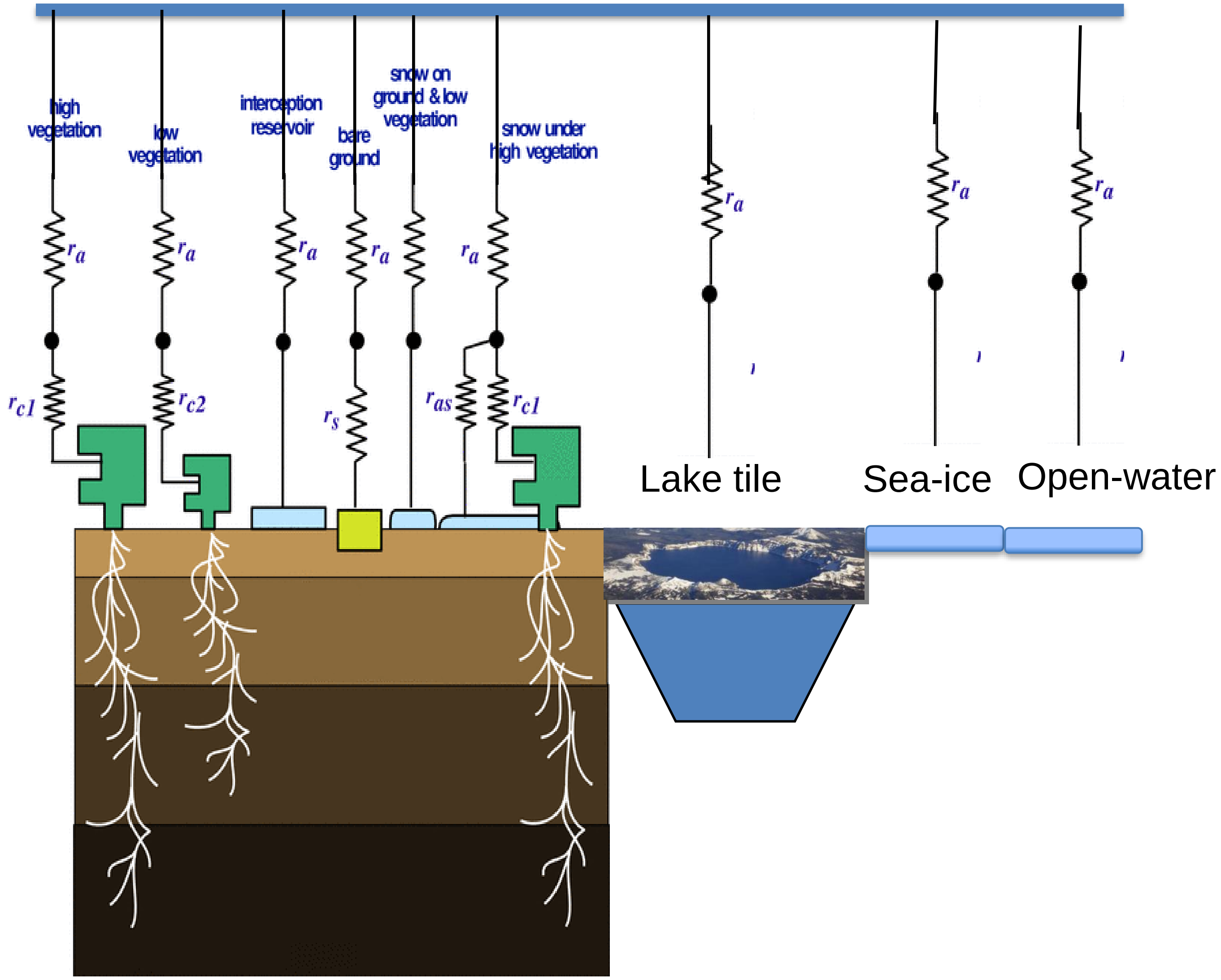
Freezing point (0 Celsius)

Idealised diurnal cycle of temperature over lake/water bodies

Spatial heterogeneity calls for high-resolution horizontal/vertical to represent the surface-atmosphere coupling

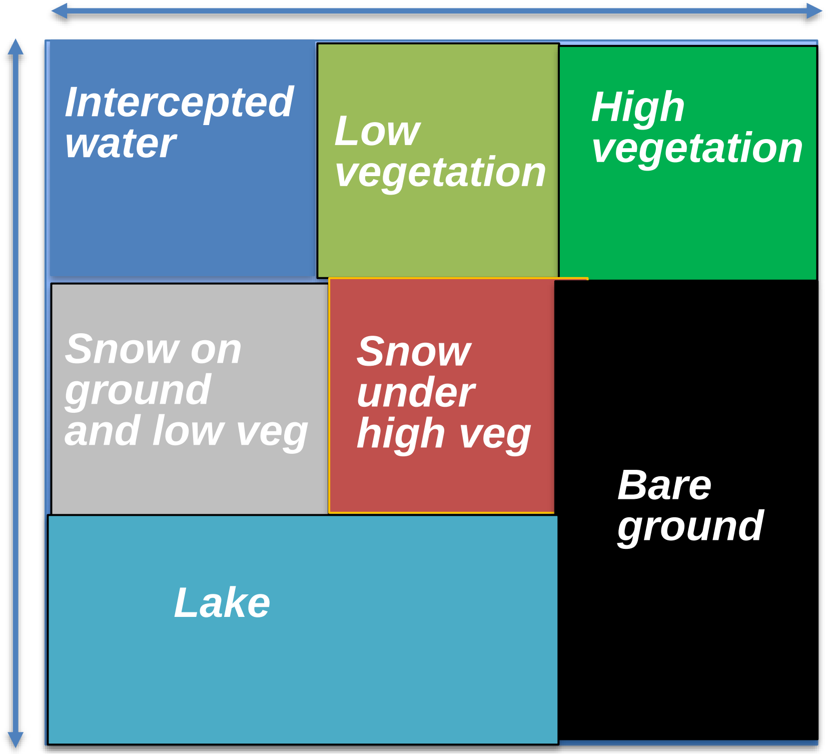
Modelling surface heterogeneity: ecLand tiling approach

Lowest atmospheric model level



- 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

Model grid-box over land


Intercepted water

Low vegetation

High vegetation

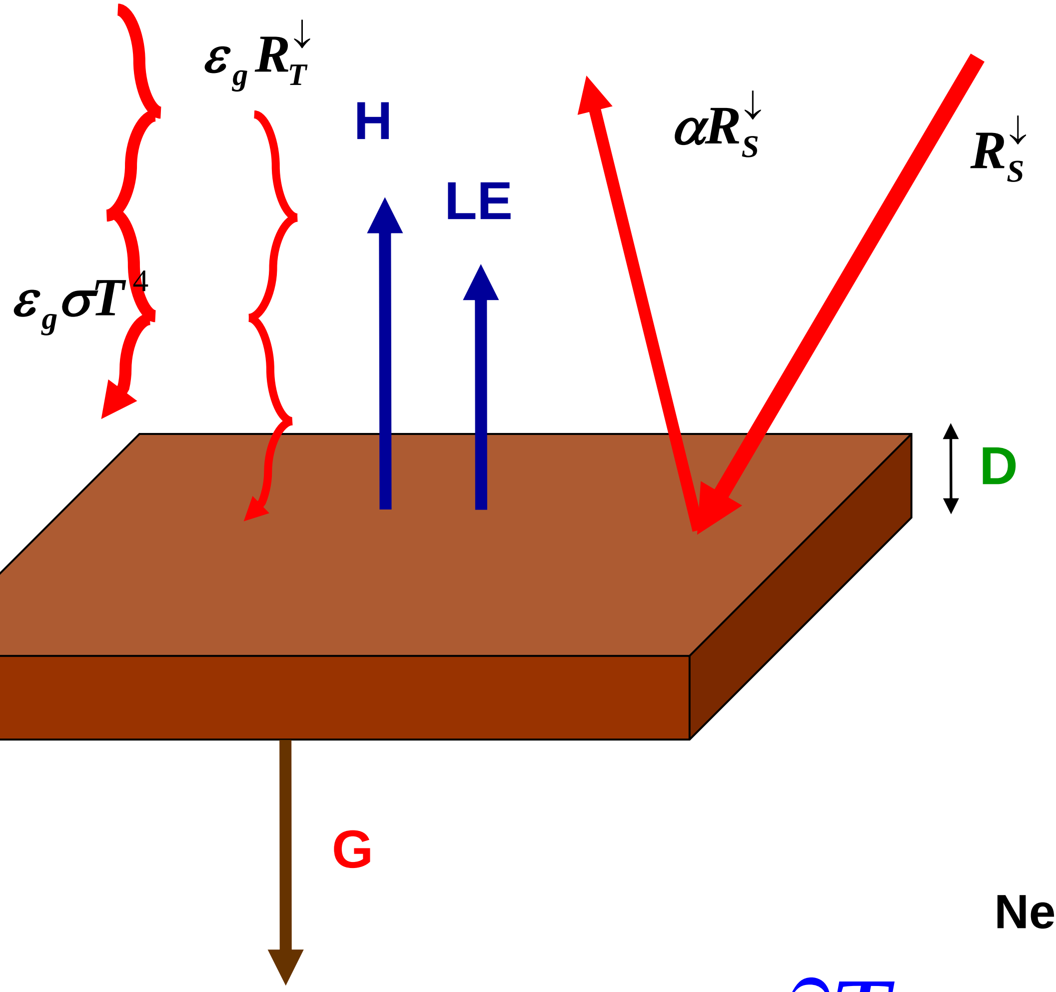
Snow on ground and low veg

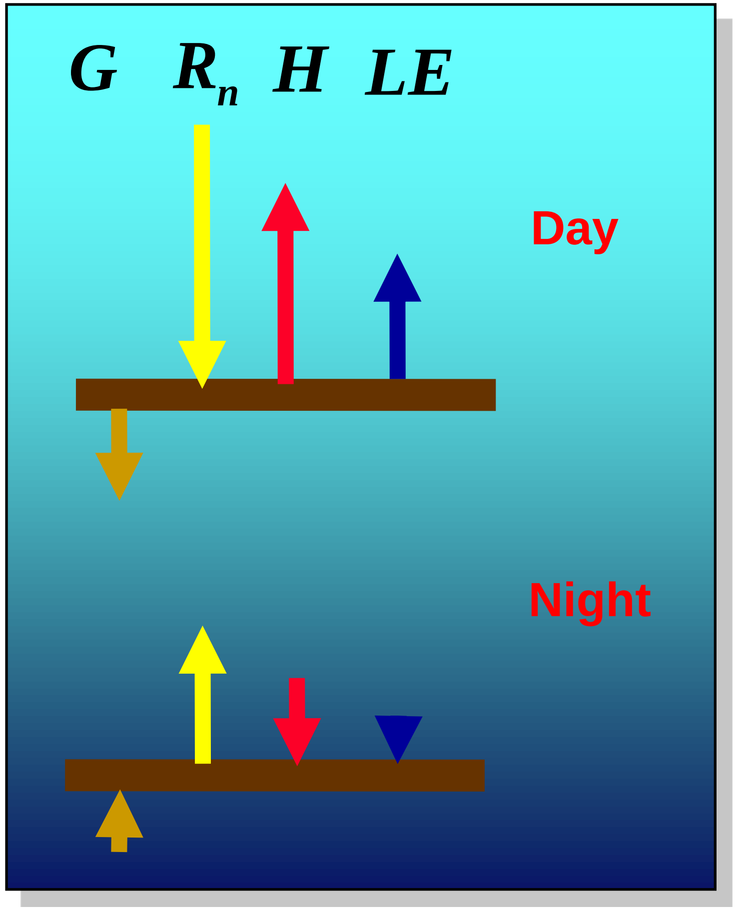
Snow under high veg

Bare ground

Lake

Schematic for the energy balance at the surface





Net radiation **Sensible heat** **Latent heat**

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

Conducted heat

HTESSEL 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!**

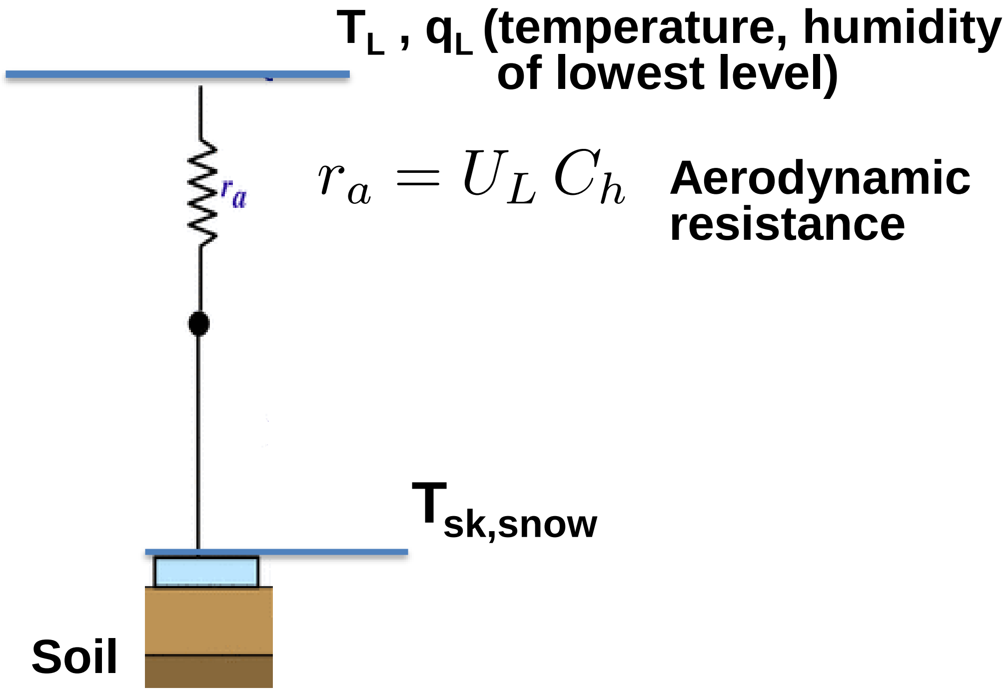
Grid-box quantities

$$\boldsymbol{H} = \sum_i \boldsymbol{C}_i \boldsymbol{H}_i$$

$$\boldsymbol{E} = \sum_i \boldsymbol{C}_i \boldsymbol{E}_i$$

$$\boldsymbol{T}_{sk} = \sum_i \boldsymbol{C}_i \boldsymbol{T}_{sk,i}$$

$\boldsymbol{C}_i$ Tile fraction



T_L , q_L (temperature, humidity of lowest level)

$r_a = U_L C_h$ **Aerodynamic resistance**

$T_{sk,snow}$

Soil

HTESSEL 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**

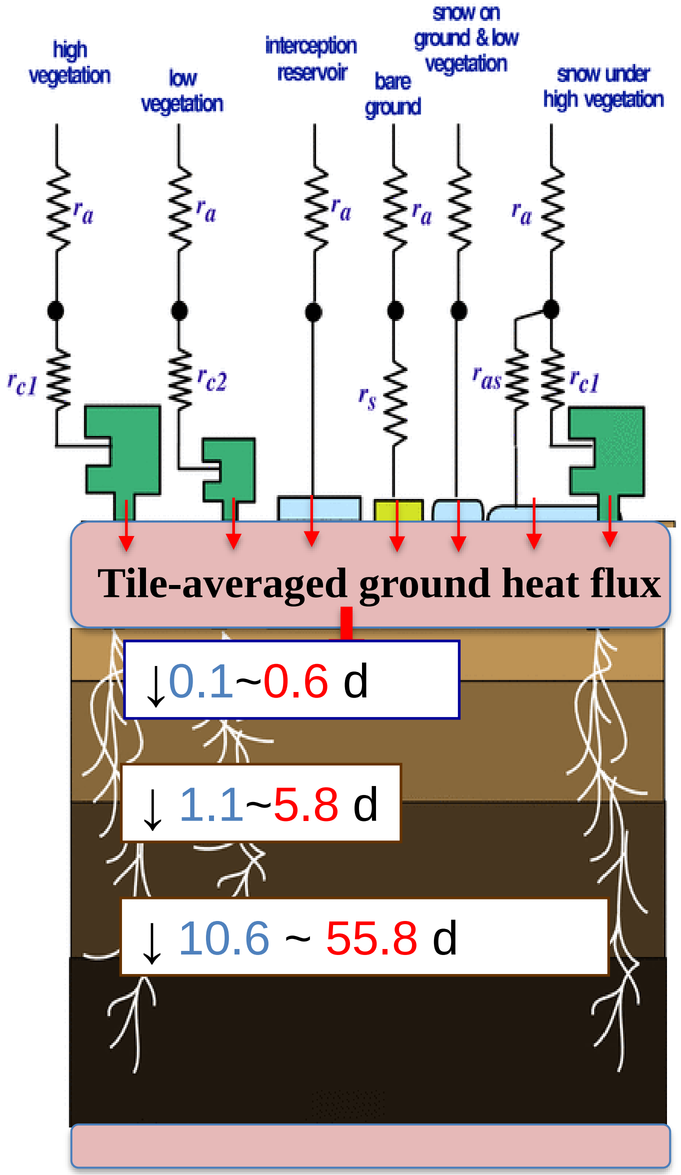
λ_T **Thermal conductivity**

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

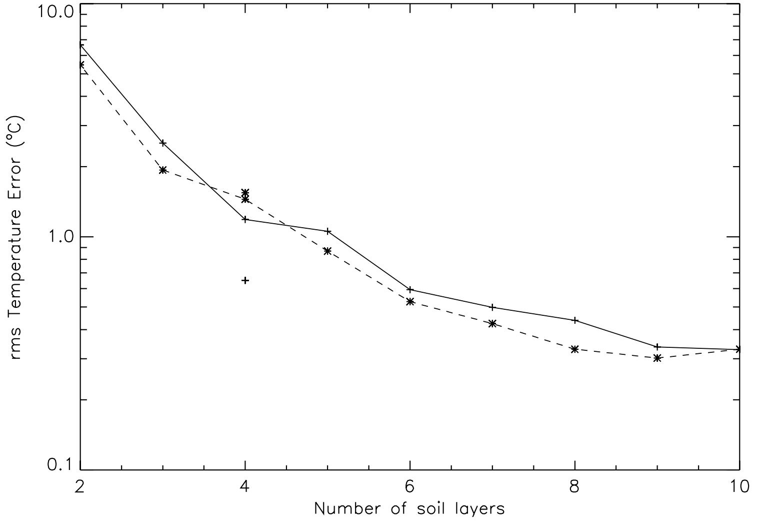


Time-scale for downward heat transfers in wet/dry soil

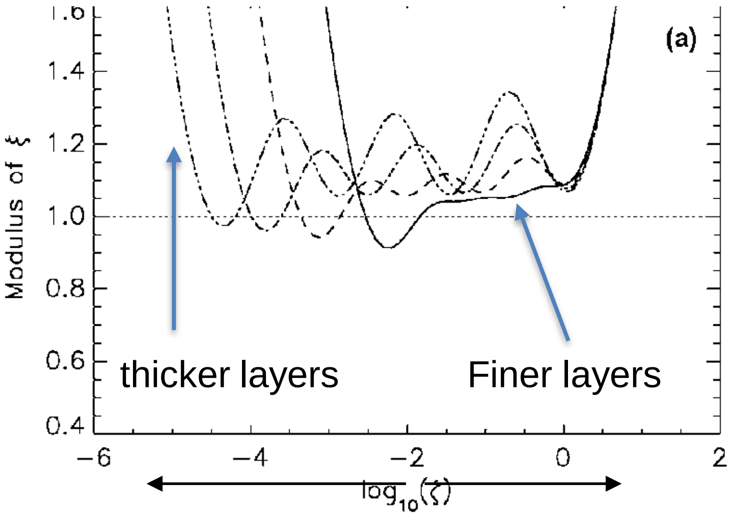
Heat transfer, considerations on vertical discretization

- The number of vertical layers, their spacing and total depth of the soil column have a direct on the skin (surface) temperature
- Top-layer responds to atmospheric forcing with sub-diurnal frequency
- No-flux boundary condition at the bottom requires a deep column to avoid heat “reflection”

Surface temperature errors as a function of the number of soil layer at a bare soil surface at Agassiz, Canada



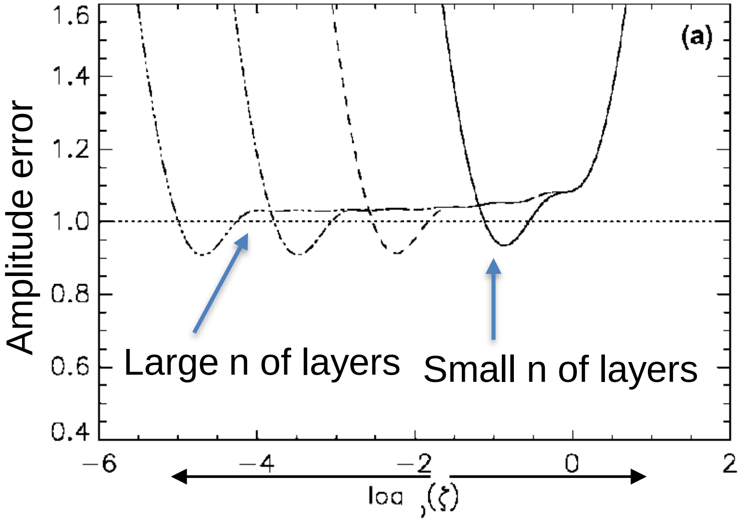
Amplitude error (Numerical wrt analytical solution) for different fixed layers but different layer thicknesses



Seasonal to yearly time-scales

Diurnal time-scales

Amplitude error (Numerical wrt analytical solution) For different number of layers and same layer thicknesses



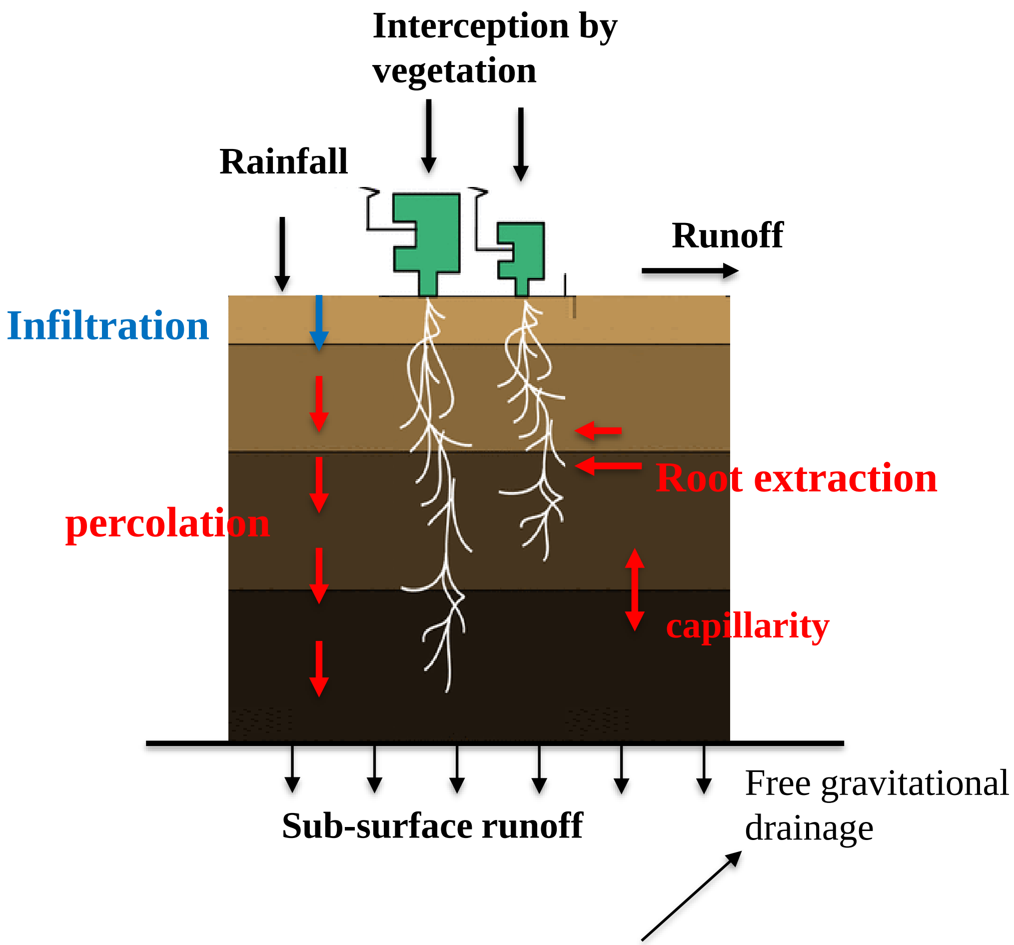
Seasonal to yearly time-scales

Diurnal time-scales

Best solution is to have a large number of layers, and deep column, and small layer vertical spacing

From Best et al. 2005 BLM

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/sink, 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

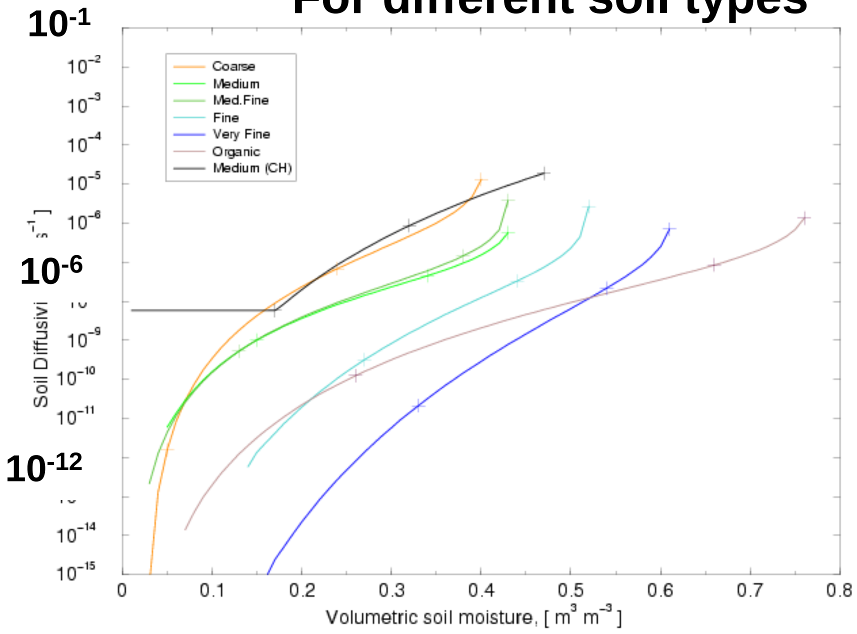
Soil water flux

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

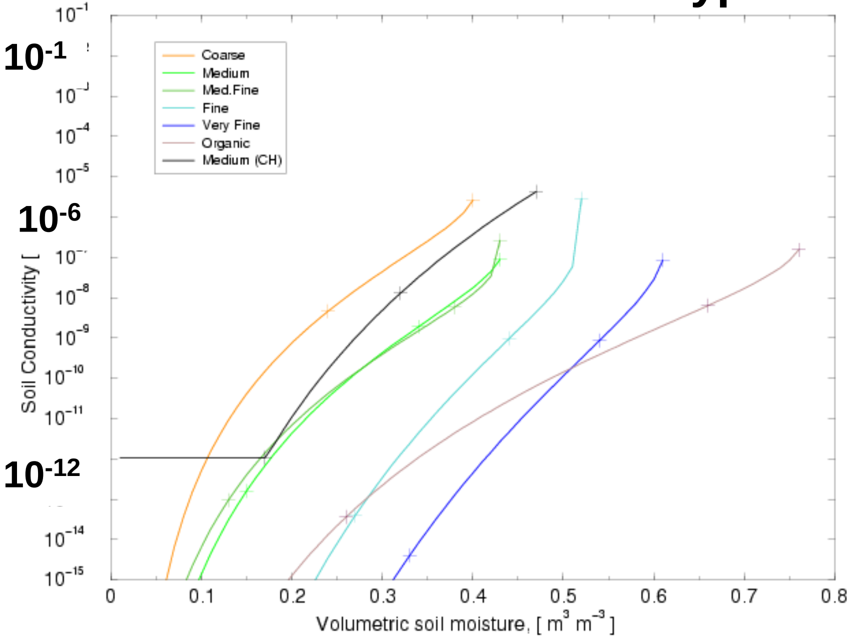
λ hydraulic diffusivity $[\lambda] = m^2 s^{-1}$

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

Hydraulic Diffusivity, For different soil types

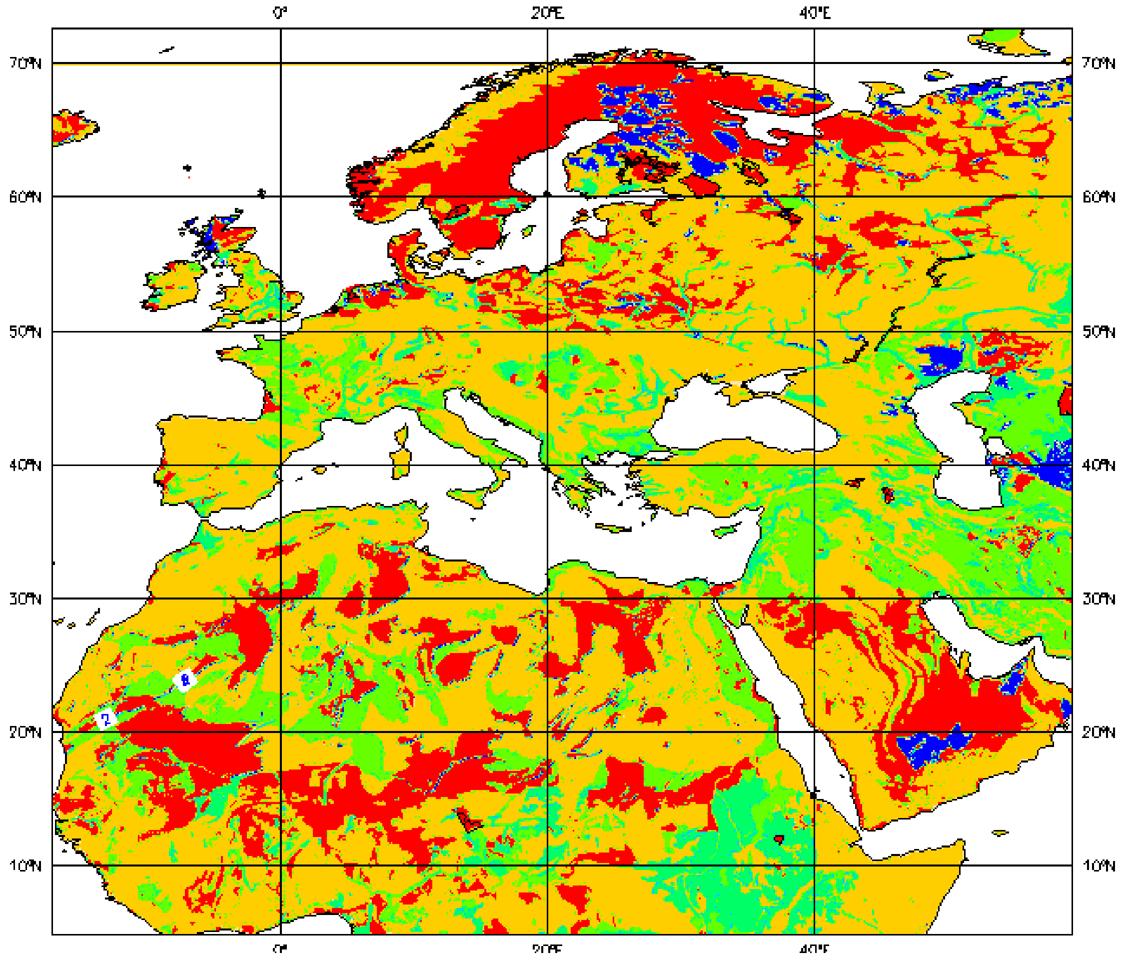


Hydraulic conductivity, for different soil types



HTESSEL hydrology scheme(1)

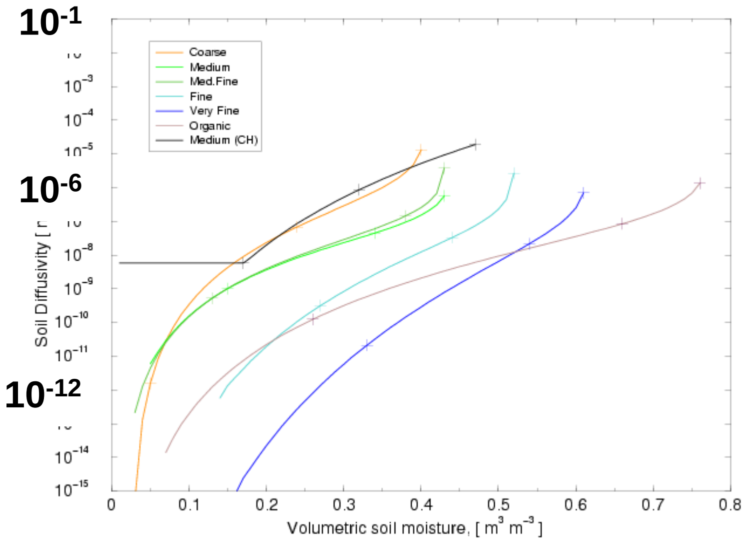
🟥 coarse 🟧 medium 🟩 med-fine 🟦 fine 🟦 very-fine 🟦 organic

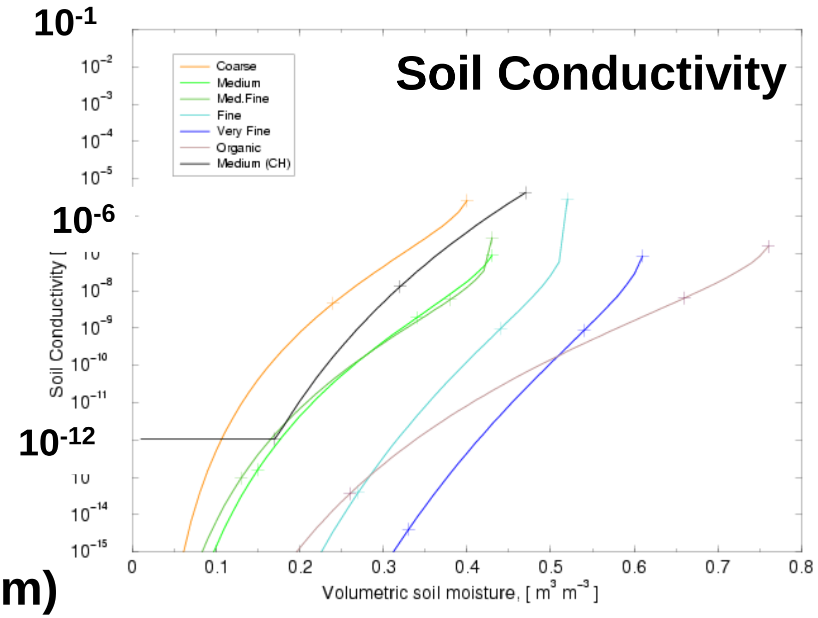


Dominant soil type from FAO2003 (at native resolution of ~ 10 km)

ECMWF

Soil Diffusivity





Soil Conductivity

HTESSEL hydrology scheme (2)

Hydrological scheme (infiltration, conductivity) based on Van Genuchten 1980

$$\gamma = \gamma_{\text{sat}} \frac{\left[(1+\alpha h^n)^{1-1/n} - \alpha h^{n-1}\right]^2}{(1+\alpha h^n)^{(1-1/n)\,(l+2)}},$$

Soil water conductivity

$$\theta(h) = \theta_r + \frac{\theta_{\text{sat}} - \theta_r}{(1+\alpha h)^{1-1/n}}.$$

Soil moisture – pressure head relationship

Table 1: Soil type specific Van Genuchten coefficients

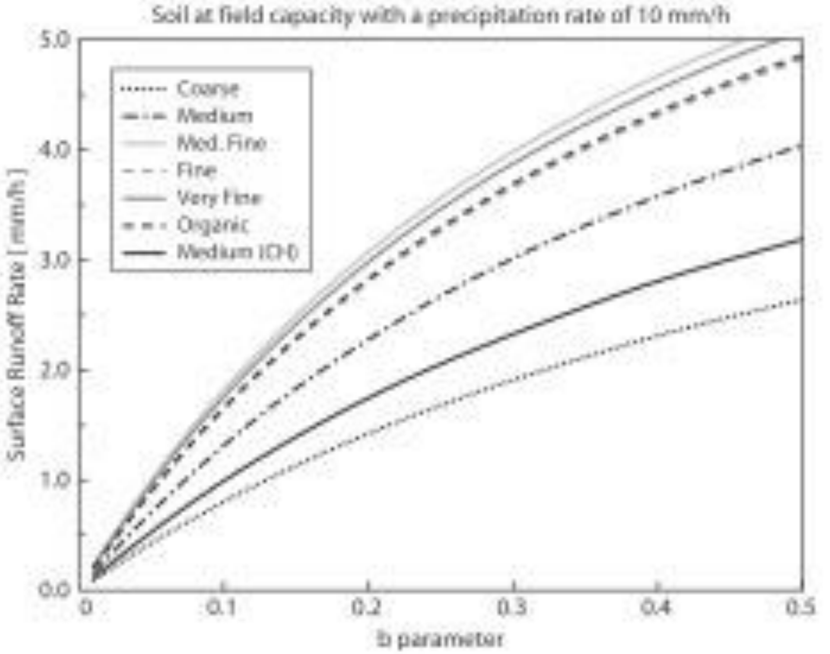
Parameter	Symbol	units	Texture class Coarse	Medium	Medium -fine	Fine	Very fine
Saturation soil moisture content	θ_{sat}	m^3/m^3	0.403	0.439	0.430	0.520	0.614
Residual soil moisture content	θ_r	m^3/m^3	0.025	0.010	0.010	0.010	0.010
Fit parameter	α	m^{-1}	3.83	3.14	0.83	3.67	2.65
Fit parameter	l	-	1.250	-2.342	-0.588	-1.977	2.500
Fit parameter	n	-	1.38	1.18	1.25	1.10	1.10
Saturated hydraulic conductivity	γ_{sat}	10^{-6}m/s	6.94	1.16	0.26	2.87	1.74

Surface runoff generation based on Dümenil and Todini 1992

$$\frac{s}{S} = 1 - \left(1 - \frac{W}{W_{\text{sat}}}\right)^b \qquad b = \frac{\sigma_{\text{or}} - \sigma_{\text{min}}}{\sigma_{\text{or}} + \sigma_{\text{max}}},$$

Fraction s of gridbox where runoff occurs

Standard deviation of orography



Van den Hurk and Viterbo 2003, Balsamo et al. 2009

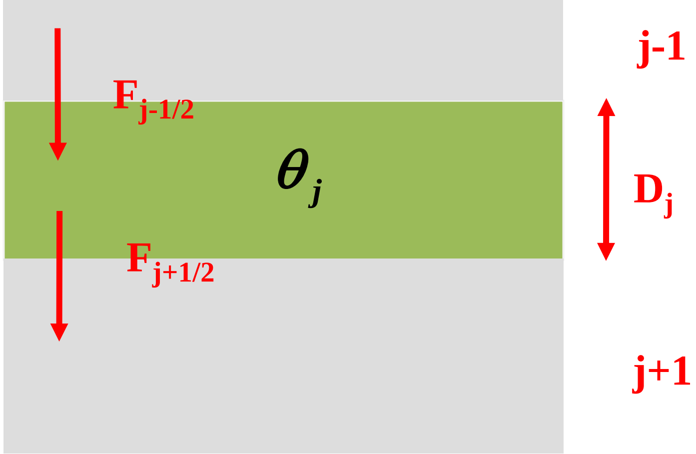
HTESSEL soil water equations, discretization

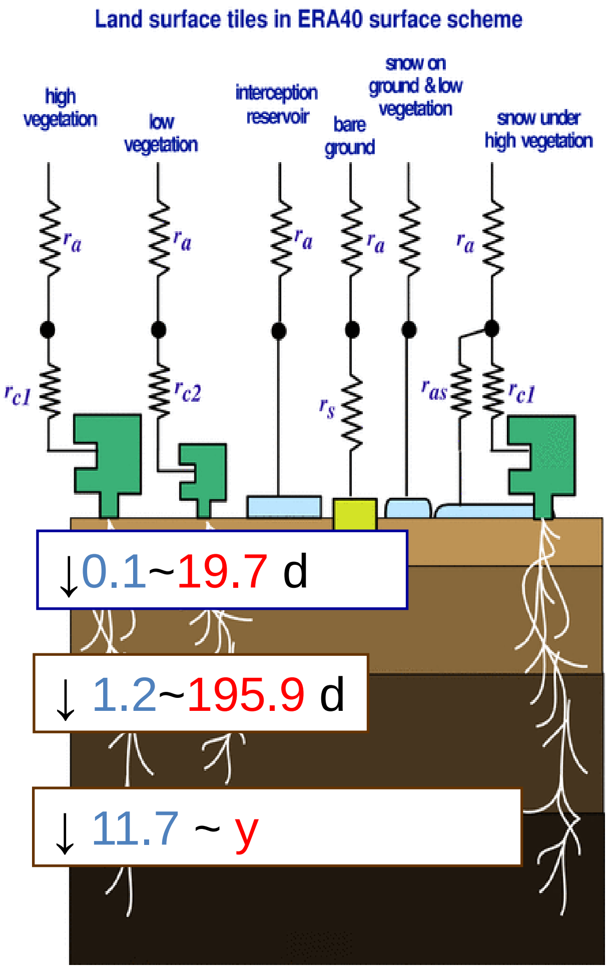
$$\rho_w \frac{\left(\theta_j^{n+1}-\theta_j^{n}\right)}{\Delta t} = -\frac{\left(F_{j+1/2}^{n+1}-F_{j-1/2}^{n+1}\right)}{D_j} + \rho_w S_{\theta,j}$$

$$F_{j+1/2}^{n+1} = -\rho_w\left(\lambda_{j+1/2}\frac{\theta_{j+1}^{n+1}-\theta_j^{n+1}}{0.5\left(D_j+D_{j+1}\right)} - \gamma_{j+1/2}\right)$$

Boundary conditions

$$F_{1/2} = T - Y_s + E_{1/2} \qquad F_{41/2} = \rho_w \gamma_{41/2}$$





↓0.1~19.7 d

↓ 1.2~195.9 d

↓ 11.7 ~ y

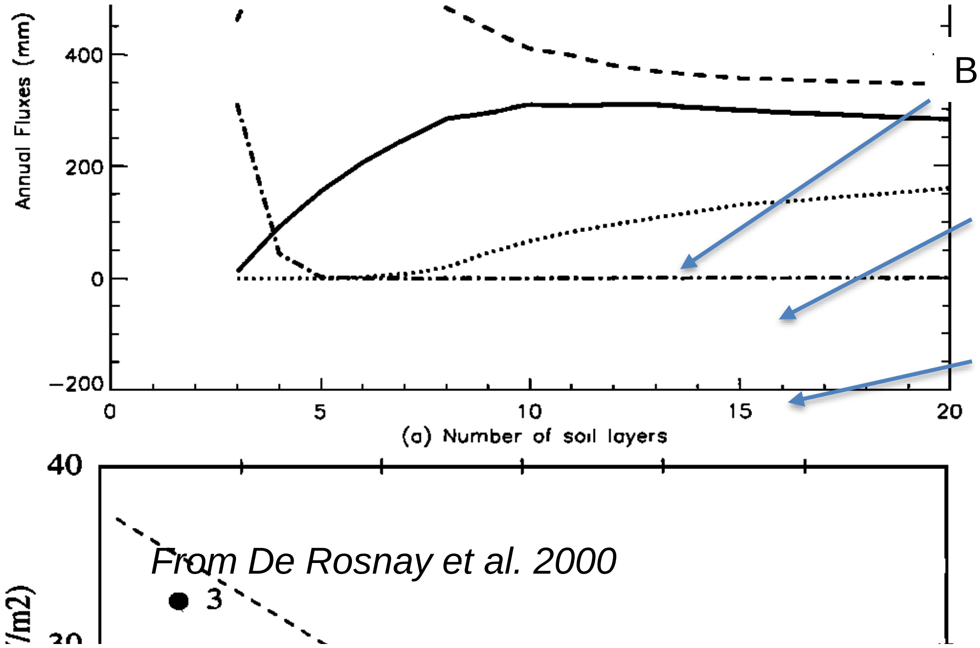
Time-scale for downward water transfers in wet/dry soil

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

Annual water balance components as a function of vertical layers (resolution of top layers increasing with number of layers)



Bare soil evapo

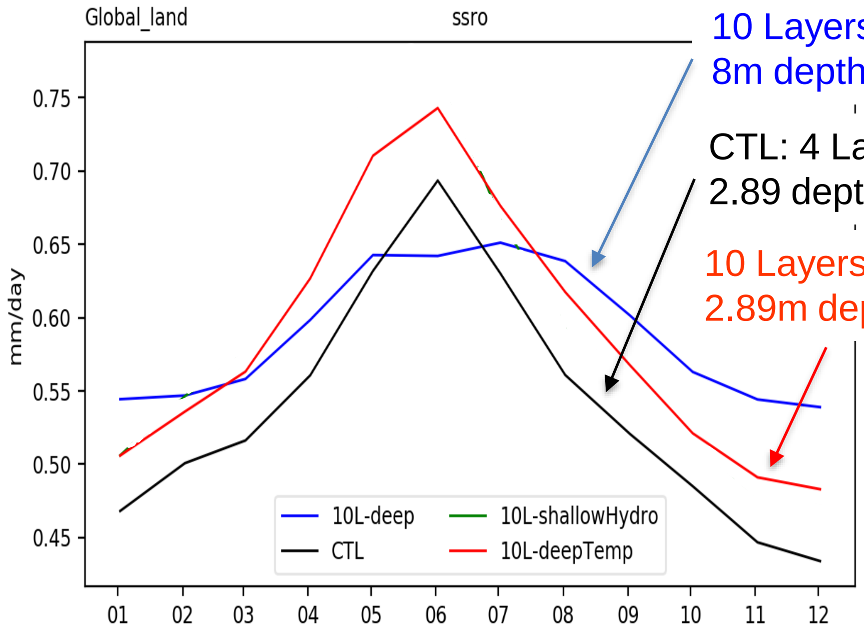
transpiration

Runoff

From De Rosnay et al. 2000

Number of vertical layers (and resolution of topmost layer)

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



10 Layers;
8m depth for water

CTL: 4 Layers;
2.89 depth for water

10 Layers;
2.89m depth for water

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.

HTESSEL

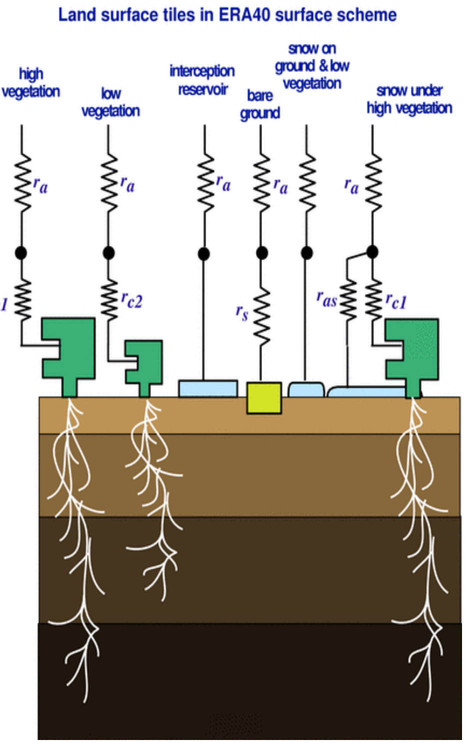
Hydrology - Tiled ECMWF

Scheme for Surface Exchanges over Land

+

FLake

Fresh water Lake scheme



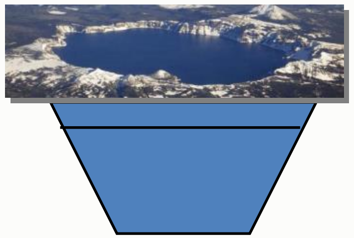
- **Lake tile**

Mironov et al (2010),

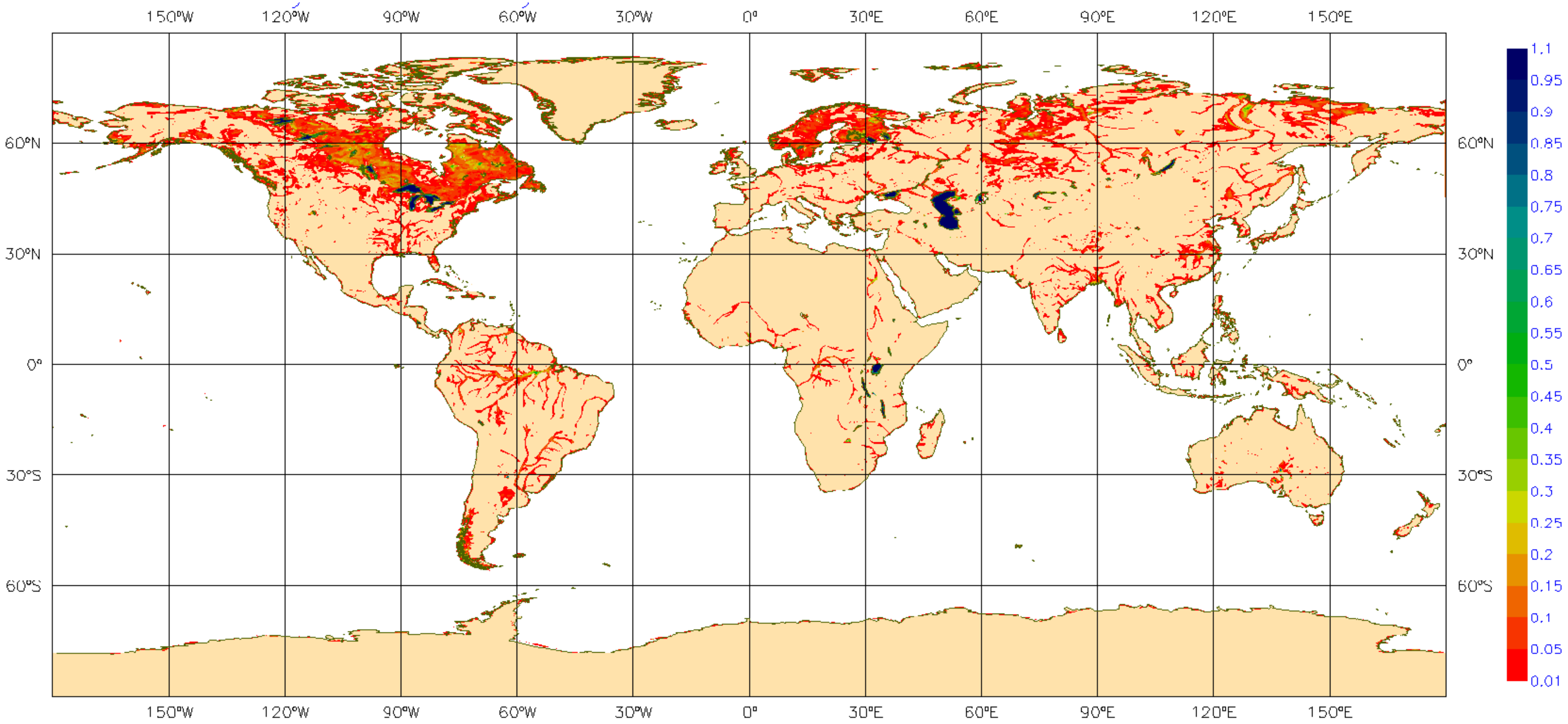
Dutra et al. (2010),

Balsamo et al. (2010, 2012, 2013)

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



Inland water bodies fraction

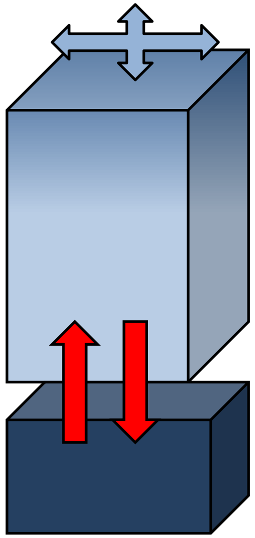


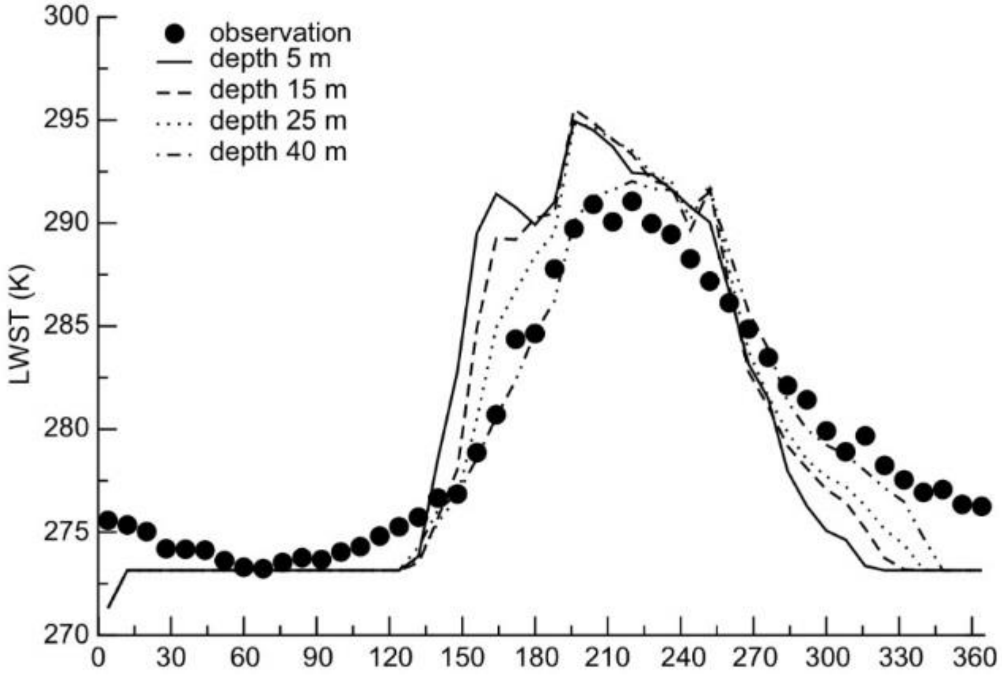
Aggregated from GLOBCOVER 300m

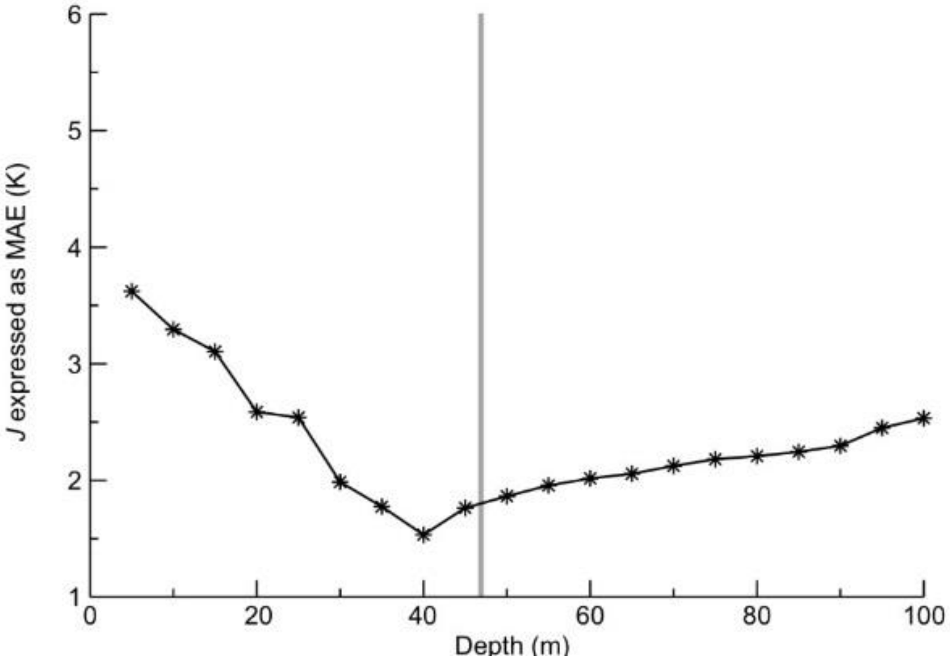
Inland water bodies heat storage

Lake depth is the main predictor for the lake temperature annual cycle

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







Energy fluxes: diurnal cycle impact of lakes

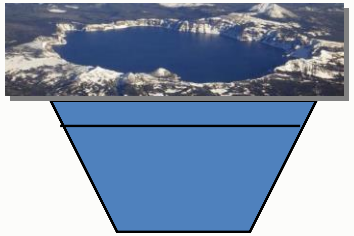
- **Lake tile**

Mironov et al (2010),

Dutra et al. (2010),

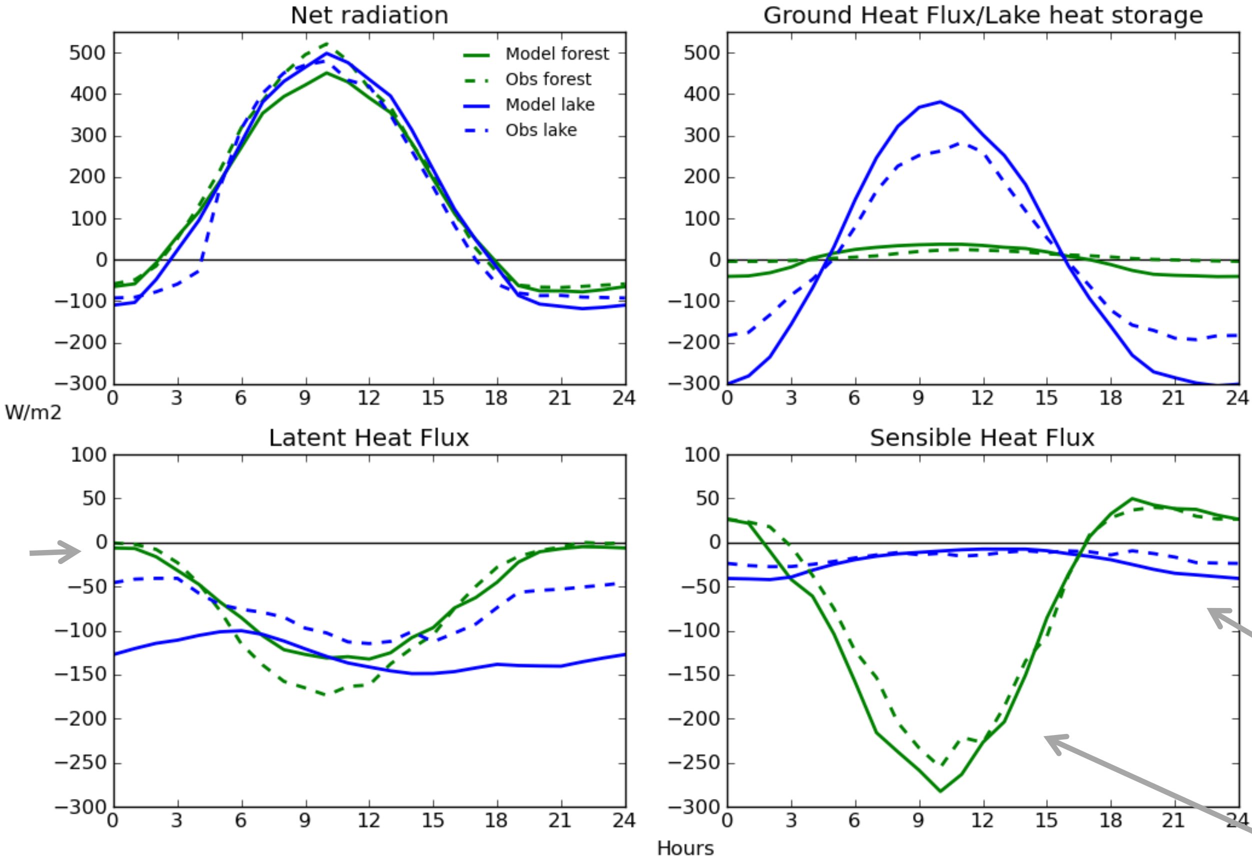
Balsamo et al. (2010, 2012, 2013)

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

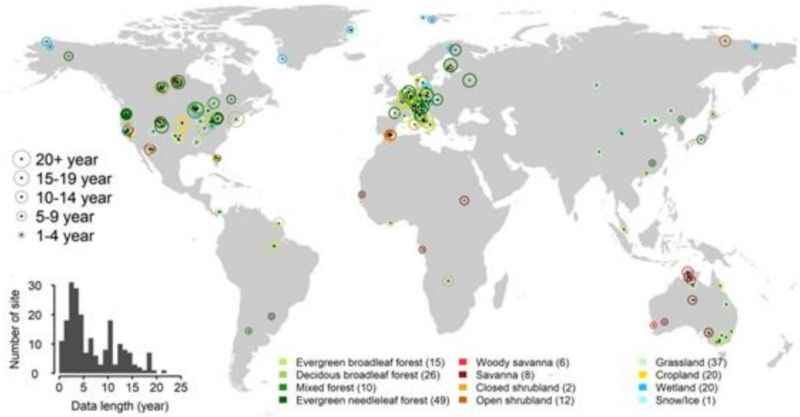
Main difference between lake & forest sites is found in energy partitioning

Process evaluation using in-situ observations

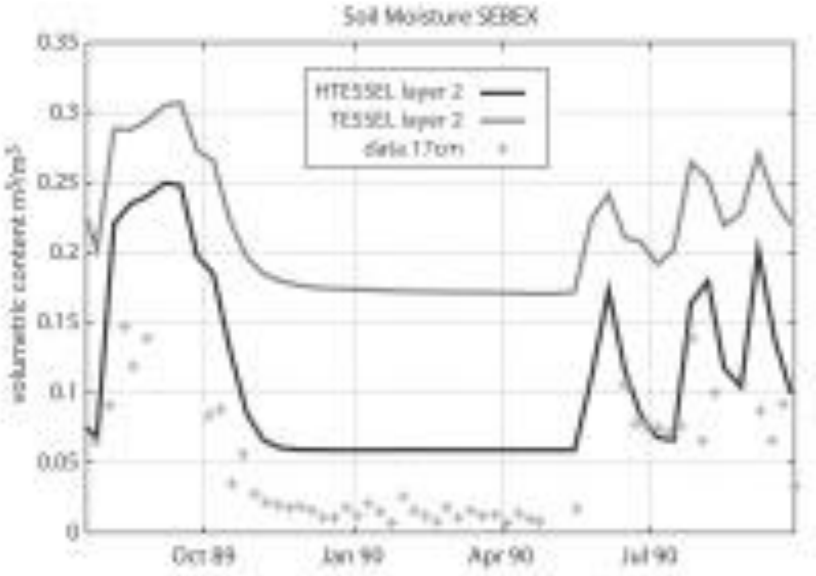
Balsamo et al 2009 JHM, Dutra et al. 2010 JHM, Arduini et al. 2019, ….

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

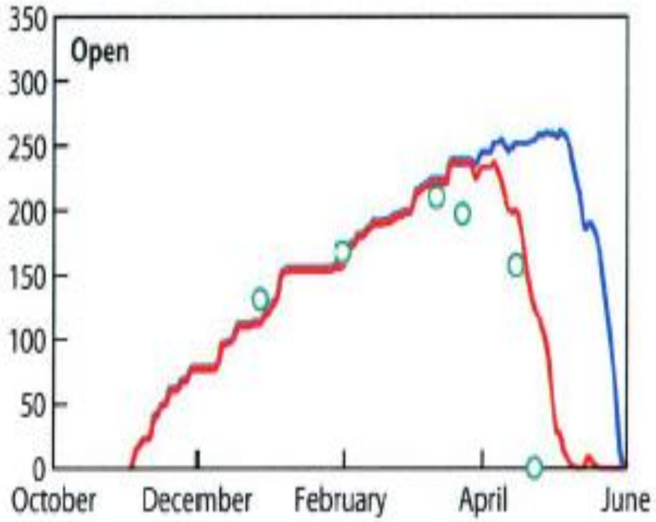
FLUXNET 2015 sites



Evolution of soil moisture for a site at SEBEX site. Observations, old (TESSEL), and **HTESSEL** schemes.



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



Col de Porte, snow site in French Alps

Weather forecasts impact of improved representation of soil/snow processes

- **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

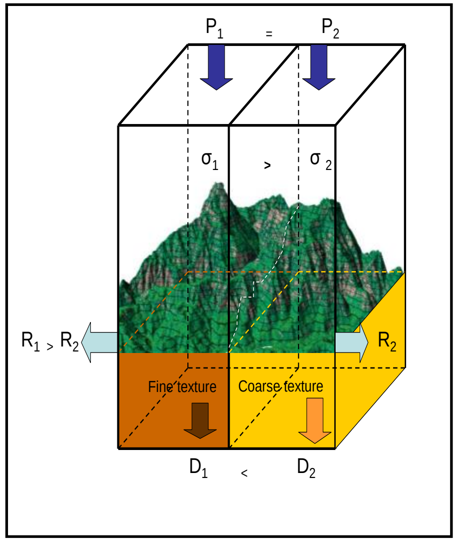
- Snow update

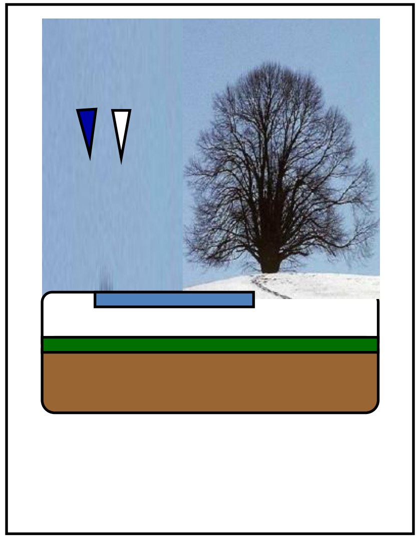
Dutra et al. (2010)

Revised snow density

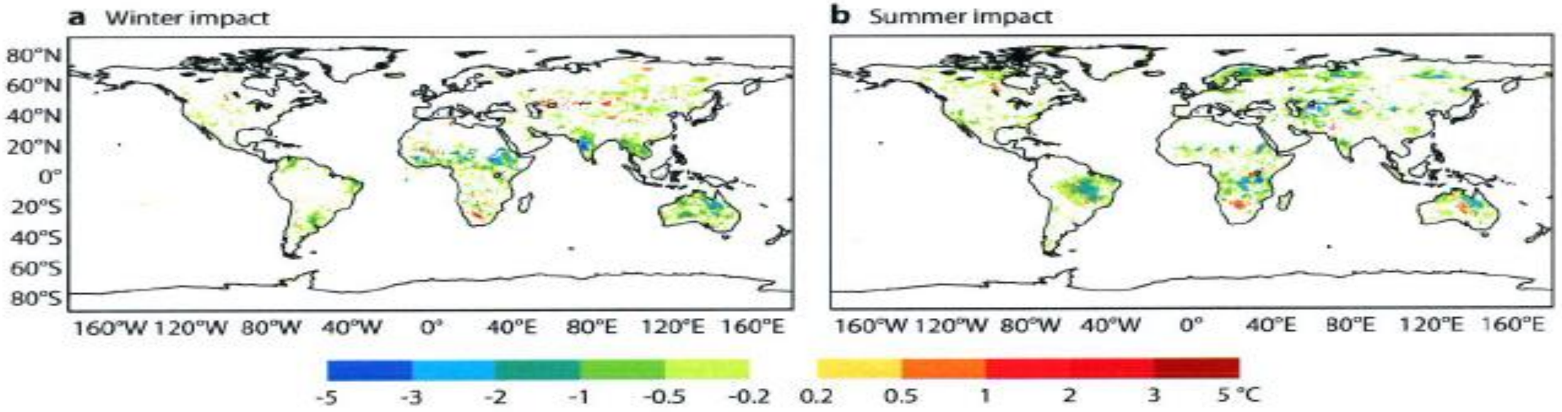
Liquid water reservoir

Revision of Albedo and sub-grid snow cover



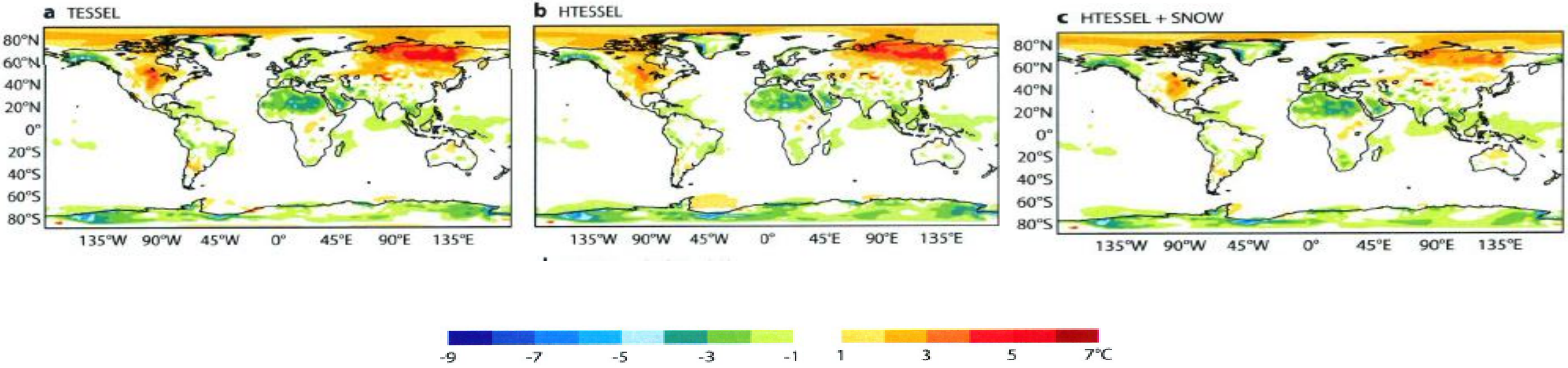


Forecast Impact (+36-hour forecast, mean error at 2m temperature)



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

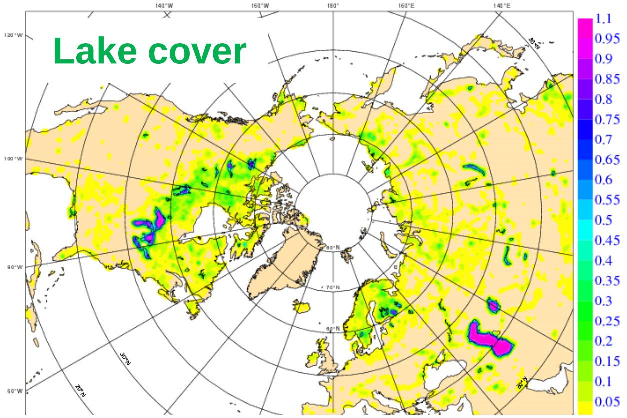
Climate improvements from land developments (soil, snow)



simulations colder than ERA-Interim **Warmer than ERA-Interim**

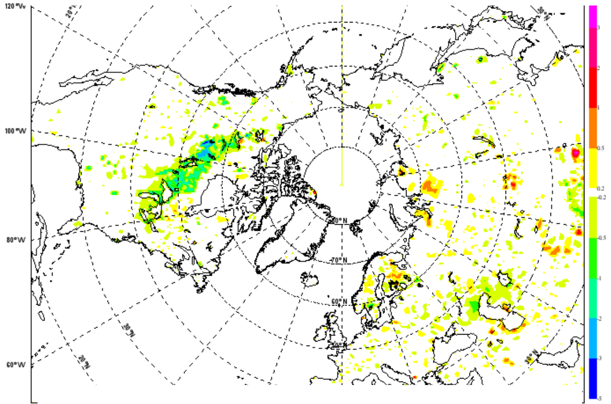
Impact of lakes in NWP forecasts

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



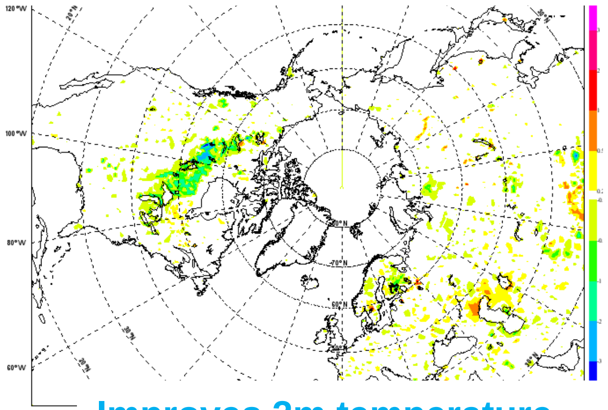
- **Forecasts sensitivity and impact of lakes is shown to produce a spring-cooling on lake areas with benefit on the temperatures forecasts (day-2 (48-hour forecast) at 2m.**
- **The lake surface temperatures are verified with MODIS LSTs as indicative of the heat-storage accuracy of the lake model**

Forecast sensitivity

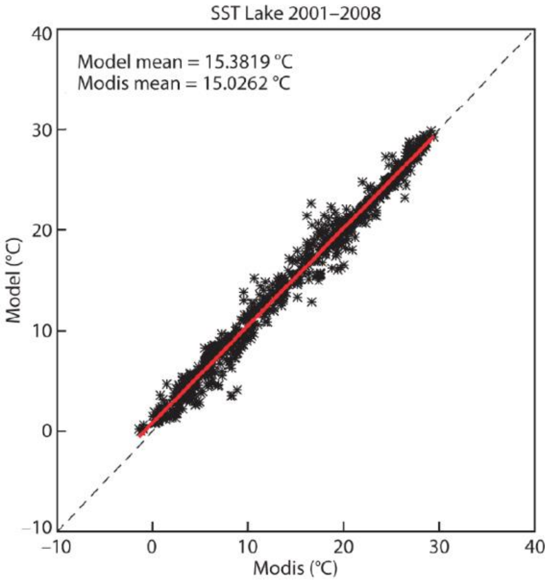


Cooling 2m temperature
Warming 2m temperature

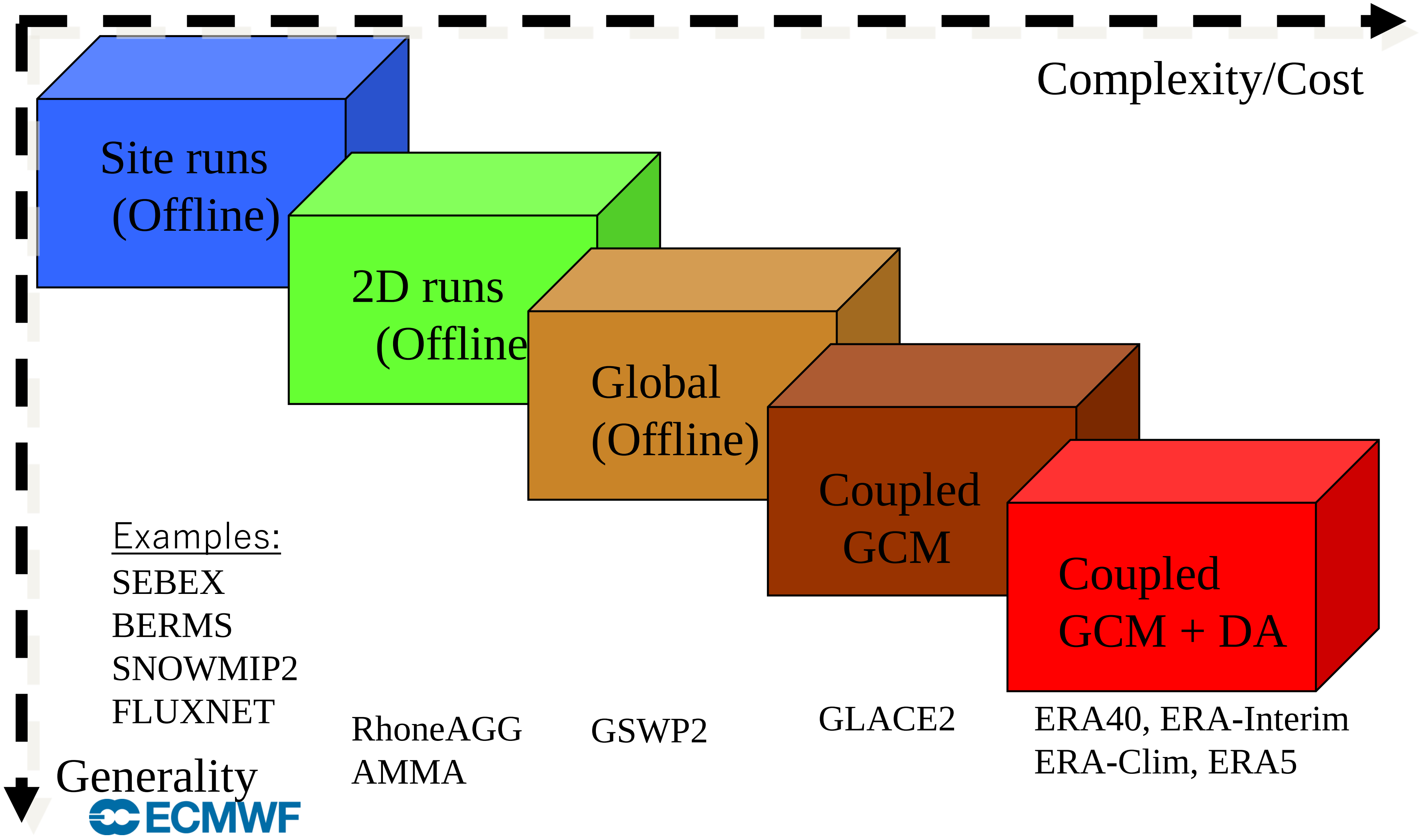
Forecast impact



Improves 2m temperature
Degrades 2m temperature



Strategy for surface model development at ECMWF (applied)



Complexity/Cost

Site runs
(Offline)

2D runs
(Offline

Global
(Offline)

Coupled
GCM

Coupled
GCM + DA

Examples:

SEBEX
BERMS
SNOWMIP2
FLUXNET

RhoneAGG
AMMA

GSWP2

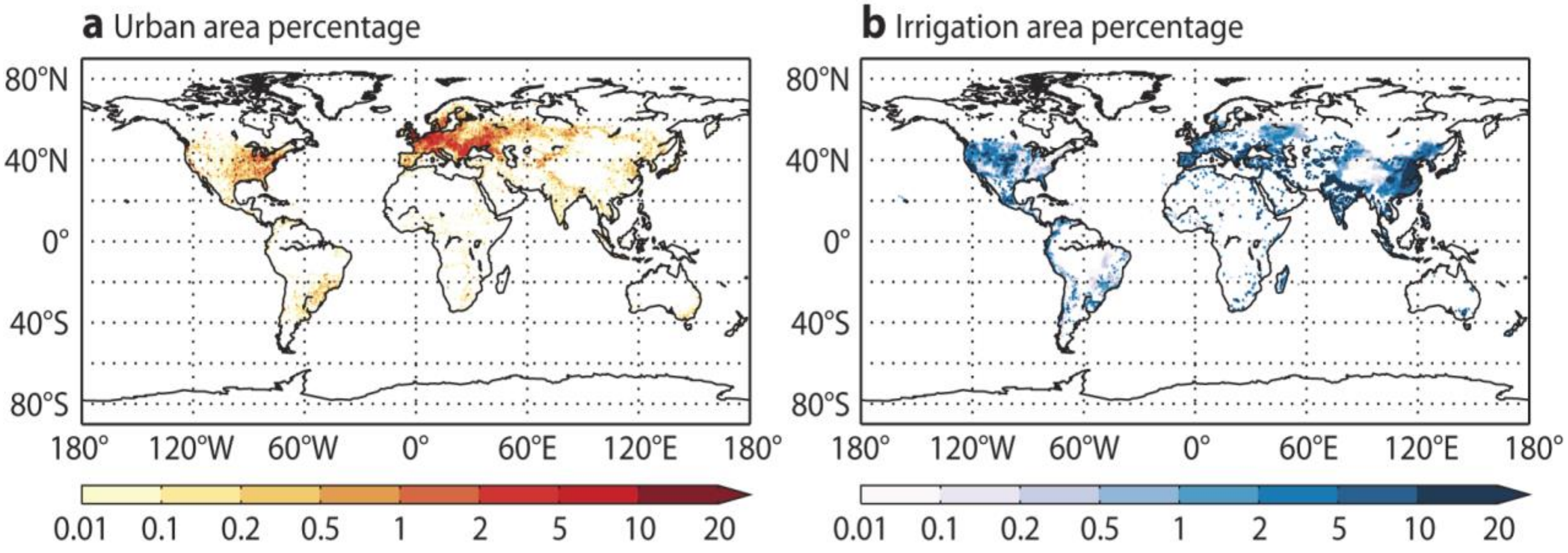
GLACE2

ERA40, ERA-Interim
ERA-Clim, ERA5

Generality

Missing surface components: An example

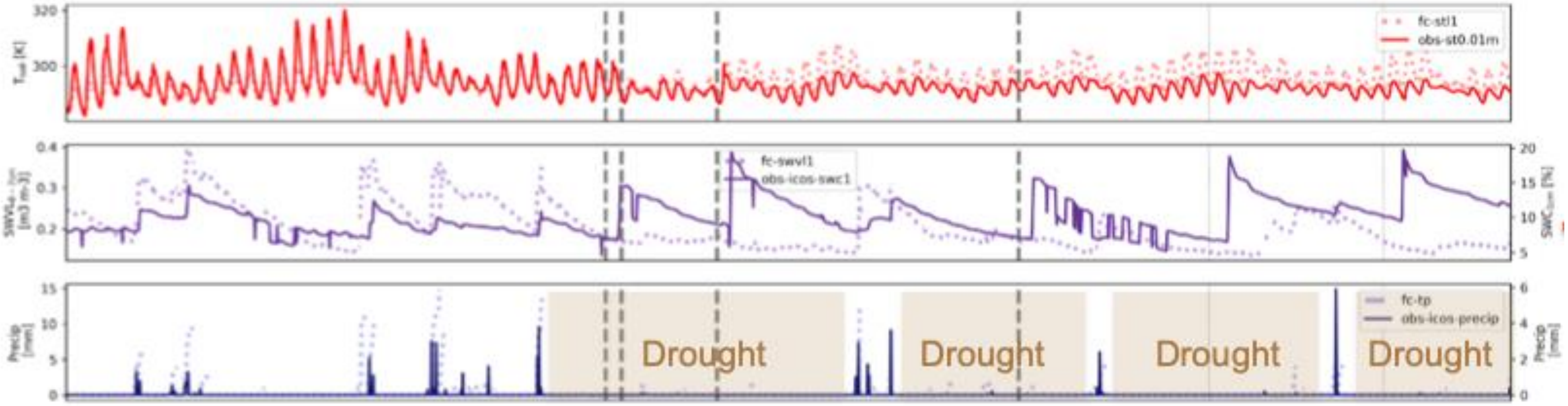
- Human action on the land and water use is currently neglected in most NWP models…



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

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

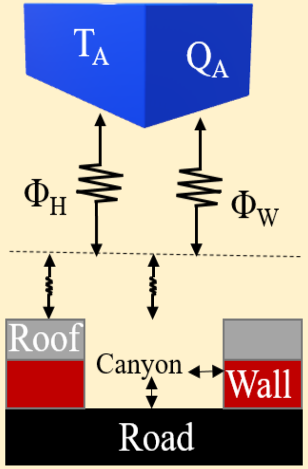
Many thanks to Florentine Weber for the plot

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

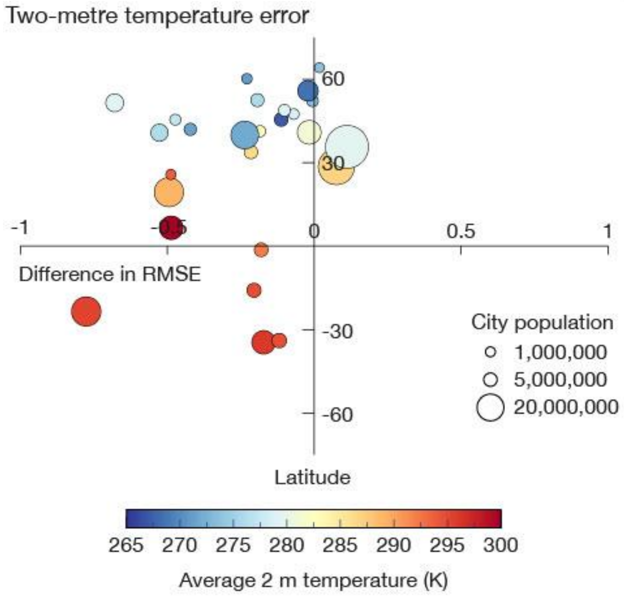
Single Layer Canopy

- Basic assumption of urban geometry e.g. infinite canyon.
- Considers fluxes from multiple surfaces.
- Shadowing and roughness lengths computed.

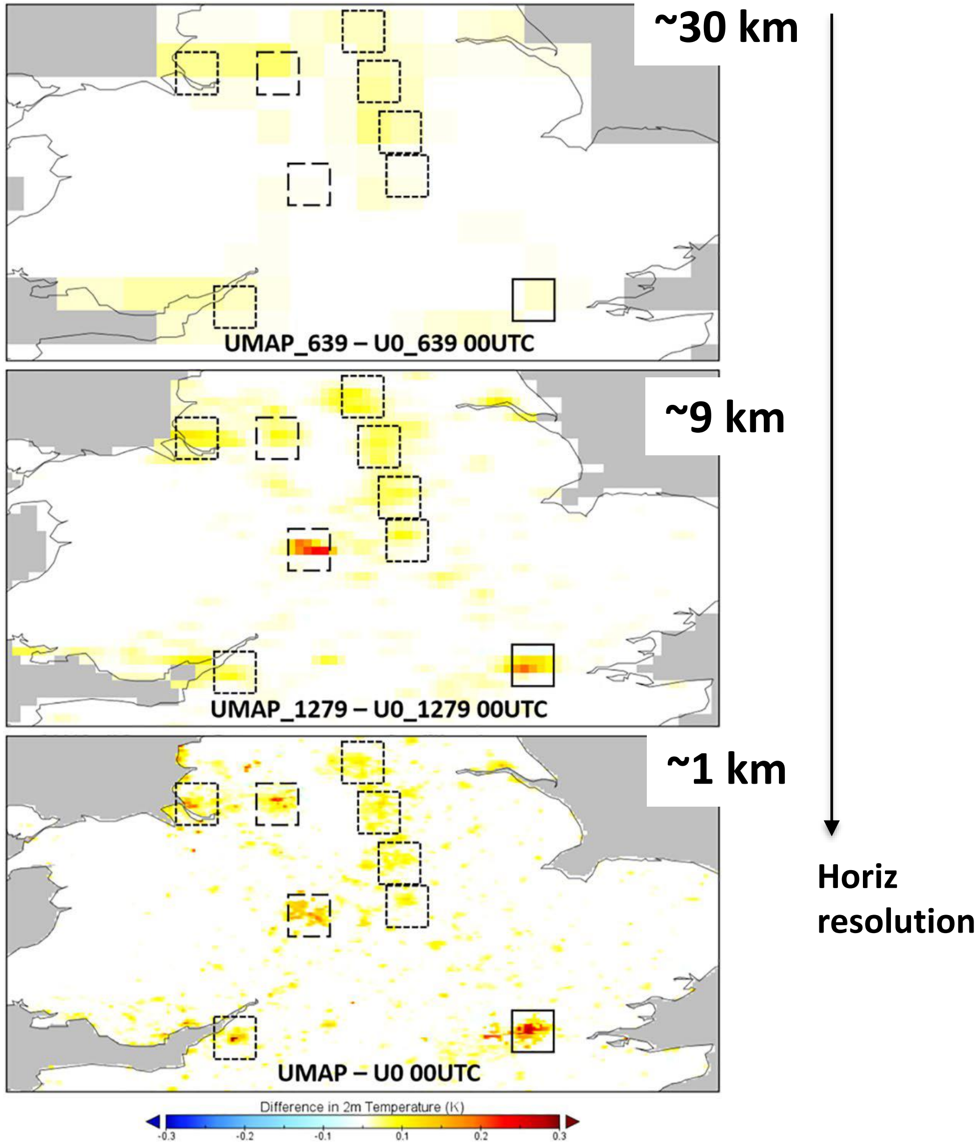


RMSE reduced with URBAN

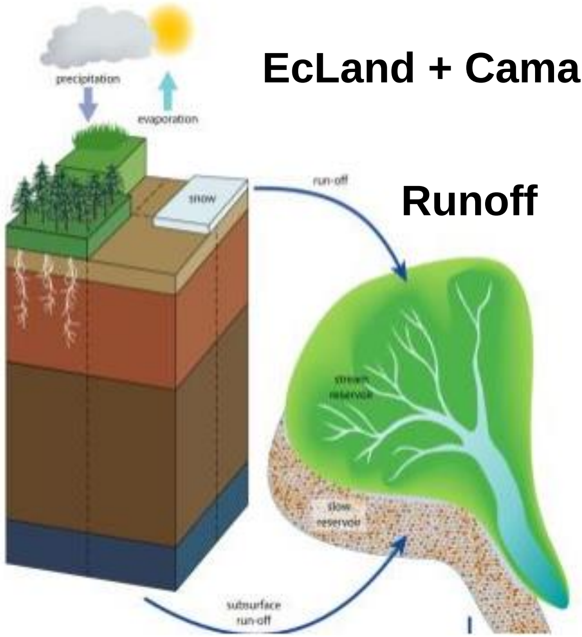
RMSE increased With URBAN



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



Toward simulating floods & inundations in ecLand and in the IFS

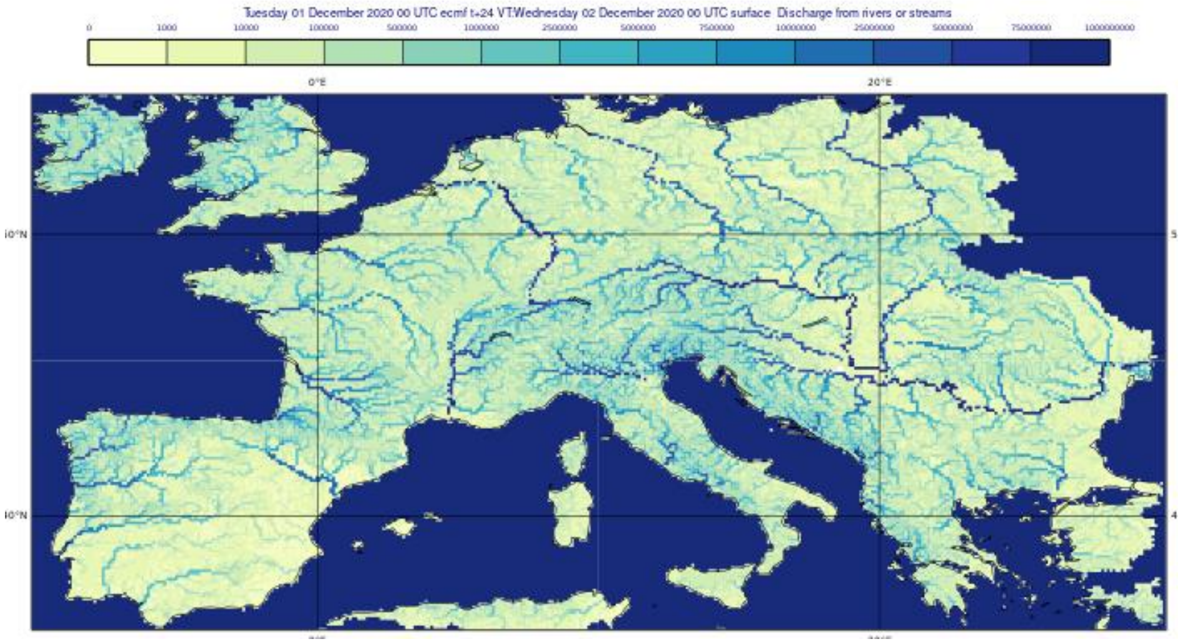


EcLand + Cama-flood

Runoff

Sub-surface Runoff

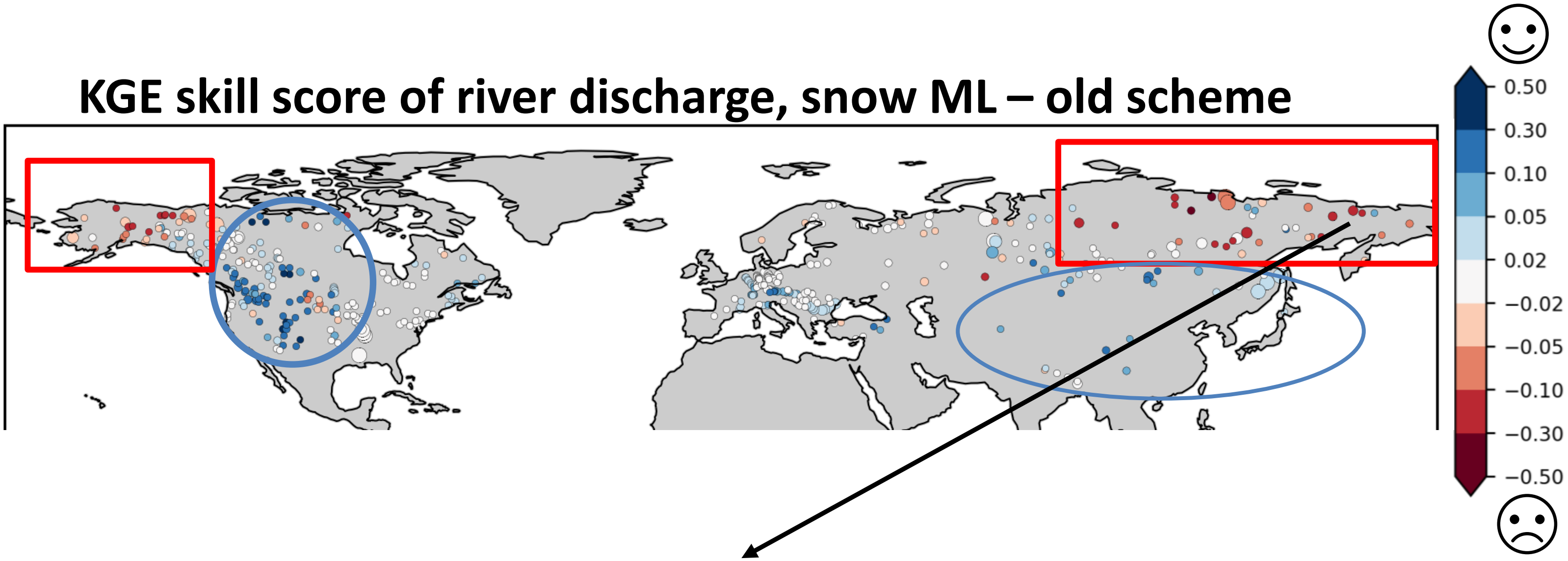
- Coupling river discharge to ecLand in future high resolution land reanalysis
- Coupling within the IFS is ongoing to permit forecasting river floods



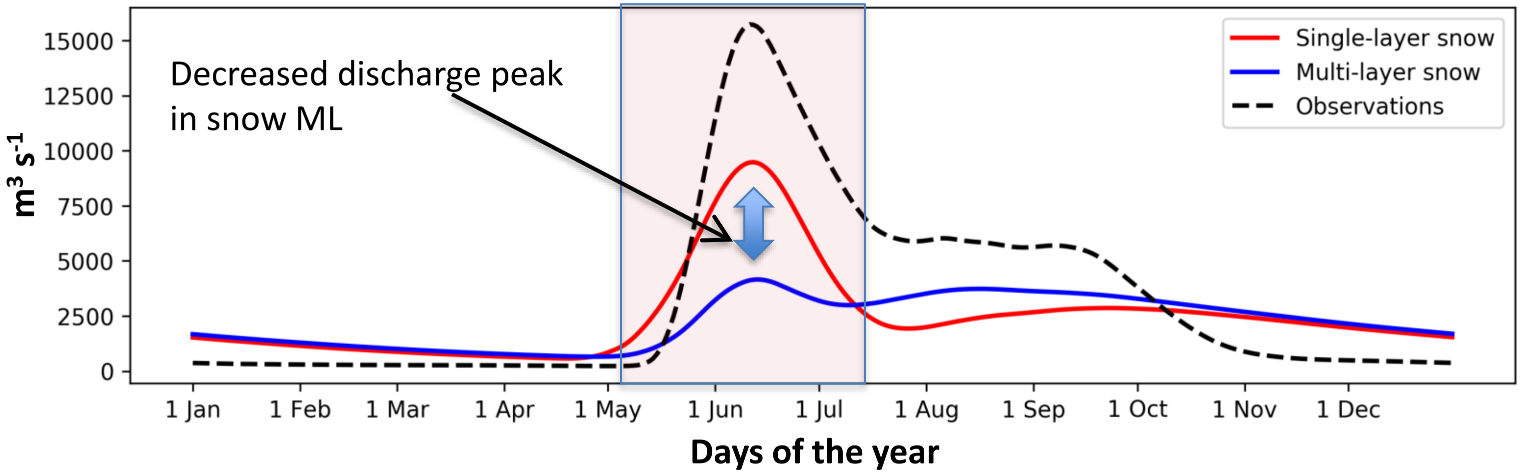
River discharge from EcLand coupled with Cama-flood over the European domain at 3arc/min resolution (~5km)

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

Perspectives

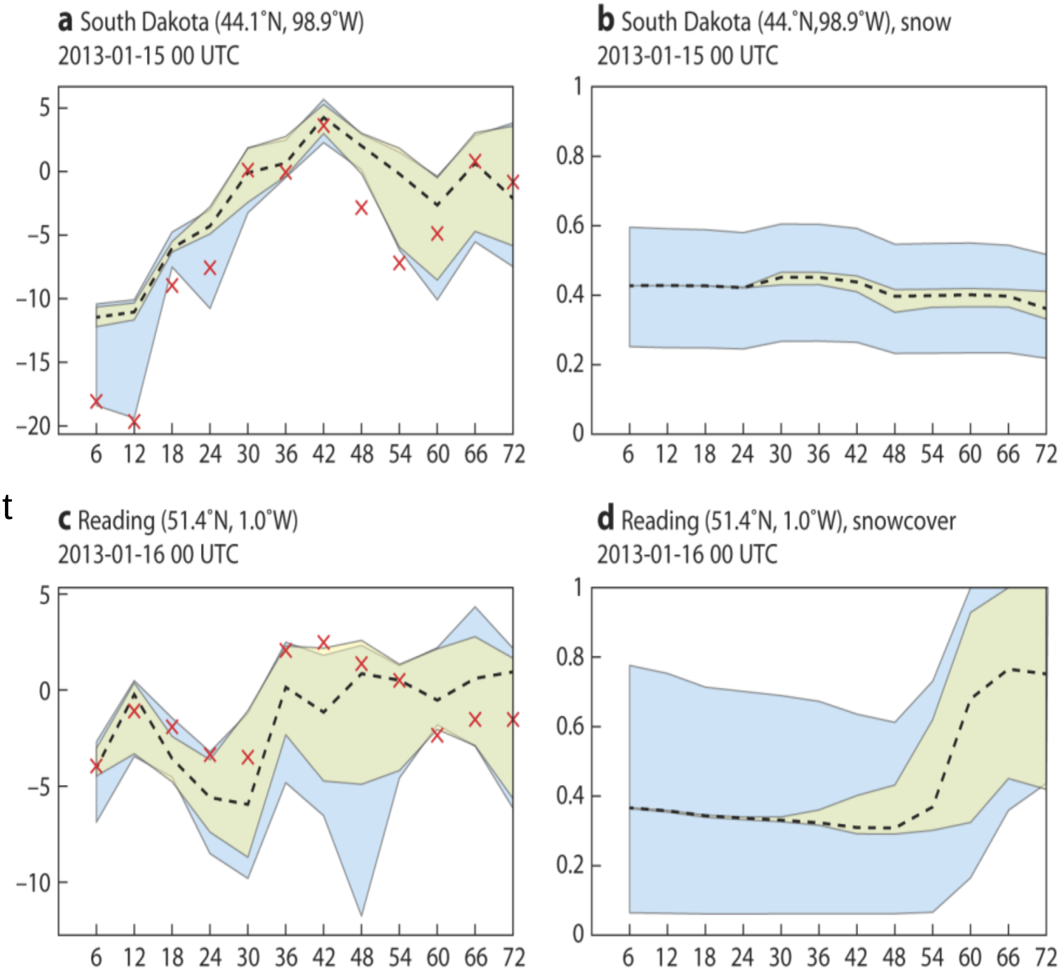
- Efforts to improve diurnal and seasonal cycles of surface state variables has transferred into weather and climate improvements and this will continue (doing things better may not sound attractive but it pays off!)
- Surface complexity is needed and permitted by the overall skill of the atmospheric 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.

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

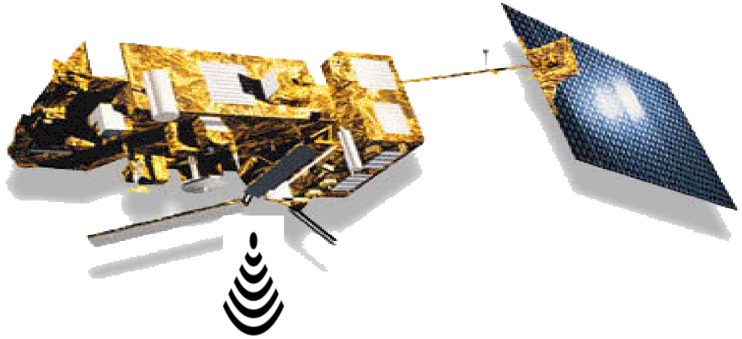
Representing land-related forecast uncertainties

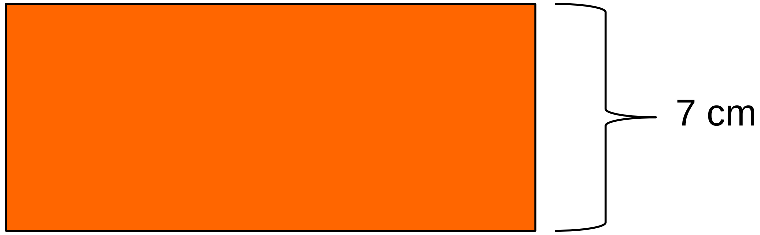
- EDA/ENS system includes land surface components (CY40R1) and perturbation also to the assimilated observations (CY40R3)
- Accounting for land surface uncertainties (particularly for snow) enhances the ensemble spread of 2m temperature prediction and its usefulness for forecasters
- The uncertainty 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

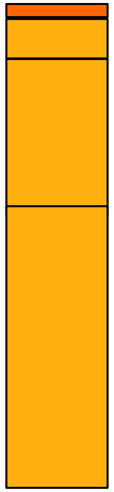


An enhanced soil vertical resolution

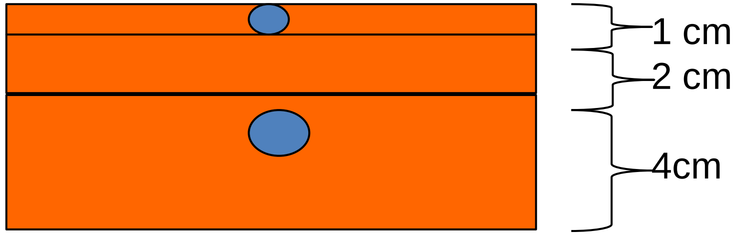
The model bias in Tskin amplitude shown by
Trigo et al. (2015) motivated the development of an enhanced soil vertical discretisation to improve the match with satellite products.





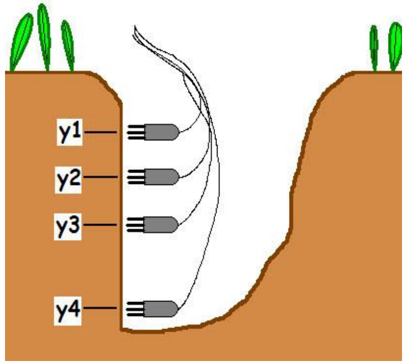


4-layers:
 # 0-7 cm
7-28 cm
28-100 cm
100-289 cm



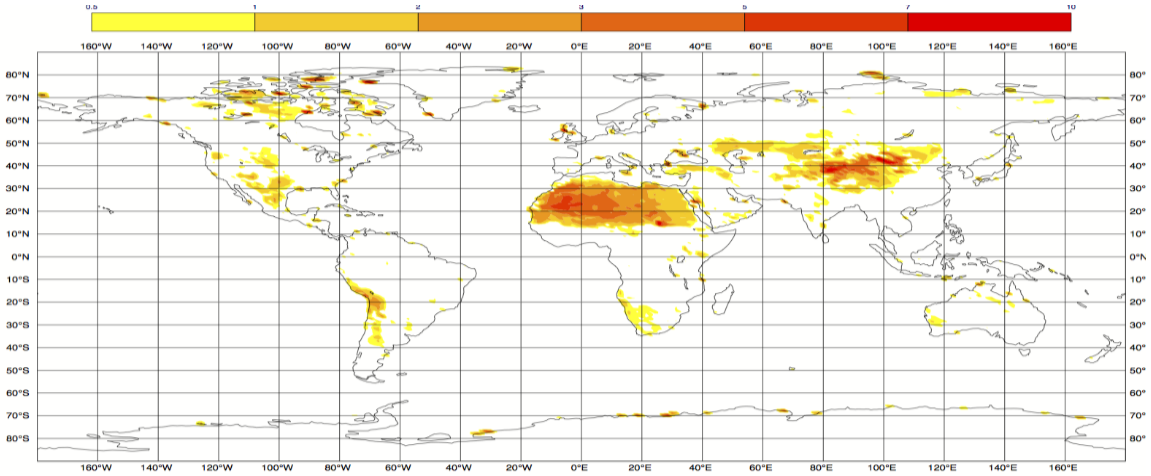
10-layers:
 # 0-1 cm
 # 1-3 cm
 # 3-7 cm
7-15 cm
15-25 cm
25-50 cm
50-100 cm

100-200 cm
200-400 cm
 # 400-800 cm



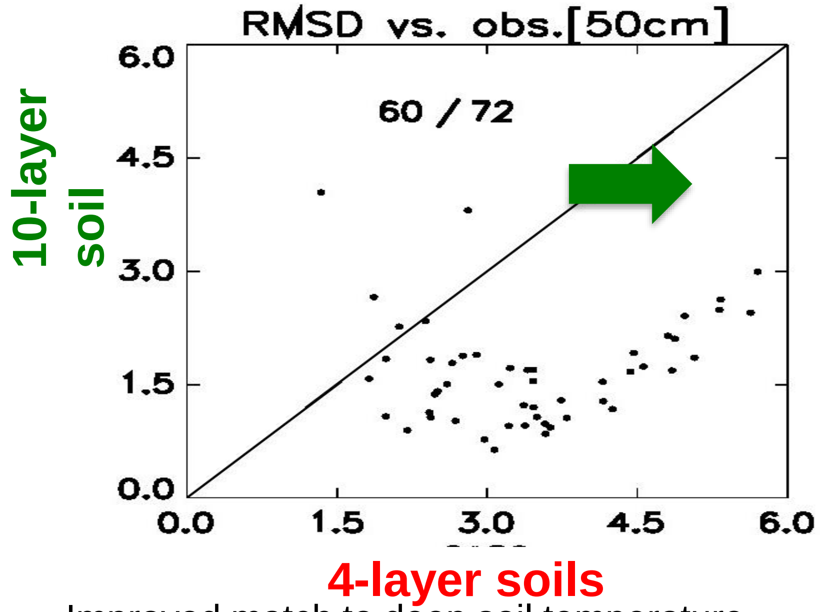
Impact of soil vertical resolution on soil temperature

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



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).