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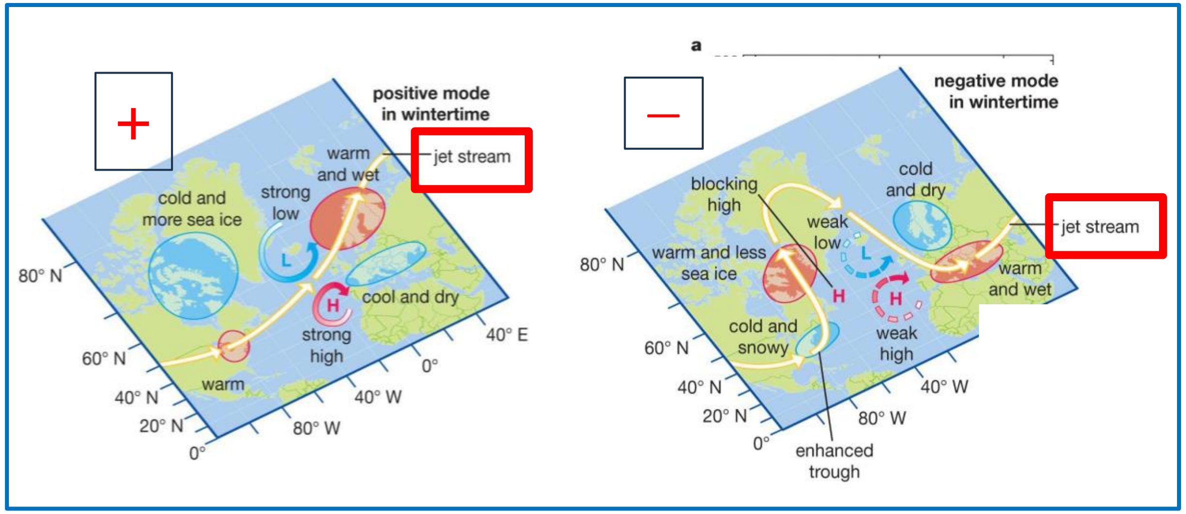
Sustainability, climate and energy

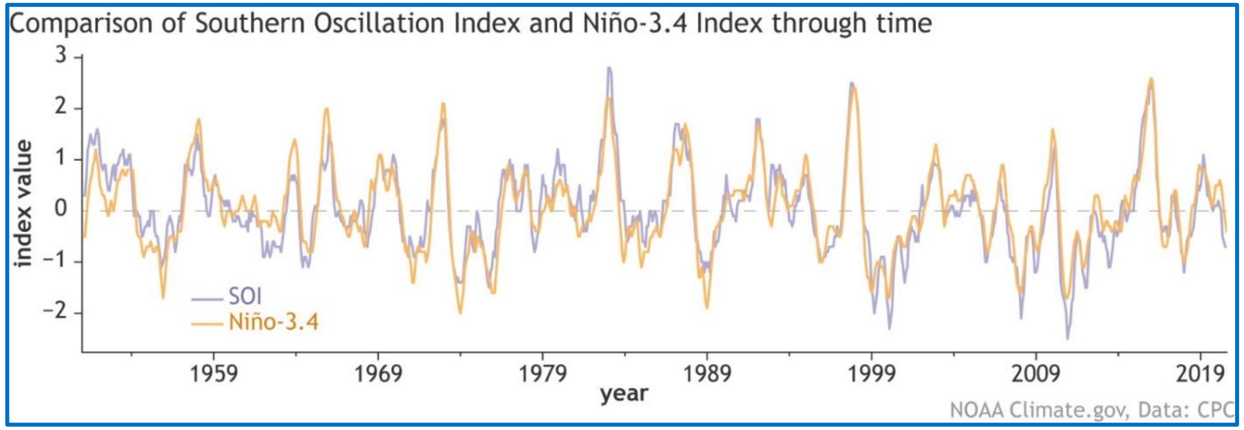
ENV-421
Jérôme Chappellaz, Jonas Schnidrig

Recap from last lecture

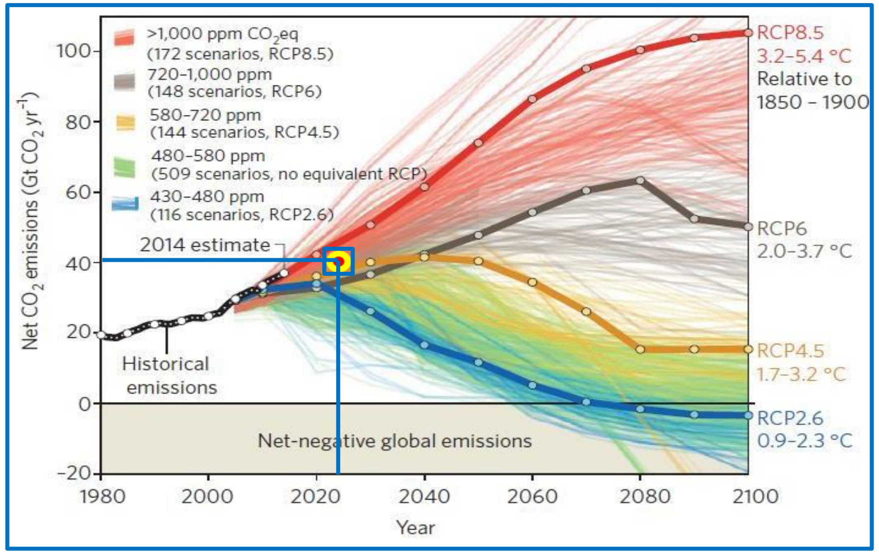
Climate variability : NAO



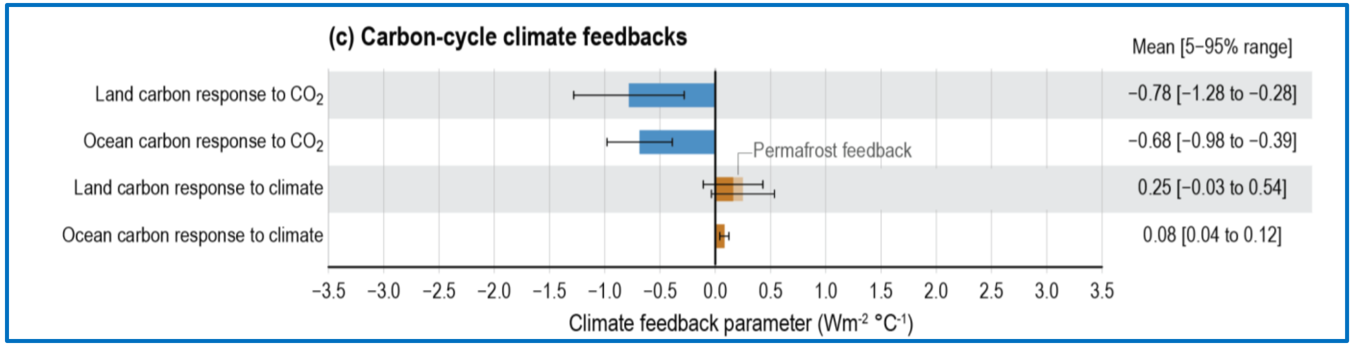
Climate variability : ENSO



Climate change scenarios: CO_2 emissions



Carbon cycle feedbacks: CO_2 and climate effects



General outline

No.	Date	Topics	Remarks
1.	18.02.2025	Introduction to the climate system. Earth energy balance. Greenhouse gases and aerosols	
2.	25.02.2025	Introduction to energy systems. Energy balance fundamentals	
3.	04.03.2025	Radiative forcing. Feedback mechanisms. Climate sensitivity	
4.	11.03.2025	Overview of energy technologies	
5.	18.03.2025	Climate archives: geological to millennial time scales	Conf. Michael Sigl + QCM evaluation (graded)
6.	25.03.2025	Climate variability. Climate change scenarios. Carbon cycle feedbacks.	
7.	01.04.2025	Technologies' impacts	Conf. Alexis Quentin
8.	08.04.2025	**Tipping points. Extreme events. Regional climate change**	
9.	15.04.2025	Climate change impacts on renewable energy systems. Impact of RES on climate	J. Castella (Watted) : PowerPlay game
10.	29.04.2025	Field visit : floating solar platform + dam (Romande Energie)	
11.	06.05.2025	Intro to systemic approach on local scale climate/energy engineering	Start of group work
12.	13.05.2025	Group work on chosen case study	
13.	20.05.2025	Group work on chosen case study	
14.	27.05.2025	Presentation of group reports	Reports are graded

Basics (1–9)

Applications (10–14)

Exam session between 16.06.2025 and 05.07.2025

Tipping points

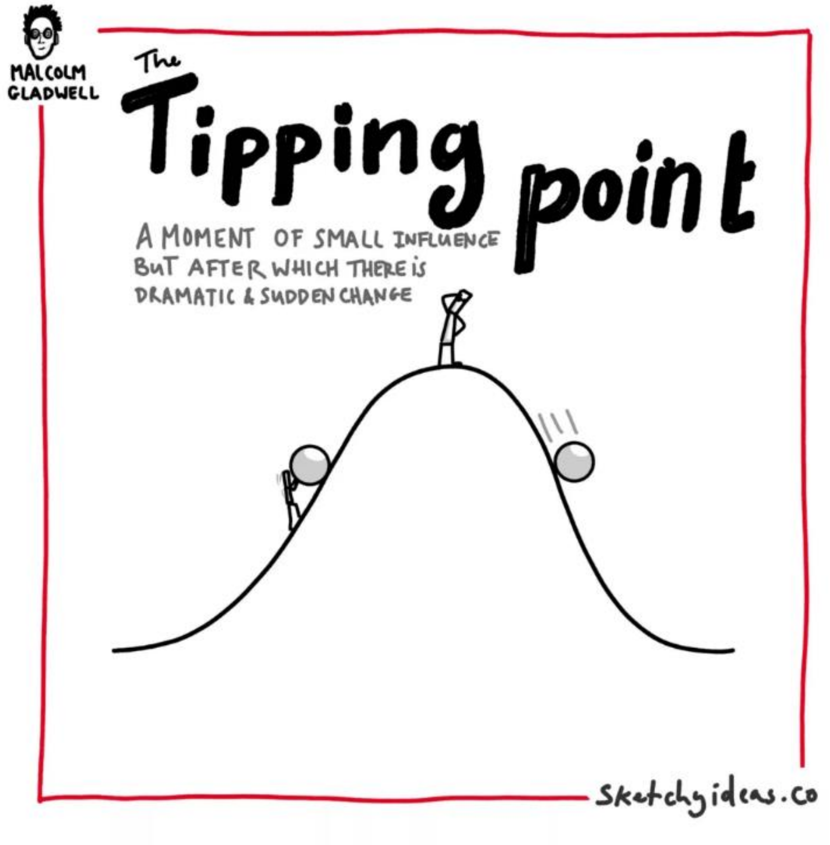
What are tipping points in the climate system ?

- Tipping points are *"critical thresholds in a system that, when exceeded, can lead to a reorganization of the system, often abruptly or irreversibly."*

- Climate tipping points: Elements of the Earth system in which small changes can kick off reinforcing loops that 'tip' a system from one stable state into a profoundly different state.

- Example: a rainforest becoming a dry savannah, due to warming. There are positive feedback loops making that the system remains "tipped" for a very long time, even if temperature falls below the threshold again.

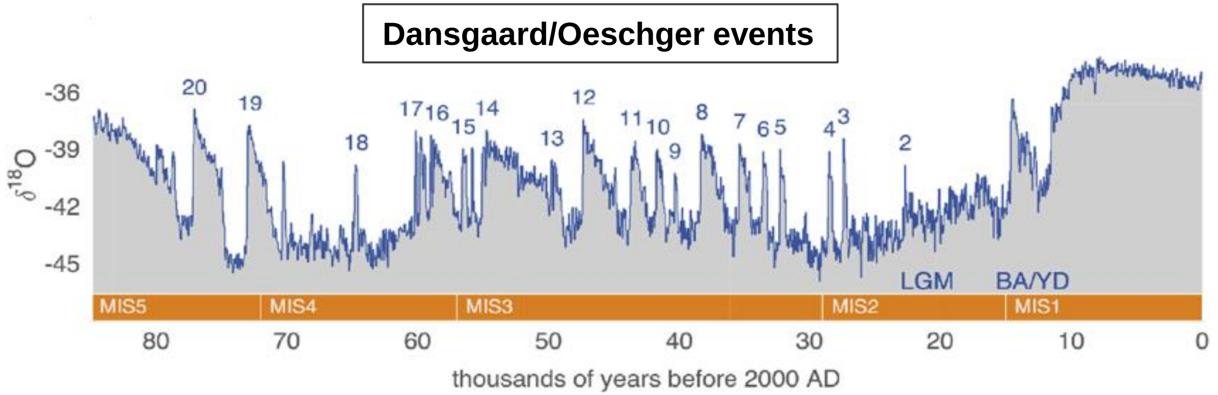
- In this case, positive feedbacks include: lower rainfall (evapotranspiration), increased fire frequency, loss of soil nutrients.



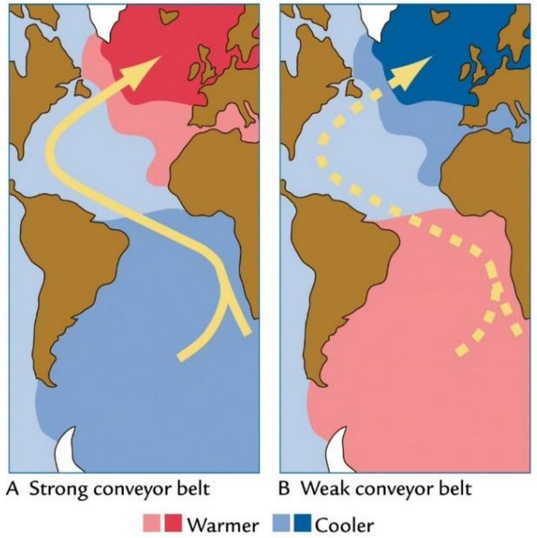
The myth of Sisyphus, in Greek mythology

Source: European Space Agency

Examples of tipping points from the recent past



Source: Li and Born, Quat. Sci. Rev. 2019



Source: Ruddiman, Earth's climate, past and future

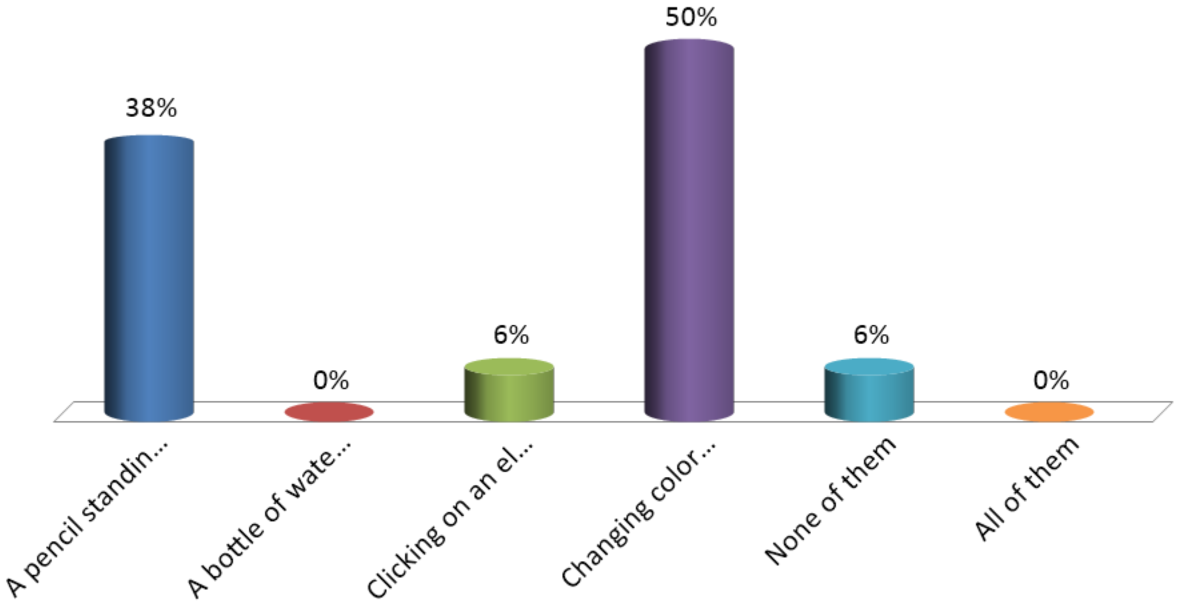
- Dansgaard/Oeschger events in Greenland temperature during the last glaciation: non-linear abrupt shifts due to Atlantic thermohaline circulation changes.

- Vanishing Laurentide ice sheet over North America during the last deglaciation and onwards: a shift from a stable state to another stable state due to orbital forcing and CO_2 amplification, with internal positive feedbacks (elevation, albedo, basal lubrication).

Source: University of Toronto

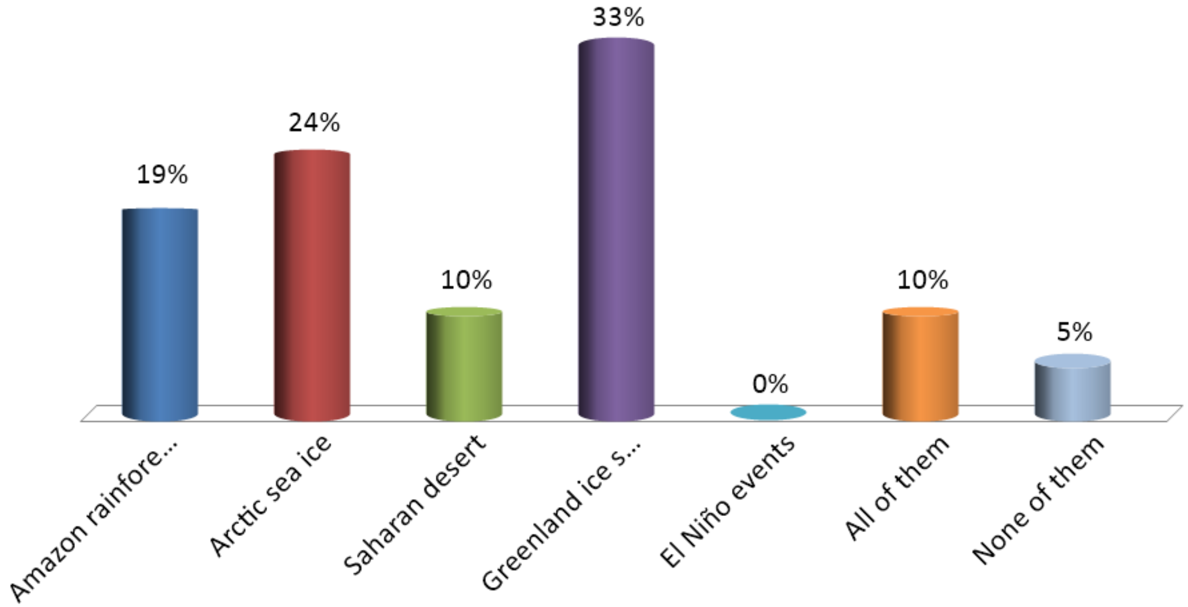
Are these tipping elements in your everyday life ?

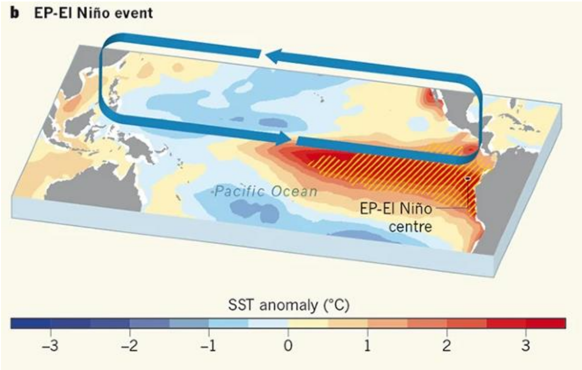
A. A pencil standing vertical on your finger
B. A bottle of water cooling in a fridge
C. Clicking on an electrical switch
D. Changing color of your toast in a toaster
E. None of them
F. All of them



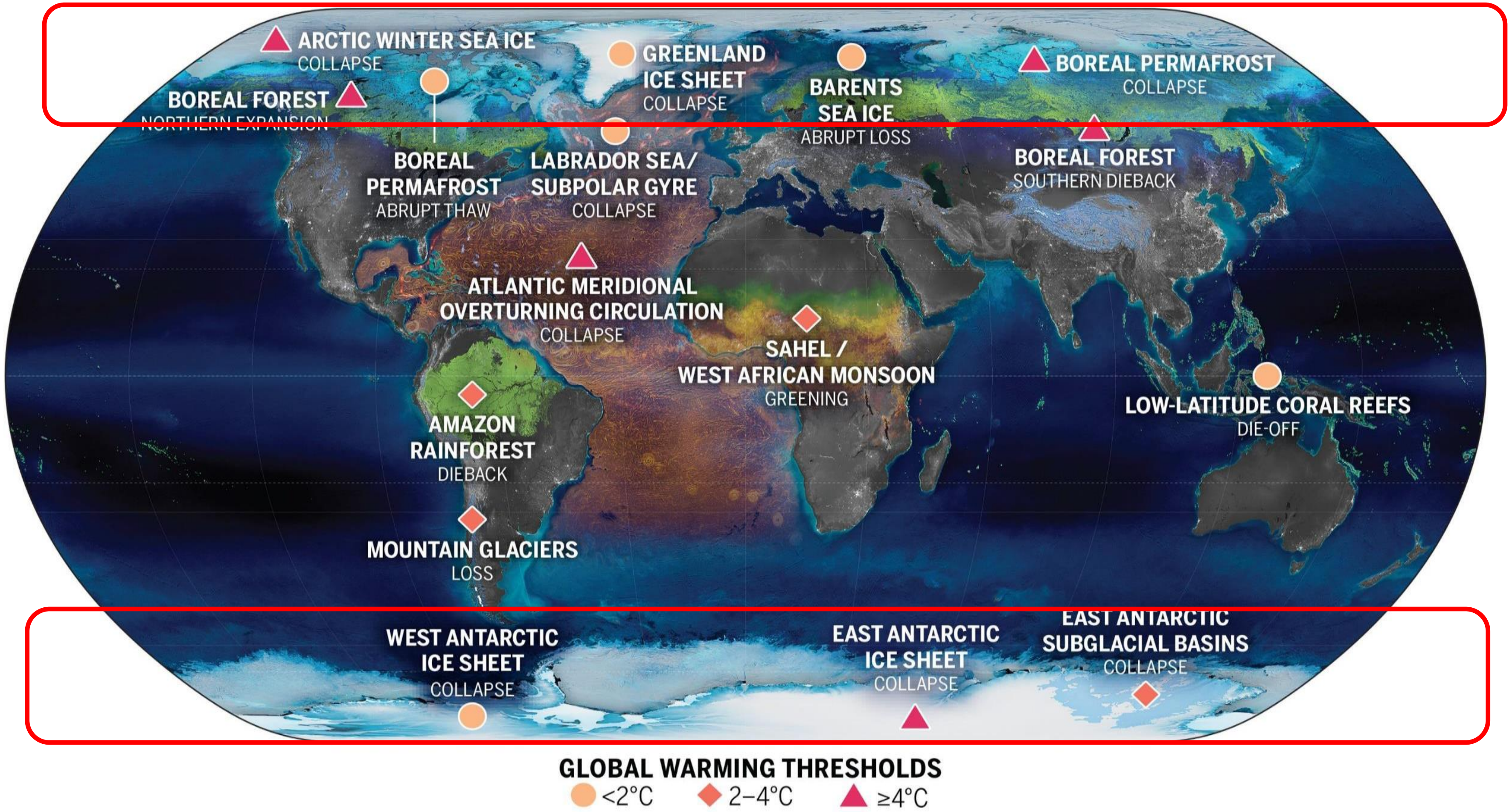
Are these tipping elements of the climate system ?

A. Amazon rainforest
B. Arctic sea ice
C. Saharan desert
D. Greenland ice sheet
E. El Niño events
F. All of them
G. None of them





Main tipping points in the climate system today



- There are threshold ranges of global warming to reach a tipping point, depending on the tipping element.
- Many tipping points are located in polar/subpolar regions.
- Tipping points are of major concern for societies: sea-level rise, disappearance of biomes, carbon cycle feedback.

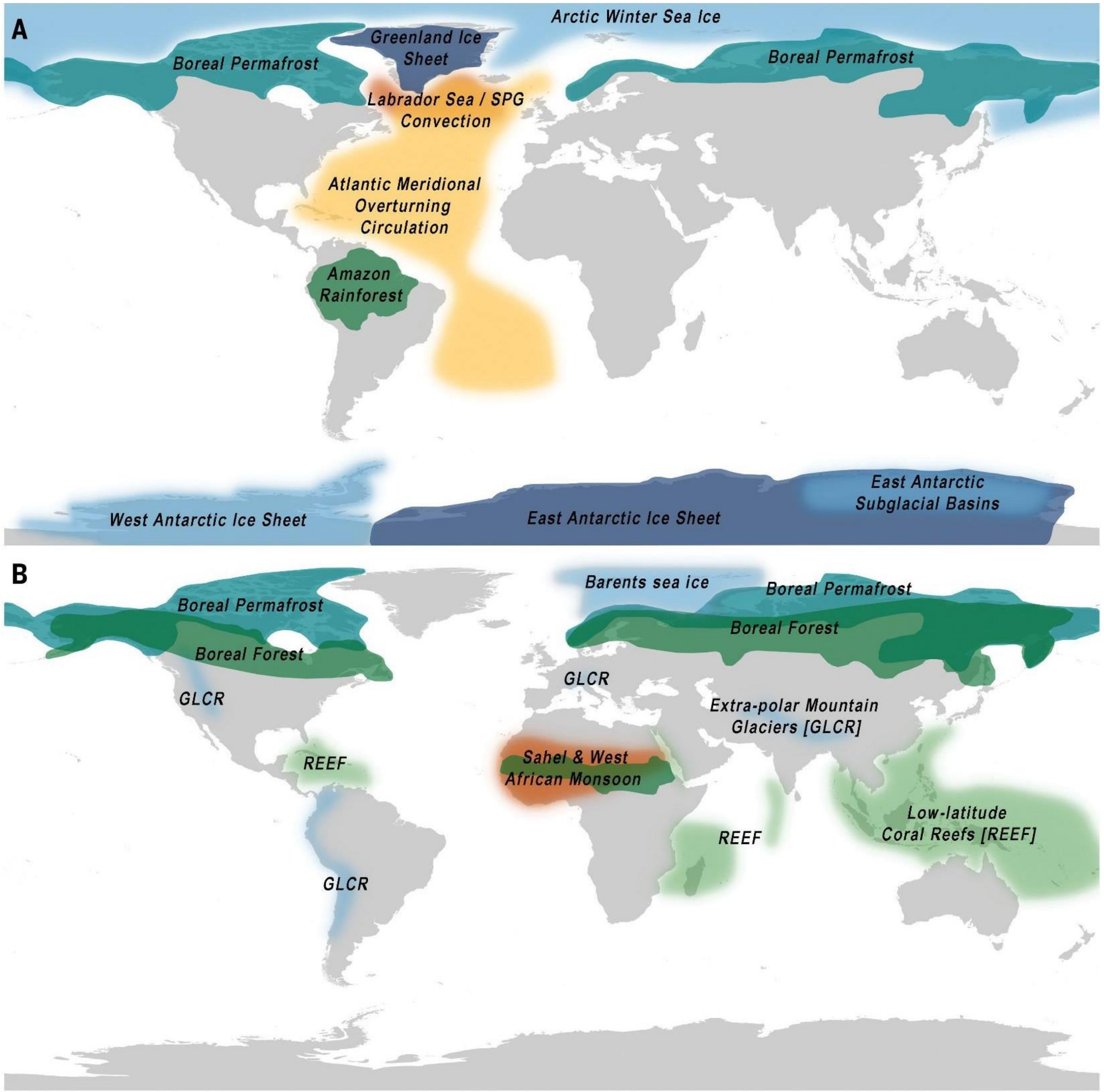
Source: Armstrong McKay et al., Science 2022

Global versus regional tipping elements

- Maps showing the global core (**A**) and regional impact (**B**) climate tipping elements*. (Blue: cryosphere* | *Green: biosphere* | *Orange: ocean-atmosphere)*.

- 9 «global core» tipping elements: they have planet-wide impacts (sea level, carbon cycle, ocean circulation). They can trigger further impact on other systems.

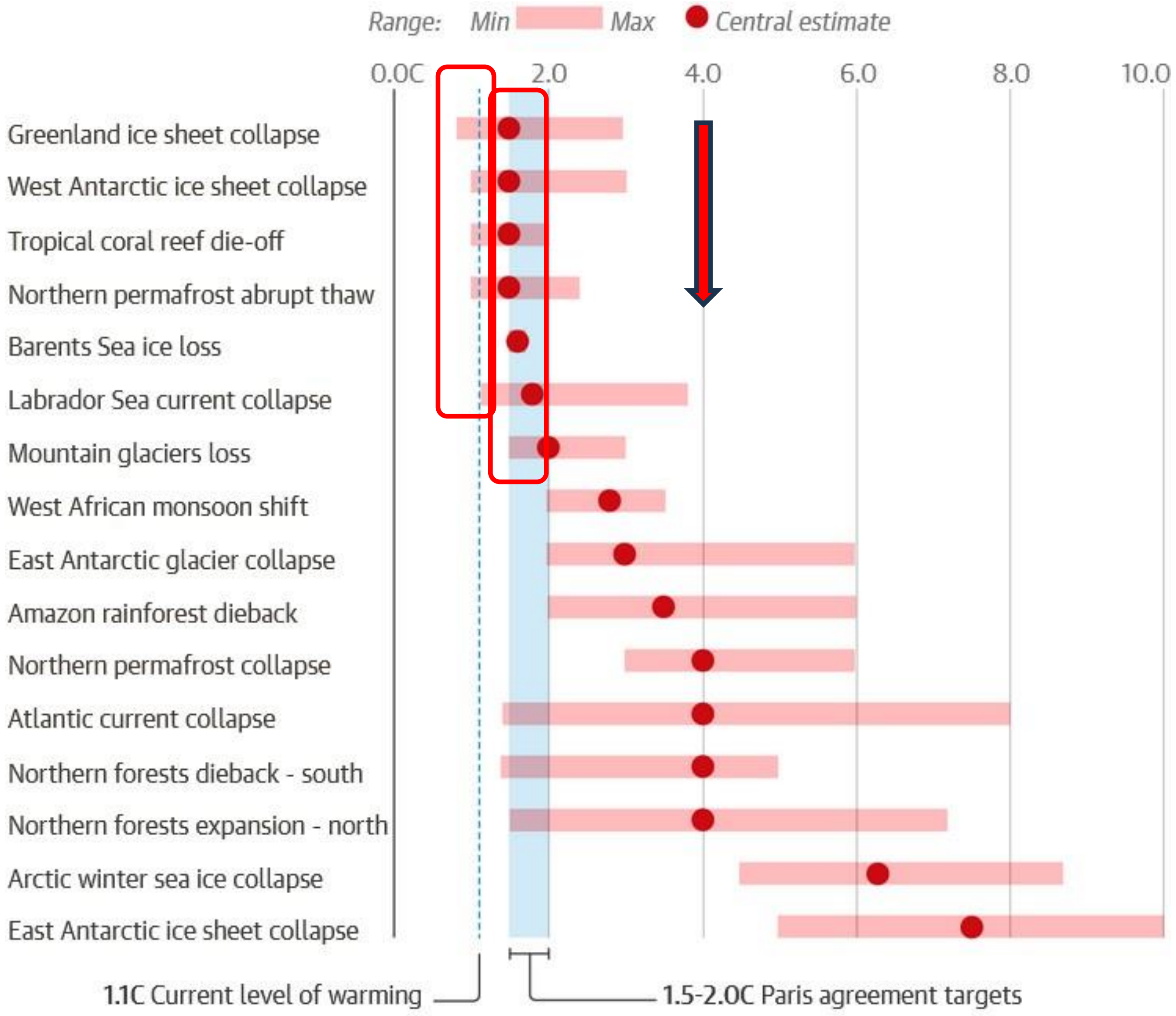
- Regional impact tipping elements: regional change not affecting the global climate system, but having large socio-ecological consequences.



Source: Armstrong McKay et al., Science 2022

Tipping points versus the Paris Agreement

- Current global warming of ~1.1°C since preindustrial times already reaches the lower end of five tipping points.
- With the Paris Agreement target of a warming lower than +2°C, seven tipping points become likely.
- Most of the tipping points reached with +4°C.

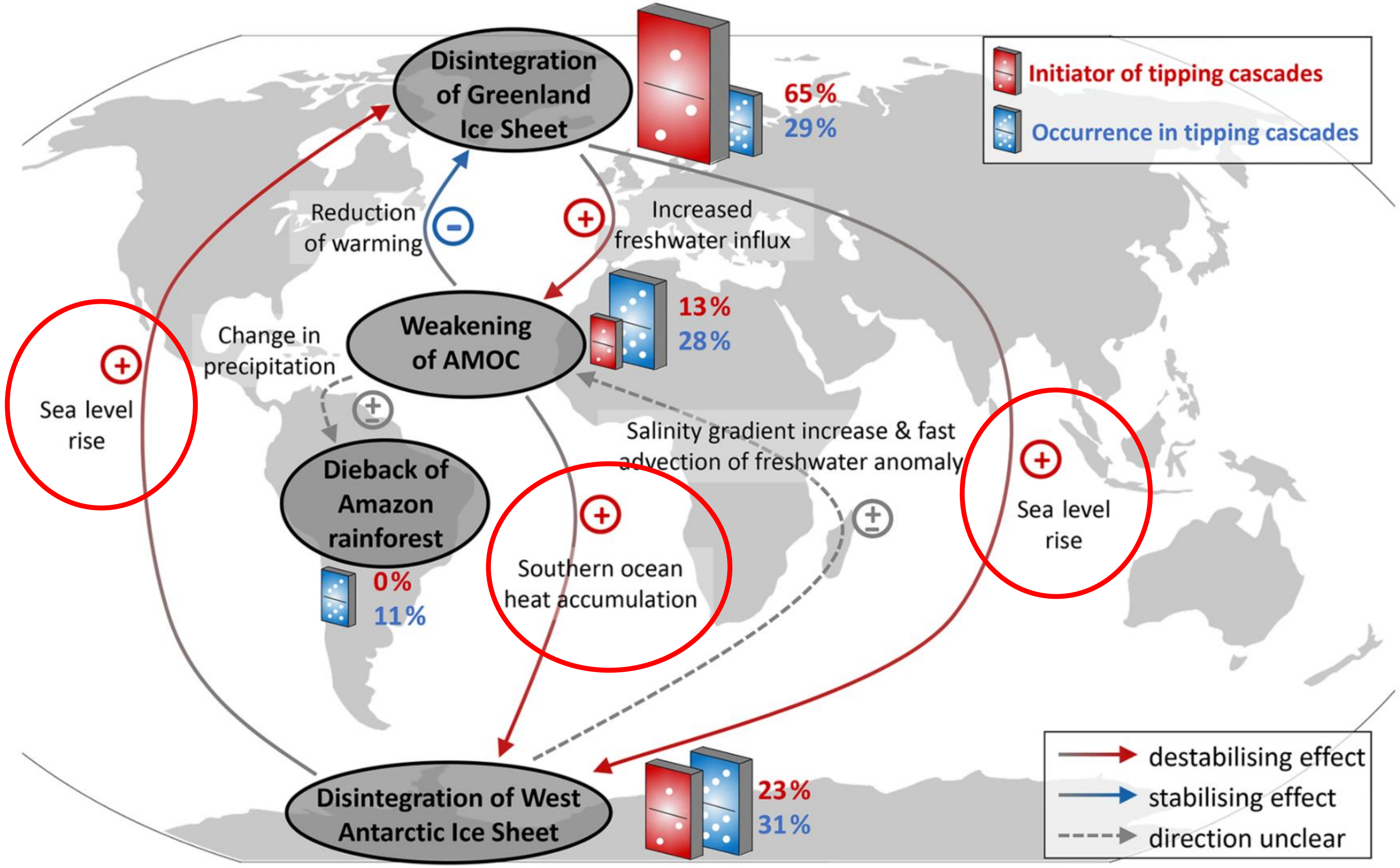


Guardian graphic. Source: Armstrong McKay et al, Science, 2022. Note: Current global heating temperature rise 1.1C Paris agreement targets 1.5-2.0C

Source: [The Guardian 2022]

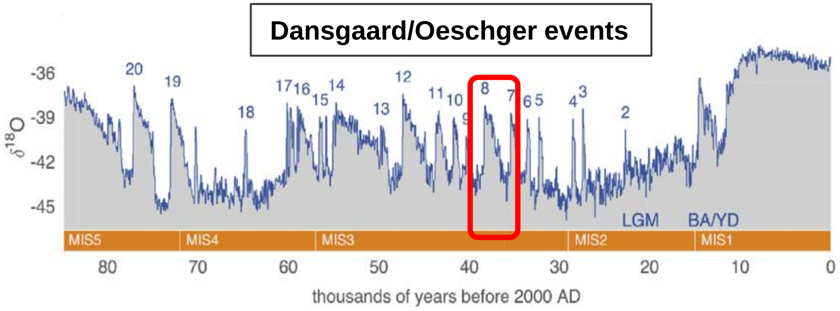
Cascading effects between tipping points

- Cascading effect: reaching a tipping point with an element of the climate system could have a destabilizing or stabilizing effect on another tipping point.
- Example: increased sea level due to Greenland or West Antarctic ice sheet disintegration can destabilize the other ice sheet margin.
- Example: a weakening of the Atlantic Meridional Overturning Circulation (AMOC) accumulates heat in the Southern ocean, favoring West Antarctic ice sheet destabilization.



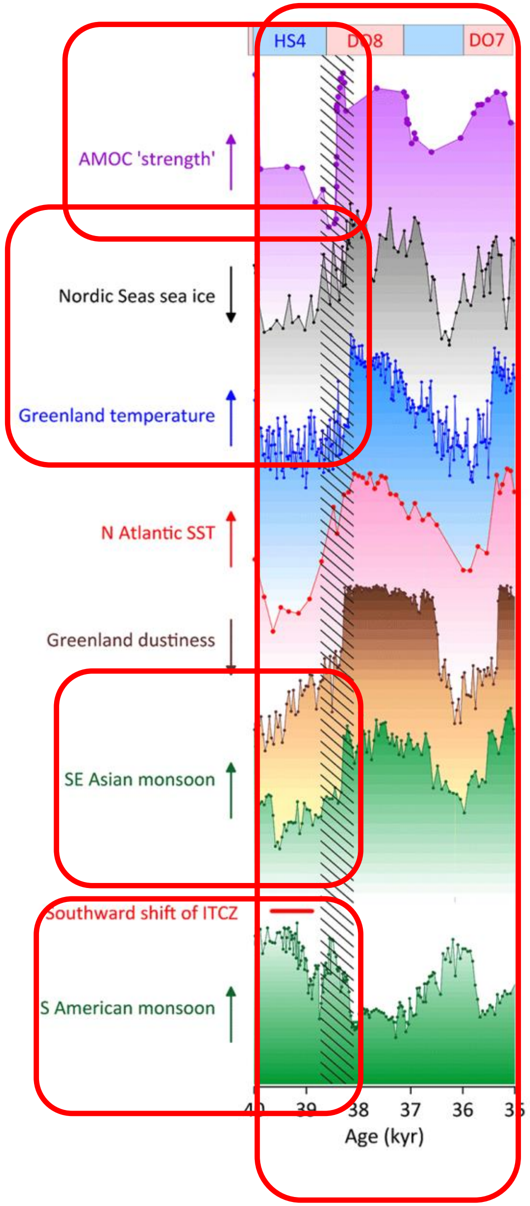
Source: Wunderling et al., Earth System Dynamics 2021

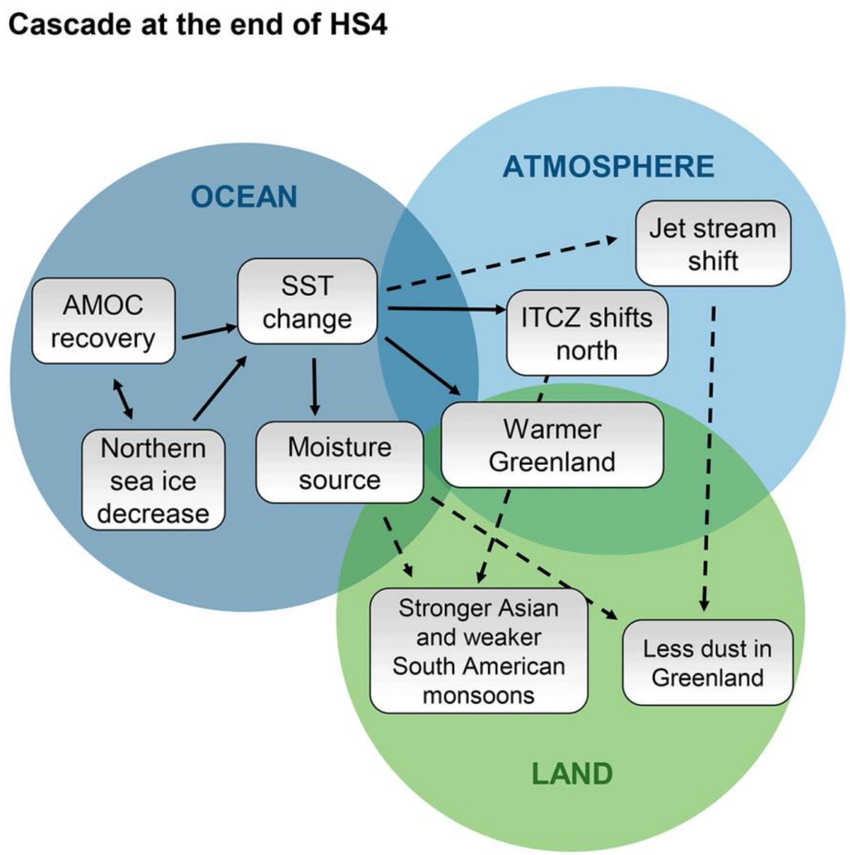
Example of cascading tipping points in the past



Source: [Li and Born, Quat. Sci. Rev. 2019]

- At the start of Dansgaard/Oeschger event 8, AMOC strengthens.
- Greenland warms up rapidly. Nordic sea ice decreases.
- South-east Asian monsoon strengthens.
- South American monsoon weakens.

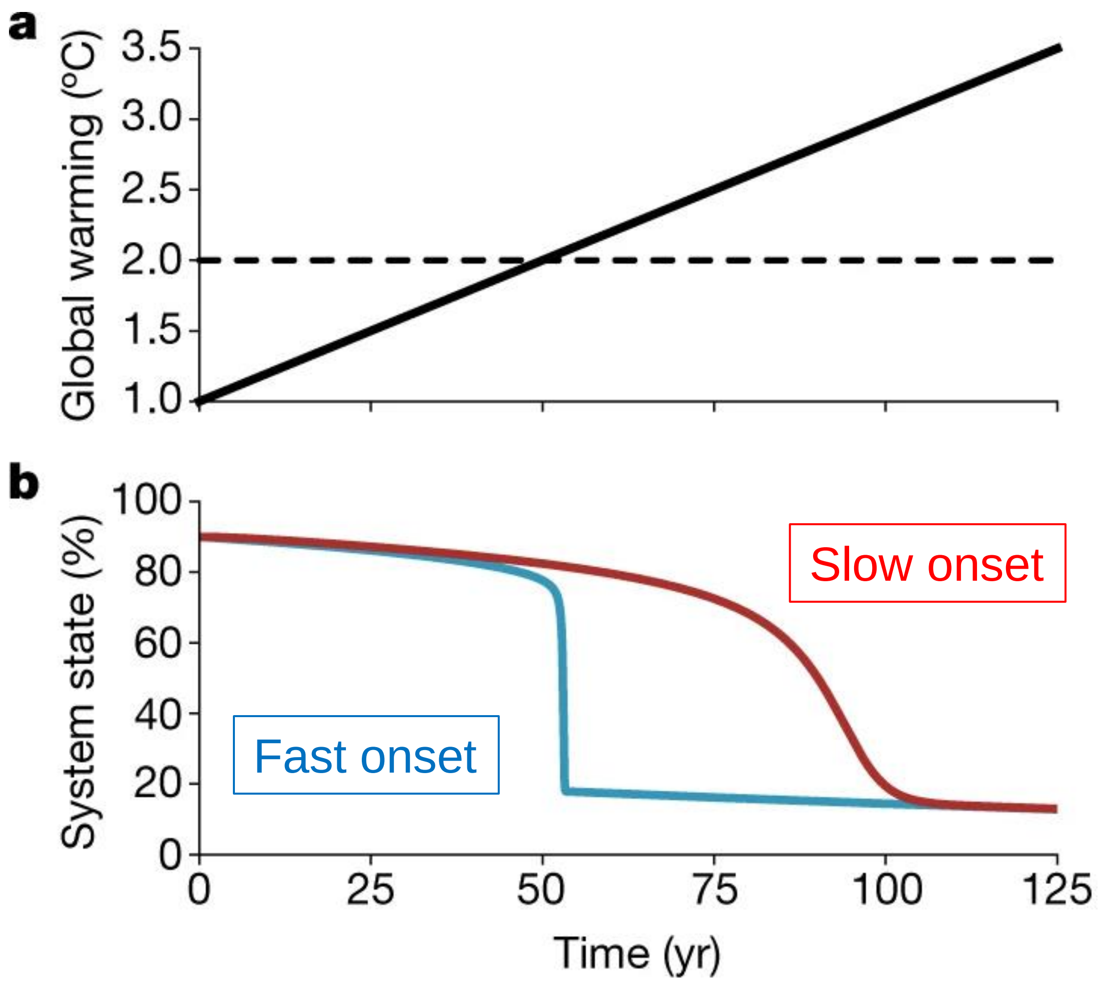




Source: [Wunderling et al., Earth System Dynamics 2024]

The importance of time scale

- Tipping points such as Amazon forest dieback can have a fast onset (decades).
- For slow-onset tipping elements (centuries) such as AMOC or ice sheets, *“the system lives on borrowed time before tipping occurs. This may allow for a temporary «safe» global warming overshoot.”*
- This means that even after reaching a temperature threshold of a tipping point, reversing the warming could still avoid unwelcome state changes. It depends on the amplitude and duration of the overshoot.



a, Idealized time series of a linear global warming crossing a threshold of 2 °C (dashed line). **b**, Time series of system state for a fast-onset tipping system (blue) and slow-onset tipping system (red), with the same threshold and the same global warming forcing as in **a**.

Source: *Ritchie et al., Nature 2021*

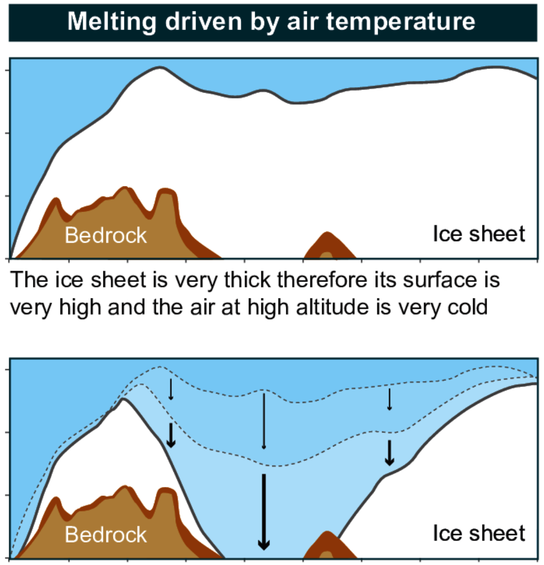
Greenland ice sheet mass balance

The Greenland ice sheet tipping point

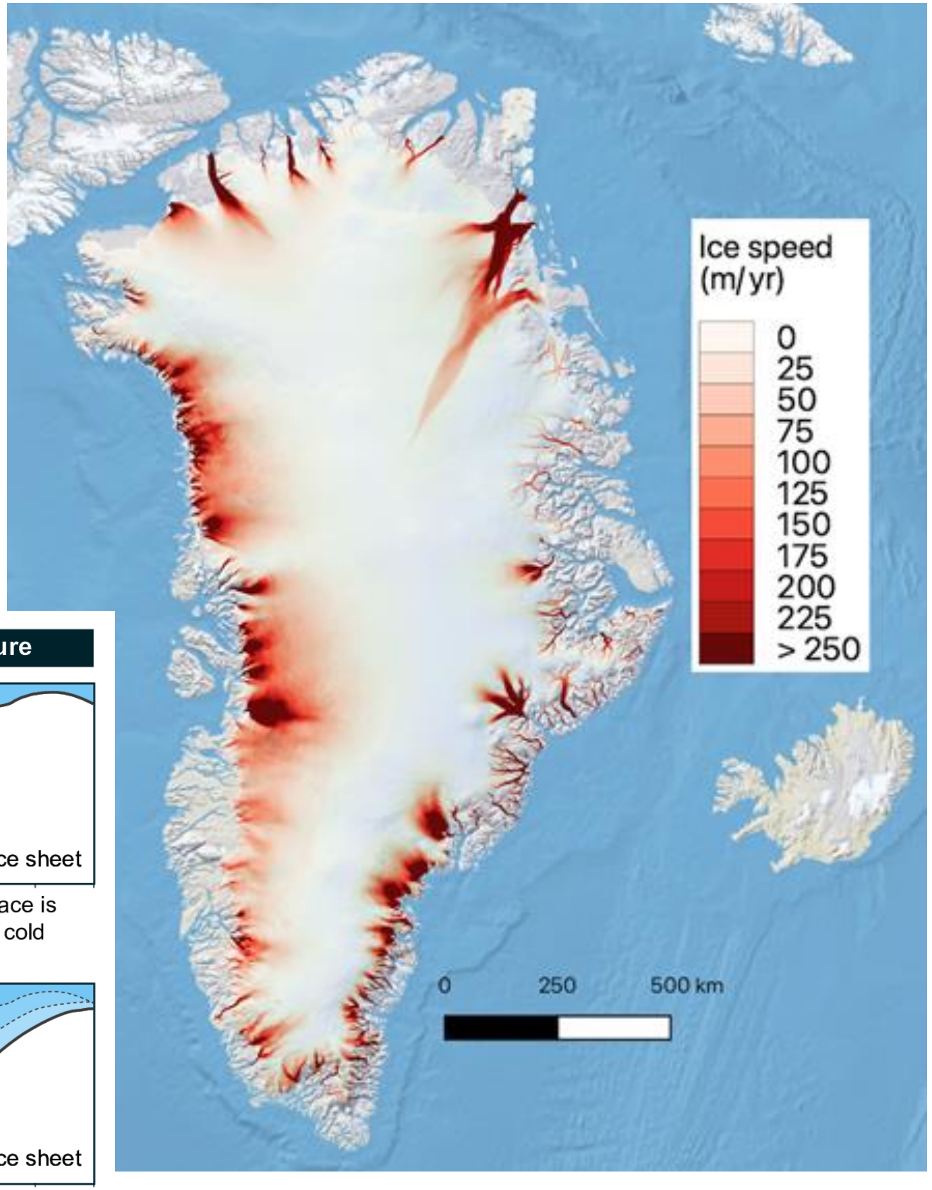
- Based on paleoclimate data and on coupled Earth system / ice sheet modelling, the current best estimates give:
  - A threshold at +1.5°C (range: 0.8 to 3.0°C) relative to pre-industrial times.
  - A time scale of 10,000 years for total decay (range: 1 to 15 kyr, depending on overshoot) if warming is sustained above threshold.

Main positive feedbacks

  - Melt-elevation (lower elevation = warmer air)
  - Ice albedo (surface darkening with melt)



Source: *IPCC AR6 WG1 Chapter 9, Fig. 9.1*



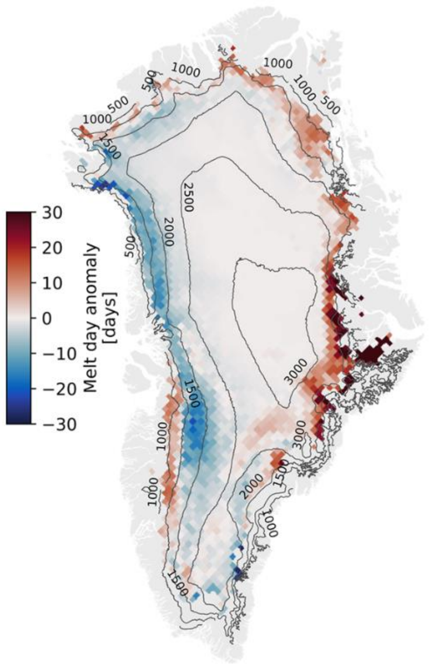
Source: *AntarcticGlaciers.org*

Source: *Armstrong McKay et al., Science 2022*

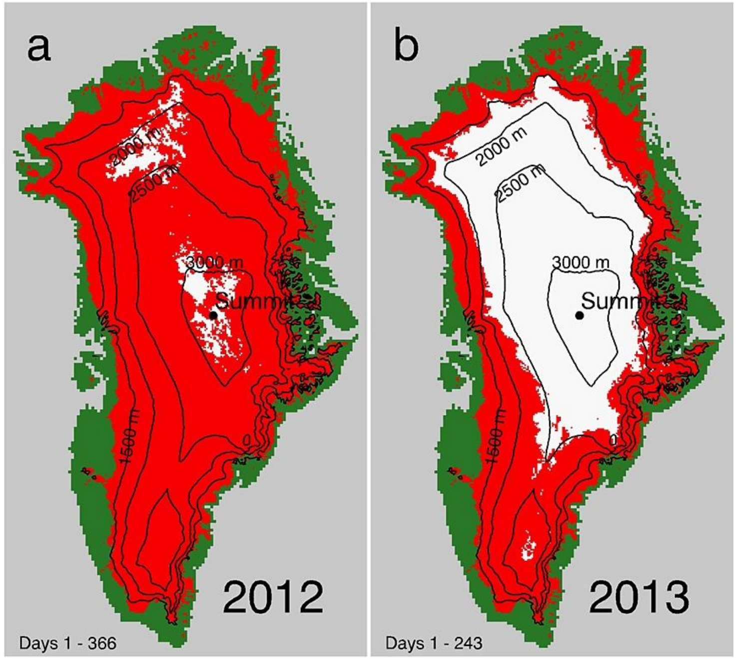
Greenland ice sheet mass balance

<u>What do we measure today ?</u>

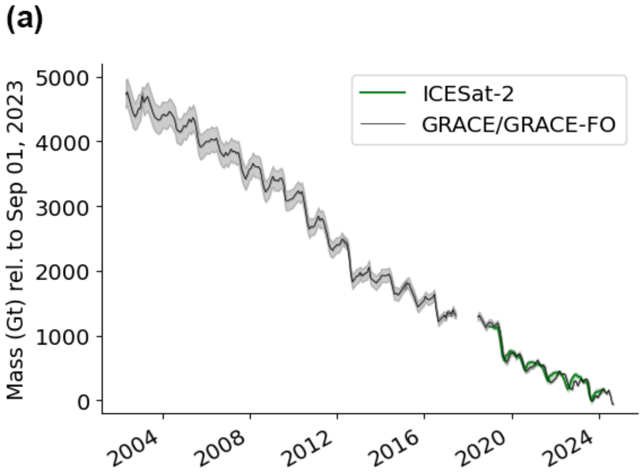
- Satellite measurements of gravimetric anomalies + laser altimetry for surface elevation changes, since 2002-2003.
- Mass loss of 200-300 Gt per year (0.7 to 1 mm of sea level increase per year).
- <u>Interannual variability</u>. 2024 saw a reasonable loss of 55 $\pm$ 35 Gt, lowest since 2013.
- In 2012, 95% of Greenland ice sheet experienced surface melt. Strong summer NAO negative index.



Source: *NOAA Arctic Report 2024*



Source: *Häkkinen et al., Geophys. Res. Lett. 2014*



Source: *NOAA Arctic Report 2024*

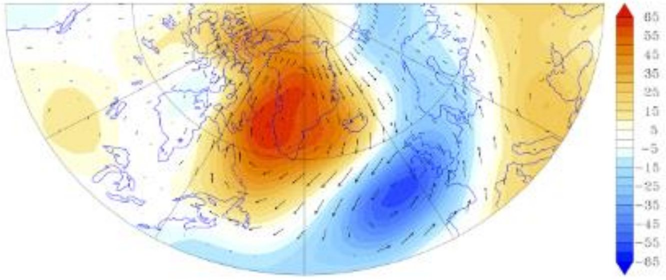
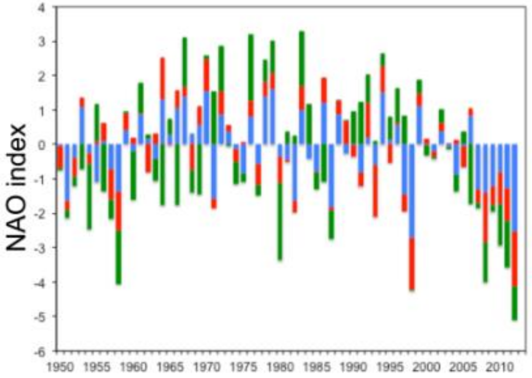


Fig. 11. 700 hmb geopotential height (m) and wind anomaly for June, July and August 2012 from the NCEP/NCAR Reanalysis data.

Source: *Tedesco et al., The Cryosphere 2013*



Greenland ice sheet and CO_2 emissions

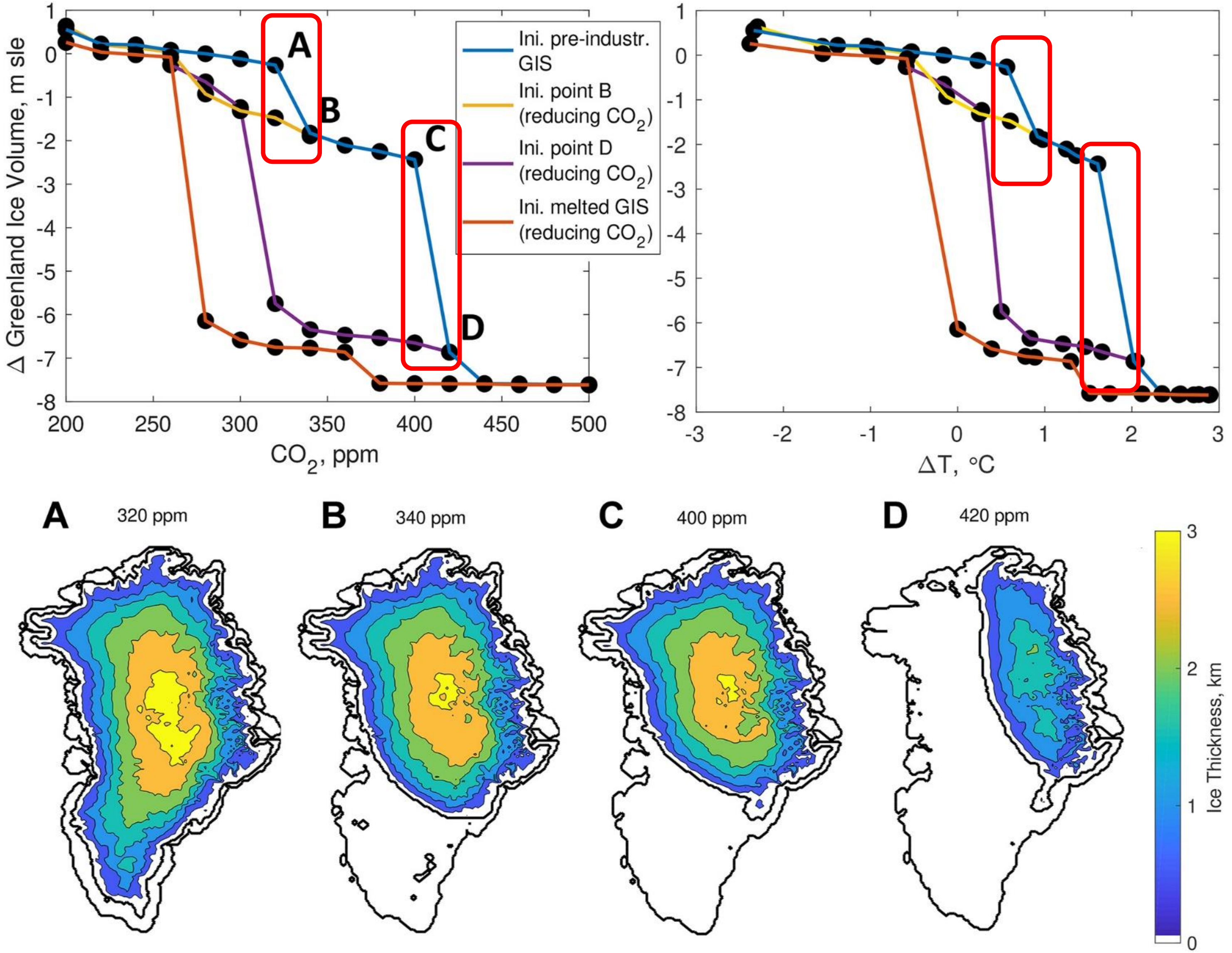
- Earth system model of intermediate complexity CLIMBER-X, run over 10,000 years, with a 16 km grid resolution over Greenland, with different CO_2 concentrations until Greenland ice sheet equilibrium is reached.

Bifurcation points:

  - Between 0.6 and 0.9°C (CO_2 from 320 to 340 ppm).
  - Between 1.6 and 2.0°C of warming (CO_2 from 400 to 420 ppm).

- The bifurcation points are reached with cumulative CO_2 emissions of 1,000 and 2,500 GtC, i.e. more than today.

- They lead to a sea level rise of 1.8 m and 6.9 m respectively.



Source: [Höning et al., Geophys. Res. Lett. 2023]

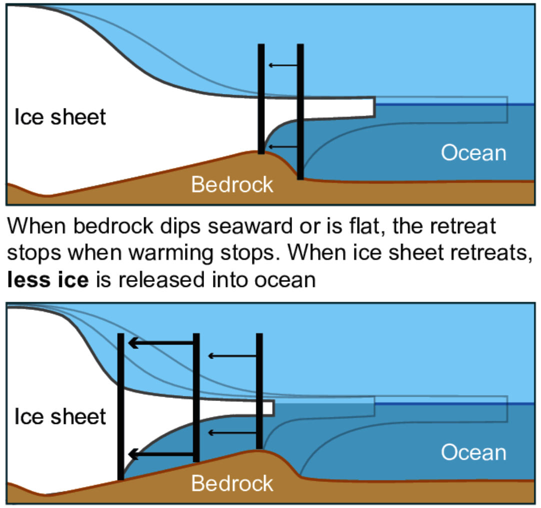
West Antarctic ice sheet

The West Antarctic ice sheet tipping point

- Based on coupled Earth system / ice sheet modelling, the current best estimates give:
  - A threshold at +1.5°C (range: 1 to 3°C) relative to pre-industrial times.
  - A time scale of 2,000 years for total decay (range: 0.5 to 13 kyr, depending on overshoot) if warming is sustained above threshold.

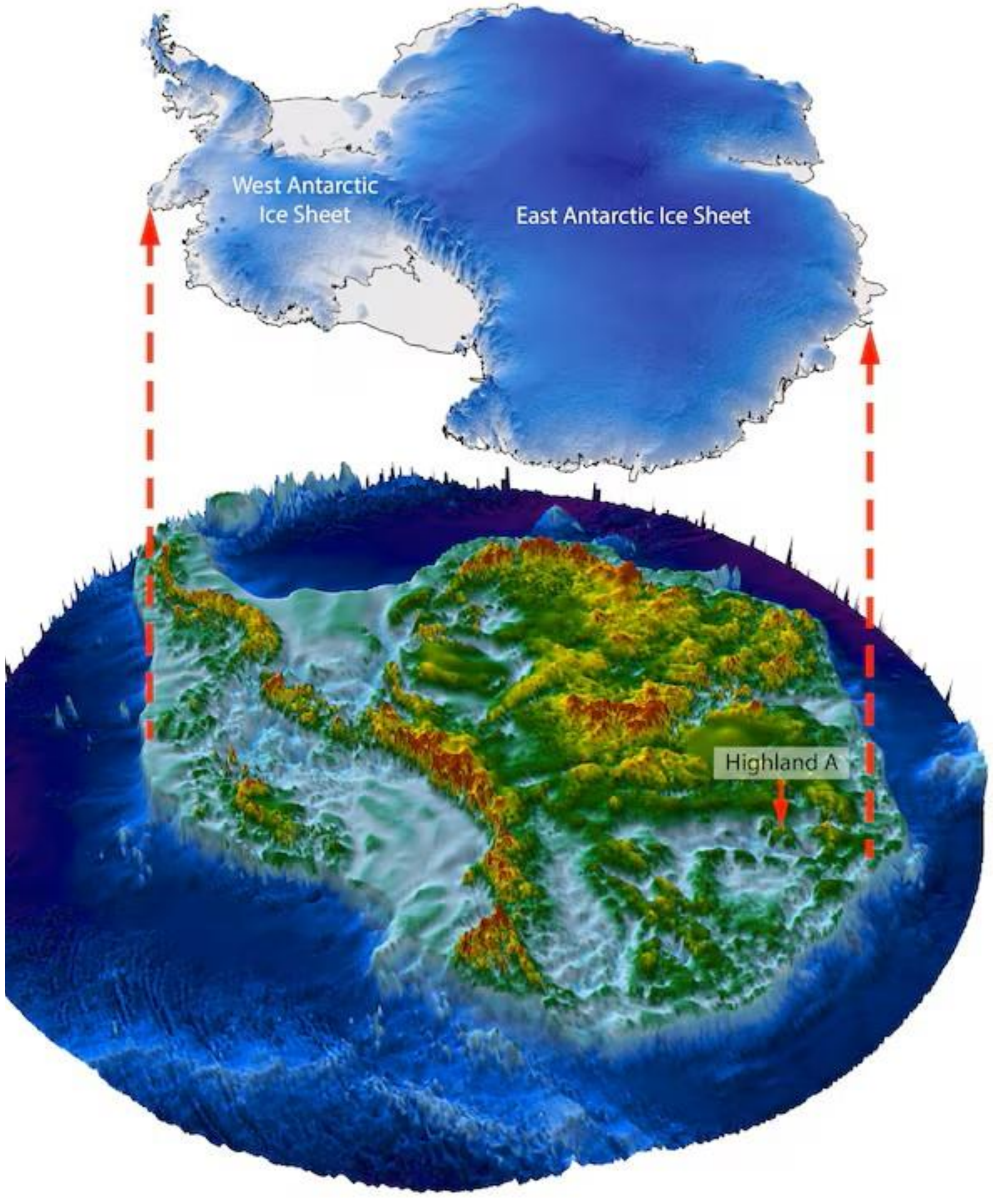
Main positive feedbacks

- Marine ice sheet instability due to retrograding bed slope.
- Ocean feedback (warm circumpolar water melting ice shelves from below).



When bedrock dips landward the retreat is quick and self-sustained. When ice sheet retreats, **more ice is released into ocean** – ice sheet retreats further

Source: *IPCC AR6 WG1 Chapter 9, Fig. 9.1*

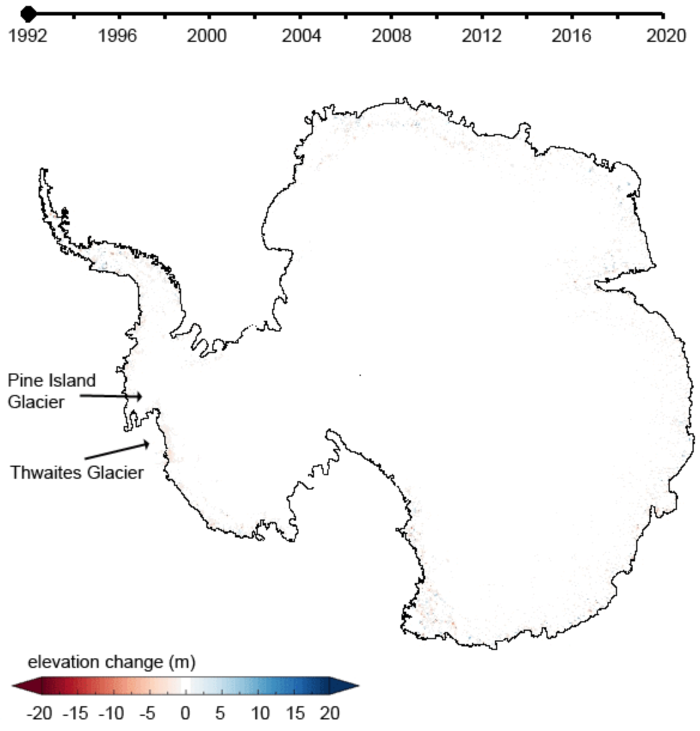


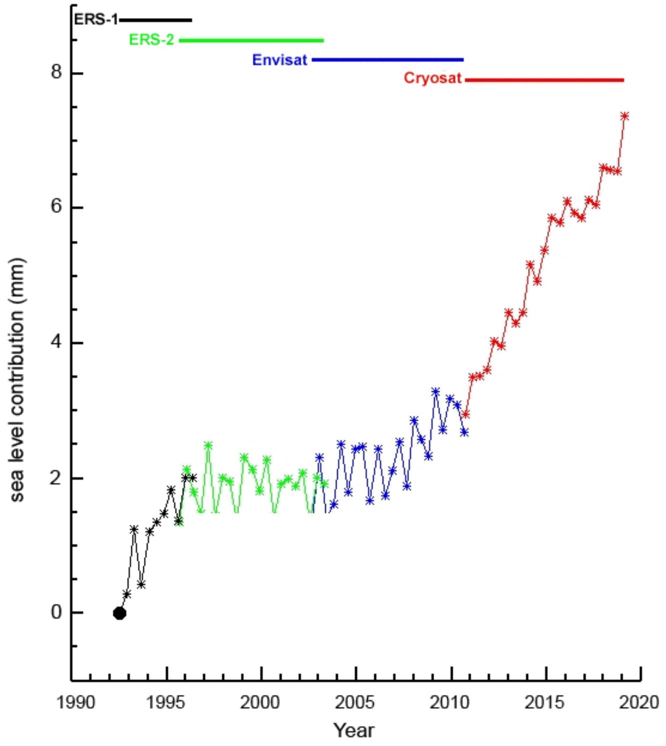
Source: *Stewart Jamieson, Durham University*

West Antarctic ice sheet

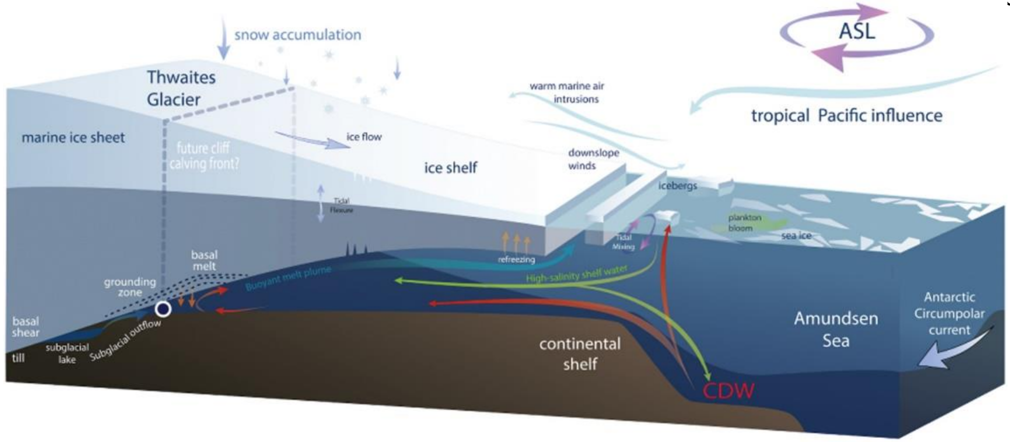
What do we measure today ?

- Satellite measurements of radar and laser altimetry for surface elevation changes since 1992.
- Mass loss of ~150 Gt per year between 2002 and 2023 (~0.4 mm of sea level increase per year).
- Main contribution from Thwaites and Pine Island glaciers. “Warm” seawater getting beneath the glaciers + grounding line retreat.
- Acceleration over recent years.





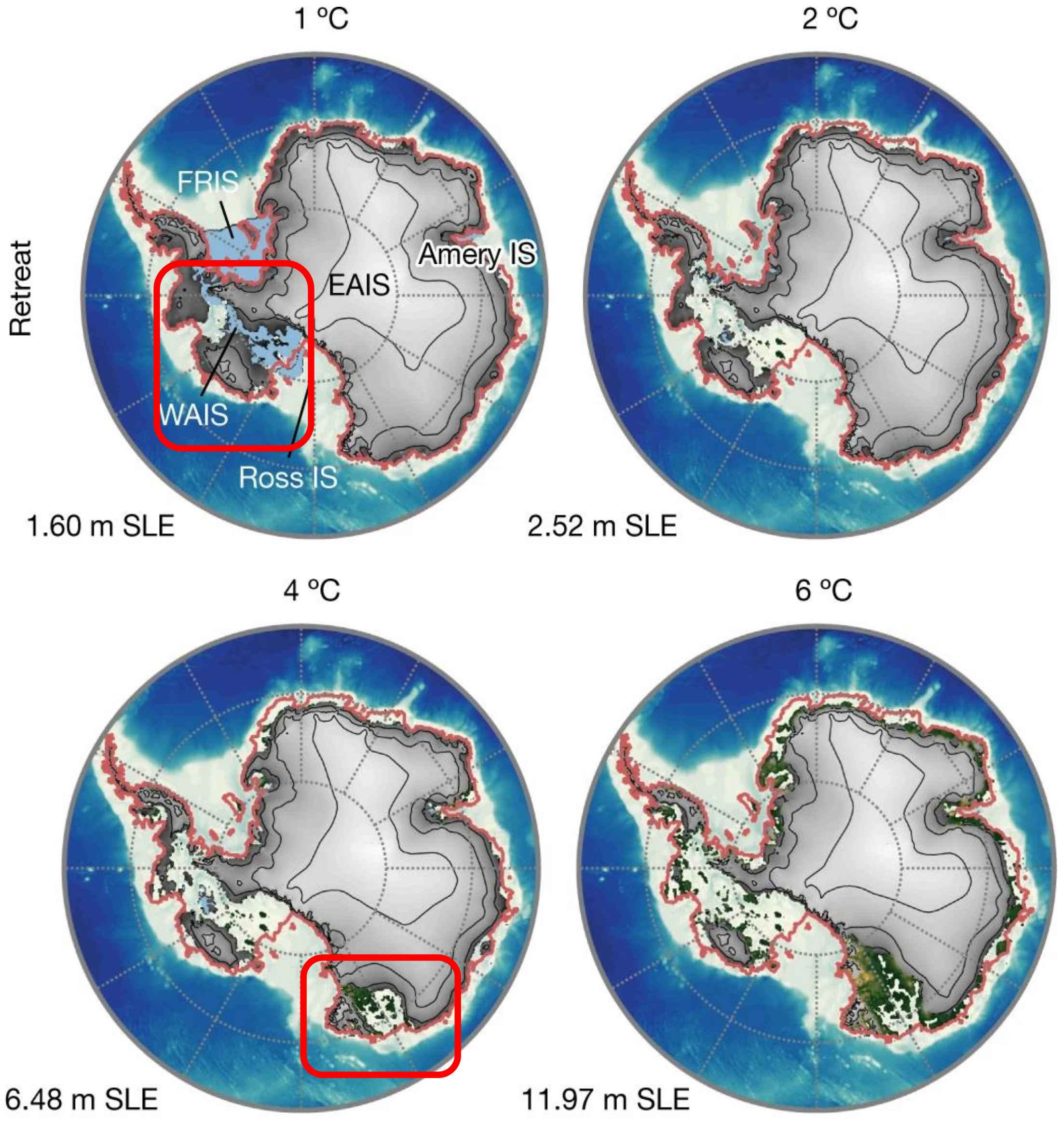
Source: European Space Agency



Source: Scambos et al., Global and Planetary Change 2017

West Antarctic ice sheet

- Parallel Ice Sheet Model (PISM), run over 20,000 years under static global mean temperature increases (1, 2, 4, 6°C), until Antarctic ice sheet equilibrium is reached.
- At +1°C, the West Antarctic ice sheet is already destabilized.
- At +4°C, part of East Antarctica is not stable anymore.
- +1.3 m of sea level per degree of warming up to 2°C.
- +2.4 m of sea level per degree of warming between 2 and 6°C.



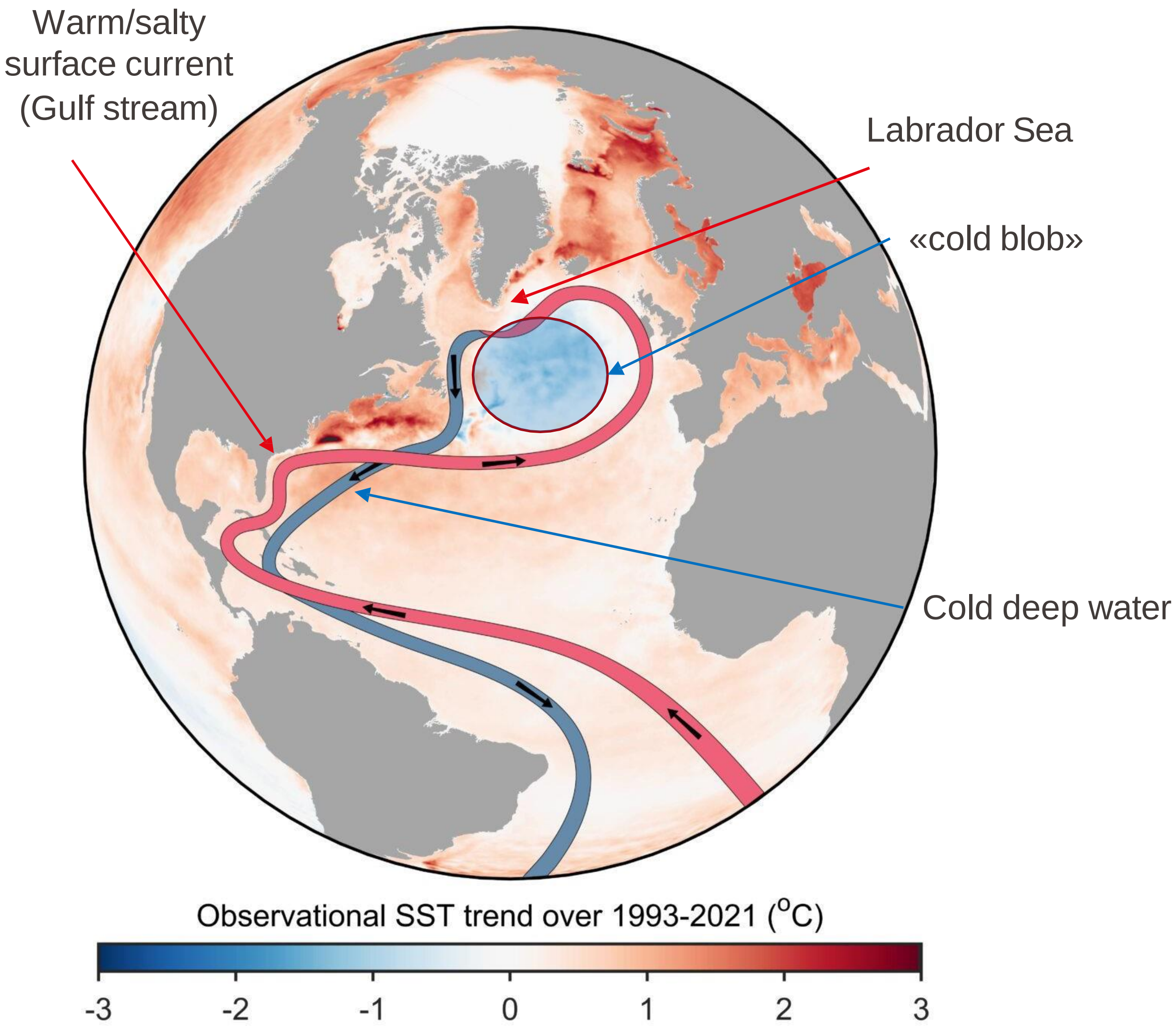
Source: Garbe et al., Nature 2020

Labrador sea current collapse

Main positive feedback
Freshwater input from Greenland and Arctic sea ice, leading to stratification.

The Labrador sea current tipping point

- Atlantic Meridional Overturning Circulation (AMOC): Warm and salty water moves northward. Then it cools down and sinks.
- Satellite measurements of sea surface temperature reveal a “cold blob” in the North Atlantic. It suggests that the AMOC is slowing down: risk of reduction of heat transport.
- A collapse would notably create:
  - North Atlantic regional cooling of 2 to 3°C.
  - Weather extremes over Europe.
- Based on CMIP5 and CMIP6 model simulations, the current best estimates give:
  - A threshold at +1.8°C (range: 1.1 to 3.8°C) relative to pre-industrial times.
  - A time scale of 10 years (range: 5 to 50 years).
- **But medium confidence because of large spread among models !**



Source: *RealClimate 2023*

EPFL

Are there positive messages ?!

With known tipping points and their risk of occurrence even at +2°C, can we have a dose of positivism somewhere ?!

Well… Let’s avoid +4°C !

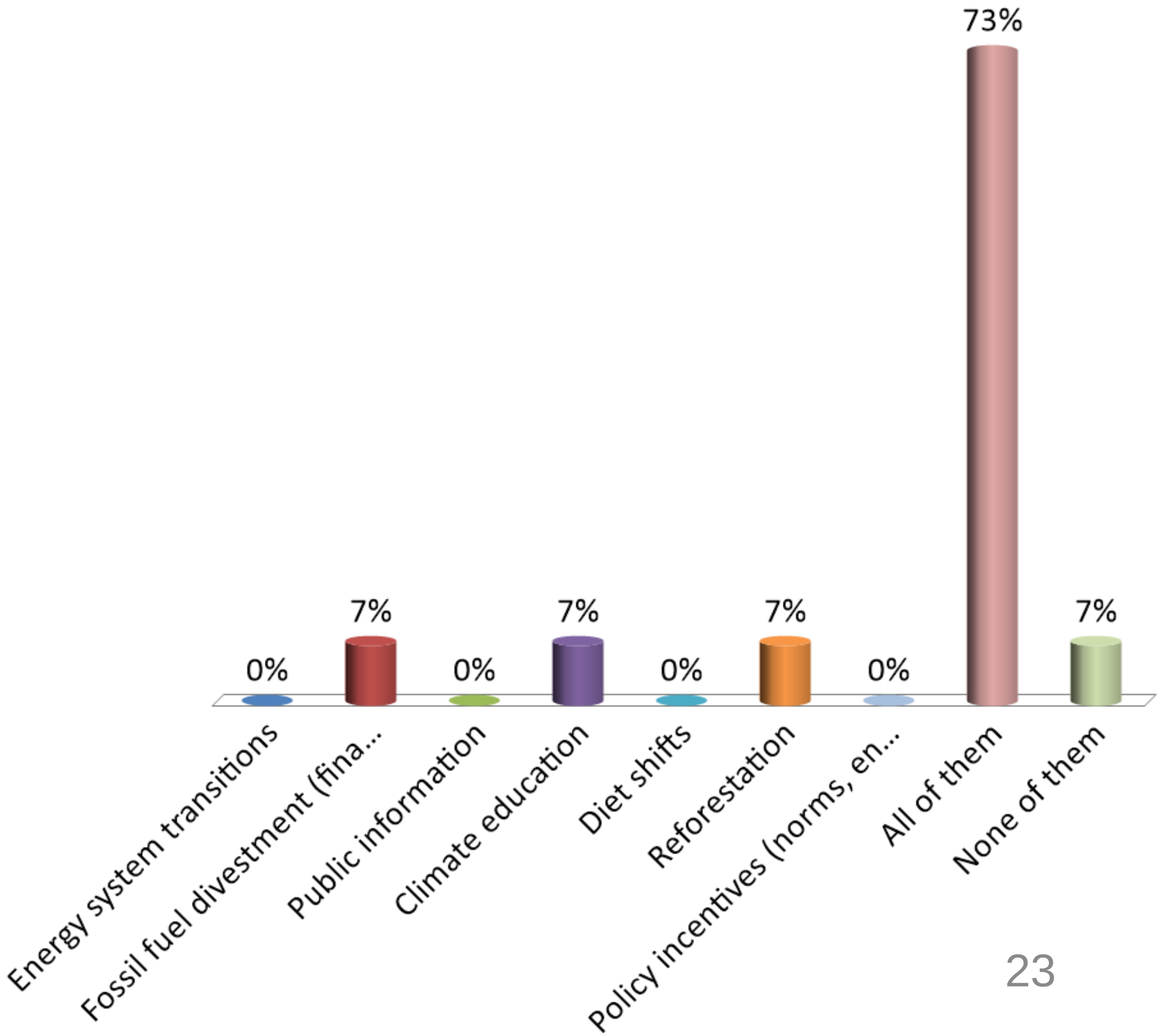
Let’s keep the +1.5°C target !

And think «positive»… Tipping points !

"You can have a last cigarette, but I must warn you, they can shorten your life."

Which item is a positive tipping point, i.e. getting into a more stable and sustainable state ?

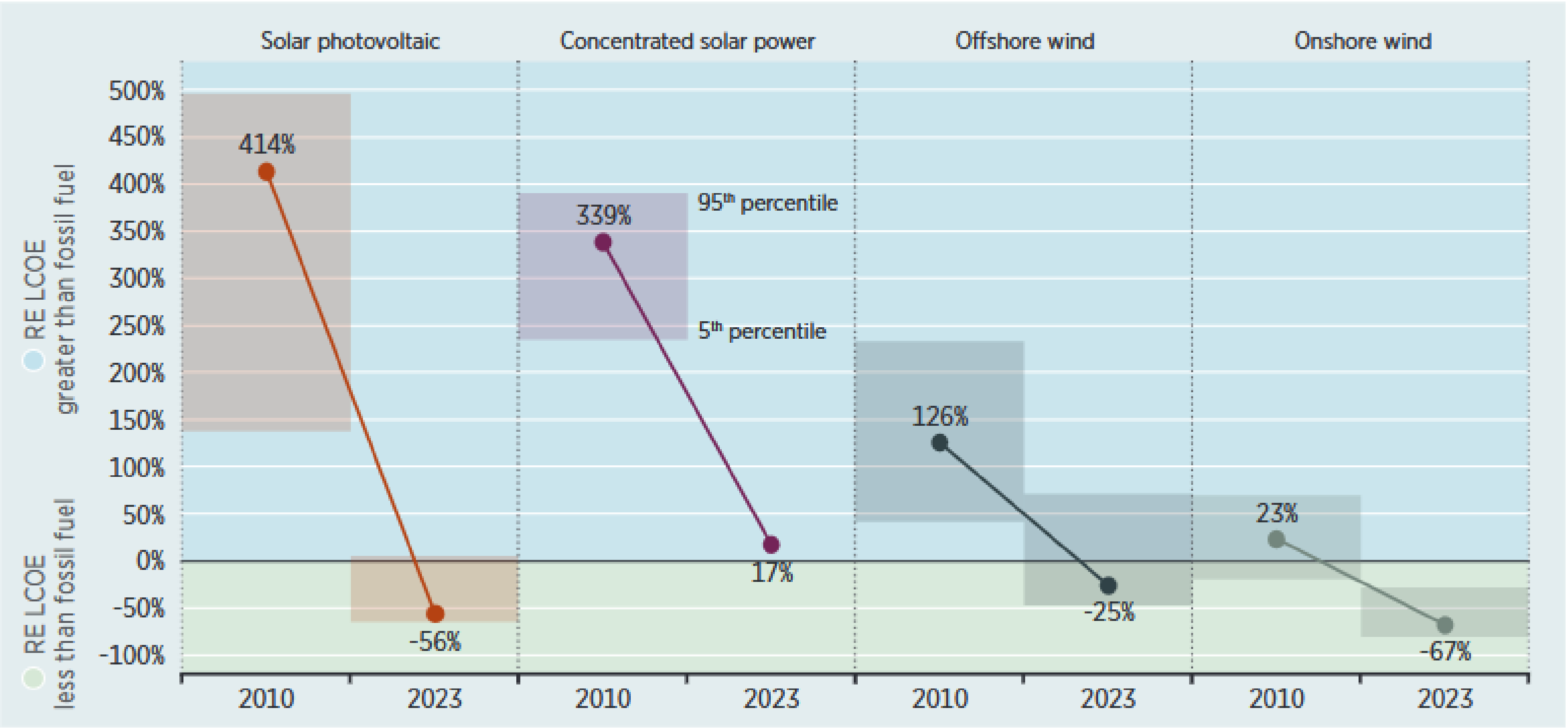
A. Energy system transitions
B. Fossil fuel divestment (financial markets)
C. Public information
D. Climate education
E. Diet shifts
F. Reforestation
G. Policy incentives (norms, environmental price)
H. All of them
I. None of them



Social tipping dynamics

- Need to accelerate social changes.
- They have to be actively enabled.
- For instance, the decreasing price of renewable energies leads to a positive tipping point of increased investments.
- In 2023, **82%** of the total global investment in new power generation was for new renewable power capacity.

Figure S1 Change in global weighted average LCOE for solar and wind compared to fossil fuels, 2010-2023



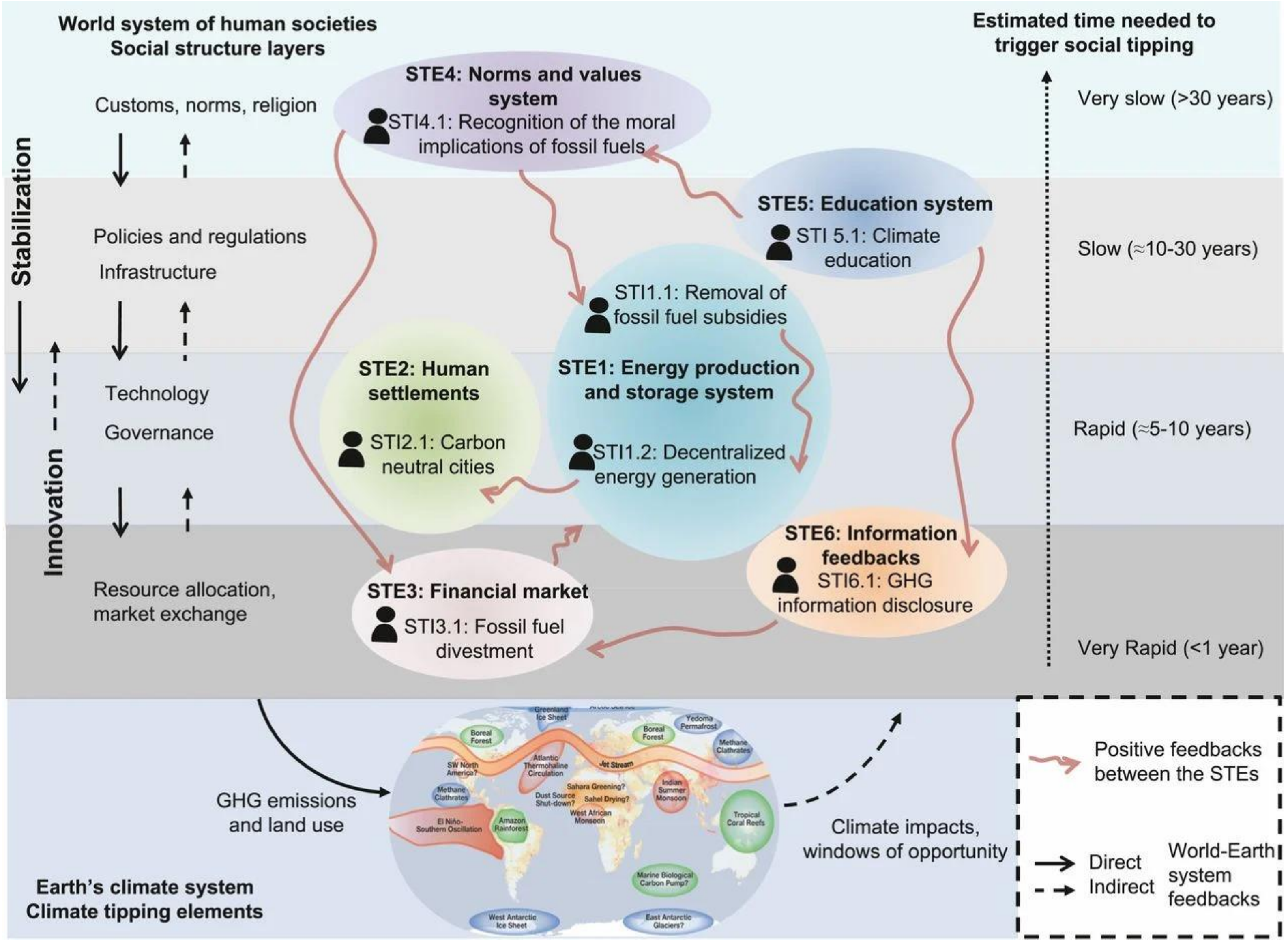
Note: RE = renewable energy.

LCOE: Levelized Cost of Energy (calculated on lifetime)

Source: *IRENA Report «Renewable Power Generation Costs in 2023»*

Social tipping dynamics

- There are positive feedbacks between social tipping elements. Example: better education leads to more political pressure.
- Some social tipping elements can be triggered very rapidly (less than 1 year) or rapidly (5 to 10 years).
- Decentralized energy generation is one of them, as stressed by Jonas.



Extreme events

Climate/weather related disasters: 152 «unprecedented» in the world in 2024, says WMO

Dubai, April 18

Brazil, May 4

River of dead fishes, Greece, August 28

Dry tributary of Amazon river, September 8

- 617 extreme weather events. 152 «unprecedented». 297 «unusual», according to WMO. A majority of «unprecedented» are heat waves.
- More than 800,000 people displaced and homeless. 1,700 killed and 1.1 million injured.
- 27 disasters in the USA with damages of at least 1 billion US$

Wilfire in Ecuador, September 24

Source of photos: AlJazeera

Climate/weather related disasters: 152 «unprecedented» in the world in 2024, says WMO

- 617 extreme weather events. 152 «unprecedented». 297 «unusual», according to WMO. A majority of «unprecedented» are heat waves.
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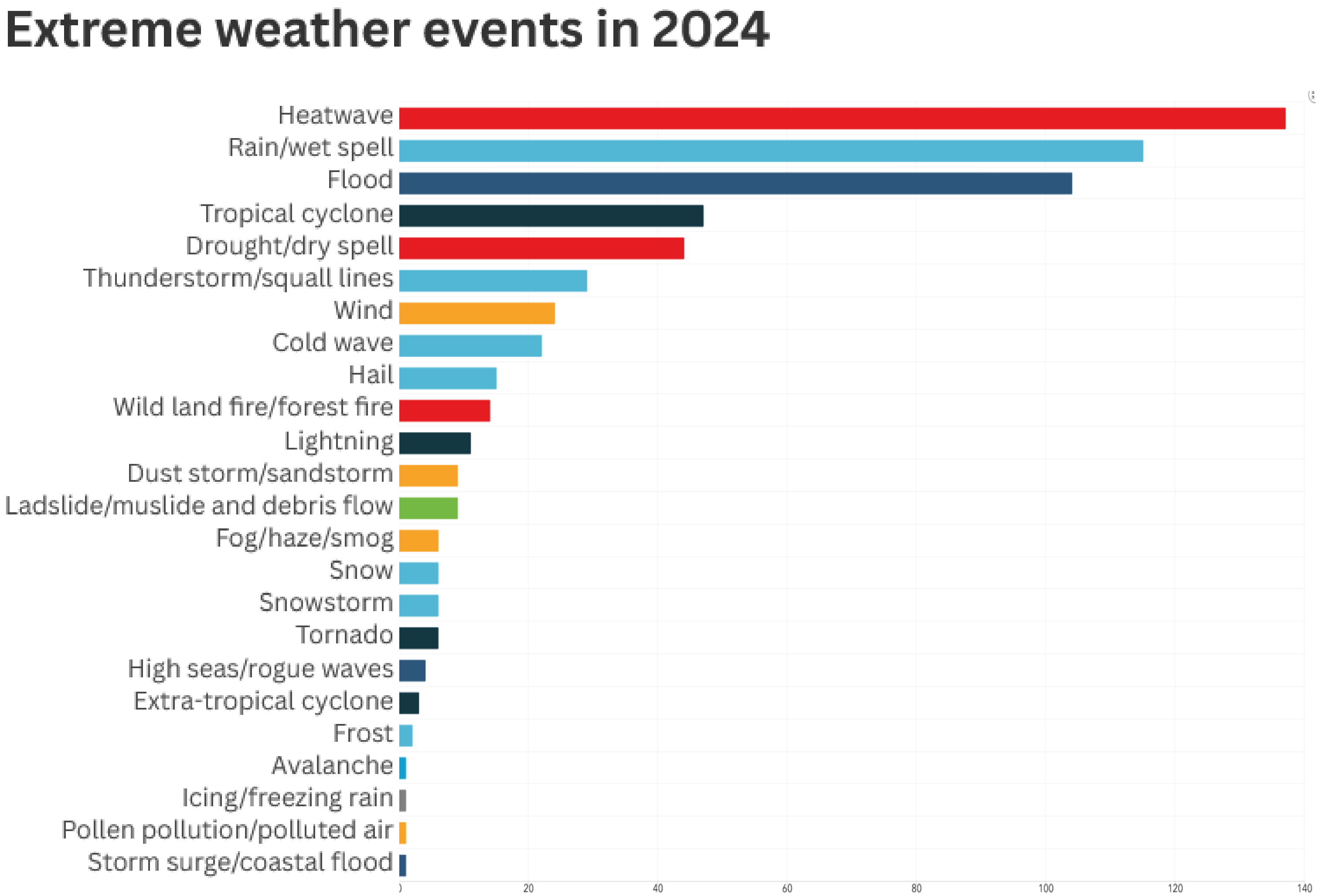
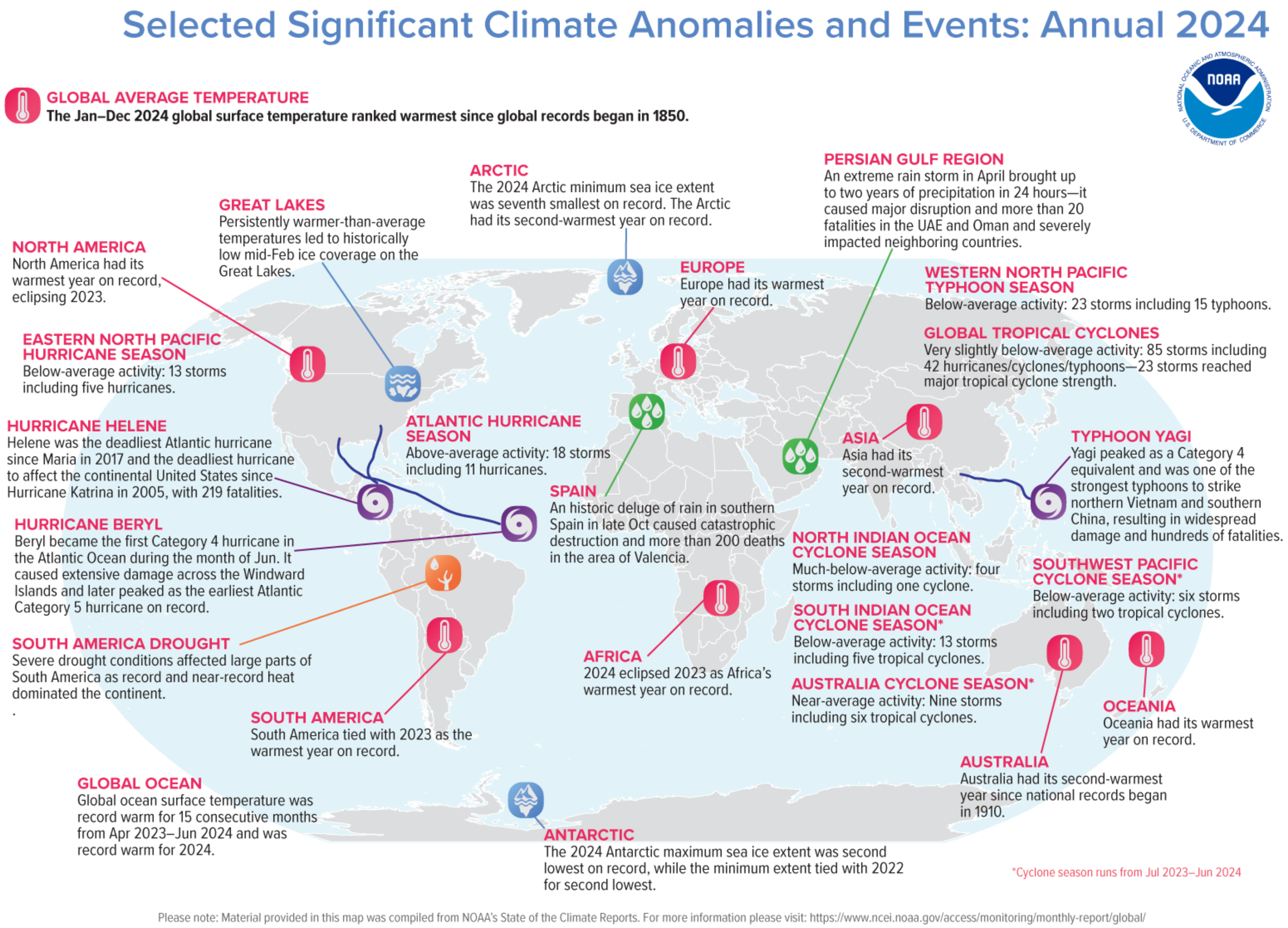


Source : [WMO Dashboard Extreme Events 2024]

Climate anomalies and events in 2024



- Source: NOAA Global Climate Report 2024

Extreme weather/climate events: definition and types

Definition: *"An occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the observed range of values."* (IPCC AR6)

But it's not only statistics. Impact on human societies matter. *"Extreme events cause disproportionate social, ecological or economic impacts due to vulnerability and exposure"* (IPCC)

Main types:

- Heatwaves
- Droughts
- Floods
- Crop failure
- Wildfires
- Tropical Cyclones / Hurricanes / Typhoons






Source: [The SENSES toolkit]

Which extreme weather event do you remember ?

EUROPEAN FLOODINGS 2018

DROUGHT LAST SUMMER :(

PASSING FROM -30 DEGREES TO 20 DEGREES...

HEAT WAVES

2023

KATRINA USA - HEAT WAVE 2003

HEAT WAVES 2019

EYJAFJALLAJOKULL

ECO-CIDES 2024

RIVER PO DROUGHT 2022

LAKE DROUGHTS IN SOUTHERN ITALY (SUMME...

2003 SUMMER, VALENCIA, LA RÉUNION HURR...

Which extreme weather event do you remember ?

Souvenir when I was 20-year old !

July 26th, 1983: an exceptionally strong tornadoe hits western France.

Ravaged downtown Niort and Poitevin marshlands.

Part of our family house seriously damaged.

DEUX-SEVRES

la Nouvelle République du Centre-Ouest

MERCREDI 27 JUILLET 1983 2,80 F 39e ANNÉE N° 11.798

BERRY - POITOU - VAL DE LOIRE

Trois campeurs écrasés par des arbres déracinés

LA TORNADE A RAVAGÉ LA RÉGION NIORTAISE

Toitures emportées et cultures détruites en trente minutes

Challenges with definition and statistics

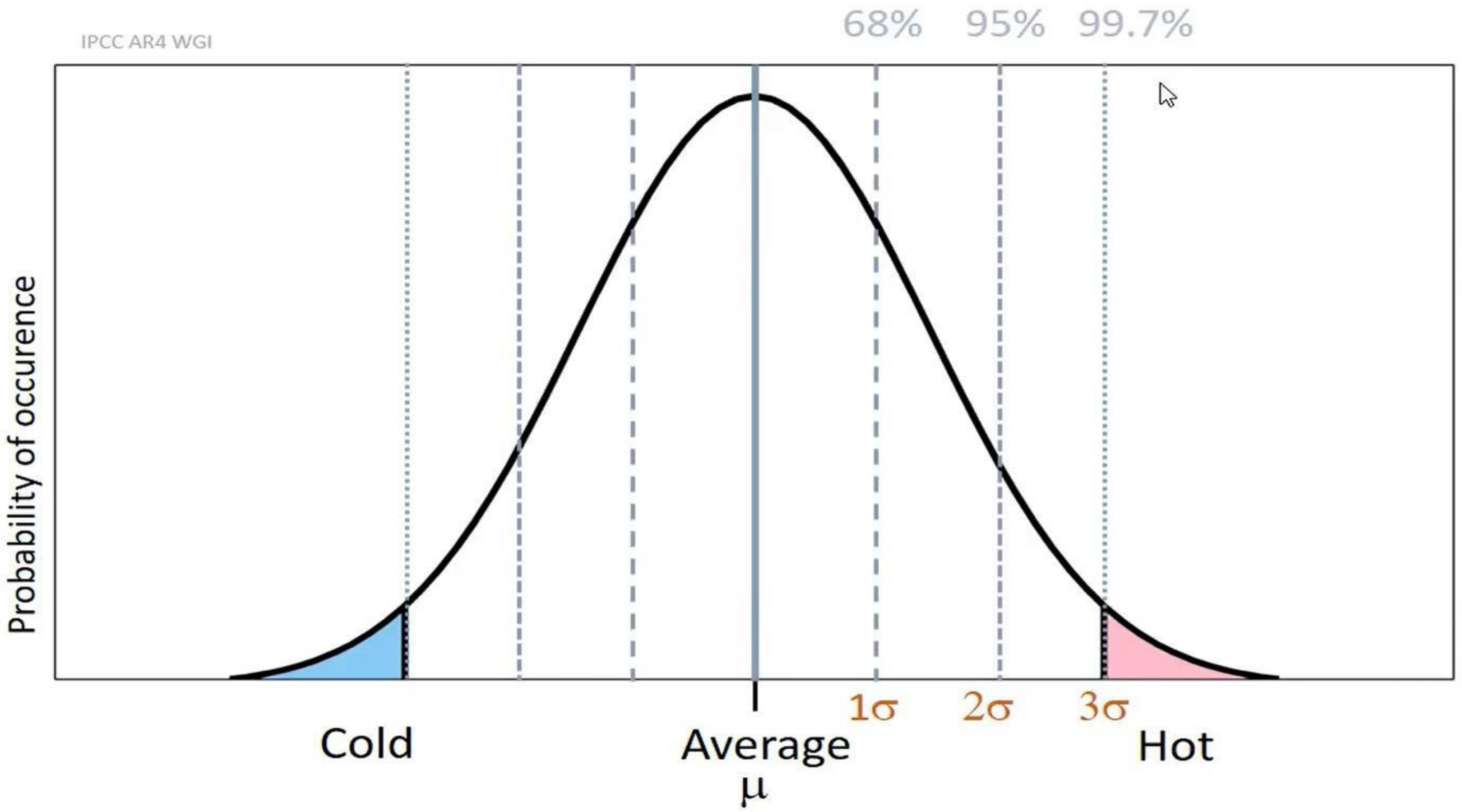
<u>**«Extreme» can be considered along different criteria**</u>:

- The event goes beyond a given threshold (absolute or relative). <u>Examples</u>: the 10^{th} or the 90^{th} percentile of a mean daily temperature, or a cumulated rainfall over one hour being above 50 mm.
- The event is exceptionally rare. <u>Example</u>: flooding of a town once per century.
- The event is unprecedented, within the period of instrumental record or historic record.
- The metric can be a disproportionate impact. <u>Example</u>: a mild typhoon hitting vulnerable and exposed populations.
- The scale of the event can vary, from local (hail storm, tornadoe) to large scale (drought, heatwave).
- An extreme in one region can be standard conditions elsewhere… **No universally valid definition !**

Source: [ARC climate extremes]

Statistics: Extreme value distributions

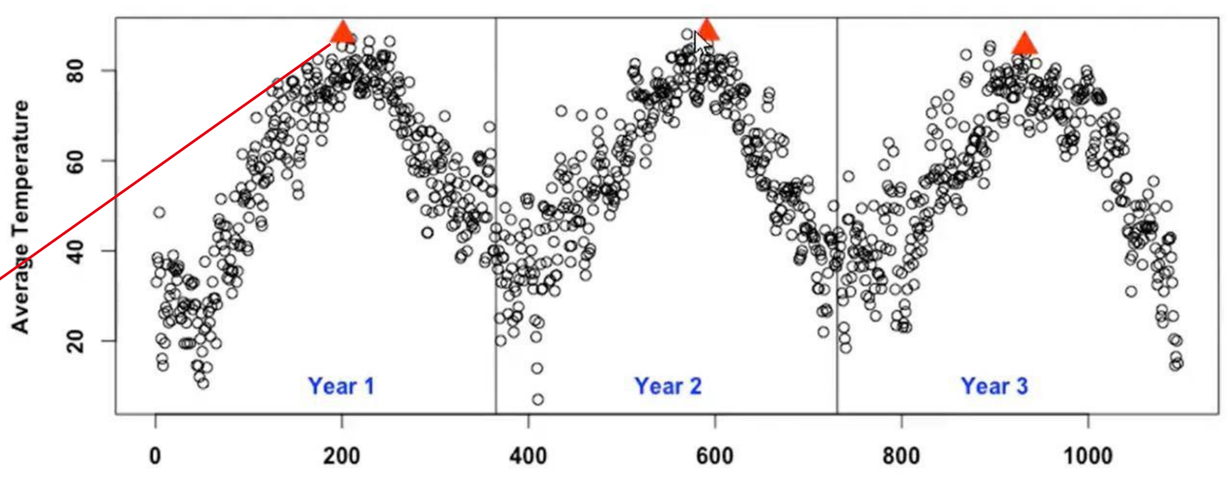
Example: Probability density function (PDF) of temperature in a given place.
Cold or hot extremes can be considered as all occurrences beyond, e.g., 2σ (95%) or 3σ (99.7%) of the distribution.



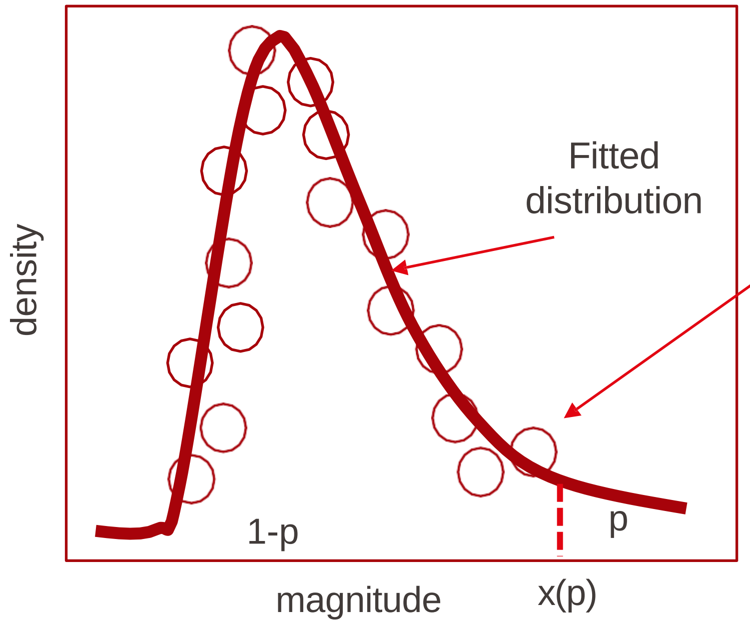
Statistics: fitting extreme value distribution

- One can extract only the single maximum (or minimum) observed over one block period (here, one year).
- Based on extreme value theory, the distribution of the maxima (or minima) will follow a generalized extreme value distribution (GEV). Condition: have a long enough time series…

Block Maxima (extract the red triangles)



Generalized extreme value distribution



Event x has probability p; x(p)

○ Block Maxima per magnitude, over, e.g., 50 years.

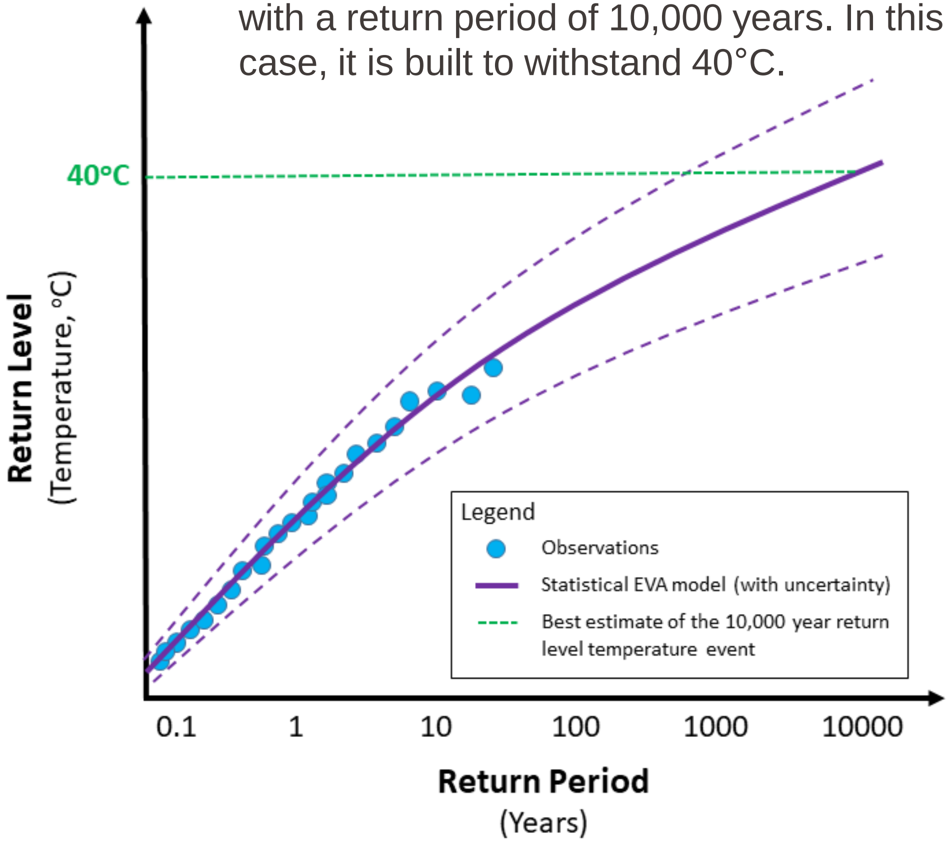
- p = probability of exceedance of the value.
- It allows to calculate a return period **T = 1/p**
- The return period (or recurrence interval) is the average time interval between occurrences of an even of a certain magnitude or greater.
- Example: if **p = 0.02**, then the return period is **T = 50 years**.

Source: Data Analysis Classroom, Lesson 60

Statistics: return levels

- The calculated return level is particularly useful in climatology and risk assessment of extreme events.
- It allows to determine how long one would have to wait until an event of a similar magnitude would happen again.

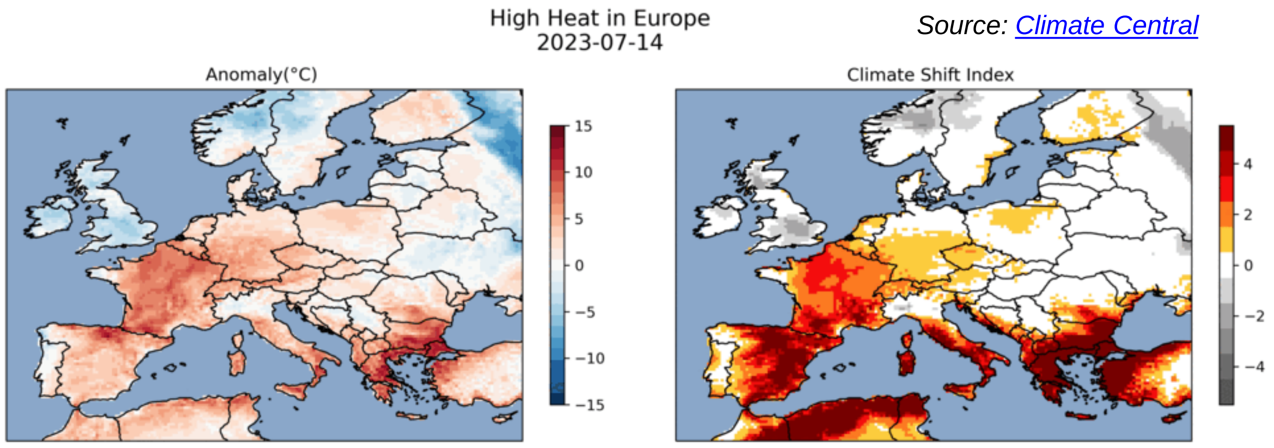
- Example: a nuclear power plant must withstand an extreme temperature event with a return period of 10,000 years. In this case, it is built to withstand 40°C.



- Uncertainty becomes larger for longer return periods (weaker statistics).
- If the system is non-stationary (changing climate), the return period will change…

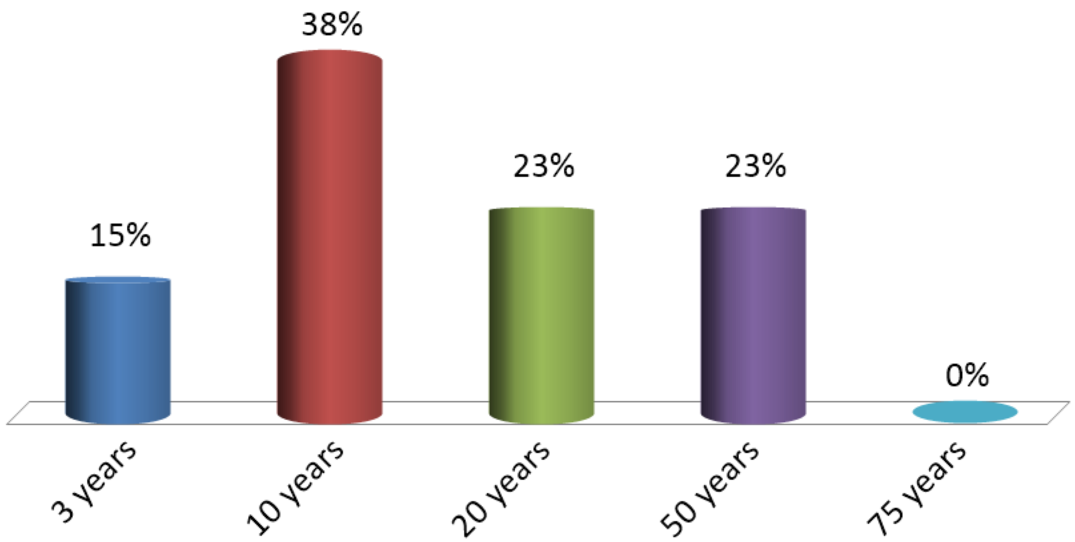
Source: MetOffice Extreme Value Analysis

What is the return level of the European heatwave of July 2023 ?



Source: Climate Central

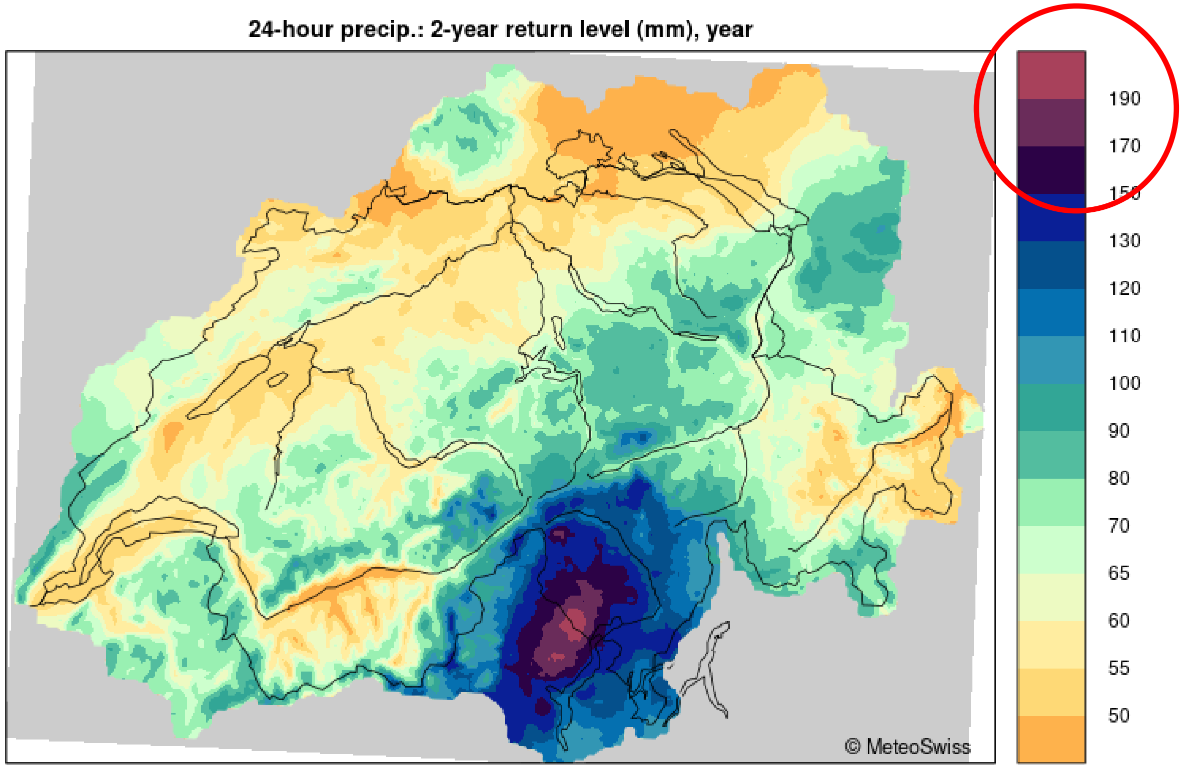
A. 3 years
B. 10 years
C. 20 years
D. 50 years
E. 75 years



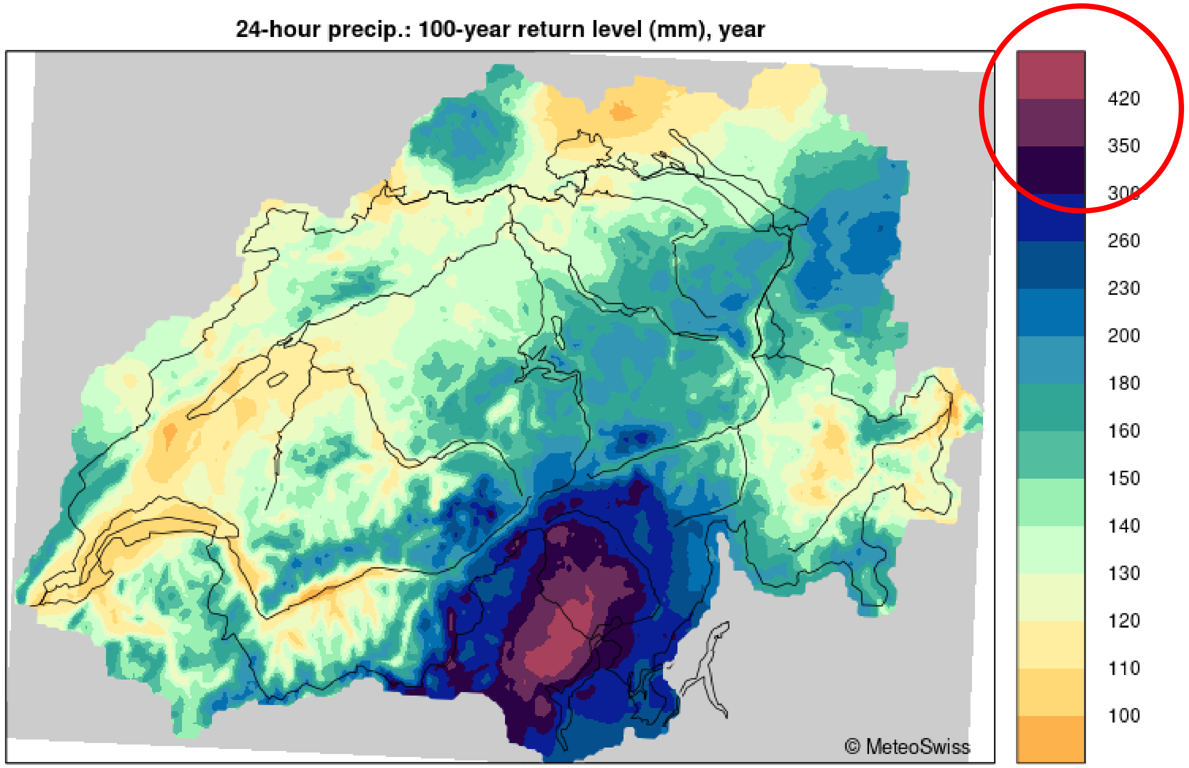
- According to the World Weather Attribution, the return level now is 10 years for Southern Europe.
- It would have been virtually impossible to occur without anthropogenic warming.

Return level: extreme precipitation in Switzerland

Cumul of precipitation (mm) over 24 consecutive hours.



2-year return level

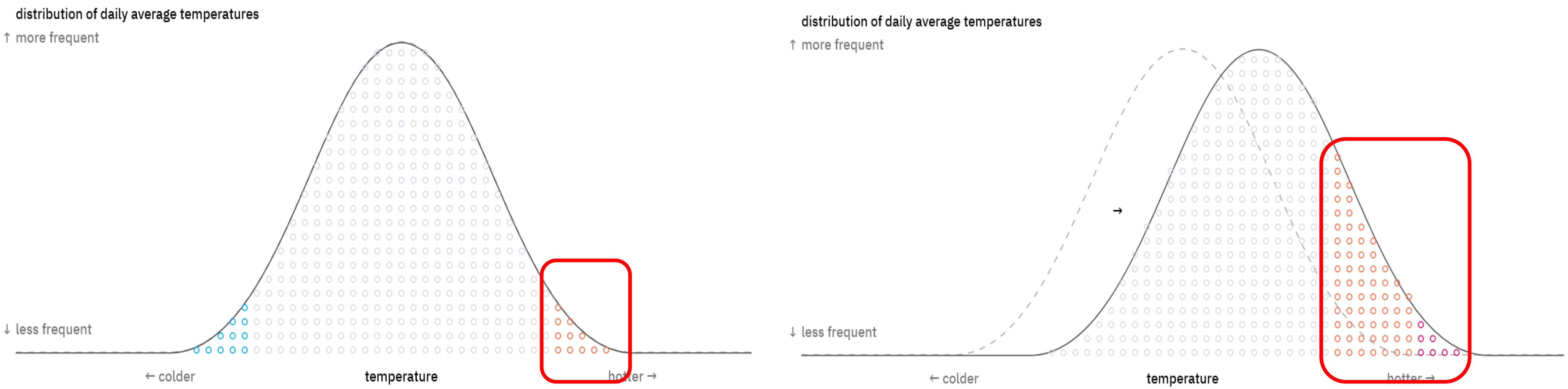


100-year return level

Do you notice something when comparing the two maps ?

Source: [MétéoSuisse, extreme precipitation]

What will happen with a changing climate ?

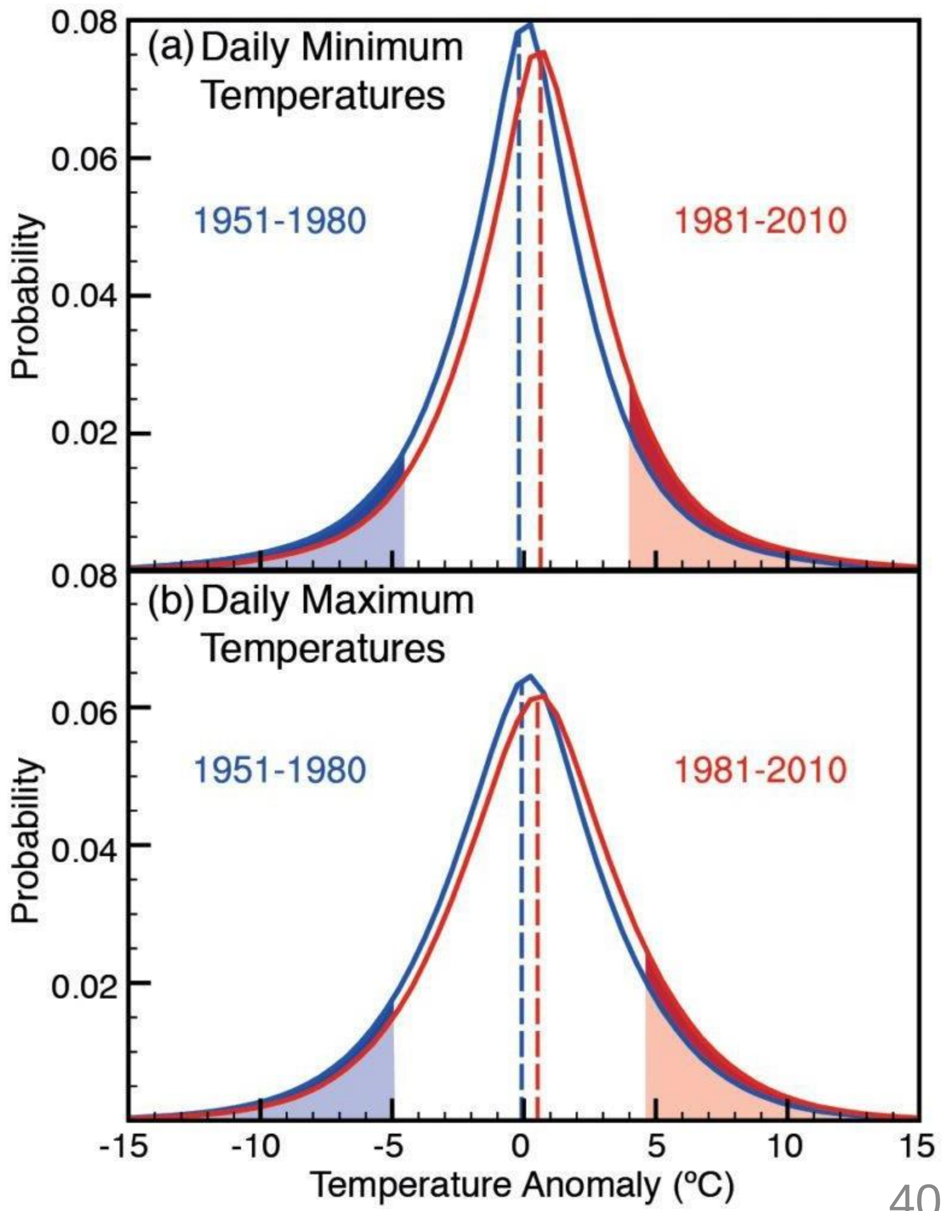


- Under climate change, the mean temperature rises, the whole distribution shifts towards higher temperatures.
- Hot days that have been rare so far will occur more frequently and they will reach even higher temperatures.

Source: The SENSES toolkit

The shift of distribution is already seen today

- *Distribution of (a) daily minimum and (b) daily maximum temperature anomalies relative to a 1961–1990 climatology for two periods: 1951–1980 (blue) and 1981–2010 (red).*
- *The shaded blue and red areas represent the coldest 10% and warmest 10% respectively of (a) nights and (b) days during the 1951–1980 period.*
- *The darker shading indicates by how much the number of the coldest days and nights has reduced (dark blue) and by how much the number of the warmest days and nights has increased (dark red) during the 1981–2010 period compared to the 1951–1980 period.*



- Observed shift of daily minimum and daily maximum temperatures between the 3 decades before and after 1980.
- Stronger for the minimum. Expected from the greenhouse gas effect (no incoming solar radiation at night, only LW radiation).
- Increase of the warmest 10%. Decrease of the coldest 10%.

Source: [IPCC AR5 WG1, FAQ 2.2]

Observed changes in temperature extremes

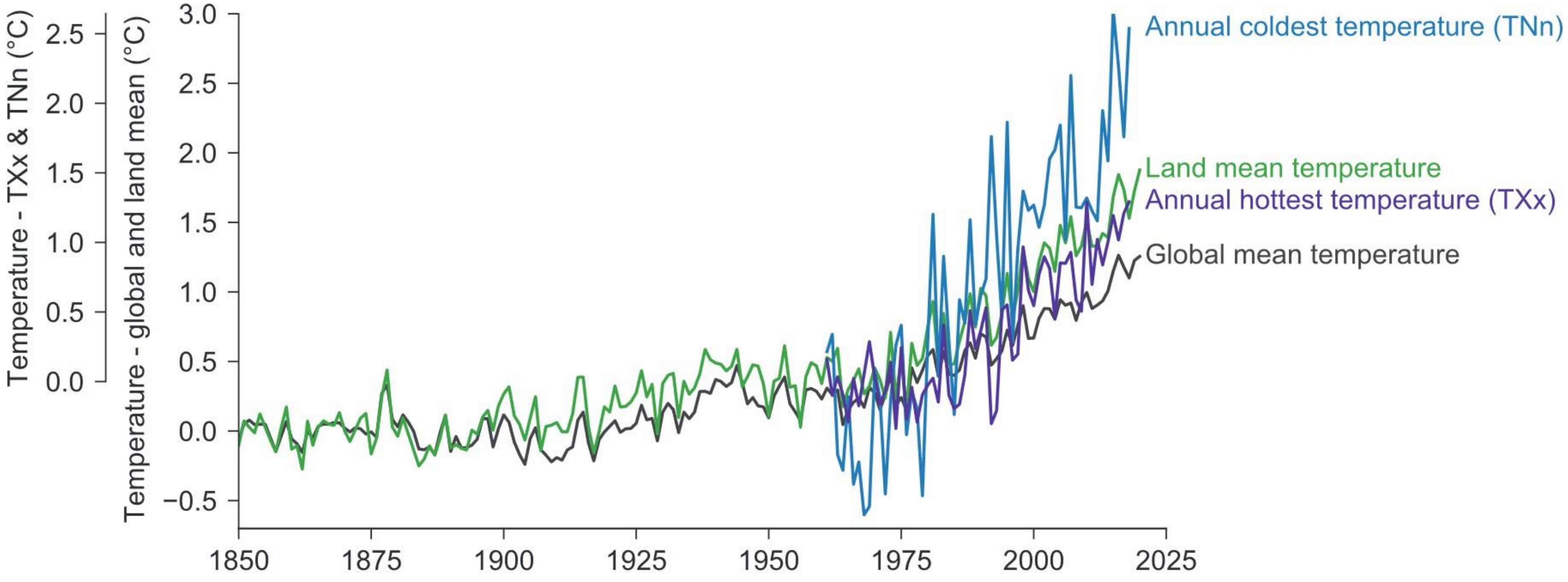


Figure 11.2 | Time series of observed temperature anomalies for global average annual mean temperature (black), land average annual mean temperature (green), land average annual hottest daily maximum temperature (TXx, purple), and land average annual coldest daily minimum temperature (TNn, blue). Global and land mean temperature anomalies are relative to their 1850–1900 means and are based on the multi-product mean annual time series assessed in Section 2.3.1.1.3 (see text for references). TXx and TNn anomalies are relative to their respective 1961–1990 means and are based on the HadEX3 dataset (Dunn et al., 2020) using values for grid boxes with at least 90% temporal completeness over 1961–2018. Further details on data sources and processing are available in the chapter data table (Table 11.SM.9).

Source: IPCC AR6 WG1 Chapter 11, Fig. 11.2

What is expected in the future ?

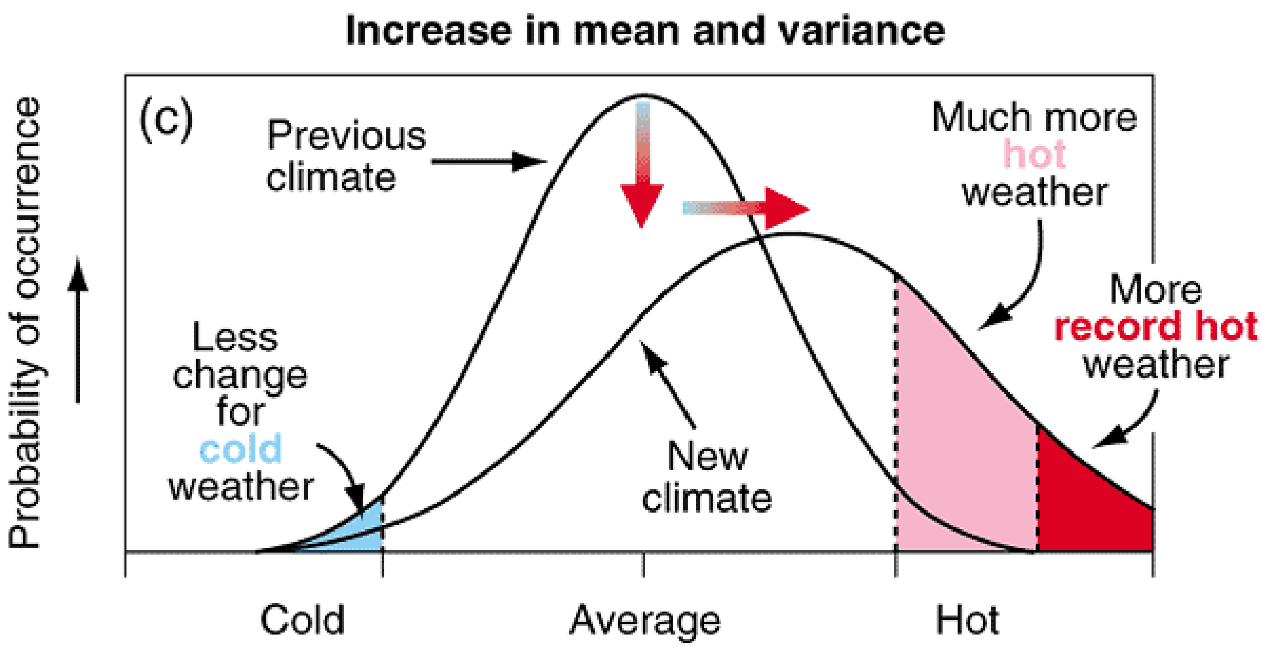
- Trust in climate models: by comparing simulations of extreme weather events under current conditions (including GHG forcing, the “actual world”), with simulations without human influence on climate (the “counterfactual world”), we can isolate the human influence on extreme weather.

- For future temperature: expected increase of both the mean and the variance.

- Meaning more record hot weather and less change for cold weather (increased variance).

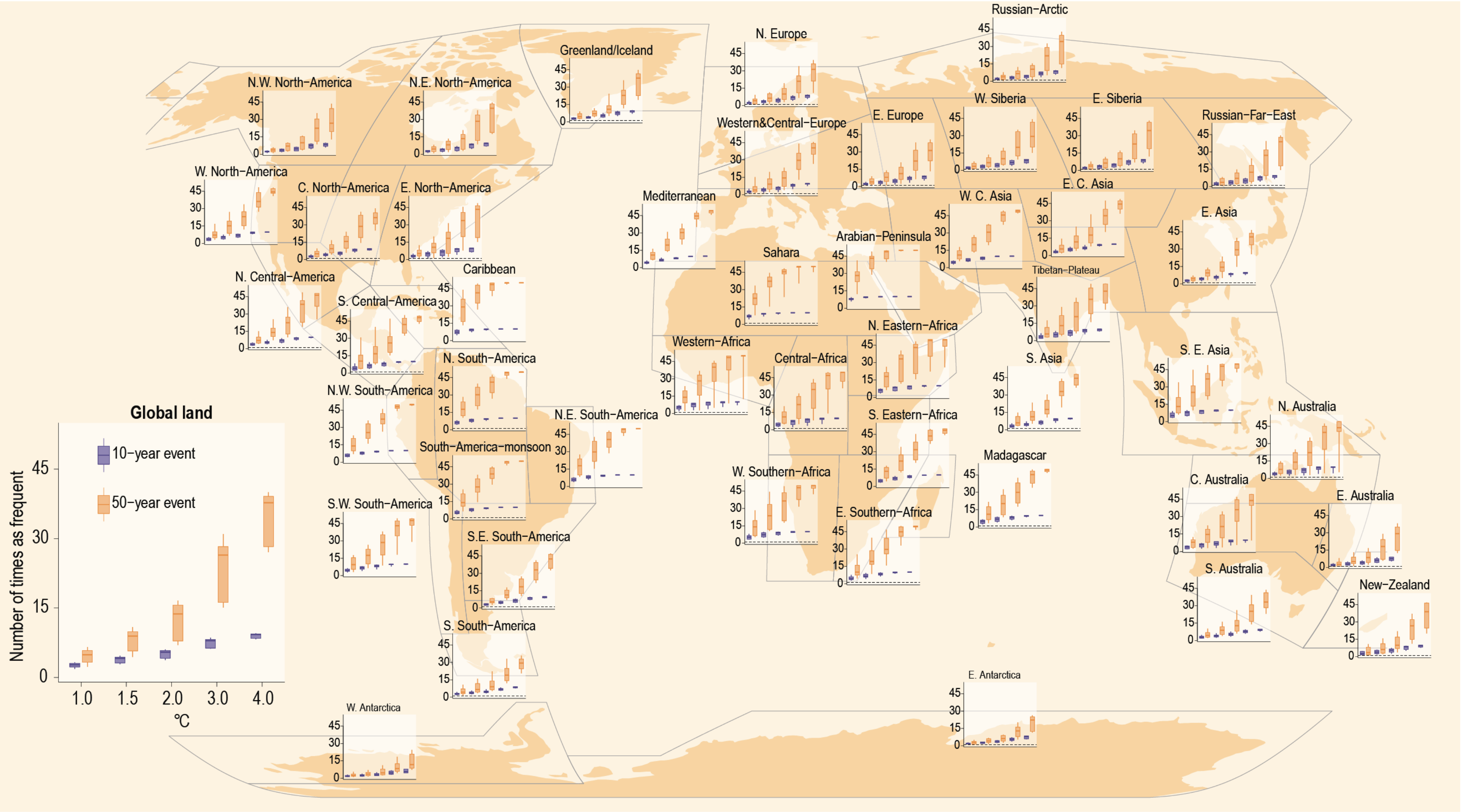
- With +1.5°C:
  - 4 times more frequent hot events having a return period of 10 years.

- With +4°C:
  - 9.4 times more frequent hot events having a return period of 10 years. It becomes the standard conditions !



Source: IPCC AR3 WG1, Fig. 2.32

Frequency of extreme temperature events

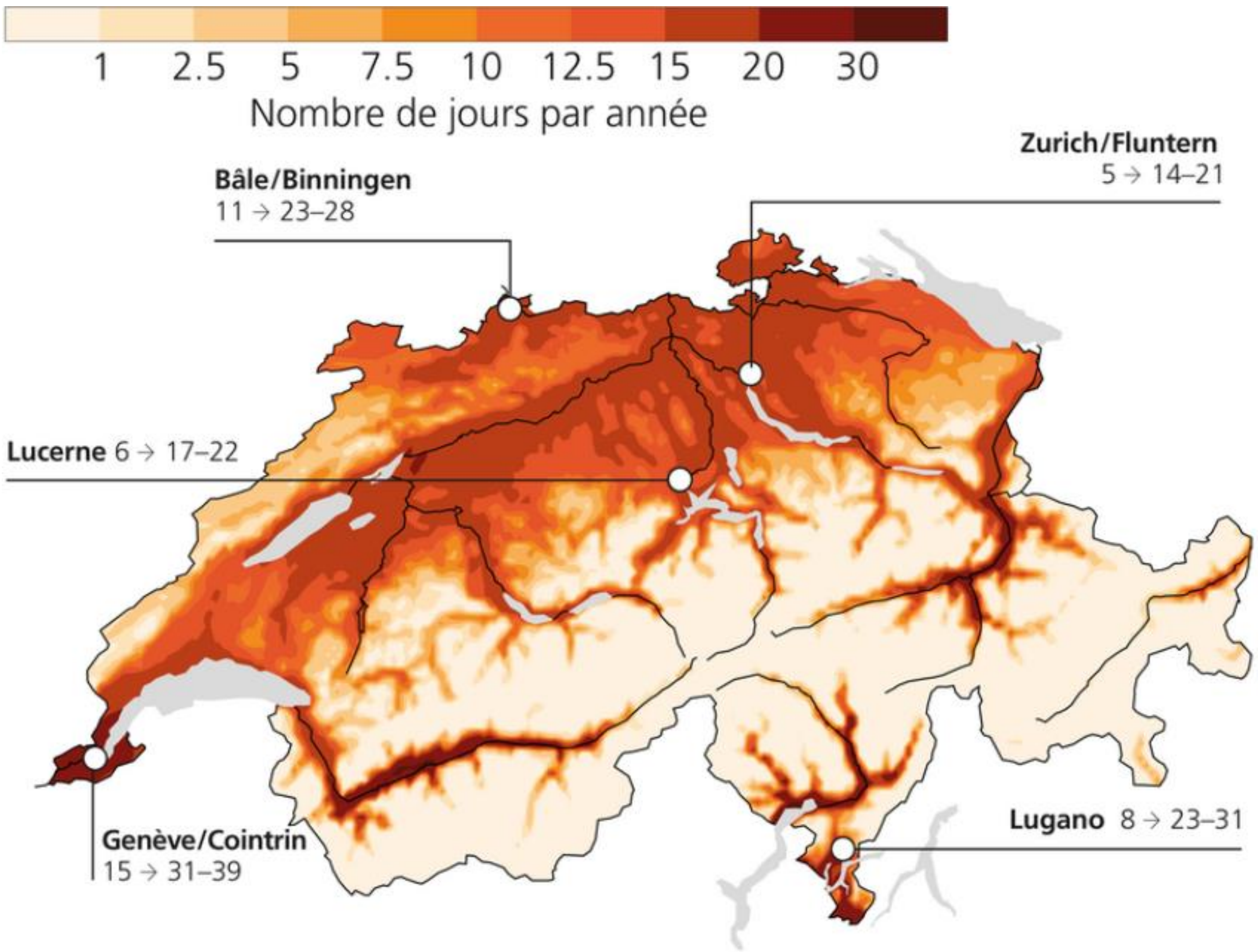


- Intensity and frequency of extremes would double at +2°C and quadruple at +3°C compared to +1.5°C.

Source: *[IPCC AR6 WG1, Chapter 11, Fig. 11.6]*

Number of «hot days» in Switzerland

- Threshold at 30°C…
- Increase of number of hot days in 2060 compared with 1981-2010 climatology
- Strong effect in Geneva, Valais and southern Switzerland.
- Additional effect of urban heat islands.
- 30°C is already a source of stress for agriculture, power grid stability, railroads… So it matters at Swiss scale !



Source: [MétéoSuisse, hot days]

Much more in the IPCC report ! Different indices

Annex VI — **Climatic Impact-driver and Extreme Indices**

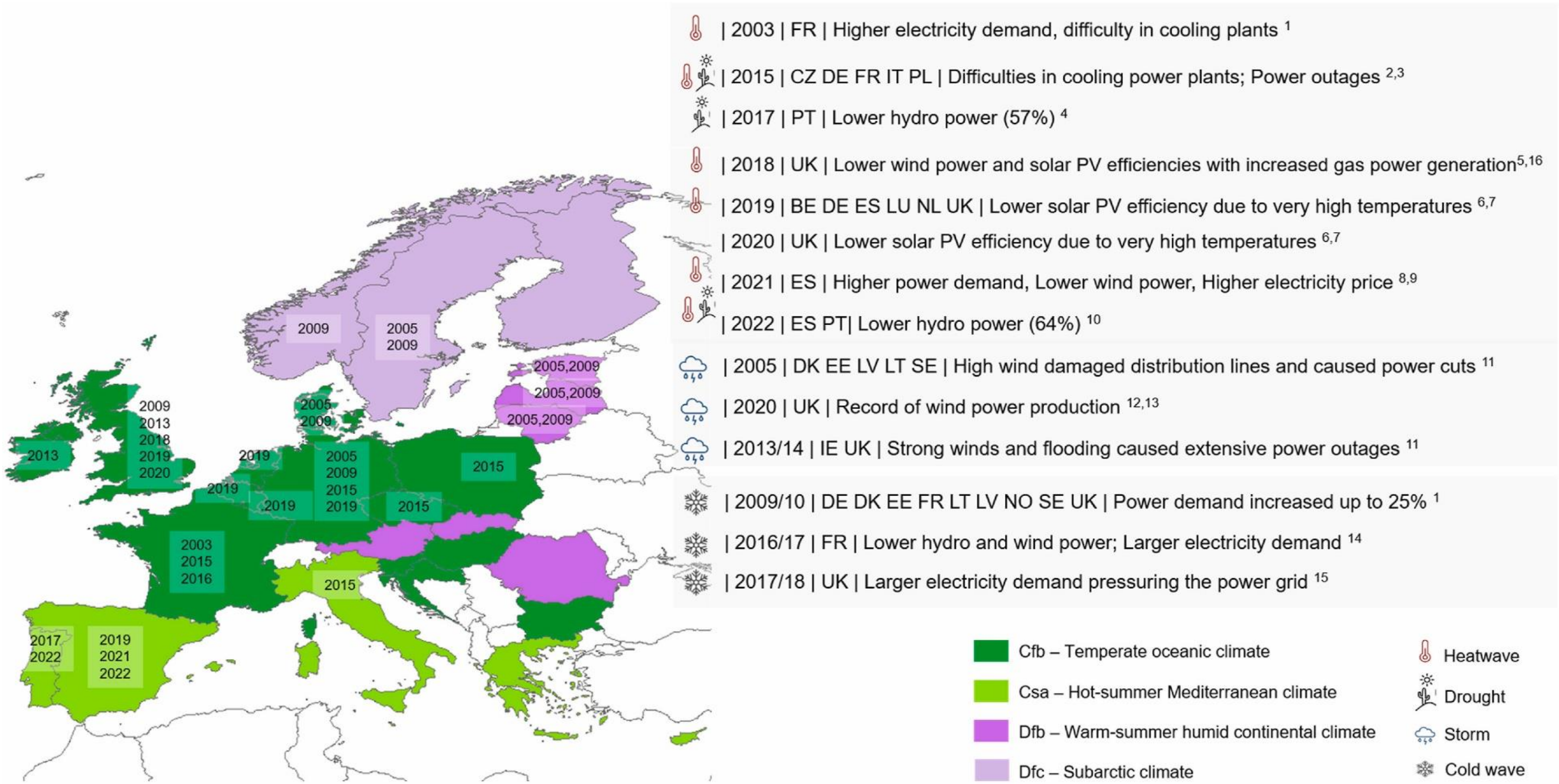
Table AVI.1 | Table listing extreme indices used in Chapter 11.

Extreme	Label	Index Name	Units	Variable
Temperature	TXx	Monthly maximum value of daily maximum temperature	°C	Maximum temperature
	TXn	Monthly minimum value of daily maximum temperature	°C	Maximum temperature
	TNn	Monthly minimum value of daily minimum temperature	°C	Minimum temperature
	TNx	Monthly maximum value of daily minimum temperature	°C	Minimum temperature
	TX90p	Percentage of days when daily maximum temperature is greater than the 90th percentile	%	Maximum temperature
	TX10p	Percentage of days when daily maximum temperature is less than the 10th percentile	%	Maximum temperature
	TN90p	Percentage of days when daily minimum temperature is greater than the 90th percentile	%	Minimum temperature
	TN10p	Percentage of days when daily minimum temperature is less than the 10th percentile	%	Minimum temperature
	ID	Number of icing days: annual count of days when TX (daily maximum temperature) <0°C	Days	Maximum temperature
	FD	Number of frost days: annual count of days when TN (daily minimum temperature) <0°C	Days	Minimum temperature
	WSDI	Warm spell duration index: annual count of days with at least six consecutive days when TX >90th percentile	Days	Maximum temperature
	CSDI	Cold spell duration index: annual count of days with at least six consecutive days when TN <10th percentile	Days	Minimum temperature
	SU	Number of summer days: annual count of days when TX (daily maximum temperature) >25°C	Days	Maximum temperature
	TR	Number of tropical nights: annual count of days when TN (daily minimum temperature) >20°C	Days	Minimum temperature
	DTR	Daily temperature range: monthly mean difference between TX and TN	°C	Maximum and minimum temperature
	GSL	Growing season length: annual (1 Jan to 31 Dec in Northern Hemisphere (NH), 1 July to 30 June in Southern Hemisphere (SH)) count between first span of at least six days with daily mean temperature TG >5°C and first span after July 1 (Jan 1 in SH) of six days with TG <5°C	Days	Mean temperature
	20TXx	One-in-20 year return value of monthly maximum value of daily maximum temperature	°C	Maximum temperature
	20TXn	One-in-20 year return value of monthly minimum value of daily maximum temperature	°C	Maximum temperature
	20TNn	One-in-20 year return value of monthly minimum value of daily minimum temperature	°C	Minimum temperature
	20TNx	One-in-20 year return value of monthly maximum value of daily minimum temperature	°C	Minimum temperature
Precipitation	Rx1day	Maximum one-day precipitation	mm	Precipitation
	Rx5day	Maximum five-day precipitation	mm	Precipitation
	R5mm	Annual count of days when precipitation is greater than or equal to 5 mm	Days	Precipitation
	R10mm	Annual count of days when precipitation is greater than or equal to 10 mm	Days	Precipitation
	R20mm	Annual count of days when precipitation is greater than or equal to 20 mm	Days	Precipitation
	R50mm	Annual count of days when precipitation is greater than or equal to 50 mm	Days	Precipitation
	CDD	Maximum number of consecutive days with less than 1 mm of precipitation per day	Days	Precipitation
	CWD	Maximum number of consecutive days with more than or equal to 1 mm of precipitation per day	Days	Precipitation
	R95p	Annual total precipitation when the daily precipitation exceeds the 95th percentile of the wet-day (>1 mm) precipitation	mm	Precipitation
	R99p	Annual precipitation amount when the daily precipitation exceeds the 99th percentile of the wet-day precipitation	mm	Precipitation
	SDII	Simple precipitation intensity index	mm day^{-1}	Precipitation
	20Rx1day	One-in-20 year return value of maximum one-day precipitation	mm day^{-1}	Precipitation
	20Rx5day	One-in-20 year return value of maximum five-day precipitation	mm day^{-1}	Precipitation
Drought	SPI	Standardized precipitation index	Months	Precipitation
	EDDI	Potential evaporation, evaporative demand drought index	Months	Evaporation
	SMA	Soil moisture anomalies	Months	Soil moisture
	SSMI	Standardized soil moisture index	Months	Soil moisture
	SRI	Standardized runoff index	Months	Streamflow
	SSI	Standardized streamflow index	Months	Streamflow
	PDSI	Palmer drought severity index	Months	Precipitation, evaporation
	SPEI	Standardized precipitation evapotranspiration index	Months	Precipitation, evaporation, temperature

- Take home: in addition to more temperature extremes, high confidence in intensification of heavy precipitation, medium confidence for tropical cyclones, high confidence for worsening of droughts.
- Projected percentage changes in frequency are higher for the rarer extreme events (high confidence).

Source: IPCC AR6 WG1, Annex VI

Recent impact on energy systems in Europe



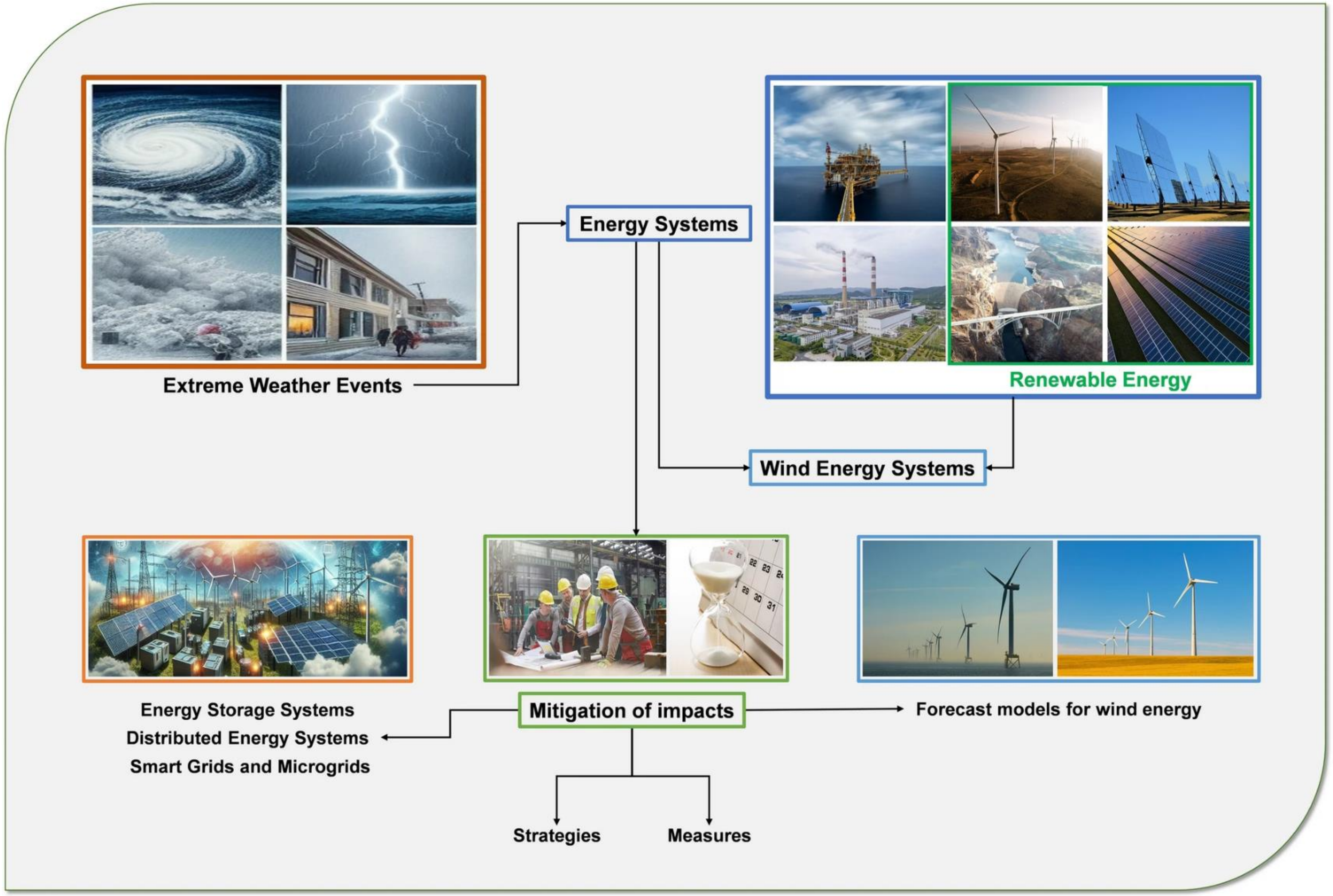
<u>**Over the period 1990 to 2019 in Europe**</u>:

- 631 events with human/economical damages.
- Large regional differences.
- Flood years / storm years increased EU hydropower by 7% / 5.8%
- Droughts/heatwaves decreased EU hydropower by 6.5% and increased central EU PV by 4.1%.

Source: *Brás et al., Renewable and Sustainable Energy Reviews 2023*

How about future impacts on energy systems ?

- Energy systems are severely affected by Extreme Weather Events, which are considered a serious risk for the energy sector and its facilities.
- Implications for the reliability and performance, and the resilience of energy supply systems.
- *“Governments and energy companies must act to enhance the resilience of energy systems to EWEs”.*

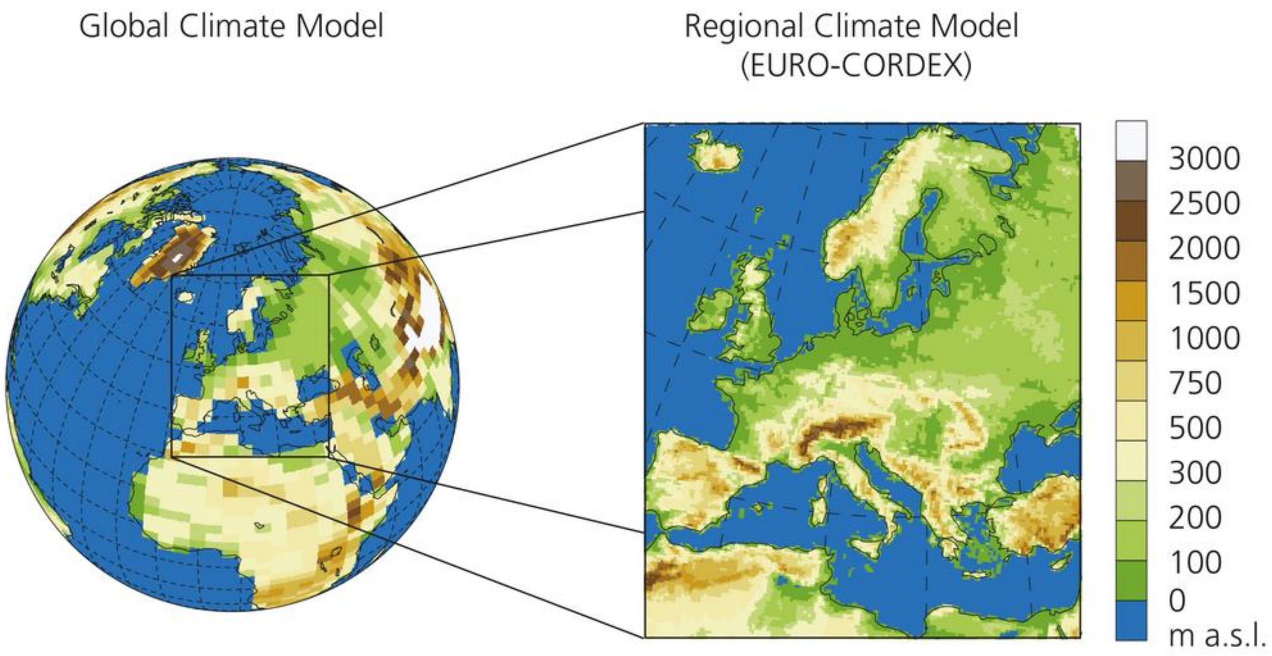


Source: Gonçalves et al., Sustainable Energy Research 2024

Regional climate change

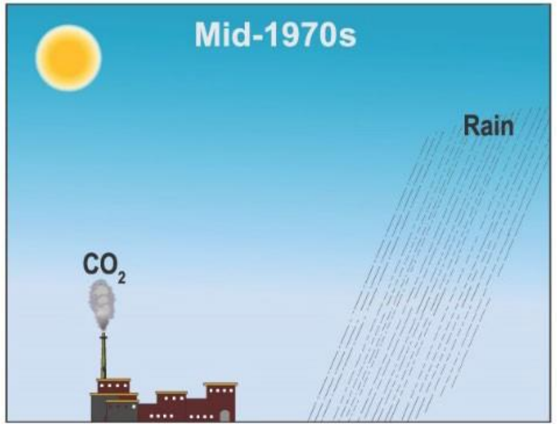
Specificities of regional climate change

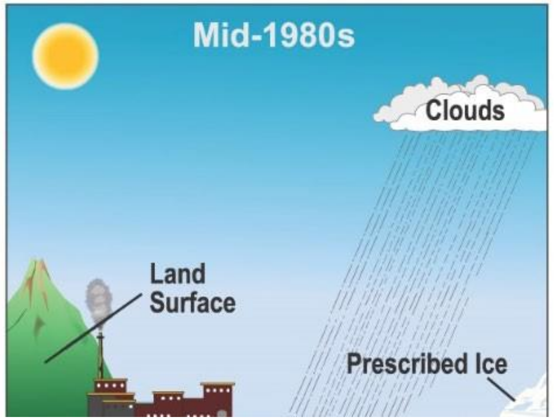
- The impact of climate change depends on regions of the world.
- It requires specific focuses on regional impacts.
- Policy and planning decisions depend on governments, cities and industries which require regional data and regional projections.
- There can be physical characteristics not being fully addressed by global Earth system models. Examples: mountains, coastlines, urban heat islands.
- This is why regional climate models (RCM, in comparison with global climate models GCM) are built.
  - They provide finer spatial resolution.
  - They allow to better address weather extremes.
  - They allow to build regional adaptation strategies.



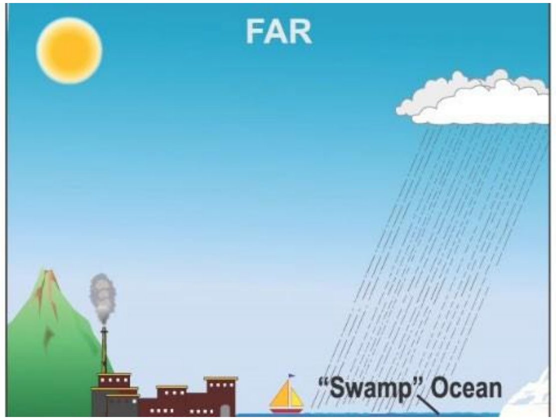
Source: MétéoSuisse CH2018

Evolution of climate models

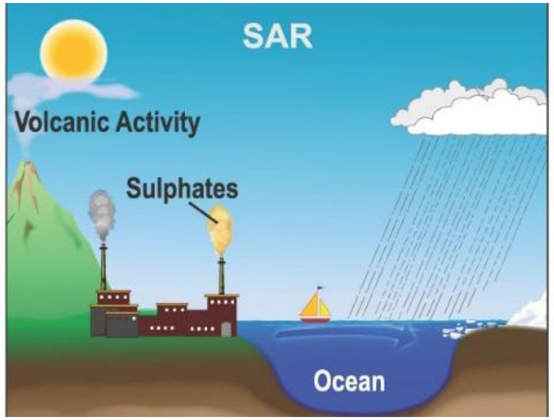




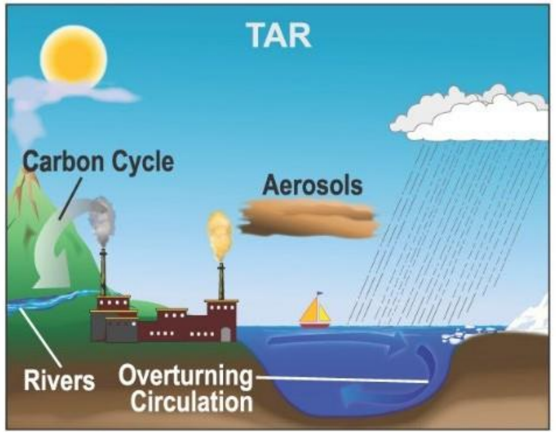
1st IPCC Assessment report



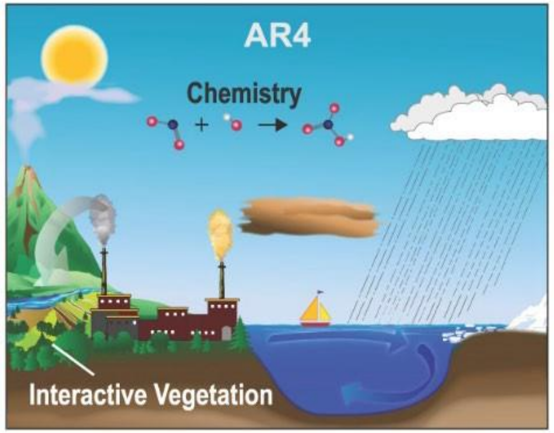
2nd IPCC Assessment report



3rd IPCC Assessment report



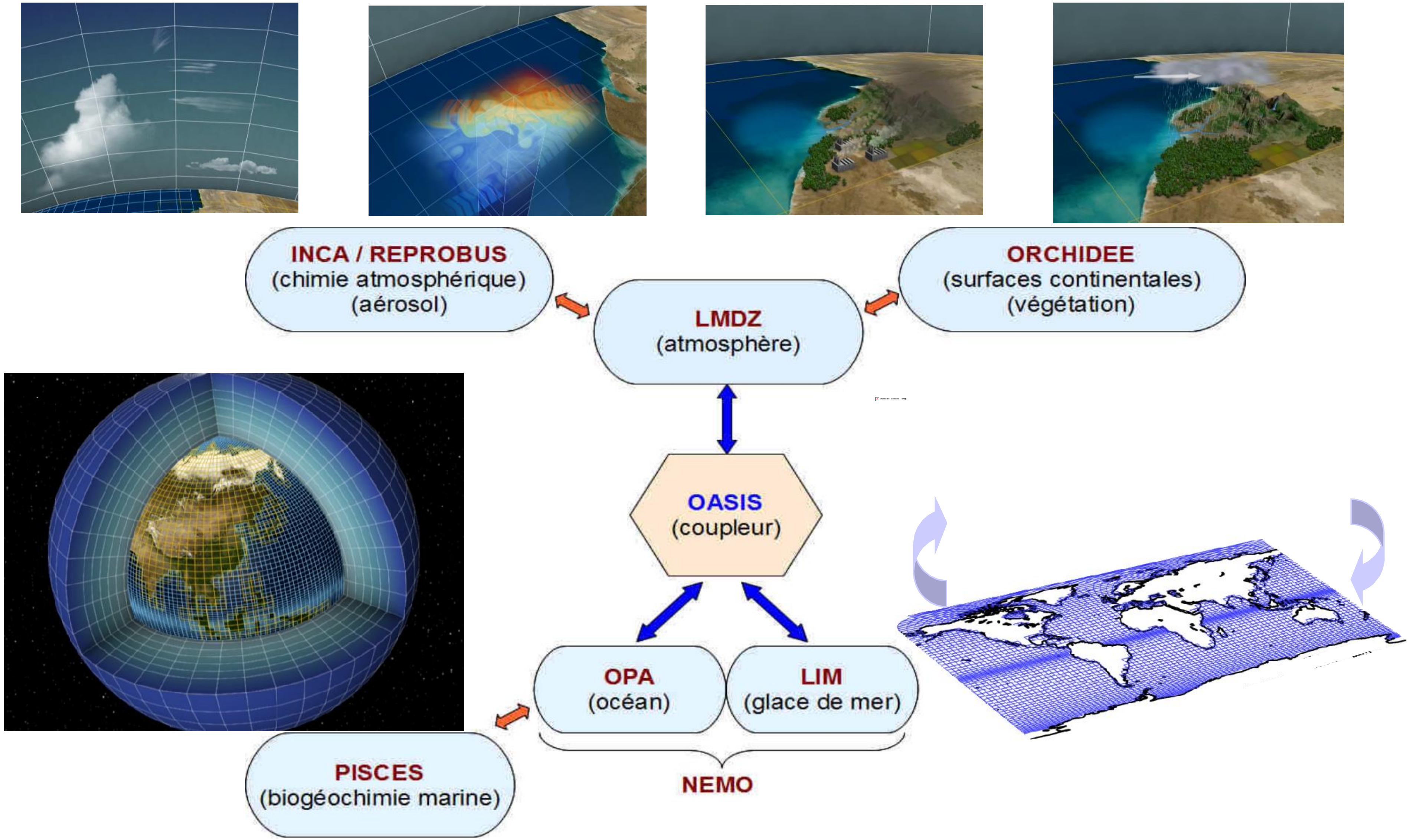
4th IPCC Assessment report



Increasing number of processes and climate system components included through time.

Source: [IPCC AR4 WG1 Figure 1.2]

An example: global climate model from IPSL-France

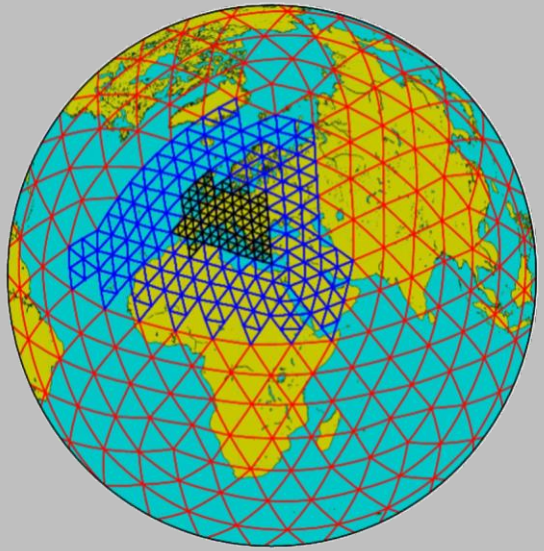


- *Source: Jean-Louis Dufresne, IPSL*

Gaining resolution: how ?

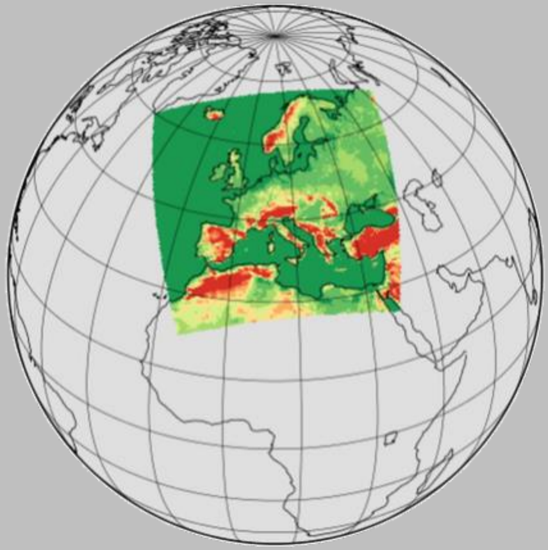
Source: Christoph Schär, ETH Zürich

GCM with local refinement



Example: Arpege model of Météo-France, down to 80 km resolution. Physically consistent. But computationally expensive.

Dynamical downscaling



Regional climate models (RCMs) concentrate computational power on subdomain (10 to 50 km resolution). Usually one-way nested into GCMs. Depend on GCM boundary quality.

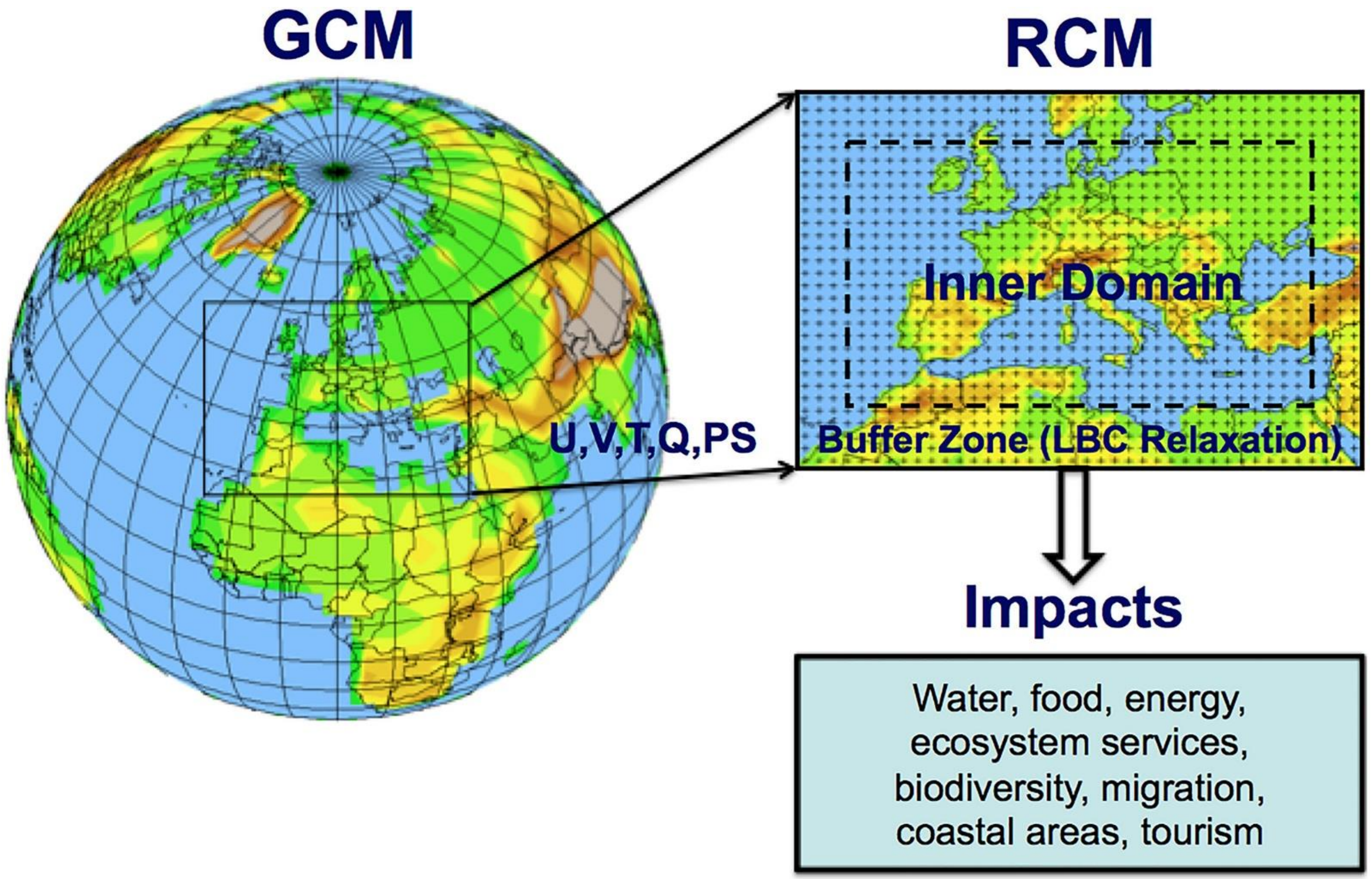
Statistical-empirical downscaling

Statistical link of large-scale variables with regional climate, calibrated using observations.

Fast and easy methodology. But uses stationarity assumption. Not physically based. Requires long, high-quality observations.

From a GCM to a RCM: Dynamical downscaling

- The first regional climate model (RCM) was built in 1989. Developed for impact studies.
- The GCM is used to calculate the effects of large-scale forcings (GHG, solar, volcanic).
- The RCM inner domain is forced by the GCM outputs. It refines calculations spatially and temporally, taking into account complex topography, coastlines, inland bodies of water, or dynamical processes occurring at mesoscale.
- RCMs usually have a spatial resolution of 12 to 50 km. Resolution can go down to 5 km to simulate convective processes (prediction of heavy rainfall).
- RCM simulations are **highly sensitive to errors in the boundary forcings**. But they can be tested against reanalysis data at fine resolution.

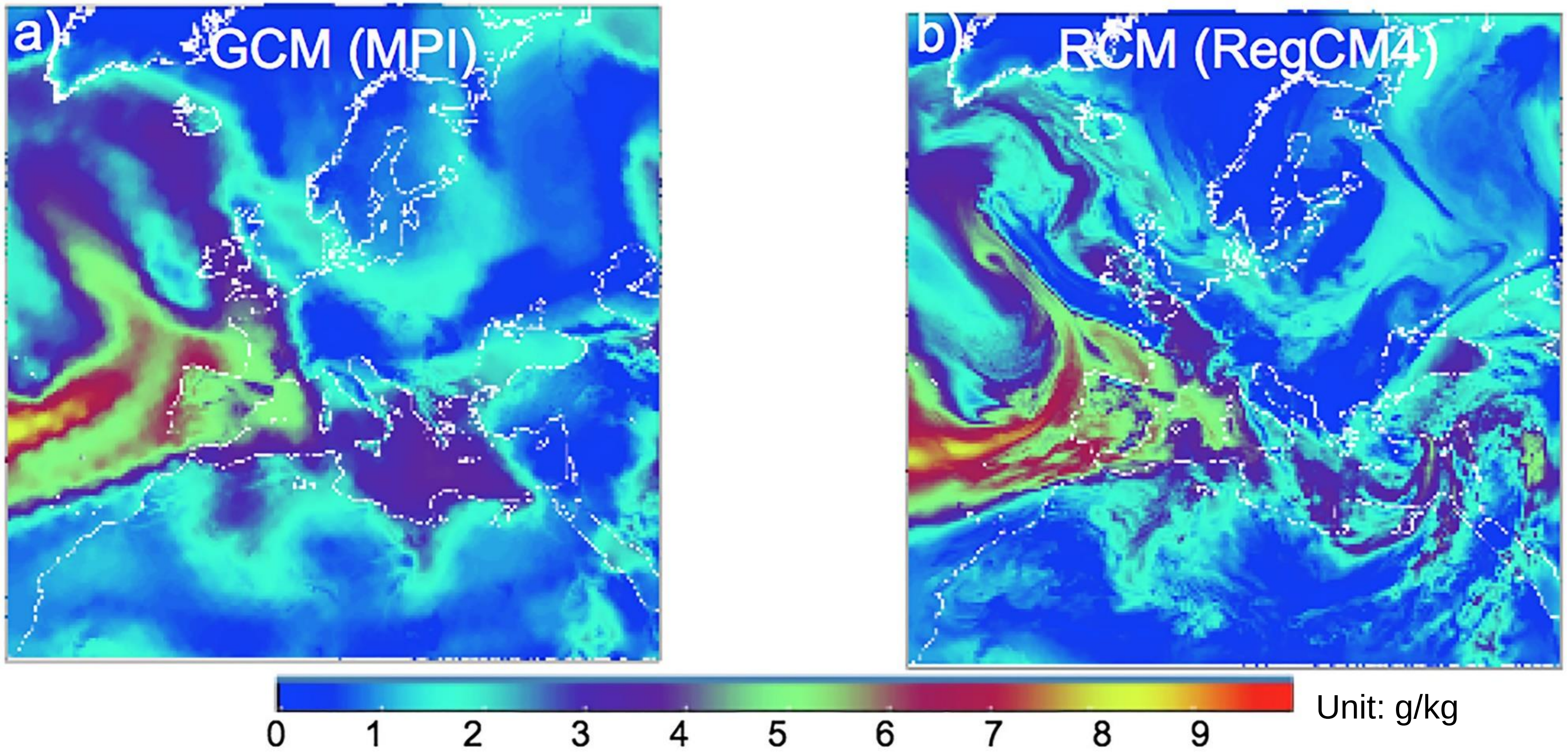


Source: Giorgi, J. Geophys. Res. Atmosphere 2019

Example of dynamical downscaling

- The RCM provides a much more refined and realistic spatial structure.

Instantaneous 850-hPa humidity field for a simulation of 12 January 2005 – 12h UTC



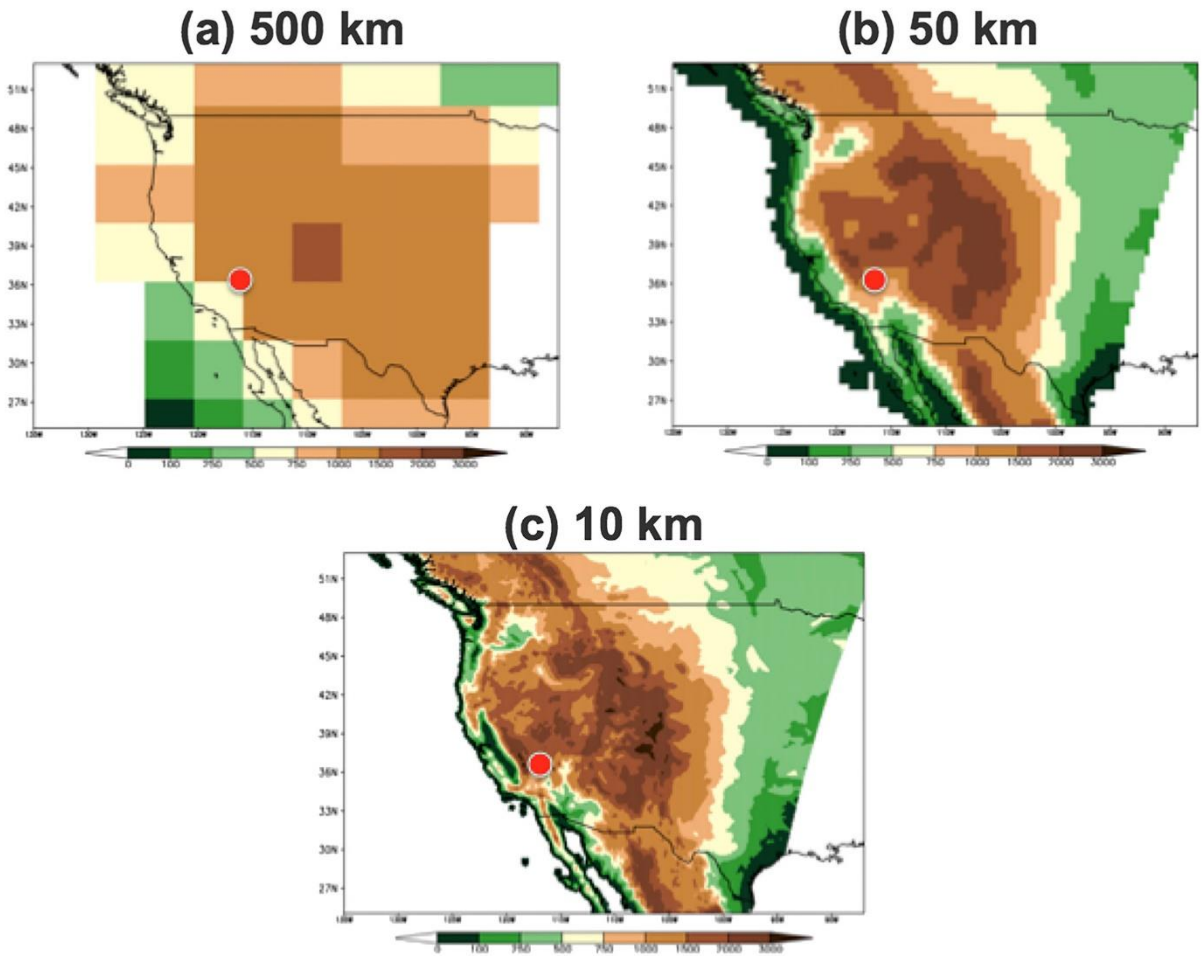
Resolution of 150 km

Resolution of 12.5 km

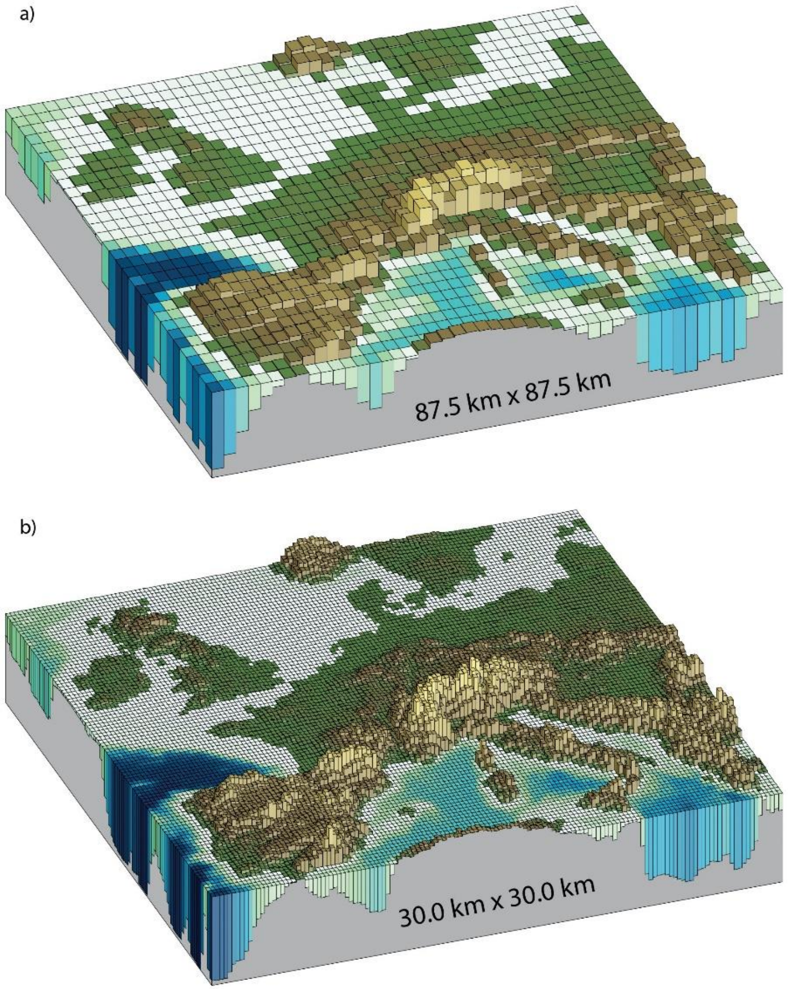
Source: [Giorgi, J. Geophys. Res. Atmosphere 2019]

Illustration with topography

- Illustration with Sierra Nevada in the USA (left) and with the Alps and other European mountains (right).
- Better representation of true altitudes. Very important to simulate rainfall patterns for instance, due to orographic effects.

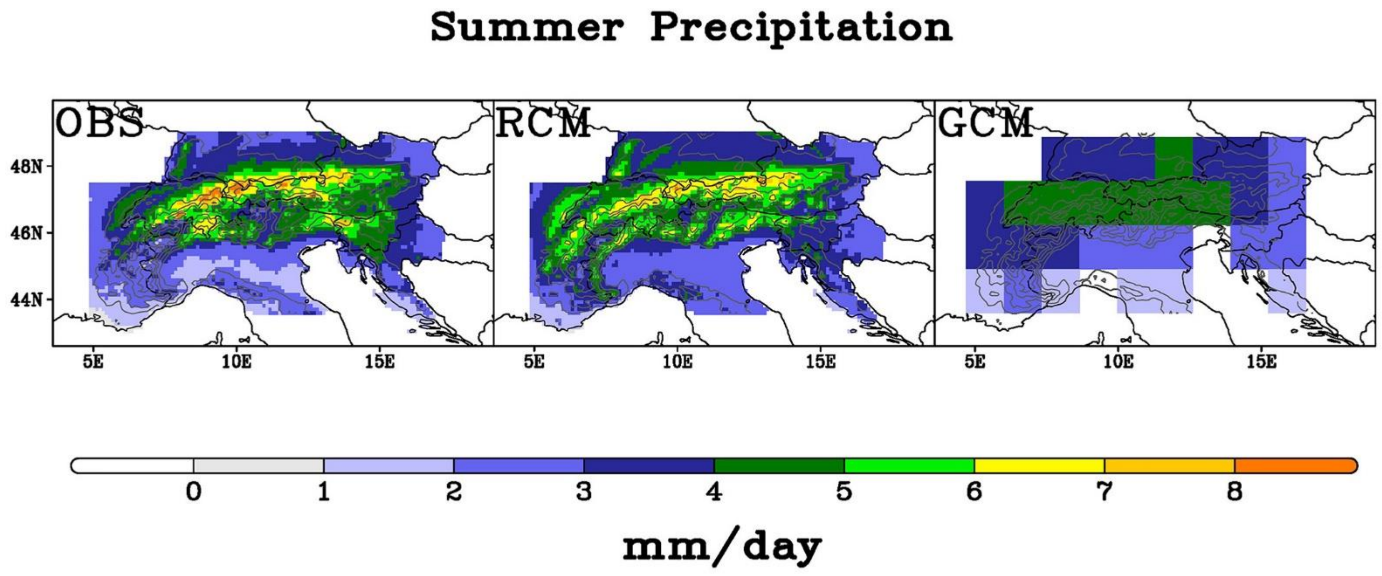


Source: *Giorgi, J. Geophys. Res. Atmosphere 2019*

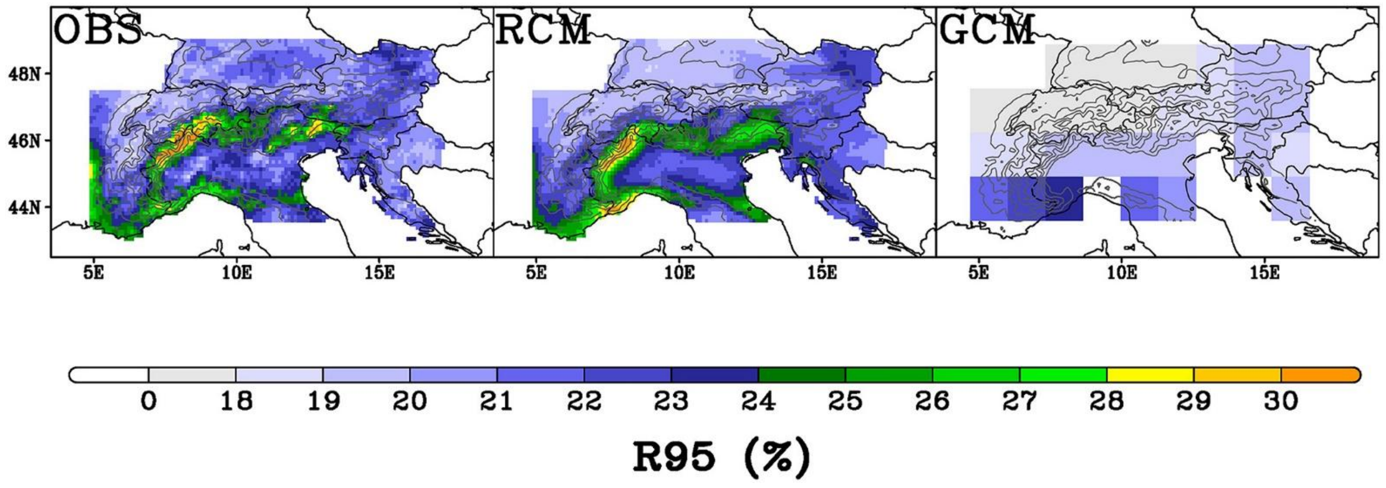


Source: *IPCC AR5 WG1 Introduction, Fig 1.14*

Illustration with topography and precipitation



The RCM much better reproduces observations (OBS) in strength and location, while the GCM largely underestimates the strength.



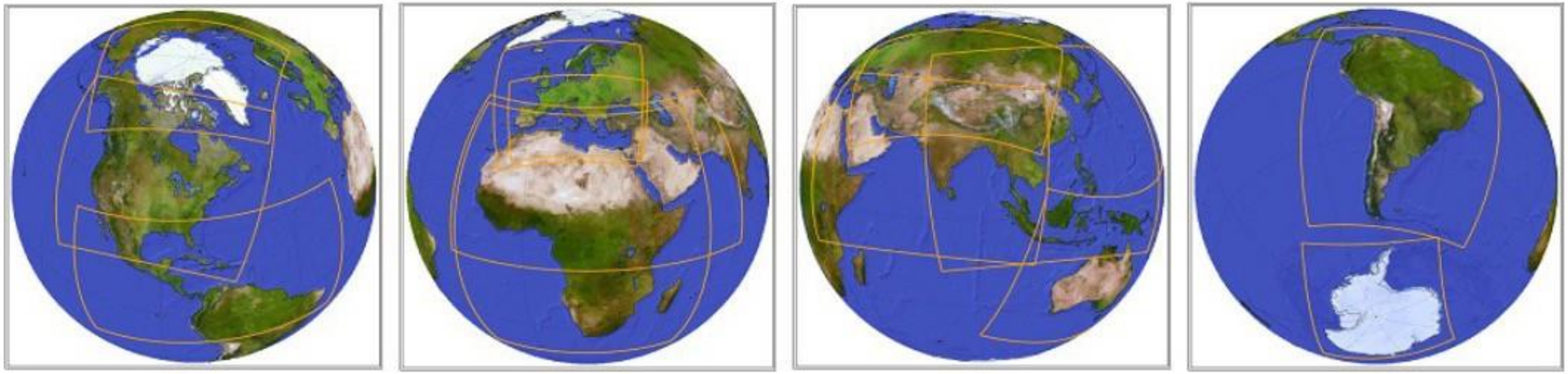
It is even more clear with the 95th percentile of heavy precipitation. The GCM totally misses the reality of OBS, while the RCM picks up their location, and reasonably well their intensity.

Source: *Giorgi, J. Geophys. Res. Atmosphere 2019*

An international initiative: CORDEX

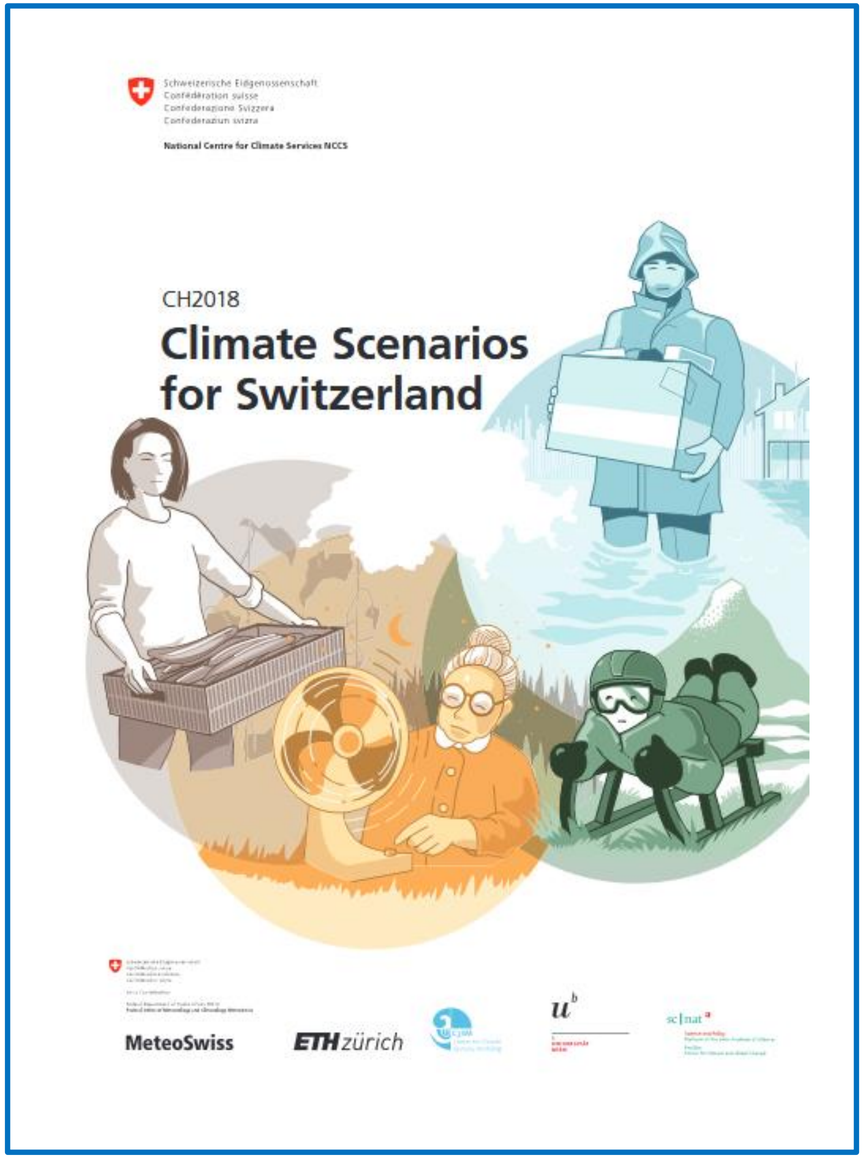
Coordinated Regional Climate Downscaling Experiment

- International framework for regional climate change projections.
- Currently 14 domains are used for most regions of the globe.



- Driven by CMIP5 and CMIP6 GCMs (RCP and SSP scenarios).
- Baseline resolution for dynamical downscaling: 50 km, in some regions higher (Europe: 12 km).
- Data provided on a distributed database (Earth System Grid Federation, ESGF).
- 30-year simulations are tested against reanalysis data.
- ~150-year simulations for scenarios, driven by a GCM boundary conditions.

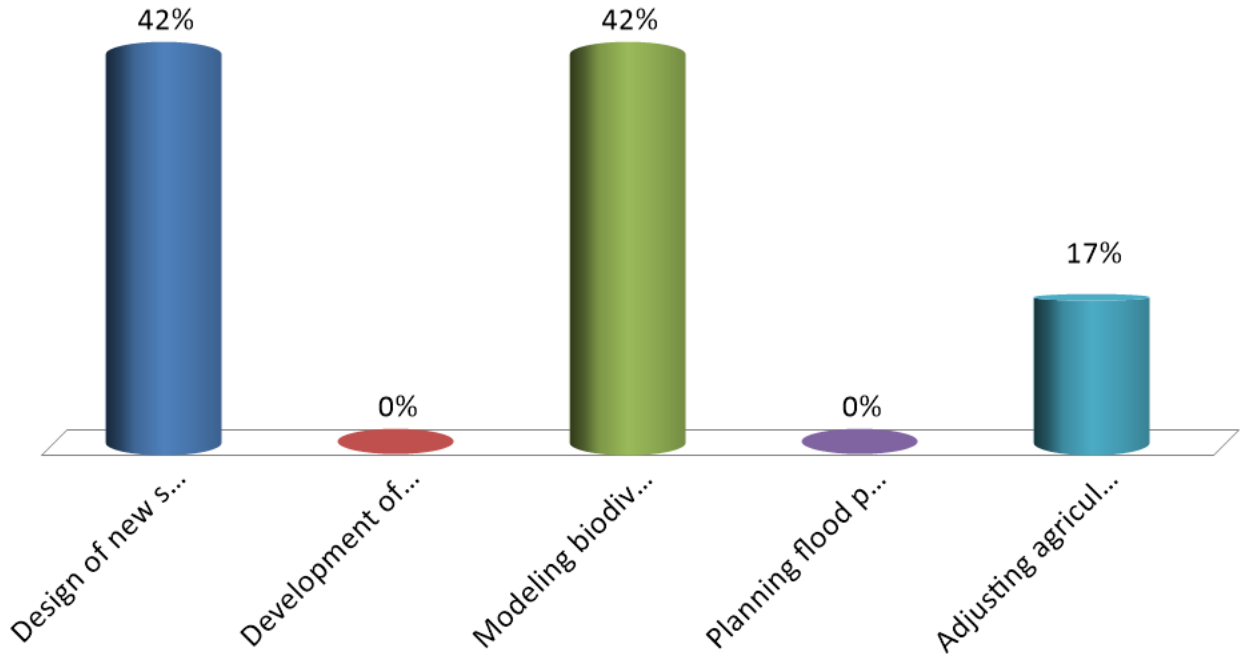
The Swiss case: CH2018



- Published on 13 November 2018.
- Very detailed technical report of 271 pages.
- An update of CH2018 is in the planning state: expected this year (CH2025)
- CH2018 uses input emission scenarios RCP2.6 and RCP8.5.
- Ensemble simulations from EURO-CORDEX (80 simulations with 10 different RCMs), using dynamical downscaling down to 12.5 km resolution.
- Statistical downscaling to 2 km resolution for impact studies.
- Changes determined with respect to the reference period 1981-2010.

Which activity is NOT directly using CH2018 ?

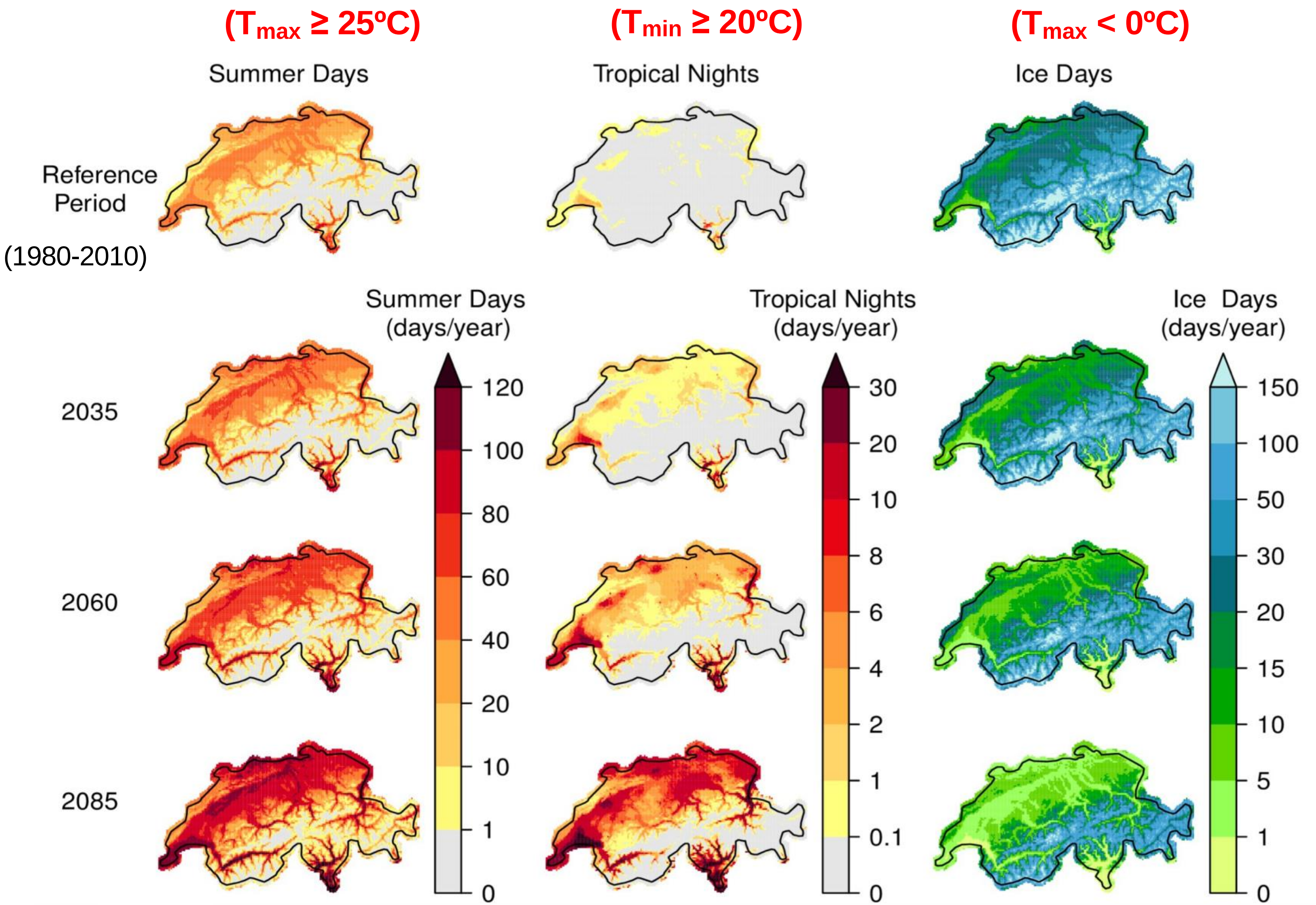
A. Design of new ski resorts
B. Development of climate adaptation policies
C. Modeling biodiversity loss
D. Planning flood protection measures
E. Adjusting agricultural practices



Source: Express, Feb. 2024

Temperatures below -2°C to -5°C required to create artificial snow.

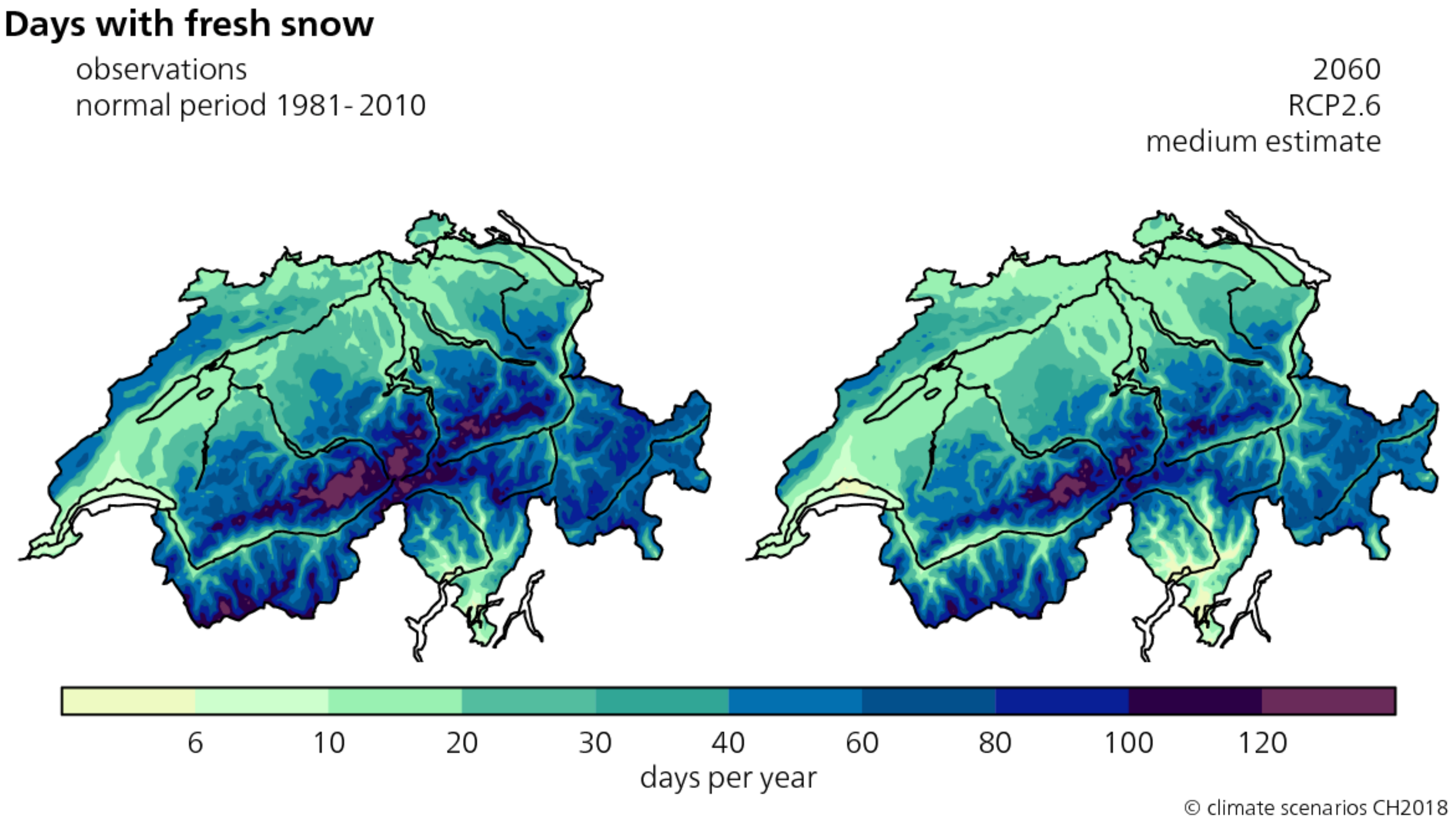
CH2018: hot summer days and ice days in Switzerland



Scales: number of days per year.

Source: *[MétéoSuisse CH2018 Technical Report, Fig. 6.5]*

CH2018: days with fresh snow

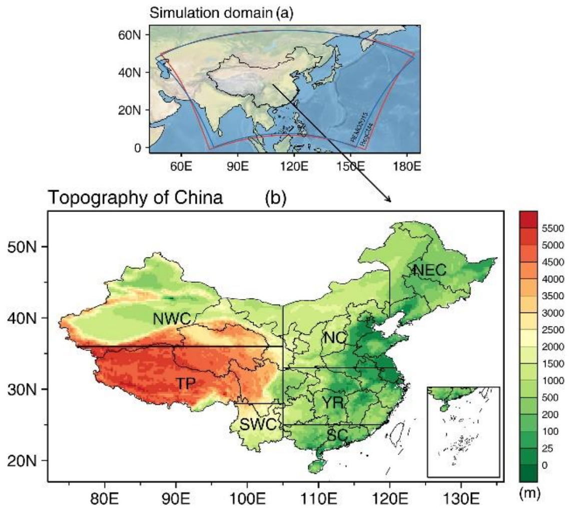


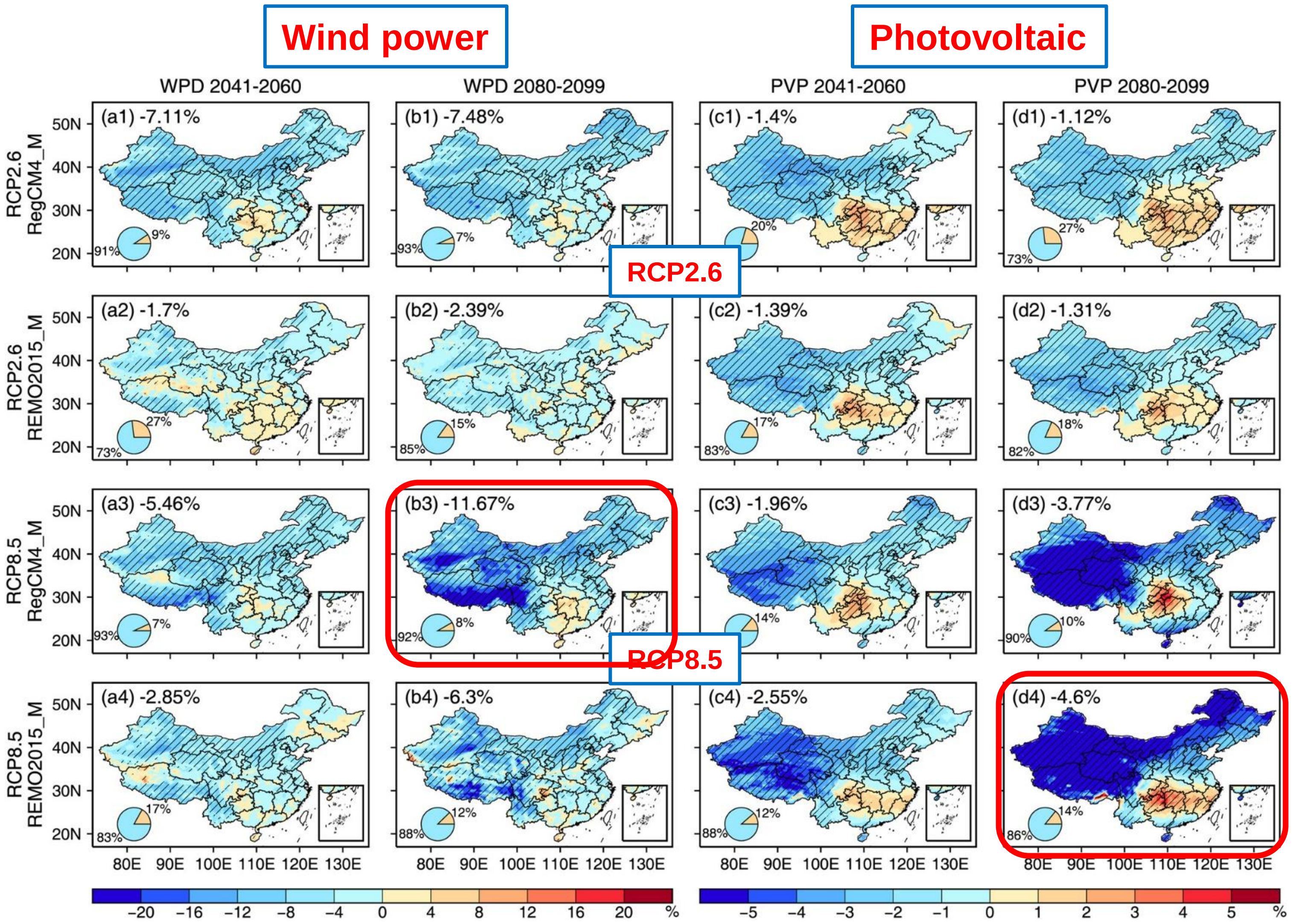
- Even with RCP2.6, large reduction of number of days per year with fresh snow in 2060.
- With RCP8.5, maxima over 120 days nearly disappear..

Source: *[MétéoSuisse CH2018 Climate Indicators]()*

Regional climate models and renewable energy

- It is a developing theme. Several applications in China so far, using CORDEX-EA-II.
- Simulations of PV and wind energy production in 2041-2060 and 2080-2099 using RCP2.6 and RCP8.5 scenarios.
- Wind power could decrease by up to 12%. PV by up to 5%.
- Regional differences within China. It may guide future investments for additional PV and WP systems.





Blue: negative change. Yellow/red: positive change.

Source: [Wu et al., J. Geophys. Res. Atmospheres 2024]

Towards km-scale regional climate modelling

WORLD METEOROLOGICAL ORGANIZATION

Weather Climate Water

Kilometre-Scale Modelling of the Earth System: A New Paradigm for Climate Prediction

● MAGAZINE ARTICLE

30 November 2023

Left: The first full picture of the Earth from space taken by Apollo 17 astronauts on 7 December 1972. Right: Simulated visible satellite image from a 1.25 km resolution simulation of the ICON model initialized with reanalysis fields on 5 December 1972

- Allows to explicitly represent vertical motions in the atmosphere, cloud physics, ocean eddies,…
- Can run only for a few days

Take-home: Tipping points, extreme events, regional climate change

- Several **tipping points** exist in the climate system and are on the verge of being crossed even at +1.5°C.
- **Time scale matters**. For tipping points associated with ice sheets, overshoots may still allow to avoid shifting to a new state.
- Resilience must be included in policies, to cope not only with climate variability but also with tipping points.
- Extreme events are the most impactful on human societies. Attribution is now possible, as well as projections.
- A warmer world means **more extremes**, both in frequency and in intensity. They already impacted and will keep impacting energy systems.
- Their projections at regional scale are one of the most important aspects of climate science in relation with governance.
- Depending on your future professional activity, you will need to rely on regional climate projections to optimize your strategy.
- Stay tuned for CH2025 from MétéoSuisse !