

Hydrological impact of the new ECMWF multi-layer snow scheme

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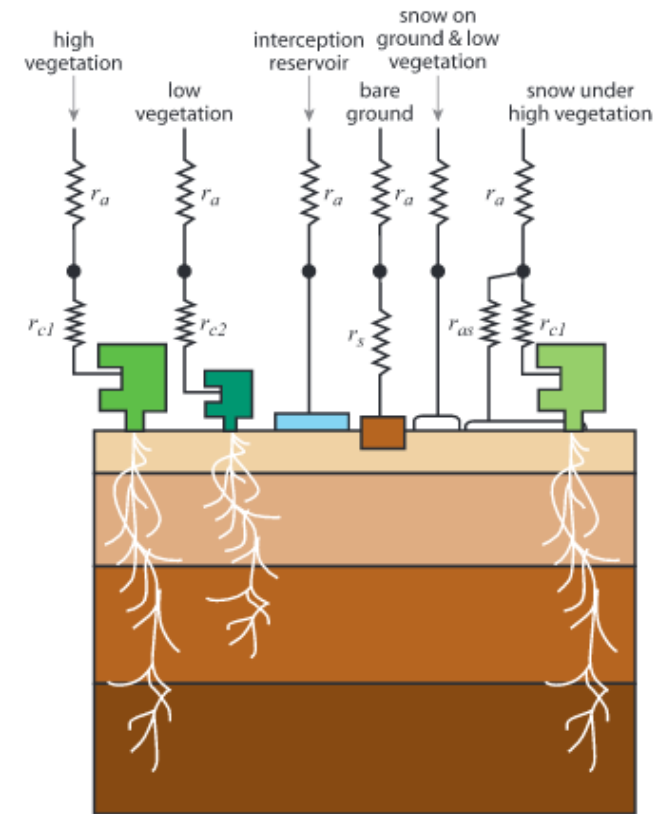


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- Snow processes, with the water stored in the snowpack and released as snowmelt, are very important components of the water balance, in particular in high latitude and mountain regions
- The evolution of the snow cover and the timing of the snow melt can have major impact on river discharge
- Land surface models are used in Earth System models to compute exchanges of water, energy and momentum between the atmosphere and the surface underneath, and also to compute the components of the hydrological cycle
- In order to improve the snow representation, a new multilayer snow scheme is under development in the HTESSEL land-surface model of ECMWF Integrated Forecasting System (IFS), to replace the current single-layer snow scheme
- The new scheme has already been shown to improve snow and 2m temperature
- **In this study, the wider hydrological impact was evaluated, to see how the improving land surface processes impact the land surface variables, in particular the river discharge**

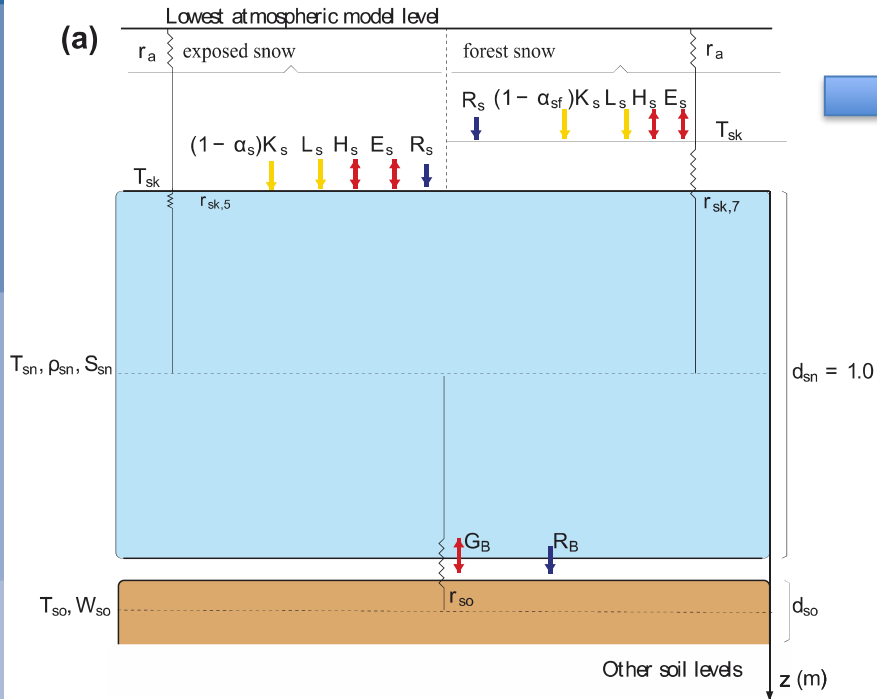


HTESSEL land surface scheme

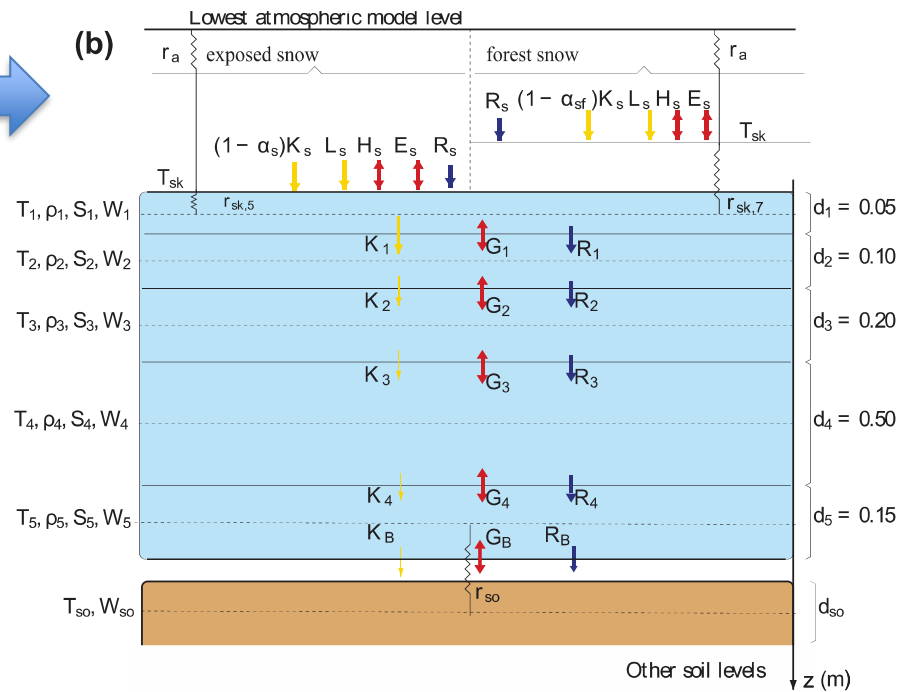


New multi-layer snow scheme

Single-layer snow scheme (SL)



New multi-layer snow scheme (ML)

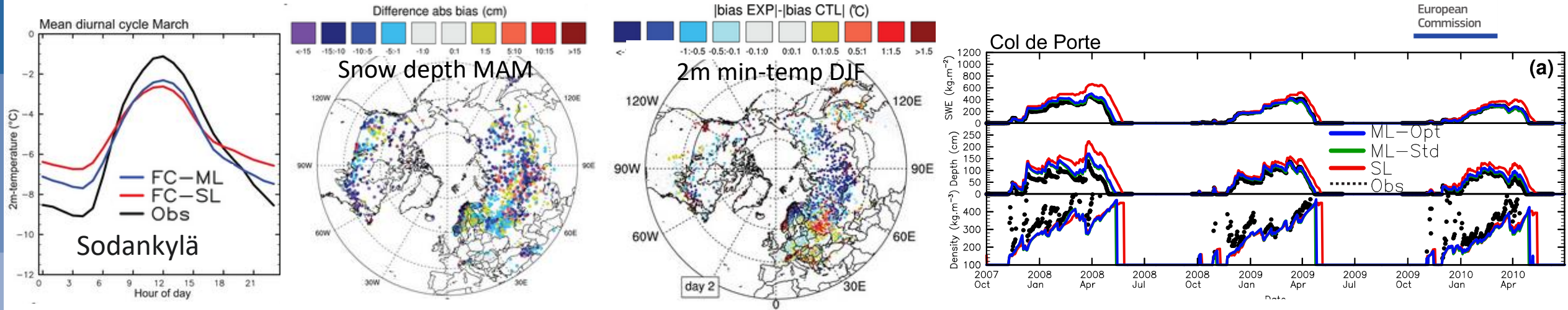


Arduini, G., Balsamo, G., Dutra, E., Day, J. J., Sandu, I., Boussetta, S., & Haiden, T. (2019). Impact of a multi-layer snow scheme on near-surface weather forecasts. *Journal of Advances in Modeling Earth Systems*, **11**, 4687–4710. <https://doi.org/10.1029/2019MS001725>

- The multi-layer snow is an intermediate complexity snow scheme
- It represents the vertical structure and evolution of snow temperature, density, liquid water content and surface snow albedo
- The number of active layers varies depending on the value of snow depth, from a minimum number of one layer to a maximum of 5
- Details of the snow scheme are provided in the Arduini et al. 2019 (above)



Multi-layer snow scheme improves snow and temperature



- The new scheme largely improves the representation of snow depth for most of the sites considered, reducing the root-mean-square error averaged over all sites by more than 30%
- The improvements are due to a better description of snow density in thick and cold snowpacks, but also due to an improved representation of sporadic melting episodes because of the inclusion of a thin top snow layer with a low thermal inertia
- The evaluation of coupled 10-day weather forecasts shows an improved representation of snow depth at all lead times, demonstrating a positive impact at the global scale.
- The multilayer snow scheme also improves the simulated minimum 2-m temperature, by decreasing the positive bias and improving the amplitude of the diurnal cycle over snow-covered regions
- However, the increased variability of the 2-m temperature can have a detrimental impact in regions characterized by preexisting errors in the daily mean temperature, associated with errors in cloud processes or surface albedo



Research questions: How does the multi-layer snow scheme impact the hydrology in reanalysis simulations globally?

- How is the match between ERA5-driven river discharge simulations and observations impacted?
- How is the flood timing impacted?

Experiments:

- Two global, offline, ERA5-driven, HTESSEL reanalysis experiments were coupled to the CaMa-Flood model, one run with the current single-layer (**SL**) and another with the new multi-layer (**ML**) snow scheme
- These were compared for the general match between the observation and the river discharge reanalysis time series and also the impact on flood timing

- **Runoff generation:**

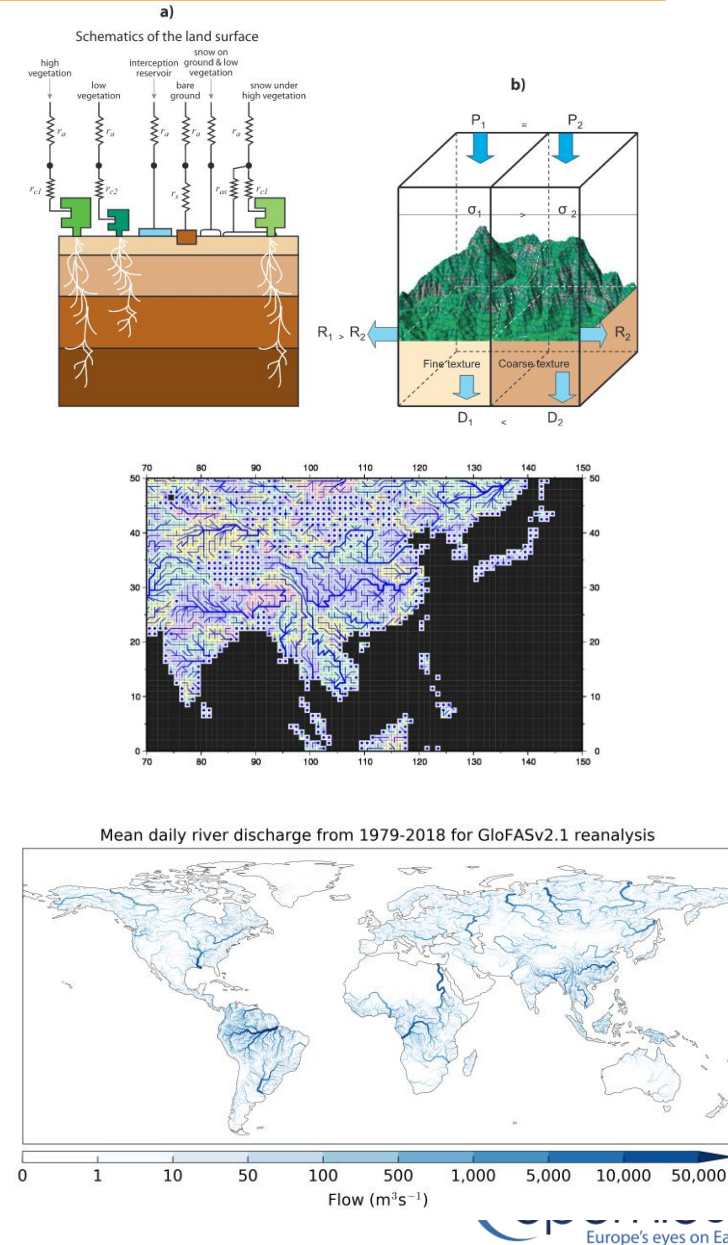
- The HTESSEL land surface model (Hydrology-Tiled ECMWF Scheme for Surface Exchange over Land; Balsamo et al. 2009) was the hydrological modelling component

- **River routing:**

- The Catchment-based Macro-scale Floodplain model (CaMa-Flood; Yamazaki et al. 2011) was used to simulate the hydrodynamics and produce river discharge from the HTESSEL runoff outputs

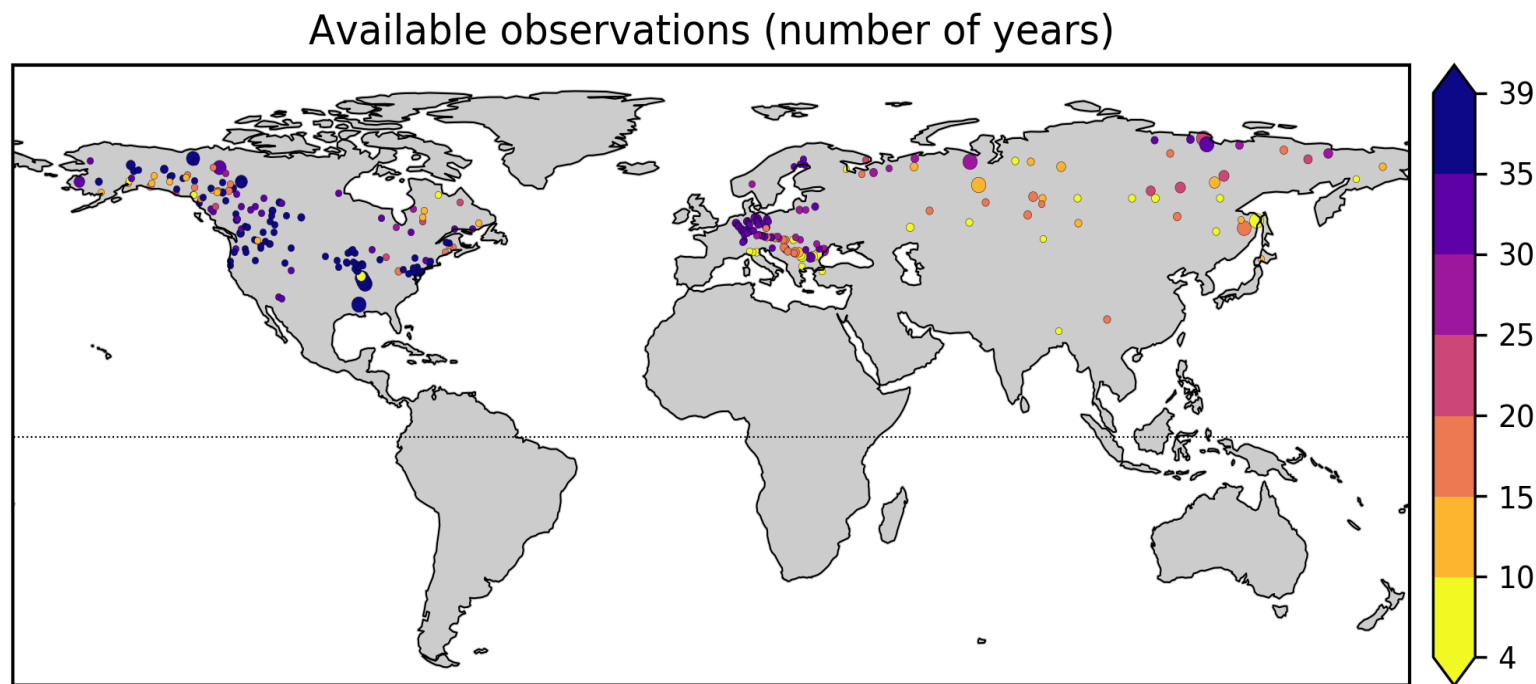
- **Atmospheric forcing:**

- ERA5 climatological reanalysis (available in Copernicus Climate Data Store)
- Over the period 1979-2018
- High-resolution component at 31 km horizontal resolution





- Discharge observations came from GloFAS, predominantly (~75 %) from the Global Runoff Data Centre (GRDC), supplemented by data collected through collaboration with GloFAS partners worldwide to improve spatial coverage
- **Minimum 4 years** of data in 1980-2018 (regardless of gaps)
- **Snow impacted:** Stations in snow impacted climate with snowfall at least 10% of the precipitation
- **Minimum KGE** (>0.4) to exclude catchments with modelling or other problems
- **Manual quality checking** to include only stations which have no observation issues and which has only minimal reservoir or lake impact
 - This step also included quantitative information from the GRAND and GLWD databases on reservoirs and lakes
- In total about 300 catchments analysed



- The hydrological model performance analysis was conducted based on the modified Kling–Gupta efficiency metric (**KGE'**; ideal value is 1):

$$\text{KGE}' = 1 - \sqrt{(r - 1)^2 + (\beta - 1)^2 + (\gamma - 1)^2} \quad \beta = \frac{\mu_s}{\mu_o} \quad \gamma = \frac{\sigma_s / \mu_s}{\sigma_o / \mu_o}$$

- We also calculated errors related to its three components:
 - Pearson correlation **pcorr** (ideal value = 1) r in KGE'
 - Relative bias **pbias** (ideal value = 0) defined as $\beta - 1$ (or its absolute value **abs-pbias**)
 - Relative variability **var** (ideal value = 0) defined as $\gamma - 1$ (or its absolute value **abs-var**)
- Finally, we used the Delay Index (**Timing** in days; ideal value is 0), measuring the time delay between the simulated and observed river discharge time series
 - Timing is expressed as the time lag (or shift) L that maximises $R_{xy}(L)$, cross correlation function $R_{xy}(m)$ with the simulated (x) and observed (y) time series shifted by L days
 - Positive/negative Timing indicate delayed/advanced simulated river discharge
 - So, for example a timing error of +5 means the simulation needs to be shifted by 5 days backwards (brought earlier) to get to the highest correlation, i.e. the simulation is generally 5-day late predicting the ups and downs in the flow time series
 - Although this is not directly equivalent to measuring the timing error of the individual high flood peaks, it is a good estimate

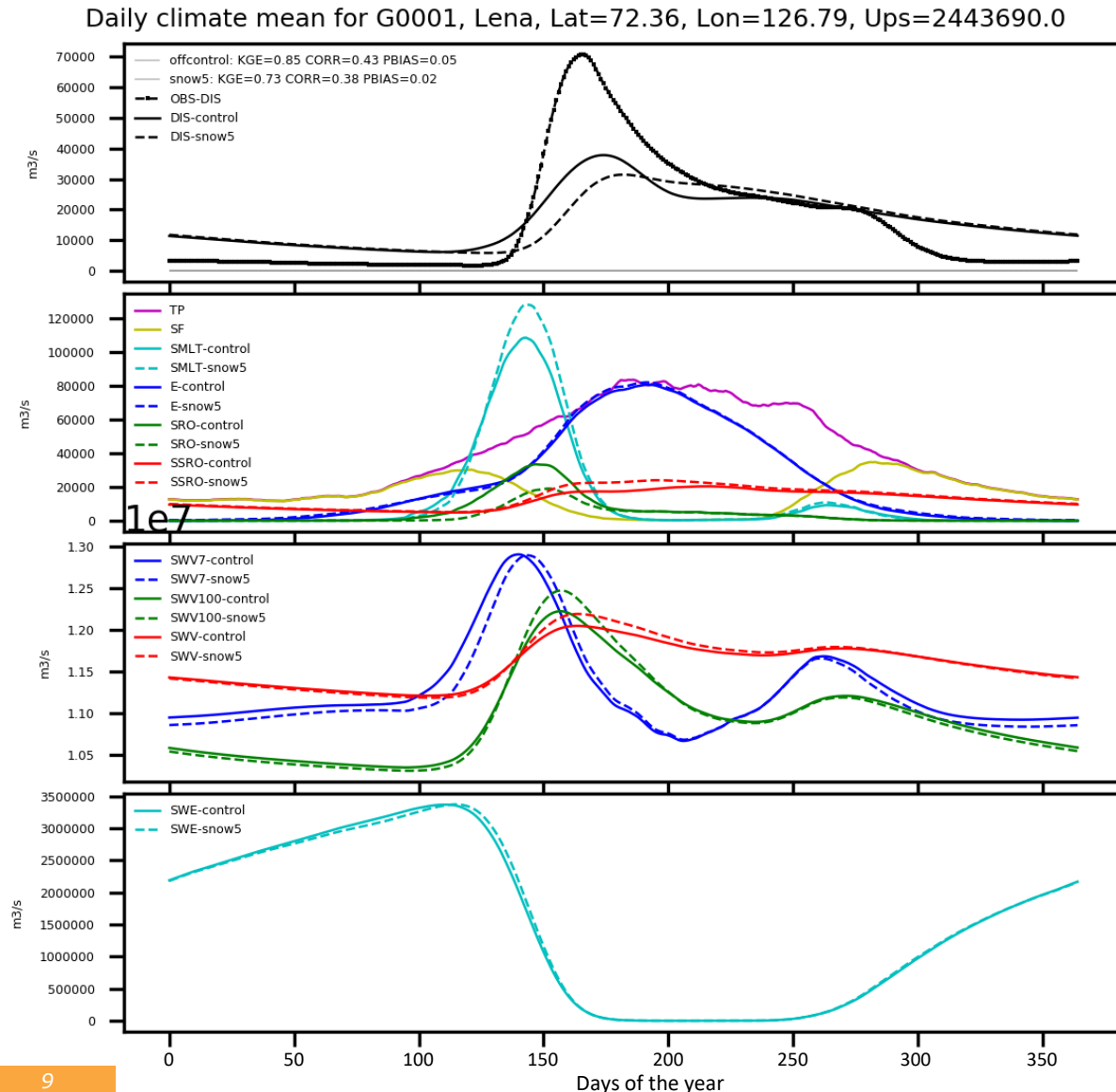


Experimental design – daily surface climatology



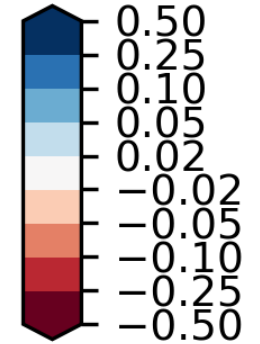
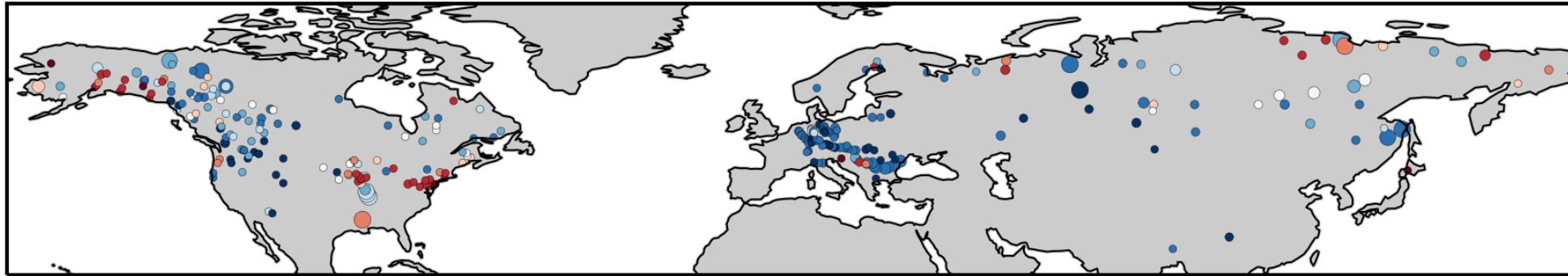
- Climagrams were produced for all analysed catchments with different surface variables, including also river discharge, as a tool to help understanding the surface processes
- The climate mean was computed for each day of the year, using a +/-10-day window
- Only those days were included in the daily climate mean computation which had available river discharge observations
- This resulted in a sample with maximum 39 (years) * 21 (days in each year) = 819 values (and minimum 4*21 values with only 4 years)
- Variables included
 - River discharge (observations, offcontrol, snow5)
 - ERA5 precipitation, snowfall (same for both experiments)
 - Evaporation (E), snowmelt (SMLT), surface runoff (SRO), subsurface runoff (SSRO), snow water content (SWE) soil water content (SWV7 as top 7cm, SWV100 as top 100cm and SWV as all the 289cm fixed-depth soil), all for both

SL and ML

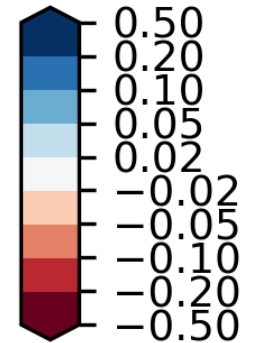




pbias SL

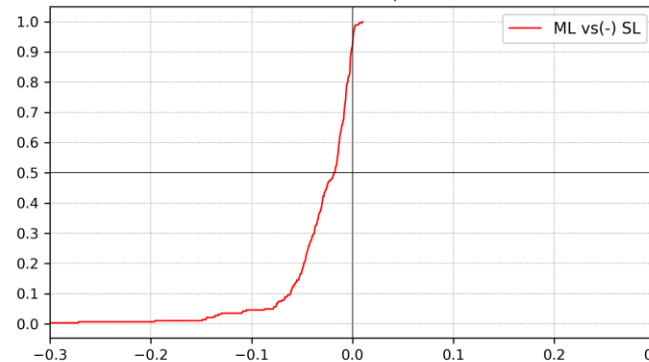


pbias abs(ML)-abs(SL)

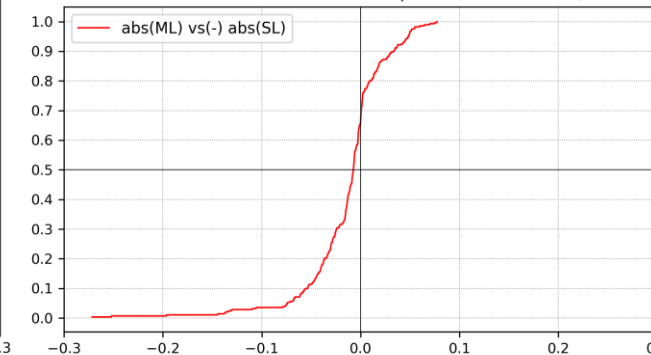


- Bias is dominantly positive in SL
- ML almost everywhere reduces the water amount
- Thus, bias improves for the majority of the catchments

Cumulative distribution for pbias (282 stations)



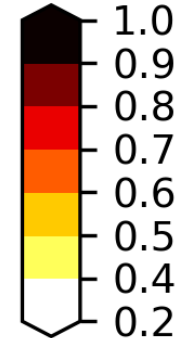
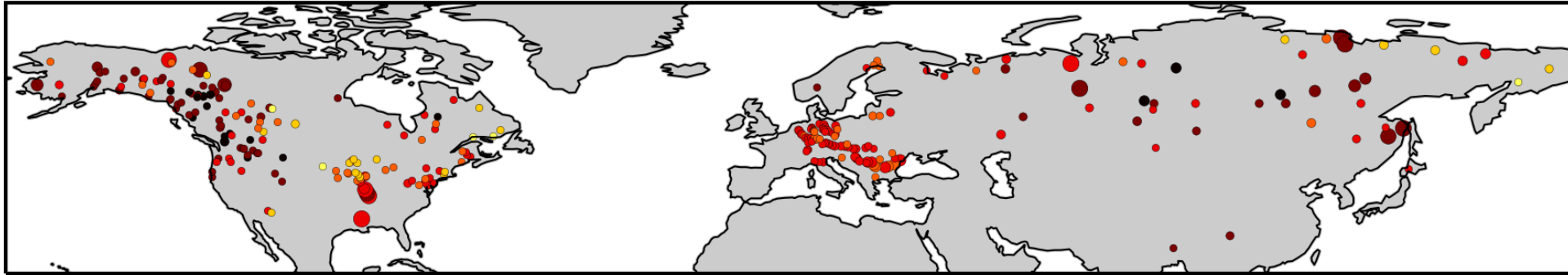
Cumulative distribution for pbias (282 stations)



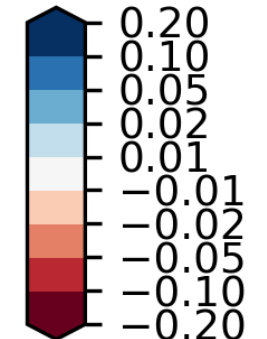


Results – correlation

pcorr SL

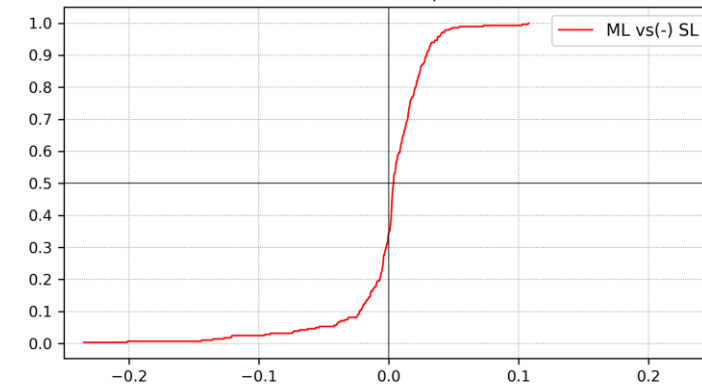


pcorr ML-SL



- Correlation varies a lot regionally
- ML tends to improve correlation, but some catchments in the cold climate areas show moderate to large drop in correlation

Cumulative distribution for pcorr (282 stations)



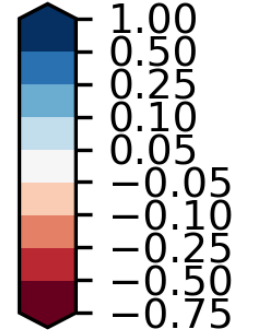
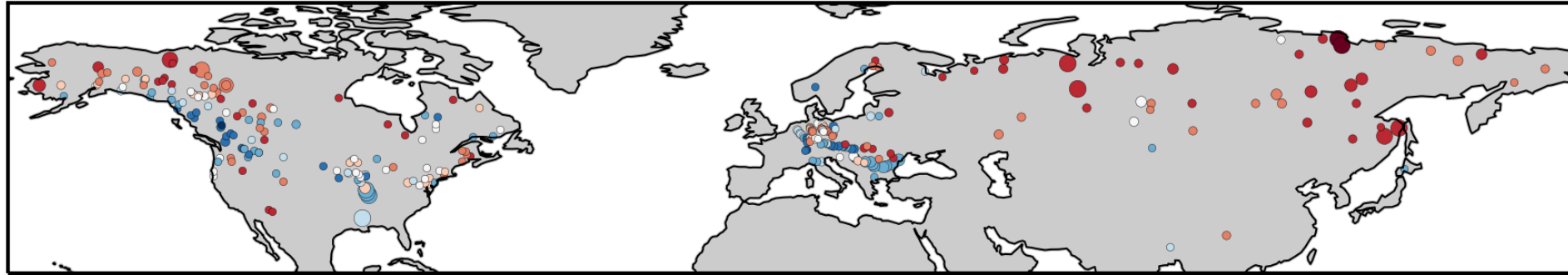


Results – variability

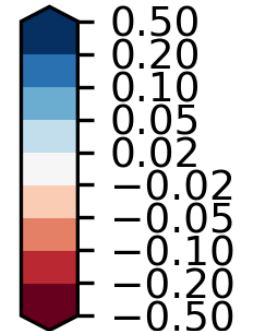
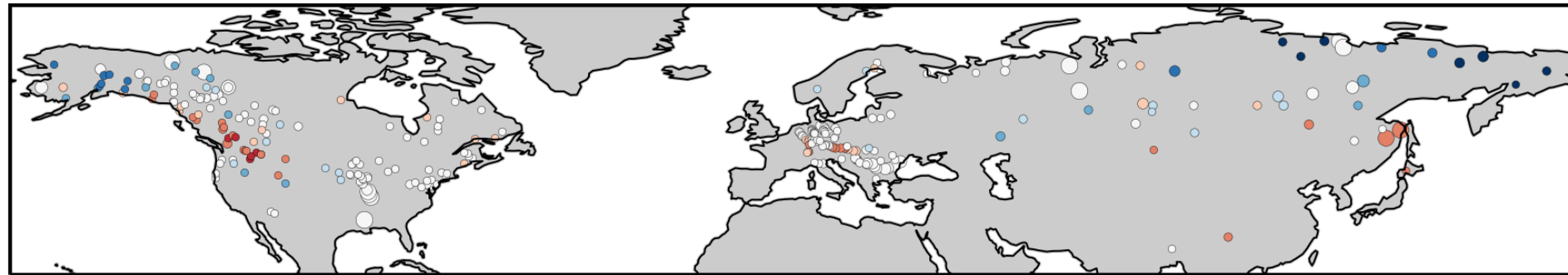


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var SL

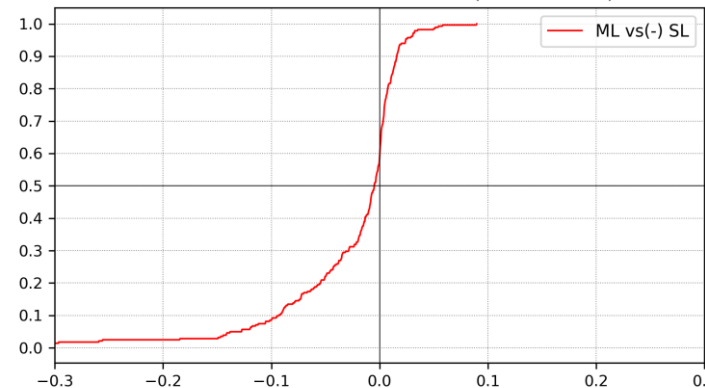


var abs(ML)-abs(SL)

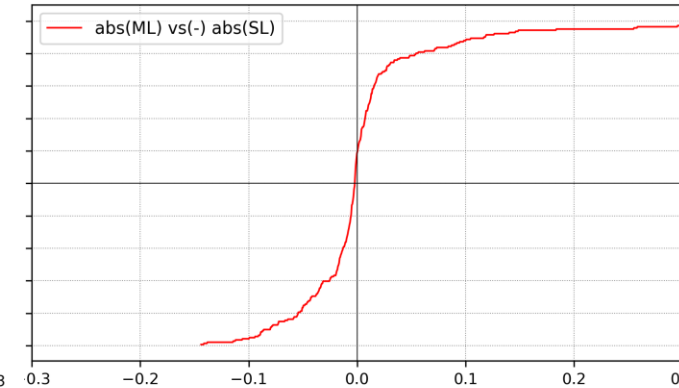


- Variability is underestimated over a large area
- ML impact is more negative
- ML tends to make it worse more in the areas of the colder northern catchments

Cumulative distribution for var (282 stations)

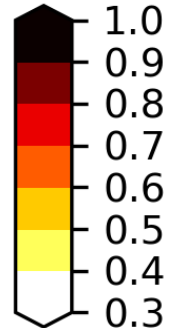
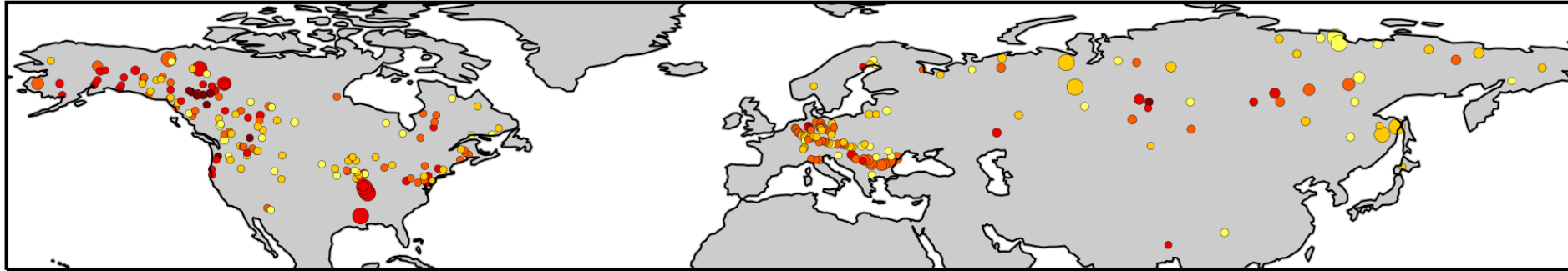


Cumulative distribution for var (282 stations)

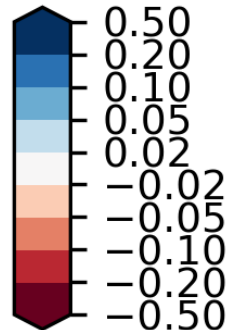
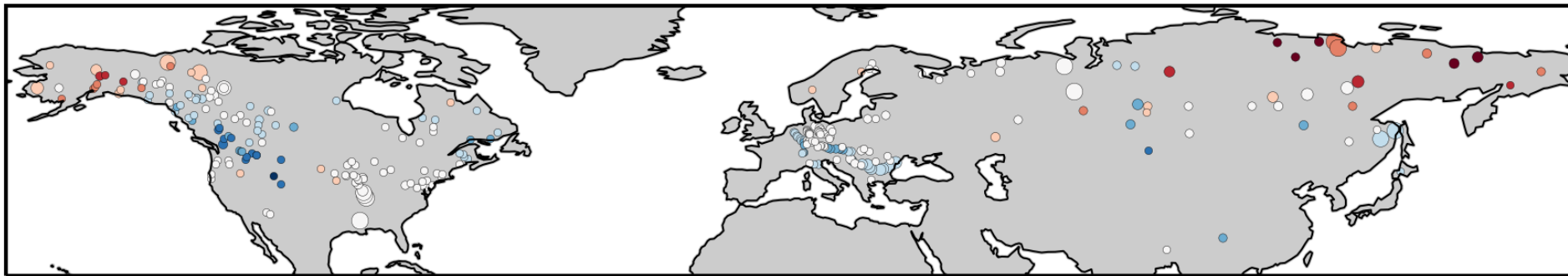




kge SL

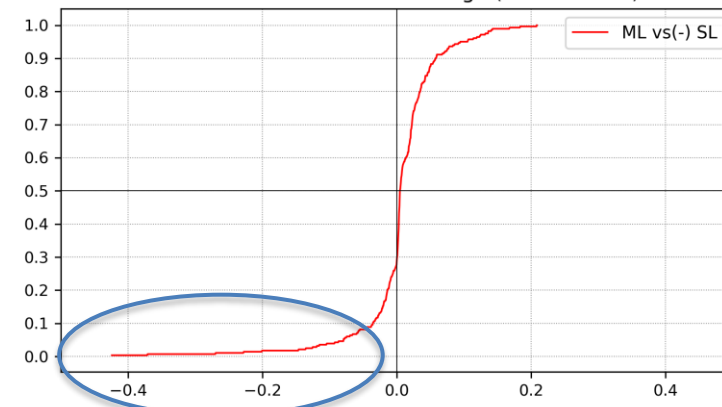


kge ML-SL



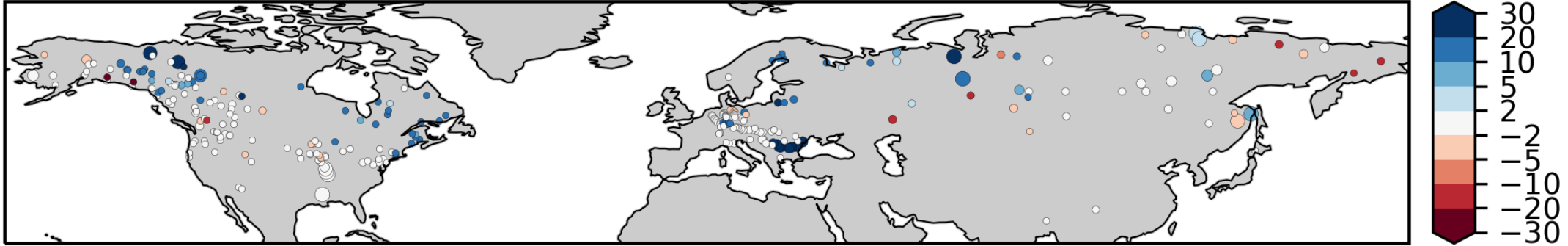
- Large variability in KGE regionally, with smaller catchments often with lower KGE
- ML improves the KGE for most of the catchments, but in the cold climate (northern Siberia and near Alaska) there are many catchments with bigger drop in performance

Cumulative distribution for kge (282 stations)

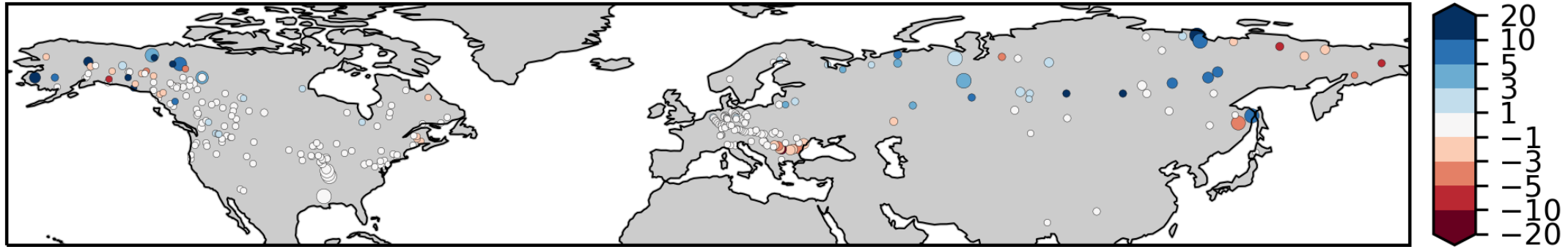




Timing error SL



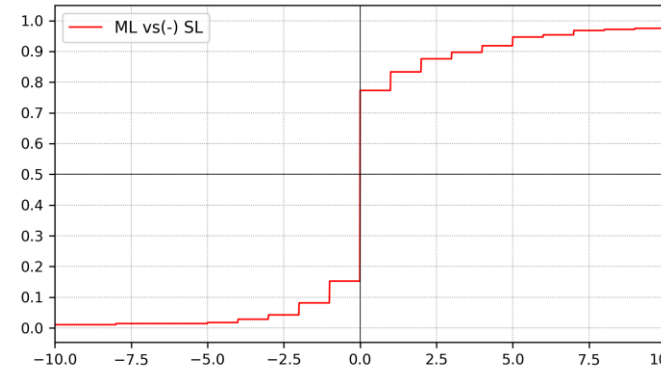
Timing error $\text{abs}(\text{ML}) - \text{abs}(\text{SL})$



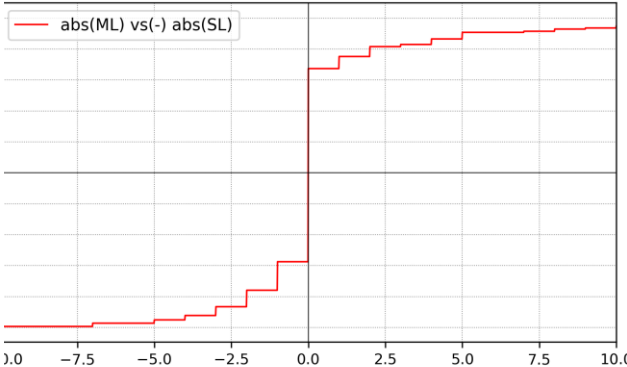
Timing error varies a lot with more catchments showing positive (too late) than negative error in the higher latitudes

ML changes the timing error in less than 40% of catchments, with a tendency of a slightly increasing the delay

Cumulative distribution for peakpcorrttime (282 stations)



Cumulative distribution for peakpcorrttime (282 stations)

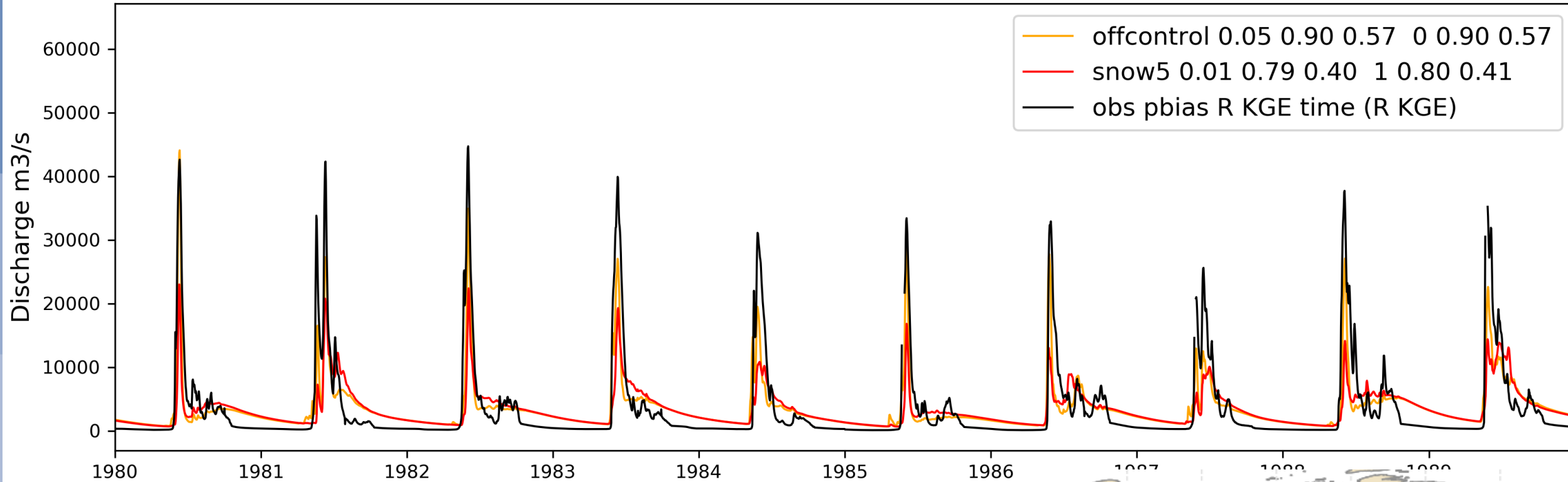




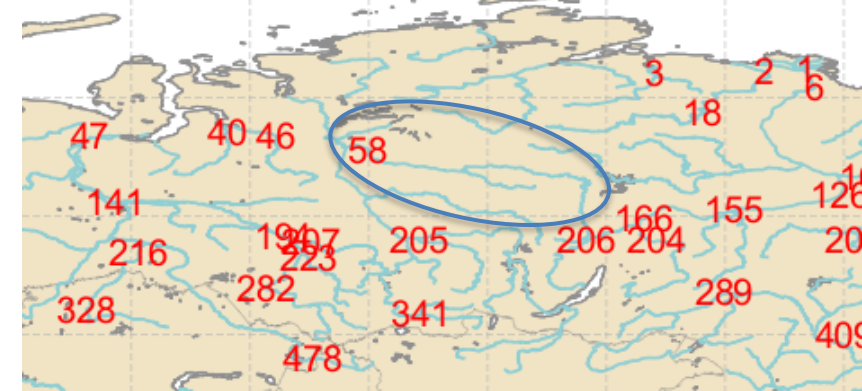
Results – cold climate problem



ID:G0058, Bol'Shoy Porog Yenisei Asia,
lat:65.55, lon:89.95, uparea:560983



- The snowmelt related biggest flood peak is usually lot more underestimated by the multi-layer snow scheme
- Both correlation and KGE clearly lower in ML than SL

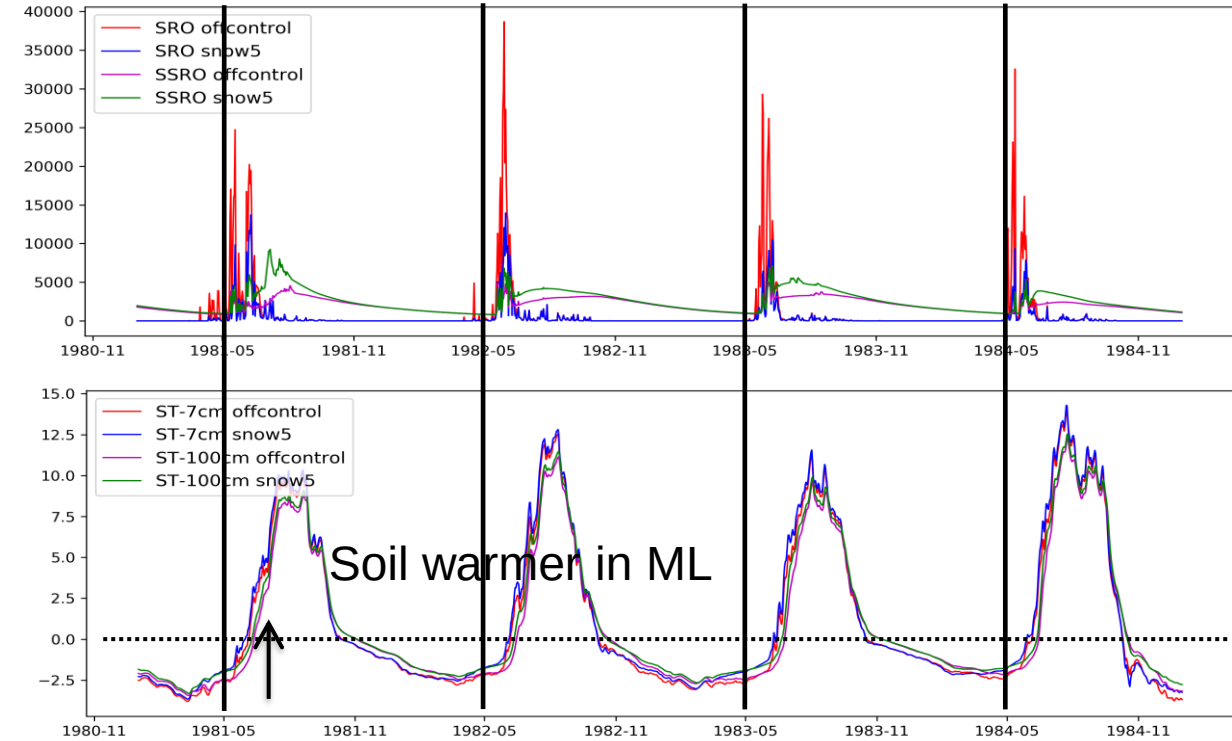
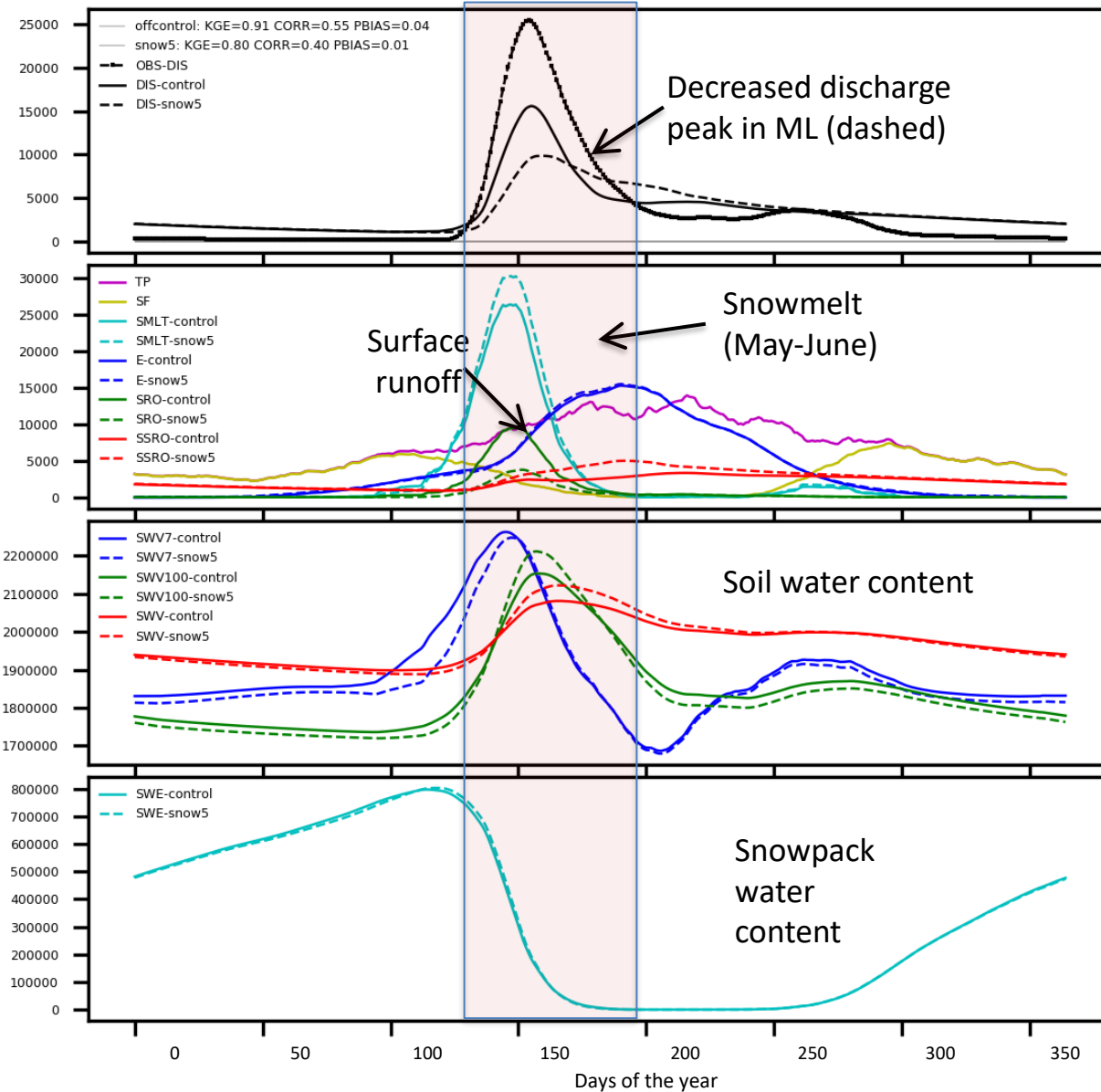




Results – cold climate problem



Daily climate mean for G0058, Yenisei, Lat=65.62, Lon=90.01, Ups=464991.0



Regardless of the slightly increasing snowmelt, river discharge is clearly smaller in ML

Surface runoff is reduced, subsurface runoff is increased, but in a delayed mode in ML

Therefore, the snowmelt-induced flood peak is reduced on ML
Snow in ML better insulates the soil, and thus more water can infiltrate into the soil



- **Work is in progress** to investigate this cold climate issue with the reduced surface runoff and reduced flood peaks in high latitudes
- The frozen soil and permafrost likely to play a major role, difficult to address
- Runoff generation processes in HTESSEL are likely related and probably will have to be looked at
- The ML snow scheme is expected to go into operations in the next major cycle at ECMWF
- Experiments of the ML scheme are being investigated for improvements of this problem
- With a target of retaining the good properties for weather parameters and at the same time improving the hydrology