The value of global hydrological reanalysis

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ECMWF

Talk outline

- Importance of global hydrological data and potential source of information
- Why using an Earth System Modelling approach?
- Example of applications of hydrological reanalysis simulations
- Conclusion and future prospects

Why global hydrological information matters?

Photo by Chris Gallagher on Unsplash

Photo by YODA Adaman on Unsplash

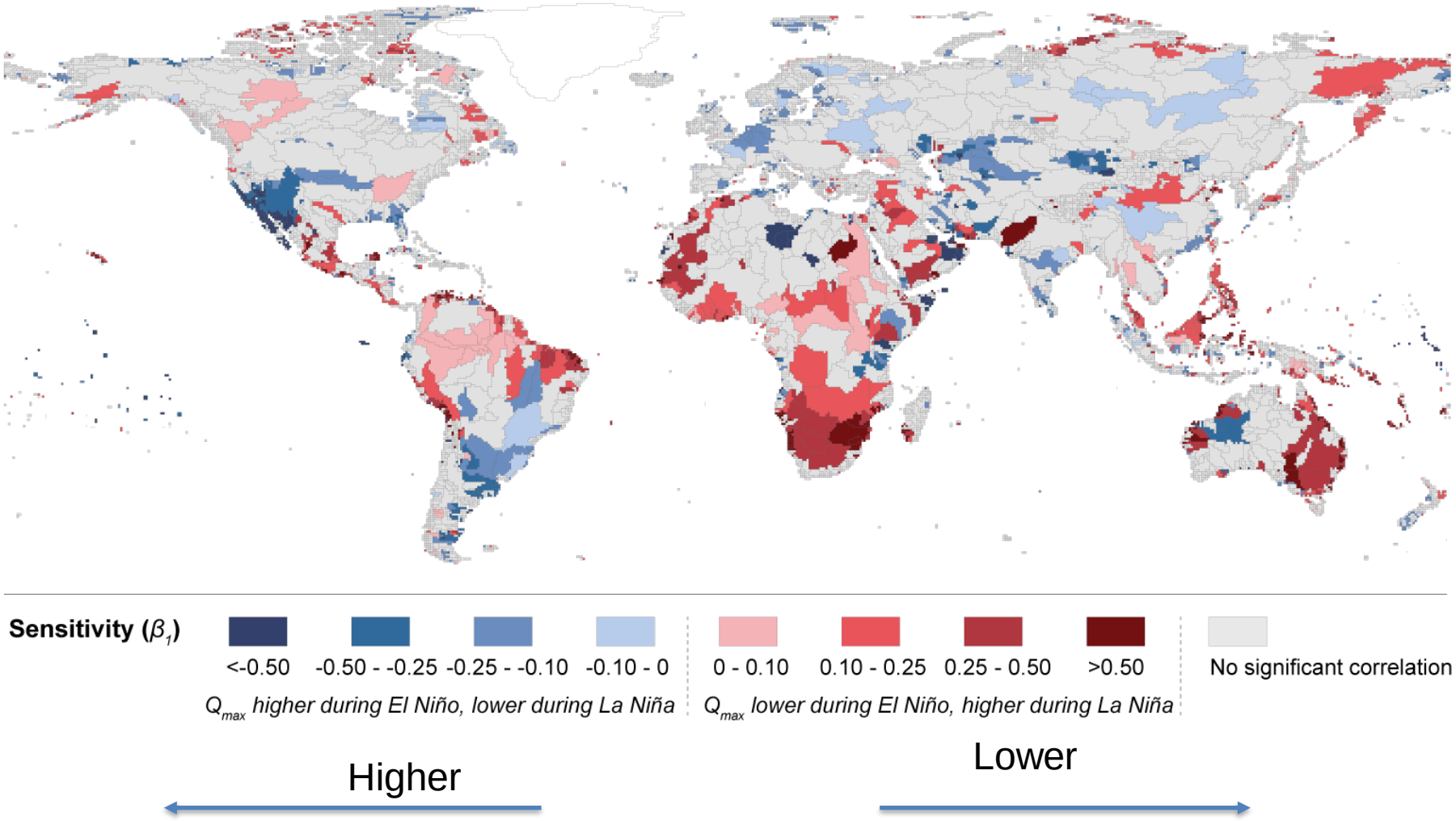
Early Warnings for All

SUSTAINABLE DEVELOPMENT GOALS

Why global hydrological information matters?

Understanding of flood risks

Example: Flood magnitude during EL Nino compared with La Nina



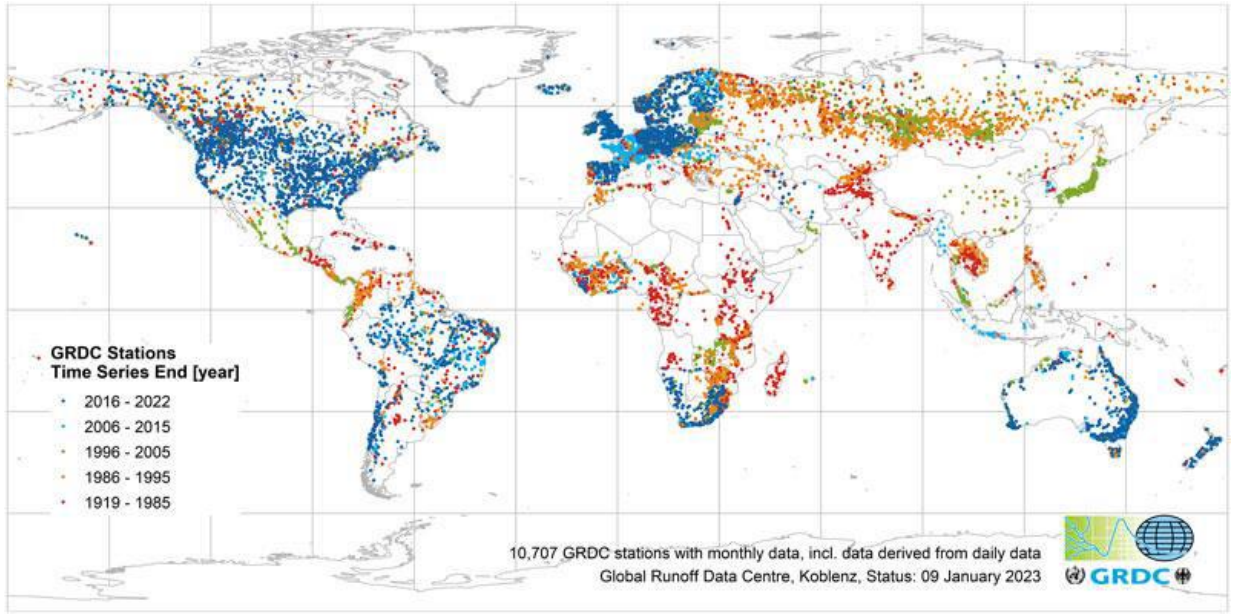
Source: Ward et al., 2014; www.hydrol-earth-syst-sci.net/18/47/2014/

Where do we have information? Observational network

In situ

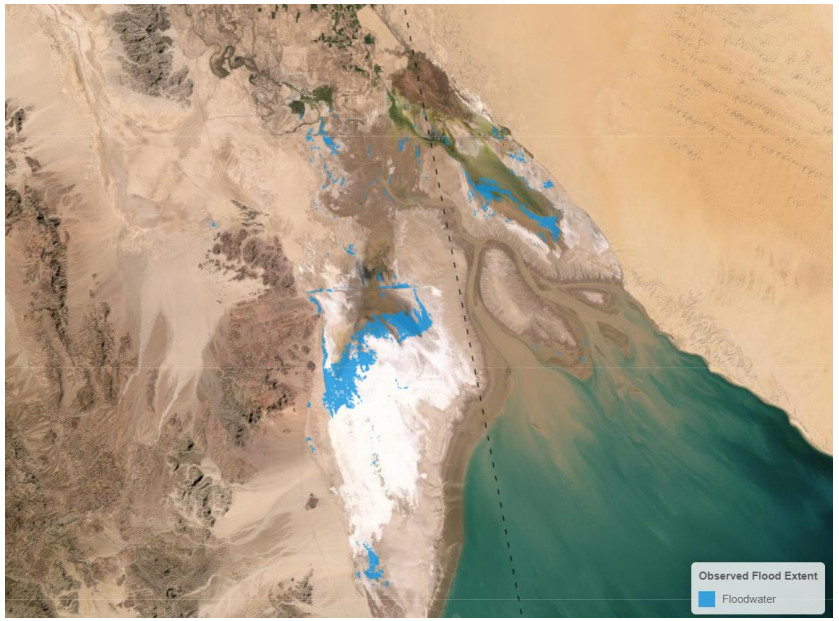
Gauging station

- **Costly** infrastructure
- River discharge not measured directly
- Lack of **near-real** time transmission
- Data **not shared**



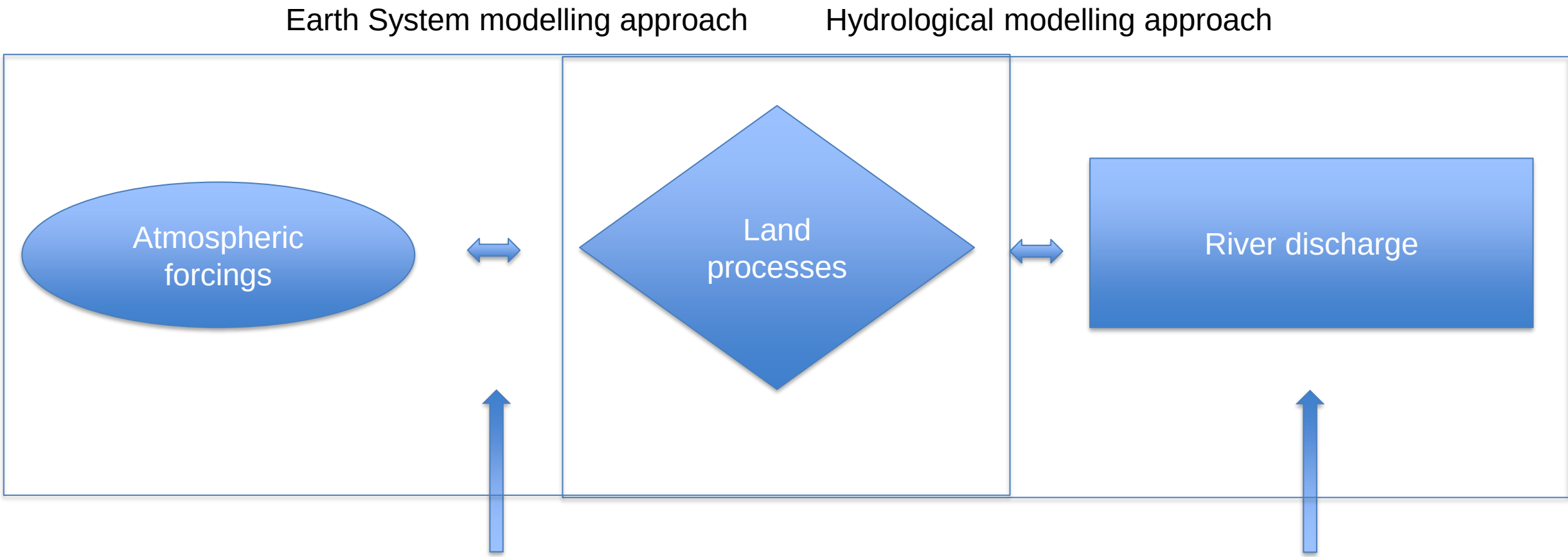
Earth-Observation

- Focus on water budget/ storage variables and **not river discharge**
- **Availability** (optical sensors)
- Update **frequency**
- No global EO- derived operational river discharge product yet



Flood extend from the Copernicus EMS Global Flood Monitoring. Source: https://www.globalfloods.eu/technical-information/glofas-gfm/

Where do we have information? Modelled datasets



Where do we have information? Modelled datasets

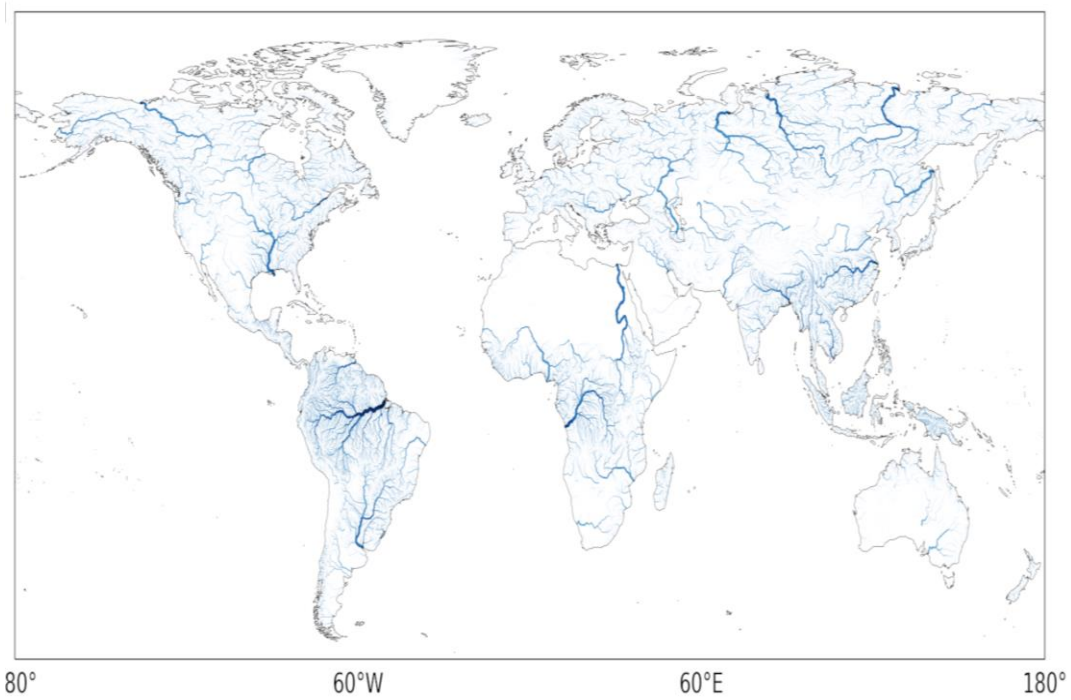
Advantages

- **Fill** spatial and temporal gaps
- **Continuous/ consistent** datasets
- Benefits from all **reanalysis advances**
- **Consistent** with forecast/ projection simulations

Limitations

- **Limited** process representation (human influence, groundwater, wetlands)
- **Dependent** on forcing quality (e.g. ERA5 precip)
- **Lack** of global evaluation/ verification

In the rest of the talk referred to as 'hydrological reanalysis'



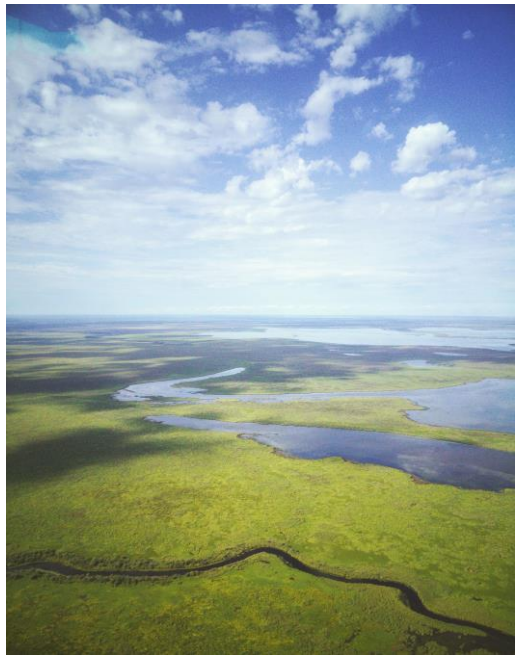


Photo by Landon Parenteau on Unsplash

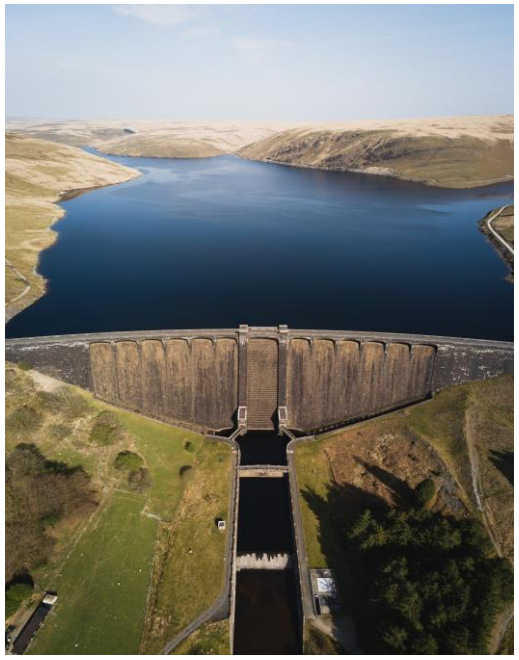


Photo by Marcus Woodbridge on Unsplash

Hydrological modelling approach: the example of GloFAS

Emergency Management

The **Global Flood Awareness System (GloFAS),** EU's global hydrological prediction system, forms part of the **Copernicus Emergency Management Service (CEMS)** and is fully operational since 2018

The Joint Research Centre of the European Commission is the entrusted entity responsible for **CEMS GloFAS** in terms of management, technical implementation and evolution. **ECMWF** is the designated contractor to implement the **operational functionalities of the CEMS-COMPUTATIONS**

- **Operational global flood Early Warning System** (hydro. forecasts; riverine flood; larger rivers)
- **Complementary** information to National Hydrological and Meteorological Services (NHMS)
- **Support** to international organisations and local decision making
- Global forecast and historical simulation data **freely available** from the C3S Climate Data Store

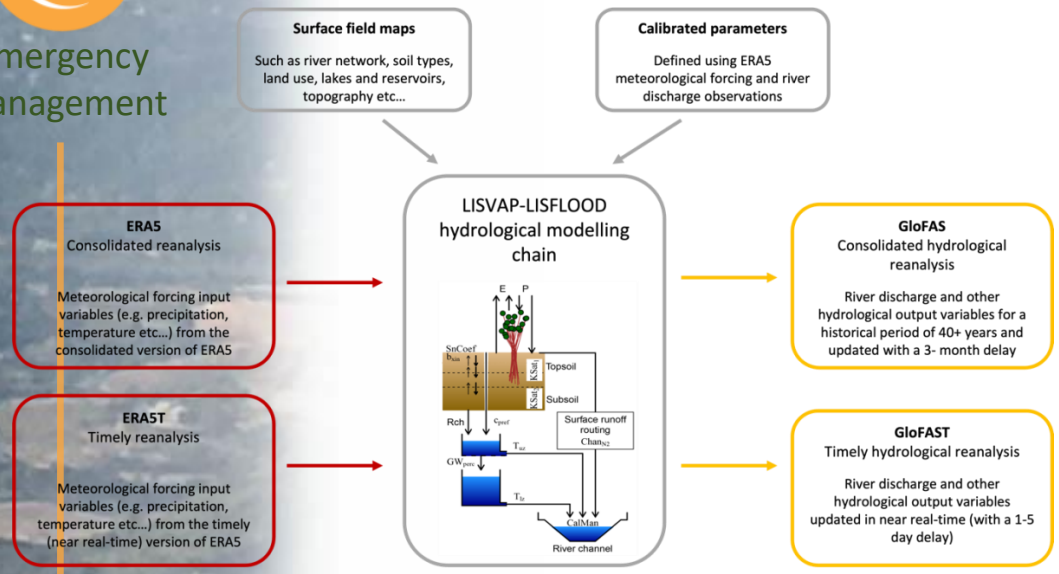
PROGRAMME OF THE EUROPEAN UNION

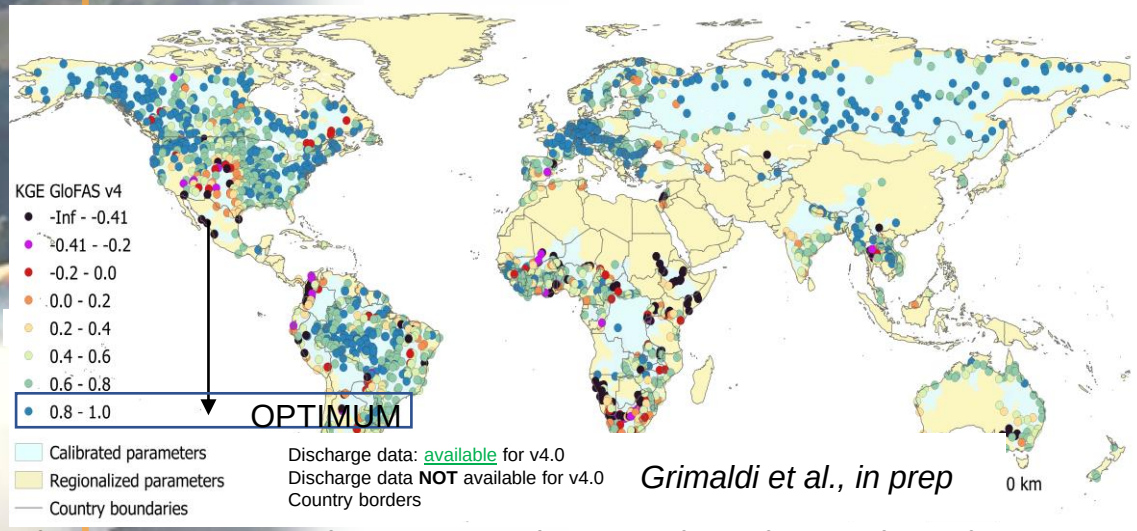
Copernicus Europe's eyes on Earth

Emergency Management

GloFAS version 4

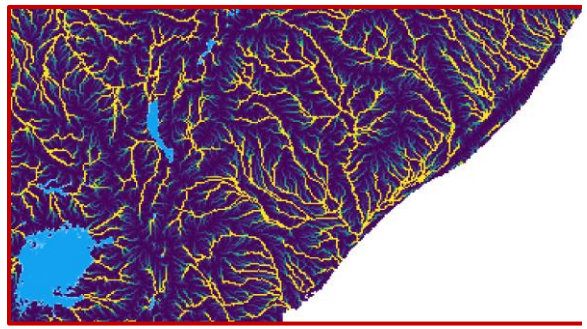
Emergency Management

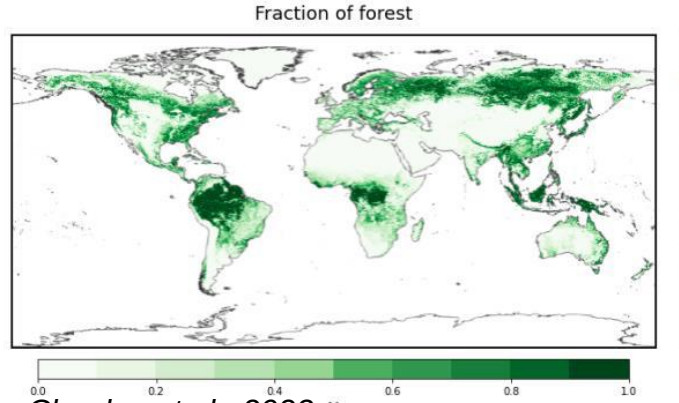




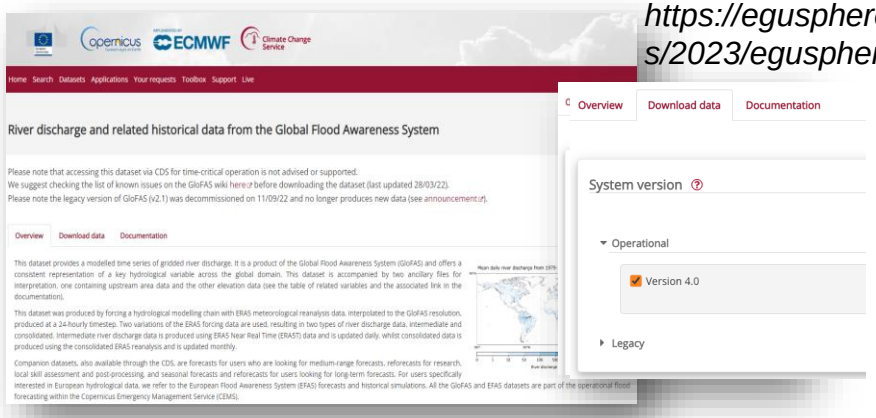
Grimaldi et al., in prep

- Gridded river discharge at 3 arcmin (~5km) everywhere in the world (except Antarctica)
- LISFLOOD-OS model + high resolution land surface fields
- **Calibrated** on nearly 2000 catchments + regionalized parameter
- Daily time series forced with ERA5 1980- present freely available without restriction of use
- Operational product released in the Copernicus Climate Data Store





Choulga et al., 2023; https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1306/

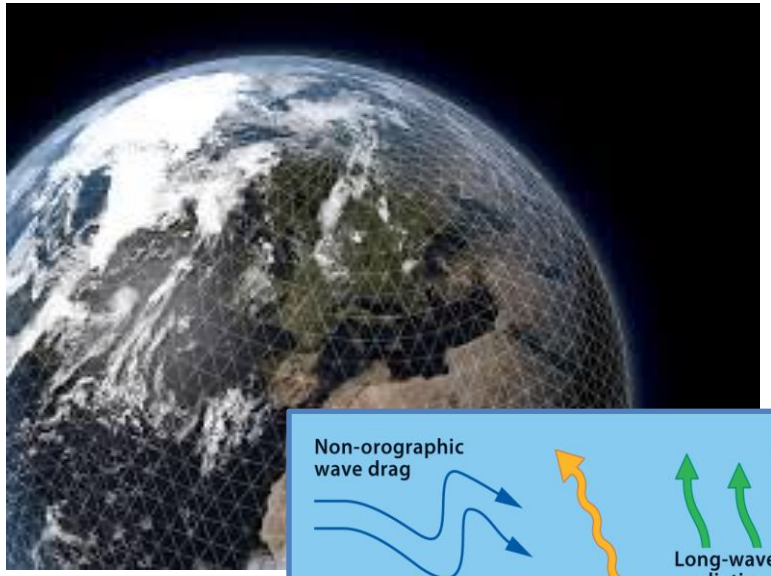


Climate Data Store
DOI: 10.24381/cds.a4fdd6b9

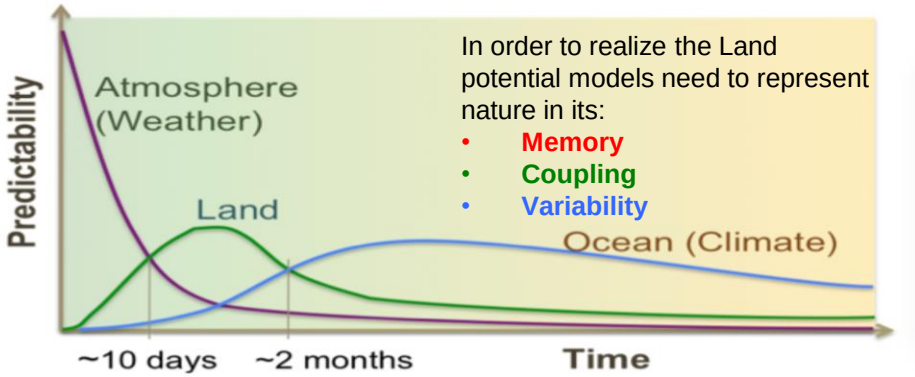
Similarity measure between observed and simulated time series

Calibration – optimization of similarity measure

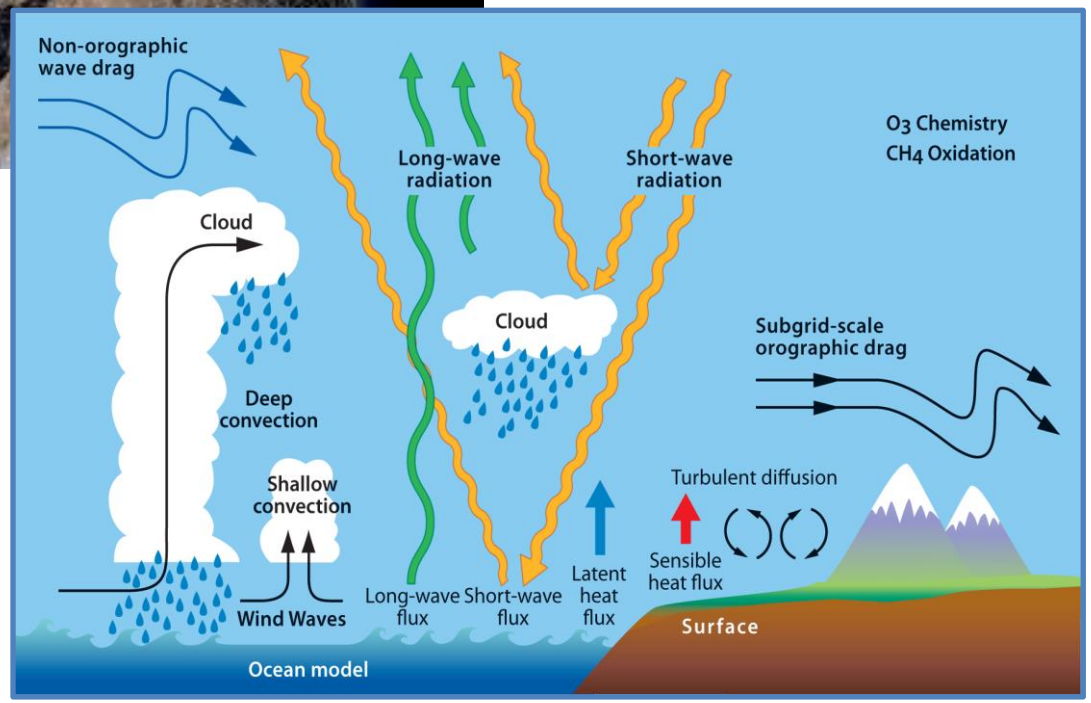
Earth System modelling approach: the example of IFS/ECLand-Hydro

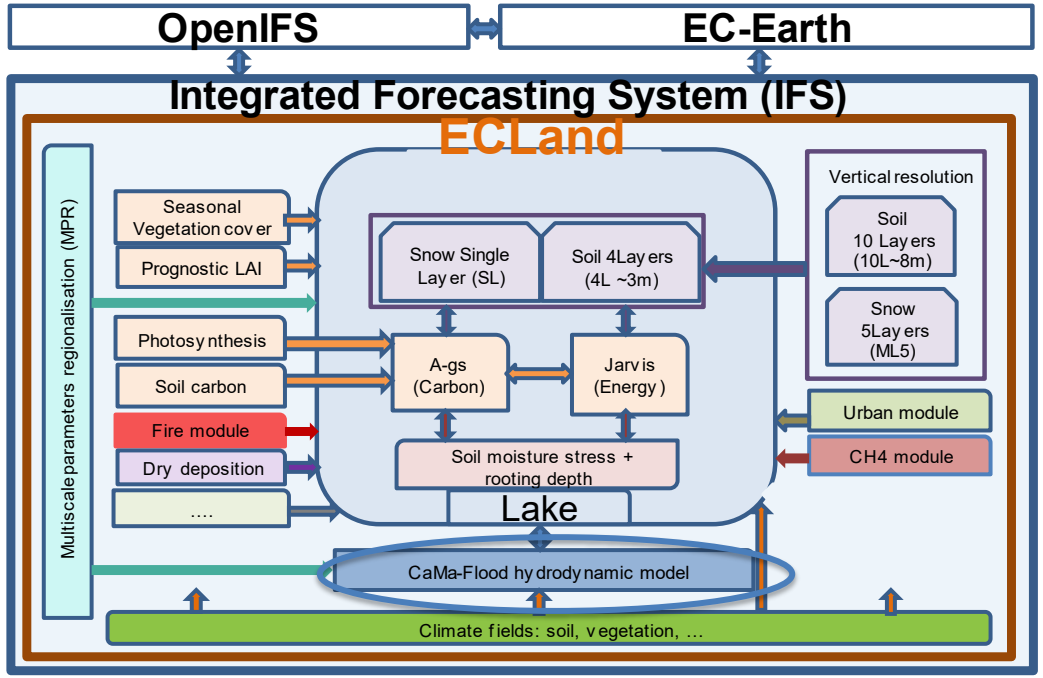


- IFS: coupled atmosphere, land, ocean and wave models
- Different spatial resolutions for different applications
- ECLand modular framework to integrate **new processes**



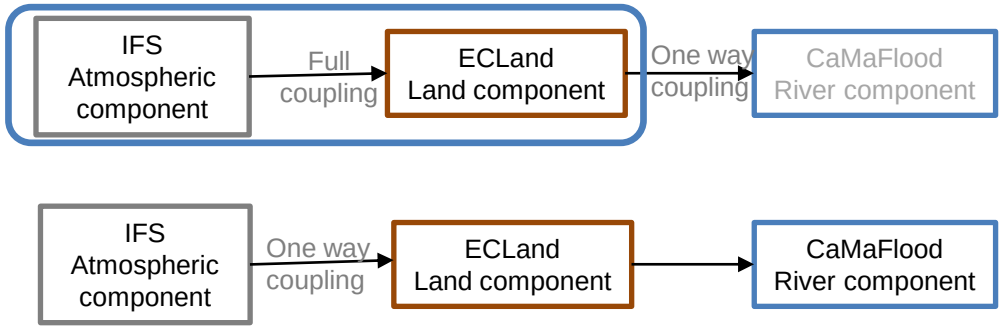
Dirmeyer et al. 2015:
http://library.wmo.int/pmb_ged/wmo_1156_en.pdf



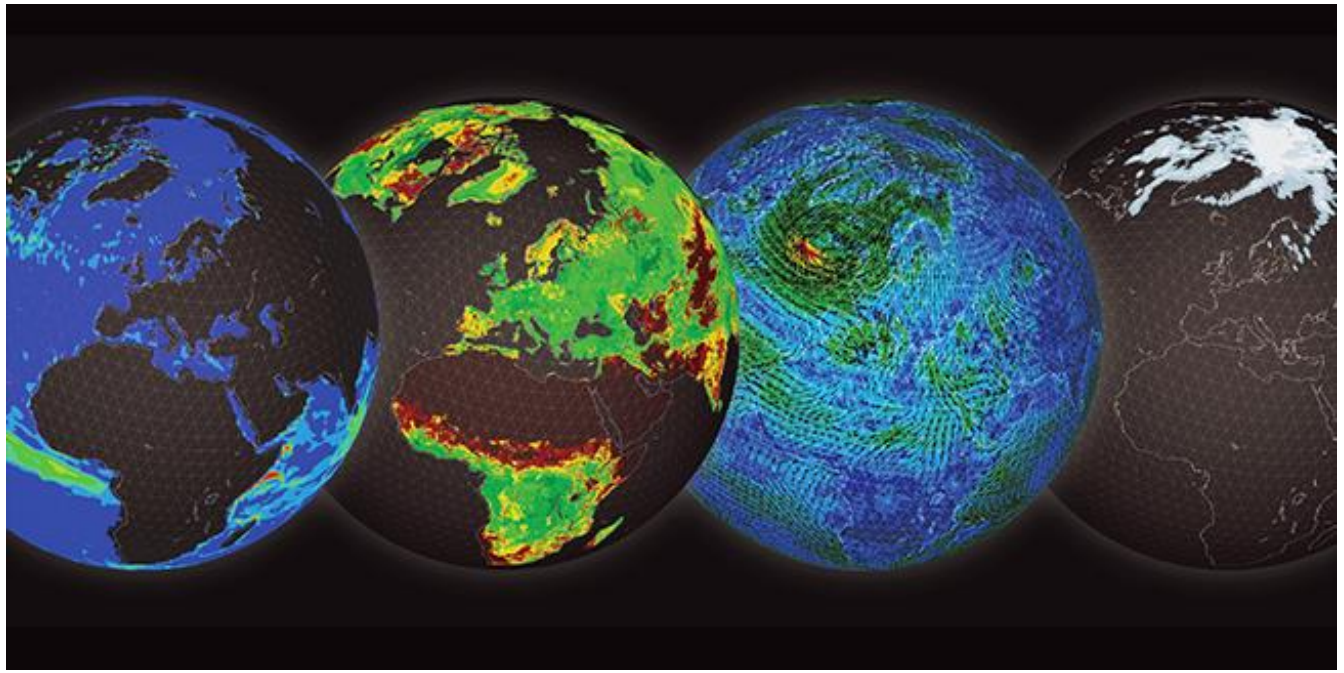


Boussetta, Balsamo, et al. 2021
https://www.mdpi.com/2073-4433/12/6/723

ECLand-Hydro set-up

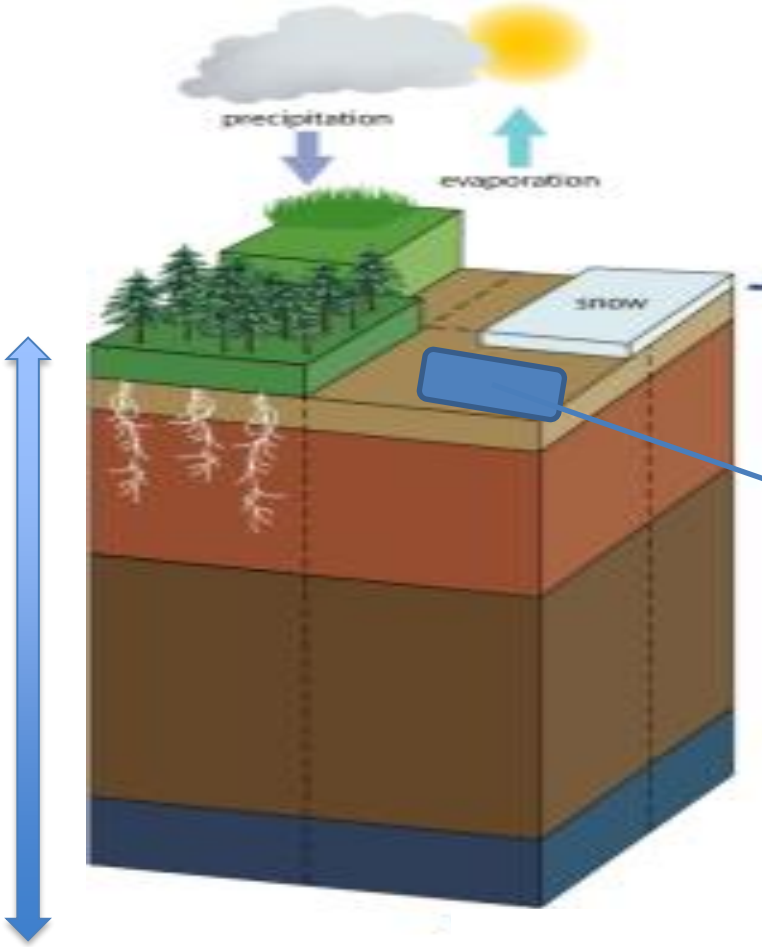


- Two (one-way) coupling configurations possible
  - Land-river discharge (with full coupling land-atmosphere)
  - Atmosphere-land
- CaMaFlood river routing model at 6, 3 and 1 arcmin spatial resolution
- Currently no river discharge calibration
- Gridded river discharge everywhere in the world (except Antarctica)
- Can be used to test any new ECLand development



Earth System Approach

Traditional Land Surface Model

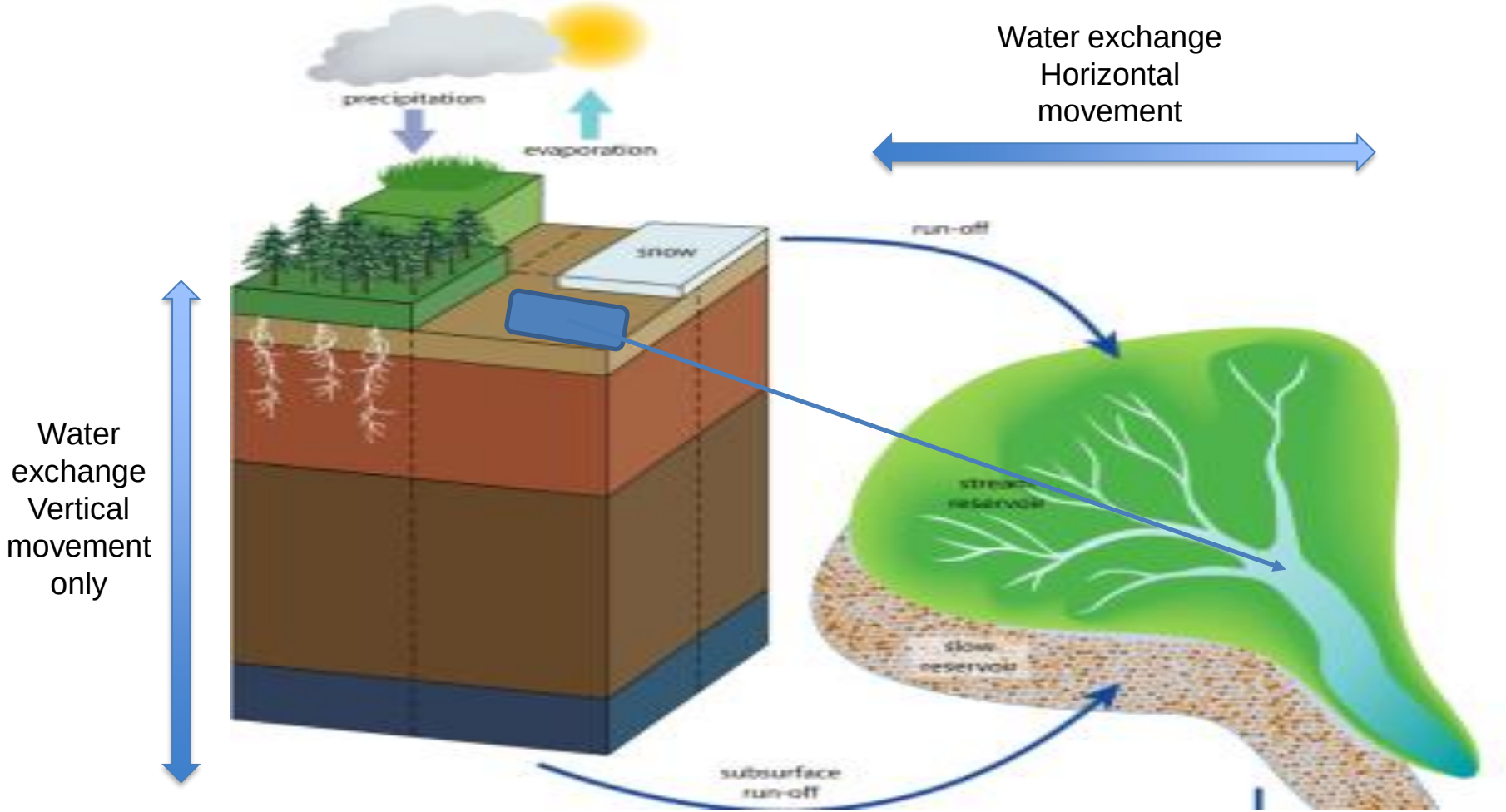


Rivers are part of the real world, but they generally don’t exist in Earth System Models

Earth System Approach – what can rivers tell us?

Traditional Land Surface Model

… and now with rivers



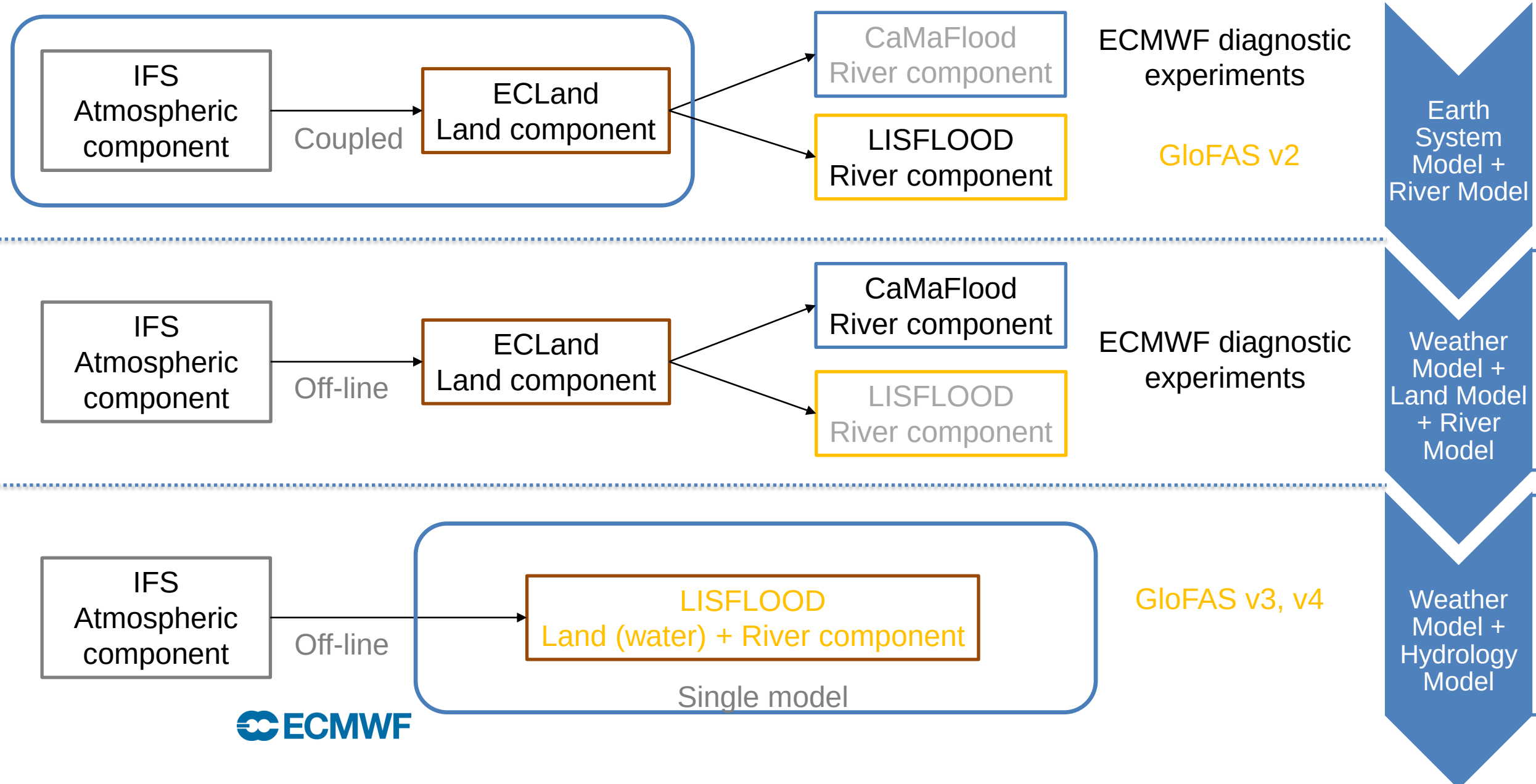
Rivers are **natural integrators** of water cycle over land
in time and space

Quality indicator of integrated water budget

Amplify signals

Independent diagnostic tool

Hydrological reanalysis: Modelling framework



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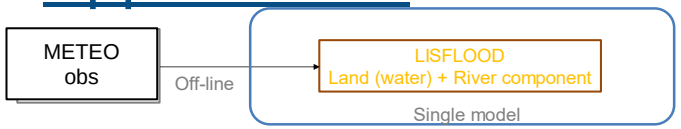
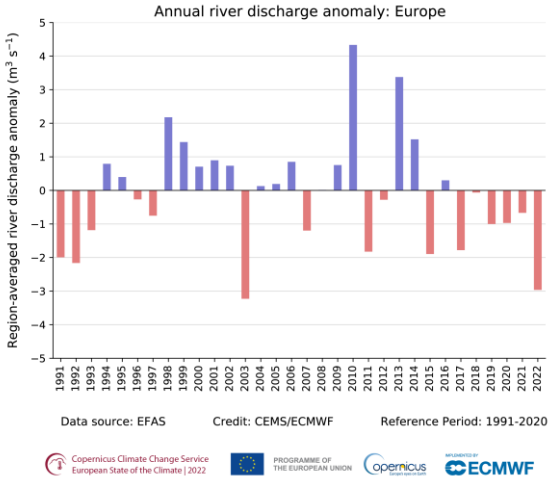
Application 1: Monitoring of water resources



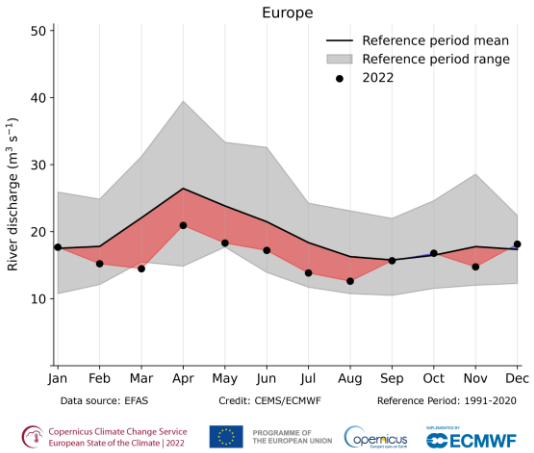
LISFLOOD off-line observed Meteo fields (full hydro calibration)

Daily river discharge calculated with <5 days delay

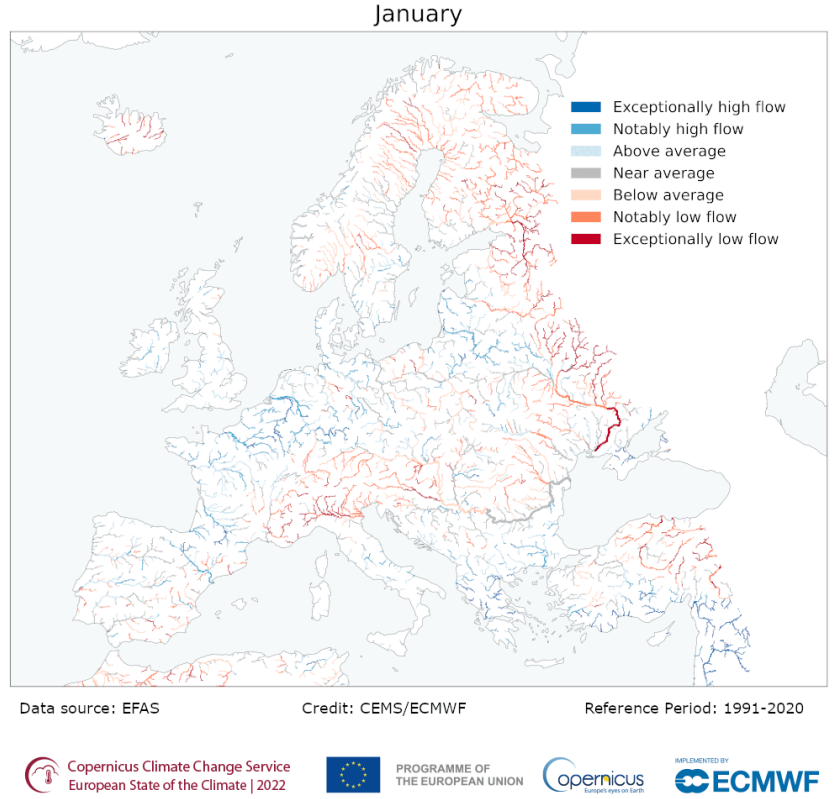
Daily river discharge reference from same model configuration from 1991-2020



Annual anomalies 1991-2022 relative to average 1991-2020



Monthly average discharge for 2022, and deviations relative to average 1991-2020

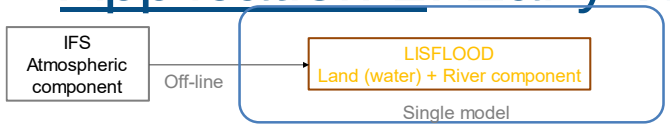


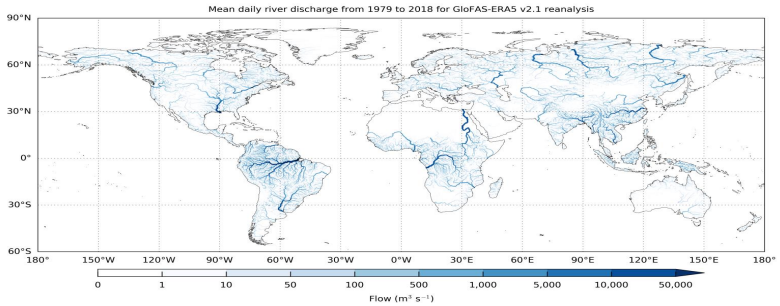
Source: European State of the Climate 2022, https://climate.copernicus.eu/esotc/2022/river-discharge

Europe benefits from **meteo observations**

GloFAS-Hydro used for WMO 'state of global water 2023' report

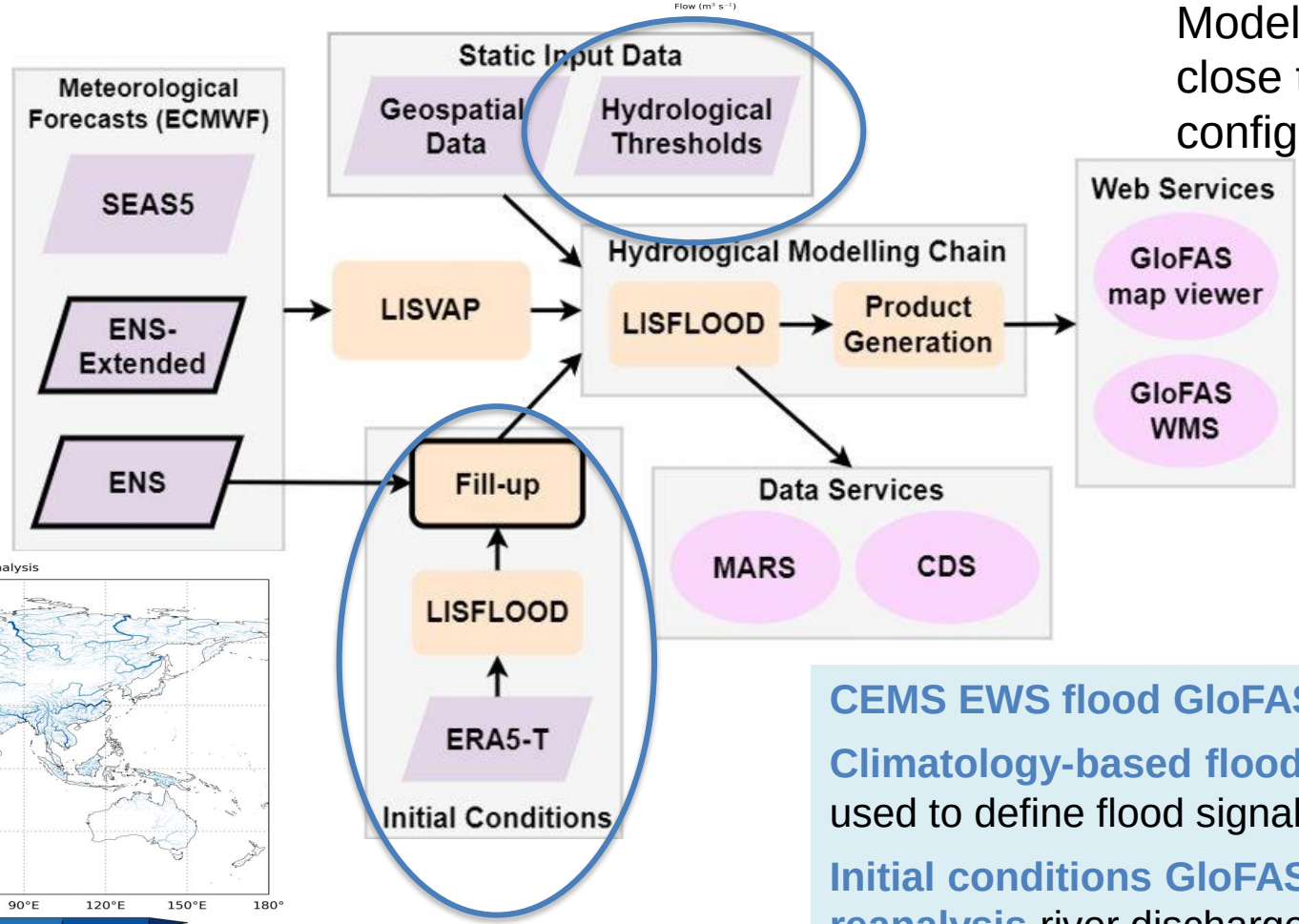
Application 2: Early Warning Systems

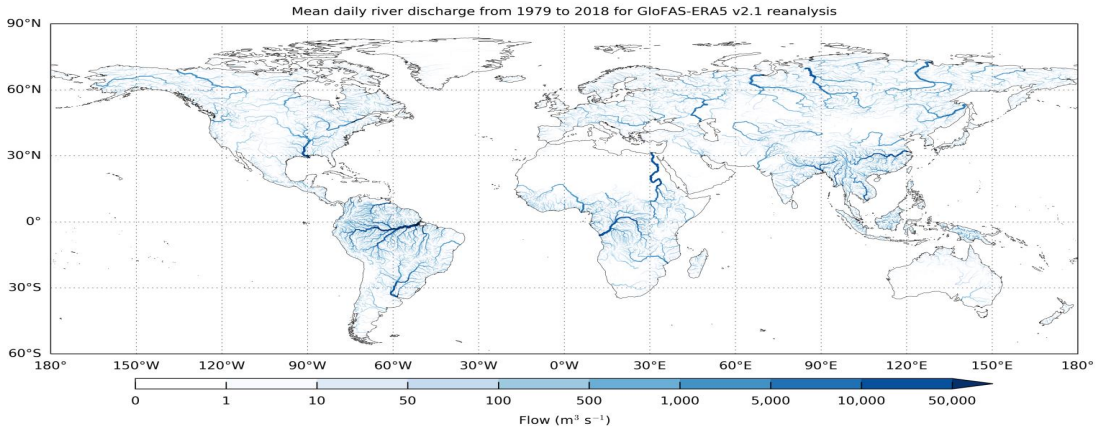




Values **everywhere** in the world
Time series **as long as possible**
Model **configuration** close to operational configuration

Value **everywhere** in the world
Time series as close to **real-time** as possible
Model **configuration** close to operational configuration





CEMS EWS flood GloFAS

Climatology-based flood thresholds used to define flood signal

Initial conditions GloFAS-Hydro reanalysis river discharge daily time series near real-time

Simulations **updated daily** freely available

ECMWF

opernicus
The European Earth Observation Programme

Application 3: GloFAS-ERA5 river discharge stationarity

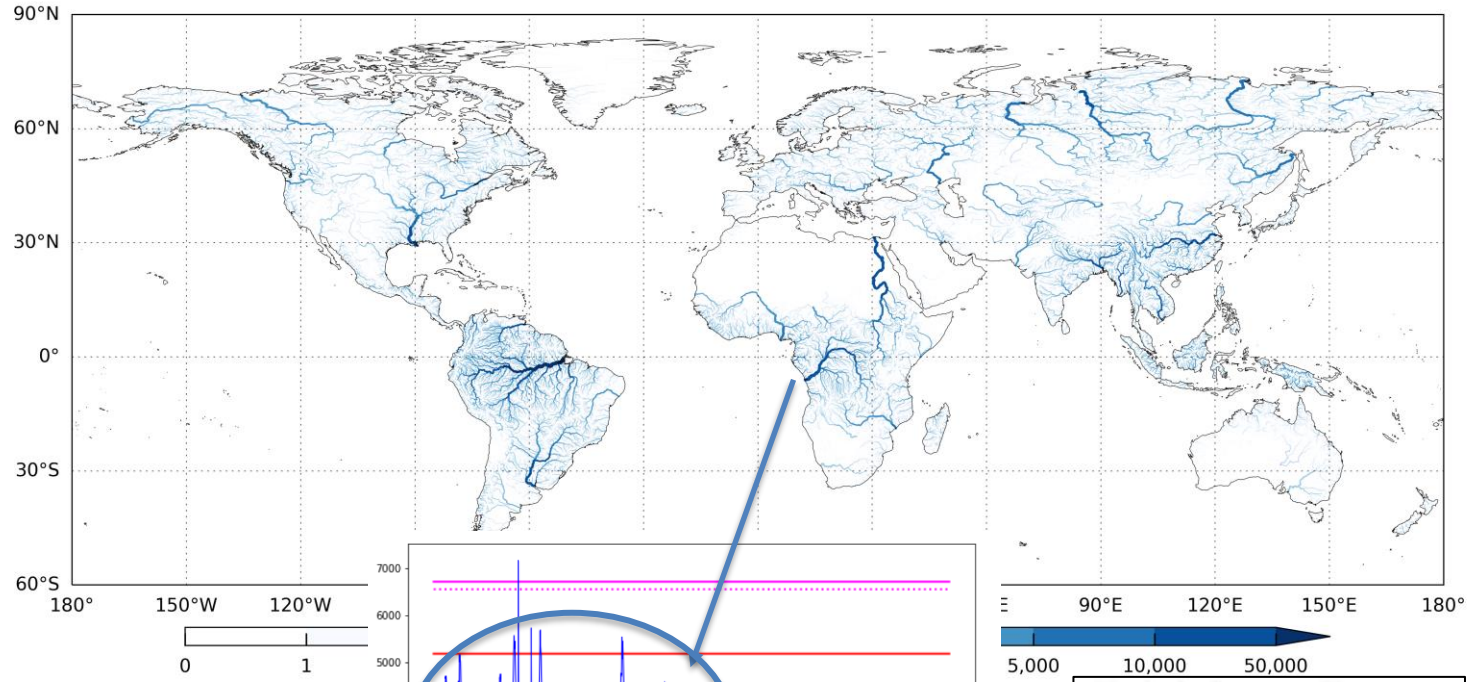
GLOFAS is Global Early Warning System for Floods of Copernicus Emergency Management Service

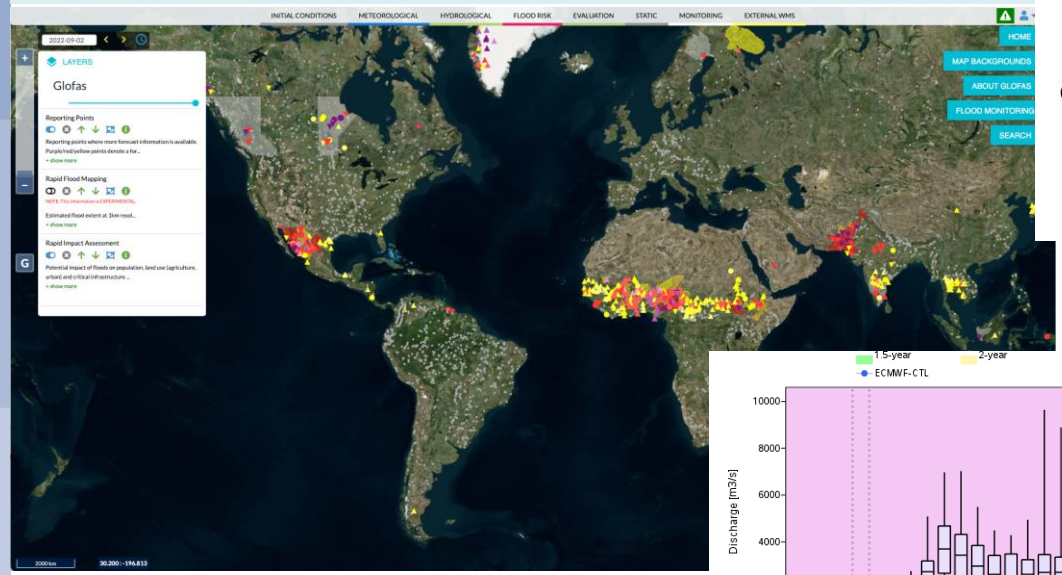
Climatology-based flood thresholds used to define flood signal

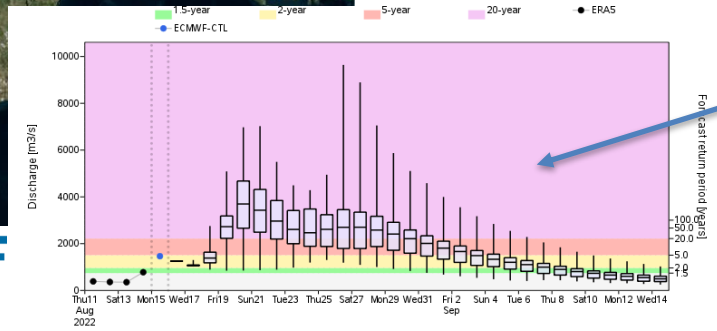
GloFAS-ERA5 reanalysis river discharge daily time series used for thresholds

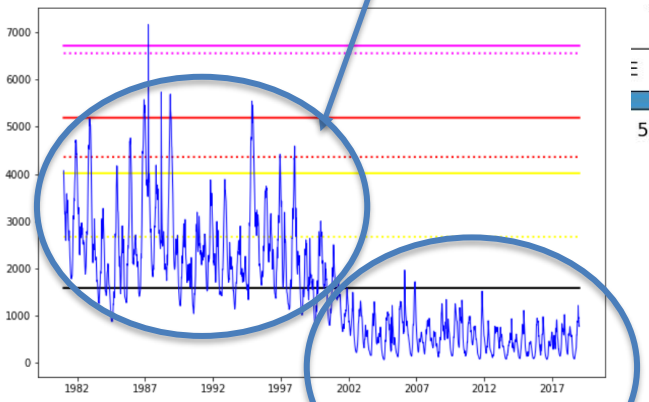
Version 2.1 upgrade highlighted **trends** in time series to be verified

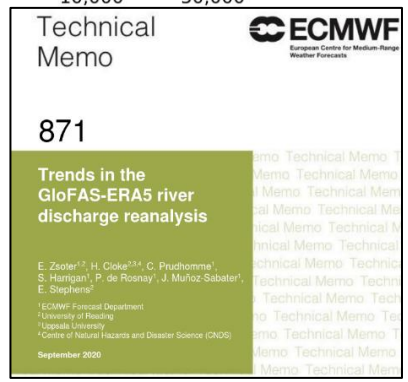
Mean daily river discharge – GloFAS-ERA5 reanalysis 1979-2018





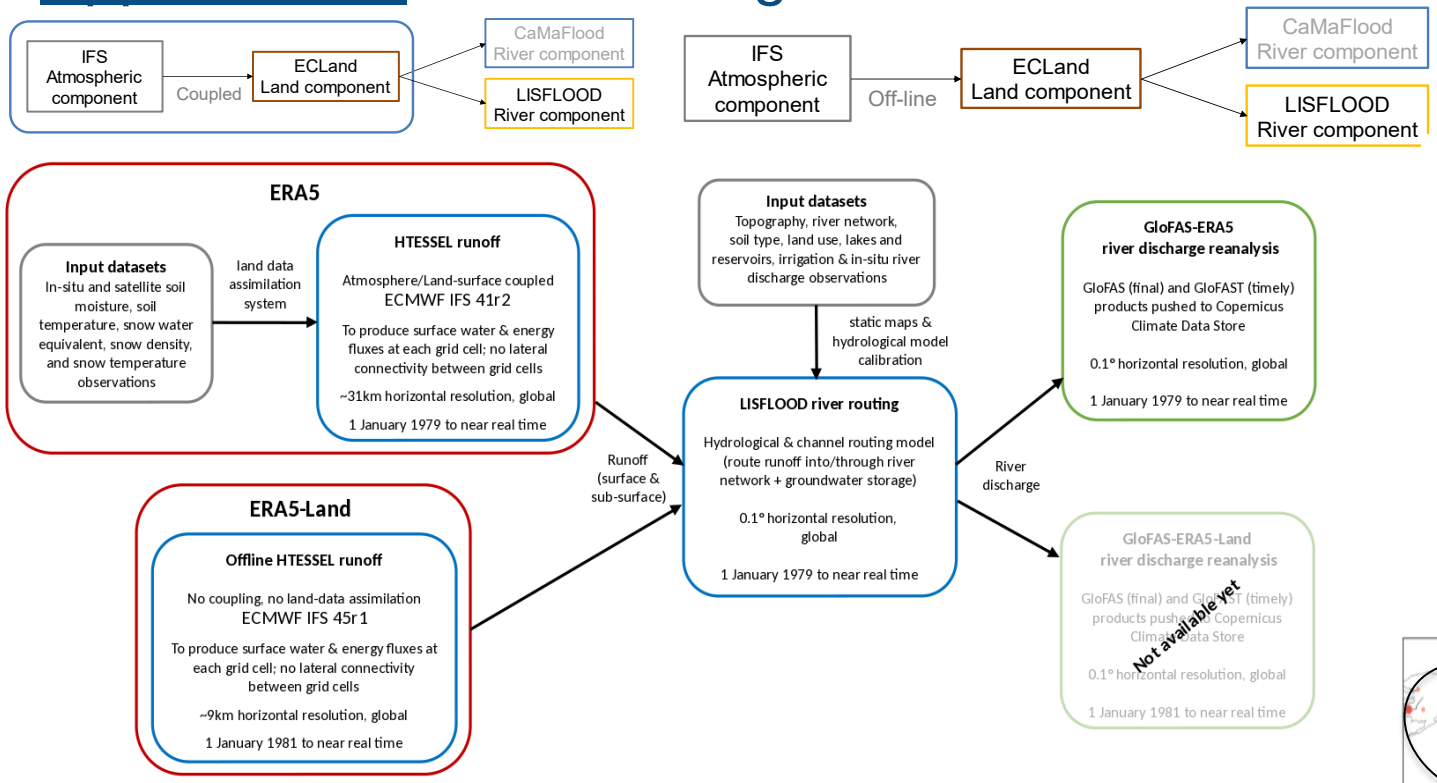






Zsoter et al., 2020, ECMWF Tech Memo 871

Application 3: Main findings



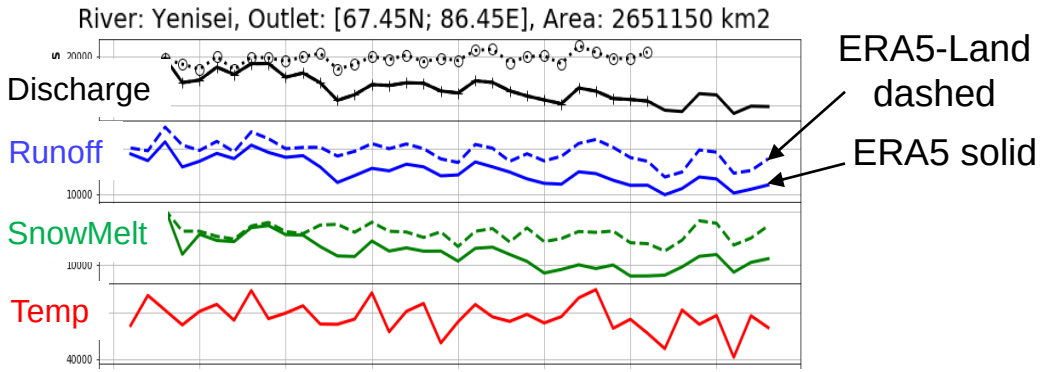
Discharge trends **not seen** in ERA5 temperature and precip

Large ERA5 snow melt trends in 1981-2003 similar to GloFAS-ERA5 river discharge spurious trends

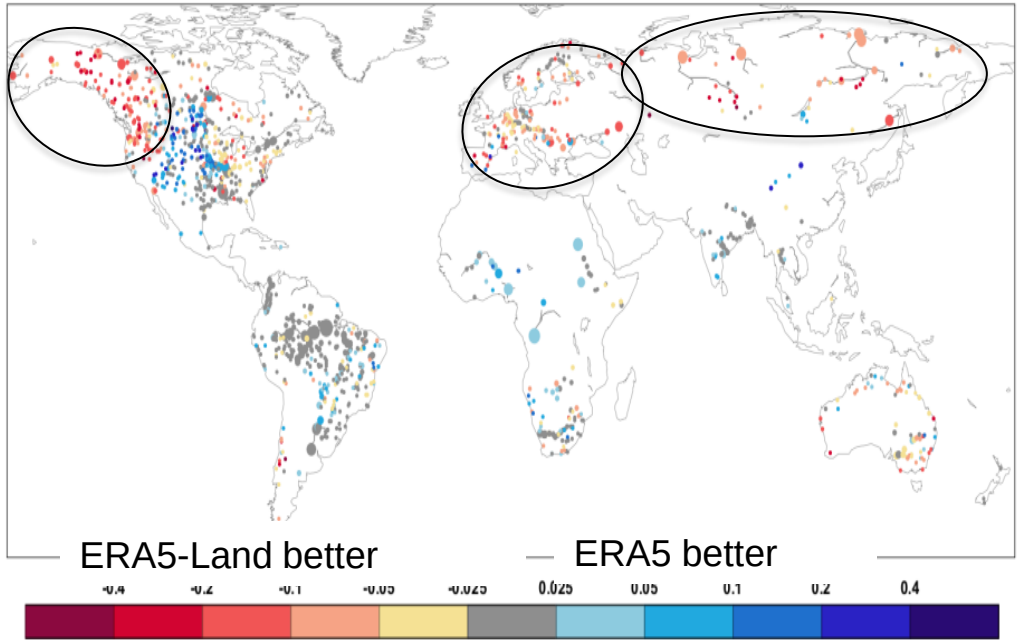
Trends much smaller in ERA5-L for same period

ERA5 assimilation of IMS snow cover (started in 2004) could be the main contribution (but likely not the only one)

ERA5 and ERA5Land annual mean evolution over land surface variables



Discharge trend 'error' differences (ERA5-Land - ERA5)



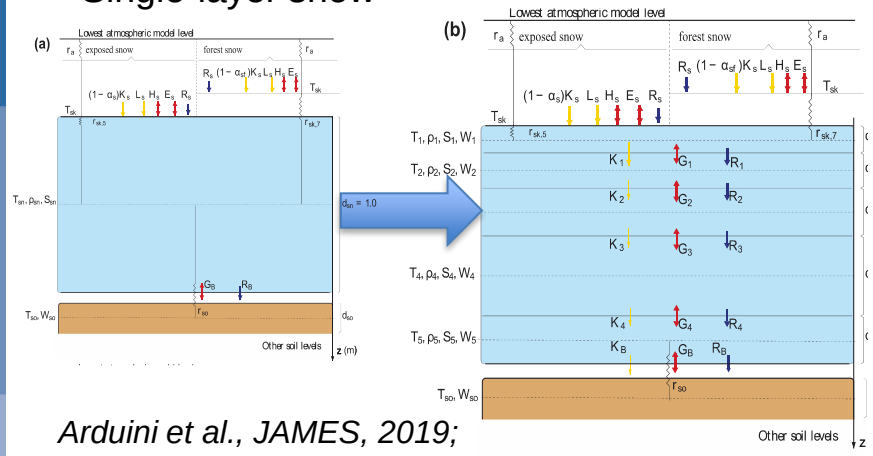
ECMWF

Work by Zsoter et al., 2020, ECMWF Tech Memo 871

Application 4: Upgrade ECLand snow-scheme

Single-layer snow

Multiple-layer snow

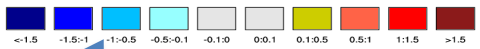


Arduini et al., JAMES, 2019;
Day et al., JAMES, 2020,
Boussetta et al., MDPI-Atm., 2021

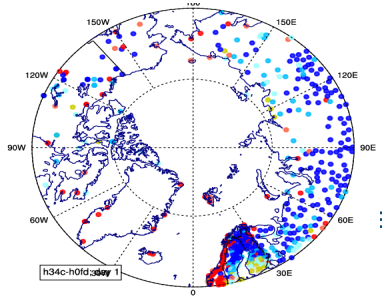
Substantial improvement in **snow depth**

Reduced error also in the forecasts of (especially) **minimum temperature** (+24h)

Explorative work for snow on sea-ice



ML snow reduces T_{min} bias

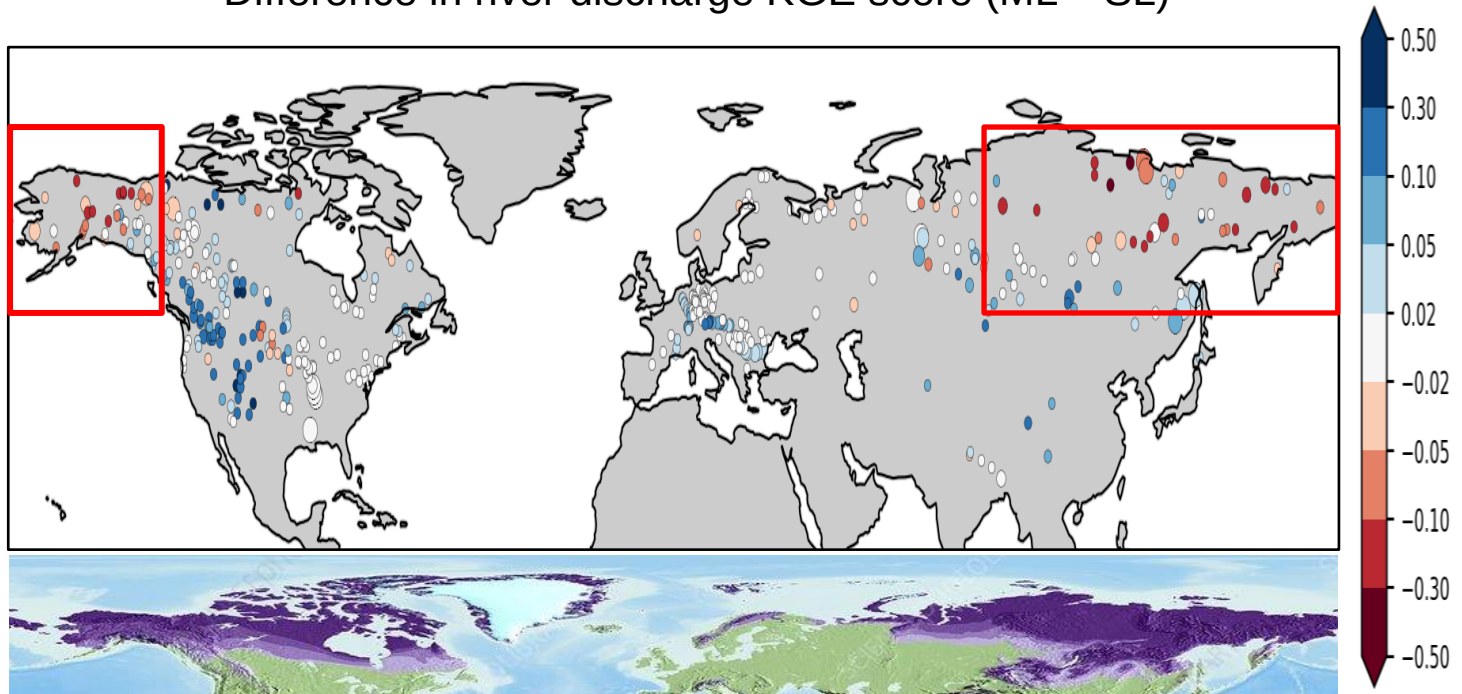


Minimum T2m

APPLICATE.eu
Advanced prediction in polar regions and beyond

Difference in river discharge KGE score (ML – SL)

ML better



ML worse

Discharge improved in mid-latitudes

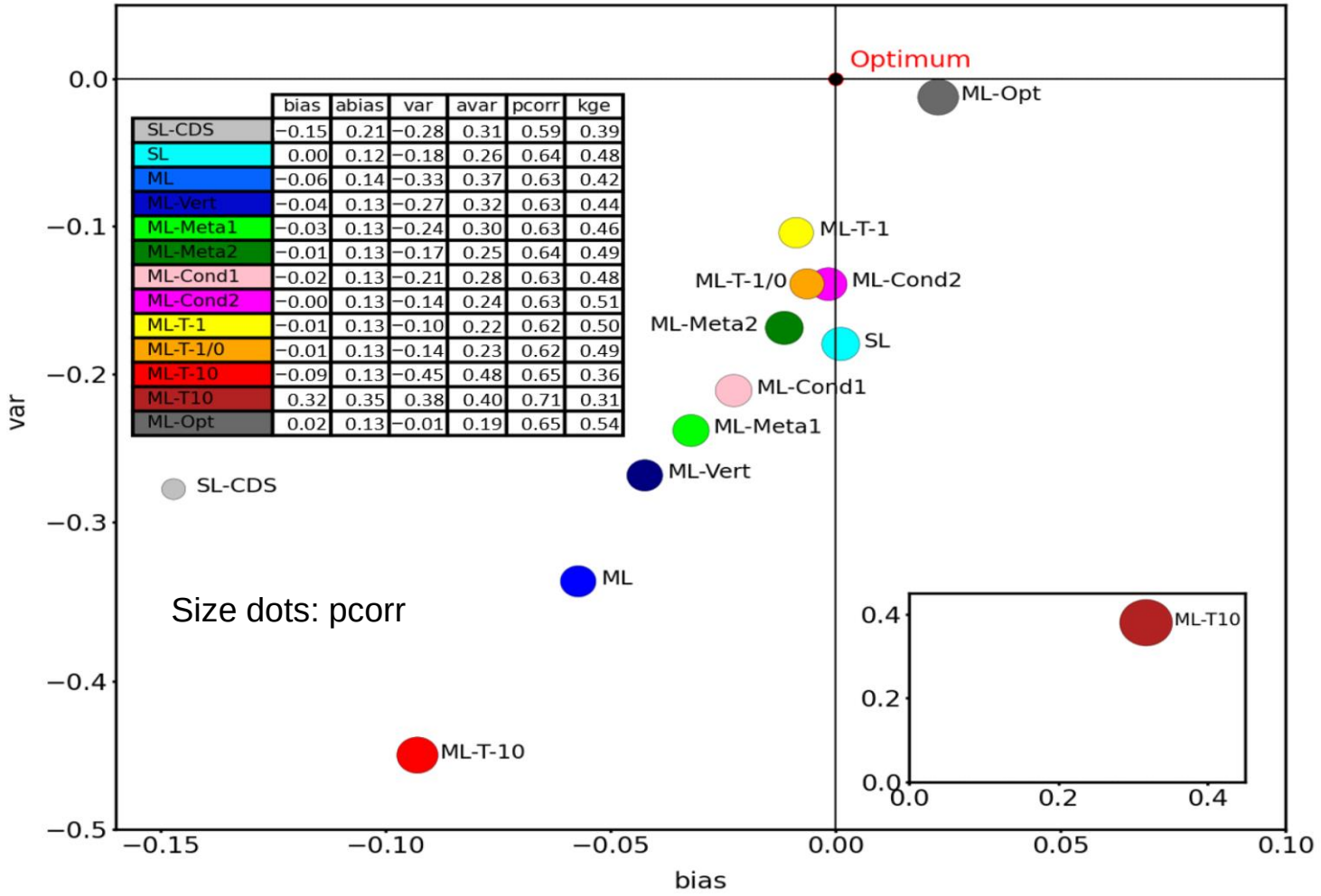
Large degradation **in cold climates**

Degradation linked with **runoff generation**

Work by Zsoter, Arduini et al., 2022, https://doi.org/10.3390/atmos13050727

Application 4: New ML snow parameterisation

Hydro performance
69 catchments in 60-80N belt of permafrost area



	bias	abias	var	avar	pcorr	kge
SL-CDS	−0.15	0.21	−0.28	0.31	0.59	0.39
SL	0.00	0.12	−0.18	0.26	0.64	0.48
ML	−0.06	0.14	−0.33	0.37	0.63	0.42
ML-Vert	−0.04	0.13	−0.27	0.32	0.63	0.44
ML-Meta1	−0.03	0.13	−0.24	0.30	0.63	0.46
ML-Meta2	−0.01	0.13	−0.17	0.25	0.64	0.49
ML-Cond1	−0.02	0.13	−0.21	0.28	0.63	0.48
ML-Cond2	−0.00	0.13	−0.14	0.24	0.63	0.51
ML-T-1	−0.01	0.13	−0.10	0.22	0.62	0.50
ML-T-1/0	−0.01	0.13	−0.14	0.23	0.62	0.49
ML-T-10	−0.09	0.13	−0.45	0.48	0.65	0.36
ML-T10	0.32	0.35	0.38	0.40	0.71	0.31
ML-Opt	0.02	0.13	−0.01	0.19	0.65	0.54

Hydrological performance able to diagnose issues in permafrost parameters

Identification of **soil temperature issues** and resulting water infiltration

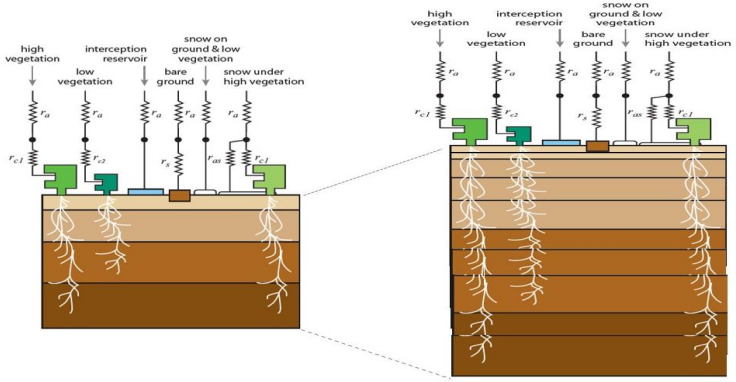
Sensitivity analysis on **13 experiments**

ML-Meta1 parameterization in CY48R1 (best compromise between improved hydrology in permafrost without degradation elsewhere)

ECMWF

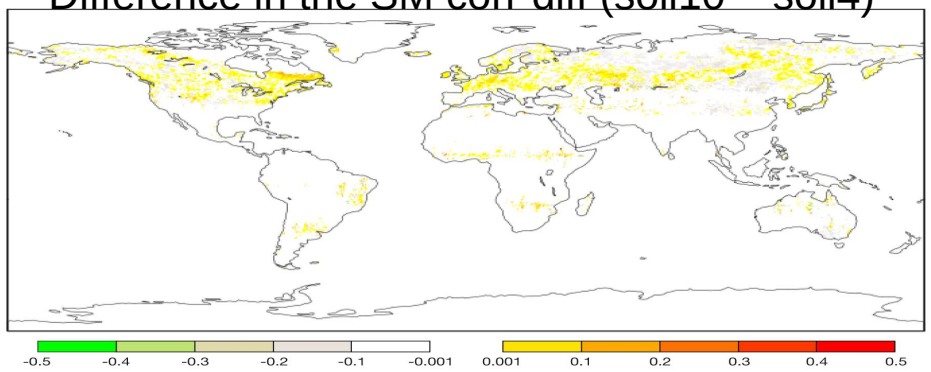
Work by Zsoter, Arduini et al., 2022, https://doi.org/10.3390/atmos13050727

Application 5: Upgrade of IFS soil scheme in ECLand



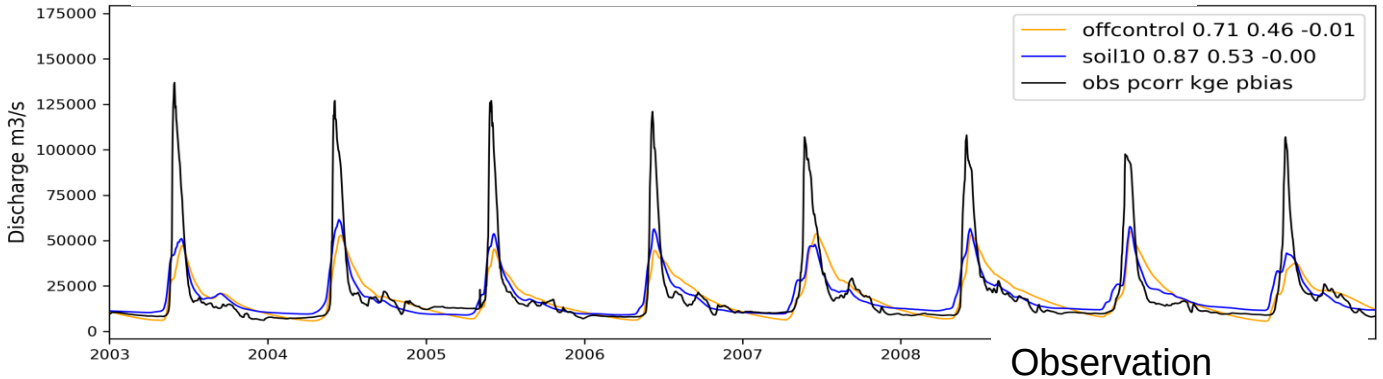
Introduced to improve **diurnal range** Land Surface Temperature
Deeper soil column
Finer **soil discretisation**

Difference in the SM corr diff (soil10 – soil4)

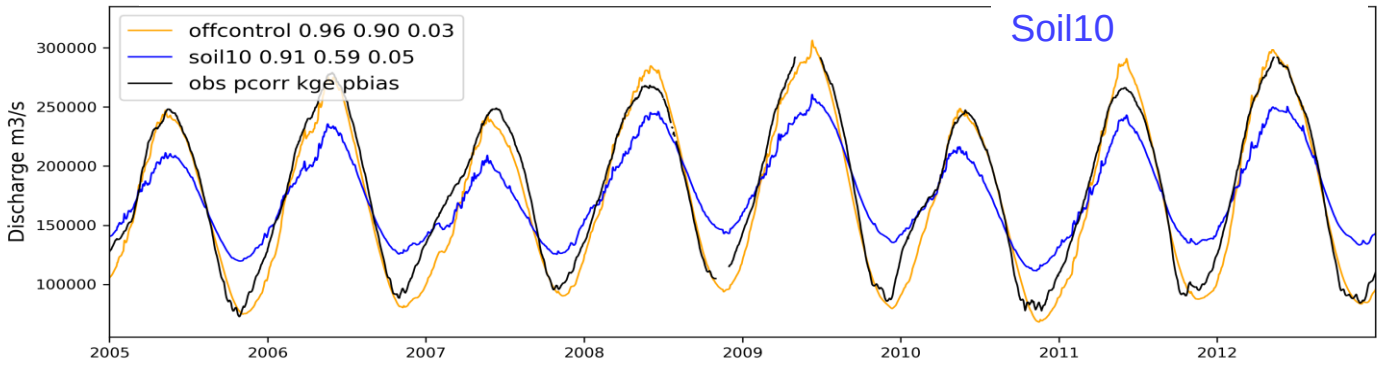


Soil10 worse **Soil10 better**

Yenisei (Asia; 6.5Mkm^2; lat 67.4)



Amazon (South America; 4.7Mkm^2; lat -1.92)



Observation
Soil4
Soil10

Soil10 impacts negatively on river discharge

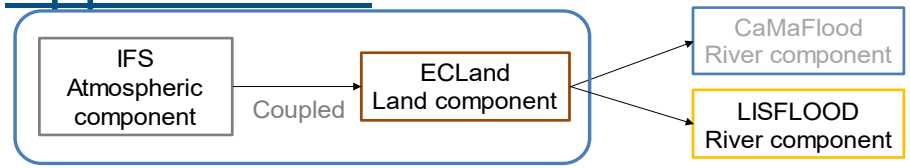
Soil10 generally **adds water**

Large discharge correlation degradation, moderate kge degradation

More prognostic needed before integration in IFS cycle

Boussetta, S., Arduini, G. et al., 2021, https://doi.org/10.5194/egusphere-egu21-9740

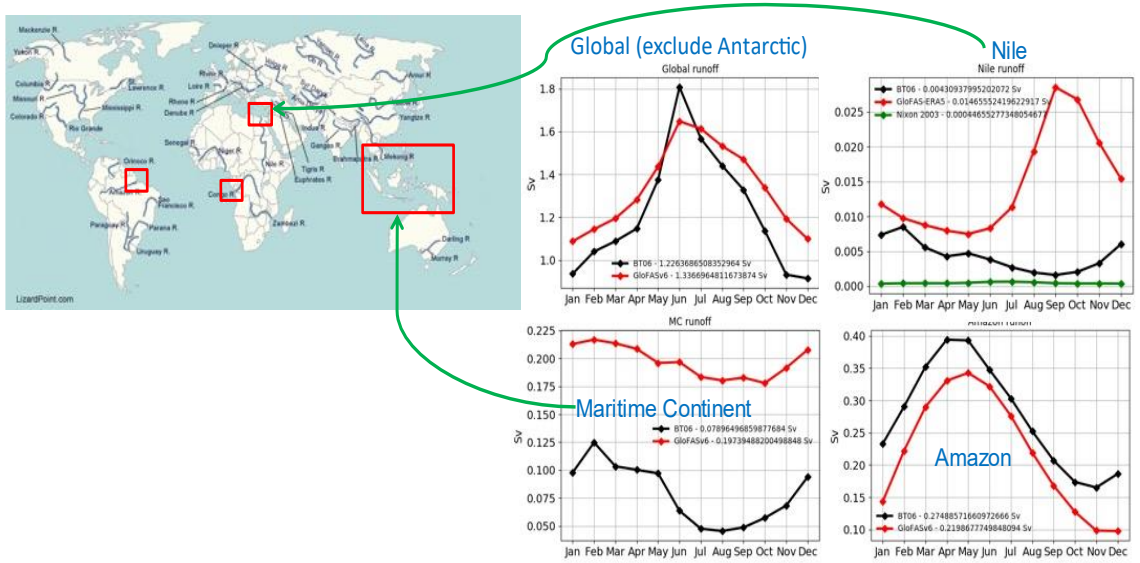
Application 6: Global Ocean Monitoring



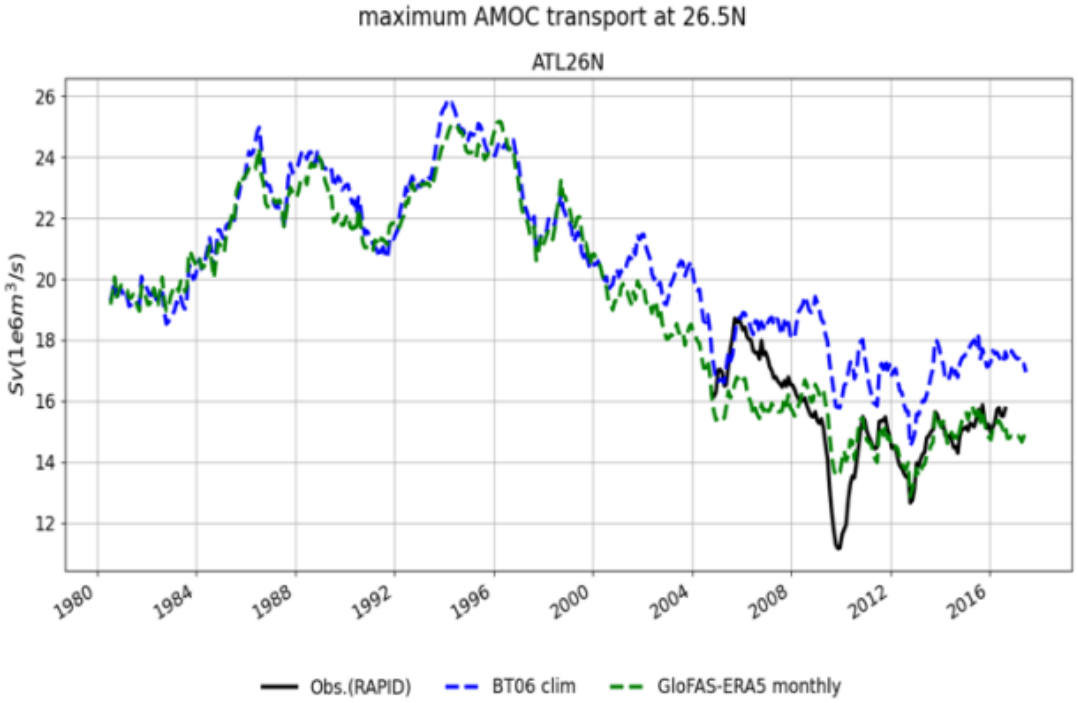
Coupled IFS – ECLand (ERA5) + LISFLOOD offline

Monthly river discharge bias corrected input to NEMO

Monthly climatology input to NEMO



Seasonal cycle of monthly mean land freshwater input (in Sv) in GloFAS-ERA5 (v2) (red line) and BT06 (black line)



Atlantic Meridional Overturning Circulation transports at 26.5ºN

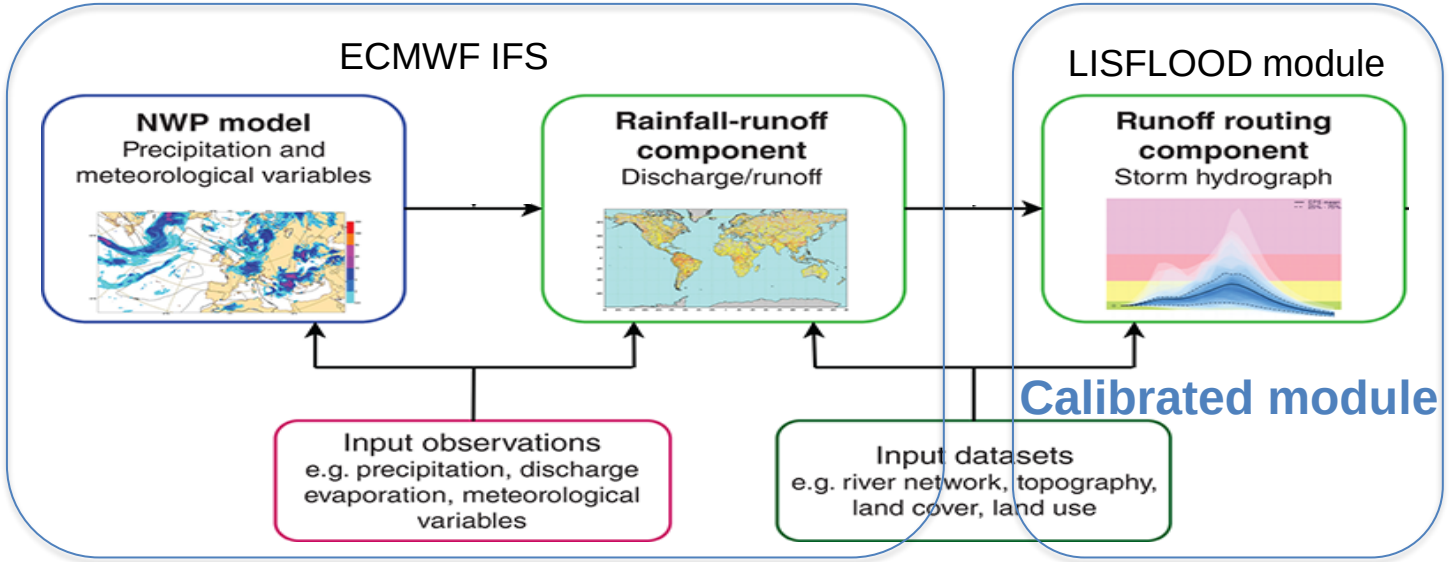
Biases in GloFAS that need correcting

Improved time series simulation of large-scale ocean circulation

Next: Research continues in CMEMS to integrate monthly river discharge in their ocean modelling

Work by Zuo et al., 2020, https://doi.org/10.5194/egusphere-egu2020-8564.

Application 7: ECLand-Hydro benchmarking



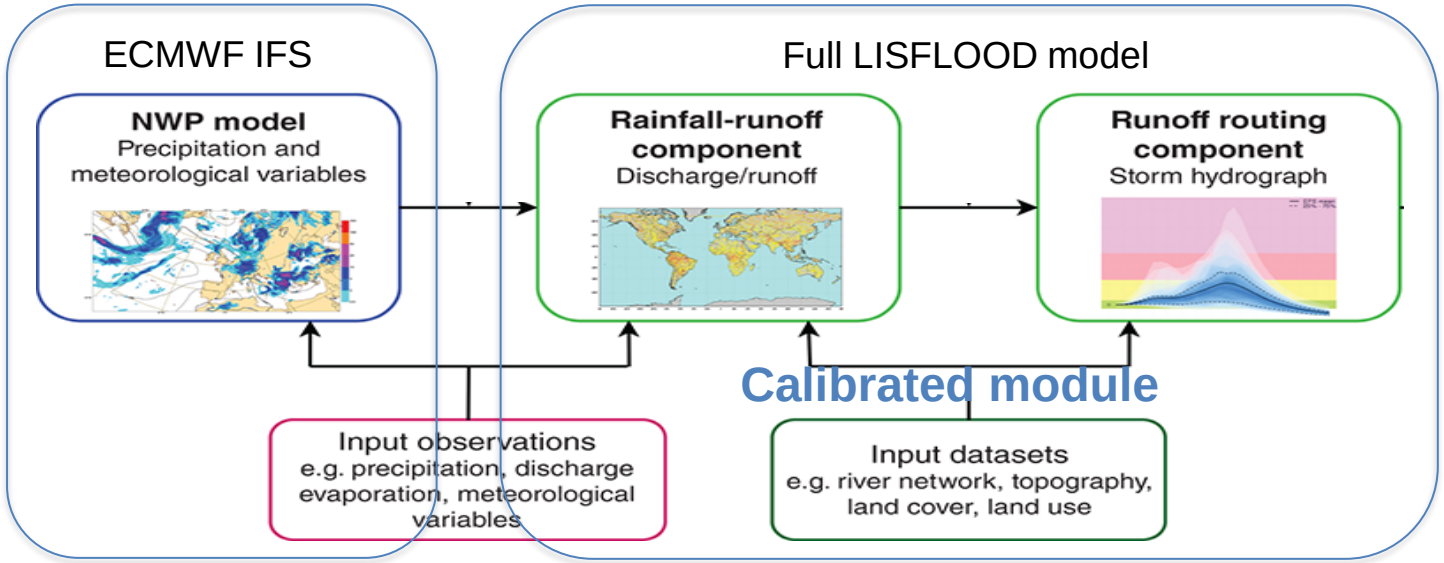
GloFASv3 release

Change in **GloFAS configuration**

Opportunity for **benchmarking ECLand-Hydrology**

Earth System Model configuration

GloFAS configuration up to GloFAS v2
LISFLOOD module calibrated GloFAS v2



Hydrological Model configuration

GloFAS configuration from GloFAS v3
Fully calibrated LISFLOOD GloFAS v3

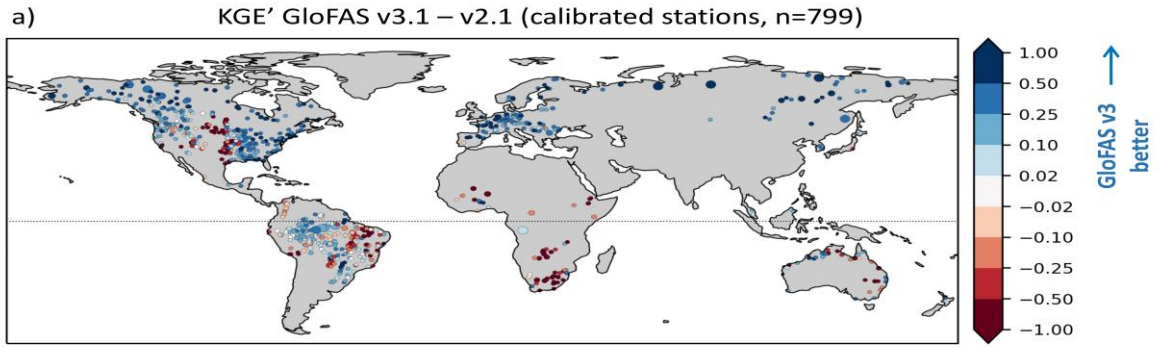
Application 7: ECLand-Hydro calibration performance

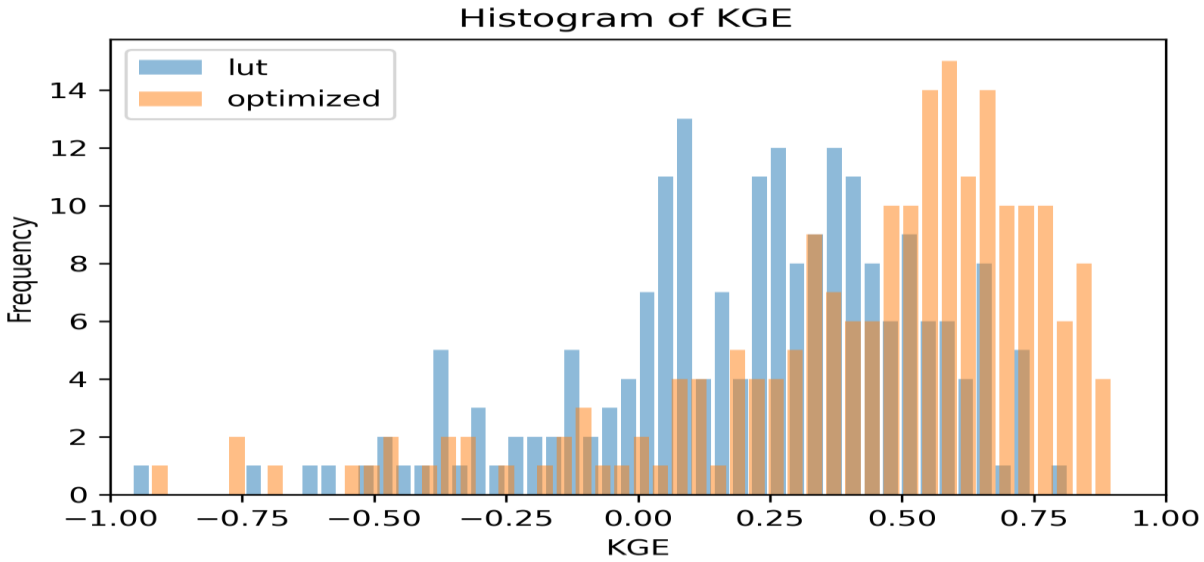
ECLand+CaMaFlood off-line ERA5-driven (lut look-up table/ default parameters)

ECLand-Hydro calibrated with MPR (single basins - 50 parameters optimized)

Daily river discharge evaluation against 153 GRDC stations in different hydro-climate regions

Difference in KGE' (v3.1 – v2.1)





Overall improvement gained by off-line full hydrological calibration **on calibration stations**

GloFASv3 default global hydrological parameters **not better** than GloFASv2 on uncalibrated catchments

Calibration of ECLand Hydro parameters **improves river discharge performance**

Next: Benchmarking of ECLand-Hydro GloFASv4 and assessing impact of hydro-calibration on ESM

Work by Samaniego et al., 2021

The value of hydrological reanalysis?

Hydrological monitoring and forecasting

- Global processes understanding - from long time series
- Hydrological extremes and water resources status – from long time series updated regularly
- Early Warning Systems – from time series updated in near real-time

Hydrological diagnostic

- River discharge natural integrator of water cycle
- Streamflow signal can amplify water budget signal
- **Hydrological simulation powerful diagnostic tool in Earth System Modelling**

Hydrological processes in IFS

- Consideration of improved process representation vs computational burden (complex IT parallelization for rivers)
- Full code refactoring for allowing flexible parameterization
- Introduction of river discharge as prognostic variable in future modelling chains (e.g. ERA6)
- **Sensitivity of ECLand-hydro calibration on water and energy fluxes still to be assessed before full coupling**

Thank you!

- **ECLand**: Boussetta, Balsamo, et al. 2021: ECLand: an ECMWF land surface modelling system, MDPI Atmosphere, Special Issue "Representation of Land Surface Processes in Weather and Climate Models" https://www.mdpi.com/2073-4433/12/6/723

- **ERA5-Hydro trends**: Zsoter, Cloke, Prudhomme, Harrigan, cd Rosnay, Munoz-Sabater, Stephens, 2020, 10.21957/p9jrh0xp, https://www.ecmwf.int/node/19762

- **Snow sensitivity**: Zsoter, E.; Arduini, G.; Prudhomme, C.; Stephens, E.; Cloke, H. Hydrological Impact of the New ECMWF Multi-Layer Snow Scheme. *Atmosphere* **2022**, *13*, 727. https://doi.org/10.3390/atmos13050727

- **Contact for ECLand**: Gianpaolo.Balsamo@ecmwf.int https://www.ecmwf.int/en/about/media-centre/news/2022/making-some-integrated-forecasting-system-open-source

- **GloFAS-Hydro data**: Climate Data Store https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=overview