Investigating the water cycle

A journey through mechanistic models, data types, and hydro-climate services for addressing societal and environmental challenges

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With special thanks to:

Giuliano Di Baldassarre

Howard Wheater

Hoshin Gupta

Maria-Helena Ramos

Florian Pappenberger

and all colleagues at SMHI

Structure of the lecture

Understanding the water cycle

- Global societal and environmental challenges
- The water cycle - Introduction
- Modelling the water cycle – Modelling at the large scale
- Data types - Monitoring the Earth

State-of-the-art hydro- & climate- services

- Forecasting, prediction & projection - Introduction
- Emergency management services
- Climate change services
- Bonus information

Learning outcomes to be expected

- *Which are the major global environmental challenges and why is improved understanding of the water cycle needed to address them?*
- *What is a model, what its purpose, and how can models be classified? Which are the challenges when modelling at the large-scale?*
- *What are the most common data types, what do we mean with big data and what are the challenges with big data?*
- *Why do we need to forecast/predict/project the environmental status of a region and which are the sources of skill?*
- *Operational state-of-the-art services for the emergency management and climate change. Which are some of the providers for Sweden, Europe and the globe?*

SOCIETAL & ENVIRONMENTAL CHALLENGES

Global challenges

#1

Extreme weather conditions
”Extreme weather events have landed on the 1st place in the Top 5 Global Risks in term of likelihood for 2018” (World Economic Forum, 2018).
Sudden intensive rainfall increase the amount of suspended and other solids carried by the river, and result in periodic excessive turbidity of the water.

50%

Water Pollution
”Around half of Europe’s rivers and lakes are still polluted” (EEA, 2015)
HAB outbreaks can have serious impacts to human health, threat the sustainability of ecosystems and pose significant economic damage to society (drinking water supply, health care, fisheries, aquaculture and tourism)

100 B€

Water Scarcity
”By 2017 at least 11% of Europe’s population and 17% of its territory had been affected by water scarcity, putting the cost of droughts in Europe over the past thirty years at EUR 100 billion”

70%

Population Growth
”70% of the world’s projected 10 billion population will live in cities by 2050, increasing the demand for water dramatically in all major use sectors”

Applications sensitive to/addressing global challenges

Drinking water treatment

Water supply

Recreation

Hydropower production

Climate change impacts

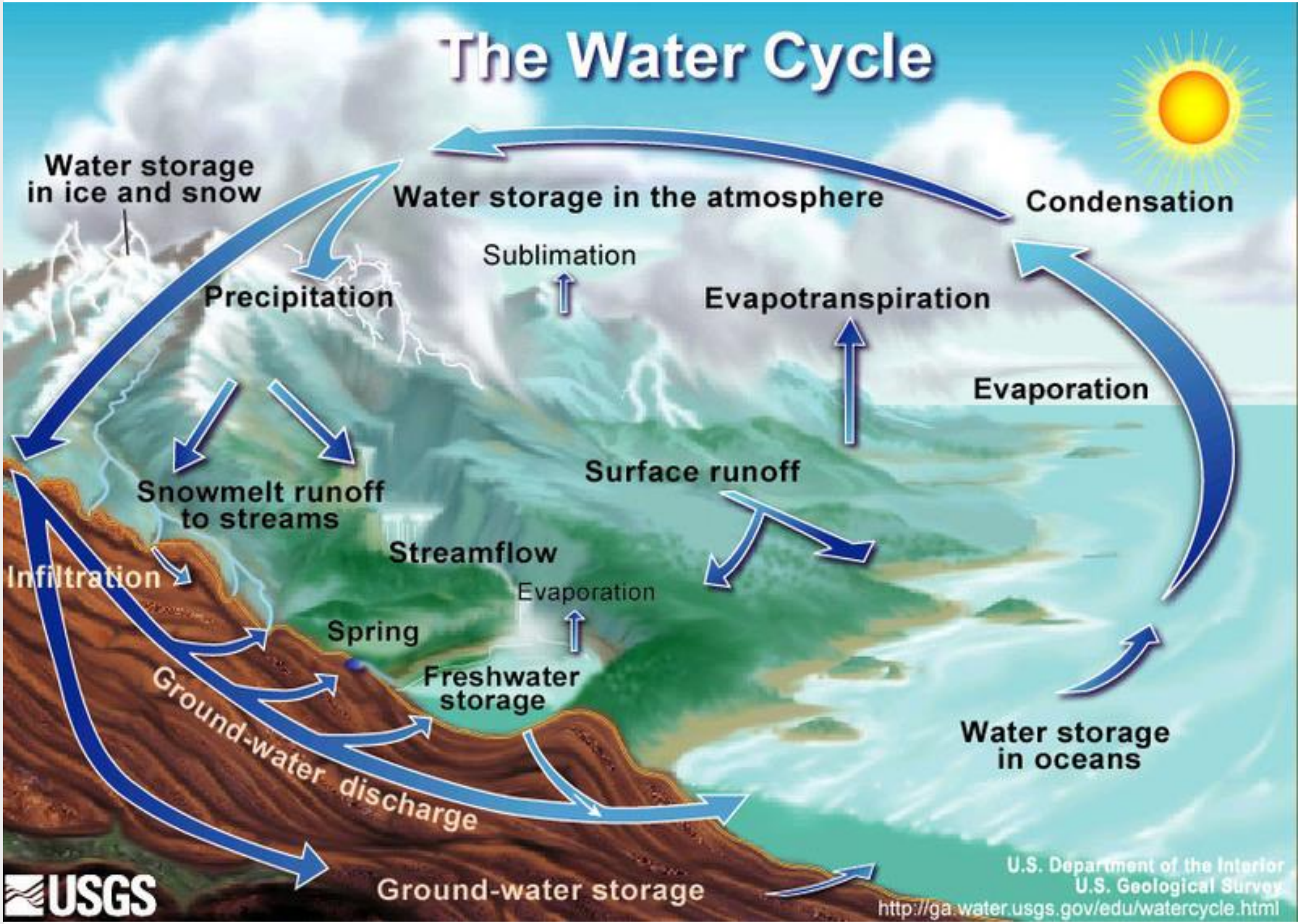
Waste water treatment

Flood control

Urban flooding

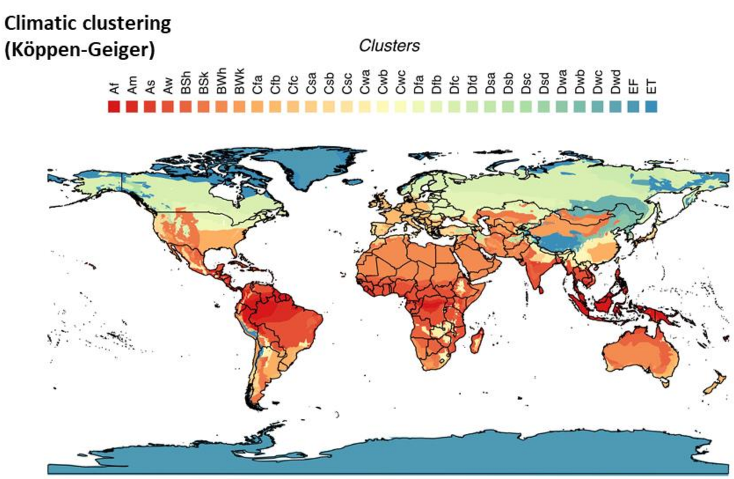
Water resources

THE WATER CYCLE


The Water Cycle
Water storage in ice and snow
Water storage in the atmosphere
Condensation
Sublimation
Precipitation
Evapotranspiration
Evaporation
Snowmelt runoff to streams
Surface runoff
Streamflow
Infiltration
Evaporation
Spring
Freshwater storage
Ground-water discharge
Water storage in oceans
USGS
Ground-water storage
U.S. Department of the Interior
U.S. Geological Survey
http://ga.water.usgs.gov/edu/watercycle.html

Understanding of the water cycle

- Nature’s basic principles are the same everywhere - however the properties of the catchment systems vary significantly.
- Key challenges: the dominant processes vary in time and space.
- Local data have high added value (although sometimes their collection is impossible), and contribute to improved understanding of dominant processes
- *Do catchment systems share common information?*



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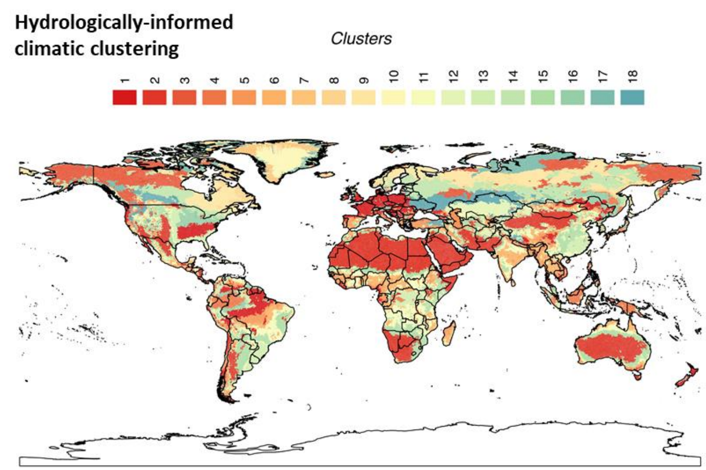
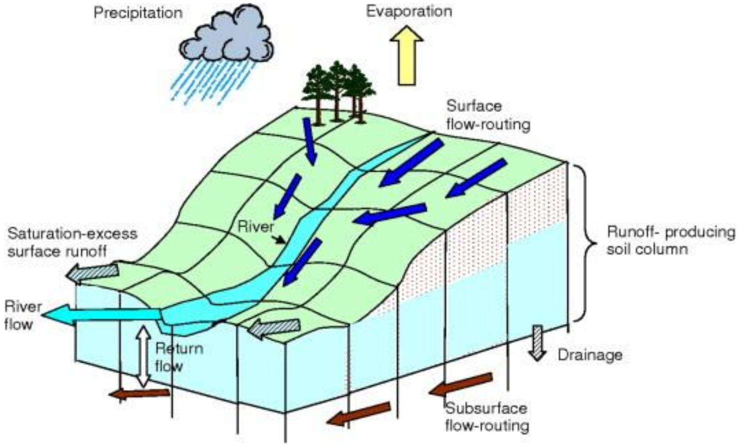


Knoben, W. J. M., Woods, R. A., & Freer, J. E. (2018). A quantitative hydrological climate classification evaluated with independent streamflow data. Water Resources Research, 54, 5088– 5109.

MODELLING THE WATER CYCLE

- ”Model is a description or presentation designed to mimic the main object or function of a thing, system or concept.” (Wikipedia)

- What is an environmental (mathematical) model?
- ”Model is a simplified version of a real system in the form of mathematical equations that simulate (as approximation) the response of a process." (Singh, 1995)



Singh, V. (1995). Computer models of watershed hydrology. Littleton, Colorado: Water Resources Publications.

- Why do we use environmental (mathematical) models?
  - Extrapolation of point measurements in space-time
  - Determine the effects of management decisions on natural systems (e.g. water-table management, water quality evaluation, estimation of crop yield, flood and drought forecasting etc.)
  - Assess impact of environmental change (e.g. land use and climate) on natural system resources
  - Improve understanding of dynamics of atmospheric, hydrological, geomorphological and ecosystem processes for the development of new or improvement of old models to cover new aspects of science

- What is an environmental (mathematical) model?
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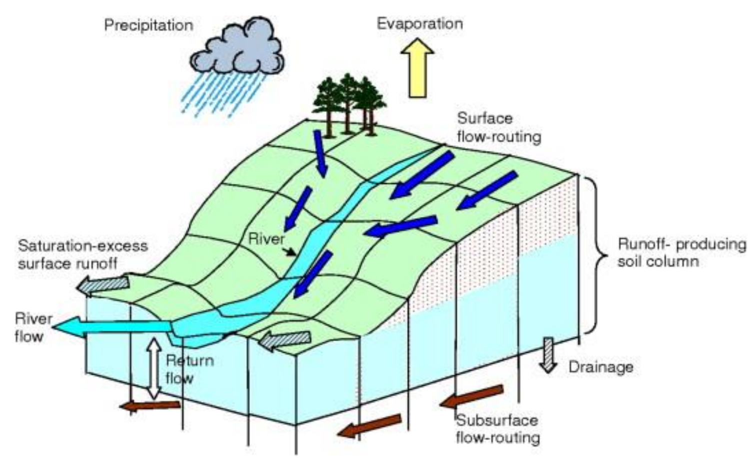
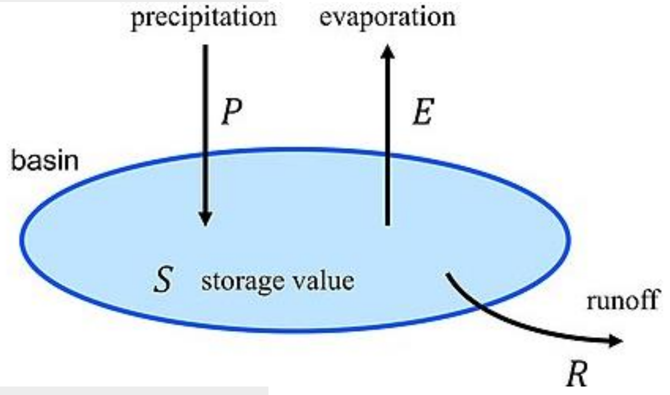


Singh, V. (1995). Computer models of watershed hydrology. Littleton, Colorado: Water Resources Publications.

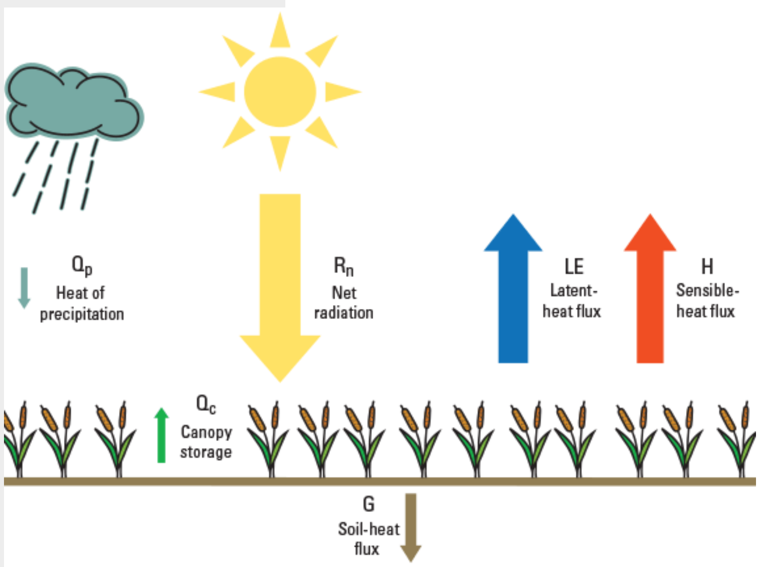
- Two basic principles (usually) set the basis of environmental models
  - Water balance



$$P = R + E + \Delta S$$

P is precipitation, *E* is evapotranspiration, *R* is runoff, Δ*S* is change in the soil moisture storage

  - Energy balance



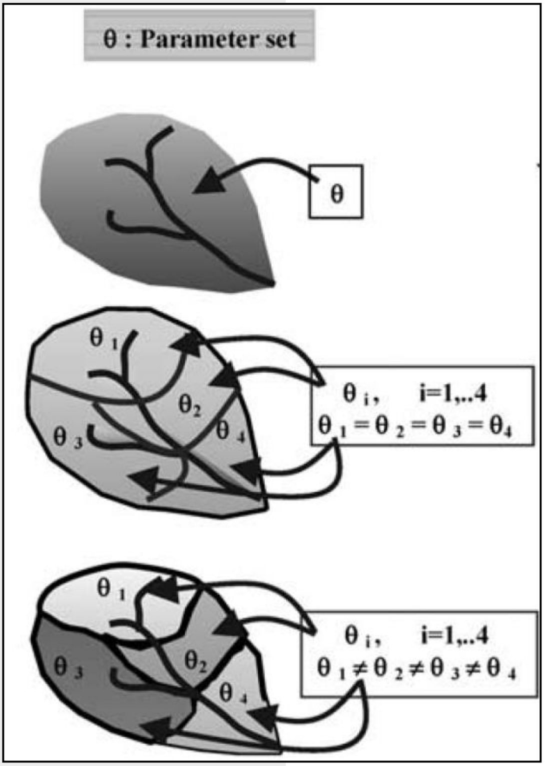
$$Rn = H + LE + G$$

Rn is net radiation, *LE* is the latent heat flux (energy to change the state of a substance without changing its temperature), *H* is sensible heat flux (energy that changes the air temperature), *G* is heat conduction to the ground (usually < *H*, *λE*)
(the equation can be extended to include photosynthesis, but << *H*, *λE*)

➤ Classification of models based on:

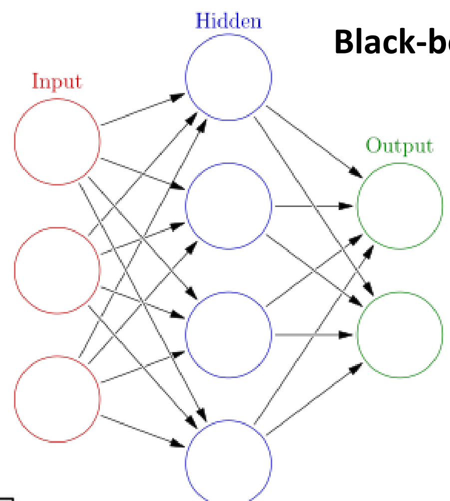
Temporal resolution	Spatial resolution	Model structure
Event-based	Lumped	Statistical / Stochastic
Continuous	Semi-lumped	Conceptual
Sub-daily, daily, monthly, yearly	Semi-distributed	Physics-based
	Fully distributed	Black-box

*A **mechanistic model** (also known as process-based model) uses a theory to predict what will happen in the real world.*

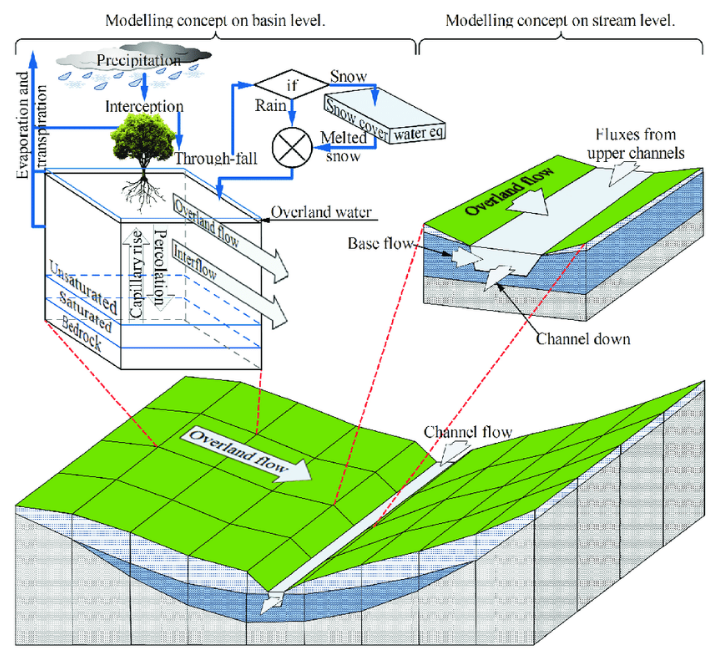


Ajami, N. K., Gupta, H., Wagener, T., & Sorooshian, S. (2004). Calibration of a semi-distributed hydrologic model for streamflow estimation along a river system. Journal of Hydrology, 298(1–4), 112–135.

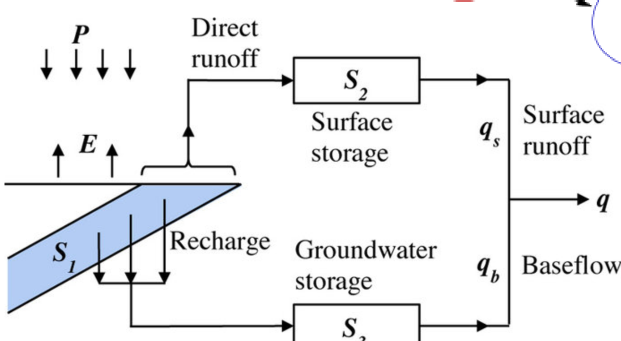
Black-box



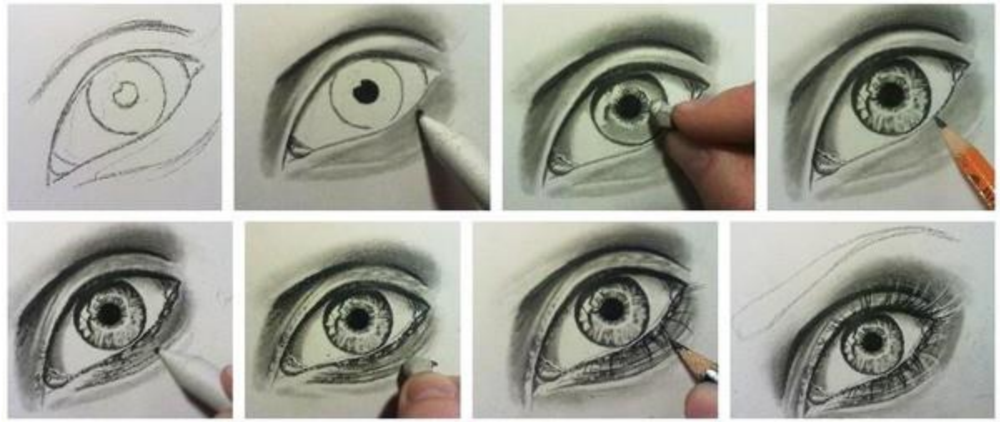
Physics-based



Conceptual

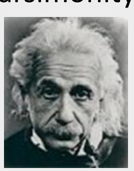


- Philosophy in environmental model setup

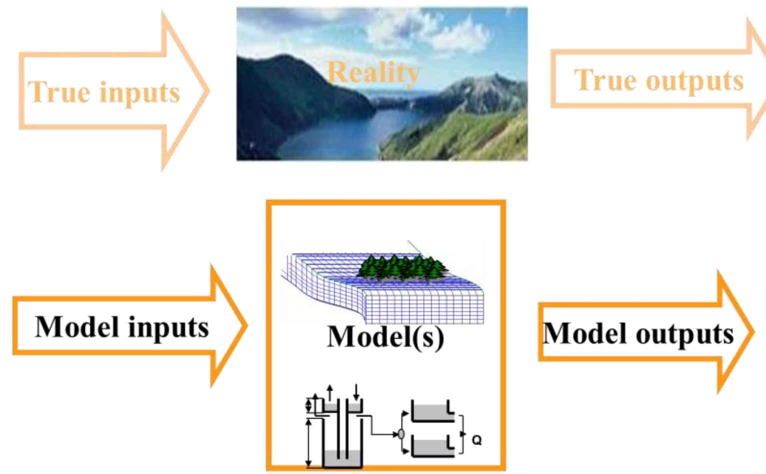


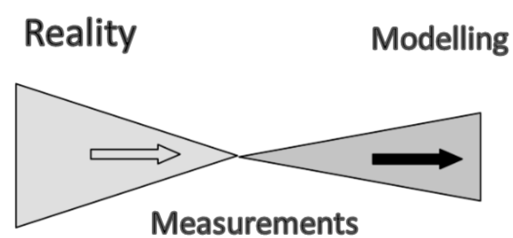
- Start with dominant processes and zoom in in both resolution and process detail
- Make something simple and useful right away

Concept of parsimonity



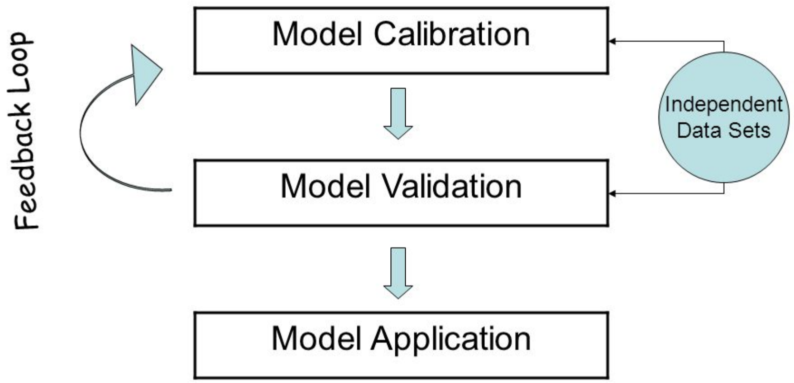
- *Describe processes as simple as possible, but not simpler*
- Avoid making some parts too complex – imbalance in complexity
- Diagnostically identify the model – ”Good model for the right reasons”

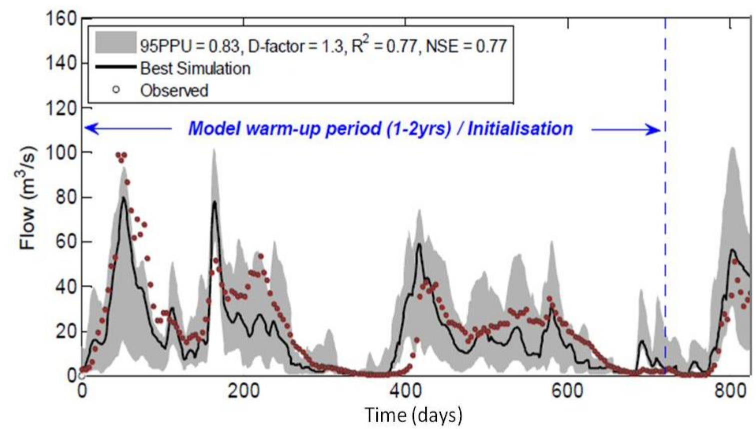


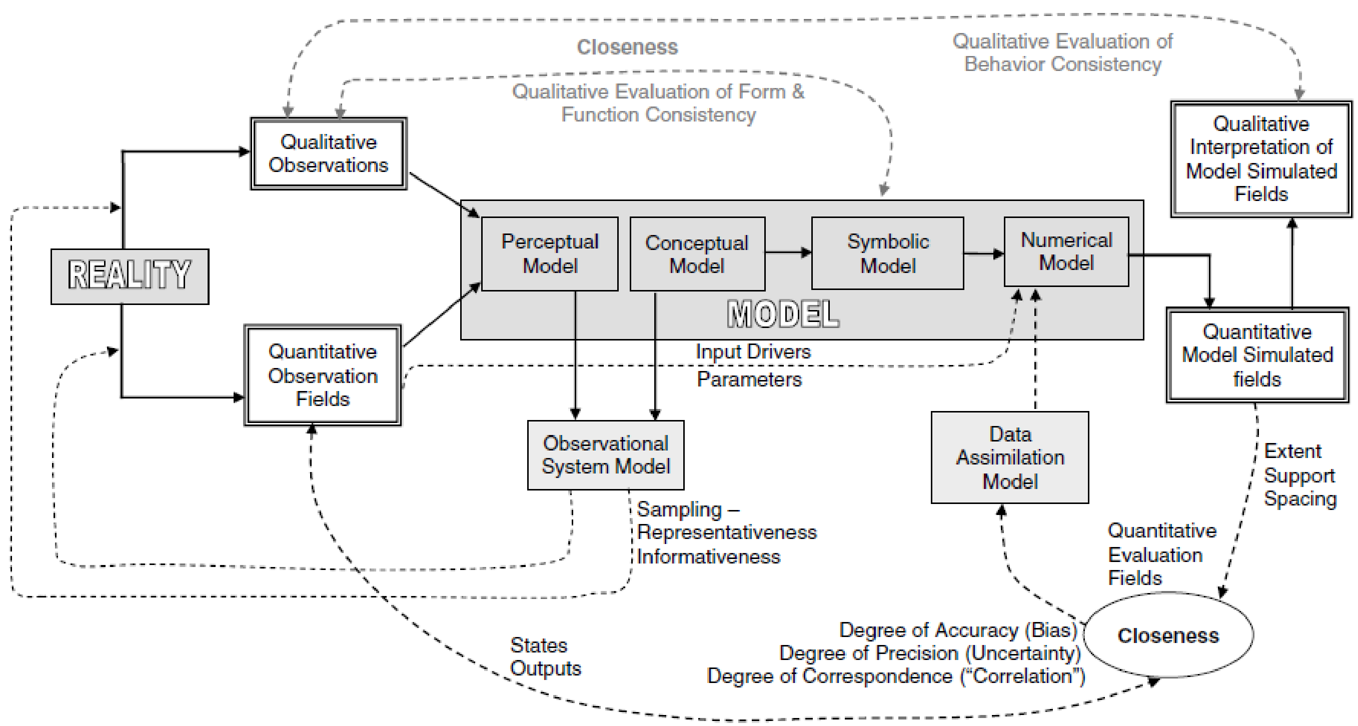


- Philosophy in environmental model setup

"Good model for the right reasons"





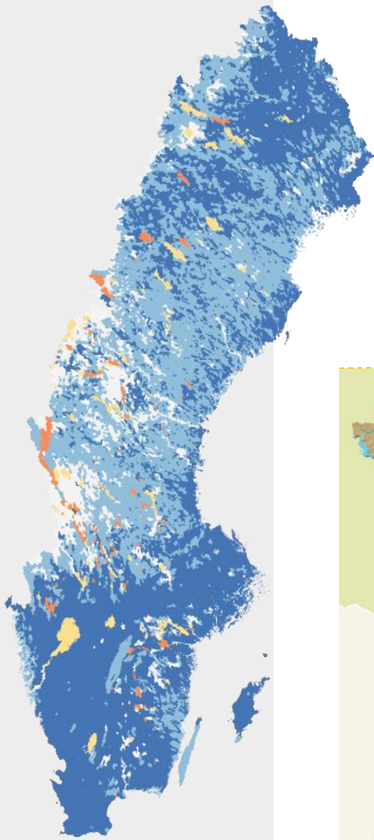


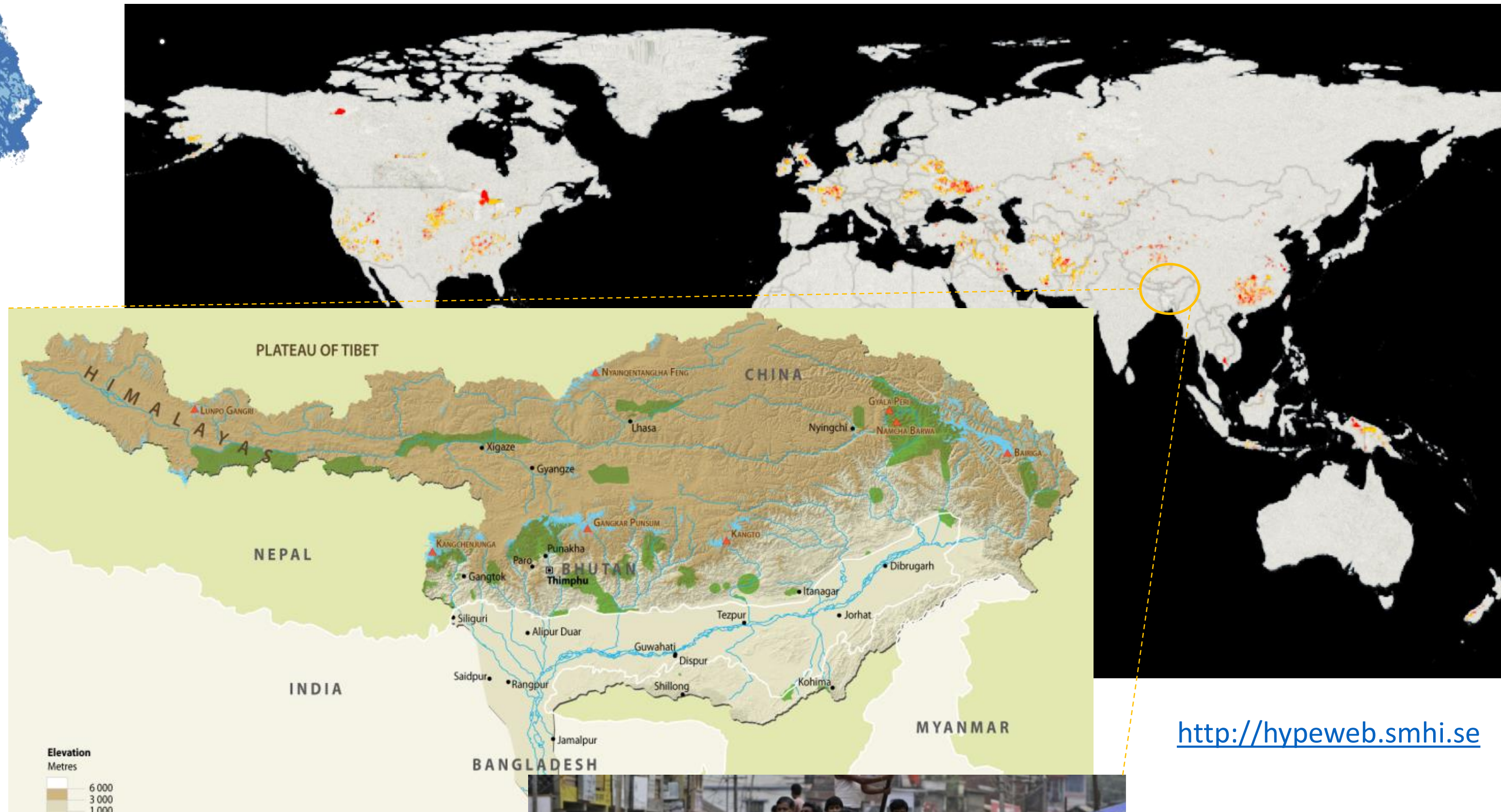
Gupta, H., Wagener, T. and Liu, Y., 2008. Reconciling theory with observations: elements of a diagnostic approach to model evaluation. Hydrological Processes, 22(18): 3802-3813.

MODELLING AT THE LARGE SCALE

What is it considered as large-scale?

Why is it important?

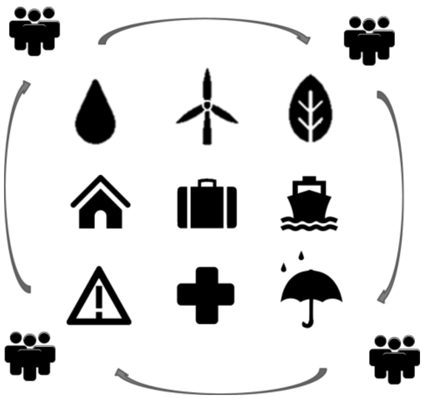




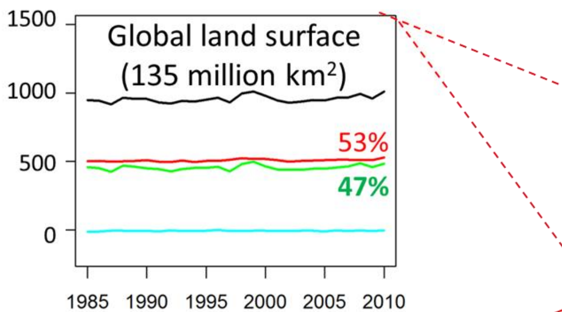
http://hypeweb.smhi.se

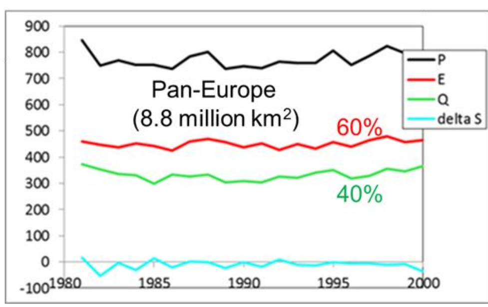
https://vattenwebb.smhi.se

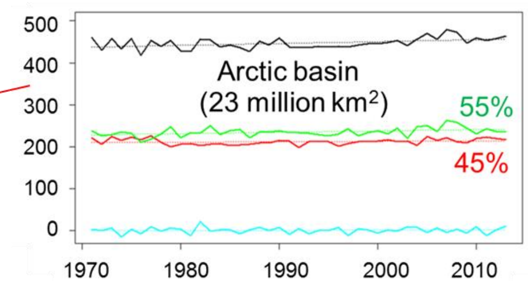
Who is interested on information at the large scale?

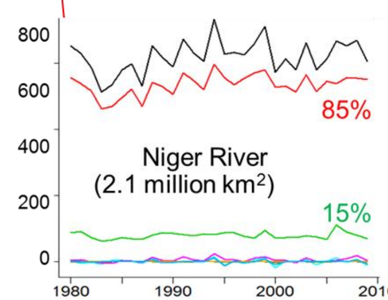


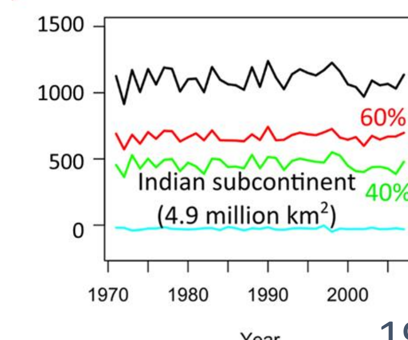
- Copernicus, World Organisations
- Civil Protection Agencies
- Emergency Response Coordination Centre
- International Red Cross and Red Crescent Movement
- … and many others





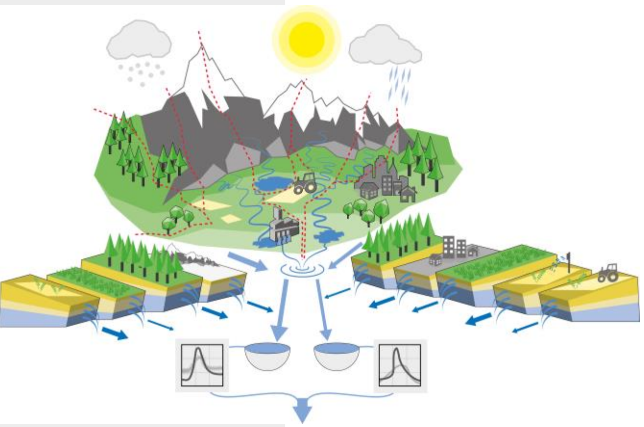


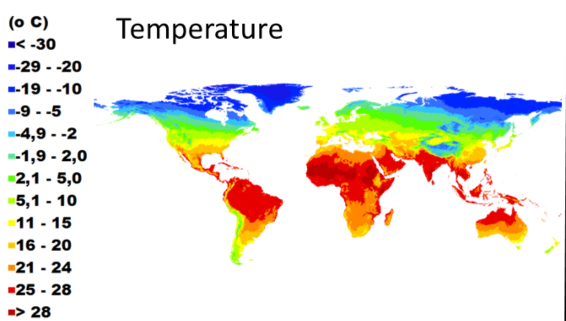


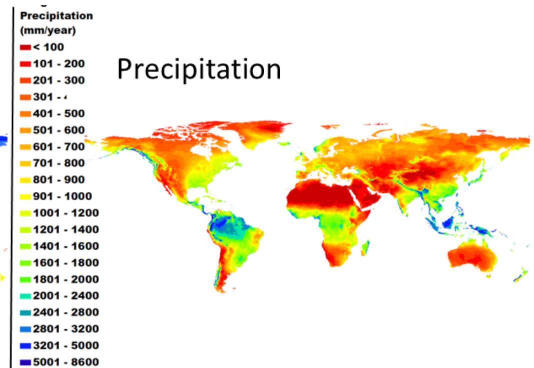


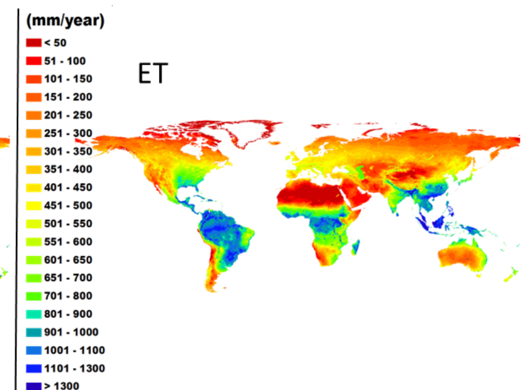
HYPE on the web:
Results: http://hypeweb.smhi.se/

➢ Information at the global scale (model: WW-HYPE)

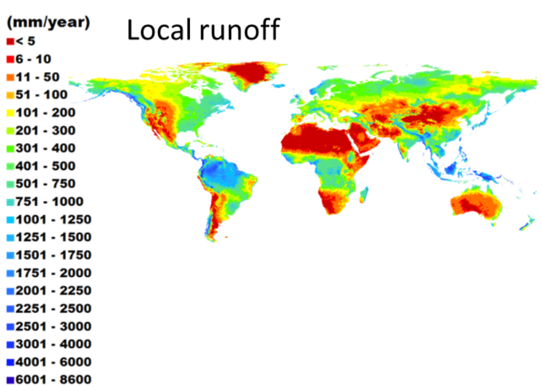


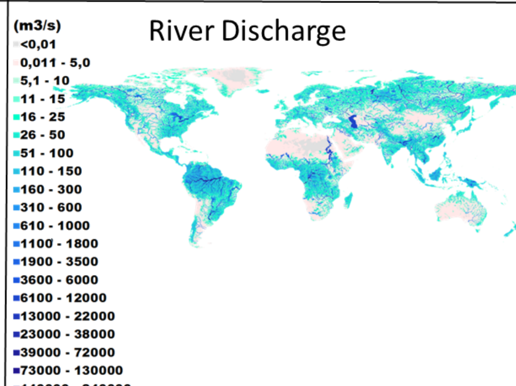


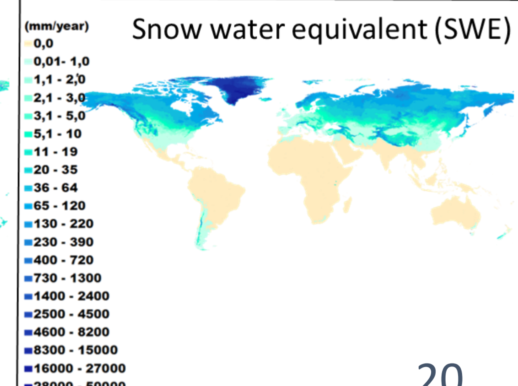




Lindström, G., Pers, C., Rosberg, J., Strömqvist, J., & Arheimer, B. (2010). Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales. Hydrology Research, 41(3–4), 295–319.

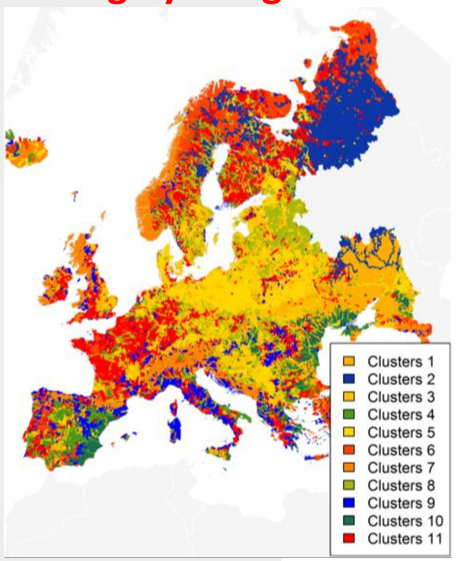






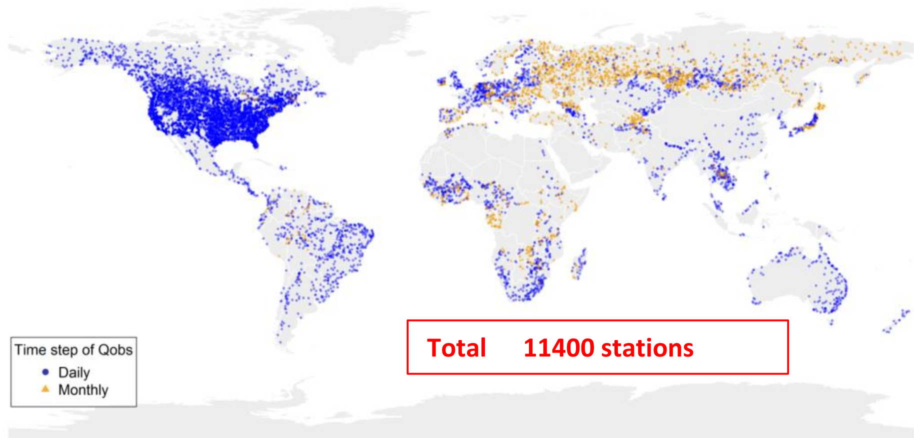
Limitations when modelling at the large-scale

Strong hydro. gradients



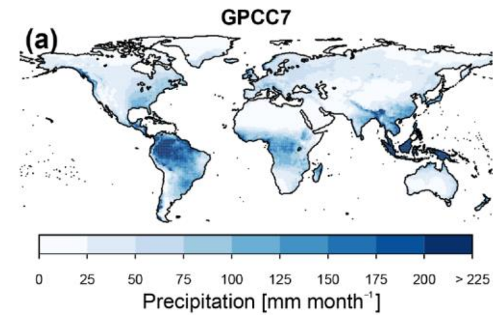
Limited Q data

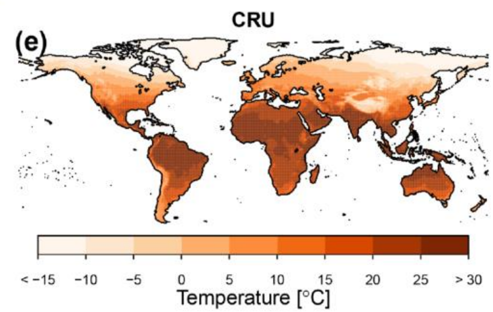
Daily or **Monthly** Discharge time series



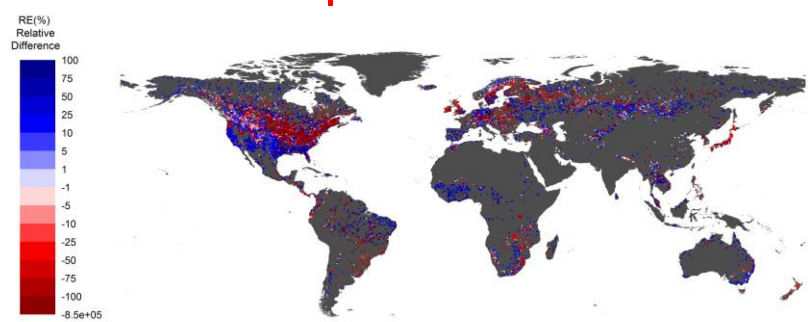
Total 11400 stations

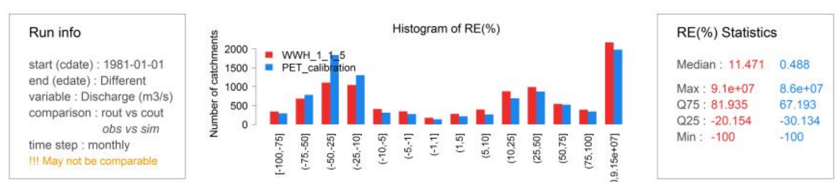
No perfect meteo dataset





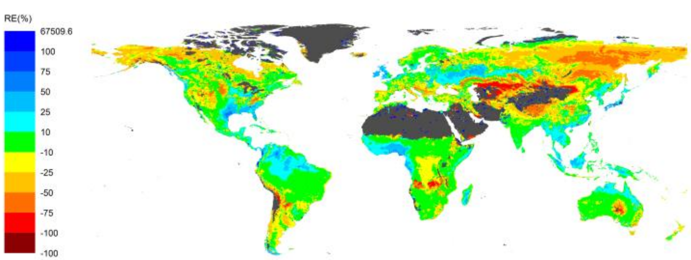
Limited model performance



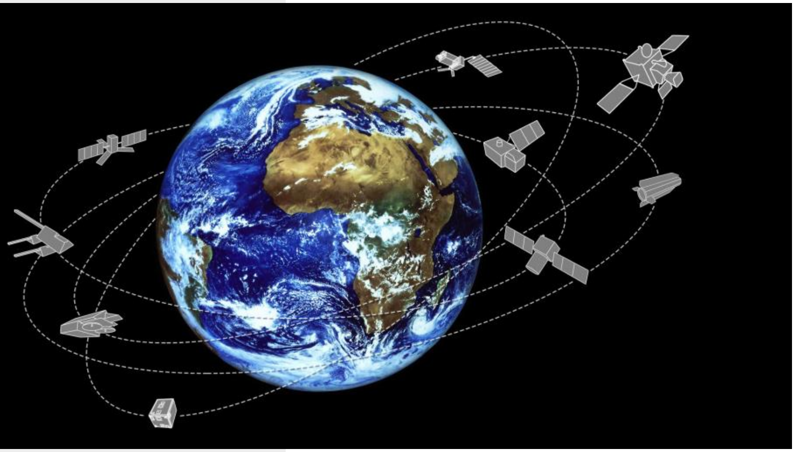


'Unknown' fluxes

Calibrated model vs MODIS PET

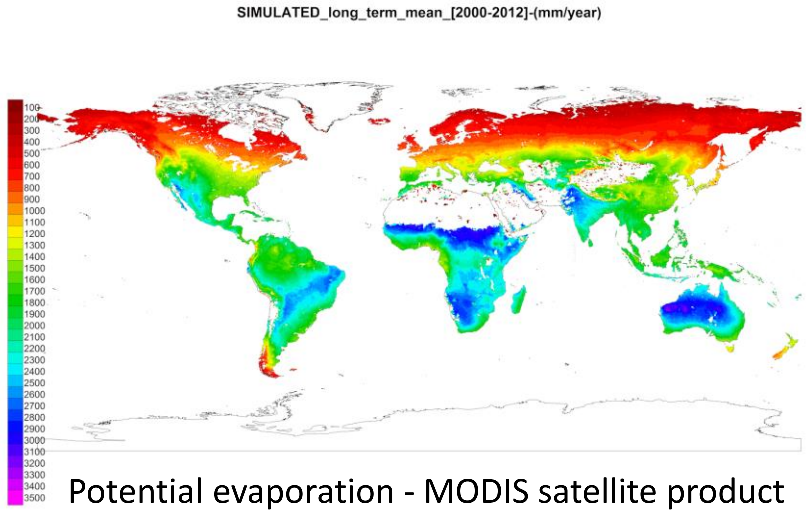


DATA TYPES - MONITORING THE EARTH



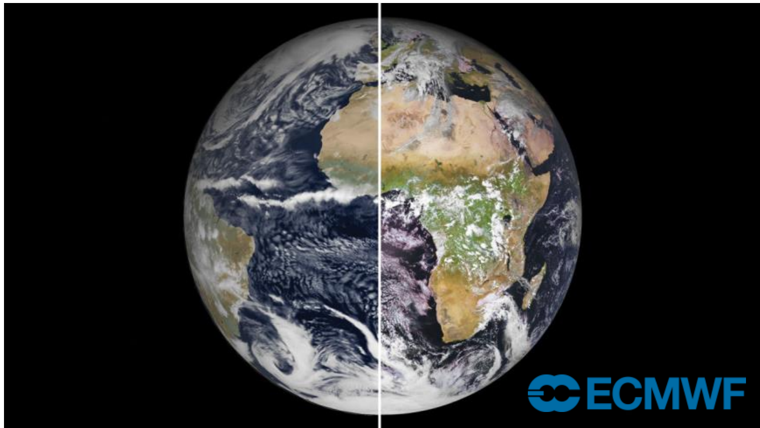
Remote sensing

***Earth observation (EO)** is the gathering of information about the physical, chemical, and biological systems of the planet via remote-sensing technologies, supplemented by earth-surveying techniques, which encompasses the collection, analysis, and presentation of data. According to the Group on Earth Observations (GEO), the concept encompasses both "space-based or remotely-sensed data, as well as ground-based or in situ data". Earth observation is used to monitor and assess the status of and changes in natural and built environments.*



Potential evaporation - MODIS satellite product

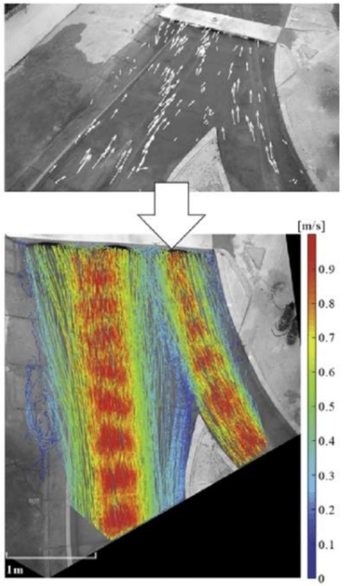
Earth's digital twin



Limiting factors:

1. Calibration;
2. Noise (need for filtering);
3. Blocking (echoes i.e. Mountains, clouds, ground, sea, buildings);
4. Space and time sampling

Image-based sensing



UAV-based sensing

Telecommunication network (Microwave links)

Topography (routing/delineation): HydroSHEDS

LandUse: Global Land Cover 2000 | GIAM

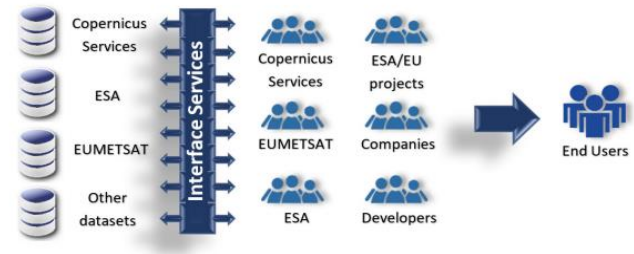
Soil: Harmonized World Soil Database

Lakes and Reservoirs: GLWD, GRanD

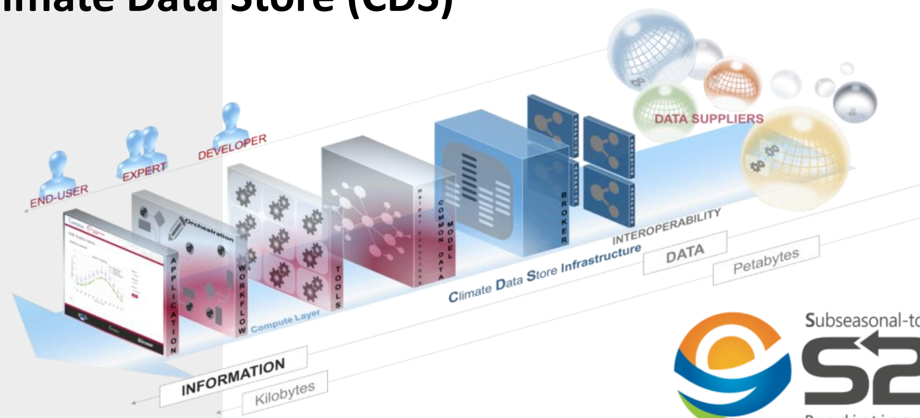
Discharge: GRDC, EWA, USGS

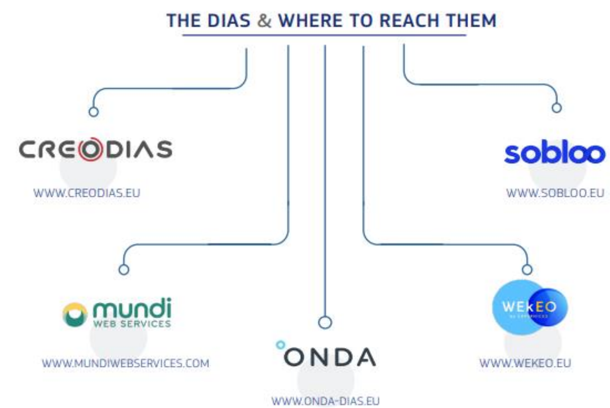
Crowdsourced data

Data and Information Access Service (DIAS)



Climate Data Store (CDS)



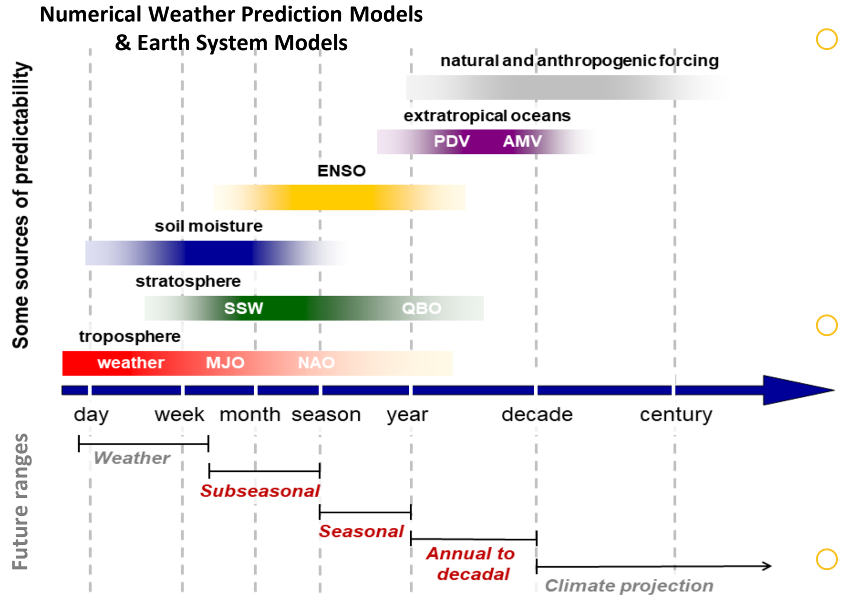


Big data is the result of having more data sources and more storage. Big data usually includes data sets with sizes beyond the ability of commonly used software tools to capture, curate, manage, and process data within a tolerable elapsed time. Big data "size" is (constantly changing) from a *few dozen terabytes to many zettabytes* of data. Big data is where parallel computing tools are needed to handle data.

Data preparation - Evaluation and Quality Control (EQC) protocols

FORECASTING, PREDICTION AND PROJECTION
-
INTRODUCTION

Forecasting / predictions / projections

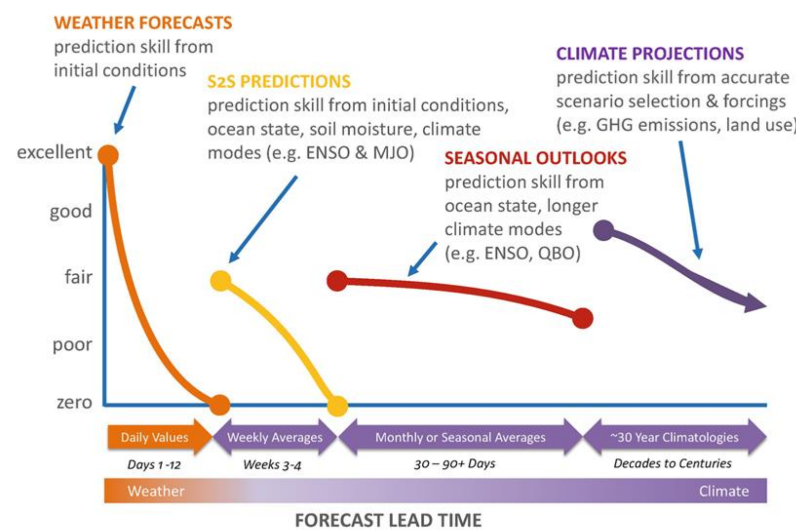


- **Forecasting** refers to a calculation or an estimation which uses data from previous events, combined with recent trends to come up a future event outcome.
- **Prediction** is an actual act of indicating that something will happen in the future with or without prior information.
- **Projections** are estimates of how the Earth system might change under different scenarios.

Merryfield, W.J., et al., 2020: Current and emerging developments in subseasonal to decadal prediction. *Bull. Amer. Meteor. Soc.*, https://doi.org/10.1175/BAMS-D-19-0037.1

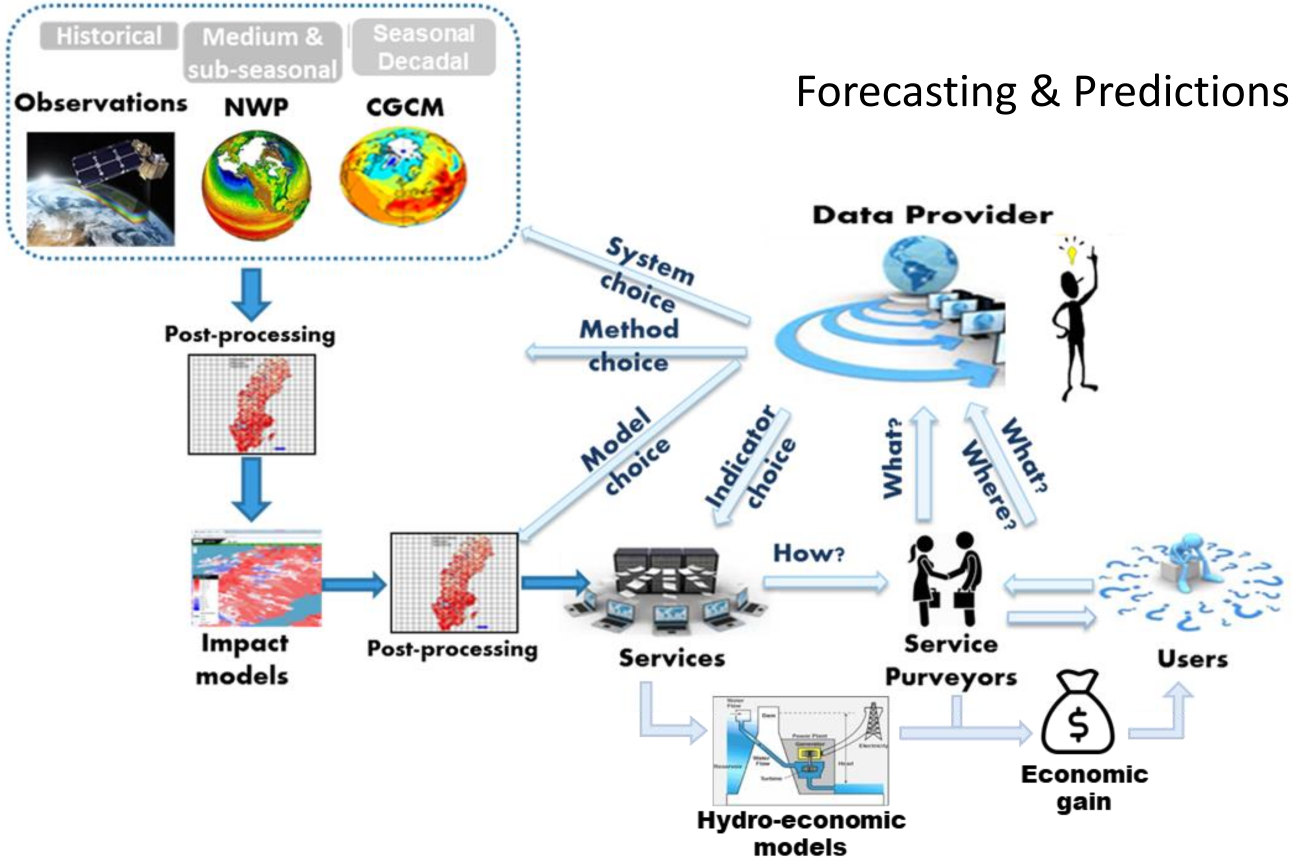
Weaver, C.P., et al., 2013: Improving the contribution of climate model information to decision making: The value and demands of robust decision frameworks. WIREs Climate Change,https://doi.org/10.1002/wcc.202

- Estimates of the future are always uncertain. To address **uncertainty**, models now provide a range of realizations (**ensembles**) to help users deal quantitatively with the probable temporal variations in the predictability of the atmosphere.
- **Skill** varies in space and depends on the season, while it decreases as a function of time. Sources of skill depend on the future range.

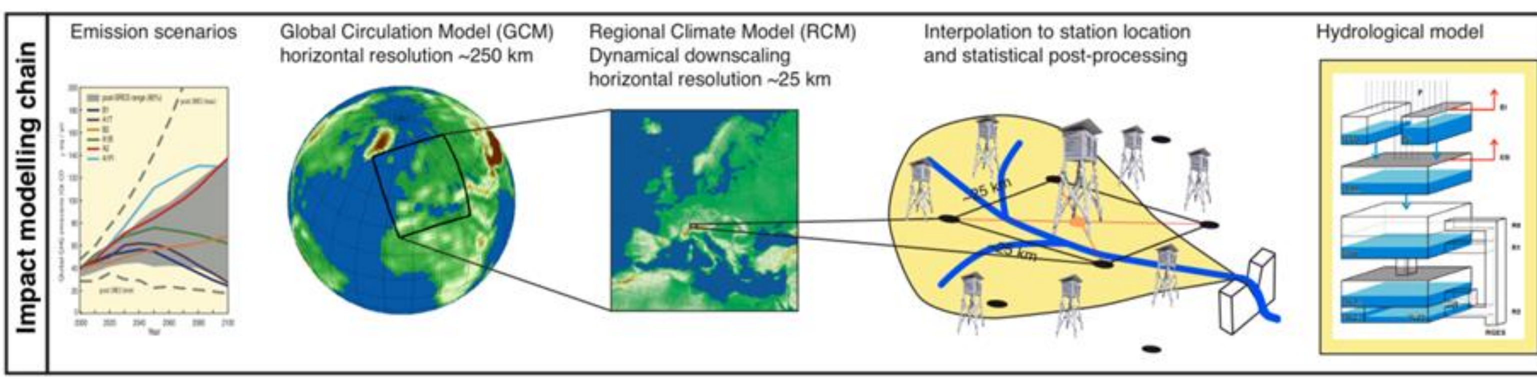


Modelling chain in forecasting / predictions / projections

Forecasting & Predictions



Projections - Assessment of climate change



Examples – forecasting and prediction

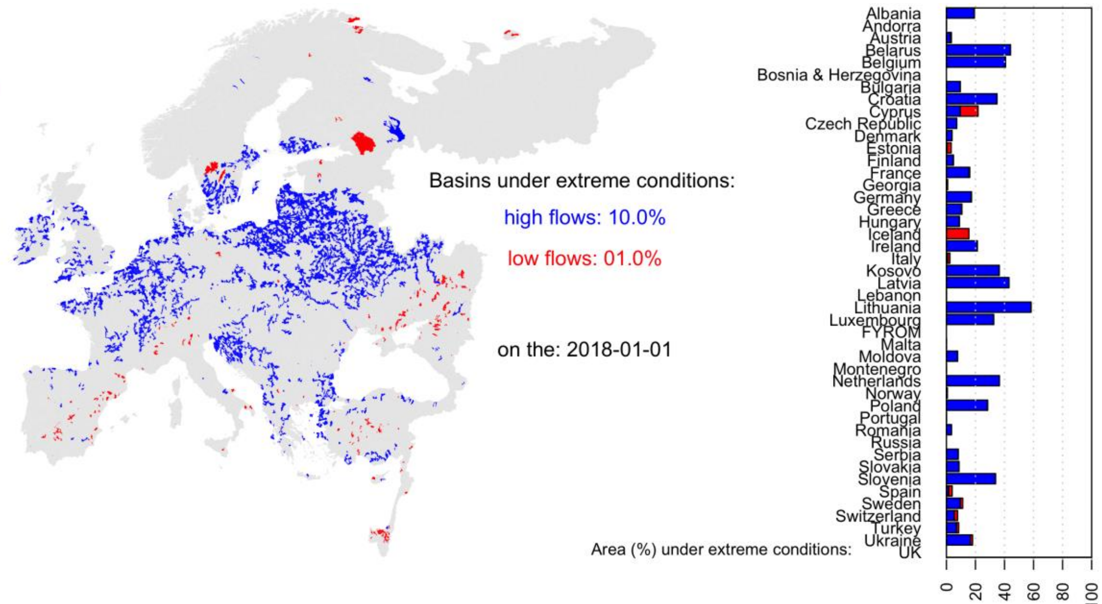
Medium-range forecasting

Model: E-HYPE

SMHI

- Flooding and hydrological drought

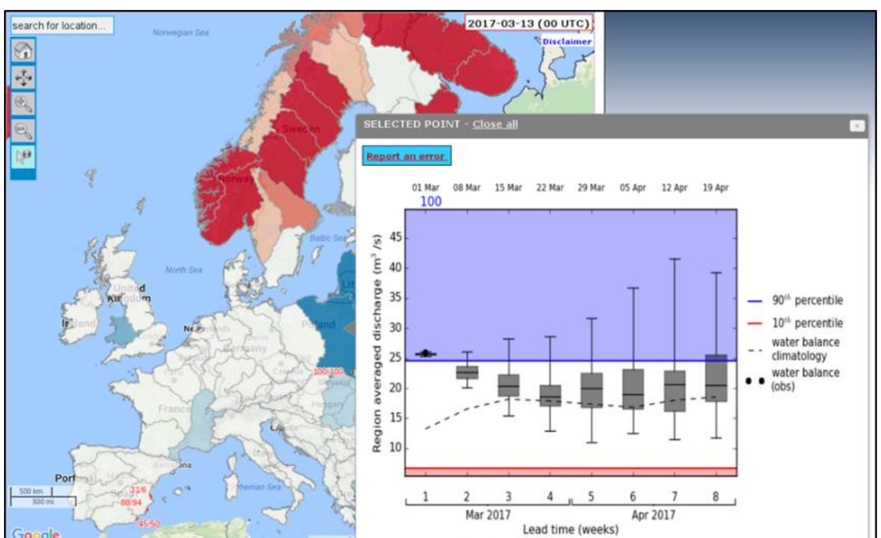
Identification of regions experiencing high and low flows based on a 10-day forecast system.



Seasonal predictions

Model: Lisflood

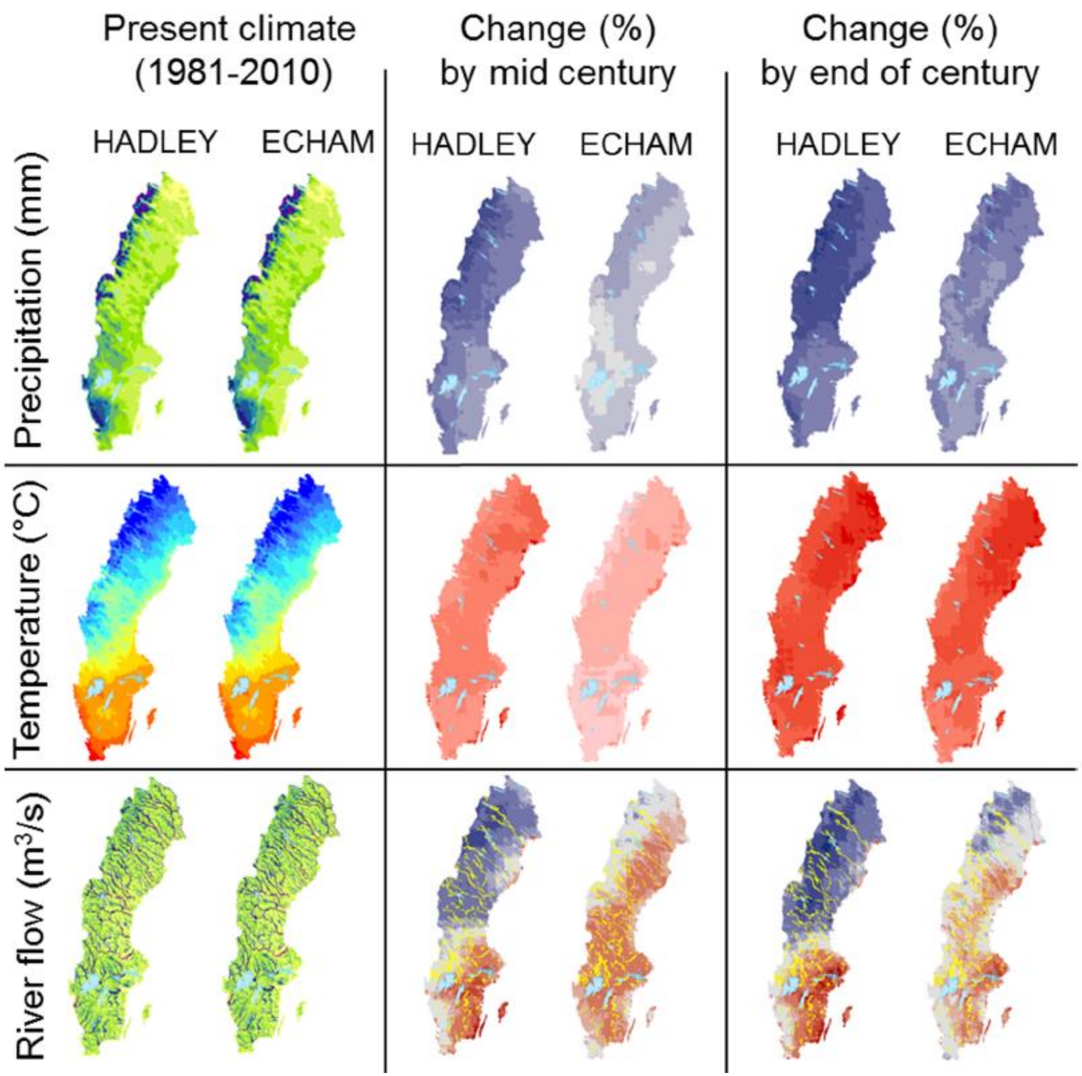
ECMWF



Identification of regions experiencing high and low flows in the coming 2 months, based on a 7 month prediction system.

Examples - projections

- Averaged status and change (30-years) in precipitation, temperature and streamflow



Centennial projections

Model: S-HYPE

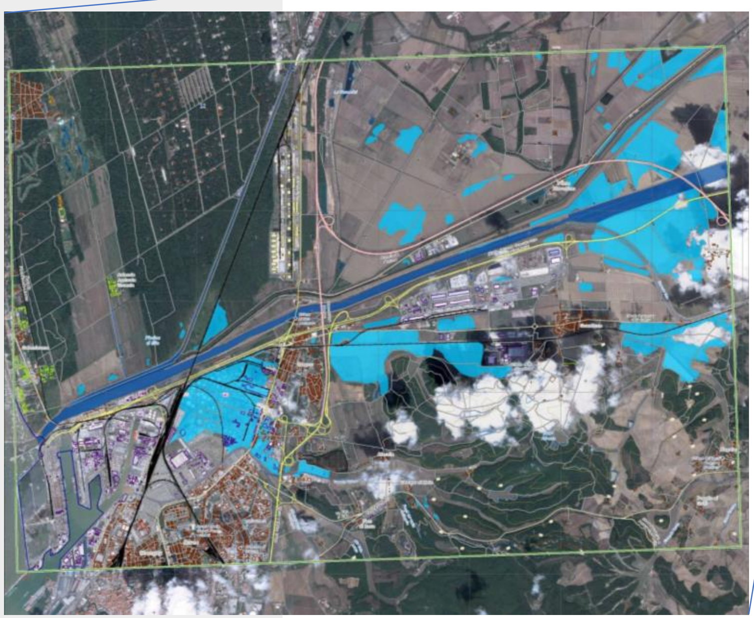
SMHI

Arheimer, B., & Lindström, G. (2015). Climate impact on floods – changes of high-flows in Sweden for the past and future (1911–2100). Hydrology and Earth System Sciences, 19, 771–784.

EMERGENCY MANAGEMENT SERVICES

Emergency management is the organization and management of the resources and responsibilities for dealing with all humanitarian aspects of emergencies (prevention, preparedness, response, mitigation, and recovery). The aim is to prevent and reduce the harmful effects of all hazards, including disasters.

- Earth observations in water security and risk reduction



Floodwater map on a given day
(source: Copernicus EMS Rapid Mapping)

Outlook of hydrological extremes

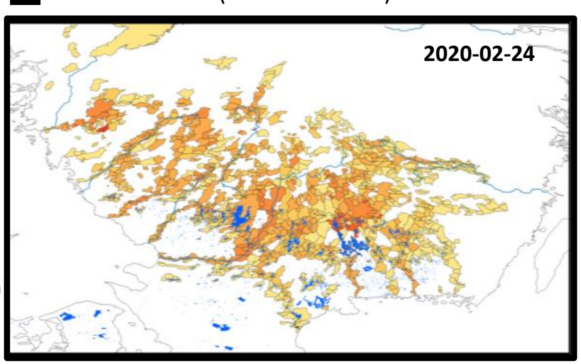
The 2020-02-23 flooding case study in Lagan, south Sweden

100-yr RP
50-yr RP
25-yr RP
10-yr RP
5-yr RP
2-yr RP

on the: 2020-02-20

Water bodies (satellite-based)
Water extents (satellite-based)

LIST

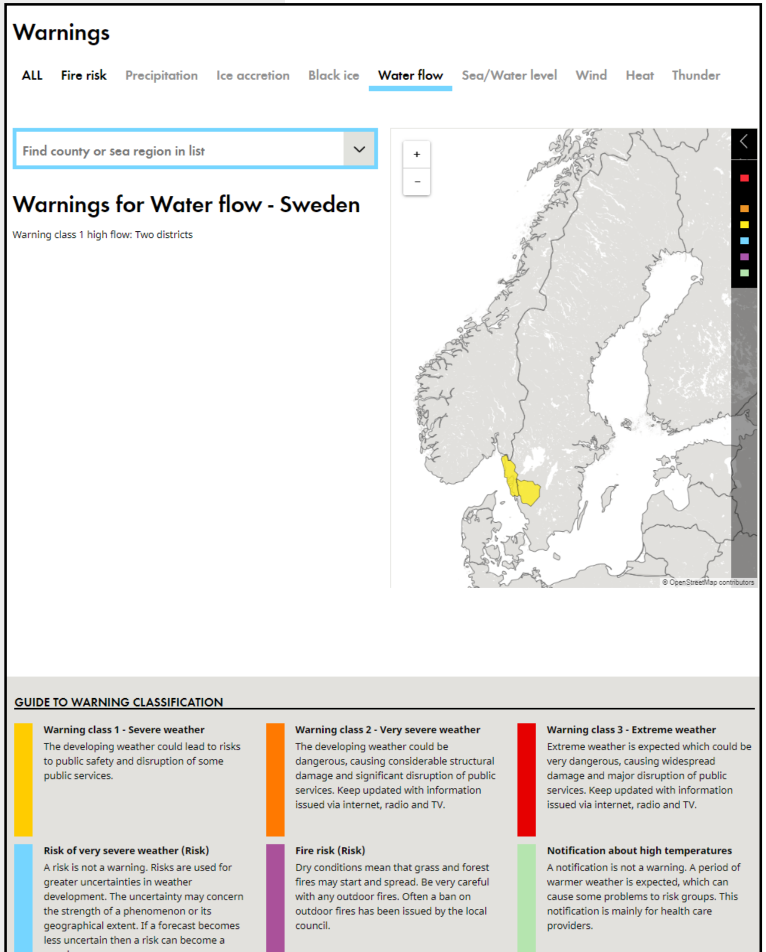


State-of-the-art Flood Early Warning Service (Sweden)

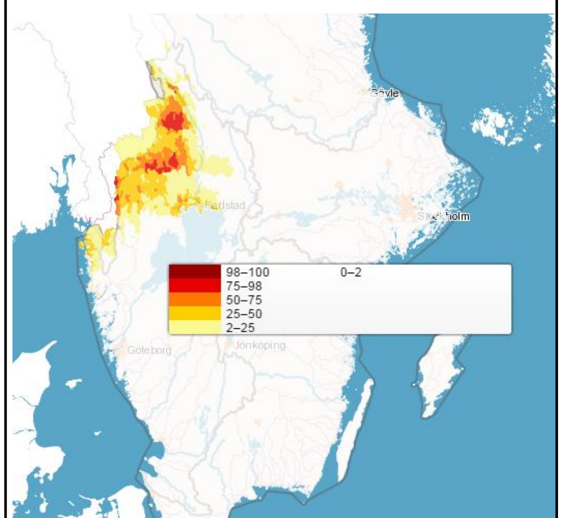
SMHI

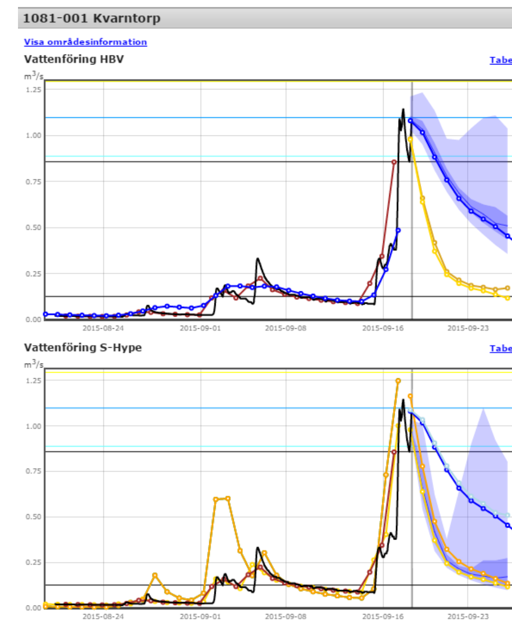
Deterministic medium-range forecasts; Probabilistic medium-range forecasts

Rapid Impact Assessments



- Hydrological ensembles made by running the model with ECMWF EPS forecasts.
- For each time step, the percentage of ensemble members above 2, 10 and 50 year flood is calculated.





- The models can often differ, in which case a mean of both can often be the best forecast.

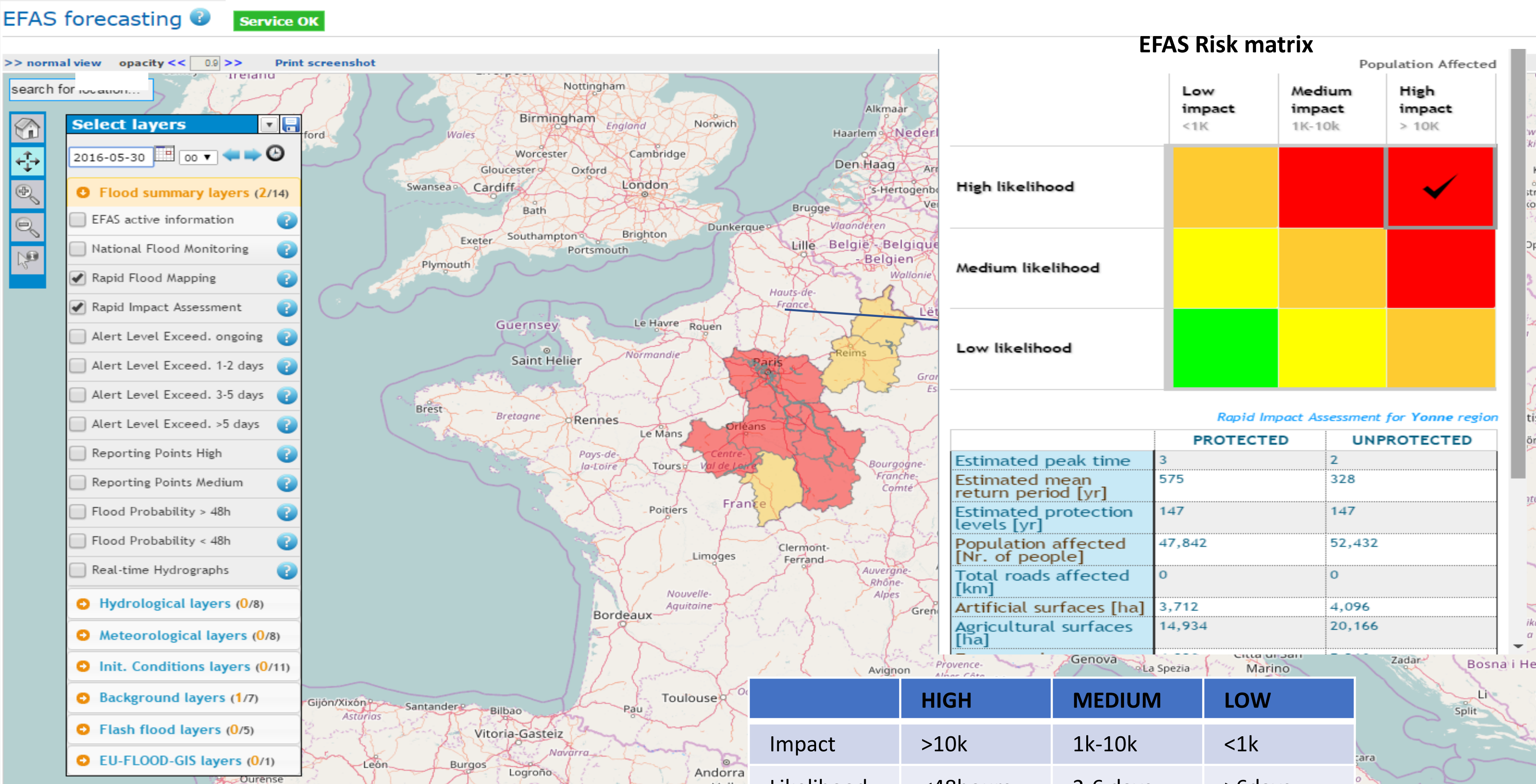
www.smhi.se
https://vattenwebb.smhi.se

Emergency
(EMS)

- State-of-the-art Flood Early Warning Service (Europe)
  - European Flood Awareness System (EFAS)

Deterministic medium-range forecasts; Probabilistic medium-range forecasts

Sub-seasonal to seasonal forecasts; **Rapid Impact Assessments**



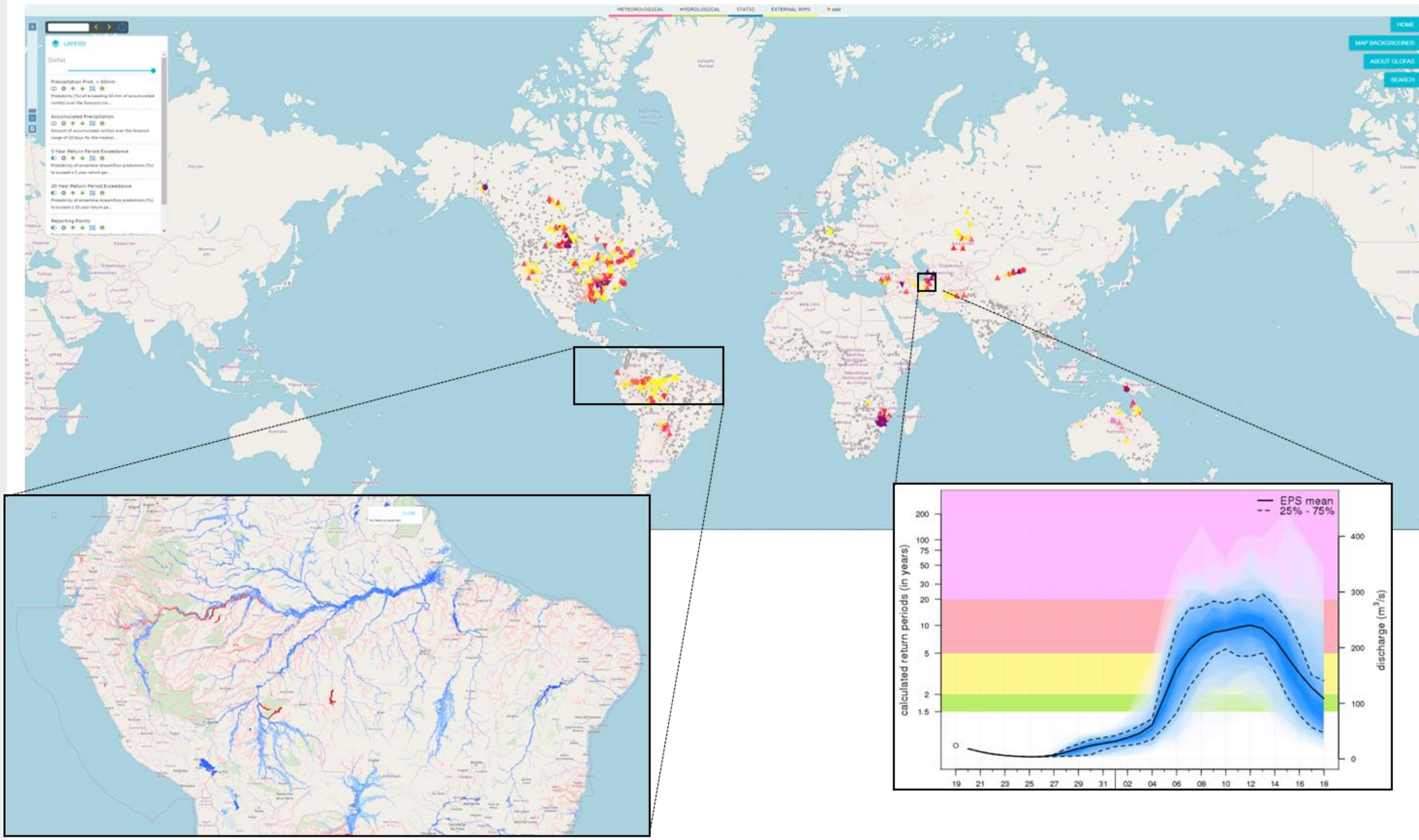
	HIGH	MEDIUM	LOW
Impact	>10k	1k-10k	<1k
Likelihood	<48hours	2-6 days	>6days

www.efas.eu

- State-of-the-art Flood Early Warning Service (Globe)
  - Global Flood Awareness System (GloFAS)

Deterministic medium-range forecasts; **Probabilistic medium-range forecasts**

Seasonal forecasts; Rapid Impact Assessments



www.globalfloods.eu

CLIMATE CHANGE SERVICES

WMO – Global Framework for Climate Services (GFCS)

What do we mean by Climate Services

A **Climate Service** is the provision of climate information to assist decision-making. The service must respond to user needs, must be based on scientifically credible information and expertise, and requires appropriate engagement between the users and providers.

WMO

The implementation of GFCS has five components:

- Observations and Monitoring
- Climate Services Information System
- Research, Modelling and Prediction
- User Interface Platform
- Capacity Development

- To involve the **production, translation, transfer and use of climate information and knowledge** in climate-informed decision-making and climate-smart policy and planning

  -> impact on the decision

- To use the **best available climate science** and need to **effectively communicate** with the user community to develop and evaluate adaptation strategies

  -> confidence in scientific knowledge

- To effectively **establish technical capacities** and active communication and exchange between provides, purveyors and user community

  -> engage and increase uptake

Subseasonal-to-Seasonal S2S Prediction Project

WCRP CORDEX

- Available datasets:
  - Historical observations
  - Reanalyses
  - S2S forecasts
  - Decadal predictions
  - Centennial projections

Example of S2S forecast providers

	Time-range	Resol.	Ens. Size	Freq.	Hcsts	Hcst length	Hcst Freq	Hcst Size
ECMWF	D 0-32	T639/319L62	51	2/week	On the fly	Past 18y	weekly	5
UKMO	D 0-60	N216L85	4	daily	On the fly	1996-2009	4/month	3
NCEP	D 0-60	N126L64	16	daily	Fix	1999-2010	daily	4
EC	D 0-35	0.6x0.6L40	21	weekly	On the fly	Past 15y	weekly	4
CAWCR	D 0-120	T47L17	33	weekly	Fix	1989-2010	3/month	33
JMA	D 0-34	T159L60	50	weekly	Fix	1979-2009	3/month	5
KMA	D 0-30	T106L21	20	3/month	Fix	1979-2010	3/month	10
CMA	D 0-45	T63L16	40	6/month	Fix	1982-now	monthly	48
CPTEC	D 0-30	T126L28	1	daily	No	-	-	-
Met.Fr	D 0-60	T63L91	41	monthly	Fix	1981-2005	monthly	11
SAWS	D 0-60	T42L19	6	monthly	Fix	1981-2001	monthly	6
HMCR	D 0-60	1.1x1.4 L28	10	monthly	Fix	1979-2003	monthly	10

Climate (C3S)

Observations

Observations are key to understanding the climate system. C3S users can access a vast variety of instrumental data records, ranging from historic weather observations to the latest measurements from space.

Read more ▶

Climate reanalyses

Climate reanalyses combine past observations with models to generate consistent time series for a large set of climate variables. Reanalyses are among the most-used datasets in the geophysical sciences.

Read more ▶

Reanalysis data on the CDS ▶

Seasonal forecasts

C3S seasonal forecasts combine outputs from several state-of-the-art seasonal prediction systems from providers in Europe and elsewhere. The latest data and products are published monthly on the Climate Data Store.

Read more ▶

Seasonal forecast data on the CDS ▶

Climate projections

Projections of future climate change are available for different scenarios for concentrations of greenhouse gases and aerosols, based on outputs from multiple global and regional climate models.

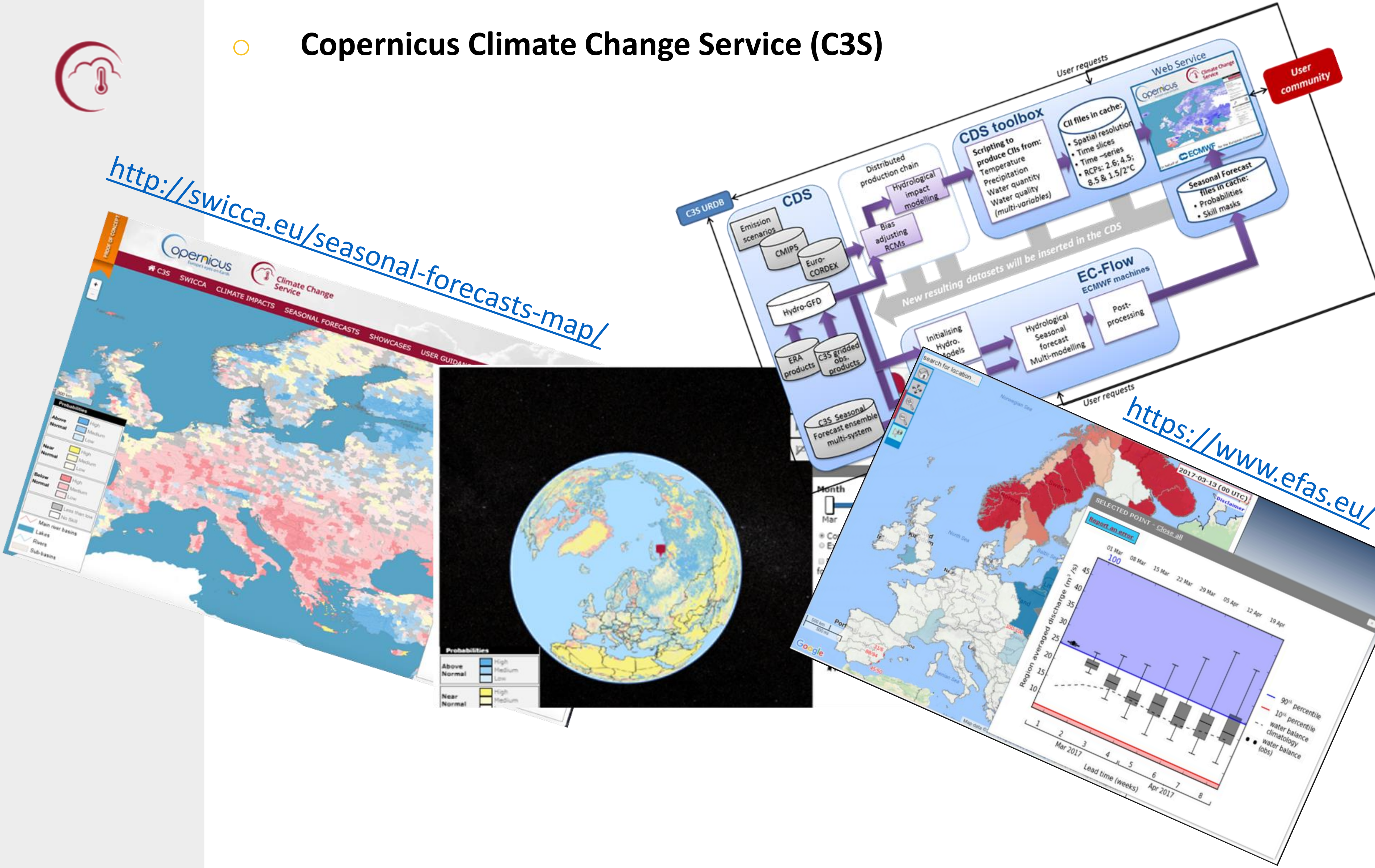
Read more ▶

Climate projection data on the CDS ▶

➢ Available hydro-climate services

○ **Copernicus Climate Change Service (C3S)**

http://swicca.eu/seasonal-forecasts-map/



https://www.efas.eu/

https://hypeweb.smhi.se/explore-water/forecasts/seasonal-forecasts-global/

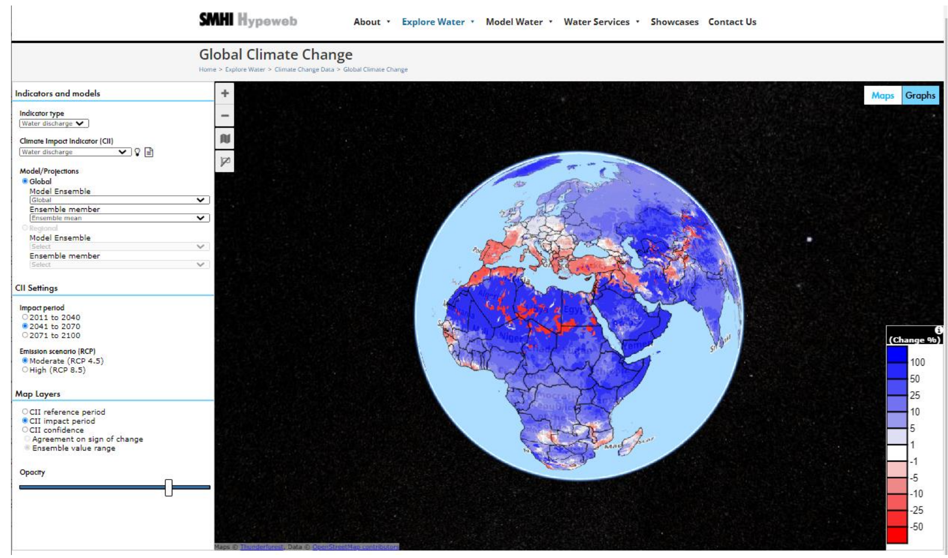
Available hydro-climate services

- Copernicus Climate Change Service (C3S)
- **National organisations**

SMHI

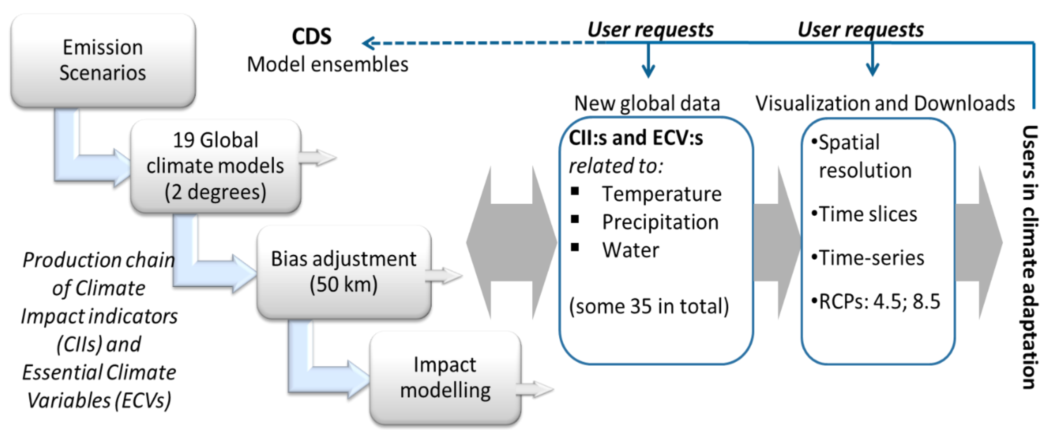
A bias-adjusted ensemble of **19 models from CMIP5** was used to force the **WW-HYPE hydrological model** over the entire globe.

A total of 35 ECVs* and CIIs** are provided in this dataset at **catchment scale** (1981 – 2100).



*Essential Climate Variable: a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth' s climate.

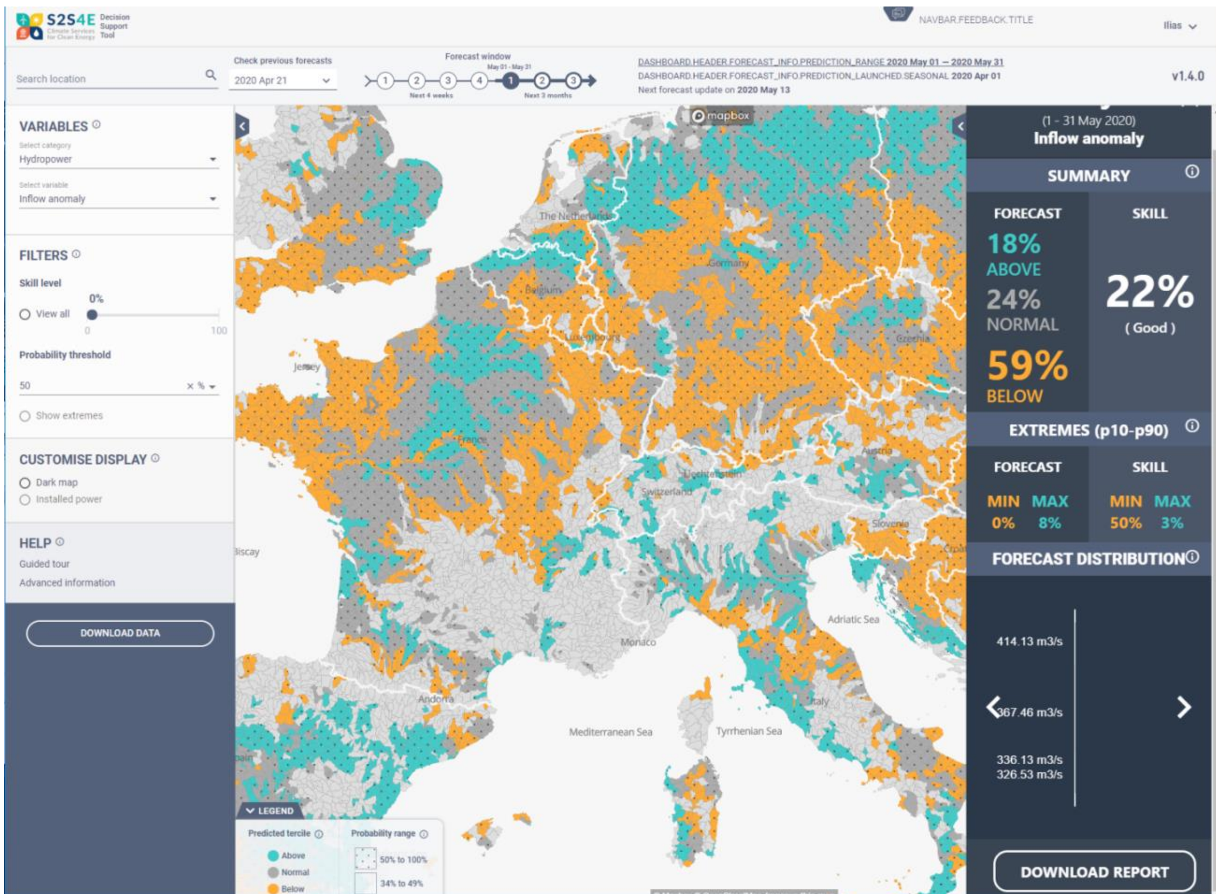
**Climate Impact Indicator: an aggregated quantitative measure used to show the impact of climate change on complex environmental phenomena in terms of trends and variability



➢ Available hydro-climate services

- Copernicus Climate Change Service (C3S)
- National organisations
- **Research programmes**

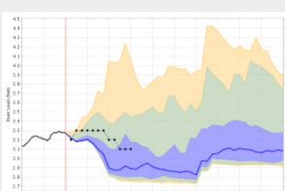
https://s2s4e-dst.bsc.eu/



The S2S4E H2020 project created a DST (Decision Support Tool) for the Energy sector, providing information for:

- Hydropower
- Energy demand
- Solar
- Wind

SUMMARY



- The world needs a new momentum into addressing the global societal and environmental challenges, i.e. **extreme weather conditions, water pollution, water scarcity, and population growth**.

- The **water cycle is controlled by the climate, geomorphology, and processes in the biosphere** (and the chemical transfer). Nature's basic principles are the same everywhere - however the properties of the catchment systems vary significantly as a function of time and space.

- There is a categorization of models based on the **spatial resolution and mathematical structure**. Modelling at the large scale is important for the coordination of emergency response and management of resources.

- Datasets can nowadays contain **remotely sensed data, crowdsourced and image-sensing data, UAV-based and telecommunication-based data and data from in-situ measurements**. Big data is the result of having more data sources and data storage. It is crucial that stored data are not erroneous, and hence **big databases follow EQC protocols and data management plans** to ensure quality, accessibility, and reliability.

- It is important to **forecast, predict and project** the various fluxes of the water cycle to better **mitigate and adapt to climate extremes, variability and change** (including other environmental stresses).

- **Hydro-climate services provide data and information** (for historical and future periods) in real time, and result in improved preparedness and decision-making.

THANK YOU FOR YOUR ATTENTION!

Q&A

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BONUS INFORMATION

Temperature forecast

SEASONAL

Model:
ECMWF SEAS5

SMHI

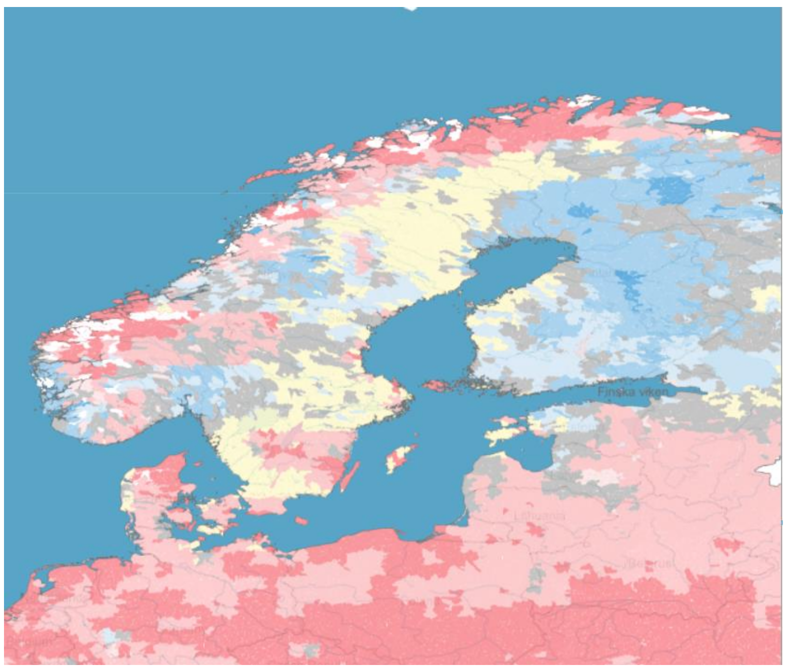
Probability terms

Low : 35% - 50%
Medium: 50% - 70%:
High: Greater than 70%

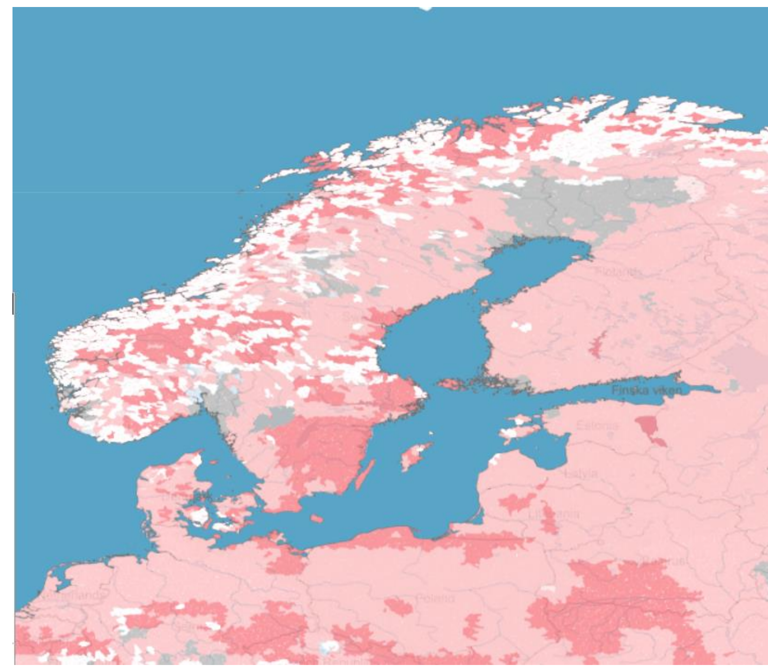
Probabilities

Above Normal	Near Normal	Below Normal
High	High	High
Medium	Medium	Medium
Low	Low	Low

January 2022



February 2022



https://hypeweb.smhi.se/explore-water/forecasts/seasonal-forecasts-europe/