Global warming and the acceleration of the water cycle

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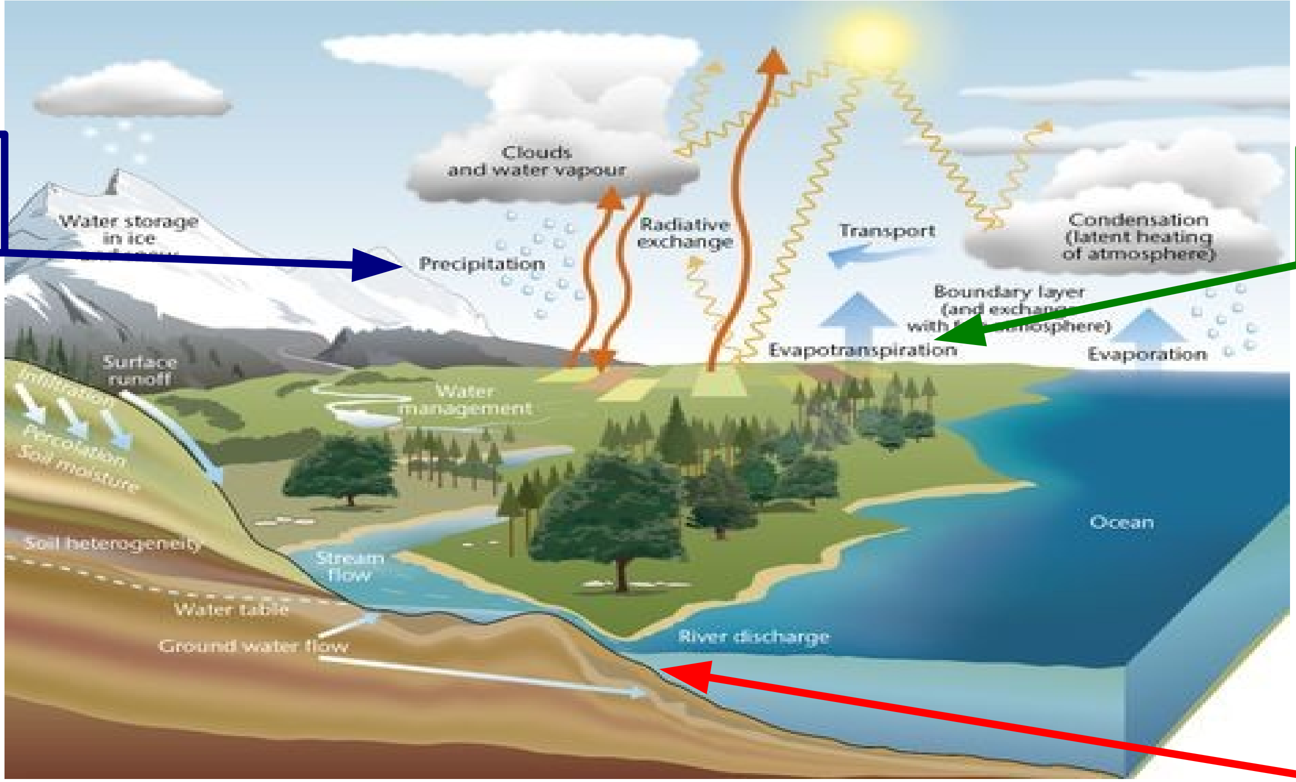
- Is the global water cycle changing in a warmer world ?
  - *What do observations tell us ?*
- Have evaporation and precipitation changed ?
  - *What can we learn from physics*
- Interactions of climate, water and land management practices :
  - *The industrial revolution also mean that water and the landscape started to be managed at a large scale.*
  - *Water management practices in a future climate.*

The water cycle

Precipitation (P)



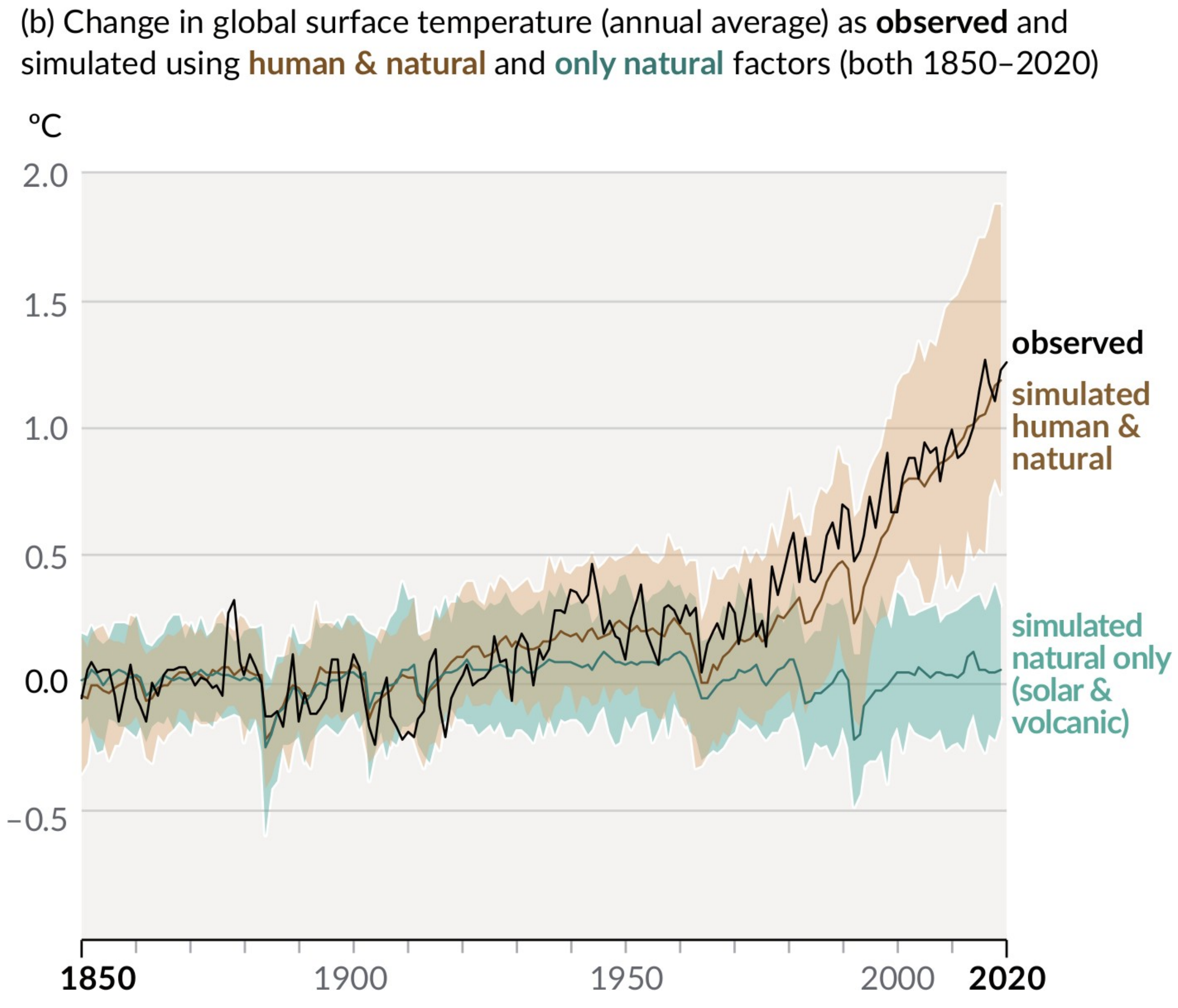
Evaporation (E)

River discharge (Q)

Over long periods the system should be in equilibrium : $P = E + Q$

But the system contains a number of processes with different time scales : hydrogeology, the cryosphere, soil moisture, vegetation, ...

Climate change

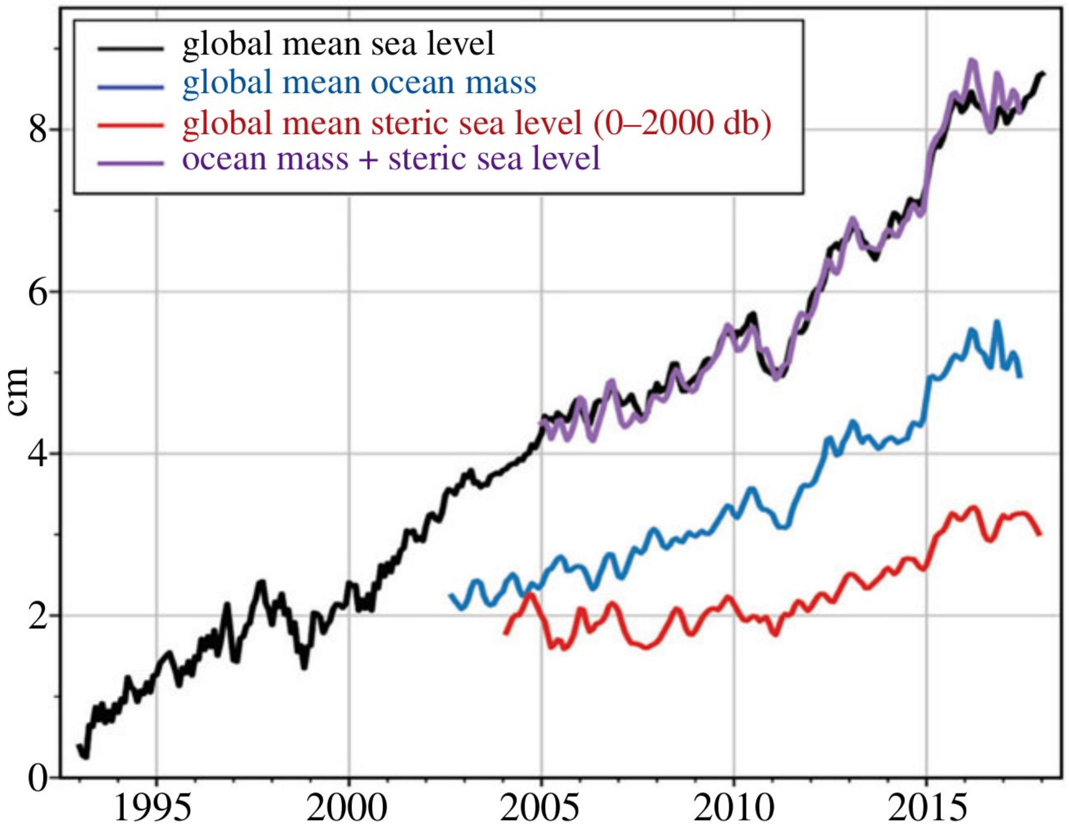


IPCC, AR6, 2021

Increasing greenhouse gases have trapped more energy close to the surface and the planet is warming.

- Observations show that the change is underway
- Models are able to reproduce the observed evolution over the last 150 years.
- These models also allow to estimate the climate we would have without this man made modification.

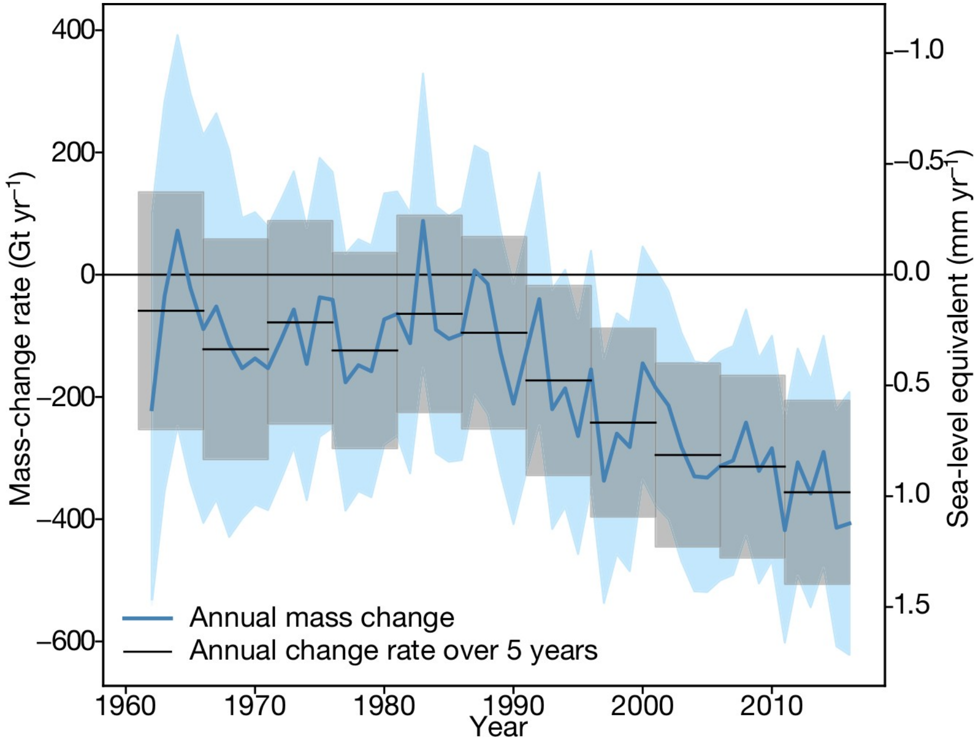
Changing sea levels

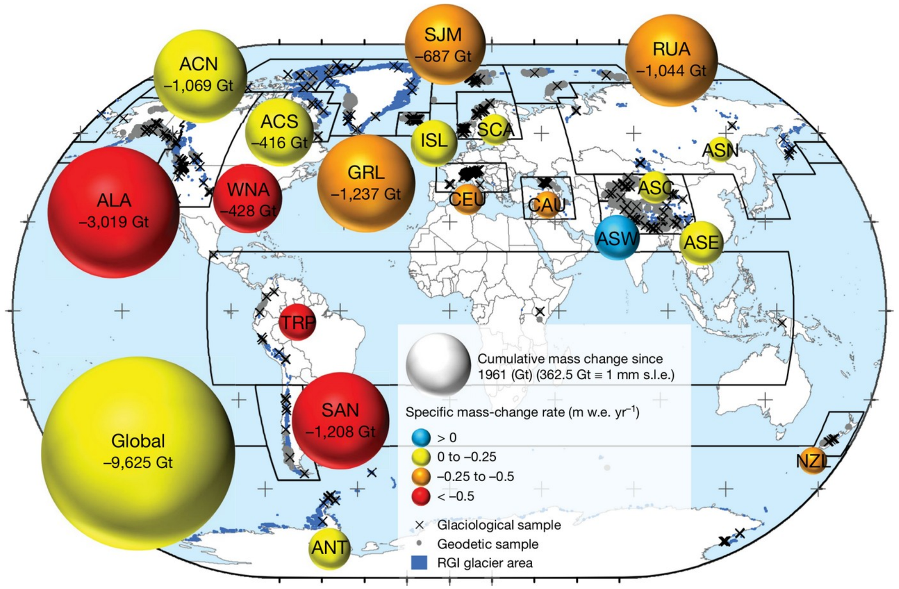


Average trend = 3.1 mm/y

- Global ocean levels are relatively easy to monitor and show a clear evolution.
- Sea levels has a complex spatial pattern. But the mean value (GMSL) is only function of the water volume.
- The volume evolves for two reasons :
  - Progressive warming of the upper ocean
  - Water mass accumulating in the oceans
- In the 2000-2005 period both effects were of similar magnitude.
- Since then the mass increase dominates. This is linked to transfers between continents and oceans
- 1.5-2.0 mm/y are explained by Greenland and Antarctica

Glacier melting





Estimating global glacier melt and its contribution to ocean mass is challenging :

- There is a large number of small glaciers.
- Each glacier is particular in its location and mass balance.
- The melt water first contributes to the local hydrology and groundwater.

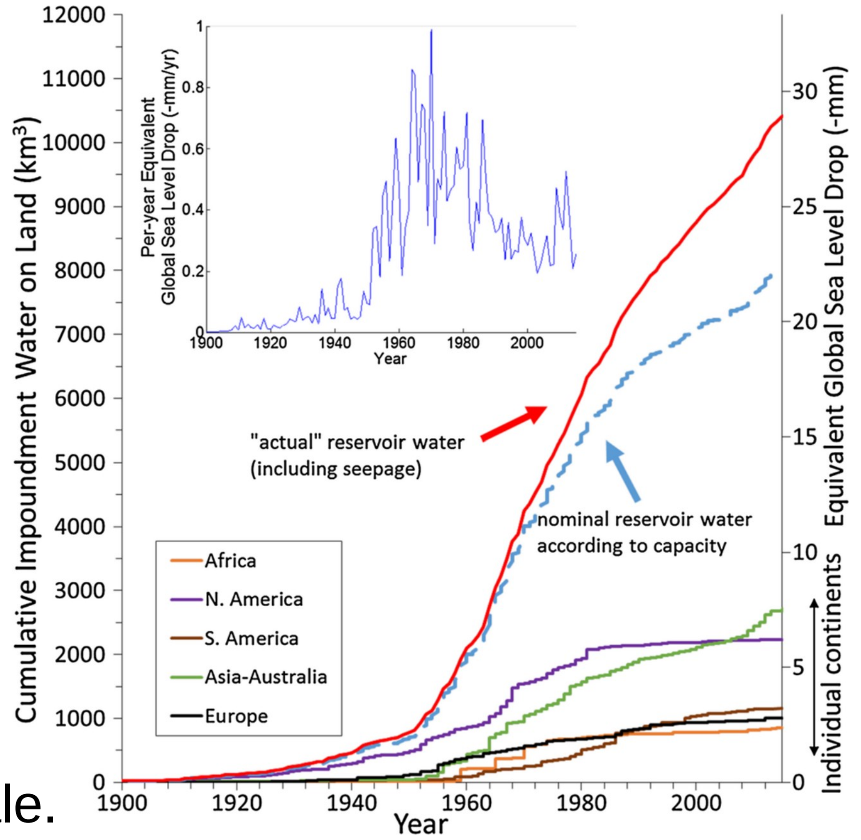
On the other hand we have good knowledge of the melting of some emblematic glaciers.

The methodologies are the same as for ice-sheets.

The high latitudes are the regions most affected by glacier melt.

Land and water usage changes

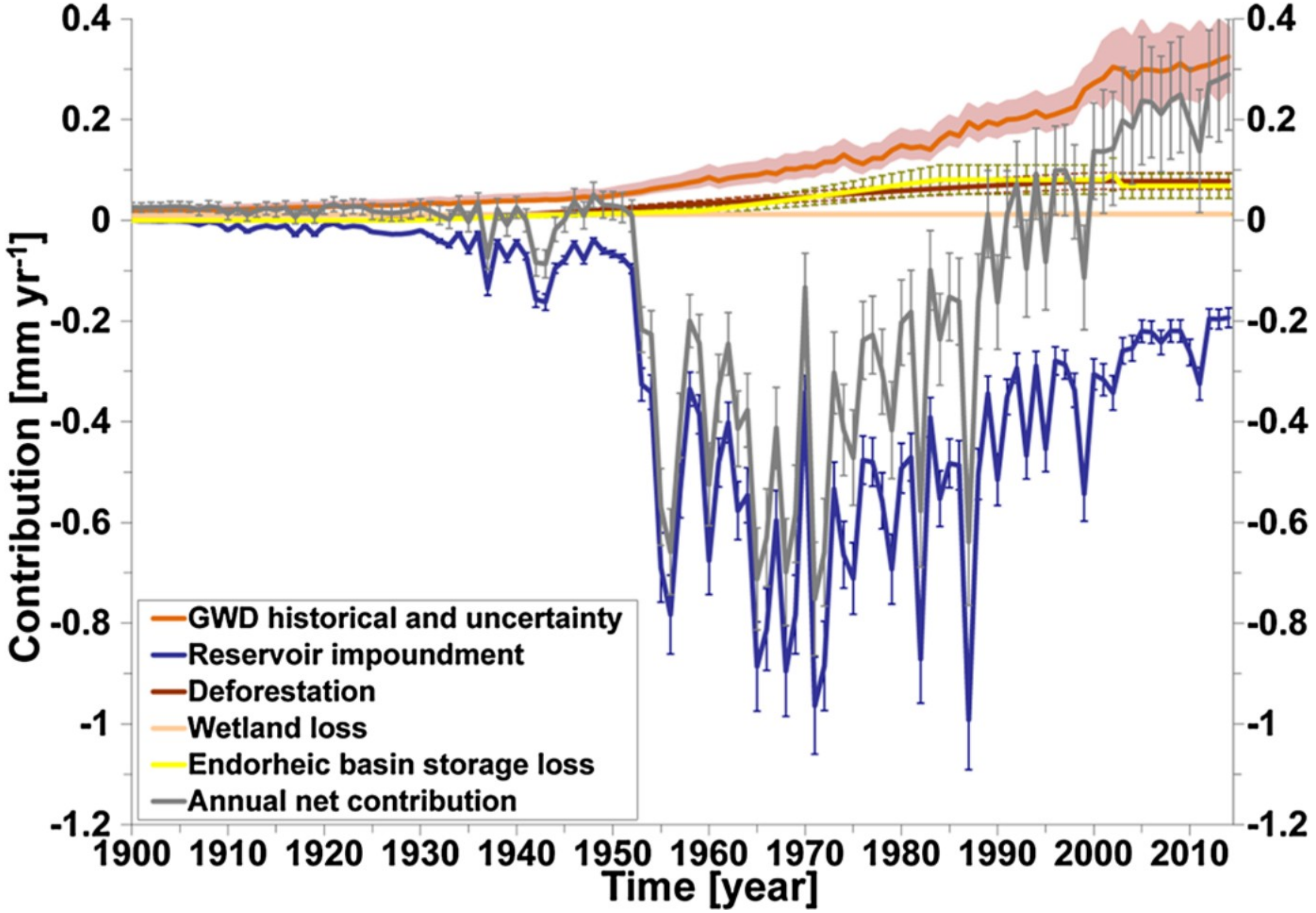
- Water impoundments
  - Dam construction and filling keeps water on continents.
  - This has been a dominant process between 1950-2000.
  - In Asia dams are still being built.
  - The estimates of contribution to GMSL decrease are based on socio-economic data and models.
- Groundwater depletion
  - Water is pumped from groundwater mostly for irrigation.
  - This occurs at local scales but affects aquifers at larger scale.
  - It is a process which has been ongoing for the last century.
  - Not all the pumped water goes directly to the ocean.
  - Remote sensing techniques give us a glimpse of the evolution of groundwater depletion.



Total contribution of land & water use to GMSL

The contribution of land surfaces to GMSL changes is complex and has changed over time.
The land contribution is not negligible :

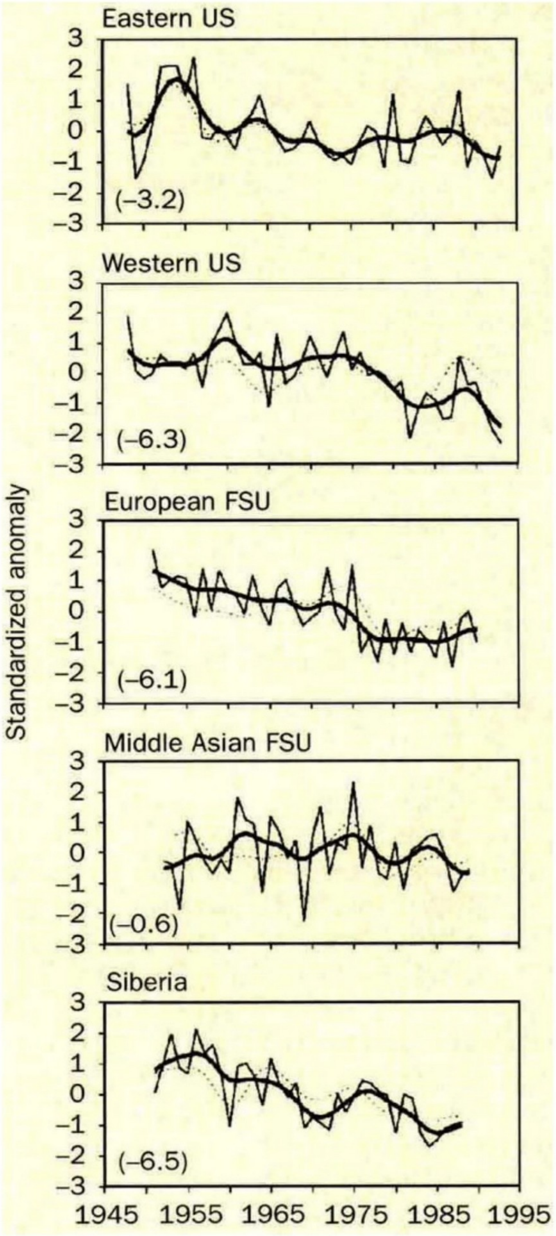
- The impoundments in the second half of the 20th century could have masked the cryospheric signal.
- A recent and growing trend is groundwater pumping.
- Currently the the continents contribute 10% to the global GMSL trend.



- In these studies the assumptions on the role of hydrology are strongly simplified.
- The impact of climate change onto hydrology is not taken into account.

Impact of climate change on evaporation

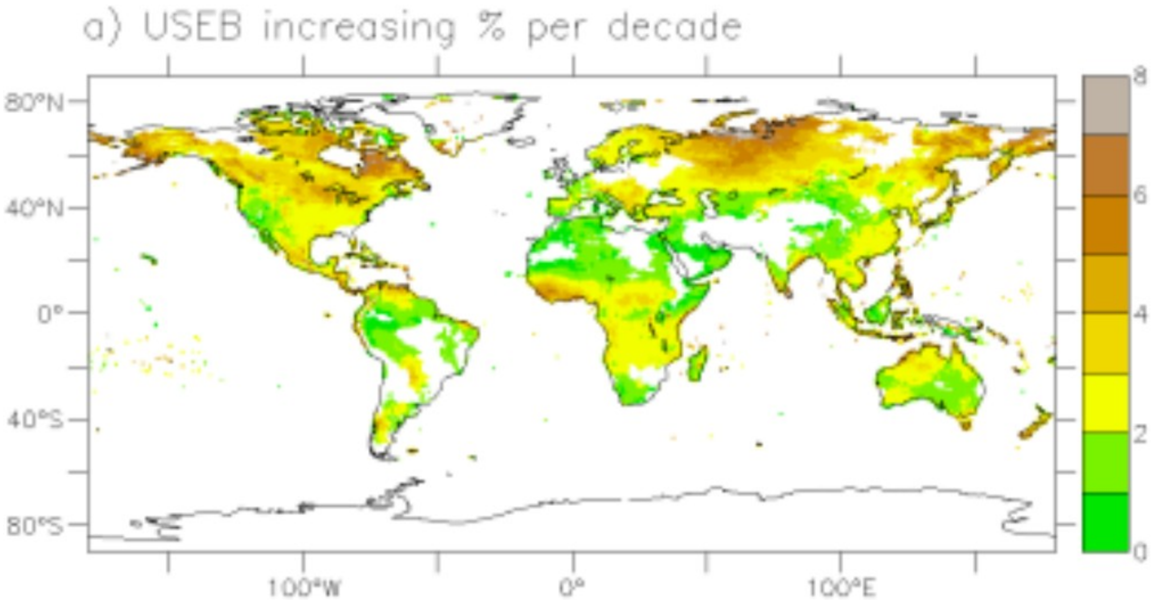
- “Pan-evaporation is a simple observation of a complex process”
- It was a surprise in 1995 when a decline over the last 40 years was found.



- These observations were in the early phase of climate change which went along with :
  - Reduced diurnal amplitude of temperature.
  - Reduced solar radiation because of changes in cloud cover and aerosols.
- Obviously pan-evaporation is not representative of natural evaporation but an estimate of the atmospheric demand.

Water demand is expected to increase

- This potential evaporation is governed by three processes :
  - Available energy at the surface,
  - The deficit of water vapour pressure in the atmosphere, and
  - Atmospheric mixing.
- In a warmer climate we expect :
  - More energy available at the surface
  - The warmer atmosphere raises the saturation vapour pressure (Clausius-Clapeyron)
  - The lower atmosphere will be more turbulent and better mixed.



Actual evaporation will also depend on :

- Available water.
- Plants ability to do photosynthesis.
- Land use

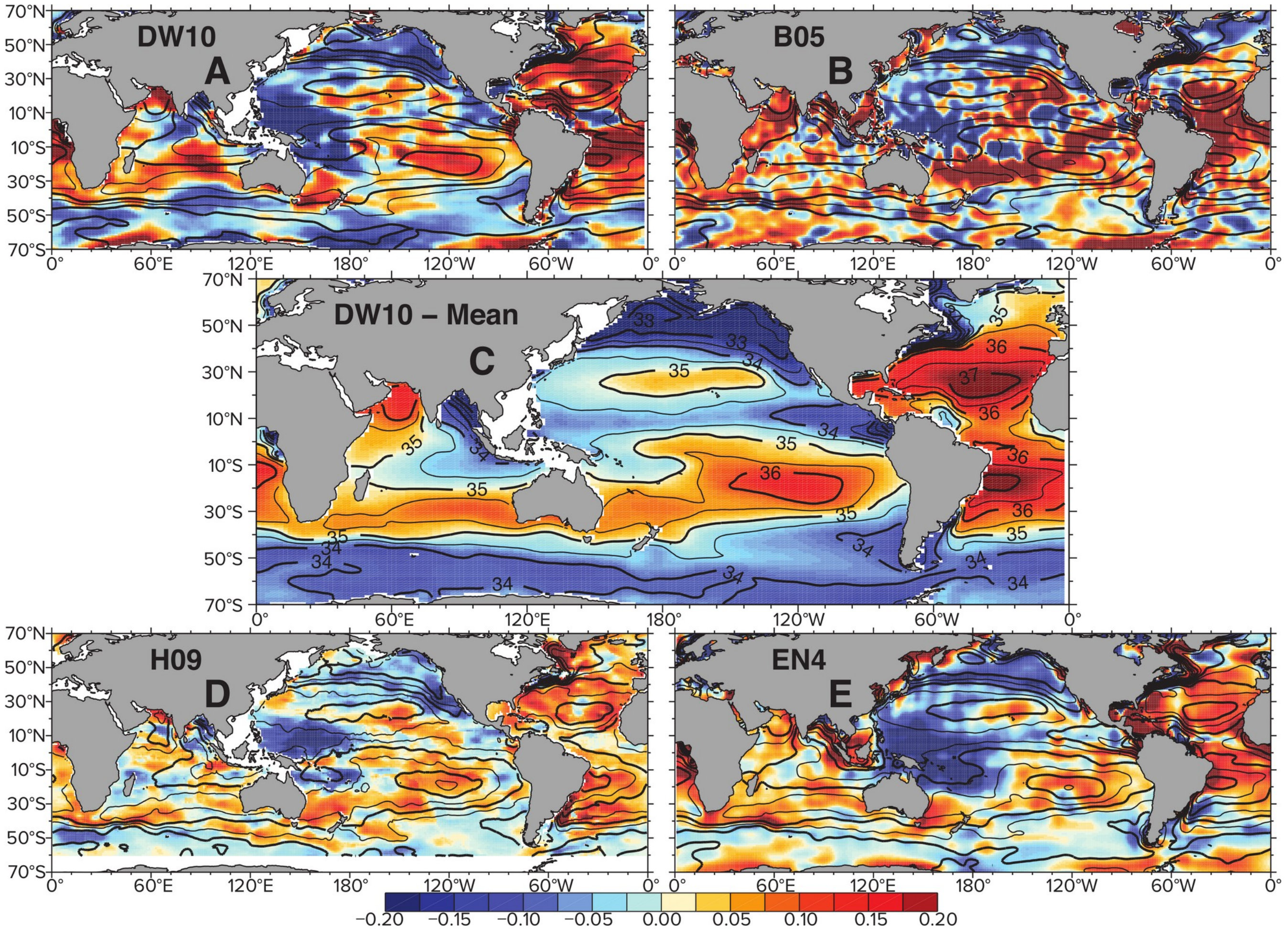
Evaporation is a flux for which we do not have large scale observations !

Ocean evaporation changes

Evaporation leaves a trace in the ocean's surface salinity. Thus we can examine how evaporation has trended in the last decades.
Do you recognize features ?

In fact, it is P-E which drives SSS changes.
Reconstructions of SSS trends over the 1950-2000 period shows a few interesting trends :

- Arid areas P-E < 0 have had increasing evaporations.
- Wet areas P-E > 0 ave seen more rainfall.

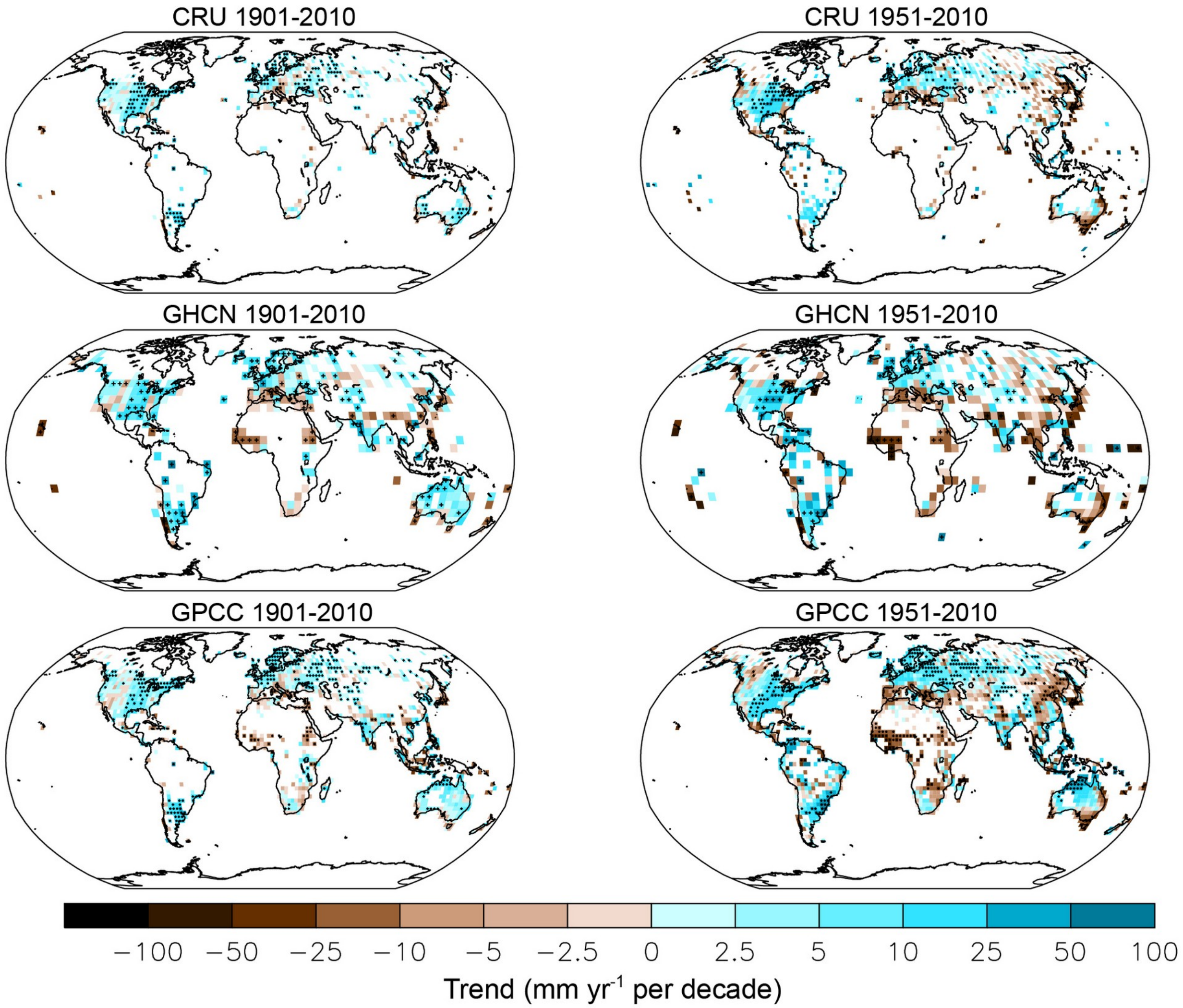


PSU (lines) &PSU per 50 years (coloring).

Produced the "Wet wetter and dry drier" phrase.

Impact of climate change on precipitation ?

- Precipitation are only reliably observed over continents.
- Questions still remain on the representativeness of rain gauge measurements. Some regions are undersampled.
- Annual mean rainfall mostly increases but the image is complex.
- Regional details vary from one estimate to another.



We do not know what happens over oceans, but an increasing trend would be consistent with considerations of the energetics of the Earth.

Intensification of daily rainfall

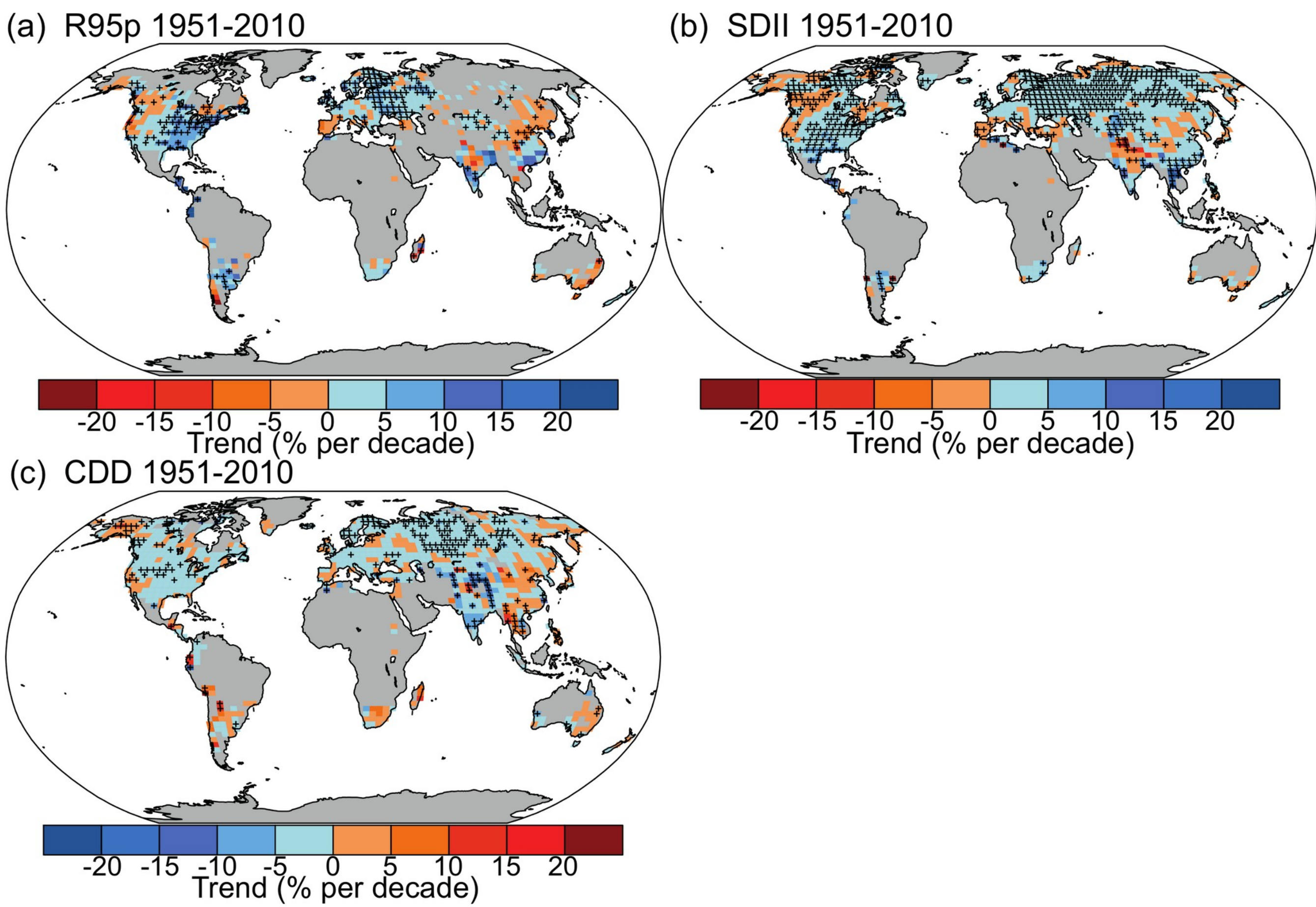
Remarkable is the intensification of rainfall :

Two metrics are used to measure it across various data sets :

- Yearly 95% quantile of daily rainfall,
- Yearly average rainfall intensity at the daily scale(SDII).

Both show a clear positive trend, in regions where data is sufficient.

The consecutive dray days (CDD) shows that the frequency of rain also increases.



➔ Consequence of CC relation

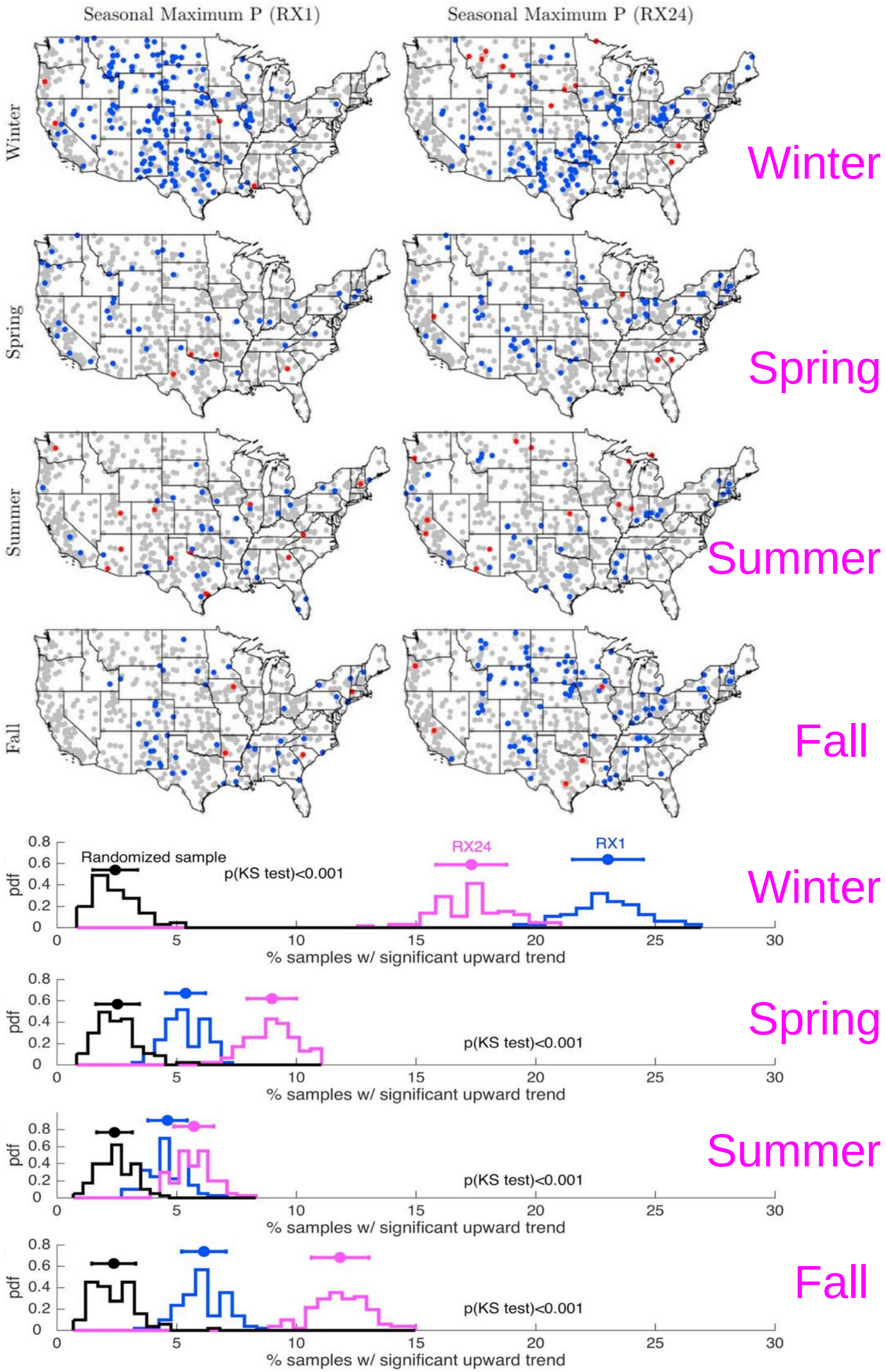
➔ Profound impact on hydrology.

Does hourly rainfall change ?

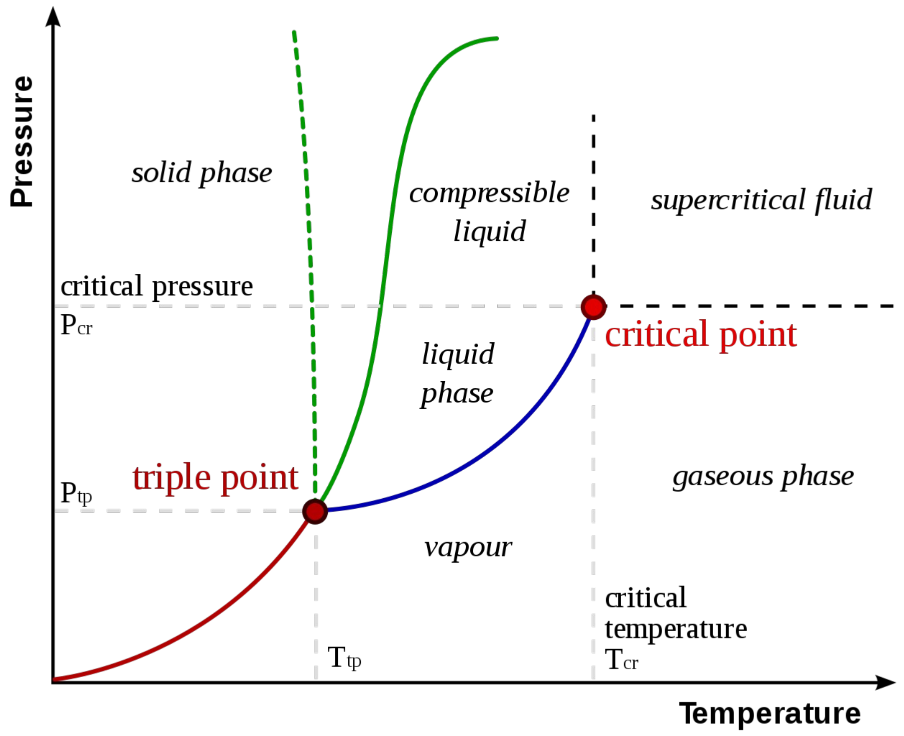
Rainfall events are shorter than a day. Does the intensification also hold at shorter times ?

Over the US enough observations are available to test the hypothesis with daily (RX24) and hourly (RX1) rain rates :

- Generally the results are consistent on both time scales.
- Not all stations show an intensification.
- A significant number of stations show a trend over all seasons. More pronounced in winter.
- Hourly rainfall does seem to have a sampling issue of events, especially in summer.
- Given the large sample (733 stations) robust statistics can be made.

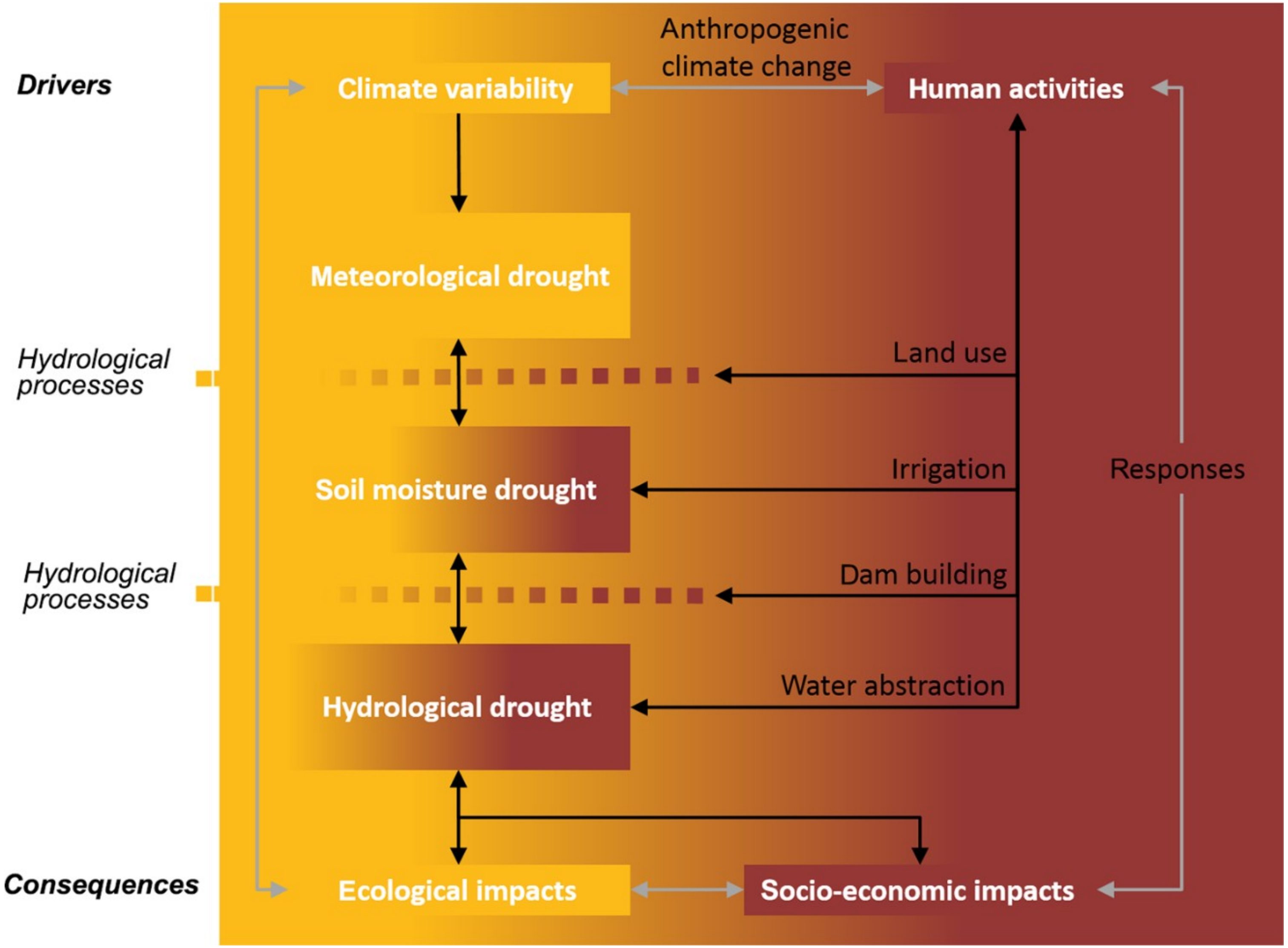


The Clausius-Clapeyron relation



- The warmer atmosphere will hold more water. This is given by the Clausius-Clapeyron relation.
- Once the atmosphere reaches its condensation point, more latent energy can be released.
- This explains the intensification of rainfall.
- The relations is difficult to establish precisely :
  - Regional characteristics of the rainfall play an important role.
  - Precipitation is not well observed.
  - We have no observations of the location in the atmosphere where condensation occurs.

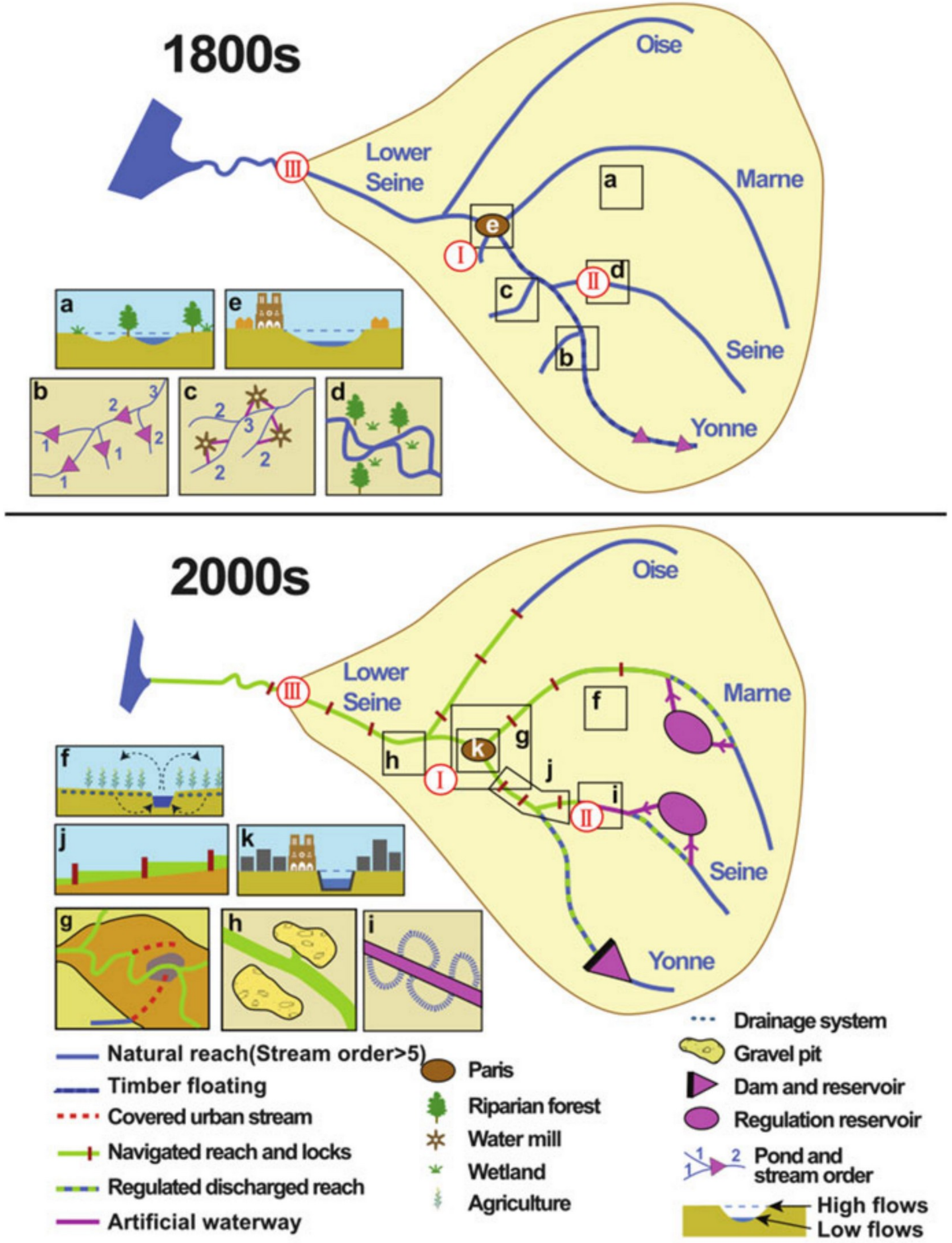
Human driver of the continental water cycle



Droughts are not only driven by atmospheric processes :

- Reforestation of mountainous areas
- Intensification of agriculture
- Irrigation
- Hydropower generation
- Groundwater pumping
- Inter-basin transfers.

All these changes interact with the water potential provided by climate.



The Seine

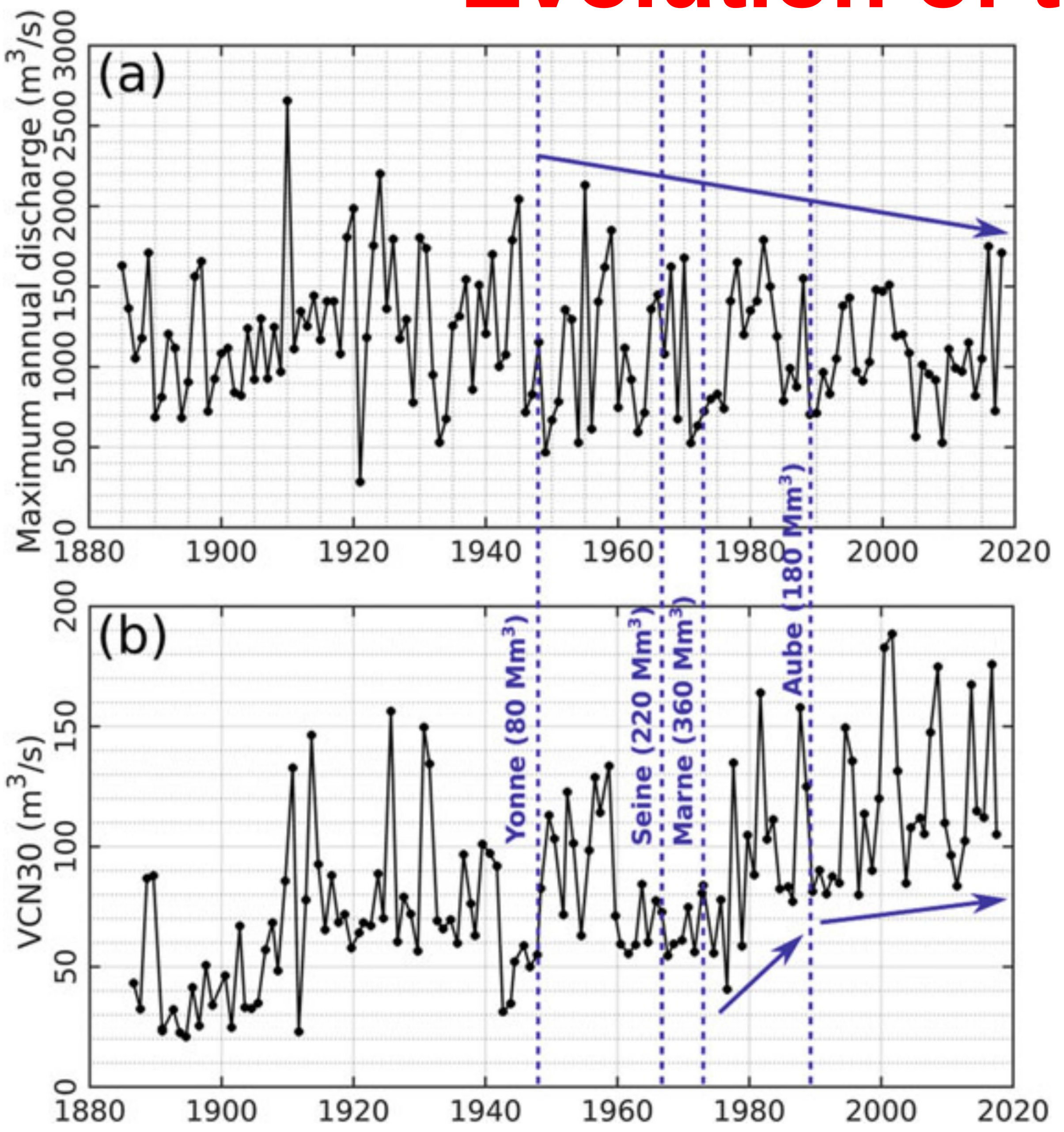
Over the last two centuries humans have engineered the hydrological system :

- Suppression of forests along rivers,
- Simplification of the river network,
- Drainage and drying of swamps
- Locks and dams
- Reservoirs

The Seine is not unique in this evolution. The Danube has started to been managed much earlier.

These managed system will now be facing a changed climate.

Evolution of the discharge of the Seine



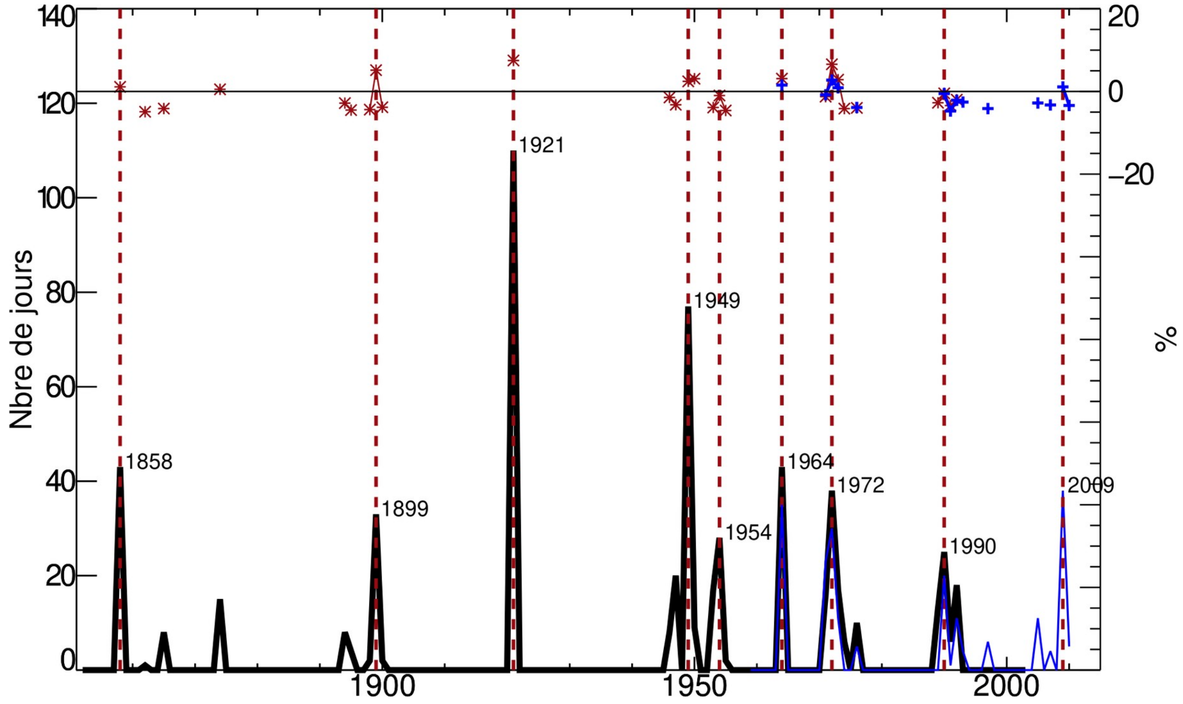
The management of the Seine has modified the annual cycle of its discharge :

- Low-flows have been quadrupled
- The flooding peaks are now reduced.

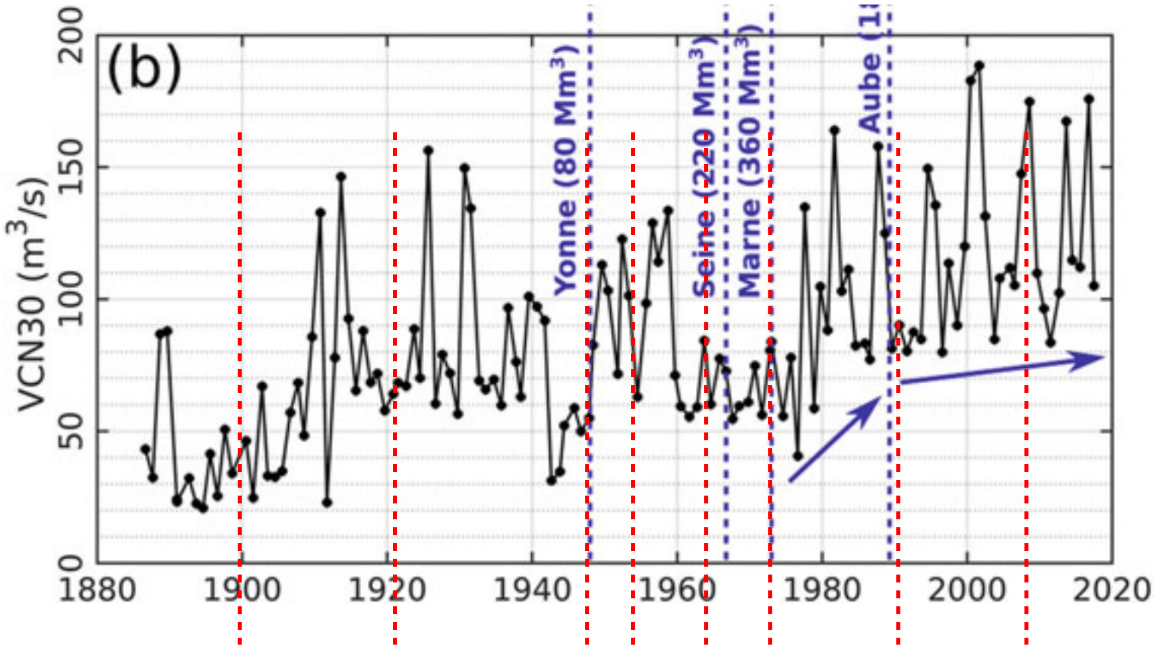
This has protected populations and made water resources more reliable.

These infrastructures have been designed based on the climate of the last 200 years. Will they be able to cope with the new climate ? What is the breaking point of this new system ?

Links between droughts and discharge of the Seine



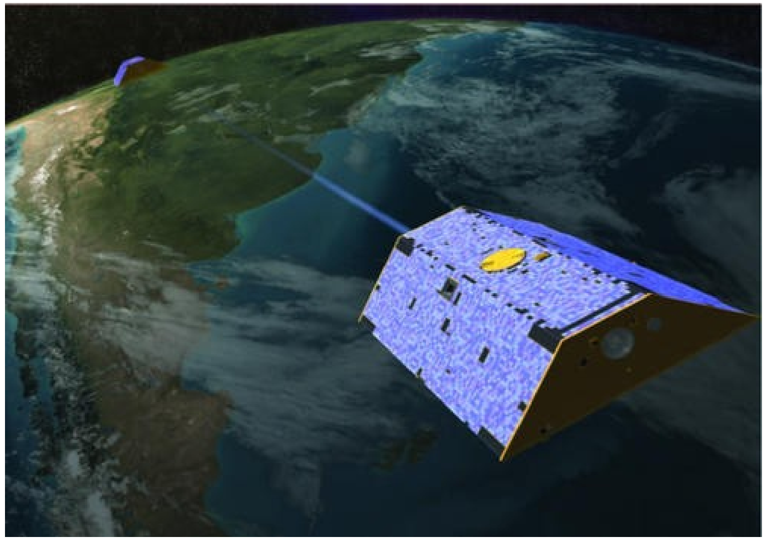
Soil moisture droughts reconstructed for a natural system.



The smallest discharge values do not coincide with natural hydrological droughts at the end of the record !

1) Water management is effective to protect our resources.
2) With how much climate change can these infrastructures deal ?

A synthesis of water resource evolution as monitored from space



The GRACE mission has observed mass changes from 2002 to 2017.
Water mass changes can be extracted from the total changes of the gravitational field.

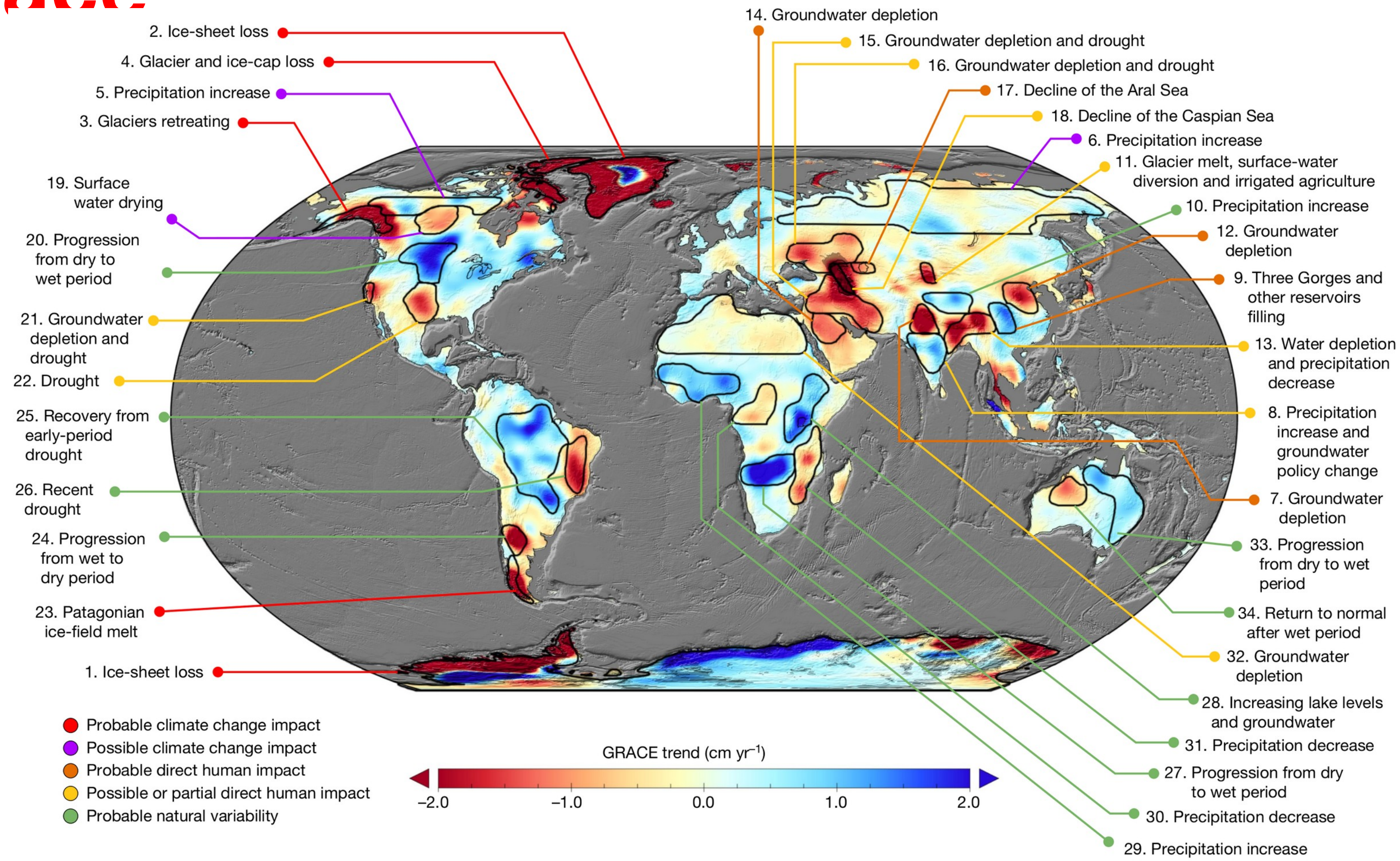


Fig. 1 | Annotated map of TWS trends. Trends in TWS (in centimetres per year) obtained on the basis of GRACE observations from April 2002 to March 2016. The cause of the trend in each outlined study region is briefly explained and colour-coded by category. The trend map was smoothed with a 150-km-radius Gaussian filter for the purpose of visualization; however, all calculations were performed at the native 3° resolution of the data product.

The attribution can only be done qualitatively at this stage !

Conclusion

- Climate change will affect the continental water cycle.
- The way humans manage water resources modified the water cycle at global scale.
- Society needs to be informed of the consequences of climate change on the **managed** water cycle.
- This will require to bridge cultural differences between various disciplines :
  - *Climate scientists consider the continental water cycle as natural.*
  - *Hydrologists use simplified relations for their dependence on weather and climate.*
  - *Engineering practices make assumptions about climate which will not be valid in the future.*
- It is paramount for society that we achieve a more unified vision of the water cycle.