

ONLINE TRAINING SESSIONS

Impact of Climate Change on Radioactive Waste
Management

Training materials – Milestone 78

Workpackage 11 Climate



Co-funded by the European Union under Grant Agreement n° 101166718

Eurad-2 WP11 Climate online training sessions – Climate fundamentals and uncertainties associated with future climate predictions



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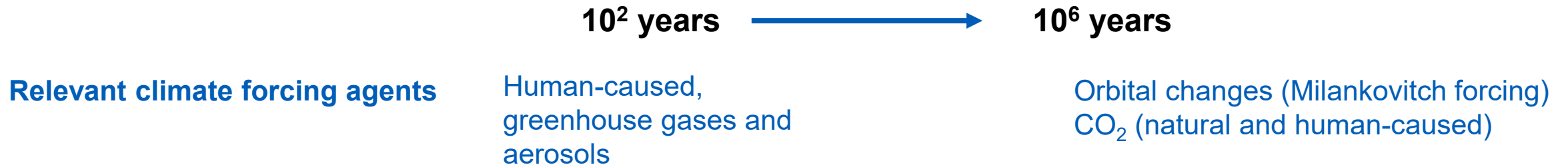
19th May 2026



Introduction

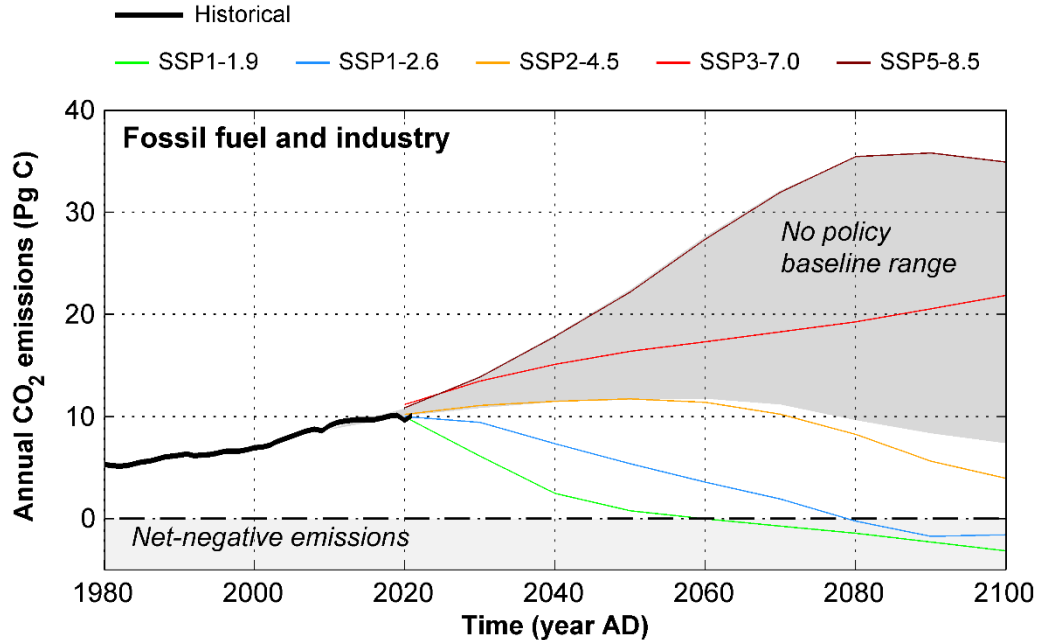
- Climate change is not a physical barrier and, by itself, does not contribute to storage safety or the long-term safety of a disposal system.
- It can influence engineered barriers and their surrounding natural environment (the surface systems and geosphere) to such an extent that long-term safety could be compromised if climate-related parameters (precipitation, temperature) and their impacts (e.g. floods, sea-level rise, ice-sheet development, permafrost) are not considered during design and site selection.

When considering safety of nuclear waste disposal systems, a **wide range of timescales** need to be considered covering operational and post-closure safety periods.



Future climate change: shorter timescales (10² years)

IPCC¹ greenhouse-gas emissions scenarios (SSPs)
(Previously RCPs)



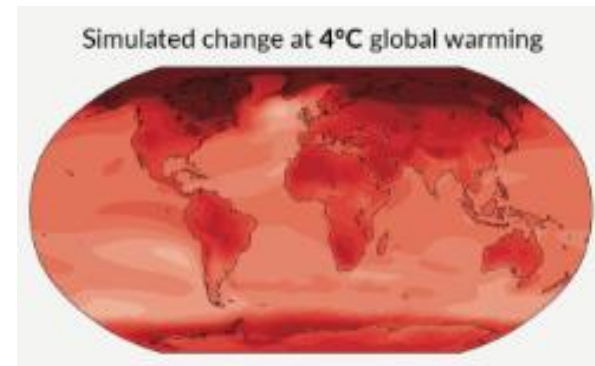
Global surface air temperature increase
relative to 1995-2014

Time period	Scenario	Global-mean warming (°C)
2041–2060	SSP1-2.6	0.9 [0.5 to 1.3]
	SSP2-4.5	1.1 [0.8 to 1.6]
	SSP3-7.0	1.3 [0.9 to 1.7]
	SSP5-8.5	1.5 [1.1 to 2.1]
2081–2100	SSP1-2.6	0.9 [0.5 to 1.5]
	SSP2-4.5	1.8 [1.2 to 2.6]
	SSP3-7.0	2.8 [2.0 to 3.7]
	SSP5-8.5	3.5 [2.4 to 4.8]

Range represents uncertainty in climate model (GCM) projections

Regionally, climate change will depend on several factors, including:

1. Arctic amplification
2. Land-ocean contrast
3. Atmosphere and ocean circulation changes

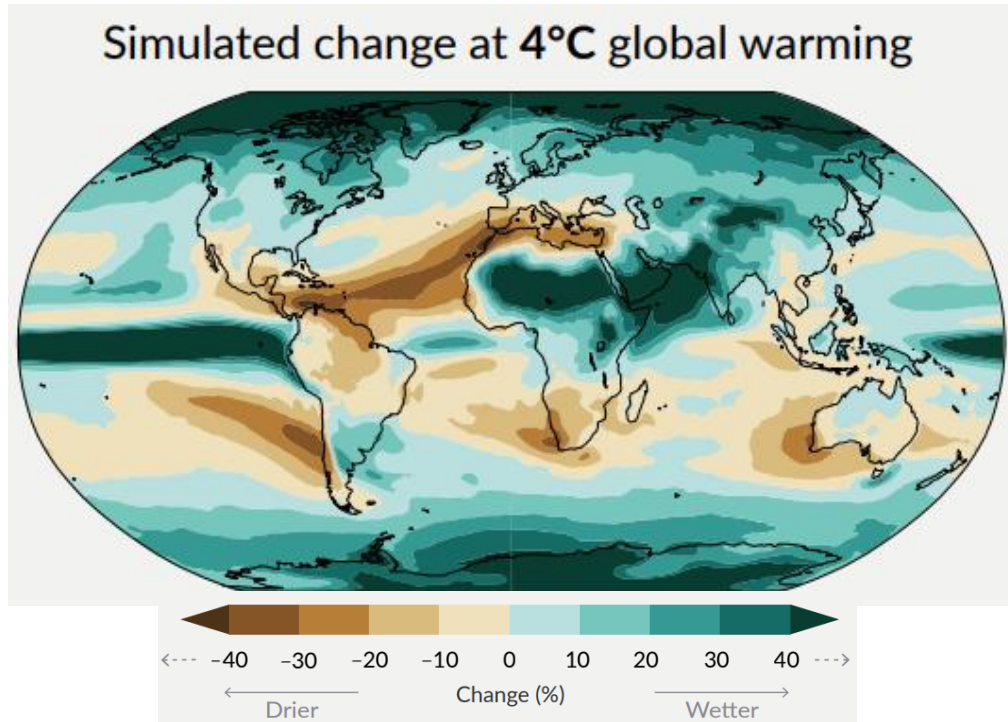


Results from several different General Circulation Models (GCMs)

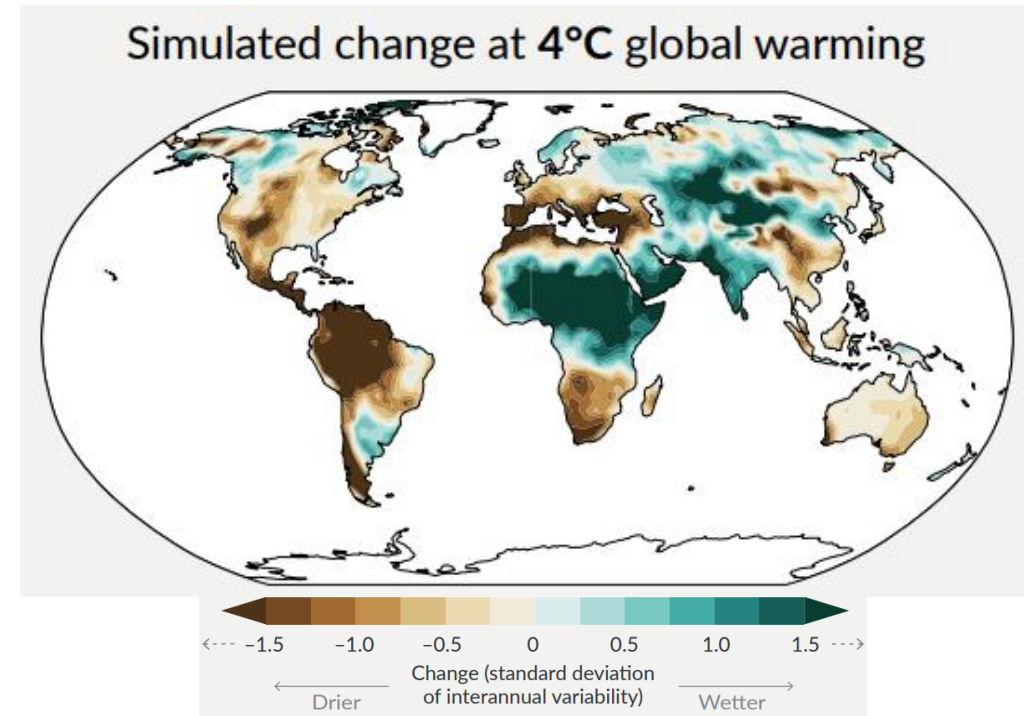
¹ IPCC: Intergovernmental Panel on Climate Change; see <https://www.ipcc.ch/assessment-report/ar6/>

Future climate change: shorter timescales (10^2 years)

Annual-mean precipitation
change relative to 1995-2014



Annual-mean soil moisture
change relative to 1995-2014



In most of Europe, evapotranspiration increases more than precipitation as a result of climate warming -> **drier conditions** (on average)

However, there are significant **seasonal variations** and **variability across models**;
see <https://interactive-atlas.ipcc.ch/>

Future climate change: risk of AMOC collapse?

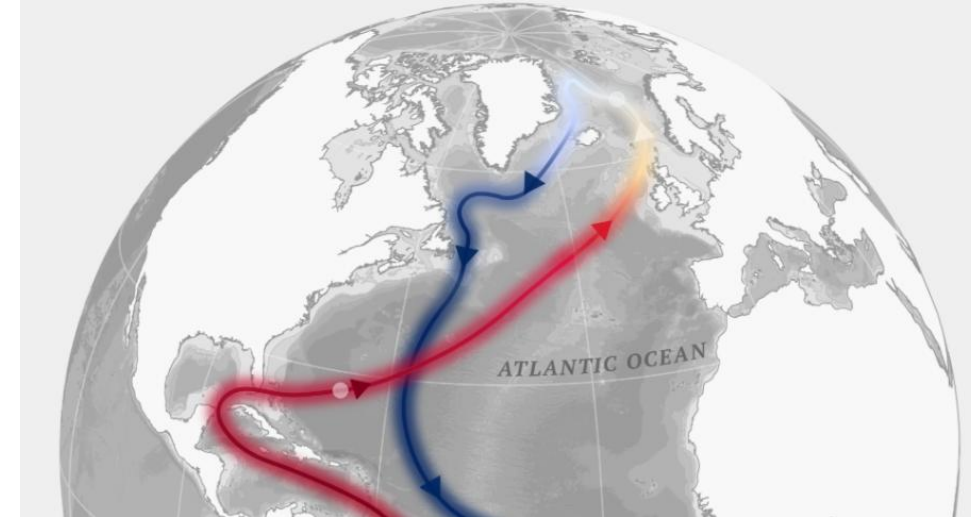
The **Atlantic Meridional Overturning Circulation (AMOC)** is density-driven flow: warm and saline surface waters lose heat as they travel north and become more dense and sink.

Europe's relatively **mild climate**, compared to regions at similar latitudes, is partly due to the AMOC.

Climate change leads to increased precipitation and meltwater forcing from the Greenland ice sheet, resulting **reduced salinity and weakening of AMOC**.

Weakening is seen in AMOC measurements (only since 2004). Climate modelling suggest a further weakening with increased warming.

IPCC says that a complete “collapse” is unlikely to occur before 2100. However, some recent studies¹ have argued that climate change could force the AMOC past a “point of no return” over the coming decades that could lead to a collapse next century.



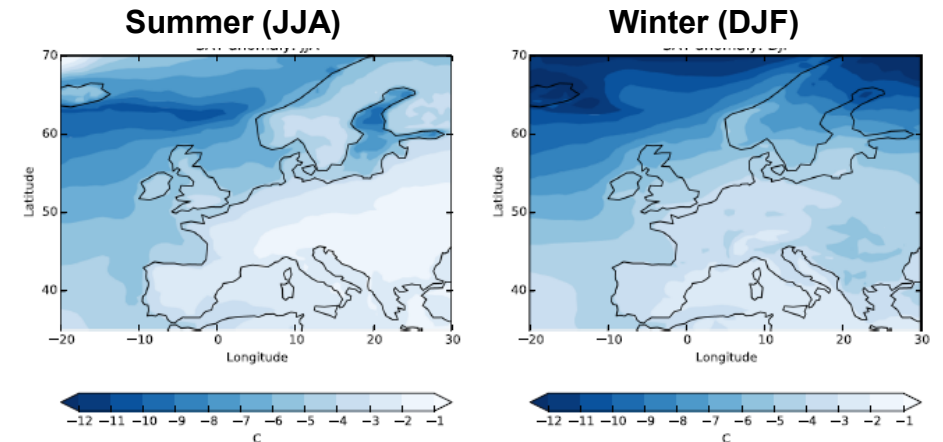
From Carbon Brief: [AMOC: Is global warming tipping key Atlantic ocean currents towards 'collapse'?](#)

Consequences of an AMOC collapse

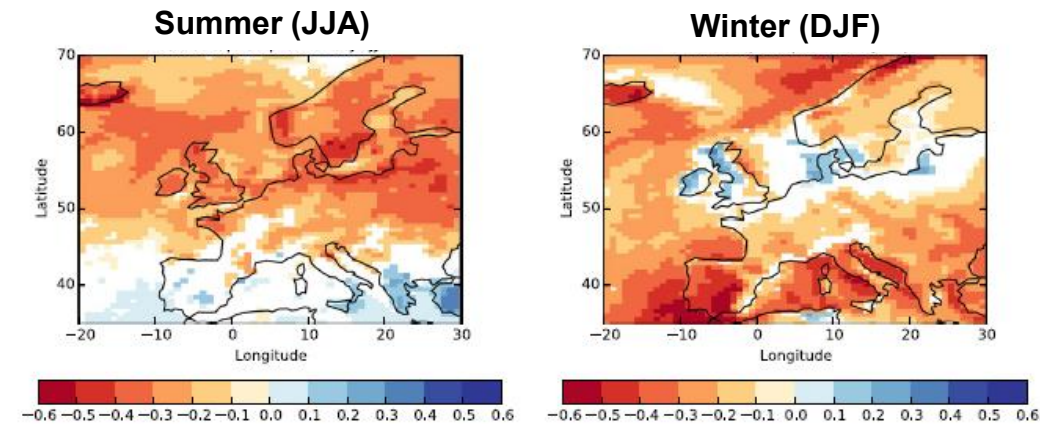
IPCC Sixth Assessment Report: “If an AMOC collapse were to occur, it would very likely cause abrupt shifts in the regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, and could result in weakening of the African and Asian monsoons, strengthening of southern hemisphere monsoons and **drying in Europe.**”

- Greatest cooling in the **winter season**, especially winter extremes can be affected (e.g. van Westen and Baatsen 2025).
- The magnitude of cooling is uncertain (model dependent).
- **For Forsmark**, the Swedish site for nuclear waste disposal, annual cooling in response to an AMOC collapse is assessed to be **2 to 6°C** (Liakka and Näslund 2025).
- Any cooling caused by an AMOC collapse will be counteracted by anthropogenic warming.
- **An AMOC collapse is projected to increased the sea level in western Europe.**

Surface air temperature anomaly



Precipitation anomaly



Jackson et al. (2015)

Beyond 2100 until 10 kyr – how warm can it become?

$$\Delta\bar{T}_s = ECS \frac{\Delta F}{\Delta F_{2xCO_2}}$$

Equilibrium Climate Sensitivity (ECS): global-mean surface air temperature increase caused by a doubling of the atmospheric CO₂ concentration.

Likely range: 2.5–4 °C (IPCC 2021)

ΔF_{2xCO_2} : increase in radiative forcing caused by a doubling of CO₂ (W m⁻²)

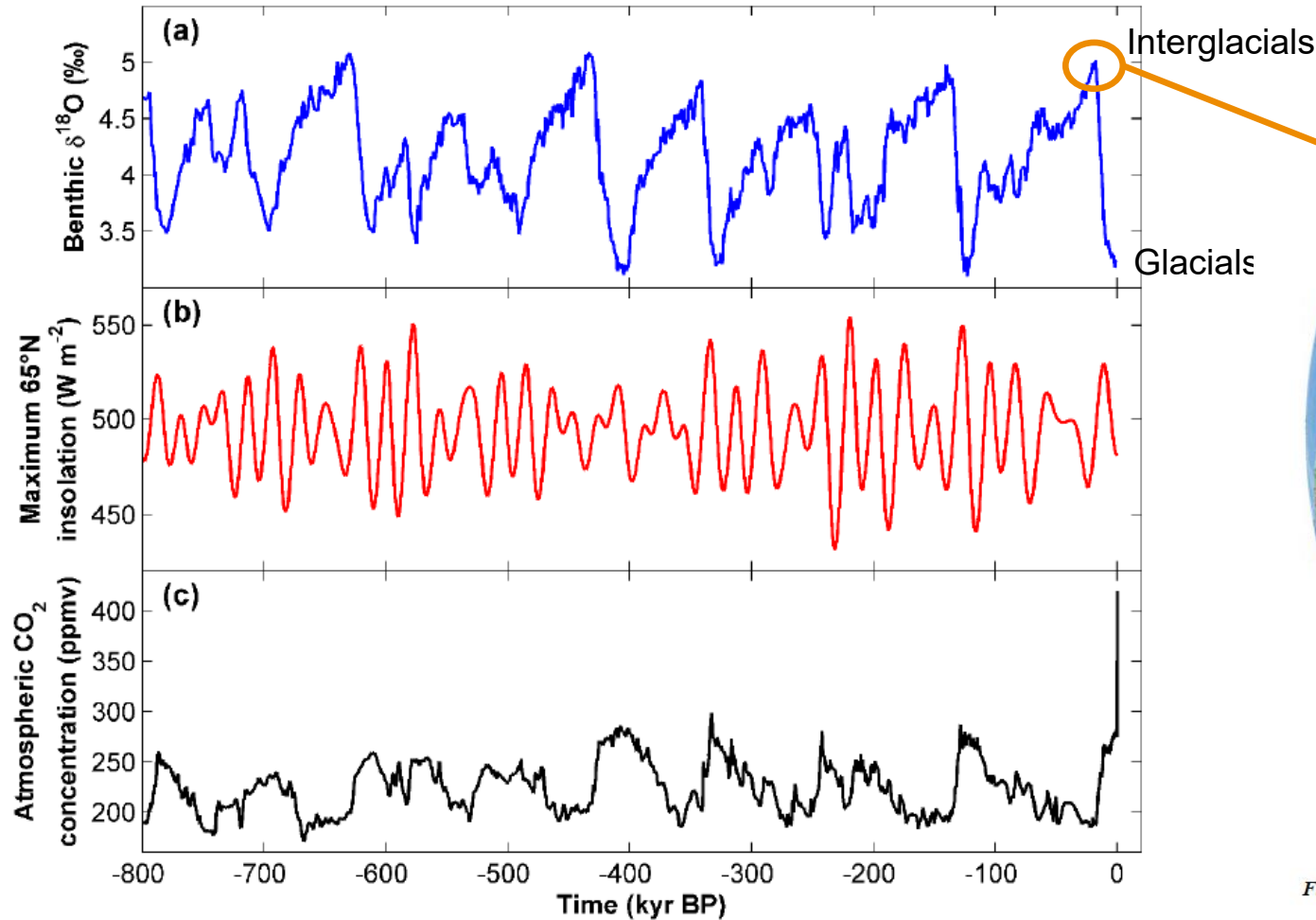
Value: 3.9 W m⁻² (Myhre et al. 1998)

ΔF : increase in radiative forcing caused by anthropogenic greenhouse-gas emissions

Scenario	Maximum warming (°C)
SSP1-2.6	0.9 [0.5 to 1.3]
SSP2-4.5	2.5 [2.0 to 3.7]
SSP3-7.0	6.8 [5.6 to 9.4]
SSP5-8.5	8.5 [7.0 to 11.7]

Beyond 10 kyr up to 1 Myr after present

... but let's first look into the past...



Last Glacial Maximum (LGM; ~20 kyr ago)

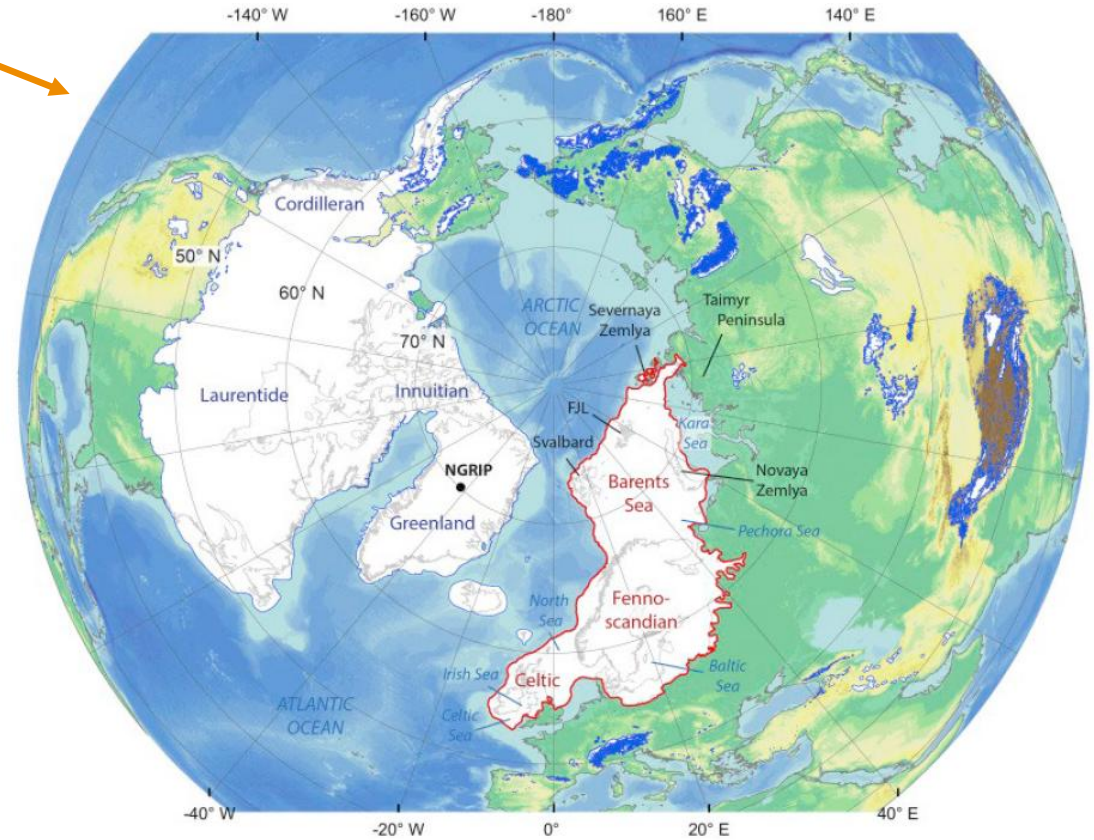
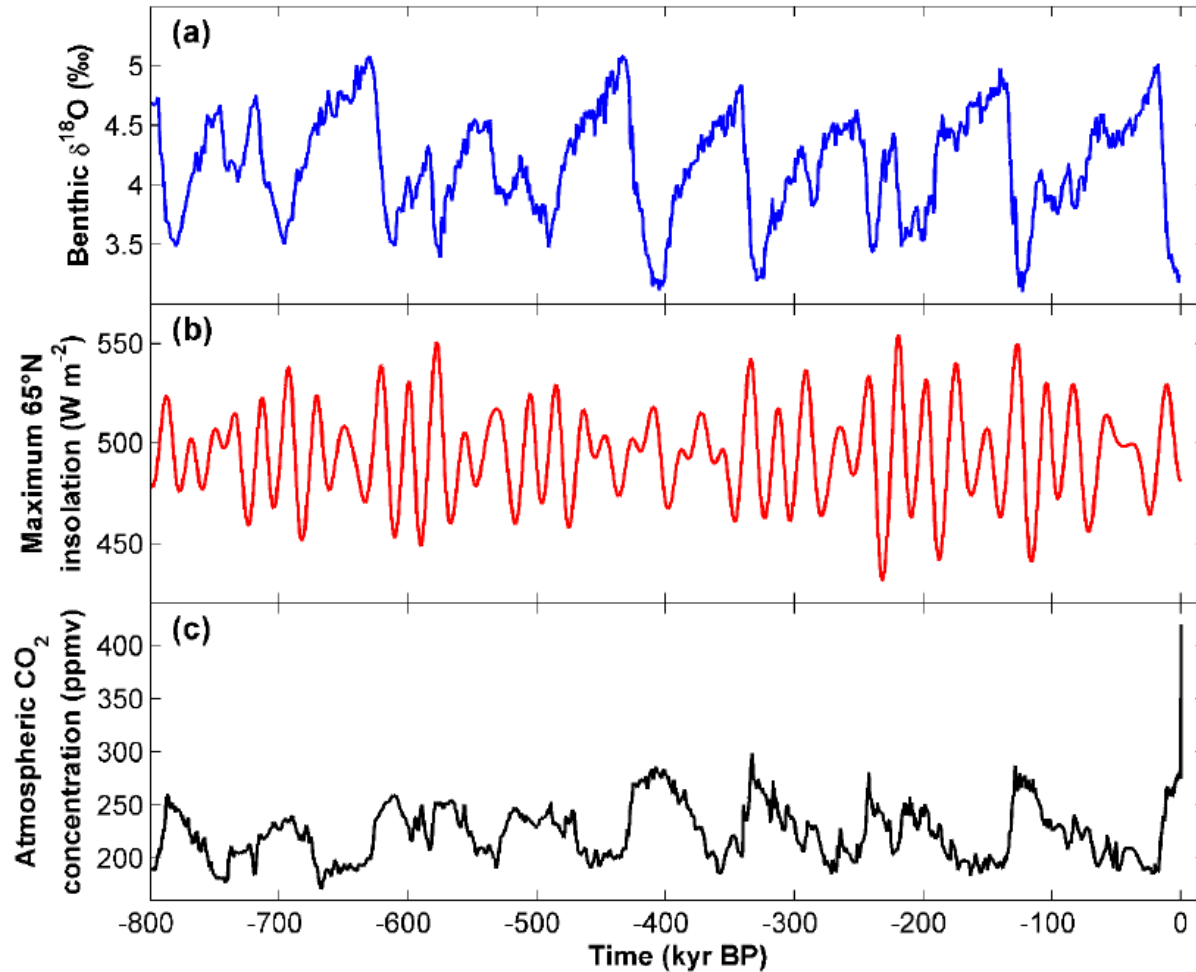


Figure 4-3. LGM Northern Hemisphere ice-sheet extent (white). From Patton et al. (2016).

Beyond 10 kyr up to 1 Myr after present

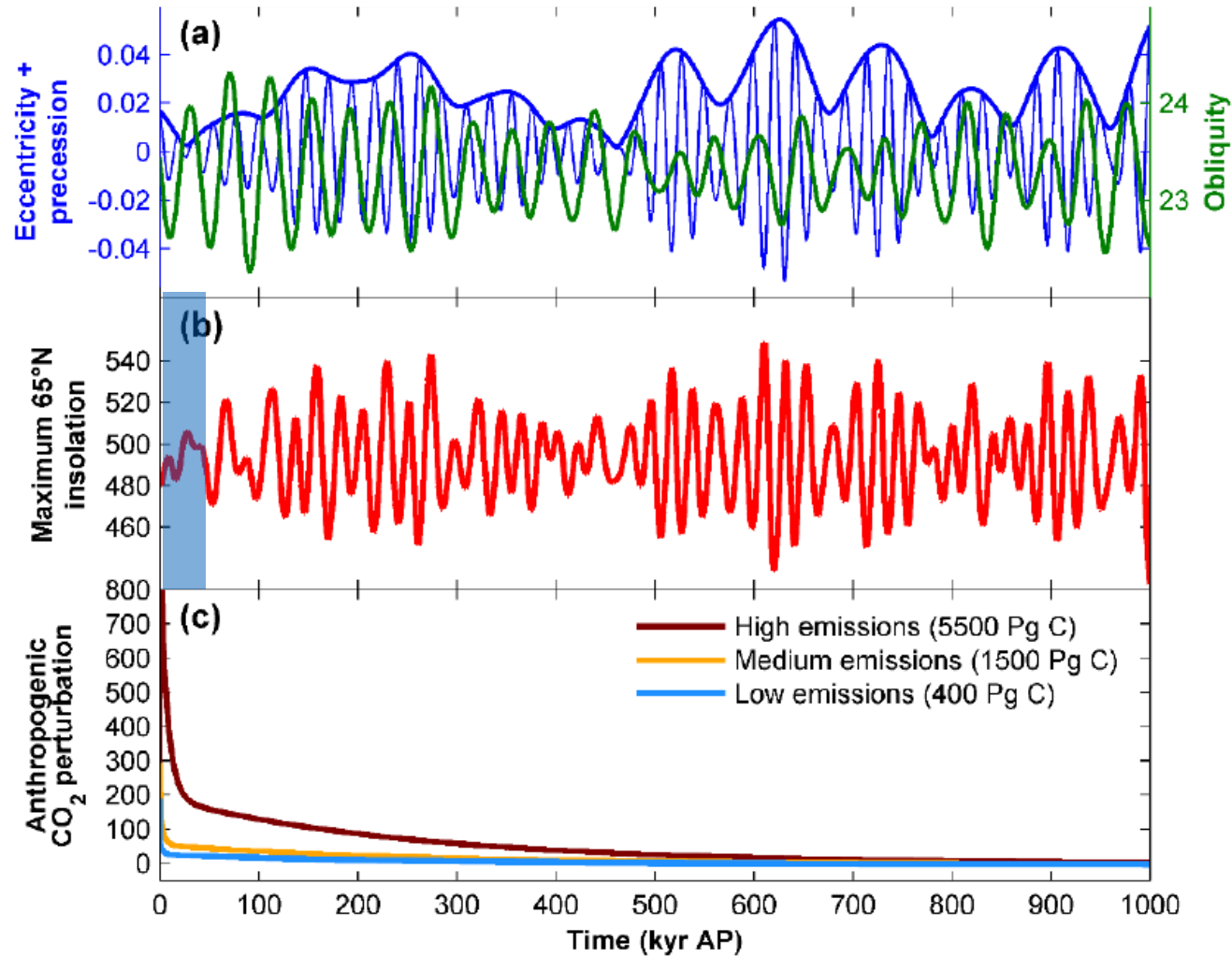
... but let's first look into the past...



Milankovitch cycles: three types of variations in Earth's orbit and orientation that influence long-term climate:

- **Eccentricity** – Changes in the shape of Earth's orbit around the Sun (from more circular to more elliptical), affecting the overall distance and energy received.
Period: ~100 kyr.
- **Obliquity** (tilt) – Changes in the angle of Earth's axis (about 22.1° – 24.5°), influencing how strongly seasons are expressed. Higher tilt = stronger seasons.
Period: ~40 kyr.
- **Precession** – The wobble of Earth's rotational axis, which alters the timing of seasons relative to Earth's position in its orbit.
Period: ~20 kyr.

Beyond 10 kyr up to 1 Myr after present

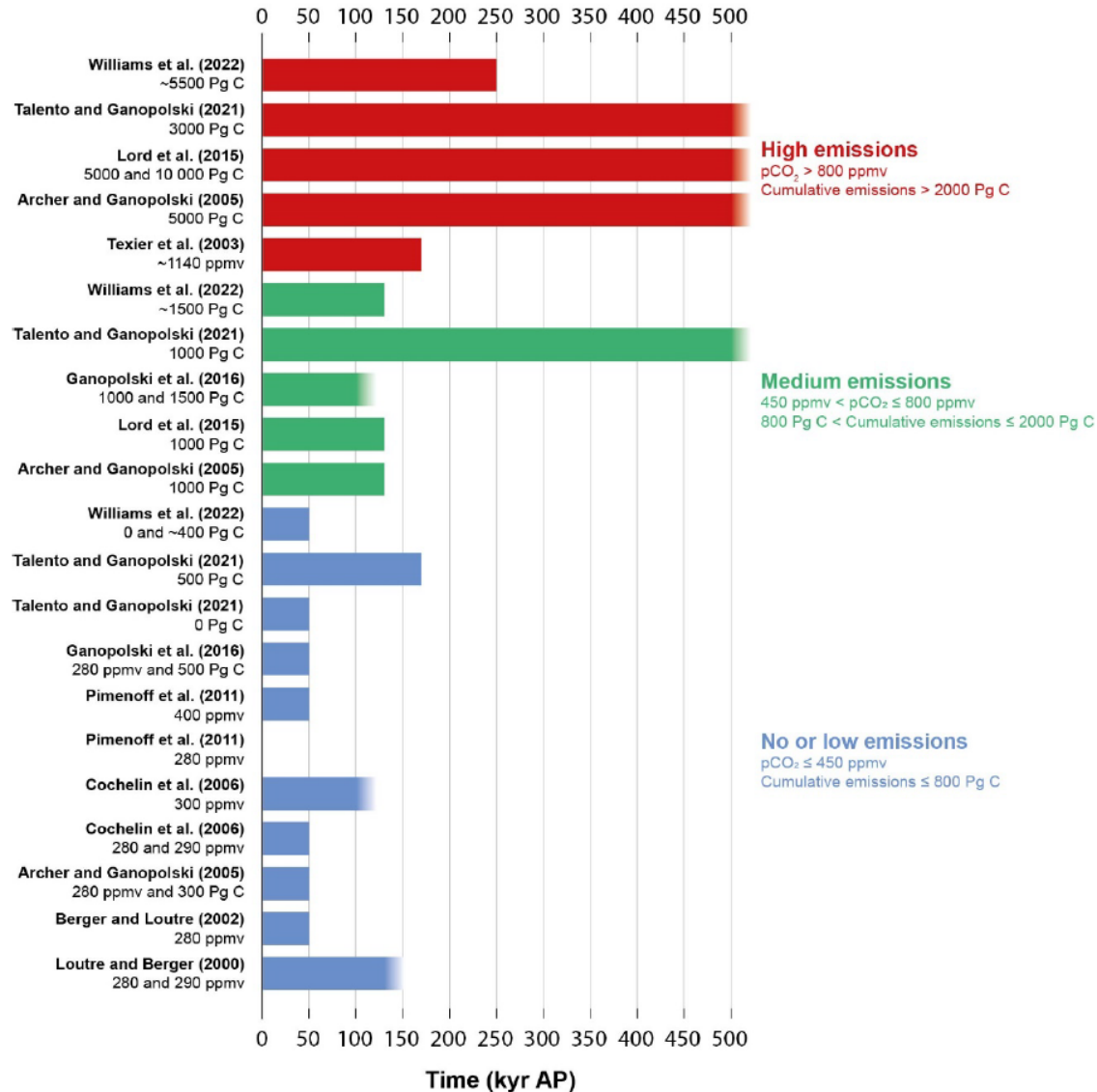


Summer insolation is currently at a **minimum**

The next 50 kyr are characterised higher summer insolation relative to present-day -> **continued interglacial conditions**

The timing of the onset of the next glacial cycle also depends on the prevailing **atmospheric CO₂ concentration**.

Beyond 10 kyr up to 1 Myr after present



- **For no or low** (~SSP1-2.6) anthropogenic emissions, the onset of the next glacial cycle occurs after **~50 kyr in most studies**
- **For medium emissions** (~SSP2-4.5), it is projected to occur after **100 kyr**.
- **For high emissions** (~SSP5-8.5): potentially delayed until **500 kyr** after present or longer.

Global to local scale...

How can we transfer information on global climate change on timescales $10^5 - 10^6$ years to local/regional change?

Hierarchy of models

General Circulation Models (GCMs)
Used by IPCC

Earth system Models of Intermediate Complexity (EMICs)
e.g. CLIMBER (see e.g. Ganopolski et al. 2016)

Global conceptual models
e.g. Paillard (1998), Liakka et al. (2024)

Reduced complexity
Reduced spatial resolution
Increased computational time

The choice of model depends on the question that you want to answer

Summary

- Climate change over the next 100 – 1000s of years will be primarily controlled by the amount anthropogenic emissions. Uncertainties are primarily associated with the amount of future emissions, (2) how will be climate respond to these emissions (output of climate models!), and (3) what happens with AMOC.
- Current interglacial is projected to prevail for at least 50 000 years into the future. The timing of the next glaciation depends on the anthropogenic emissions.
- The climate evolution following the next glaciation is associated with even larger uncertainty. For this period, the models used need to be tailored to the specific question that should to be answered.

Further reading

- [EURAD-2 - Domain Insight 4.3.2 Climate change | Eurad](#)
- SKB TR-25-07: [Climate and climate-related issues for Forsmark. State of knowledge report 2025 – SKB](#)

CLIMATE MODELLING AND SCENARIOS FOR CONSTRUCTION AND OPERATIONAL PHASES

19 May 2026 (Tue)

Jin Beak Park, WP11 Task 3 lead (VTT)



Co-funded by the European Union under Grant Agreement n° 101166718



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- (5 types) Interdependency and Cascading Risks
- (7 scenarios) Interdependency and Cascading Risks

- **Modelling Approach focusing on Facility**

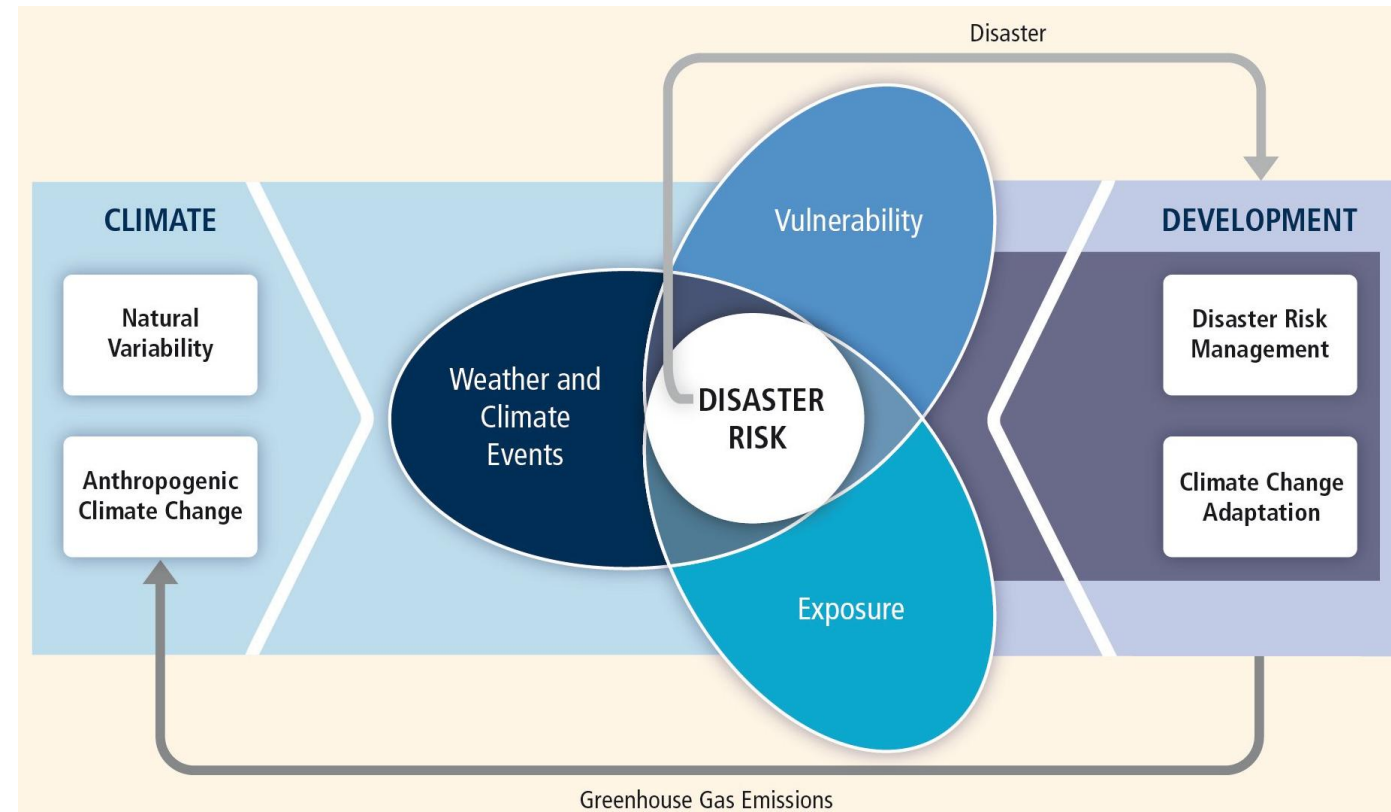
- **Synthesis and Findings : Facility-Specific Insights**

CLIMATE RISK APPROACH

$$\text{RISK} = \text{HAZARD} \times \text{EXPOSURE} \times \text{VULNERABILITY}$$

Climate risk is defined by the IPCC as a function of hazard, exposure, and vulnerability:

- **Hazard** – the potential occurrence of damaging climate-related **events** (e.g. droughts, floods, heatwaves)
- **Exposure** – the presence of people, assets, or systems that could be **affected** by these events(hazard)
- **Vulnerability** – the **sensitivity** and capacity of the exposed elements to cope with or adapt to the hazard



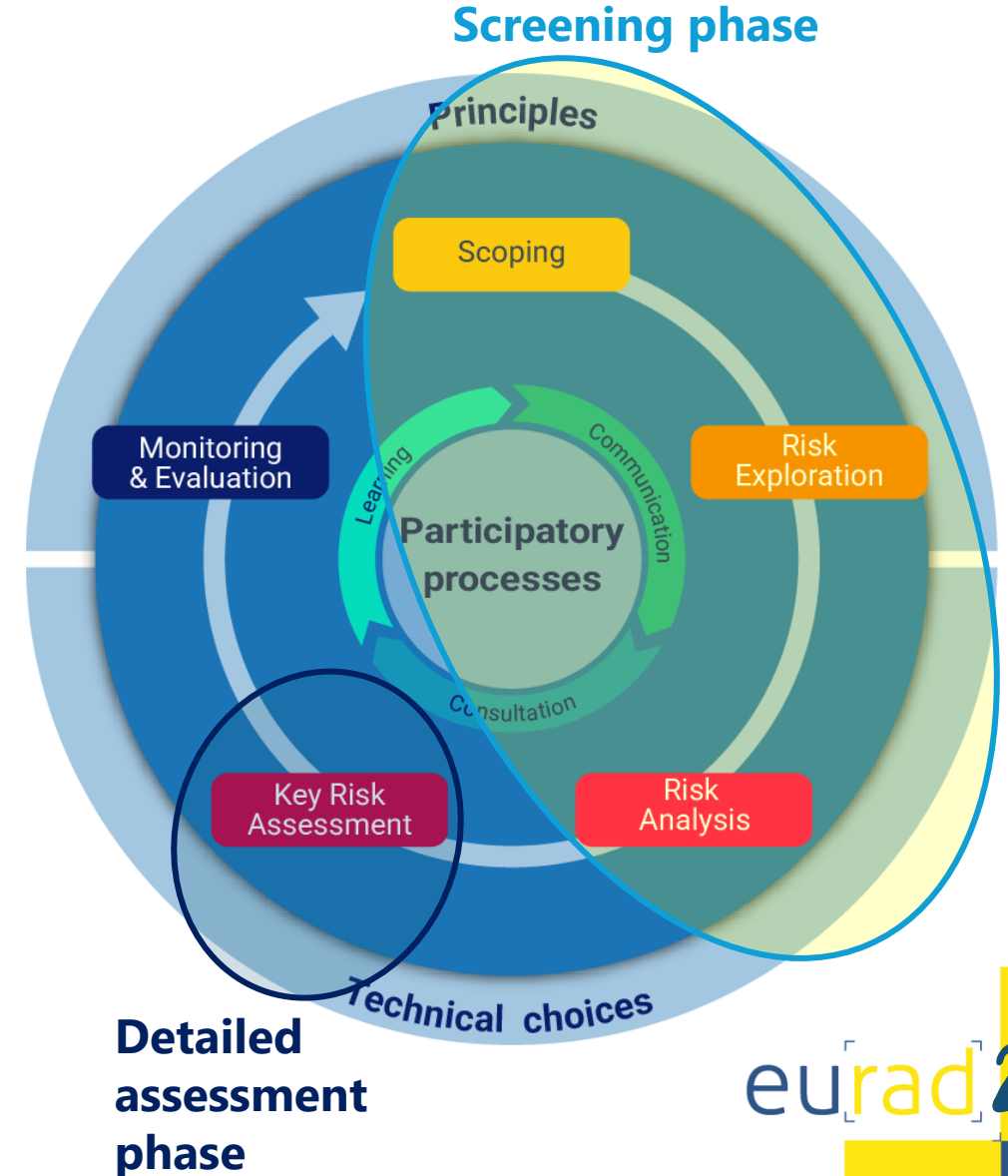
CLIMATE RISK APPROACH

This **two phase approach** is recommended by international frameworks such as IPCC AR6, ISO 14091:2021, and the CLIMAAX Methodology, as it supports evidence-based prioritisation, efficient use of resources, and clear communication of preliminary results to stakeholders and regulators.

This framework illustrates a structured approach to climate risk management, built around an **iterative** evaluation:

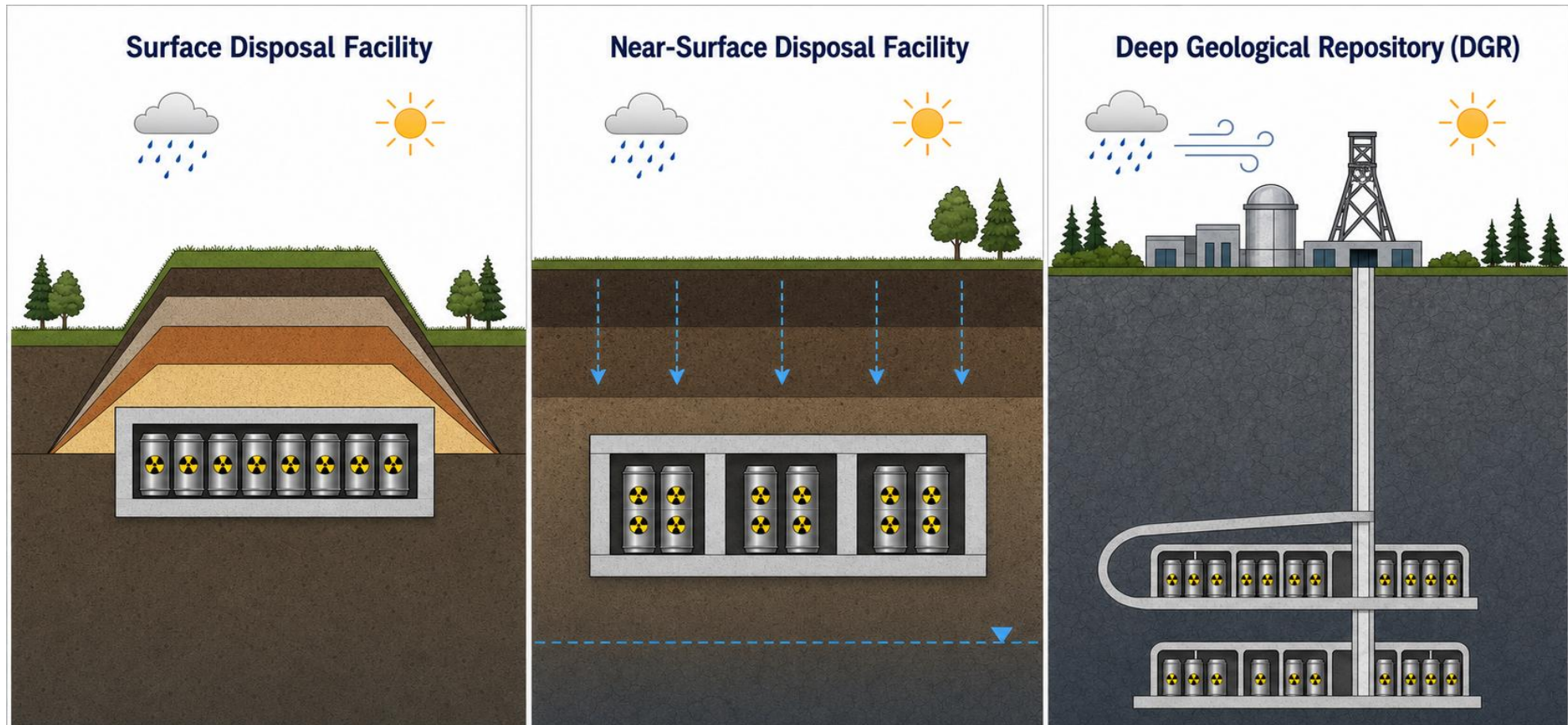
- 1. Screening phase:** identifies projected climatic changes and highlights **potential hazards** and at-risk facilities using a broad but consistent set of criteria
- 2. Detailed assessment phase:** focuses on those **identified priorities**, applying more detailed modelling and site-specific analysis.

<https://www.climaax.eu/handbook/framework/>



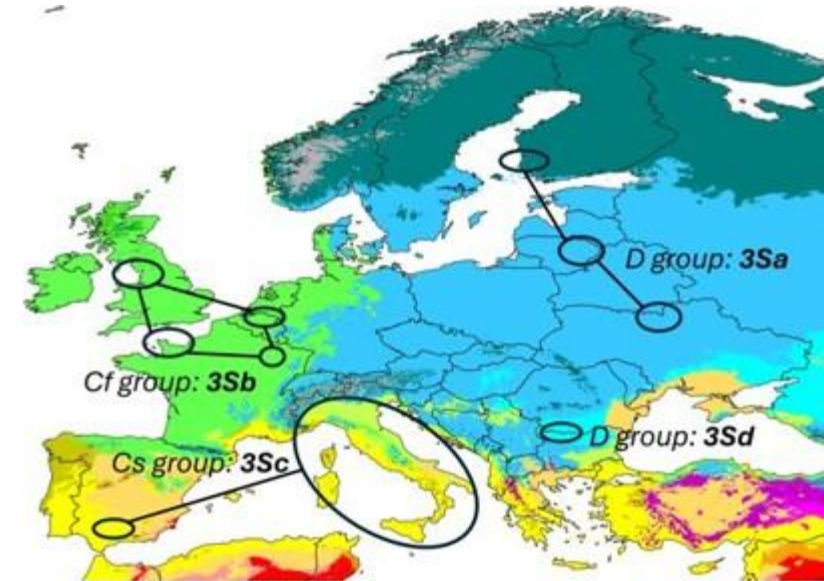
EXPOSURE TARGETS FROM CLIMATE HAZARD (ABOUT 100 YEARS AP)

- Just concepts of target facilities



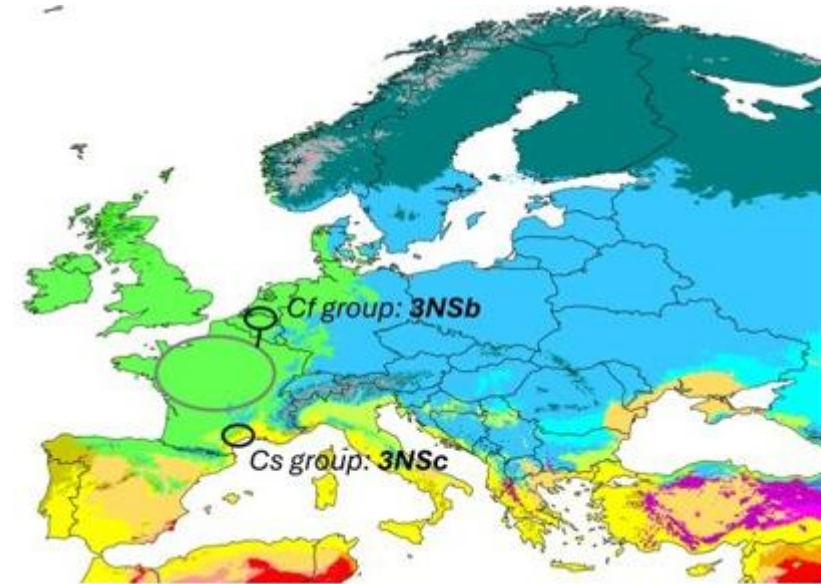
TASK 3 CLIMATE GROUP : SURFACE FACILITY

Group	Disposal type	Climate group	Countries(Facilities)	Contributors
3Sa	Surface	Dfc	Finland (Olkiluoto)	Mitta, VTT, GTK
			Lithuania (Ignalina B19, B25)	FTMC
			Ukraine (ENSDF L3)	SSTC NRS
3Sb	Surface	Cfb	Belgium (Dessel)	SCK CEN
			UK (LLWR)	NWS
			France (CSM/CSA)	Andra, ASNR, BRGM
3Sc	Surface	Cs	Spain (El Cabril)	Amphos 21
			Italy (Deposito Nazionale-site selection)	ENEA
3Sd	Surface	D	Bulgaria (Radiana)	GI-BAS, TUS



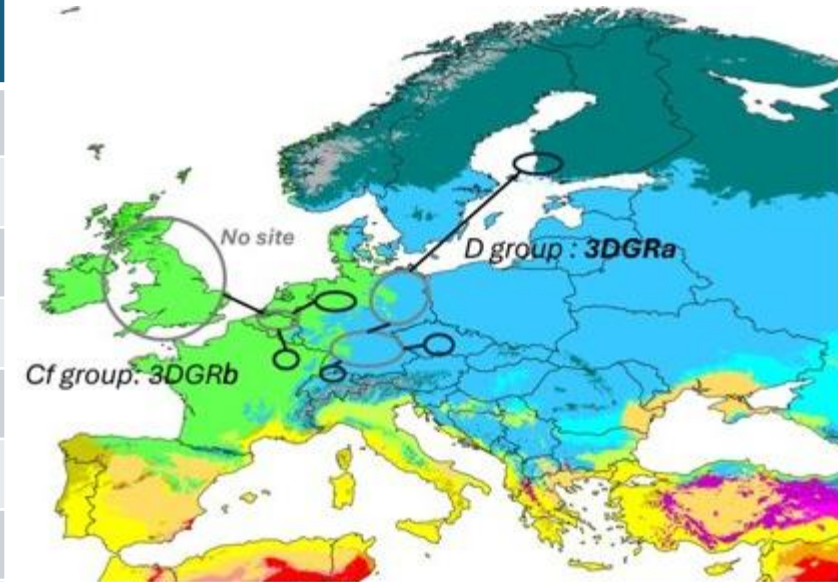
TASK 3 CLIMATE GROUP : NEAR-SURFACE FACILITY

Group	Disposal type	Climate group	Countries	Contributors
3NSb	Near-surface	Cfb	Belgium (Olen)	SCK CEN
			France (FAVL-site selection)	Andra, ASNR, BRGM
3NSc	Near-surface	Cs	France (Malvesi)	Andra, ASNR, BRGM



TASK 3 CLIMATE GROUP : DGR FACILITY

Group	Disposal type	Climate group	Countries(Facilities)	Contributors
3DGRa	Deep Geological	Dfb	Finland (Onkalo)	Mitta, VTT, GTK
		Cfb, Dfb	Germany (No site)	BGE, GRS
		Dfb, Dfb	Czechia (Czechia (Dunaj))	SÚRAO, TUL
		Cfb, Cfa	Switzerland (Nördlich Lägern)	Nagra
3DGRb	Deep Geological	Cfb	Germany (Konrad)	BGE, GRS
			UK (No site)	NWS
			Belgium (No site)	SCK CEN
			France(Cigeo)	Andra, ASN, BRGM



CLIMATE SCENARIOS OF TASK 3 GROUP : SUMMARY

- 15 Primary climate hazards vs. 8 climate groups (●-Both Screening & Detailed phase, ○-Screening phase only)

Hazard	3Sa	3Sb	3Sc	3Sd	3NSb	3NSc	3DGRa	3DGRb
1. Heavy Rainfall	●	●	●	●	●	●	●	●
2. Flash Flooding	●	○	●		●	●	○	○
3. River Flooding	●	●	○		●	●	○	○
4. Coastal Flooding	●	●				○	●	○
5. Sea Level Rise	●	●			○	○	●	
6. Heat Waves	●	●	●	●	●		●	●
7. Cold Spells	○	○					○	○
8. Droughts	○	○	○	○	○	○	●	●
9. Windstorms	●	●	○	●	○		○	○
10. Soil Erosion	●	○	●	●	○	●		
11. Water Table Variations	●	●	●		●	○	○	●
12. Desertification			○					
13. Wildfires		●	●			○	○	
14. Permafrost Thaw							●	
15. Landslides	○						○	○

(5 TYPES) INTERDEPENDENCY AND CASCADING RISKS

1.Sequential Cascades

2.Compound Events

3.Infrastructure Cascades

4.Temporal Accumulation

5.Spatial Propagation

1. Sequential Cascades

- May involve primary hazards triggering secondary and tertiary effects through cause-and-effect chains.
 - Heavy rainfall → flash floods → soil erosion → degradation of protective covers → increased infiltration potential → groundwater table rise → ultimately affecting engineered barrier integrity.
 - This cascade develops over timescales ranging from hours (flooding) to decades (barrier degradation).

2. Compound Events

- Can occur when multiple hazards coincide temporally, producing impacts exceeding the sum of individual hazards.
 - Coastal storm surge coinciding with extreme precipitation and high tide creates compound flooding with dramatically higher inundation than any single event.
 - Drought combined with heat waves overwhelms cooling systems while simultaneously reducing water availability for emergency response.
 - Winter storms, combining extreme wind, heavy snow, and freezing temperatures, stress multiple facility systems concurrently.

(5 TYPES) INTERDEPENDENCY AND CASCADING RISKS

1.Sequential Cascades

2.Compound Events

3.Infrastructure Cascades

4.Temporal Accumulation

5.Spatial Propagation

3. Infrastructure Cascades

- propagate through interconnected waste management facility and systems.
 - Windstorm damages to power distribution causes HVAC failure during heat wave climate conditions, resulting in worker safety risks and operational shutdown.
 - Flooding of drainage systems leads to surface water intrusion, causing humidity control loss, accelerating corrosion of containment function and systems.
 - These cascades demonstrate the vulnerability of technical systems to climate-driven perturbations.

4. Temporal Accumulation

- involves repeated modest-intensity events causing cumulative degradation exceeding the effects of a single extreme event.
 - Seasonal freeze-thaw cycling progressively fractures concrete structures, creating infiltration pathways.
 - Repeated drought-rewetting cycles degrade clay barrier plasticity and swelling capacity.
 - This temporal accumulation challenges traditional design approaches based on single extreme event scenarios.

(5 TYPES) INTERDEPENDENCY AND CASCADING RISKS

1.Sequential Cascades

2.Compound Events

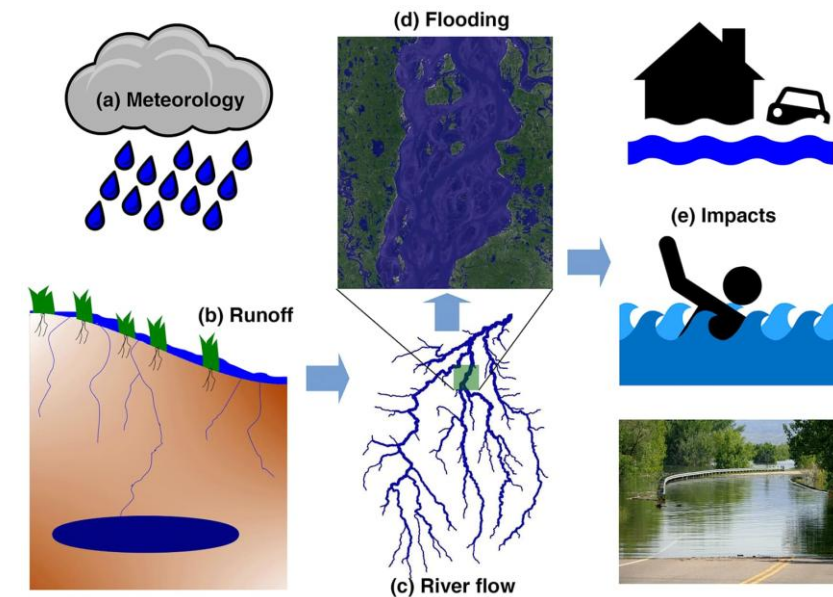
3.Infrastructure Cascades

4.Temporal Accumulation

5.Spatial Propagation

5. Spatial Propagation

- Can transmit climate impacts through environmental pathways beyond the immediate facility footprint.
 - Upstream watershed changes can alter downstream flood characteristics at the facility location.
 - Regional groundwater depletion can modify local hydrogeological conditions.
 - This spatial propagation requires assessment beyond facility boundaries to watershed and regional scales.





(7 SCENARIOS) INTERDEPENDENCY AND CASCADING RISKS

- 1. Drought-Heat Wave Compounds**
- 2. Coastal Storm Surge with Extreme Precipitation and High Tide**
- 3. Heavy Precipitation on Frozen or Saturated Ground**
- 4. Windstorm with Power Outage During Heat Wave**
- 5. Pluvial-Fluvial Compound Flooding**
- 6. Fire-Drought-Heat Compound**
- 7. Winter Storm with Ice Accumulation and Power Loss**

(7 SCENARIOS) INTERDEPENDENCY AND CASCADING RISKS

1. Drought-Heat Wave Compounds

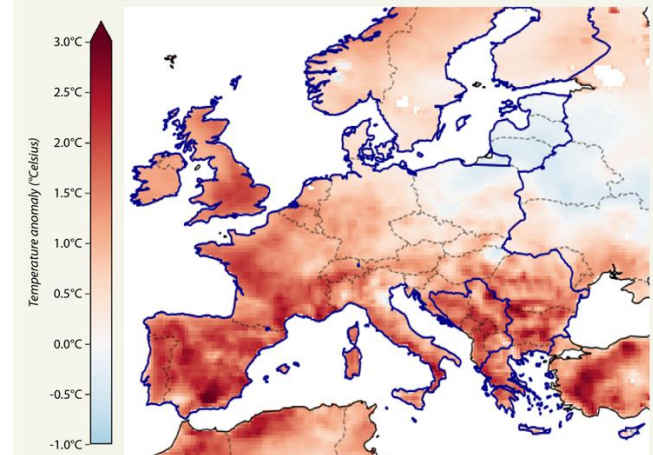
- The simultaneous occurrence of prolonged drought periods with extreme heat waves can create severe operational challenges through multiple pathways.
 - Limited water availability reduces cooling system capacity precisely when cooling demands are at their peak.
 - Drought-stressed vegetation fails to provide evapotranspiration cooling, worsening heat island effects at disposal facility sites.
 - Soil moisture deficits can increase dust generation, impacting air quality and equipment, while allowing deeper heat penetration that affects underground structures.
 - This combination particularly impacts facilities with substantial cooling needs.
- The historical analogue of the 2003 European heatwave
 - Combined with severe drought, this analogue demonstrates cascading failures in facility cooling systems, agricultural water supply, and ecosystem services.
 - Projections indicate increasing co-occurrence probability of drought and heat under climate change, requiring integrated assessment and adaptation strategies.



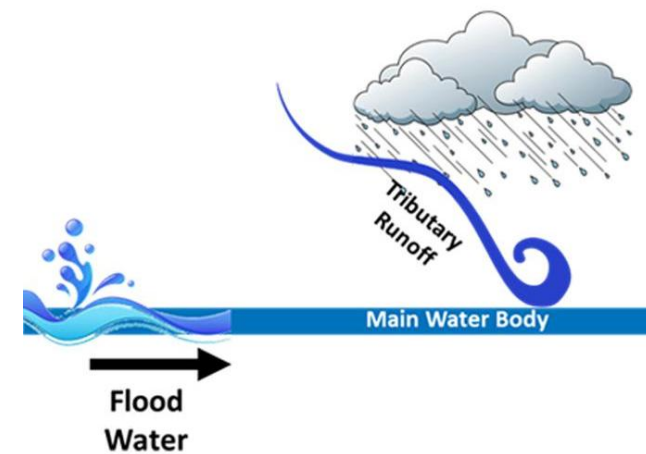
Europe Endures Fourth Hottest Summer on Record

Scientists analyzed climate models and health records to estimate that 68 percent of 24,400 heatwave deaths in the summer of 2025 in 854 European cities can be attributed to human-caused warming, primarily sparked by burning oil, gas and coal, as well as deforestation. In Northern Europe, their report showed, nearly all of the heatwave deaths were attributable to human-caused warming.

EUROPEAN TEMPERATURE ANOMALY—SUMMER 2025
In degrees Celsius, deviation from 1990-2020 average temps, June-Aug, 2025



(7 SCENARIOS) INTERDEPENDENCY AND CASCADING RISKS



2. Coastal Storm Surge with Extreme Precipitation and High Tide

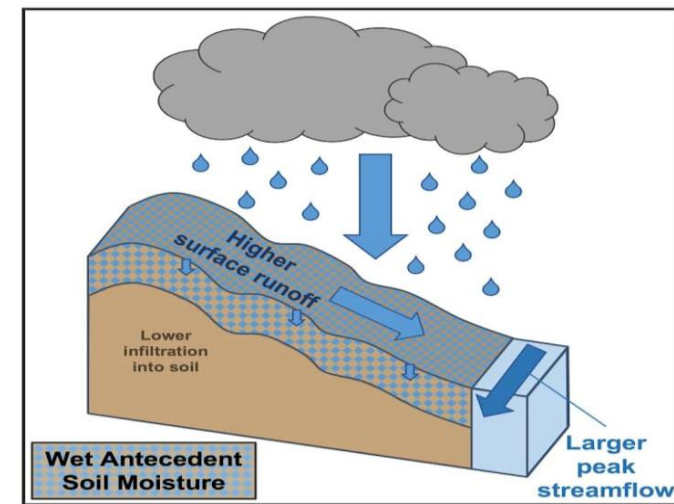
- Compound coastal flooding can combine multiple drivers:
 - Astronomical high tide provides an elevated baseline water level, storm surge from low-pressure systems and wind stress can raise water levels further,
 - Extreme precipitation overwhelms inland drainage systems, preventing discharge, and wave action can add dynamic overtopping and impacts.
- The timing coincidence of these factors can create a flood severity that dramatically exceeds any individual component.
 - This compound can critically affect coastal facilities.
- Climate change can increase compound coastal flooding risk through multiple mechanisms:
 - Sea level rise can elevate the baseline for all components, a potential increase in storm intensity enhances surge,
 - Intensified precipitation can increase inland runoff contribution, and modified storm tracks may alter timing relationships.



(7 SCENARIOS) INTERDEPENDENCY AND CASCADING RISKS

3. Heavy Precipitation on Frozen or Saturated Ground

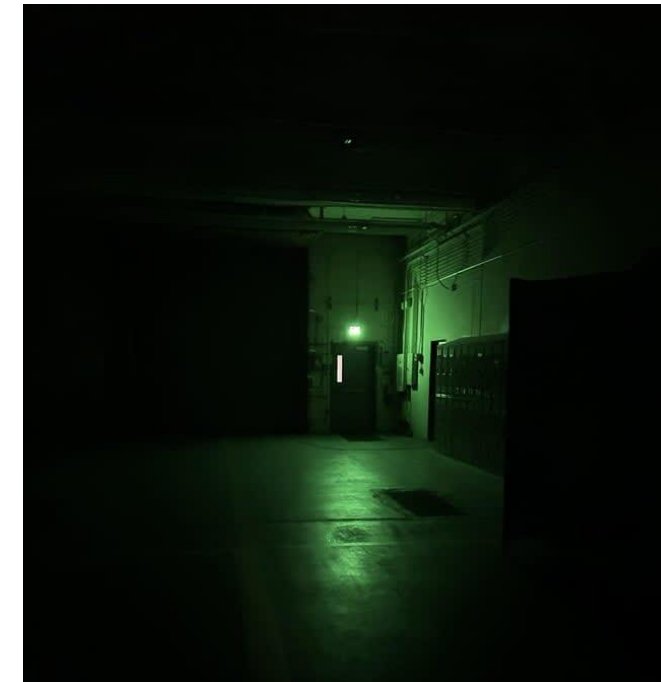
- Heavy rainfall occurring on frozen ground during the winter-spring transition, or on already saturated soils following antecedent precipitation, can produce rapid runoff with minimal infiltration.
 - Frozen or saturated soils can prevent precipitation storage, concentrating the entire rainfall into immediate surface flow.
 - This compound can create flash flooding, exceeding expectations based on precipitation intensity alone.
 - Particular concern exists for facilities experiencing freeze-thaw transitions.
- Climate change can modify this compound through altered freeze-thaw timing,
 - Increased likelihood of rain-on-snow events (more winter precipitation) falls as rain rather than snow, and potential for higher-intensity precipitation events during transitional seasons.



(7 SCENARIOS) INTERDEPENDENCY AND CASCADING RISKS

4. Windstorm with Power Outage During Heat Wave

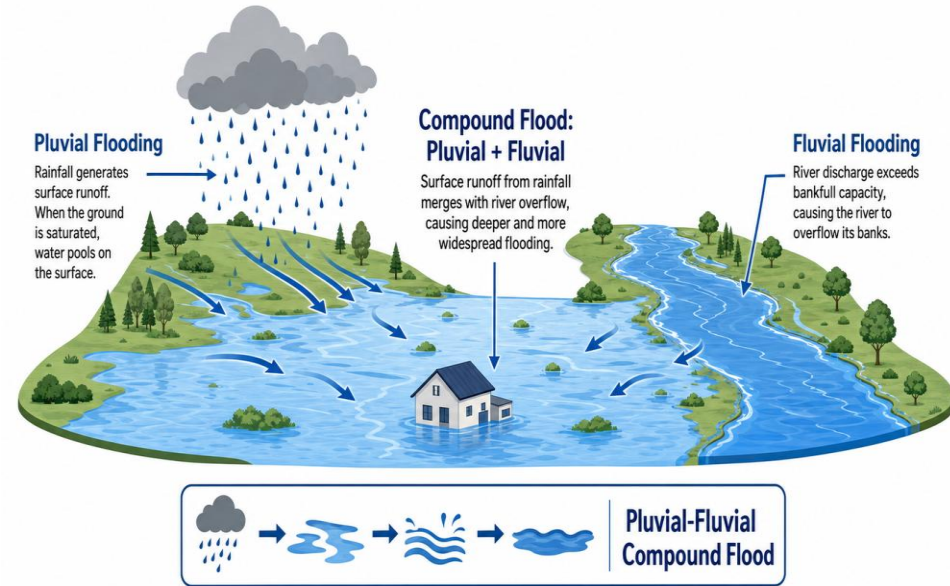
- Severe windstorms damaging electrical distribution infrastructure can cause extended power outages coinciding with heat wave conditions
 - It can create compounding risks to facility operations and worker safety.
 - Loss of powered cooling and ventilation during extreme heat leads to rapid internal temperature rise, potential equipment failure, and hazardous working conditions.
 - Emergency power systems can face maximum stress when most critical.
 - This compound can affect all climate groups but particularly those with substantial heat loads.
- Adaptation measures for this compound require redundant cooling systems
 - Enhanced emergency power capacity and fuel reserves, passive cooling design reducing powered cooling dependency, and
 - Operational procedures for safe facility evacuation (minimal staffing during compound events).



(7 SCENARIOS) INTERDEPENDENCY AND CASCADING RISKS

5. Pluvial-Fluvial Compound Flooding

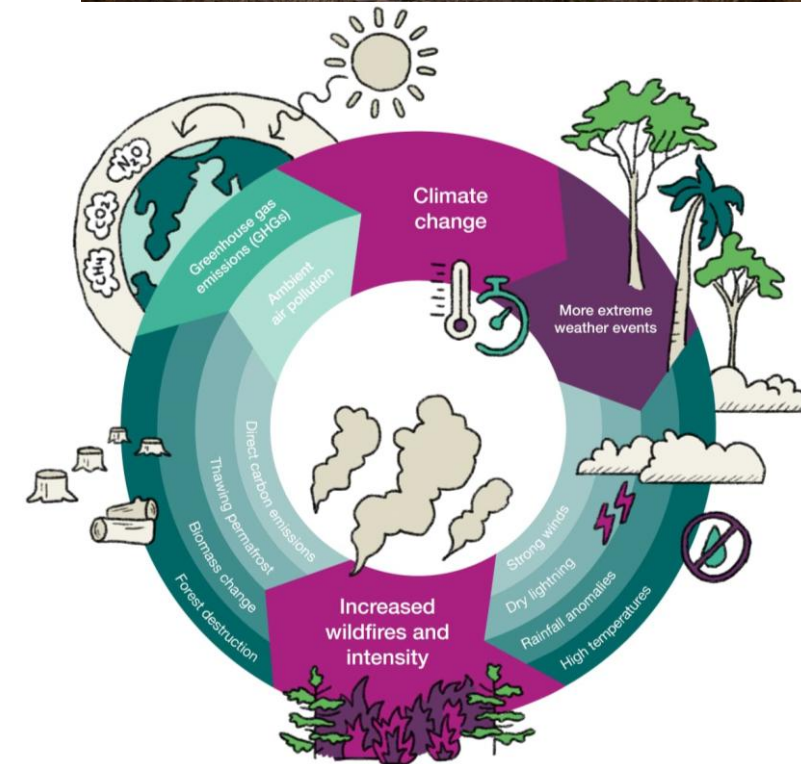
- Compound flooding can occur when intense local precipitation (pluvial flooding) coincides with high river water levels (fluvial flooding)
 - Can create backwater effects preventing drainage system discharge.
 - Urban and developed areas can experience particularly severe impacts as storm drainage systems become surcharged and reverse-flow, causing widespread surface flooding.
 - Facilities in river valleys can face this compound risk.
- Climate change can amplify the combined impact of rain and river floods by:
 - Increasing extreme rainfall which leads to higher runoff, altering river discharge patterns with rising peak flows, and
 - Possibly expanding the area affected by storms, raising the chances of precipitation events coinciding at local and watershed levels.



(7 SCENARIOS) INTERDEPENDENCY AND CASCADING RISKS

6. Fire-Drought-Heat Compound

- In Mediterranean and continental climate, facilities can face compound wildfire risks.
 - Where prolonged drought can dehydrate vegetation, extreme heat can lower ignition thresholds and can speeds up fire spread, and windstorms facilitate fire dissemination.
 - Post-fire conditions can create secondary hazards such as loss of erosion control, hydrophobic soils that change infiltration and runoff, and increased debris flow risk.
- This compound can exhibit strong positive feedback:
 - Drought-stressed vegetation can become more flammable, heat can accelerate vegetation water stress, fire can remove vegetation, increasing drought sensitivity of residual plants, and bare soil can experience the enhanced heating.



(7 SCENARIOS) INTERDEPENDENCY AND CASCADING RISKS

7. Winter Storm with Ice Accumulation and Power Loss

- Compound winter storms combining freezing rain,
 - Causing ice accumulation on infrastructure, strong winds stressing ice-laden structures, and power outages from transmission line failures can create severe operational challenges for northern facilities.
 - Ice loading exceeding structural design limits can risks collapse of overhead structures, loss of power can prevent active heating, causing facility freeze-up, and emergency response access becomes limited.
- Climate change can affect on this compound show greater uncertainty,
 - Some projections suggest the decreased ice storm frequency in warming climates, while others indicate potential increases in transitional seasons when temperatures fluctuate around freezing.





MODELLING APPROACHES FOCUSING ON FACILITY

- 1. Heavy Rainfall and Drainage Performance (including Example)**
- 2. Heat Waves and HVAC Reliability**
- 3. Drought Impacts on Water Supply and Cooling**
- 4. River and Coastal Flooding**
- 5. Water Table Variations and Barrier Performance**
- 6. Soil Erosion and Cover Degradation**
- 7. Coastal Sea Level Rise and Storm Surge**

MODELLING APPROACHES FOCUSING ON FACILITY

1. Heavy Rainfall and Drainage Performance

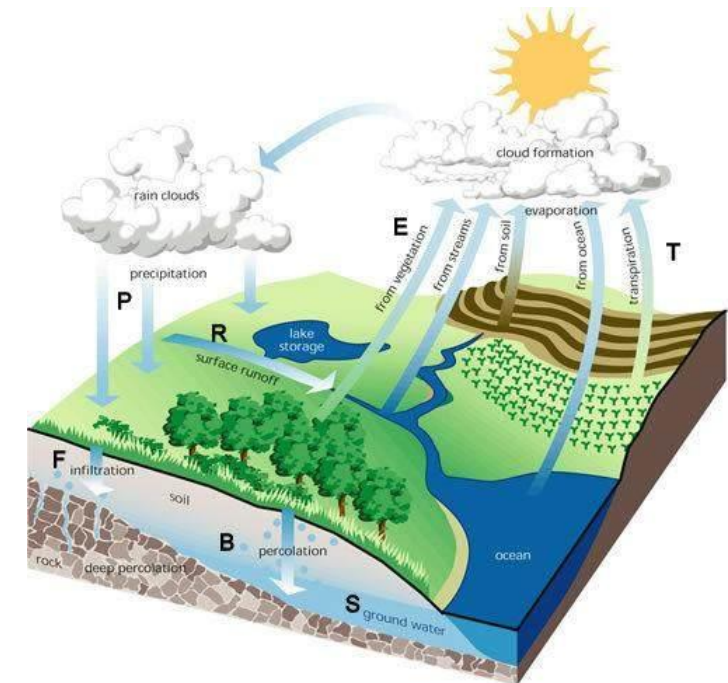
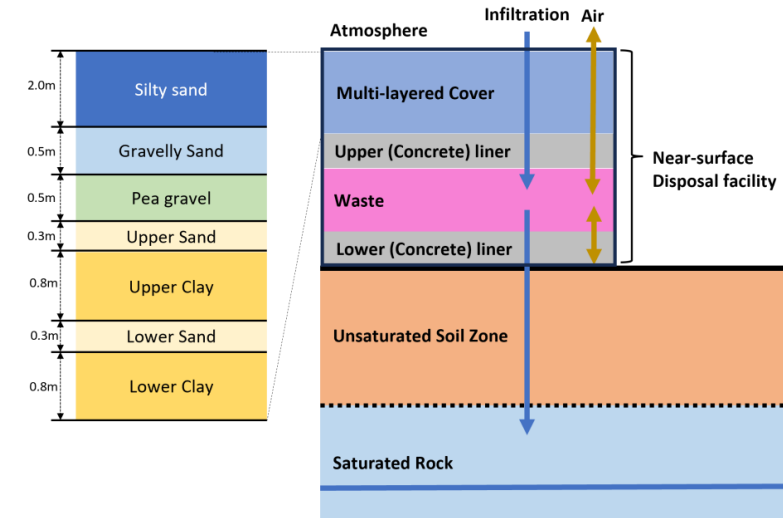
- Task groups typically select heavy rainfall for detailed evaluation,
 - Employing high-resolution hydrological modelling, hydraulic analysis of drainage systems, and assessments of infrastructure vulnerability.
- Facilities designed according to historical data are:
 - Expected to face exceedance probability increases by the end of the century under high-emission scenarios.
 - Drainage infrastructure generally does not incorporate design margins sufficient to address these predicted increases.
- Key concerns include:
 - Surface water ponding at facilities beyond their design capacity,
 - Infiltration through covers into disposal cells which may mobilize contaminants, and
 - Erosion affecting cover structures and layered protective barriers.

EXAMPLE : HEAVY RAINFALL OVER THE DISPOSAL COVER

- How does changing-rainfall under different climate scenarios affect the rate of water infiltration through the cover?
- What does that mean for long-term radionuclide transport and potential radiation dose?
- Rainfall(P) comes in, part(Q) runs off, part(ET) returns to the atmosphere, and the remainder(F) infiltrates through the cover into the disposal facility

$$F = P - Q - ET \approx P - Q$$

- F = infiltration through cover into disposal cell (mm/yr)
- P = rainfall precipitation (mm/yr)
- Q = surface runoff (mm/yr)
- ET = evapotranspiration (mm/yr)
- **Assumption :**
 - Rainfall(P) is significant enough that infiltration(F) consistently exceeds evapotranspiration (ET), which can be disregarded in the context of the impact of annual rainfall



EXAMPLE : HEAVY RAINFALL OVER THE DISPOSAL COVER

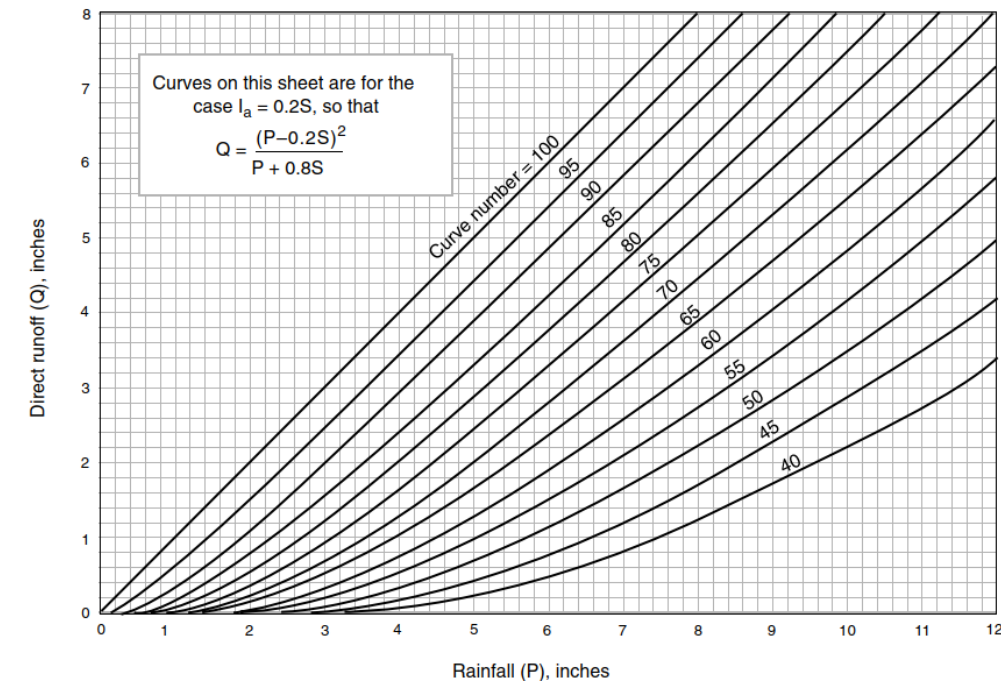
- **If so, how much rainfall(P) can be run off(Q) amounts?**
 - Run off curve number (CN) method (USDA 1986)

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

- Where, S is the potential maximum retention after runoff begins and,
- **S can be represented by runoff Curve Number (CN) that is determined based on soil properties and conditions.**

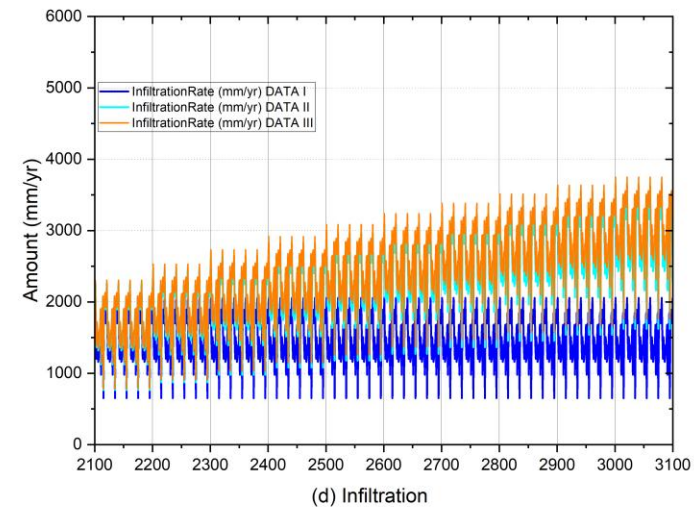
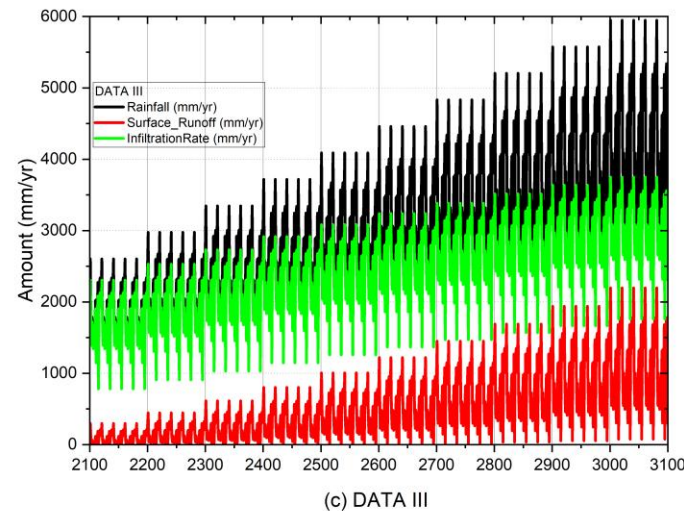
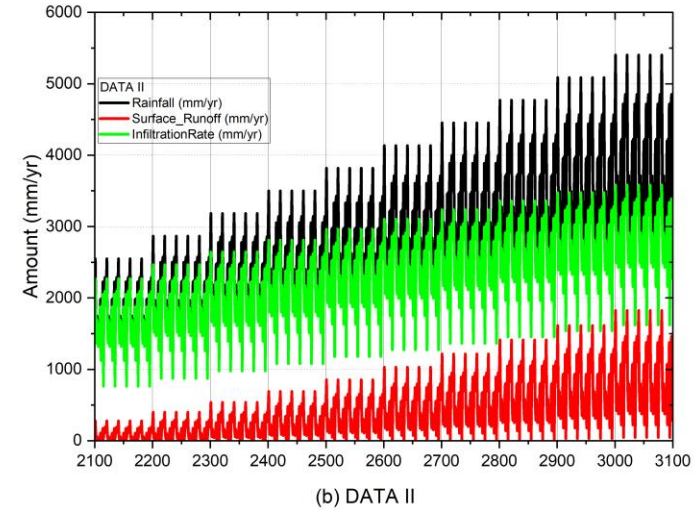
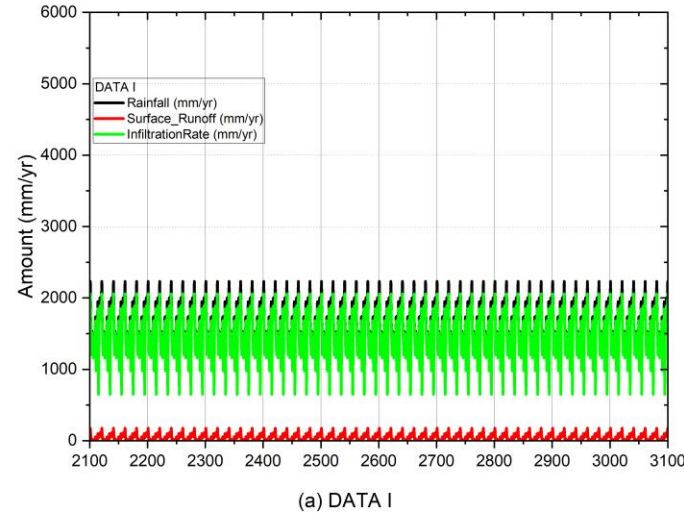
$$S = \frac{1000}{CN} - 10$$

Figure 2-1 Solution of runoff equation.

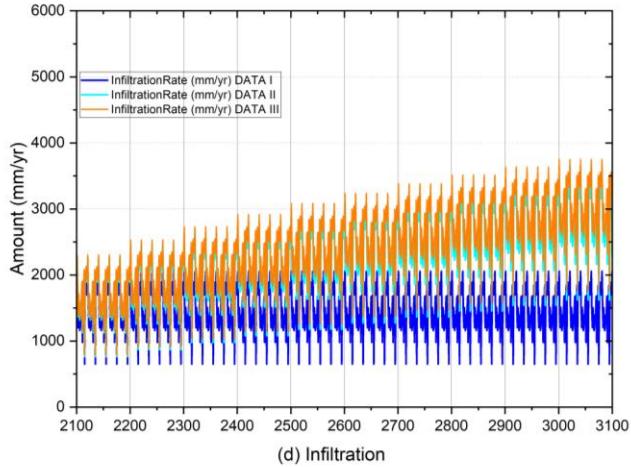


EXAMPLE : HEAVY RAINFALL OVER THE DISPOSAL COVER

- **Set of Rainfall cases : (a), (b) and (c)**
 - DATA I : historical average annual rainfall during 1,000 years
 - DATA II : 14.2% increase of every 100 years of annual rainfall during 1,000 years (SSP2-4.5)
 - DATA III : 16.6% increase of every 100 years of annual rainfall during 1,000 years (SSP5-8.5)
- **Set of infiltration cases : (d)**
 - Infiltration rates (mm/yr) as the boundary condition over the disposal cover for water infiltration and transport calculation



EXAMPLE : HEAVY RAINFALL OVER THE DISPOSAL COVER

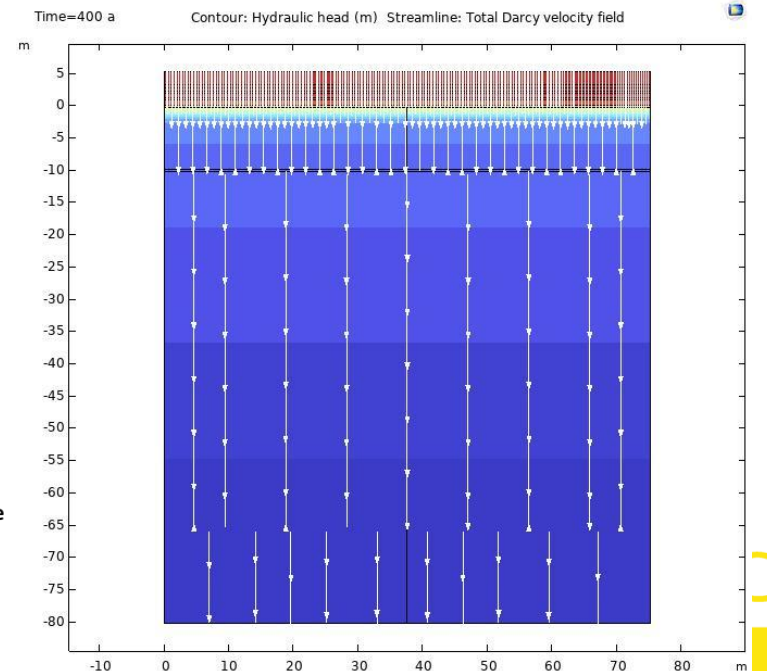
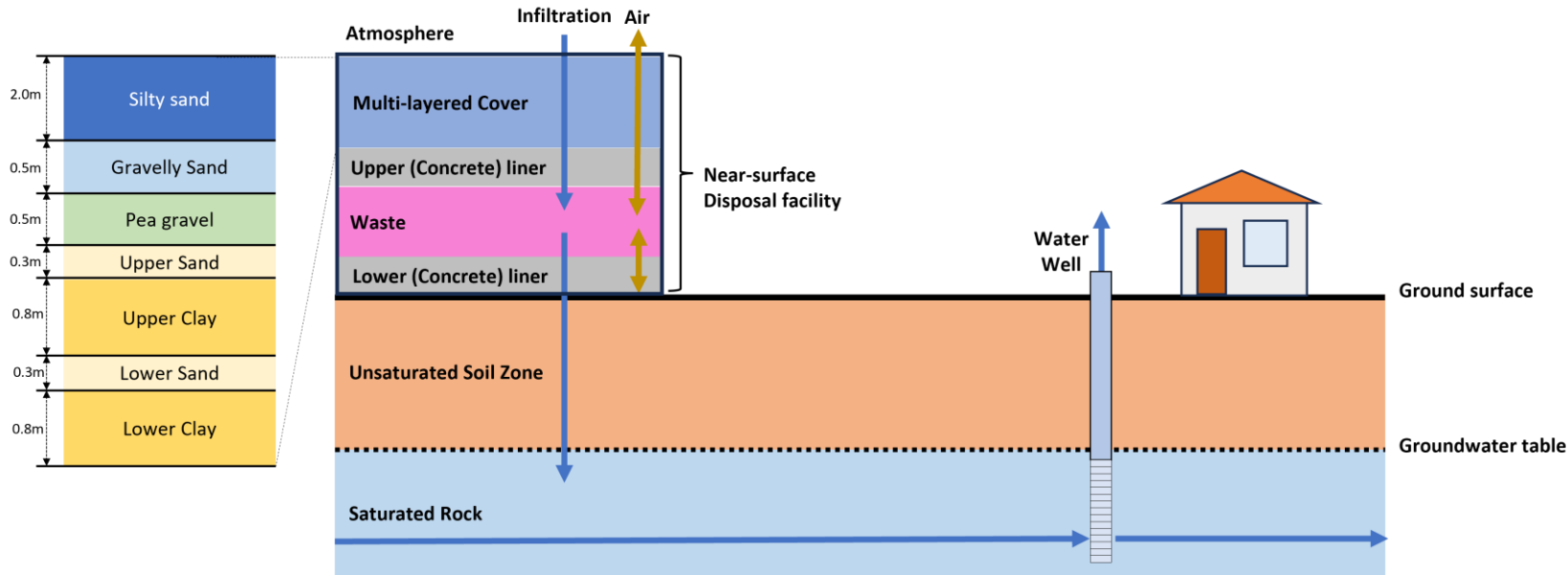


• Water infiltration modeling

- Along the multi-layered cover, waste area, unsaturated and saturated zone for the flow velocity and hydraulic head
 - Different permeability (Hydraulic conductivity) of each layer
 - Lateral drainage function of sand layers

• Radionuclide transport and exposure dose (well) modeling

- Groundwater flow velocity of saturated zone



MODELLING APPROACHES FOCUSING ON FACILITY

2. Heat Waves and HVAC Reliability

- Focusing on thermal modelling of buildings and systems, HVAC performance simulation, and development of operational heat stress protocols.
- Performance degradation of the HVAC system,
 - When cooling demands reach their peak, can cause potential operational failures.
- Electronic control systems and instrumentation can face temperature-induced failures
 - Worker productivity and safety decline under extreme heat, potentially necessitating operational restrictions during periods of peak demand.
- Construction activities face constraints from concrete temperature specifications and worker safety limits.



**Cooling System Failures in Industrial Equipment:
Summer Troubleshooting Guide**

MODELLING APPROACHES FOCUSING ON FACILITY

3. Drought Impacts on Water Supply and Cooling

- Groups of DGR facilities in water-stressed regions or those with substantial cooling requirements.
- Extended drought periods can threaten:
 - Facility water supply for cooling systems, concrete curing, dust suppression, and worker facilities.
 - Drought can simultaneously reduce water availability while increasing cooling demands during associated heat waves, creating compound stress on operations.
- Drought-induced vegetation stress can affect erosion control, effectiveness of vegetated covers, potentially triggering accelerated degradation.
- Soil moisture deficits can modify infiltration patterns and groundwater recharge, with long-term implications for barrier performance.



MODELLING APPROACHES FOCUSING ON FACILITY

4. River and Coastal Flooding

- River flooding is particular concern
 - Where facilities were sited based on historical flood frequencies potentially underestimating future risk.
- Coastal flooding is critical especially
 - Where sea level rise occurs along with storm surge and extreme precipitation.
- Facilities flooding risks can be amplified by climate change through multiple mechanisms:
 - Increased precipitation intensity raises watershed runoff, modified seasonal patterns shift flood timing, and sea level rise elevates coastal flood baselines.
- Detailed assessment of river and coastal flooding requires:
 - Hydrodynamic modelling coupling with watershed hydrology, river hydraulics, and facility-scale inundation mapping, integrated with climate projections spanning range of plausible futures.



MODELLING APPROACHES FOCUSING ON FACILITY

5. Water Table Variations and Barrier Performance

- Water table variation impacts for detailed assessment requires:
 - Coupled climate-hydrogeological modelling, geotechnical testing of barrier materials under cyclic saturation conditions, and long-term performance simulation.
- Groundwater table fluctuations can critically affect:
 - Engineered barrier systems, particularly clay-based barriers sensitive to saturation state.
 - Rising water tables can increase hydrostatic pressure on structures and enhance contaminant transport potential, while falling water tables cause settlement and structural stress.
- Seasonal and inter-annual water table variations can induce wet-dry cycling in clay barriers, progressively degrading plasticity, swelling capacity, and hydraulic performance.

MODELLING APPROACHES FOCUSING ON FACILITY

6. Soil Erosion and Cover Degradation

- Long-term landscape evolution modelling, vegetation dynamics simulation under changing climate, and engineering analysis of cover system resilience.
- Progressive erosion of engineered cover systems can present a critical risk to surface and near-surface facilities.
 - Climate change can amplify erosion through increased precipitation intensity, drought-weakened vegetation, and potentially enhanced wind erosion in drying regions.
- Erosion processes operate cumulatively over decades to centuries,
 - Potentially reducing cover thickness below design specifications or creating preferential flow paths compromising barrier function.

MODELLING APPROACHES FOCUSING ON FACILITY

7. Coastal Sea Level Rise and Storm Surge

- Integrated coastal modelling spanning ocean dynamics, groundwater, and facility response.
- Coastal facilities can face threat from projected sea level rise combined with storm surge intensification.
 - Mean sea level rise (0.5-1.0 meters or more by 2100) fundamentally alters facility relationship to marine environment, with storm surges propagating further inland and reaching higher elevations.
- Saltwater intrusion into groundwater systems can threaten facility operations and potentially accelerates corrosion.
 - Coastal erosion progressively reduces buffer distance between facility and shoreline.

SYNTHESIS AND FINDINGS : FACILITY-SPECIFIC INSIGHTS

- **Surface Disposal Facility**

- Exhibit maximum exposure to atmospheric climate hazards with direct impacts on waste emplacement zones.
- Erosion and cover system degradation represent unique long-term concerns.
 - These facilities benefit most from robust engineered covers, enhanced drainage, and vegetation management.

- **Near-Surface Disposal Facility**

- Show intermediate exposure with particular sensitivity to groundwater table fluctuations and infiltration.
- Vault and barrier performance under moisture cycling represents a critical concern.
 - These facilities require emphasis on hydrogeological monitoring and barrier material selection tolerant to saturation variations.

- **Deep Geological Repository (Surface temporary infrastructure performance)**

- Surface facilities exposed to climate hazards, while underground disposal areas remain buffered.
- Interim Storage Facilities represent the highest-intensity operations with maximum cooling and infrastructure requirements.
 - Elevated vulnerability to heat waves, power outages, and operational disruptions from extreme weather.

CLIMATE MODELLING AND SCENARIOS FOR THE POST-CLOSURE PHASE

WP CLIMATE training session 1 – Tuesday 19 May 2026

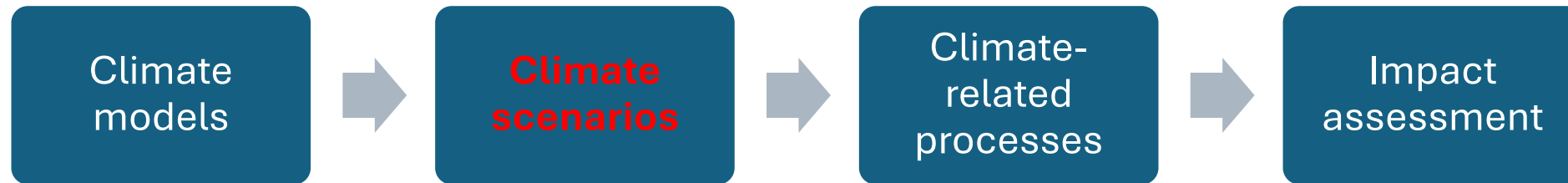
Koen Beerten SCK CEN



Co-funded by the European Union under Grant Agreement n° 101166718

INTRODUCTION

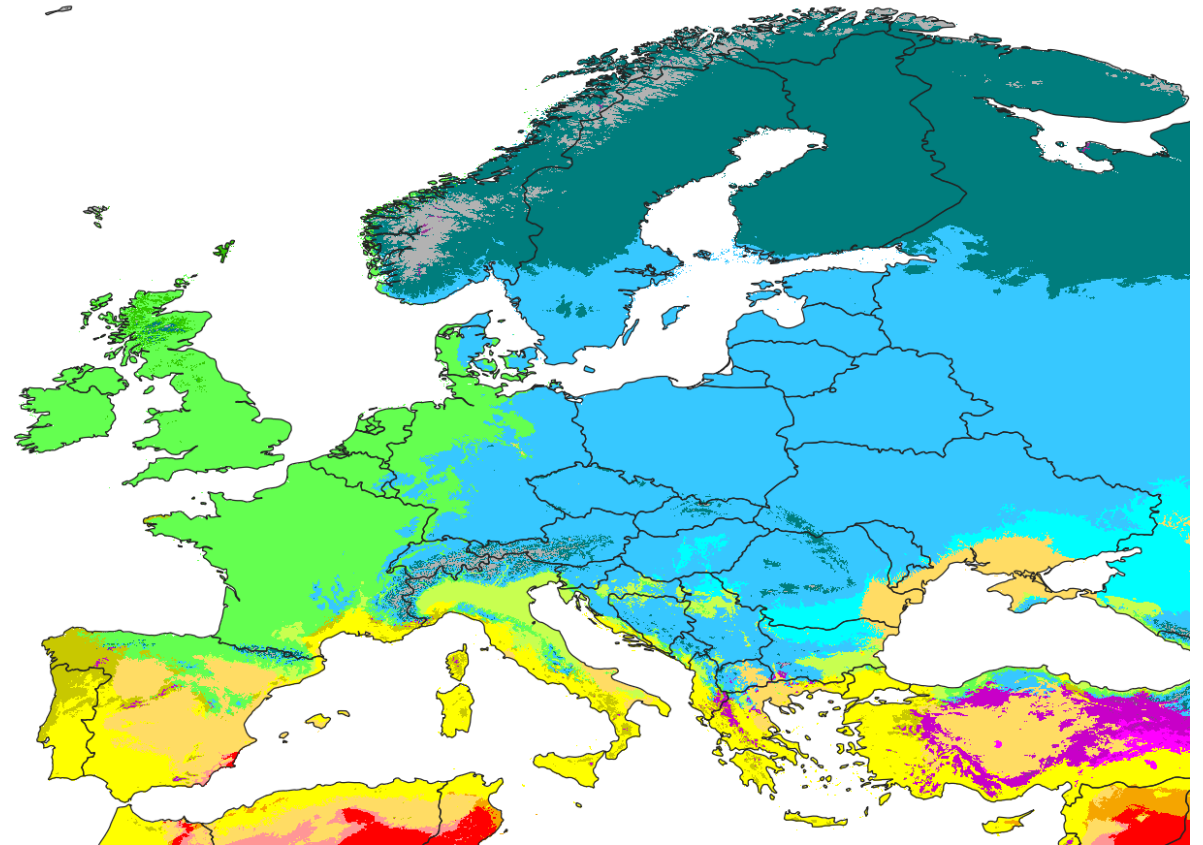
- How can output from climate models (numerical or conceptual) be used **to build relevant climate scenarios** to assess the impact of climate-related processes



INTRODUCTION

- **Short-term, up to 1,000-10,000s years**
 - Climate scenarios for climate zone Cfb
 - Climate scenarios for climate zone Csa
 - Climate scenarios for climate zone Dfb
- **Long-term, up to 10,000-100,000s years**
 - Climate scenarios for climate zone Cfb
 - Climate scenarios for climate zone Csa
 - Climate scenarios for climate zone Dfb

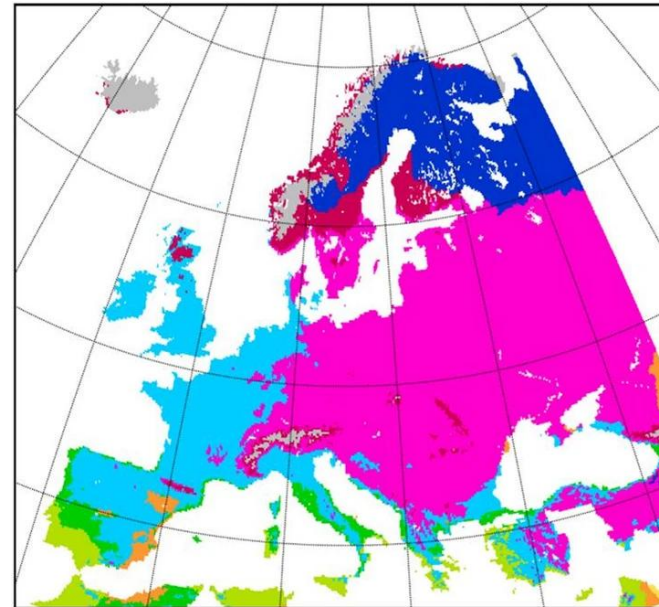
Köppen-Geiger	Köppen-Trewartha
Cfb	(Do)
Csa	(Cs)
Dfb	(Dc)



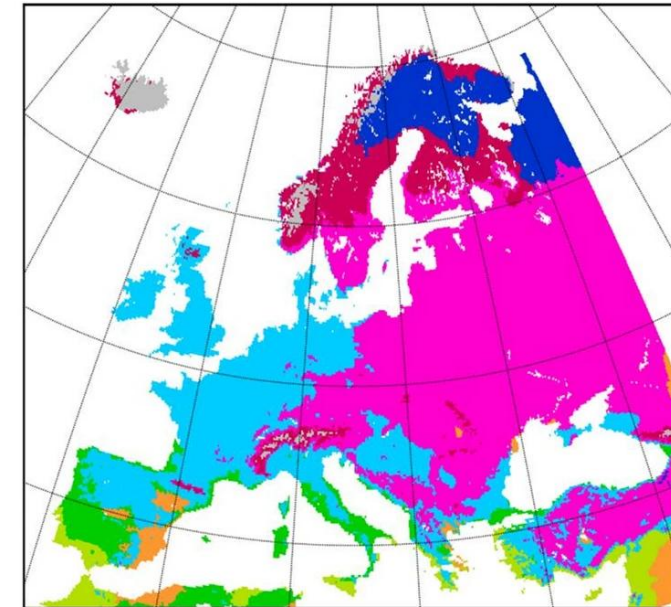
- Cfb (Temperate, no dry season, warm summer)
- Csa (Temperate, dry summer, hot summer)
- Dfb (Cold, no dry season, warm summer)

Code	Climate group/type Köppen-Trewartha	Main criterion
B	Dry climate	Annual precipitation below Trewartha aridity threshold
BW	Desert	Pann < aridity threshold
BS	Steppe/semi-arid	Pann ≥ aridity threshold but Pann < 2 × threshold
C	<i>Subtropical</i>	8 or more months ≥ 10°C, but not tropical
Cs	Mediterranean / dry-summer subtropical	C climate; dry summer
Cw	Subtropical monsoon / dry-winter subtropical	C climate; dry winter; often treated as part of humid subtropical group
Cf	Humid subtropical	C climate; no strong dry summer
D	<i>Temperate</i>	4–7 months ≥ 10°C
Do	Oceanic temperate	D climate; Tcold ≥ 0°C
Dc	Continental temperate	D climate; Tcold < 0°C
E	Boreal/subarctic	1–3 months ≥ 10°C
F	Polar	All months < 10°C

1961-1990



1991-2020

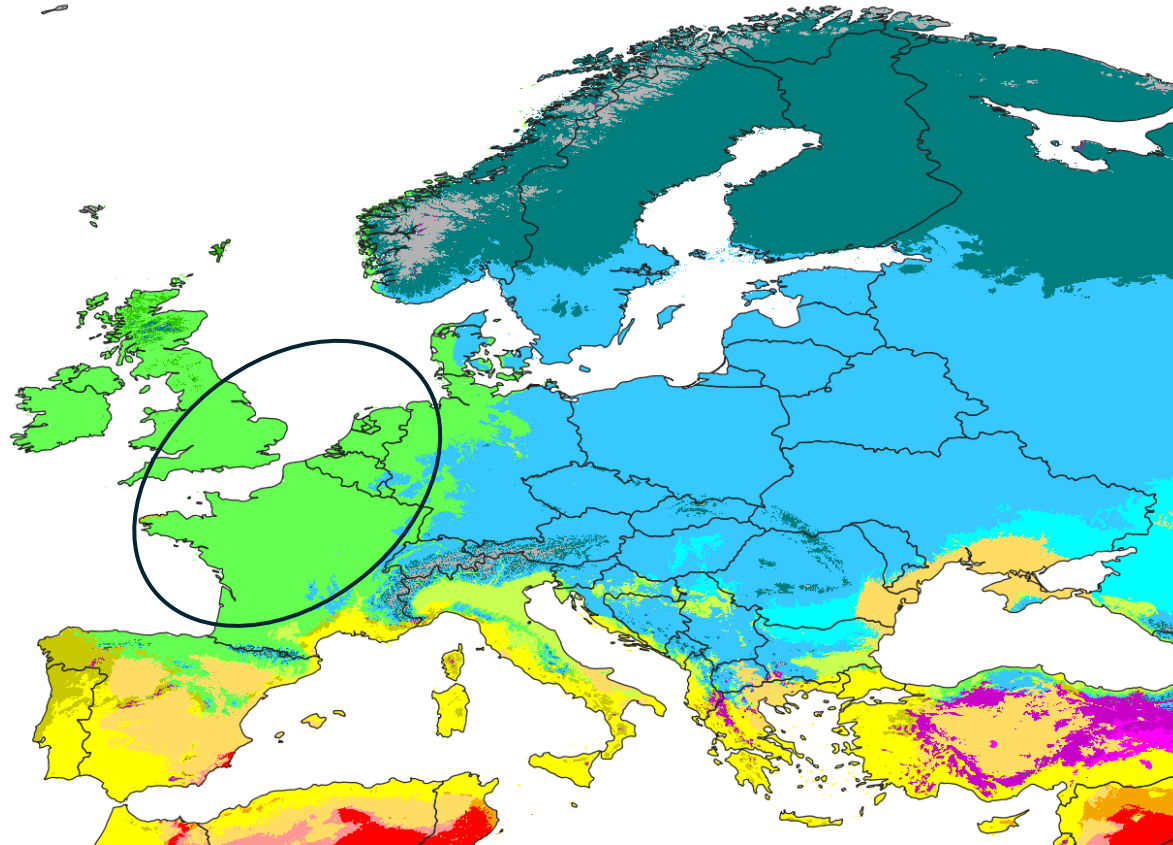


Holtanová, E., Belda, M., Randriatsara, HR. et al. Scenarios of Köppen-Trewartha climate types in Europe based on GCM-RCM combined projections. Theor Appl Climatol 156, 596 (2025).

INTRODUCTION

- **Cross-cutting all climate zones and time frames is this question: from which source/data the scenario is derived?**
 - High-resolution climate models, e.g., GCMs, is typically what IPCC is producing
 - Global Circulation Models, complex three-dimensional models of the atmosphere
 - Low-resolution long time window climate models, e.g., EMICs
 - Earth System Models of Intermediate Complexity, include physical climate processes plus biological and chemical systems
 - Reduced-complexity models, in which only a few processes are included (mathematically), focusing on one parameter e.g. ice volume on Earth
 - Simple energy-balance models, non-distributed models (representing time, not space)
 - Conceptual models such as past climatic cycles (e.g., the last glacial-interglacial cycle)

SHORT TERM, CLIMATE Cfb

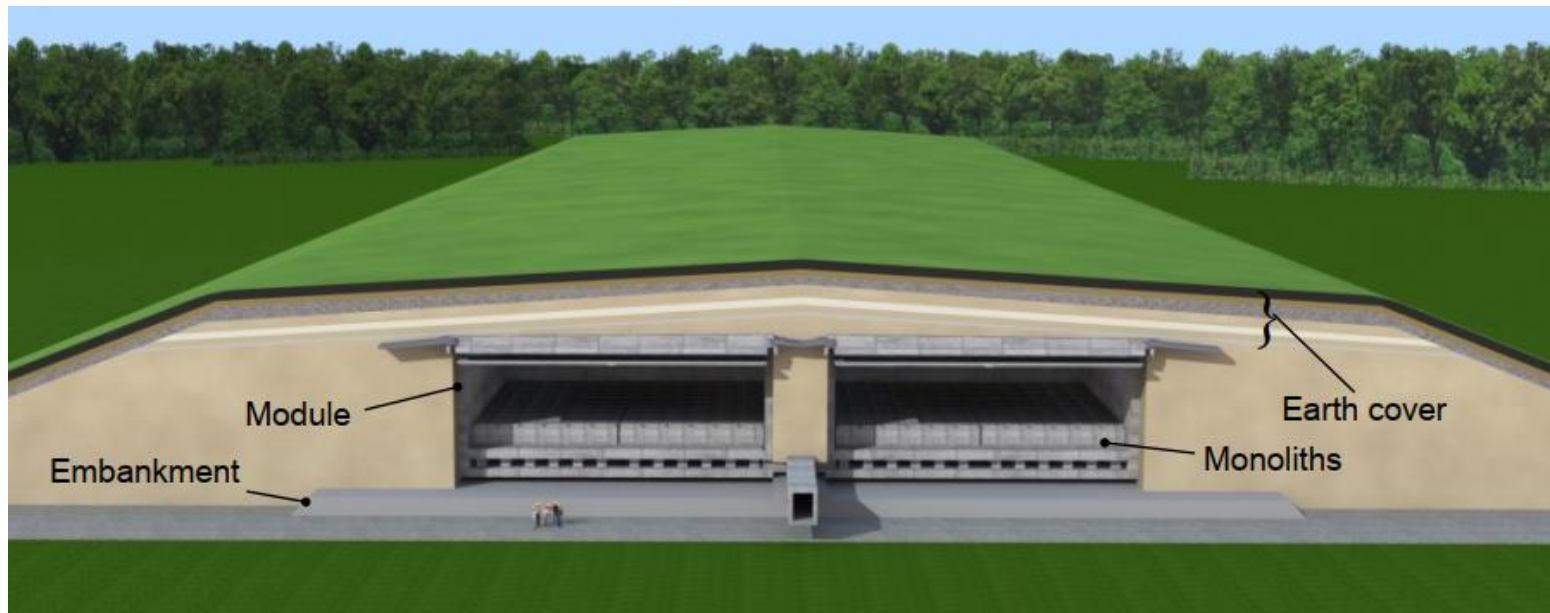


Date

Event

CLIMATE CHANGE SCENARIOS FOR THE SURFACE DISPOSAL FACILITY AT DESSEL, BELGIUM (ONDRAF/NIRAS)

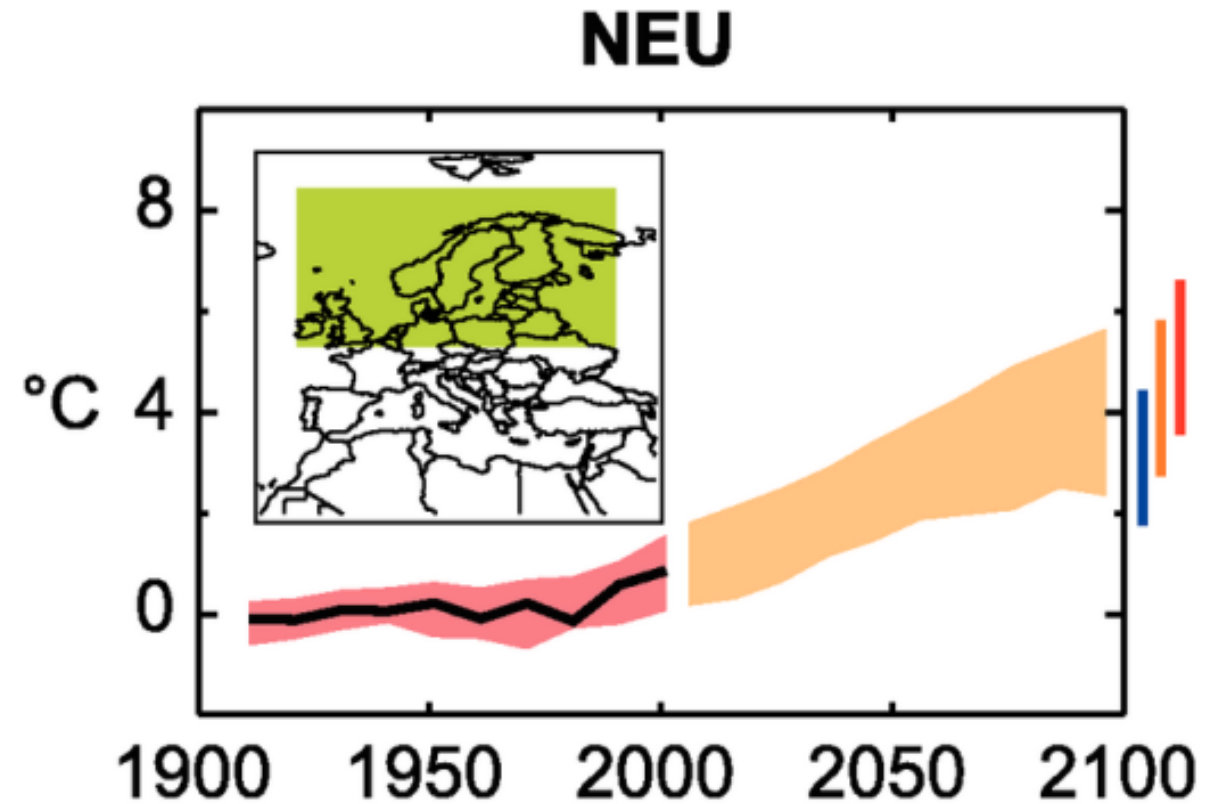
- **Climate-related processes of interest**
 - Erosion of the earth cover
 - Infiltration of water through the earth cover
- **Models: what is needed is meteorological/climatic input data (ET and P)**
- **Up to 10,000 years AP**



NIROND-TR 2009-07E
Version 2 19 October 2018

CLIMATE CHANGE UNTIL 2100

- Back then (*early 21st century*): IPCC studies show that there are significant ranges in the values of climate change parameters predicted for northern Europe until 2100 CE, due to basic uncertainties in the amounts of emitted man-made greenhouse gases
- Temperature anomalies with respect to 1901-1950 average for Northern Europe region
 - 1906 to 2005 (black line) and as simulated (red envelope) by the multi-model data set (MMD) models incorporating known forcings (SRES scenarios – prior to RCP's and SSP's)
 - As projected for 2001 to 2100 by MMD models for the A1B scenario (orange envelope). The bars at the end of the orange envelope represent the range of projected changes for 2091 to 2100 for the B1 scenario (blue), the A1B scenario (orange) and the A2 scenario (red)



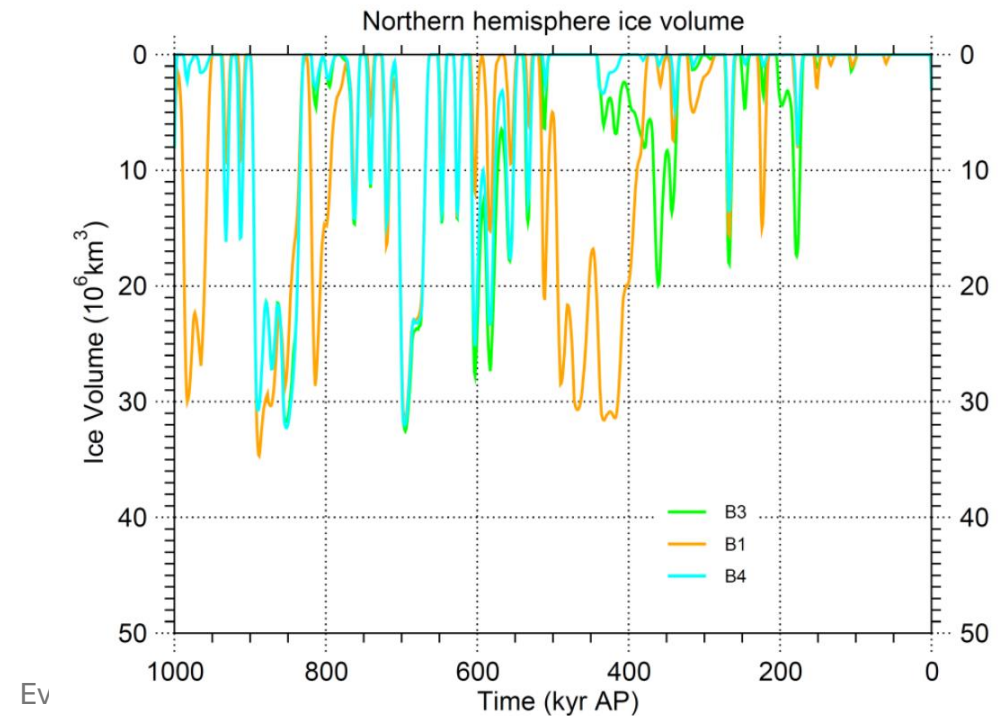
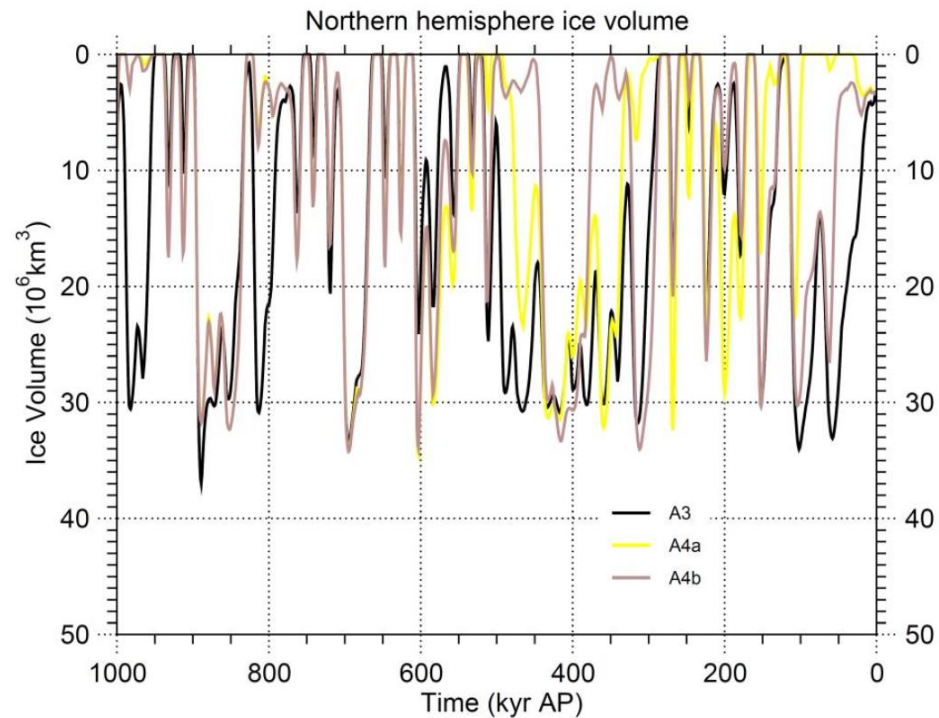
Scenario	Description
A1	Fast growing economy, new/efficient technologies, population peak around mid-century and decline thereafter. Three storyline subgroups: fossil intensive (A1FI), fossil energy sources (A1T) and balanced use of all sources (A1B).
A2	Heterogeneous world, preservation of local identities, continuous population growth. Economic/technological progress is more fragmented and slower than in other scenarios.
B1	Global population as in A1, services and information society, clean and resource efficient technologies.
B2	Global population as in A2 but slower evolution, intermediate economic development, more diverse evolution in technology than in the A1 and B1 storylines.

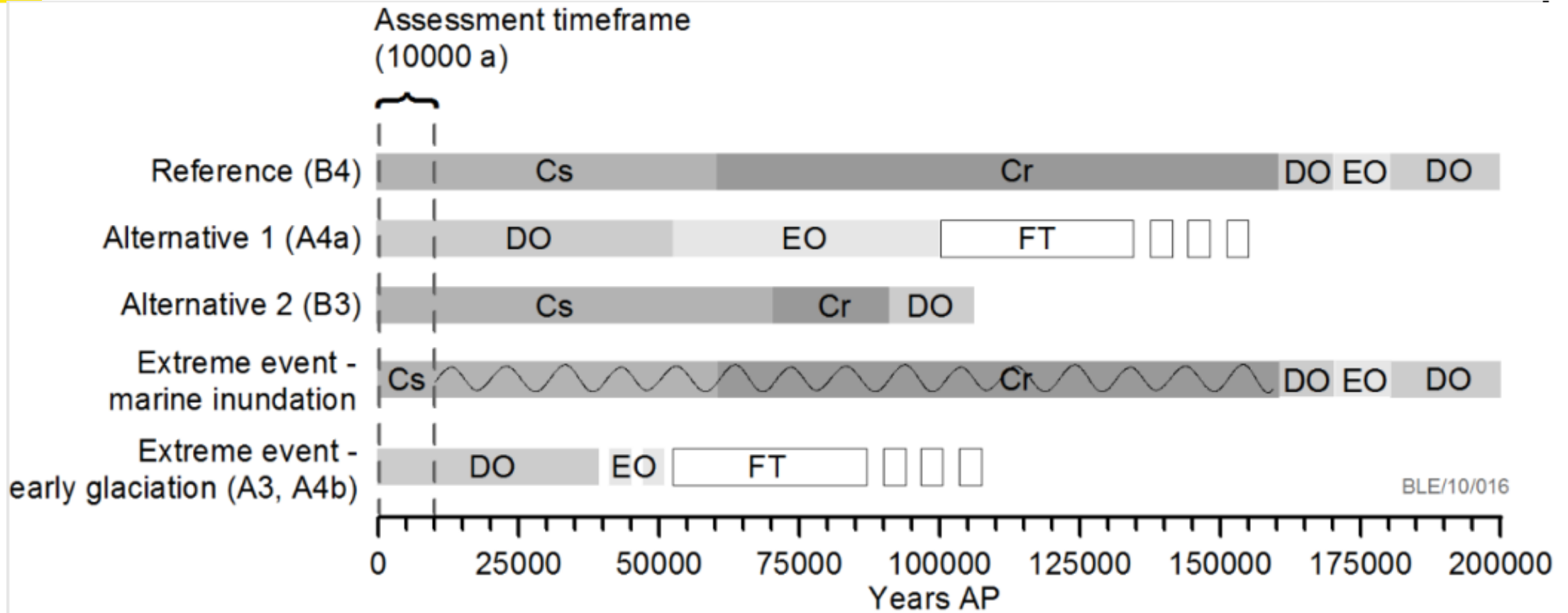
CLIMATE CHANGE AFTER 2100

- IPCC climate change projections predict a Cs/Cr climate (Köppen-Trewartha) by the next century
- IPCC extended the projections for a scenario that follows A1B to 2100 CE and then keeps atmospheric composition, hence radiative forcing, constant until 3000 CE. By that time, the warming range is still compatible with Cs/Cr climate
- This is also in line with BIOCLIM simulations (see next slide) that account for strong anthropogenic CO₂ forcing (in addition to insolation), and which predict warm conditions for at least the next 170,000 years
- However, another set of BIOCLIM simulations with natural CO₂ variations only, suggests that the current climate may persist for the next 10,000 years
- Thus, two possible climate states for the next 10,000 years for Dessel: Cs/Cr and Do (current climate)

IPCC VS BIOCLIM

- IPCC: high-resolution Global Circulation Model ensembles for the next 100 years
- BIOCLIM (figures below): lower-resolution Earth System Model of Intermediate Complexity for the next million years – *forcings: insolation + CO2*







A TIERED APPROACH

- **Tier 1** uses meteorological data from a climatic analogue station that matches the overall regional averages of temperature and precipitation projections from a set of global models
- **Tier 2** uses downscaled GCM/RCM derived climate data

TIER 1: LOOKING FOR METEOROLOGICAL DATA FOR A FUTURE CLIMATE IN DESSEL FROM ANALOGUE STATIONS

• Criteria

- Temperature and precipitation
- Elevation
- Distance to moisture source



Station	Mean annual temperature (°C)	Annual precipitation (mm a ⁻¹)
DO		
Dessel, Belgium (1990-2009)	10.6	890
Cs		
Ourense, Spain (1986-2000)	14.5	807
Huelva, Spain (1986-2000)	18.1	479
Cádiz, Spain (1971-1991)	17.7	536
Cr		
Gijon, Spain (1983-2000)	13.8	947

TIER 2: LOOKING FOR METEOROLOGICAL DATA FOR A FUTURE CLIMATE IN DESSEL FROM DOWNSCALED GCM/RCM-DERIVED CLIMATE DATA

- CCI-HYDR project
- High/Wet, Mean/Mild and Low/Dry hydrological scenario was defined
- The three hydrological scenarios are based on an ensemble that consists of 22 GCM simulations (from the IPCC AR4 database) run with medium-coarse resolution (150-450 km) for the IPCC A1B, A2, B2 scenarios (from SRES) and 10 RCM simulations (from the PRUDENCE database) run with high resolution (50 km) for the A2 and B2 scenarios.

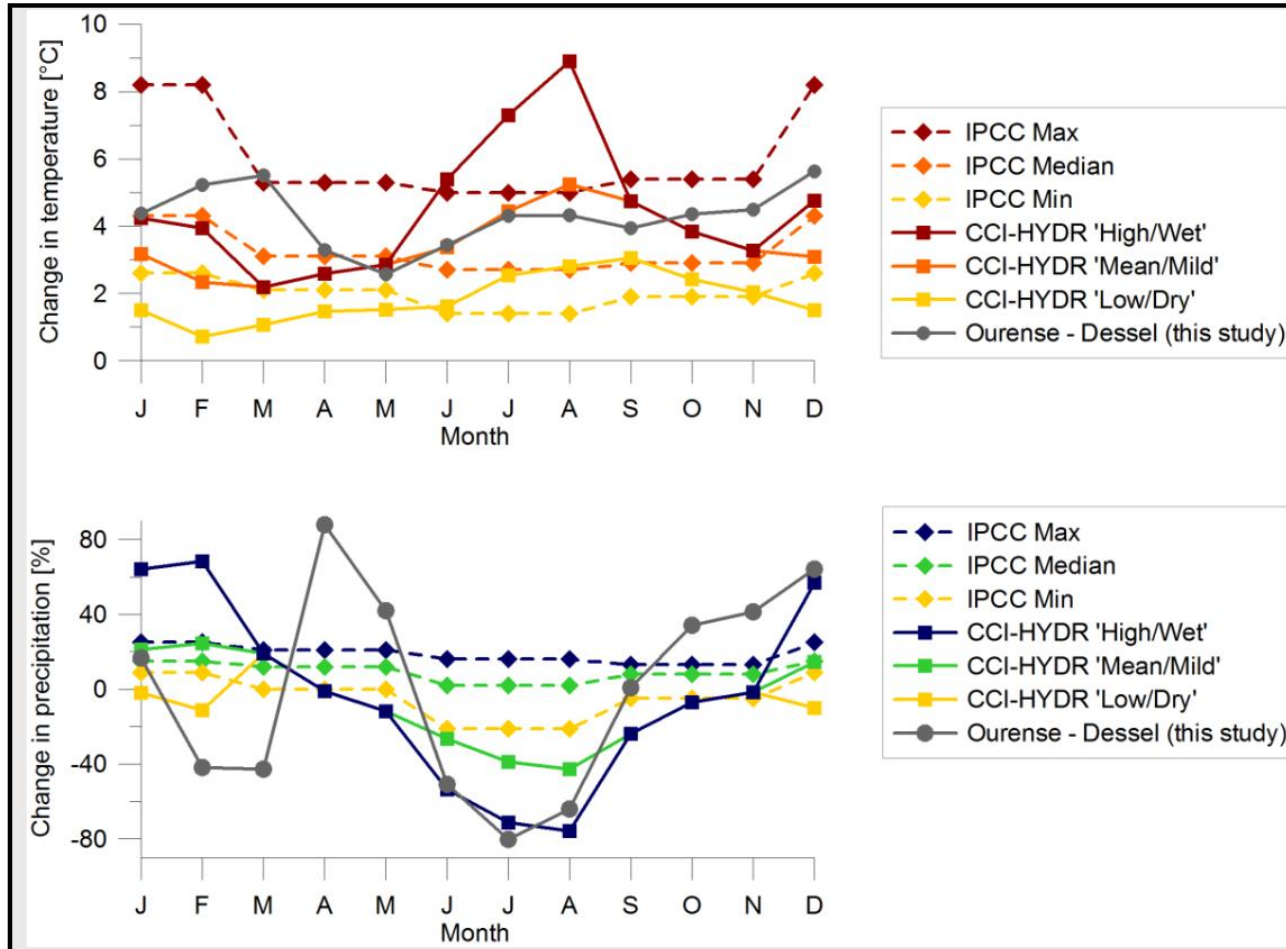
Current Dessel	Current Ourense	CCI-HYDR 'Low/Dry'	CCI-HYDR 'Mean/Mild'	CCI-HYDR 'High/Wet'
DO	Cs	DO	Cr	Cs

TIER 2: TEMPERATURE AND PRECIPITATION

Month	Dessel (mm month ⁻¹)	Ourense (mm month ⁻¹)	'Low/Dry' (mm month ⁻¹)	'Mean/Mild' (mm month ⁻¹)	'High/Wet' (mm month ⁻¹)
1	74.3	86.6	72.9	90.0	122.0
2	71.2	41.4	63.2	88.6	119.9
3	65.2	37.3	77.7	77.7	77.7
4	48.0	90.2	47.5	47.5	47.5
5	58.1	82.4	51.2	51.2	51.2
6	79.2	39.0	36.8	58.2	36.8
7	95.5	18.9	27.5	58.4	27.5
8	74.5	26.7	18.0	42.6	18.0
9	76.5	77.2	58.4	58.4	58.4
10	75.3	101.1	70.1	70.1	70.1
11	84.9	120.2	83.6	83.6	83.6
12	87.5	143.7	78.9	100.4	137.5
Annual (mm a⁻¹)	890.3	864.5	685.9	826.8	850.2

Month	Dessel (°C)	Ourense (°C)	'Low/Dry' (°C)	'Mean/Mild' (°C)	'High/Wet' (°C)
1	3.6	8.0	5.1	6.8	7.8
2	4.2	9.4	4.9	6.5	8.1
3	6.8	12.4	7.9	9.0	9.0
4	9.9	13.2	11.4	12.5	12.5
5	13.9	16.5	15.4	16.8	16.8
6	16.3	19.7	17.9	19.7	21.7
7	18.3	22.6	20.8	22.7	25.6
8	18.1	22.5	20.9	23.4	27.0
9	14.8	18.7	17.8	19.5	19.5
10	11.0	15.3	13.4	14.8	14.8
11	6.7	11.2	8.8	10.0	10.0
12	3.6	9.2	5.1	6.6	8.3
Annual (°C)	10.6	14.9	12.5	14.0	15.1

CCI-HYDR HIGH/WET SCENARIO WAS TAKEN FORWARD BECAUSE MOST CONSERVATIVE



Date

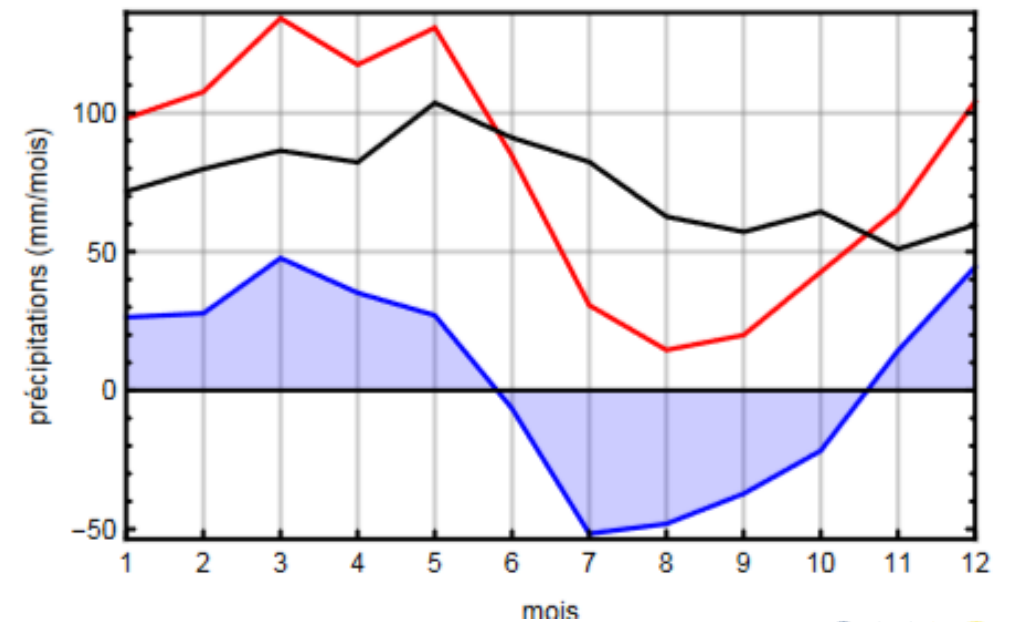
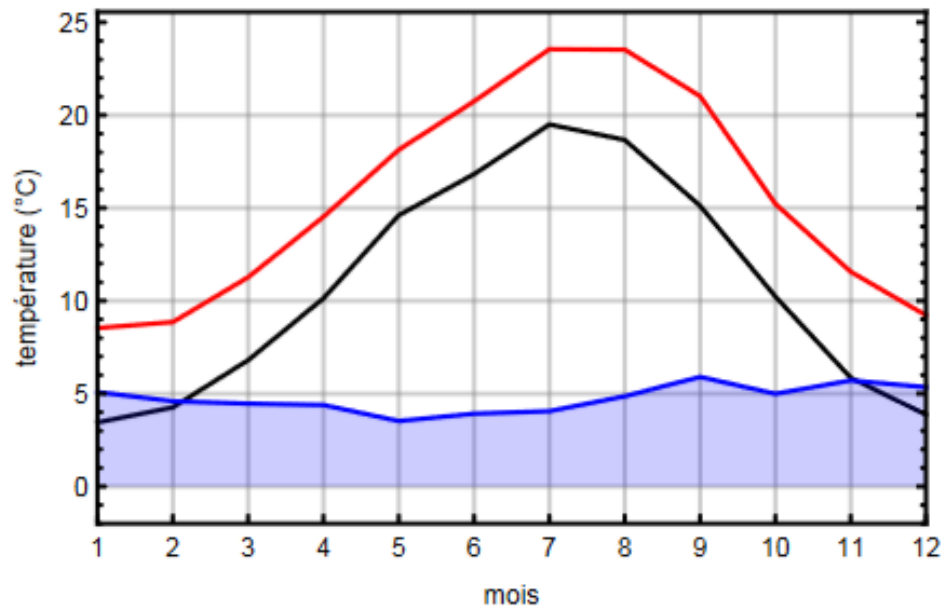
Event

HOW IS THIS INCORPORATED IN THE SAFETY CASE?

- **Until 1000 years AP, expected evolution, Cs or Do climate**
 - Impact of erosion on the multi-layer cover is considered to be low, and no water can penetrate the disposal facility
- **After 1000 years AP, expected evolution, Cs or Do climate**
 - Gradual and slow degradation of the earth cover, such that in the end water infiltration is only inhibited by evapotranspiration from remaining vegetation
- **Until 1000 years AP, alternative evolution, Cs or Do climate**
 - Extreme erosion and fully eroded earth cover shortly after the control period
- **After 2000 years AP, penalizing scenario, Cs or Do climate**
 - Fully degraded disposal system

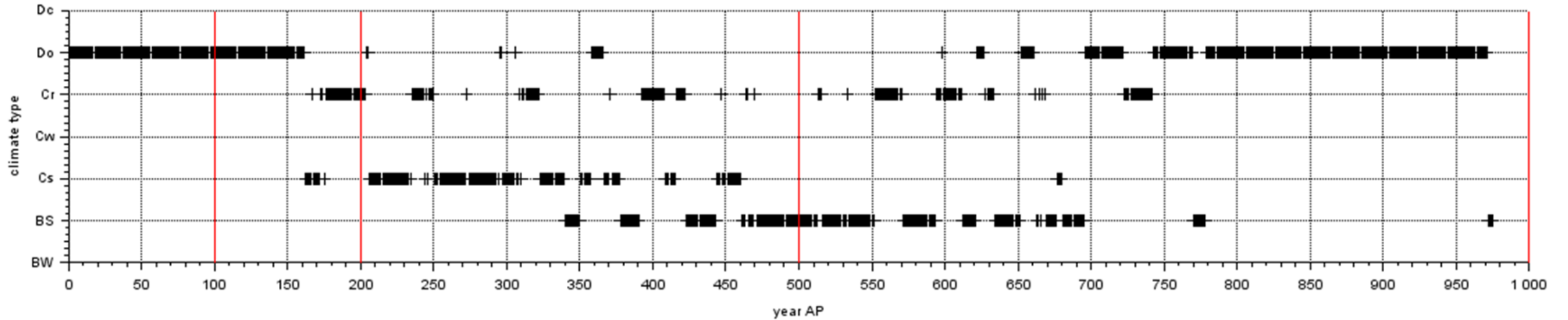
SHORT-TERM CLIMATE SCENARIOS DEVELOPED BY ANDRA (F)

- Climatic evolution (with monthly data) computed for the critical emission scenario Bioclim5000 (5000 Gt or 1635 ppm CO₂; ~RCP8.5), with iLoveClim model that provides monthly mean rainfall and temperature, and converted into climate types and potential biomes



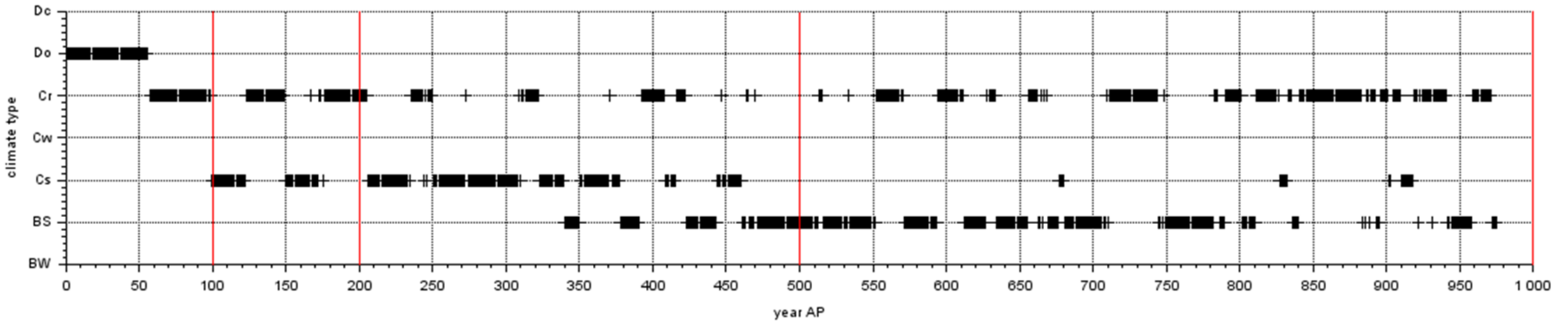
Paillard, Didier, et Didier Roche. 2020. « RÉVISION DE LA SIMULATION DU CLIMAT SUR LE SITE DE STOCKAGE DE L'AUBE AU COURS DES PROCHAINS 1000 ANS ». Document technique externe CGRPFS3C200004. FAVL. ANDRA.

SHORT-TERM CLIMATE SCENARIOS DEVELOPED BY ANDRA (F)



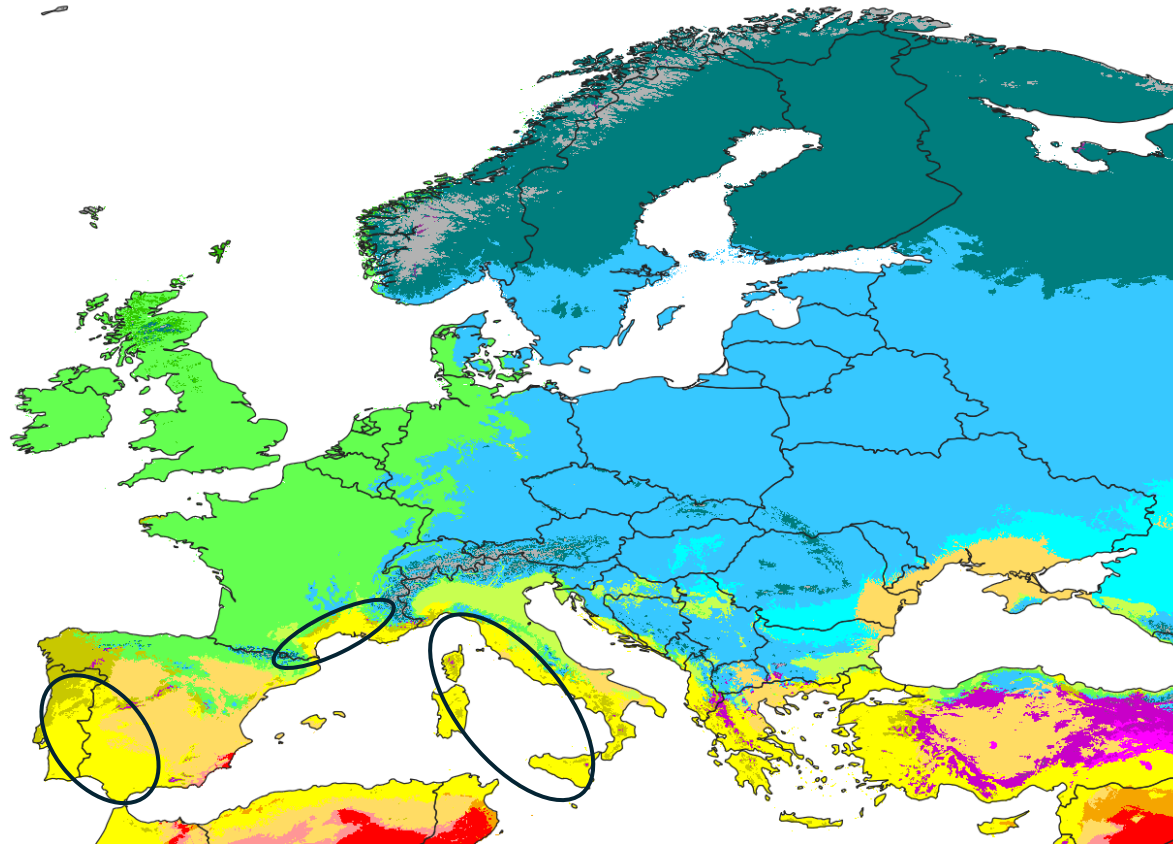
SHORT-TERM CLIMATE SCENARIOS DEVELOPED BY ANDRA (F)

- iLoveClim gives a low (global) temperature value compared with other models: only +2°C, compared with +2 to +4.5°C for other models, therefore temperature anomaly (given by the simulation results) was multiplied by 2, yielding another sequence of typical climates





SHORT TERM, CLIMATE Csa



Date

Event



CLIMATE GROUP Cs (ENRESA)

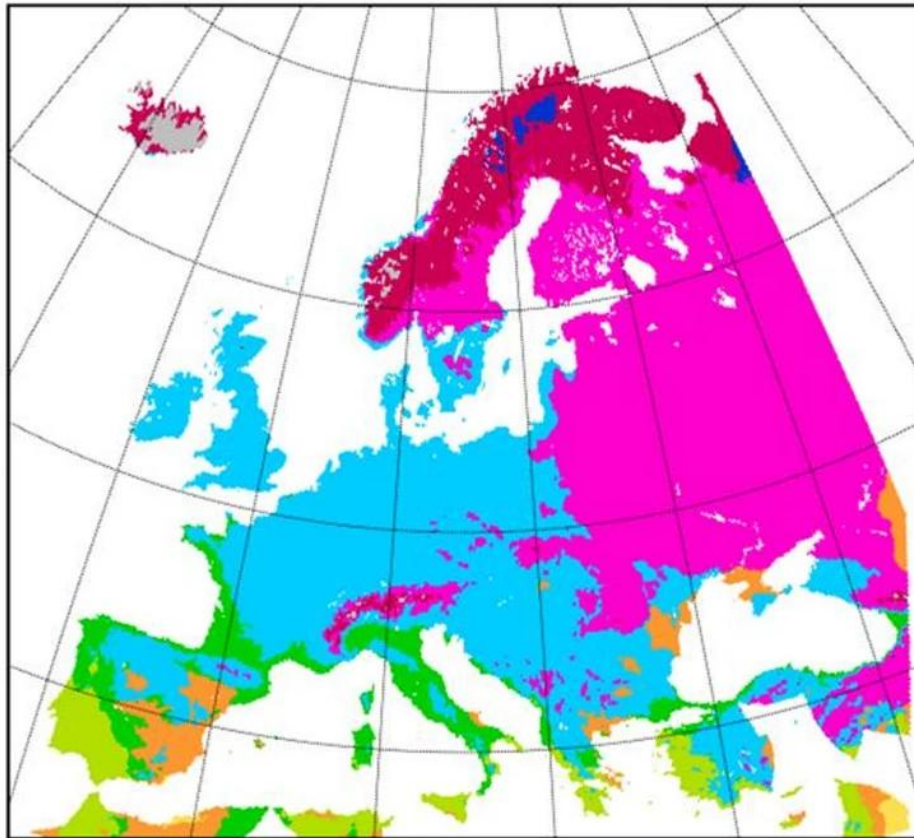
- **IPCC predictive models for the most unfavorable case, RCP 8.5, up to the year 2100**
- **Projected warm–dry transition (Csa to BSh climate)**
 - Higher temperatures and equal or reduced mean precipitation
 - Greater hydroclimatic variability
 - Increased erosive potential
 - General decline in soil moisture and aquifer recharge
- **Nevertheless, given the projected greater hydroclimatic variability, two alternative scenarios affecting site precipitation are taken into account for the longer term**
 - Scenario EC1 postulates a change in average annual precipitation, leading to a **change in the potential infiltration flux** through the barriers, affecting the processes of contaminant release and transport within the storage facility and in the geosphere
 - Penalising scenario EC2 postulates a **rise in the water table** such that the groundwater comes into contact with the waste, altering the source term with respect to that estimated in the reference scenario

ENRESA (2022). Documento Técnico soporte del estudio de impacto ambiental del proyecto de construcción de la plataforma sureste para almacenamiento definitivo de residuos de baja y media actividad (RBMA).

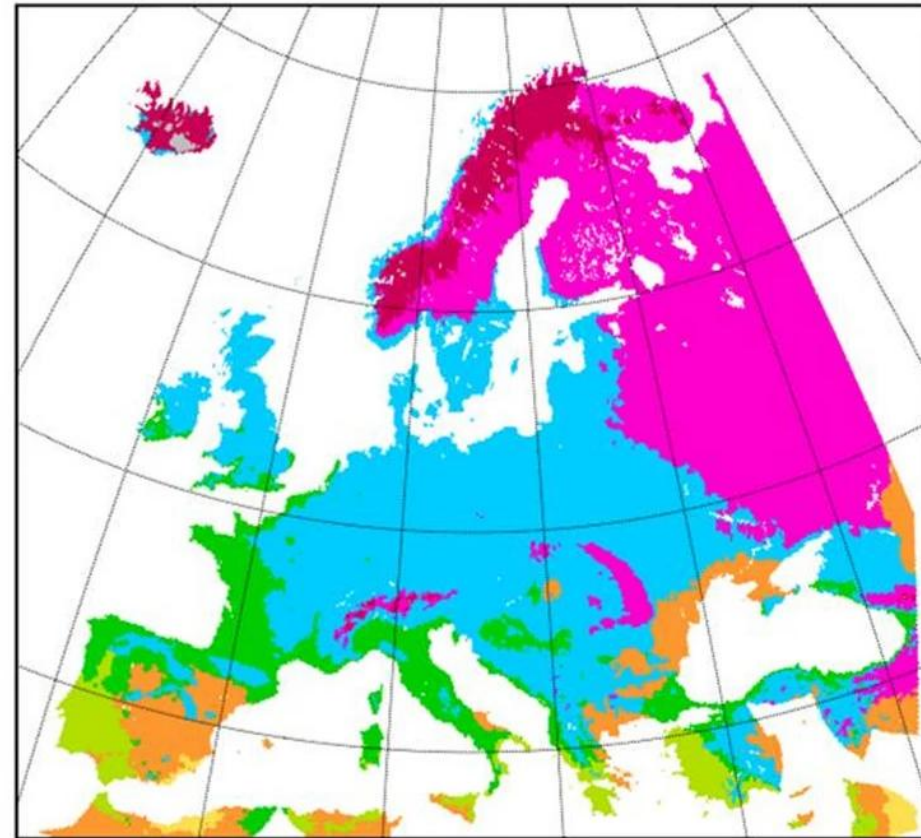
Joaquín Farias et al. (2025). ENRESA. El Cabril LILW and VLLW repository
Climate aspects (Oral presentation).

END OF 21ST CENTURY CLIMATE MAP

EURO-CORDEX RCP4.5



EURO-CORDEX RCP8.5

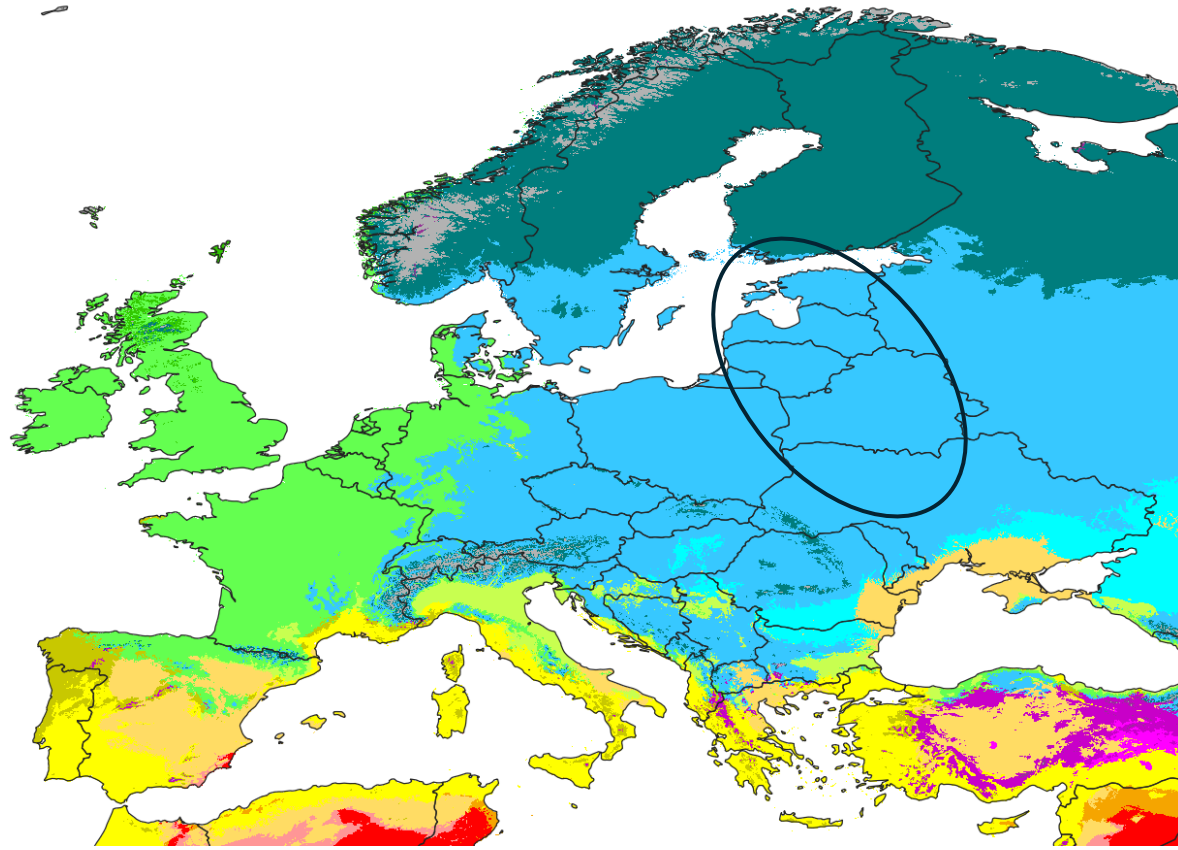


BW BS Cs Cw Cf Do Dc Eo Ec Ft Fi





SHORT TERM, CLIMATE Dfb



Date

Event



CLIMATE Dfb

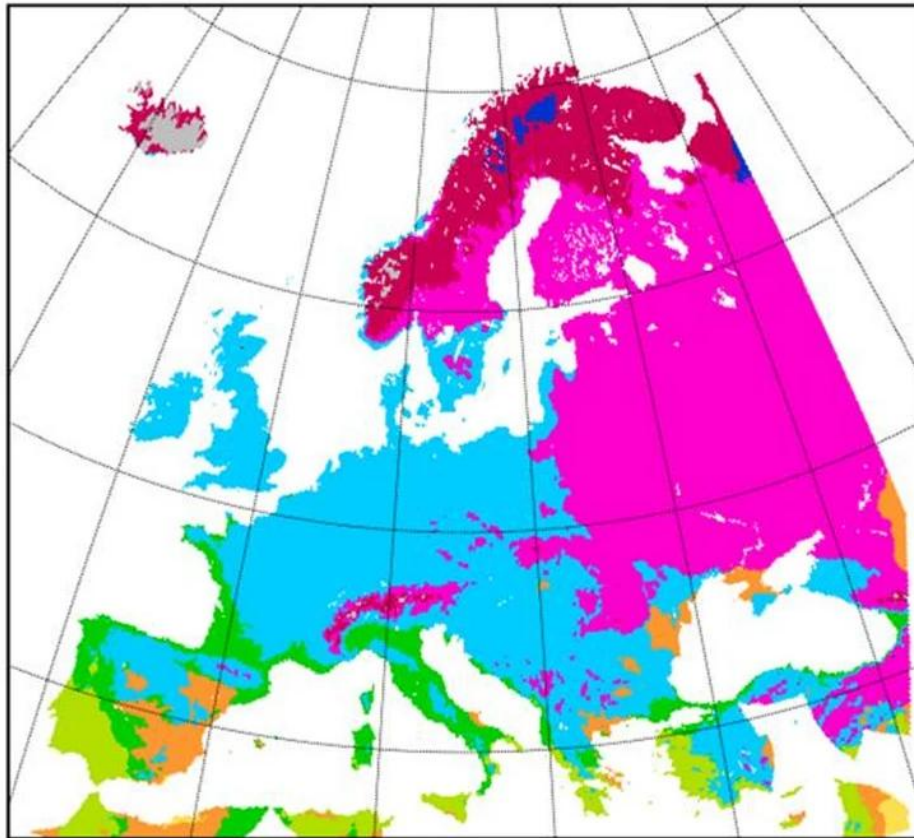
- **Extensions of RCPs 4.5 and 8.5**

- Nordic regions
 - Dfb remains Dfb under RCP4.5
 - Under RCP8.5 coastal areas may be submerged for a while (500-900 AP), after which isostatic uplift is emerging the land again
- Baltic regions
 - Shift from Dfb to Dfa, and to Cfb under RCP8.5
- Continental regions
 - Warming of ~2–3 °C (RCP 4.5) to > 4 °C (RCP 8.5) by 2100
 - A shift to Dfa after 100 years AP and lasting until 1000 years AP

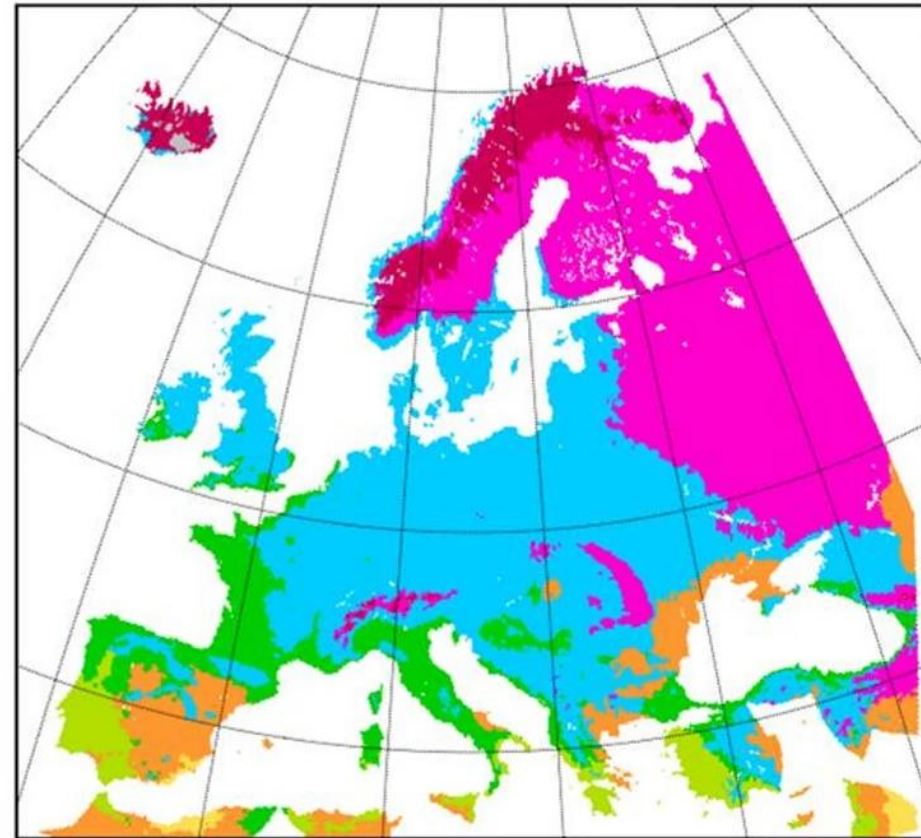
From multiple sources, see WP CLIMATE Synthesis Report

END OF 21ST CENTURY CLIMATE MAP

EURO-CORDEX RCP4.5



EURO-CORDEX RCP8.5

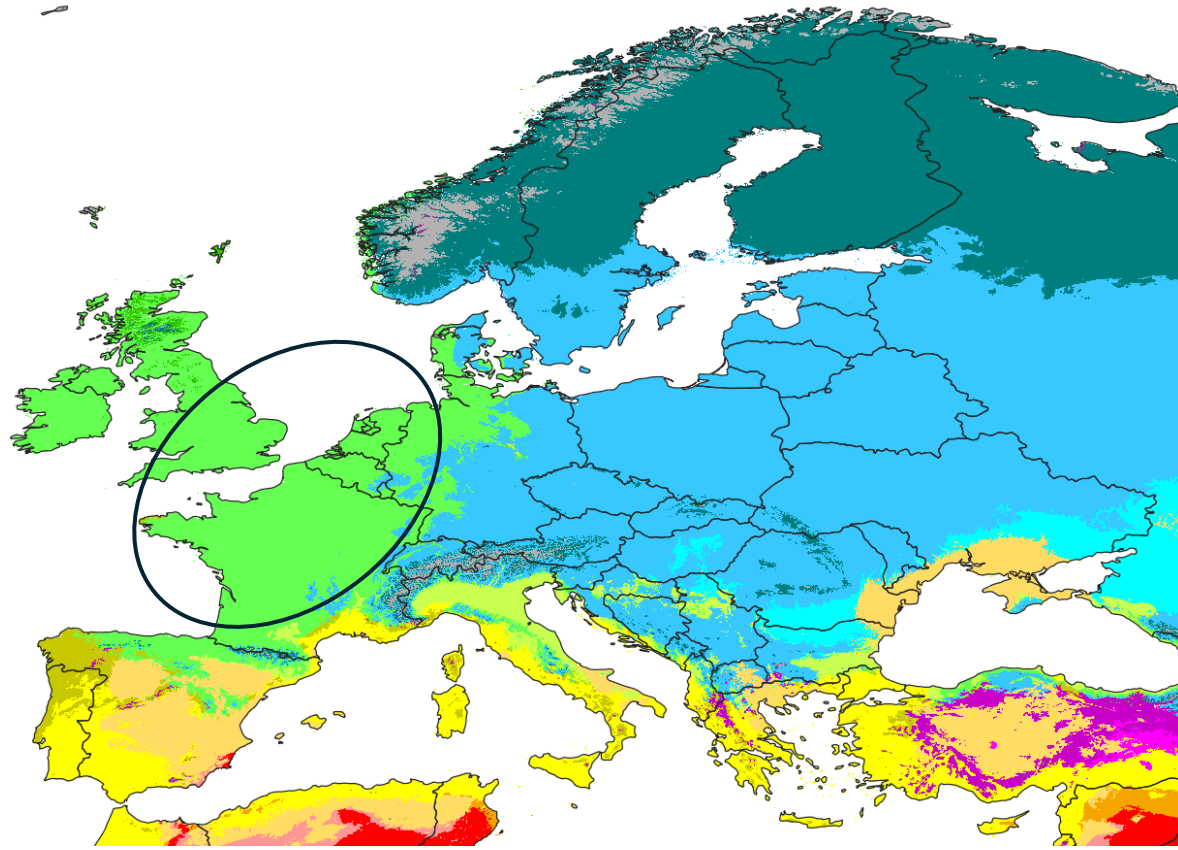


BW BS Cs Cw Cf Do Dc Eo Ec Ft Fi





LONG TERM, CLIMATE Cfb



Date

Event



REPRESENTATIVE CLIMATE STATES (BELGIUM, ONDRAF/NIRAS)

- Based on results from the BIOCLIM project
- Modelling sequential BIOSphere systems under CLIMate change for radioactive waste disposal
- EURATOM fifth European framework programme
- Launched in October 2000 for a three-year period
- Aimed at providing a scientific basis and practical methodology for assessing the possible long term impacts on the safety of radioactive waste repositories in deep formations due to climate and environmental change

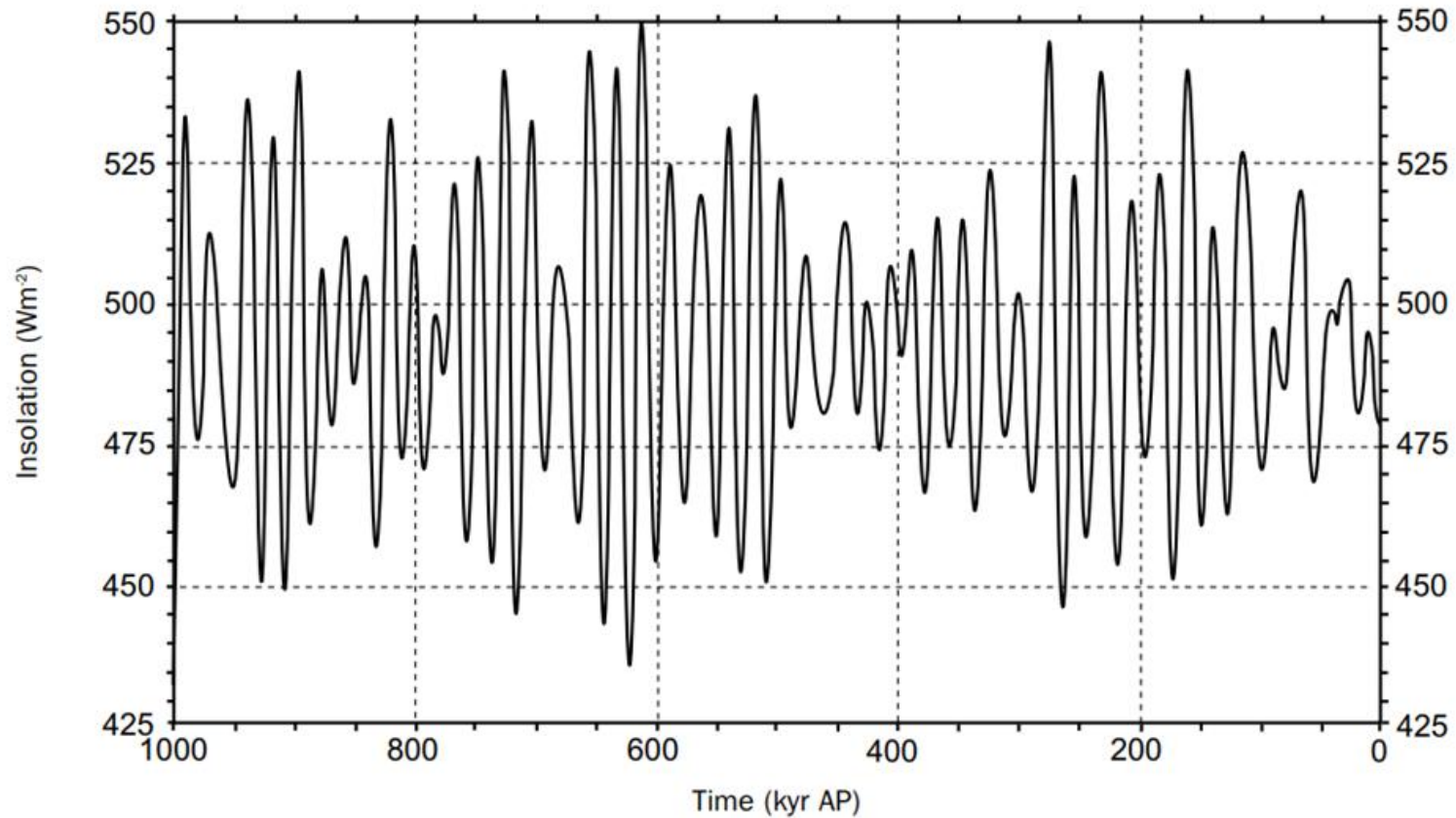
De Craen, M., Beerten, K., Honty, M., & Gedeon, M. (2012). Geo-scientific evidence to support the I2 isolation function (geology & long-term evolution) as part of the Safety and Feasibility Case 1 (SFC1). (0 ed.) (SCK CEN Reports; No. ER-184). SCK CEN.

BIOCLIM

- **LLN 2-D NH (two-dimension Northern Hemisphere) climate model developed in Louvain-la-Neuve has been used to simulate the global climate change over the next one million years**
- **The primary forcing of this model is the computed latitudinal and seasonal distribution of insolation linked to orbital variations**
- **The atmospheric concentration of CO₂ plays an important role in modifying the amplitude of the long term climatic response to solar forcing**
 - Natural CO₂ variation is an integral component of the biosphere system. However, the model does not include a full carbon cycle that would allow the atmospheric CO₂ concentration to be internally computed
 - Besides, human activities also introduce additional greenhouse gases (including CO₂) into the atmosphere from fossil fuel burning
- **Therefore, various alternative scenarios of the future greenhouse gas concentration have been identified and are considered as an external forcing mechanism**

BIOCLIM (WP2 DELIVERABLE 3)

- Insolation at 65°N

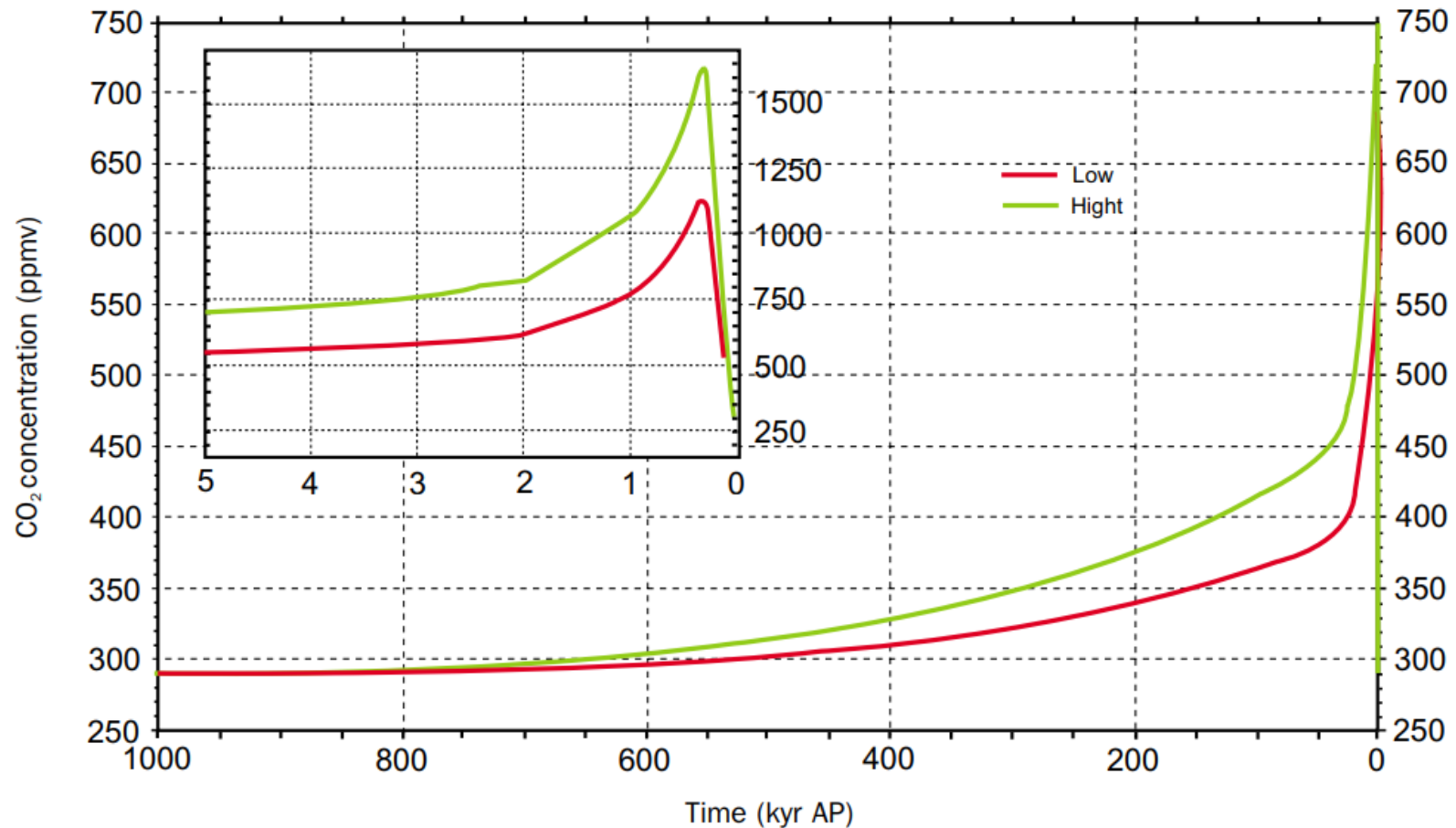


Date

<https://www.andra.fr/mini-sites/bioclim/pdf/d3.pdf>

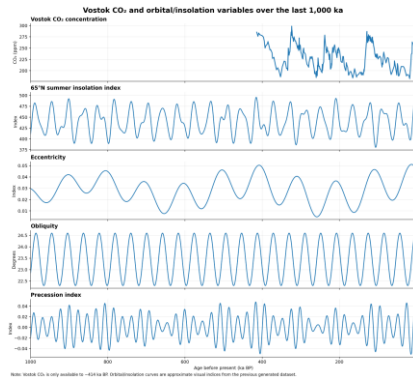
BIOCLIM: 2D NORTHERN HEMISPHERE INSOLATION-DRIVEN CLIMATE MODEL COUPLED WITH NATURAL AND FOSSIL FUEL CO2 CONTRIBUTIONS

- Fossil fuel

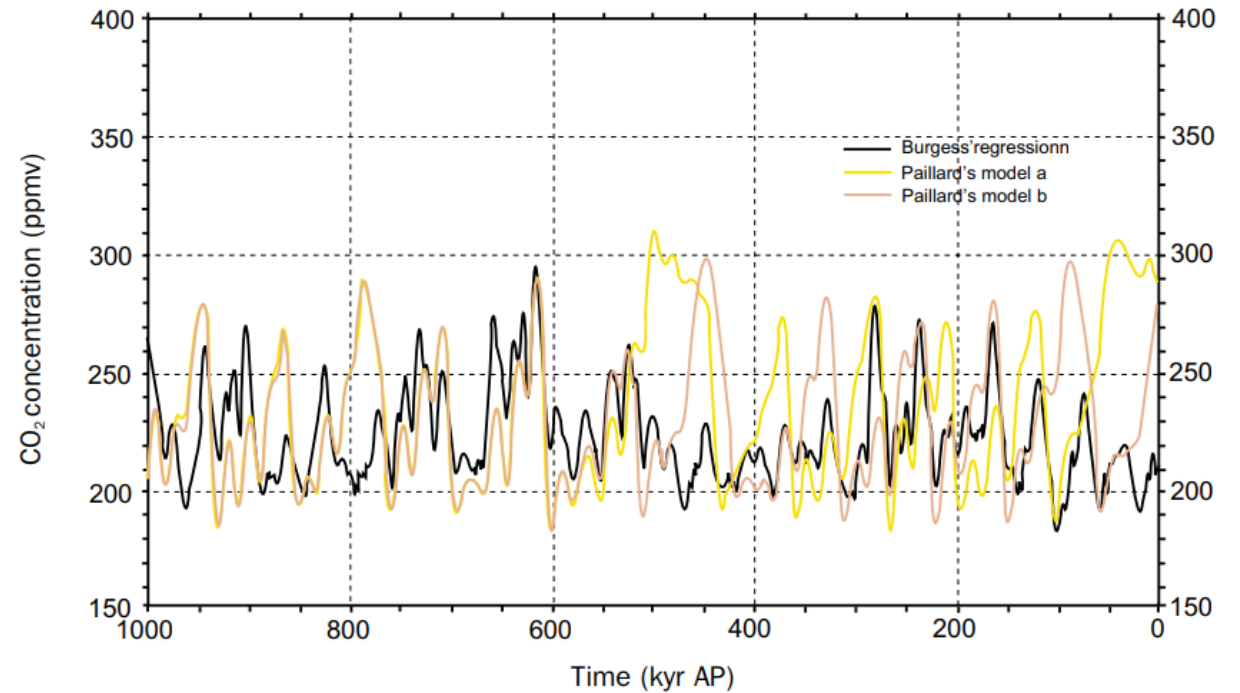


BIOCLIM: 2D NORTHERN HEMISPHERE INSOLATION-DRIVEN CLIMATE MODEL COUPLED WITH NATURAL AND FOSSIL FUEL CO2 CONTRIBUTIONS

- **Natural**
 - Regression

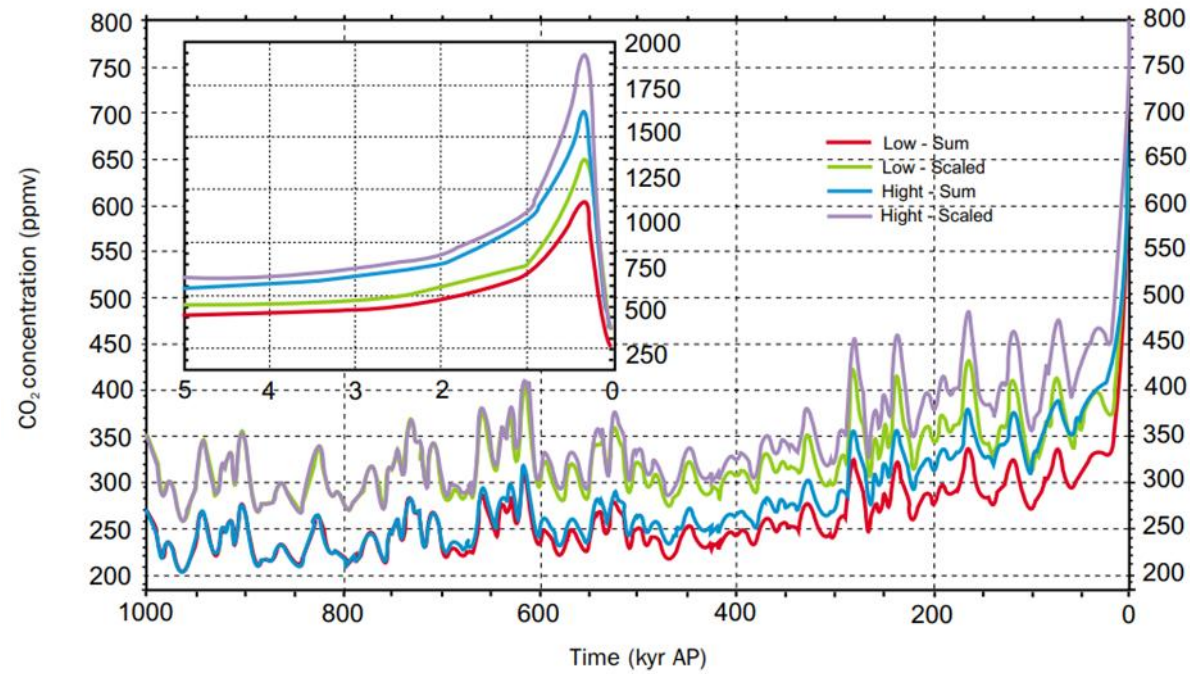


- Threshold model
 - Describes time evolution of ice volume and CO₂
 - Two states: interglacial and glacial
 - Transition from one state to the other when threshold values for insolation, obliquity and ice volume are crossed
 - CO₂ is then relaxed towards prescribed values, according to regime (state) and forcing



BIOCLIM

- Combined natural + fossil



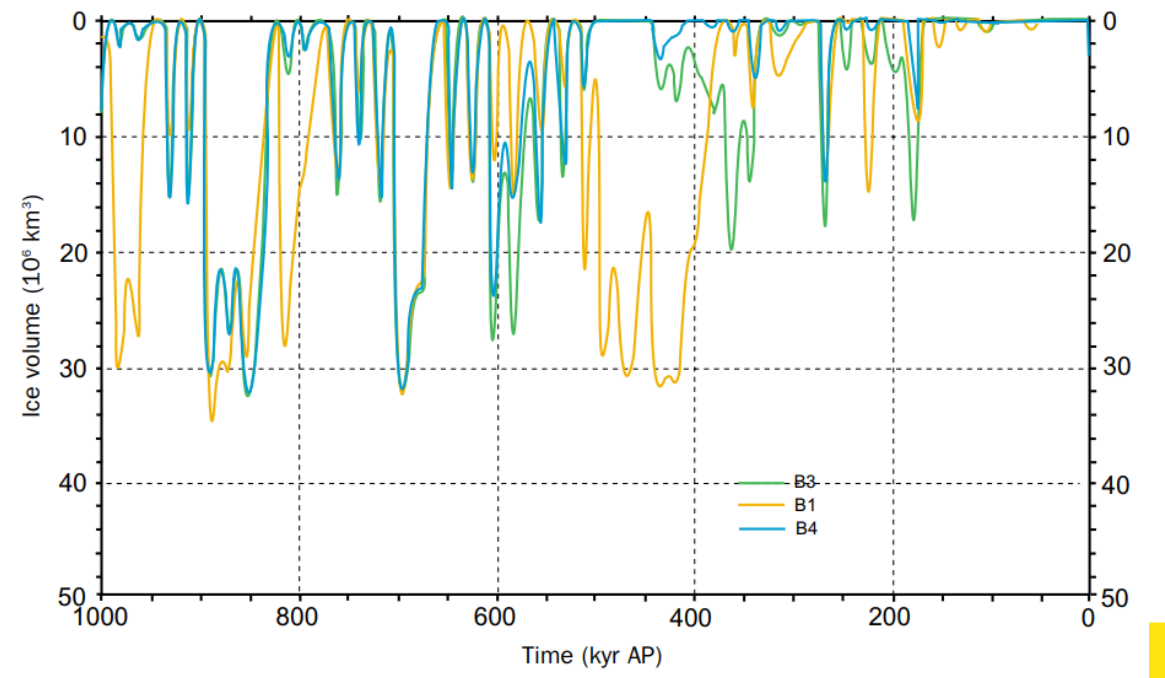
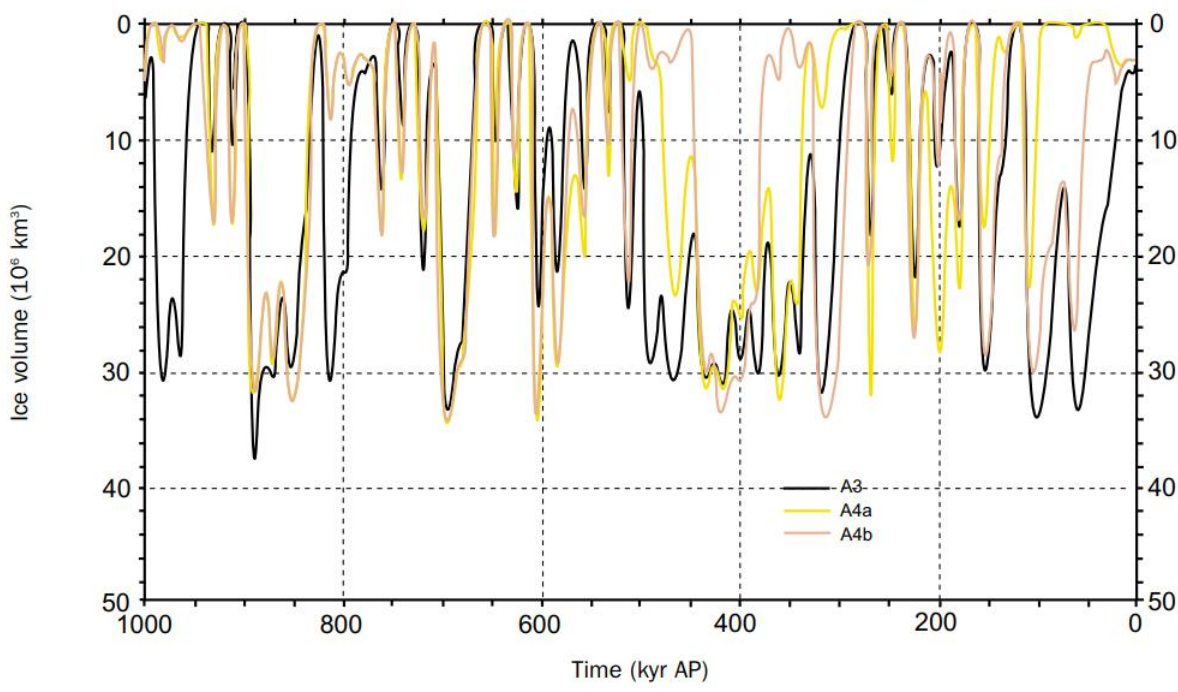
BIOCLIM

CO ₂ scenarios	Constant	Natural variations		Fossil fuel contribution		Combined	
		Burgess's regression	Pallard's threshold model a b		low	high	
A1	280 ppmv				X		+
A2	280 ppmv					X	+
A3		X					
A4a			X				
A4b				X			
A5	210 ppmv						
A6	280 ppmv						
B1		X			X		+
B2		X				X	+
B3			X		X		+
B4			X			X	+
C1		X			X		⊕
C2		X				X	⊕
C3			X	X	X		⊕
C4			X	X		X	⊕



BIOCLIM

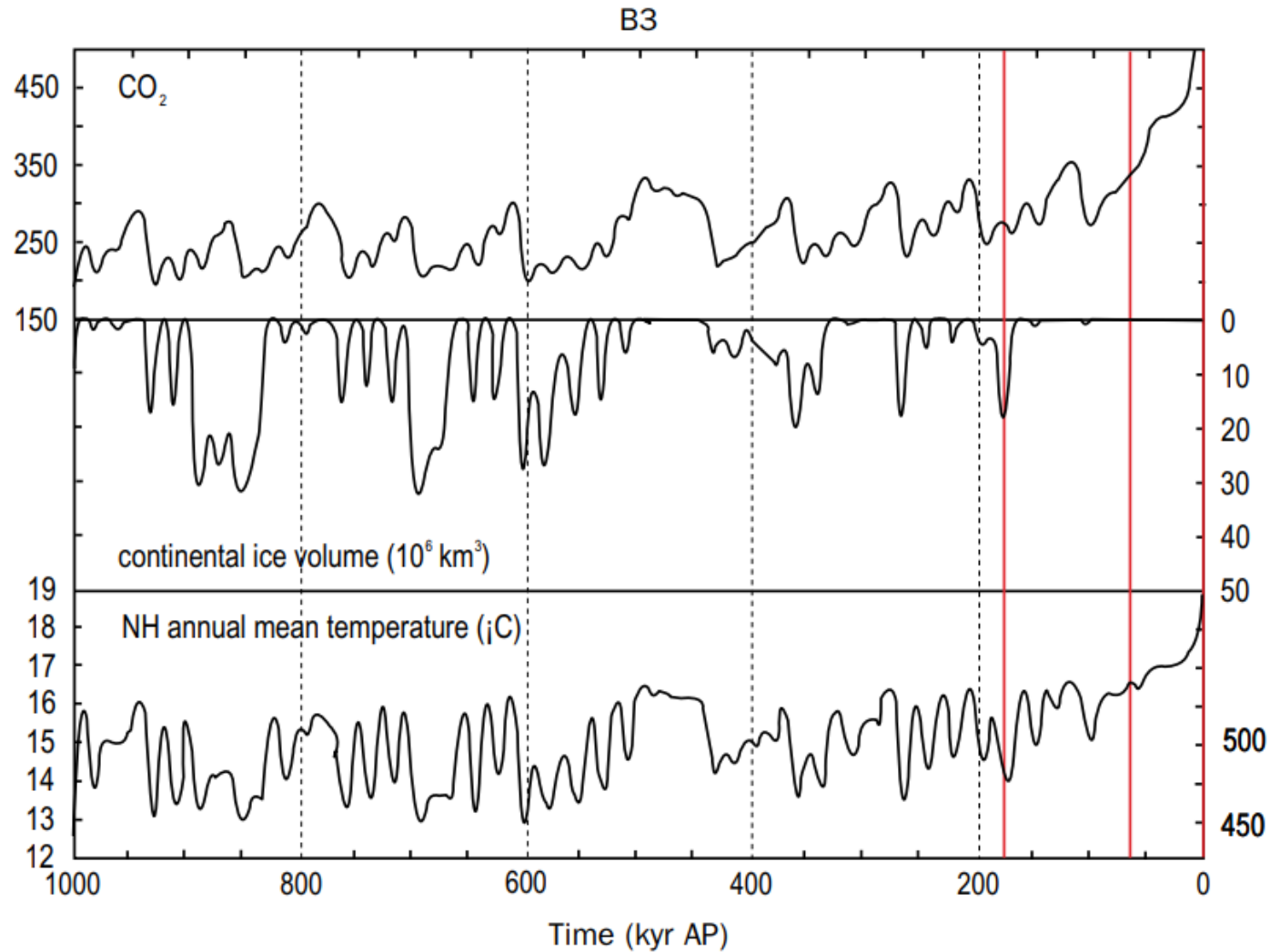
- Northern hemisphere ice volume



Date

Event

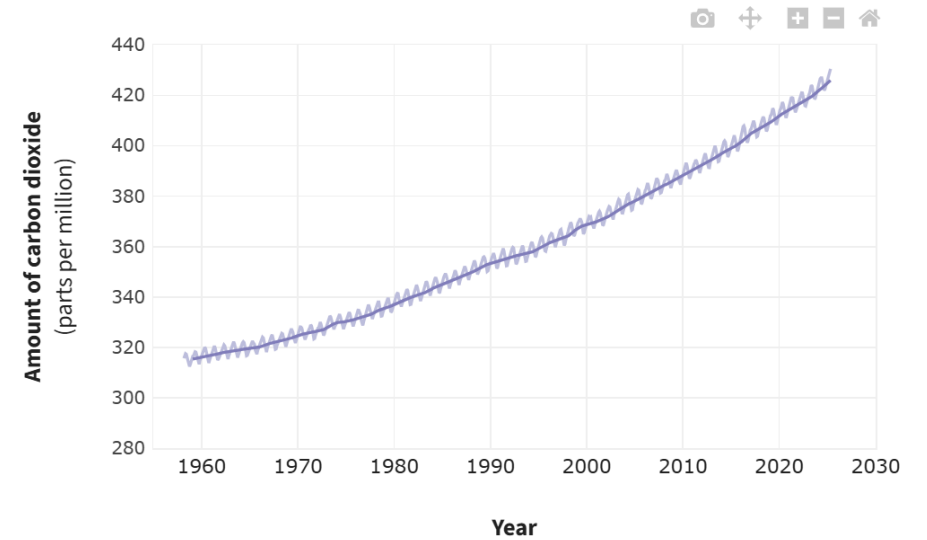
GLOBAL FUTURE CLIMATE: GCM SIMULATIONS OF SNAPSHOTS



Name	Time (kyrAP)	Insolation (Wm-2)	CO ₂ (ppmv)	NH ice volume (106km ³)
"Baseline"	0	0	345	3.2
"A"	0	0	1100	3.2
"B"	0	0	550	0
"C"	67	+42	550	0
"D"	67	+42	345	0
"E"	67	+42	345	3.2
"F"	178	+25	280	17.4

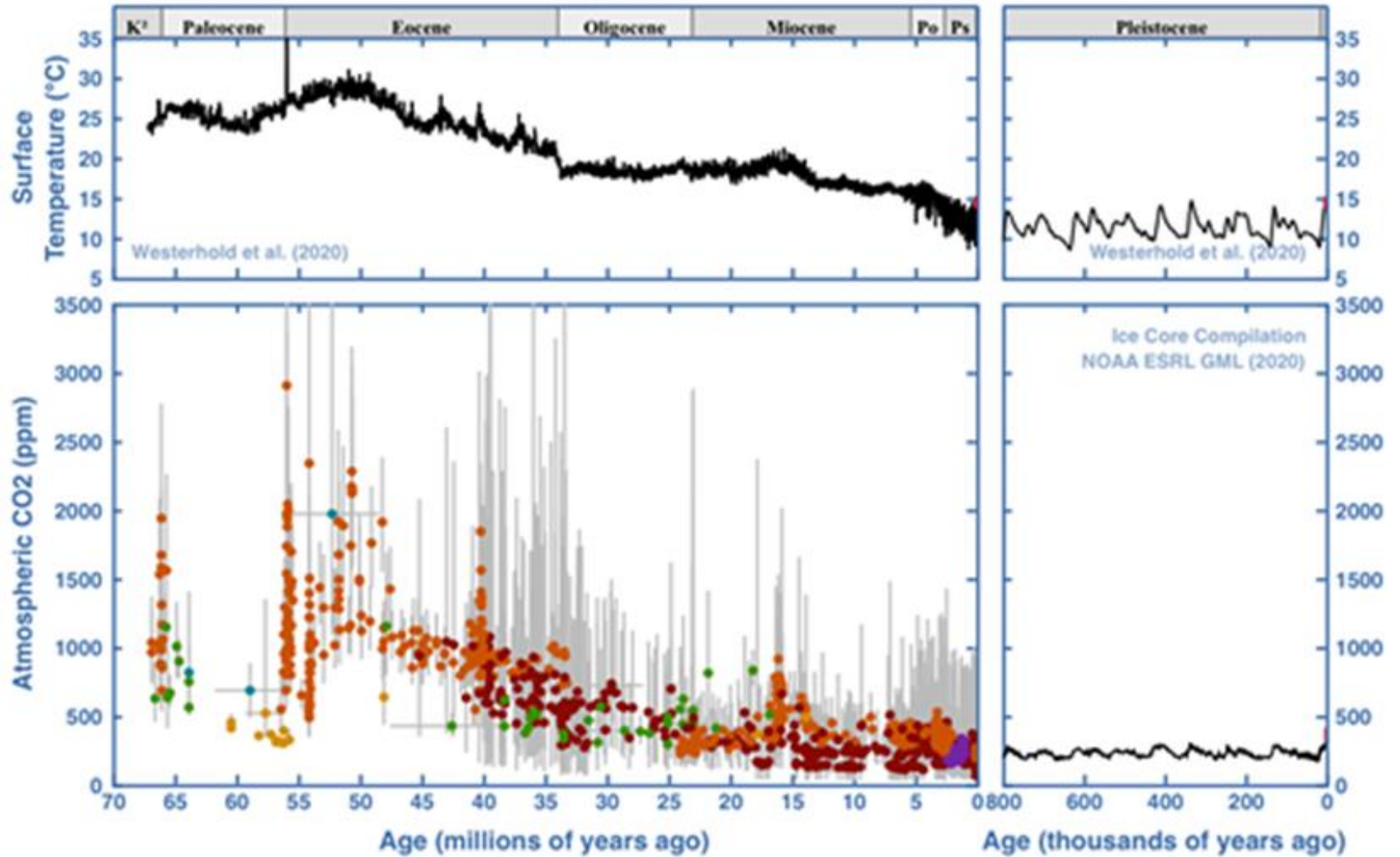
	Globe, ANN	Europe, ANN	Europe, DJF	Europe, JJA
	ΔT_{ANN} Δp_{ANN}	ΔT_{ANN} Δp_{ANN}	ΔT_{DJF} Δp_{DJF}	ΔT_{JJA} Δp_{JJA}
"A"	+2.2 +0.82	+3.0 -9.7	+2.7 -6.8	+3.3 -22.0
"B"	+0.77 +1.1	+0.94 +2.3	+0.75 +2.7	+1.1 +6.0
"C"	+0.69 -0.044	+1.8 +6.6	+1.1 +4.9	+3.6 -2.1
"D"	-0.14 -0.17	+0.69 +8.4	-0.22 +7.3	+2.5 +2.8e-4
"E"	-0.063 -0.087	+0.82 +4.2	-0.024 +1.6	+2.4 -6.8
"F"	-0.95 -0.98	-0.85 +7.7	-0.87 +5.3	-0.33 +1.3

ATMOSPHERIC CARBON DIOXIDE



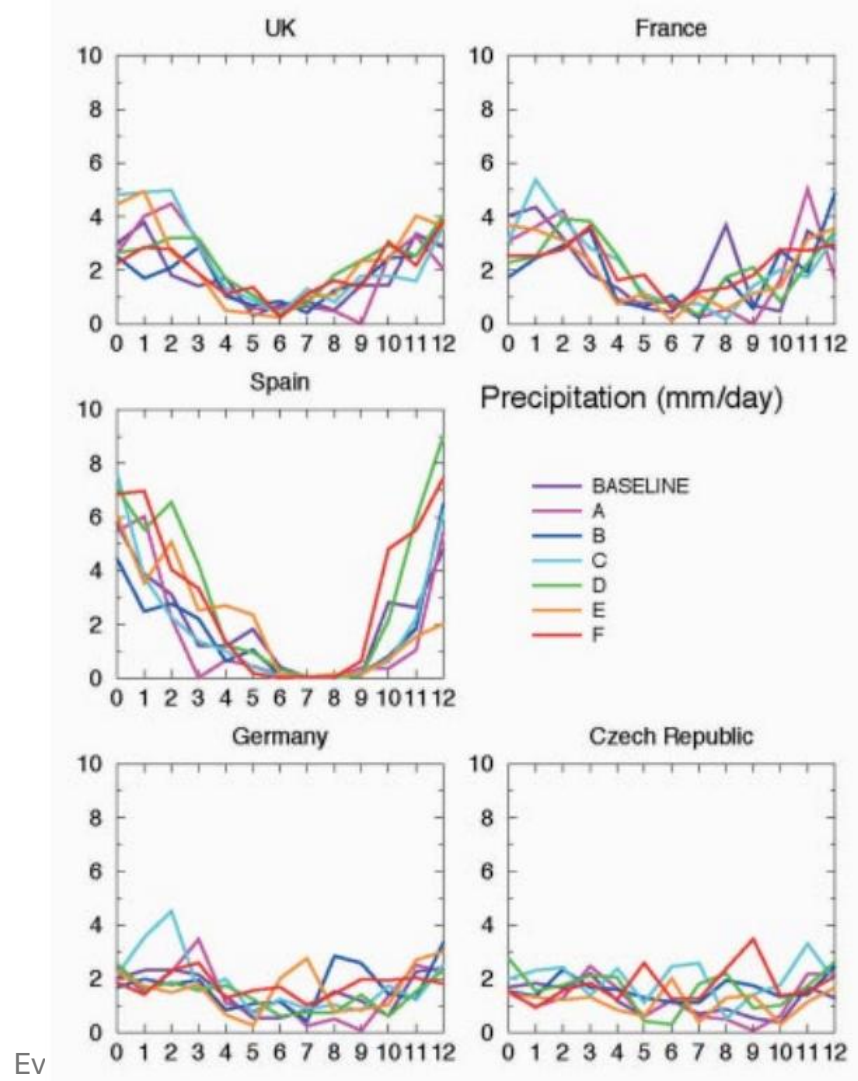
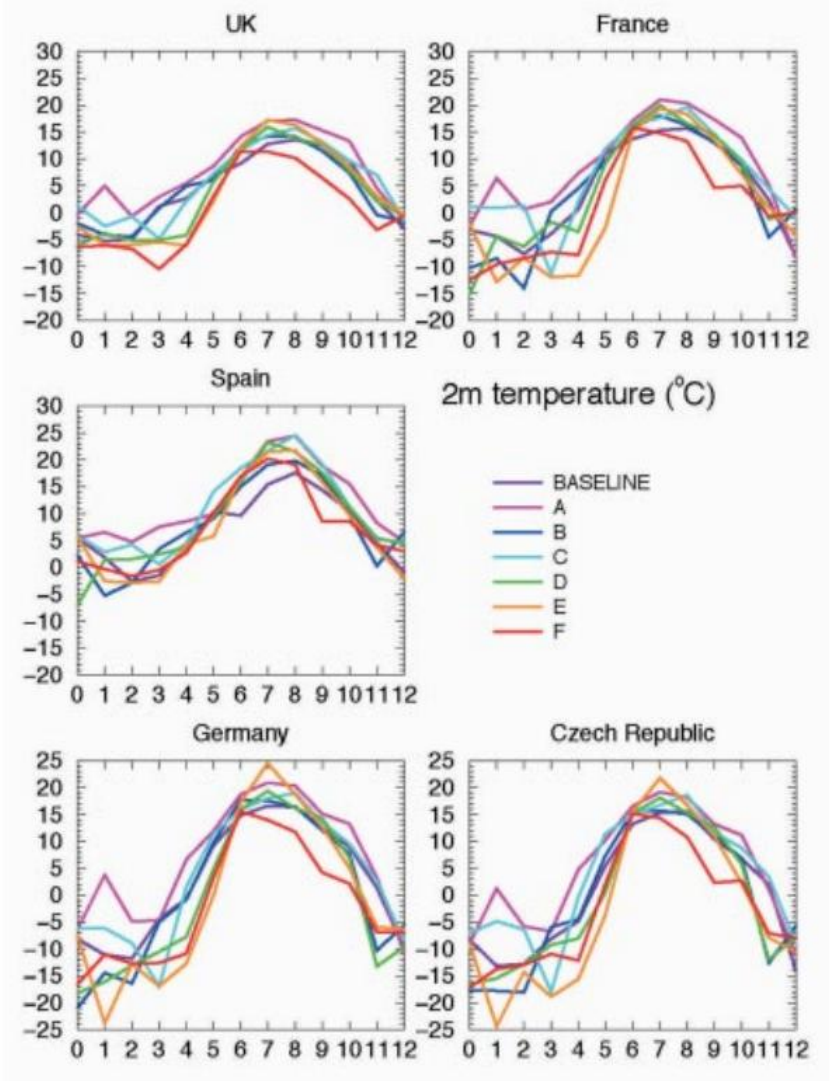


- Phytoplankton
- Boron Proxies
- Stomatal Frequencies
- Leaf Gas Exchange
- Liverworts
- Land Plant $\delta^{13}\text{C}$
- Paleosols
- Nahcolite





DOWNSCALING



Date

Ev



THE FOLLOWING STATEMENTS WERE FORMULATED WITH REGARD TO FUTURE CLIMATE PREDICTIONS FOR NORTHERN BELGIUM

- **Alternation of warm interglacial periods and cold glacial periods will be continued in the next 1 Ma**
 - The Quaternary has been characterised by an alternation of warm interglacial periods and cold glacial periods. Also for the next 1 Ma, it is expected that this alternation of warm and cold periods will be continued
- **It is impossible to predict exact timing and intensity of future glacial and interglacial periods**
 - The future climate scenarios are extremely dependent on the CO₂ scenarios that are used in the calculations
 - Hence, the precise timing of glacial/interglacial periods and the volume of ice caps is considerably different for various climate simulations, especially in the period 0-600 ka AP
- **A spectrum of representative climate conditions is identified for the next 1 Ma**
 - The results of climate modelling and knowledge of past climate changes is used as guidance of the extremes of climate changes to be considered

REPRESENTATIVE FUTURE CLIMATE CONDITIONS FOR NORTHERN BELGIUM (STATUS 2012)

Initial condition	Current climate
Warm interglacial period	Global warming without marine transgression Global warming with marine transgression
Cold glacial period	Cold climate without permafrost Cold climate with permafrost Cold climate with ice-sheet development over Belgium
Transitions	Warm-cold transition Cold-warm transition

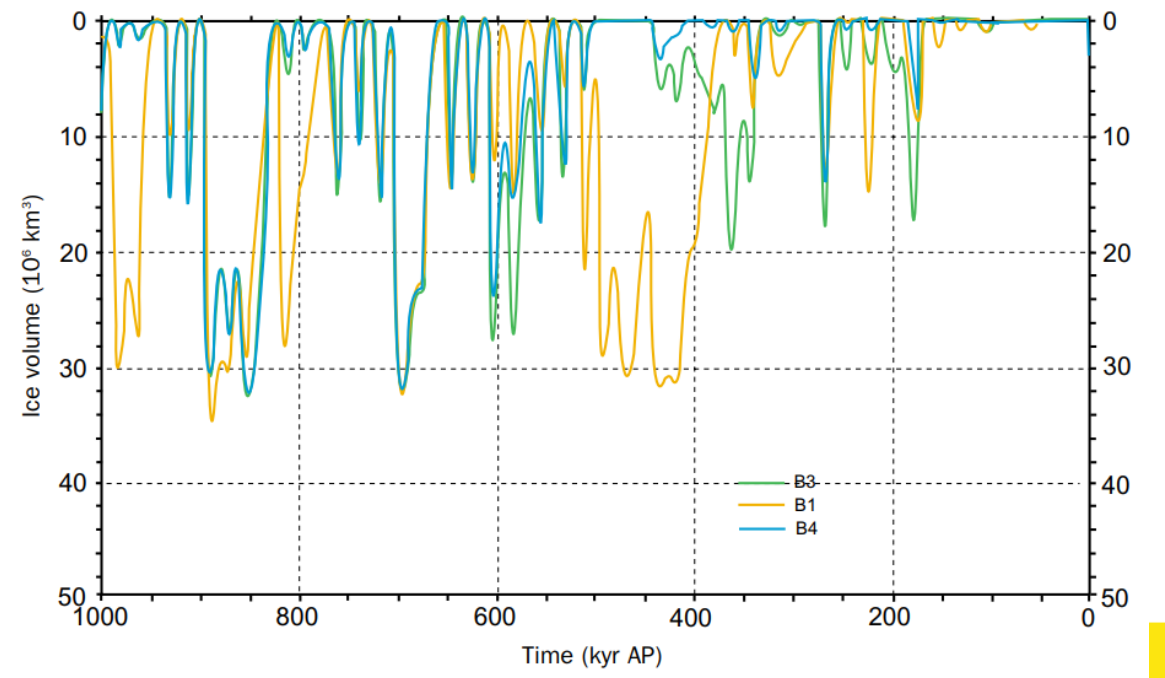
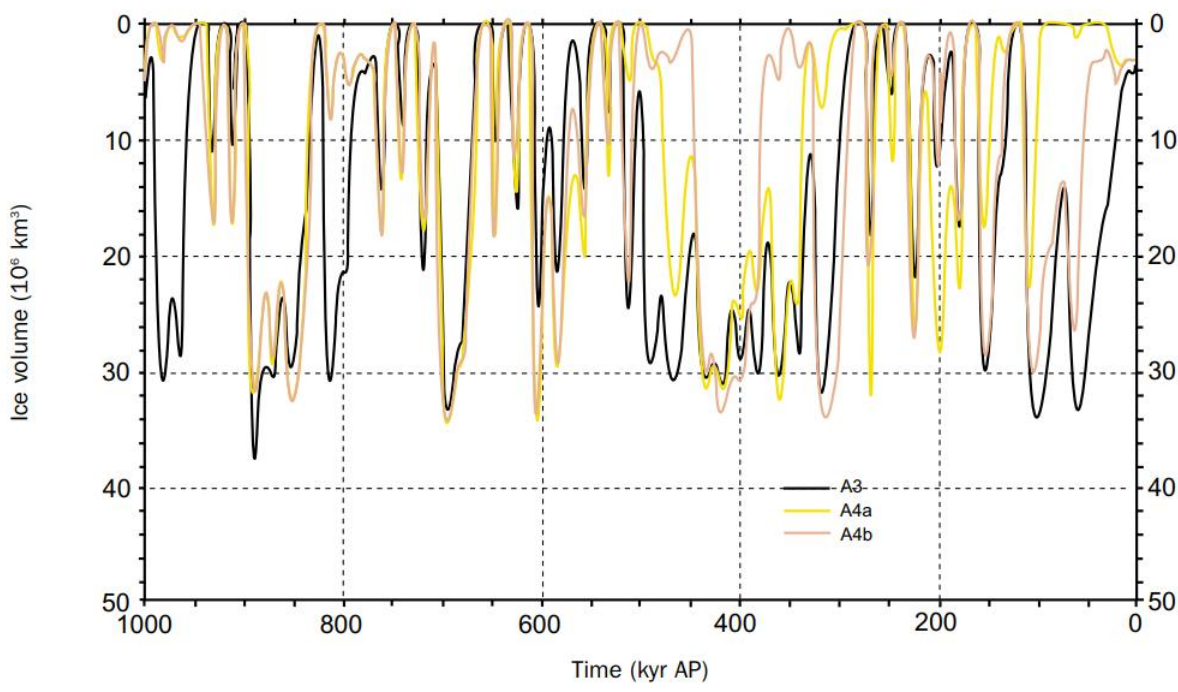
RELEVANT TIMEFRAMES

the period 0-10 ka	Representative for the thermal phase, including a considerable safety margin
the period 10-50 ka	Representative for a warm period without ice caps (A3 and A4b scenarios)
the period 50-170 ka	Representative for a warm period without ice caps (B1, B3 and B4 scenarios)
the period 170-400 ka	Representative for the period with less severe glaciation (B1, B3 and B4 scenarios)
the period 400-1000 ka	Representative period of alternation of warm interglacial periods and cold glacial periods



BIOCLIM

- Northern hemisphere ice volume



Date

Event

CATEGORIES OF LIKELIHOOD

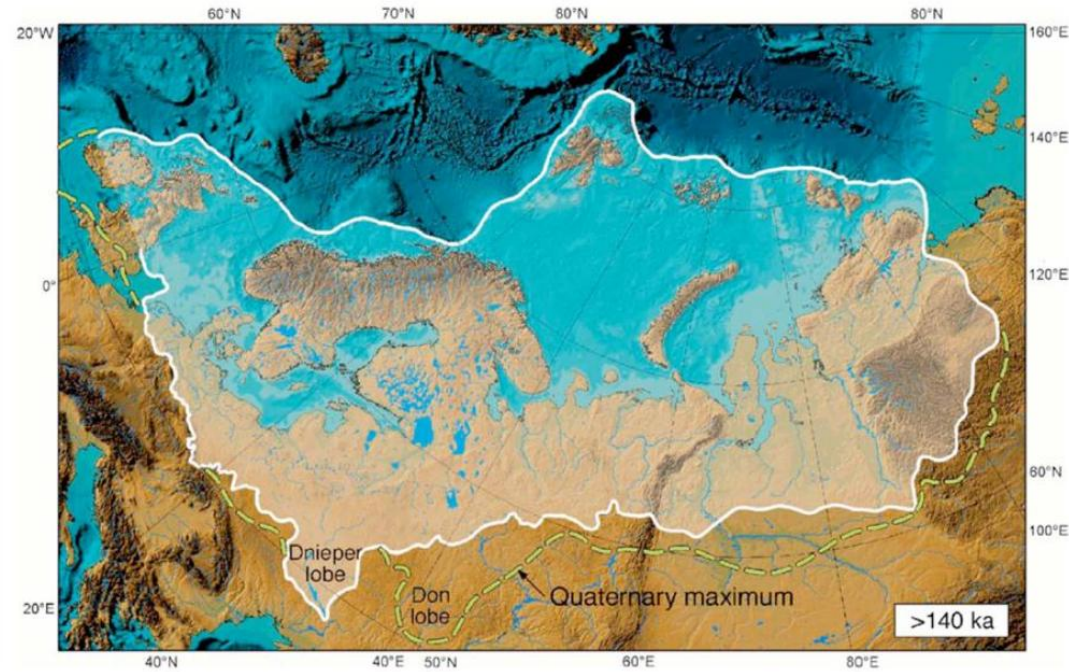
Expected	Such a climate condition is expected to occur within the considered time frame.
Possible	The occurrence of such a climate condition is somewhat possible to occur within the considered time frame.
Unexpected	Such a climate condition is not expected to occur within the considered time frame.

CLIMATE CONDITIONS AND EVALUATION OF THE LIKELIHOOD OF OCCURRENCE IN NORTHERN BELGIUM FOR RELEVANT TIME FRAMES

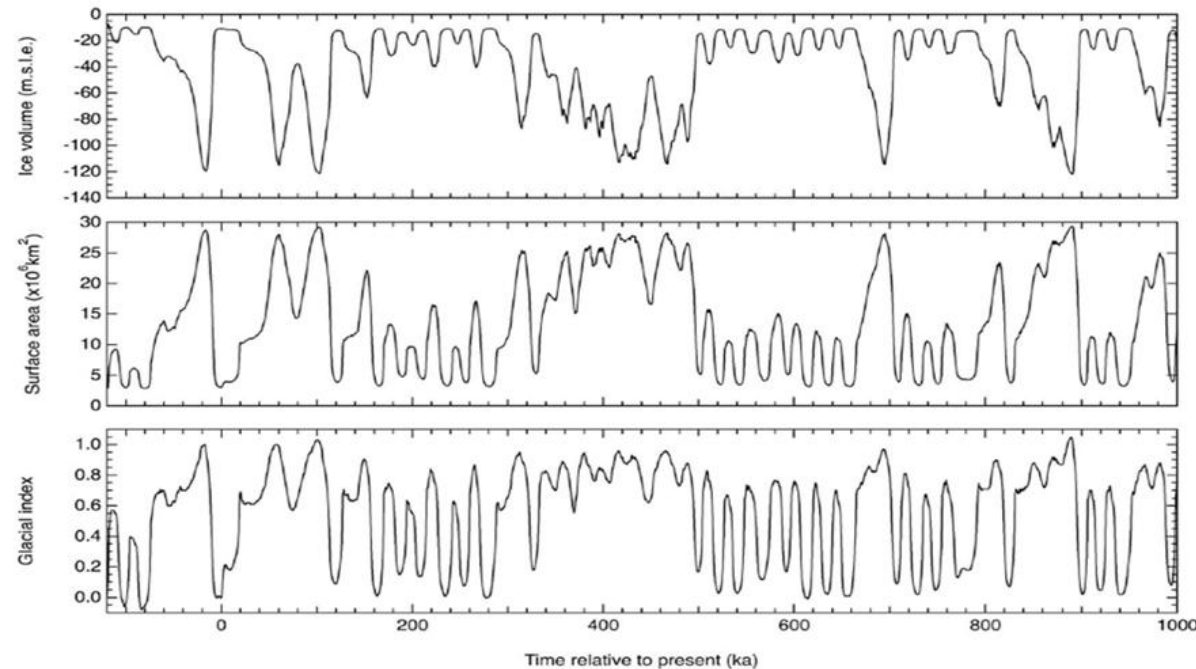
	Period 0-10 ka	Period 10-50 ka	Period 50-170 ka	Period 170-400 ka	Period 400-1000 ka
Current climate	Expected	Expected	Expected	Expected	Expected
Global warming without marine transgression	Expected	Expected	Expected	Expected	Possible
Global warming with marine transgression	Possible	Possible	Possible	Possible	Possible
Cold climate without permafrost	Unexpected	Possible	Possible	Expected	Expected
Cold climate with permafrost	Unexpected	Unexpected	Possible	Possible	Expected
Cold climate with ice-sheet development	Unexpected	Unexpected	Unexpected	Unexpected	Unexpected

EVOLUTION OF NORTHERN HEMISPHERE ICE SHEET CONFIGURATION

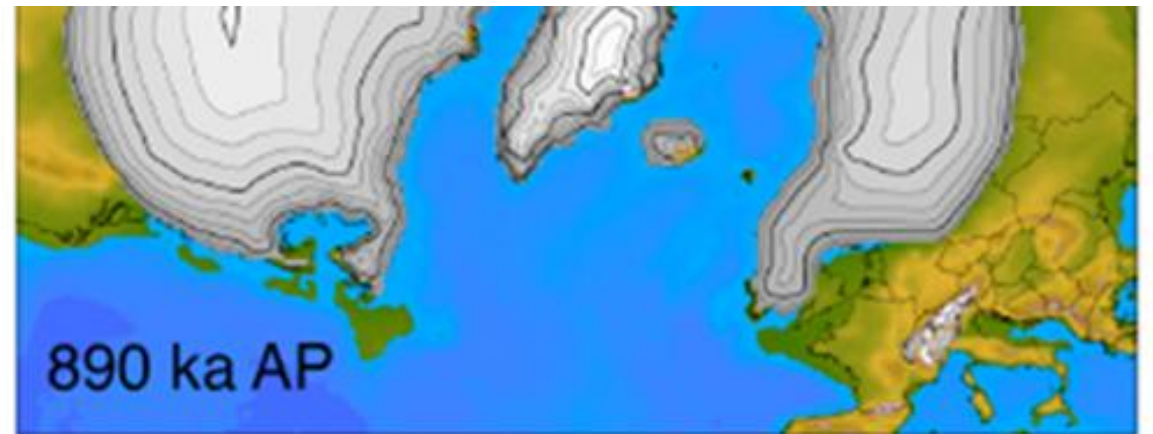
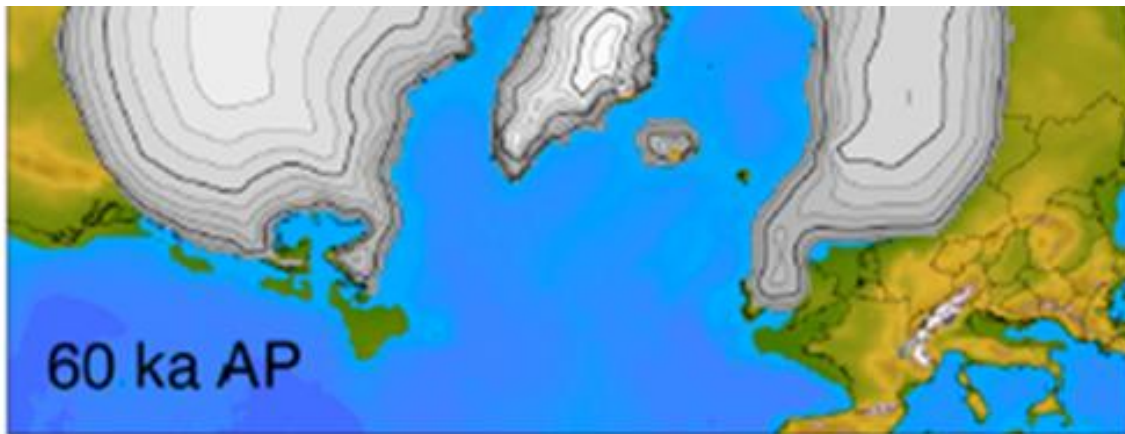
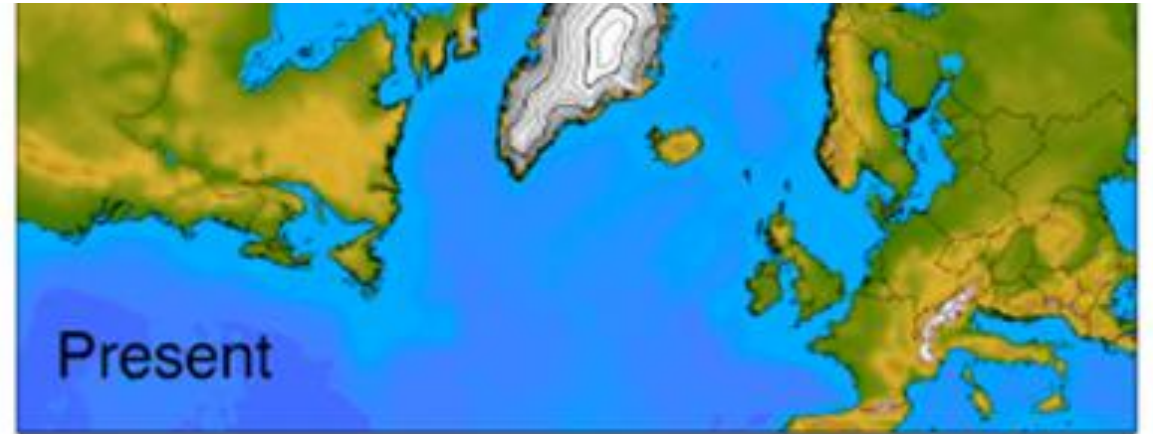
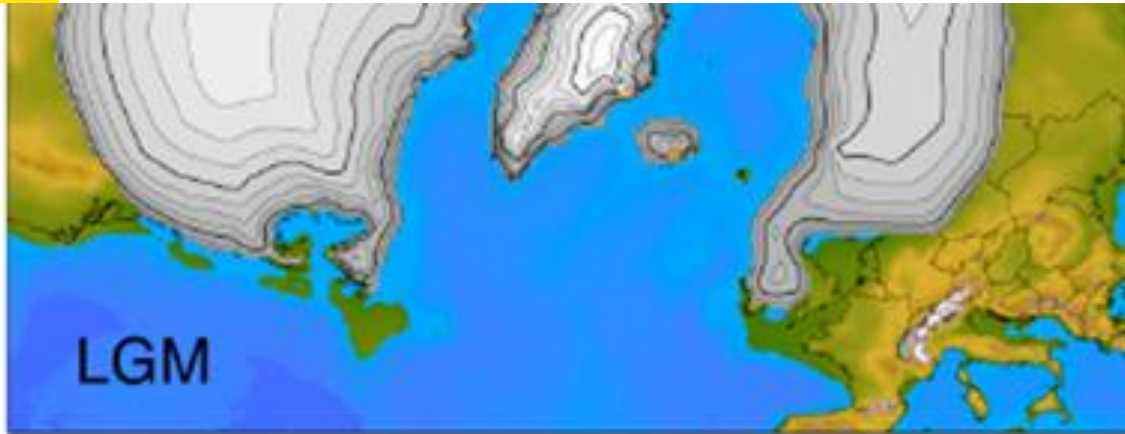
- Evidence from the geological record
- BIOCLIM A3 scenario
- Model that predicts the 3-dimensional geometry of ice sheets in response to changes in
 - surface temperature
 - precipitation
 - eustatic sea level



Svensson, 2004



Huybrechts, 2010



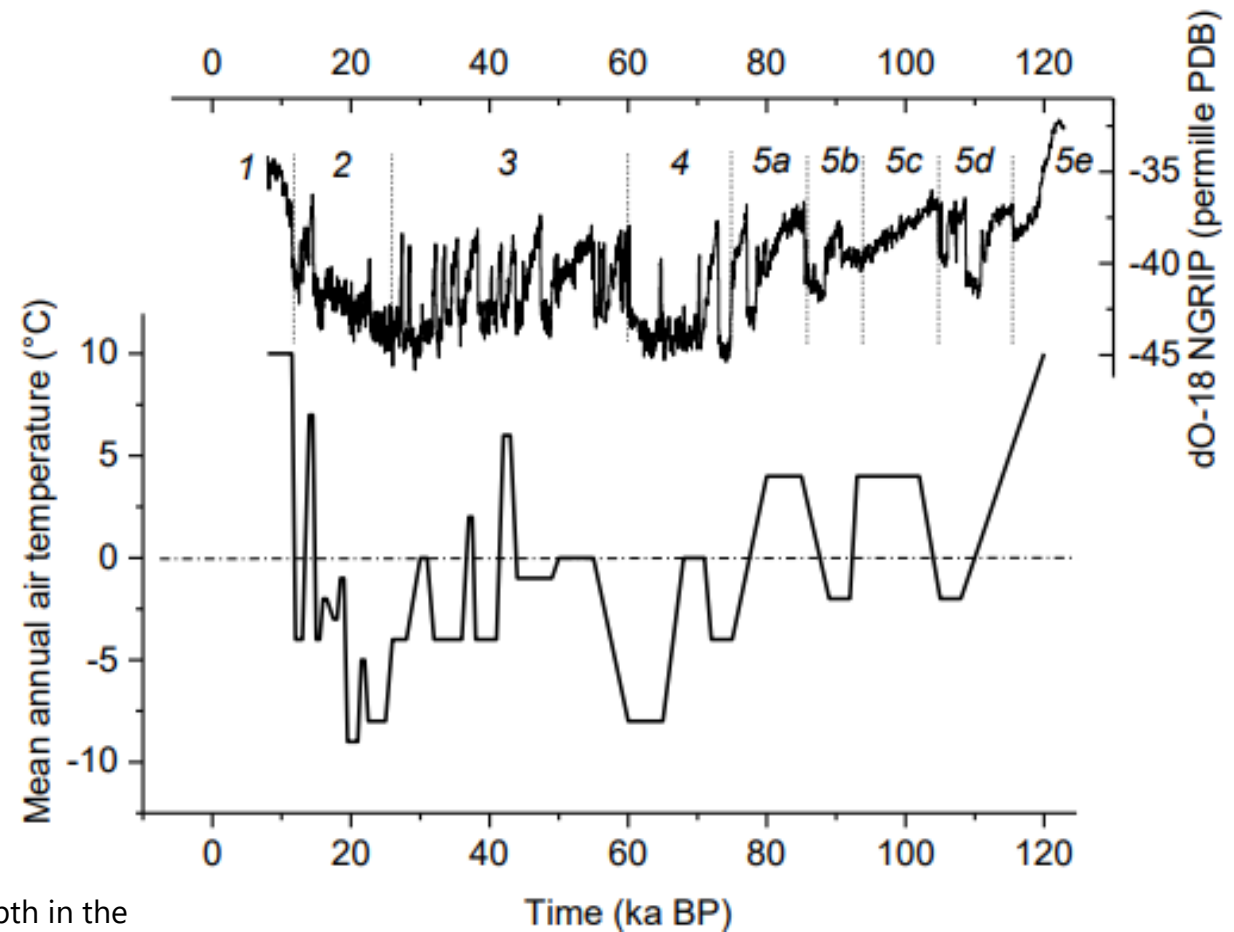
Huybrechts, 2010

Date

Event

PAST GLACIAL CYCLE AS AN ANALOGUE FOR PERMAFROST EVOLUTION DURING A NEXT GLACIAL PHASE: BEST ESTIMATE (NETHERLANDS, COVRA)

- MIS5: pollen data
- MIS4: periglacial deformation phenomena in the subsoil
- MIS3: periglacial features + pollen data
- MIS2: periglacial features

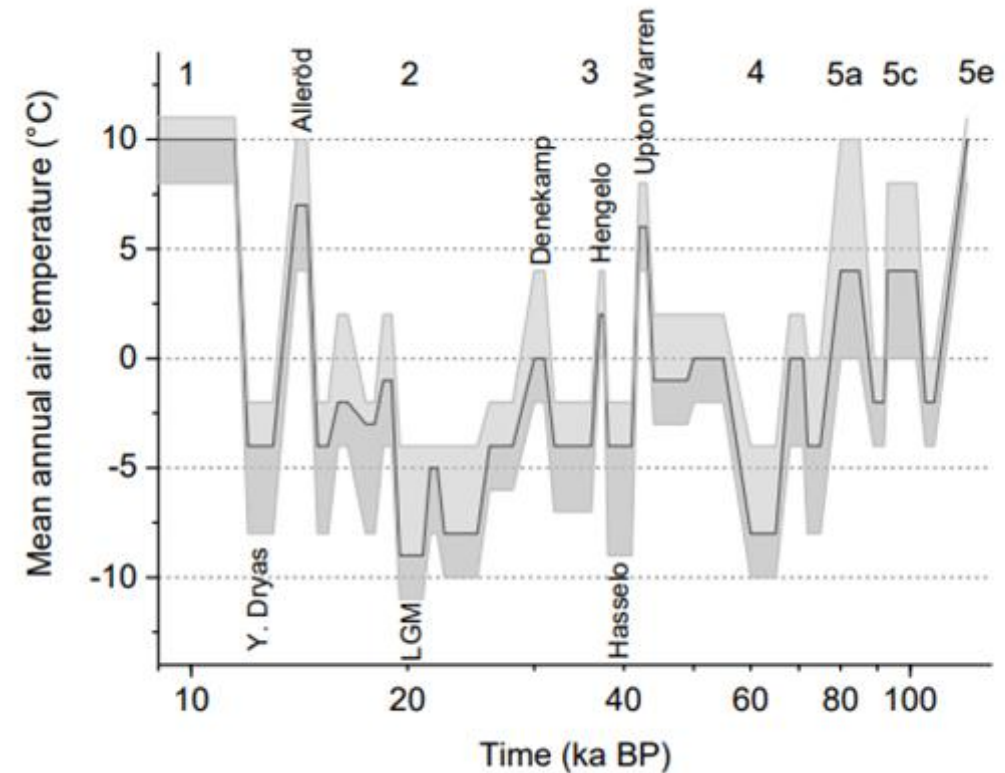


Govaerts, J., Beerten, K., & ten Veen, J. (2016). Weichselian permafrost depth in the Netherlands: a comprehensive uncertainty and sensitivity analysis. *The Cryosphere*, 10, 2907-2922. <https://doi.org/10.5194/tc-10-2907-2016>

PAST GLACIAL CYCLE AS AN ANALOGUE FOR PERMAFROST EVOLUTION DURING A NEXT GLACIAL PHASE: UPPER AND LOWER BOUNDS

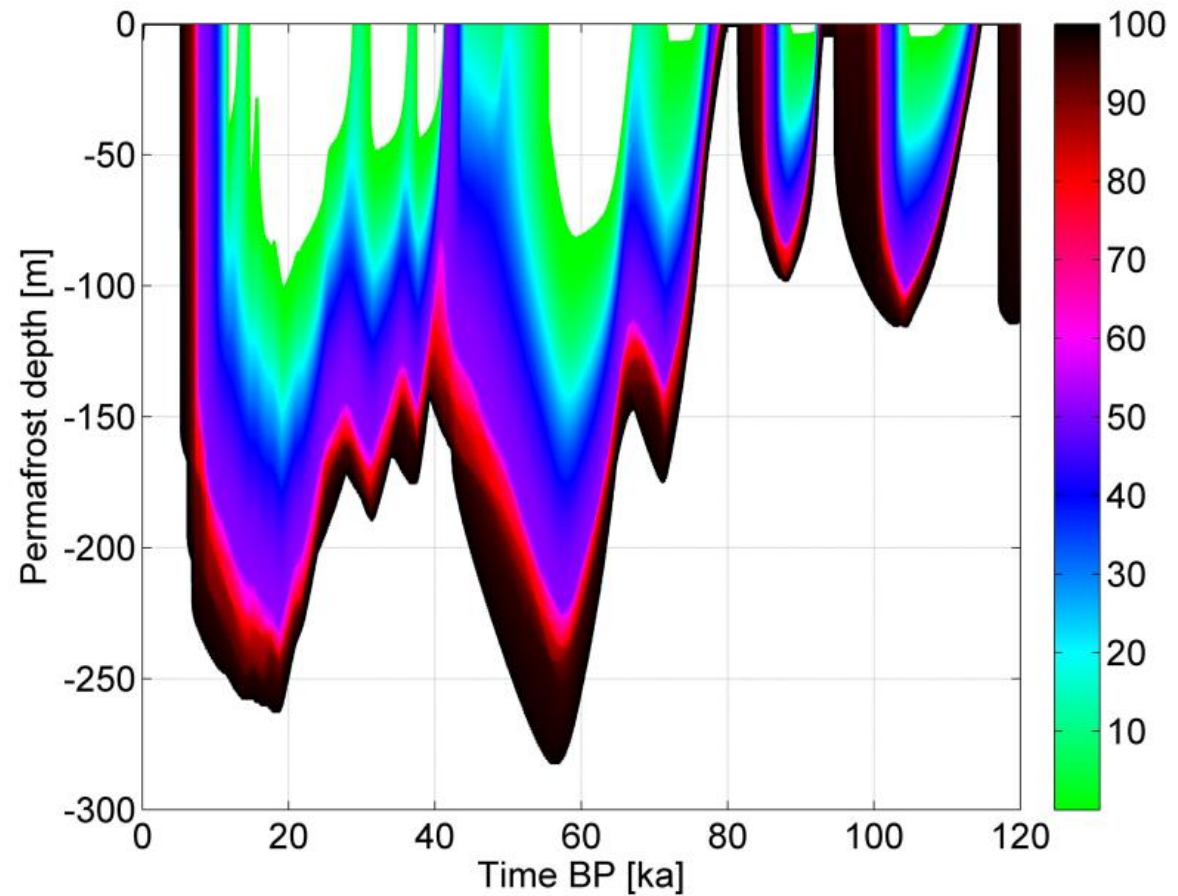
- **Different sources of uncertainty**

- reliability of the palaeotemperature proxy
- transferability towards a future glacial climatic cycle
- temperature gradients across the country
- atmosphere–soil temperature coupling



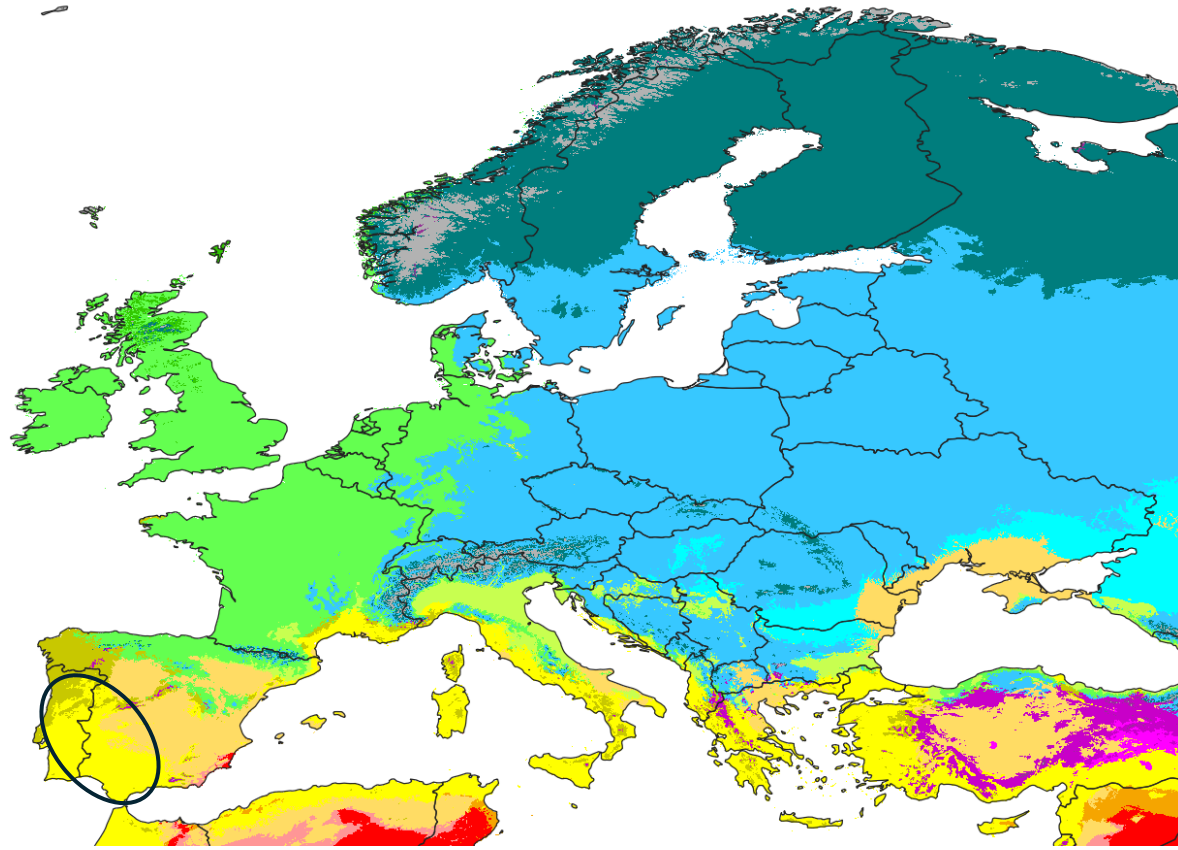
STOCHASTIC UNCERTAINTY ANALYSIS OF NATION-WIDE PERMAFROST PENETRATION DEPTH

- Upper boundary condition: temperature
- Lower boundary condition: geothermal heat flux
- Subsoil properties
 - Density
 - Porosity
 - Specific heat
 - Thermal conductivity





LONG TERM, CLIMATE Csa



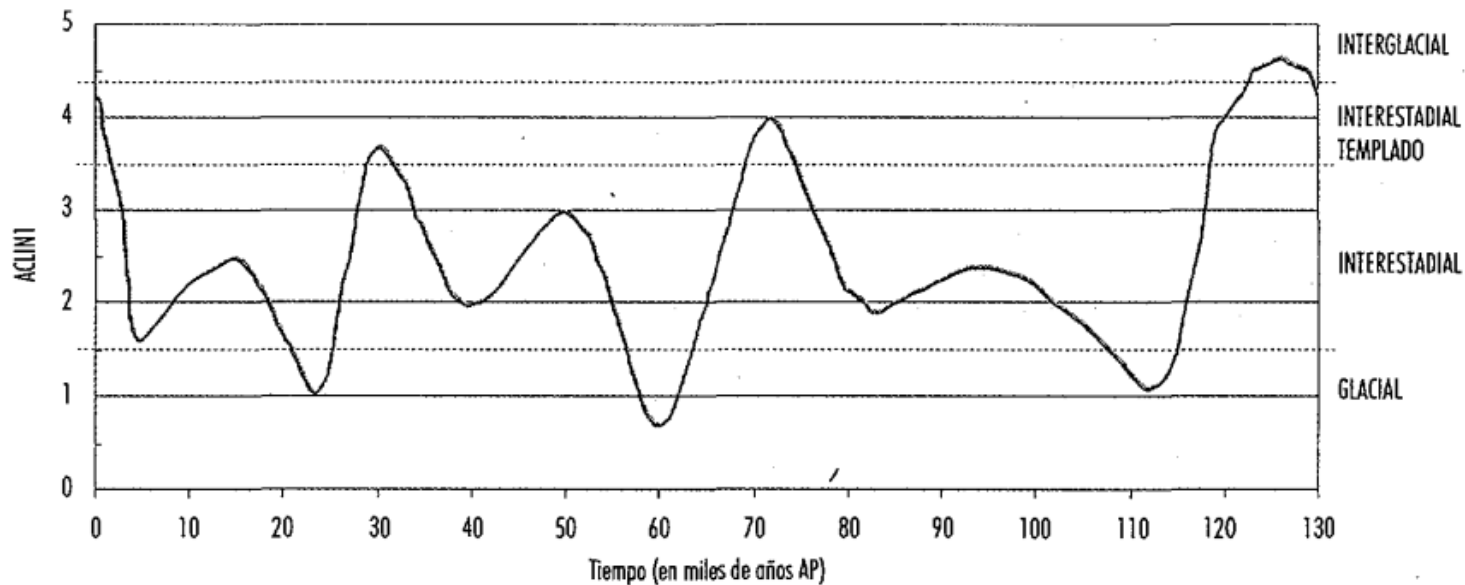
Date

Event



LONG-TERM PROJECTIONS (ENRESA), STATUS 2001

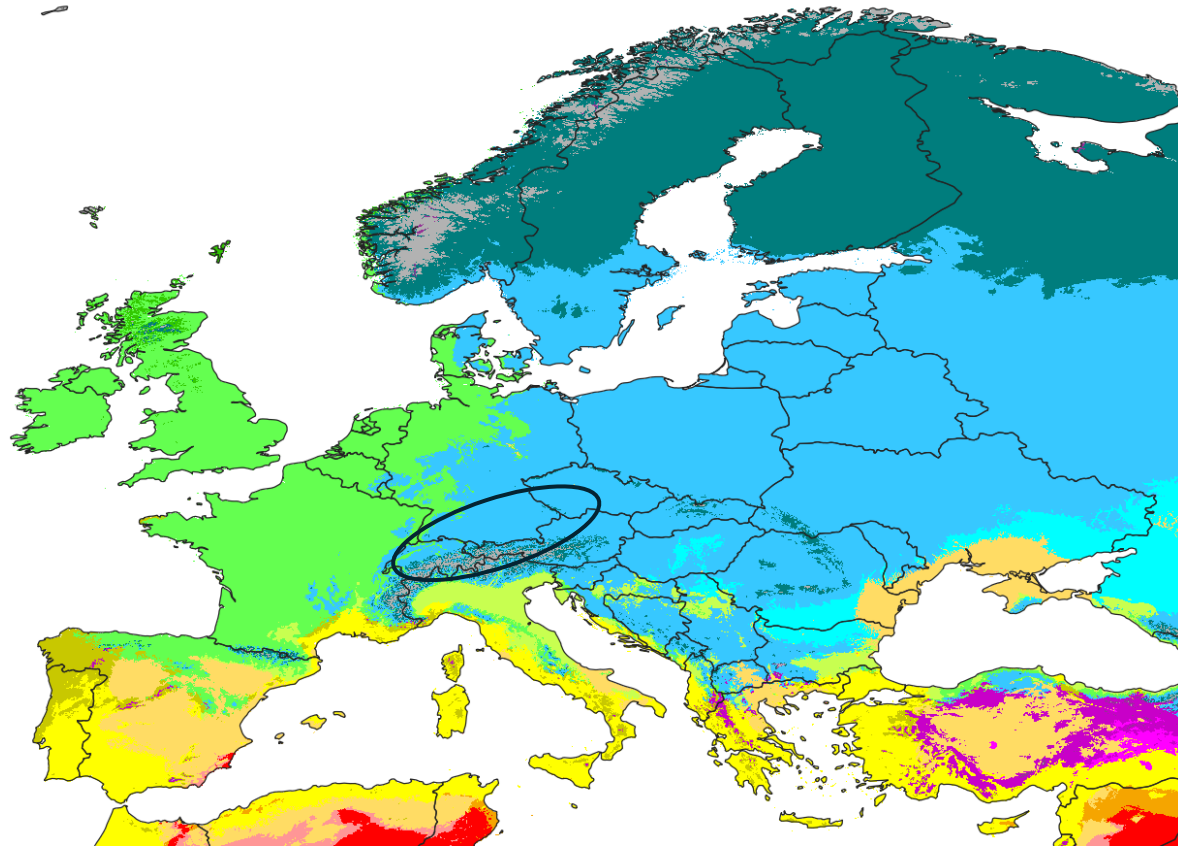
- Combination of paleoclimatic and paleohydrological reconstructions from geological records with orbital climate models calibrated against Quaternary marine stratigraphic series
- Alternation between prolonged “cold-wet” and “warm-arid” phases



Delgado, A., Reyes, E., Pinedo, P., Recreo, F., Torres, T., Cortés, A. 2001. La evolución climática a largo plazo y evaluación de la seguridad. IV Jornadas de I+D en gestión de residuos radiactivos. Sesión V: Evaluación de la seguridad de las instalaciones de gestión de residuos radiactivos.
Date Event



LONG TERM, CLIMATE Dfb <50°N



Date

Event



HYPOTHETICAL CLIMATE SEQUENCE (SURAO, CZ)

- A hypothetical scenario (scenario D) by combining modelling and extreme Quaternary climatic conditions
- 0 – 50 ka AP: **Current climatic conditions, cf. extended interglacial**
 - Average annual temperatures 5 – 9 °C. Average annual precipitation 700 mm. Groundwater recharge: cca 4 l/s/km² = 126 mm/year.
- 50–150 ka AP: The period of **glacial onset**, from past glacial cycles (typically ca. 100,000 years)
 - Average annual temperatures of –2 to 5 °C with highly variable average annual precipitation of ~300–600 mm. A 20% increase in groundwater recharge compared to the current state (151 mm/year).
- 150–175 ka AP: The **peak of the glacial** period with the presence of **permafrost** and zero groundwater recharge (periglacial conditions, maximum cooling and drying of the climate). Is usually a bit shorter but conservative approach
 - Average annual air temperatures ~–7 to –2 °C with average annual precipitation from 250 to 350 mm.
- 175–200 ka AP: **Interglacial conditions** (maximum warming and humidification of the climate. Usually a bit shorter but conservative approach)
 - Average annual air temperatures of ~8–11 °C with average annual precipitation of ~800–900 mm. A 30% increase in groundwater recharge compared to the current state (164 mm/year).

REDUCED COMPLEXITY MODEL TO ESTIMATE GLACIATIONS (CH, NAGRA)

- **Computationally inexpensive modelling tool which can simulate the future evolution of the global ice volume and CO₂ concentration in response to anthropogenic perturbation**

Talento, S. and Ganopolski, A.: Reduced-complexity model for the impact of anthropogenic CO₂ emissions on future glacial cycles, *Earth Syst. Dynam.*, 12, 1275–1293, <https://doi.org/10.5194/esd-12-1275-2021>, 2021

- **Equation for global ice volume**

$$\frac{dv}{dt} = \frac{b_1 v - b_2 v^{3/2} - b_3 (f - \bar{f}) - b_4 \log(\text{CO}_2)}{1 - b_5 M_v} + b_6$$

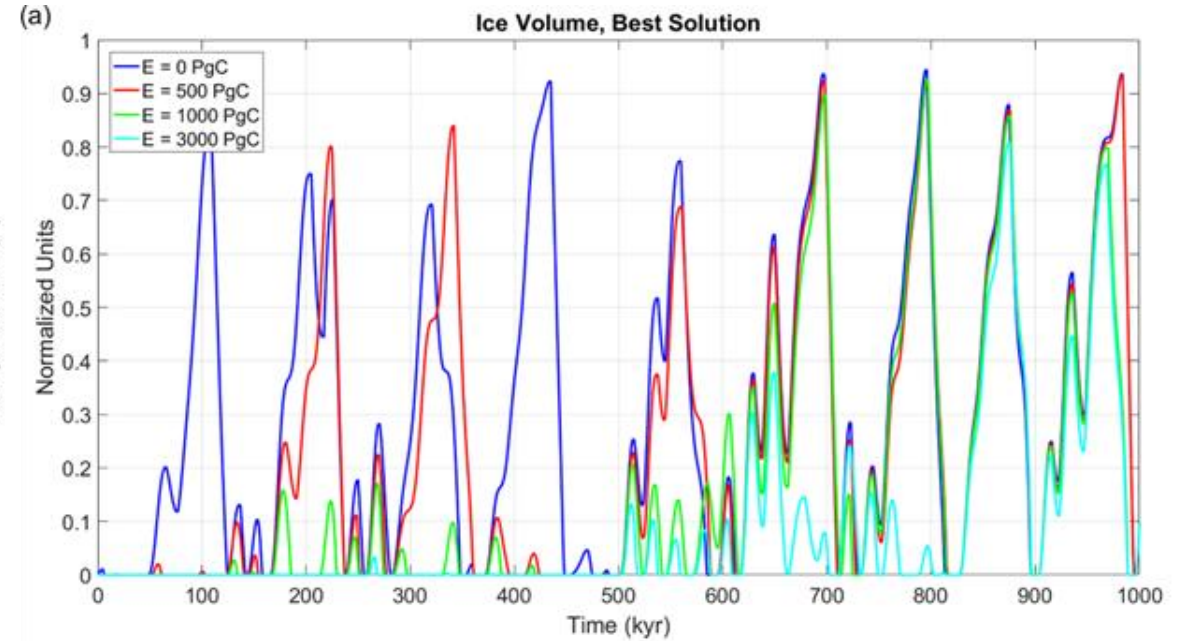
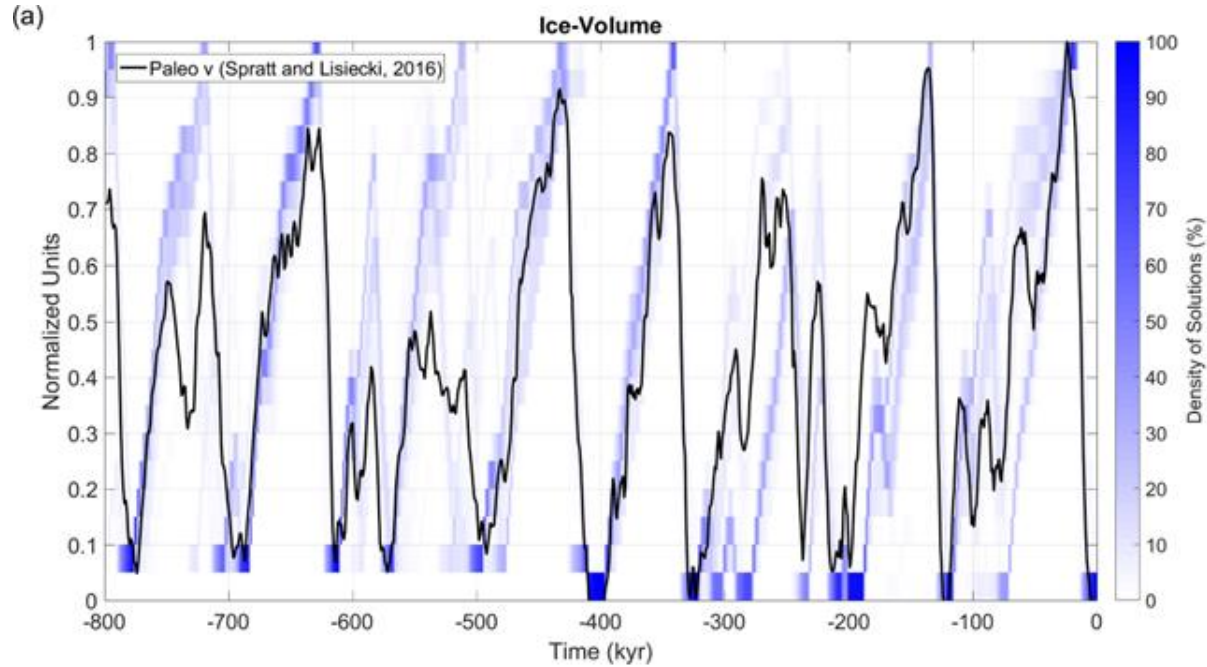
- **Equation for atmospheric CO₂ concentration**

$$\text{CO}_2 = c_1 T + c_2 v + c_3 \min\left(\frac{dv}{dt}, 0\right) + c_4 + \text{Anth}_{\text{CO}_2}$$

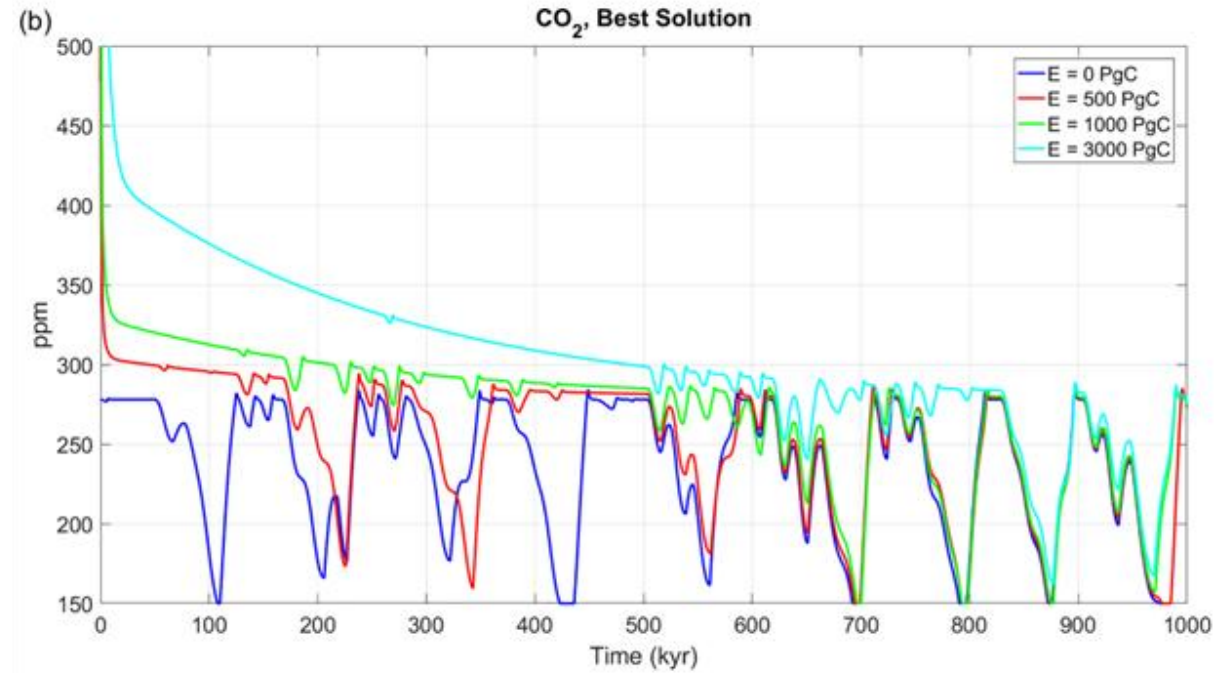
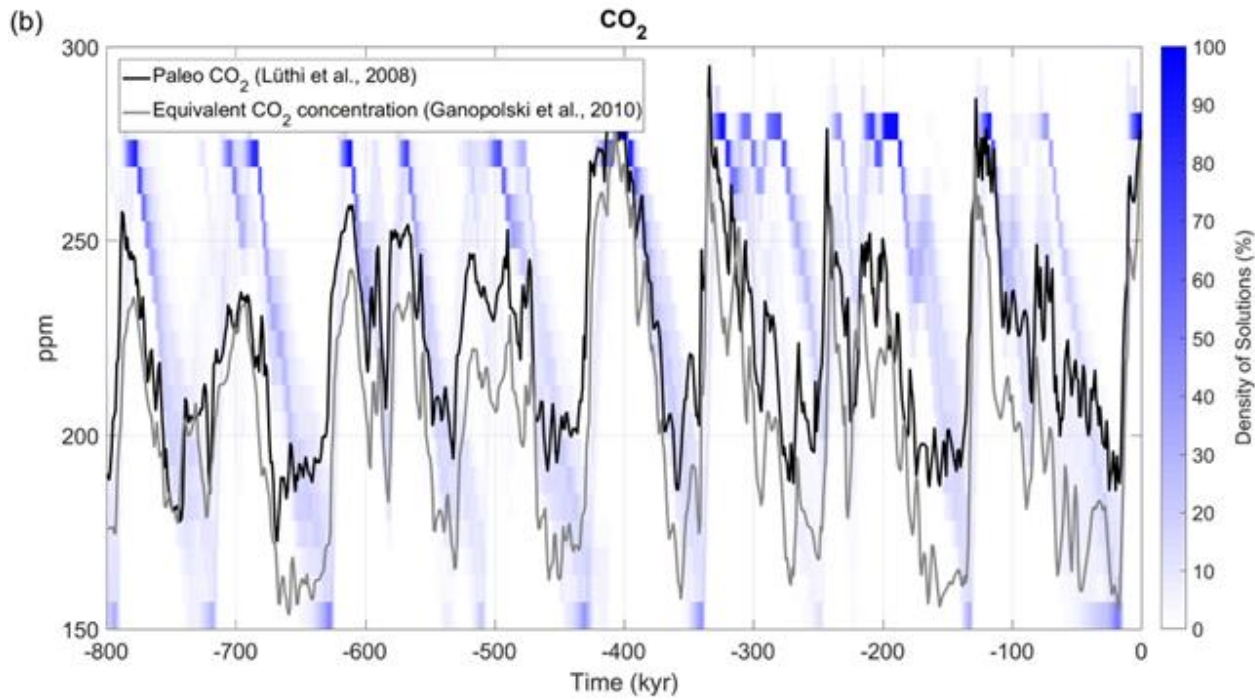
- **Equation for global mean surface temperature**

$$T = d_1 v + d_2 \log\left(\frac{\text{CO}_2}{278}\right)$$

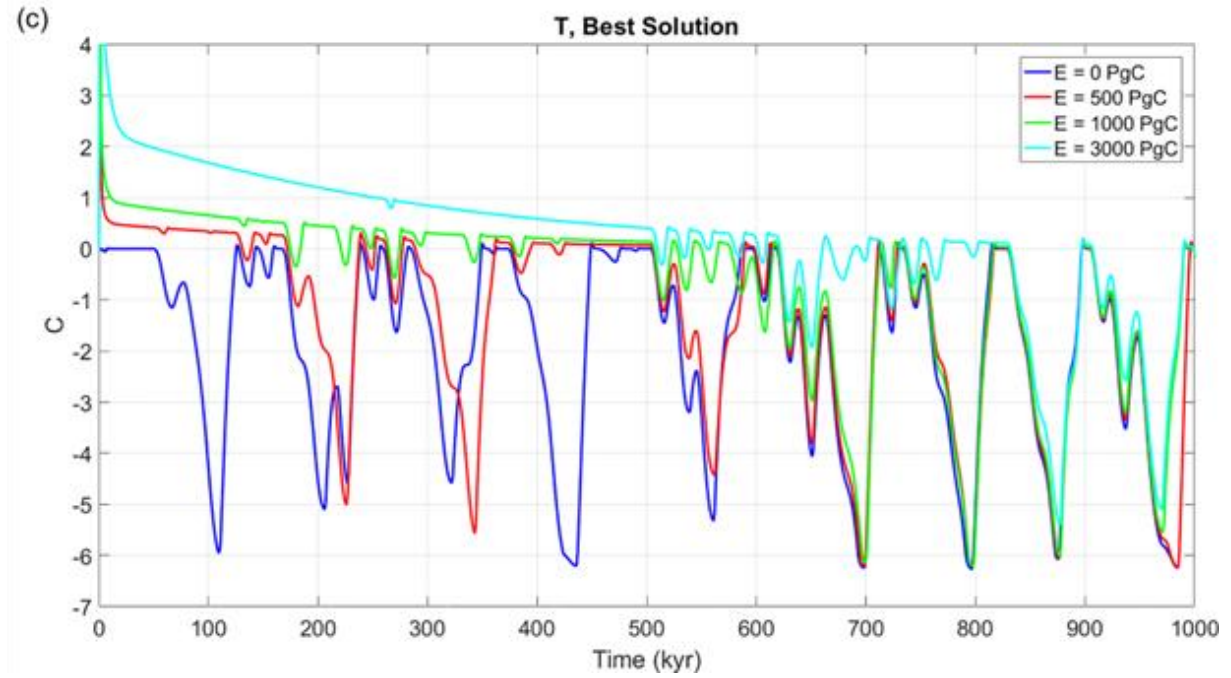
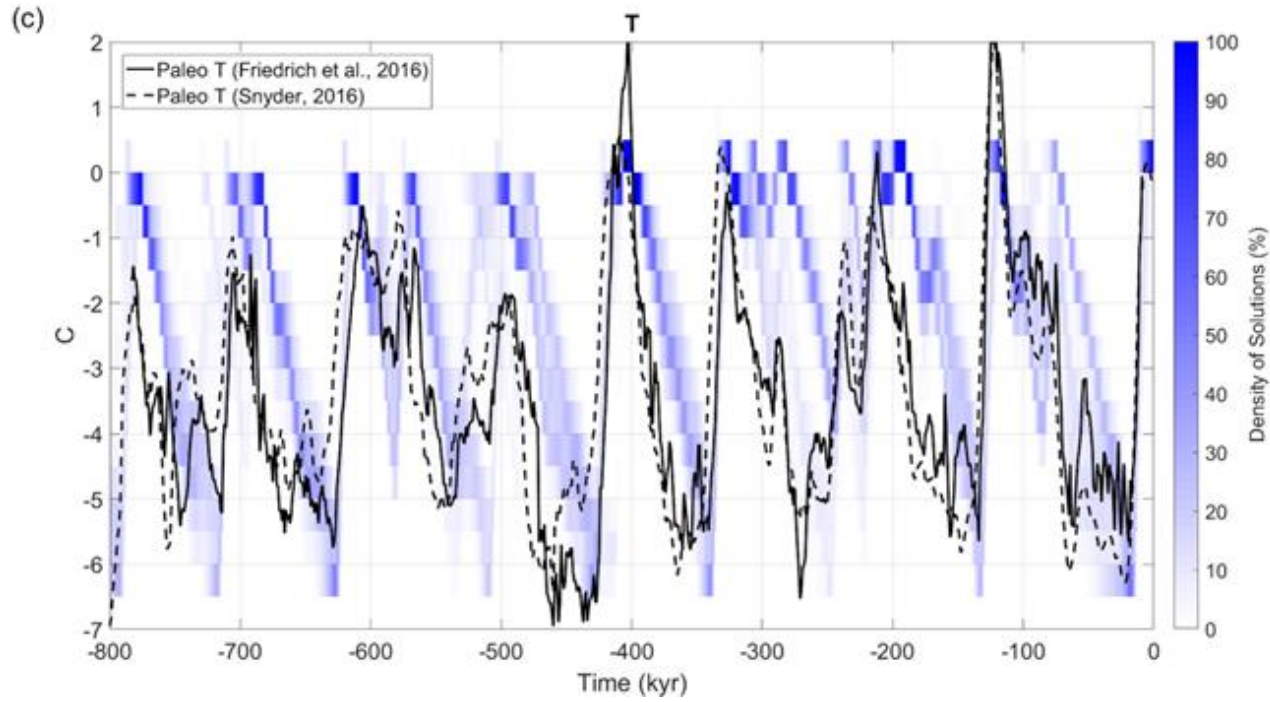
ICE VOLUME



CO2 CONCENTRATION

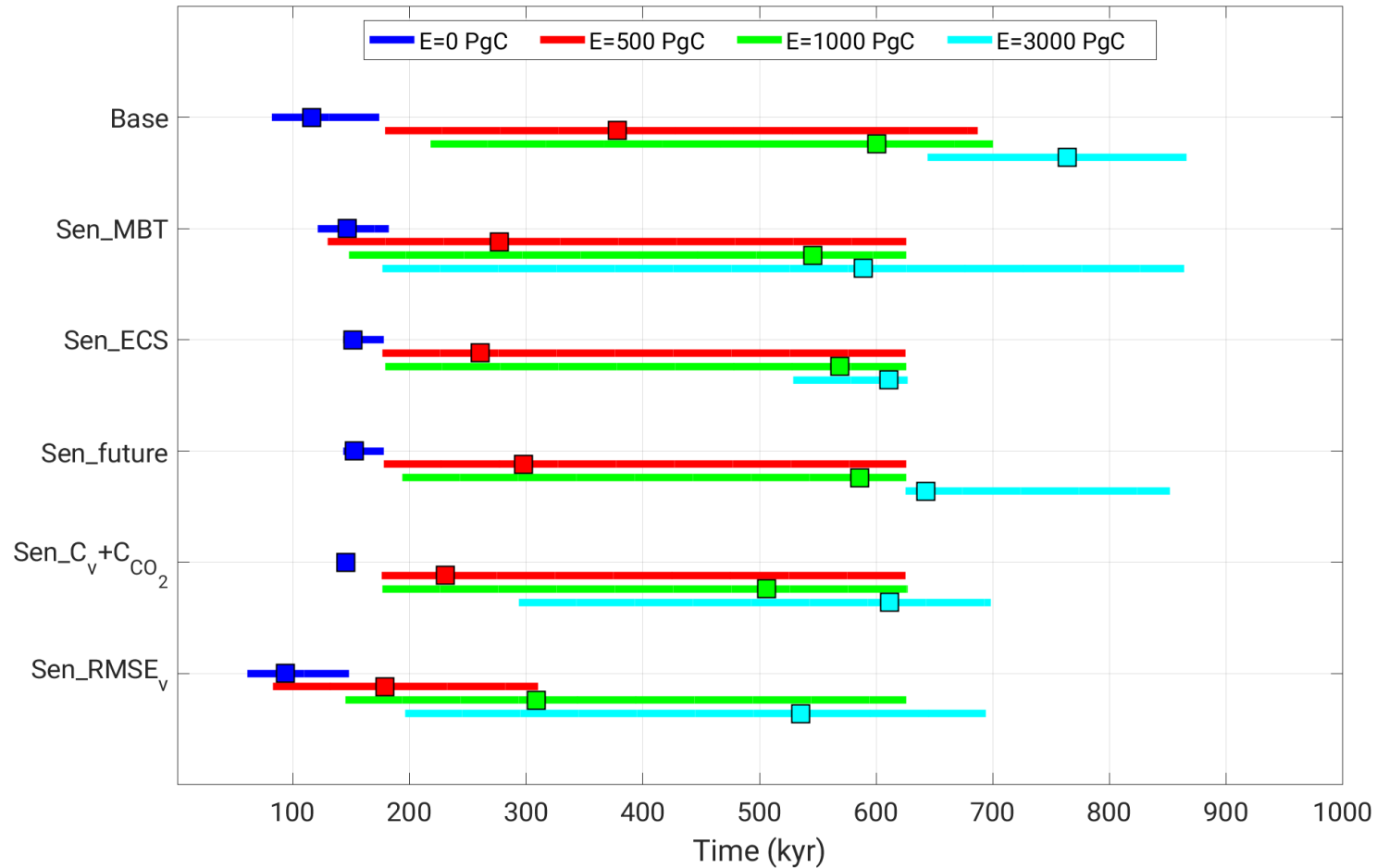


TEMPERATURE



POSSIBLE SCENARIOS

Sensitivity experiments:
Timing of next Full Glacial conditions
Accepted ensemble



CONCLUSIONS

- **Climate change is fast – impact assessment scenarios from the beginning of the century may not be representative anymore**
- **Gap between typical climate change scenarios for the next 100 years from GCMs and long-term scenarios for the next hundred thousands of years**
 - Long-term:
 - EMICs and GCMs: meteorological variables available but very computational expensive
 - Reduced-complexity and energy balance models: can be sufficient if looking at one phenomenon (e.g. ice-sheet)
 - Past climatic cycles
- **Many different approaches**
 - Various degrees of conservatism
 - Detailed time-series vs. representative climate states
 - Climate classifications not always precise enough when detailed meteorological parameters are needed
- **Future work: find a common and consistent approach to formulate assessment scenarios, taking into account uncertainties**

Climate add-on of the PEP game

WP11 - CLIMATE online training session

Alexis Geisler-Roblin, NTW, Task 5 leader
Julien Dewoghélaëre, NTW



Co-funded by the European Union under Grant Agreement n° 101166718

WHAT IS THE PEP ?



PEP is an acronym for Pathways Evaluation Process

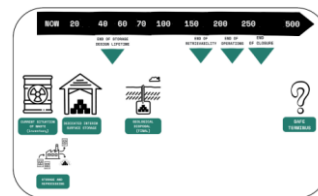
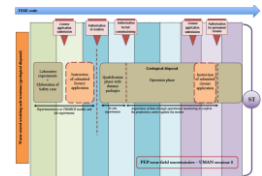
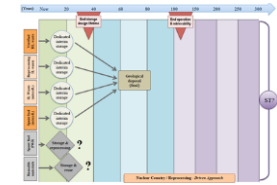
- It is an interactive dialogue tool in the form of a serious game, enabling a discussion on PEP scenarios (concrete situations elaborated by the participants) related to the long-term management of radioactive waste

Objectives of PEP

- Putting into discussion different strategies (pathways) allowing to reach a safe situation for the long term (safe terminus)
- Identifying issues that would really matter for different categories of actors who do not have the same vision of what should be the safe situation of radioactive waste for the long term
- Enabling a better understanding of the different participants' views and fruitful interactions

CONTEXT OF THE PEP EMERGENCE

- SITEX-II project (2015-2017) : task dedicated to intergenerational governance in the framework of radioactive waste
 - 2015-2017 - PEP on **High-Level** radioactive waste development and tests
 - 2017-2019 - development of other PEP tools:
 - PEP on **authorization and qualification** phase,
 - PEP on **very low-level** radioactive waste
 - 2023-2024 - development of two PEP tools in EURAD-1:
 - PEP on **monitoring issues** (MODATS WP)
 - PEP on **near-field uncertainties issues** (UMAN WP)
- The dissemination and development of this dialogue method is now ensured by **SITEX.Network**
 - 2024-2025 - update of the design and methodology : new version of the PEP + Online tool



Climate change add-on: pluralistic design



- Preparatory work based on:
 - Outcomes from **CLIMATE pluralistic Workshop 1** of 26-27 March 2025 (Keynotes with views on the different types of actors)
 - Adaptation of **existing PEP material** (board and cards)
 - Technical inputs from other tasks
 - Climate fresk: <https://climatefresk.org/world/>
- Pluralistic discussions on this work with Task 5 members (25 Oct 2025, 16 December)
- Collaborative work on a shared document

PEP - Pathway and Safe terminus

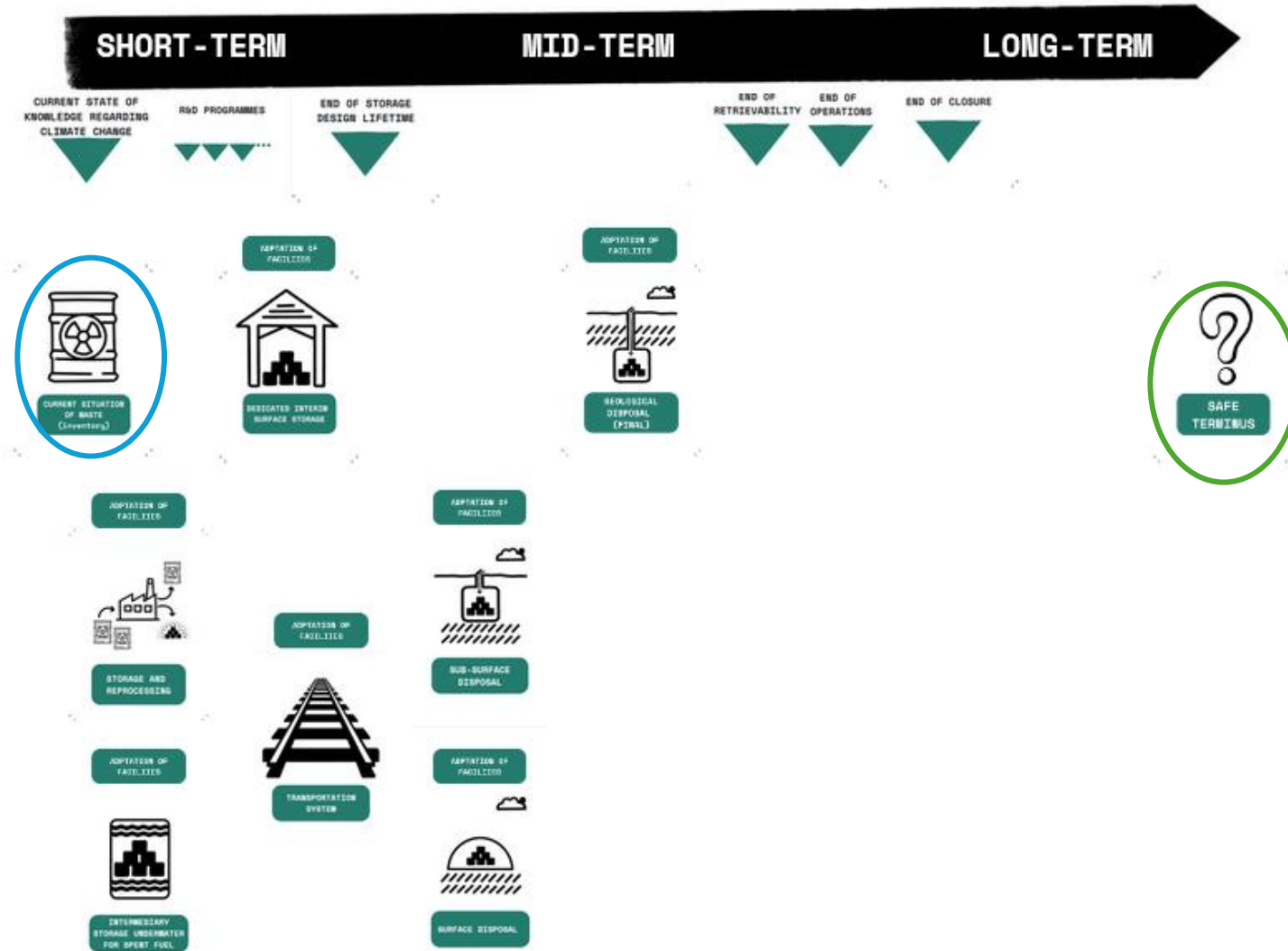
Pathway: strategy retracing the steps of a possible evolution from the **current situation** of RWM as a whole to a **final state** (ST).

Safe Terminus: common goal - a safe situation of the waste for the Long term (protection of environment and health)

Case of a nuclear Country with reprocessing

DRIVEN approach

Driven Pathway: A strategy with a safe terminus already decided, with implementation and closure as soon as possible of the geological disposal.

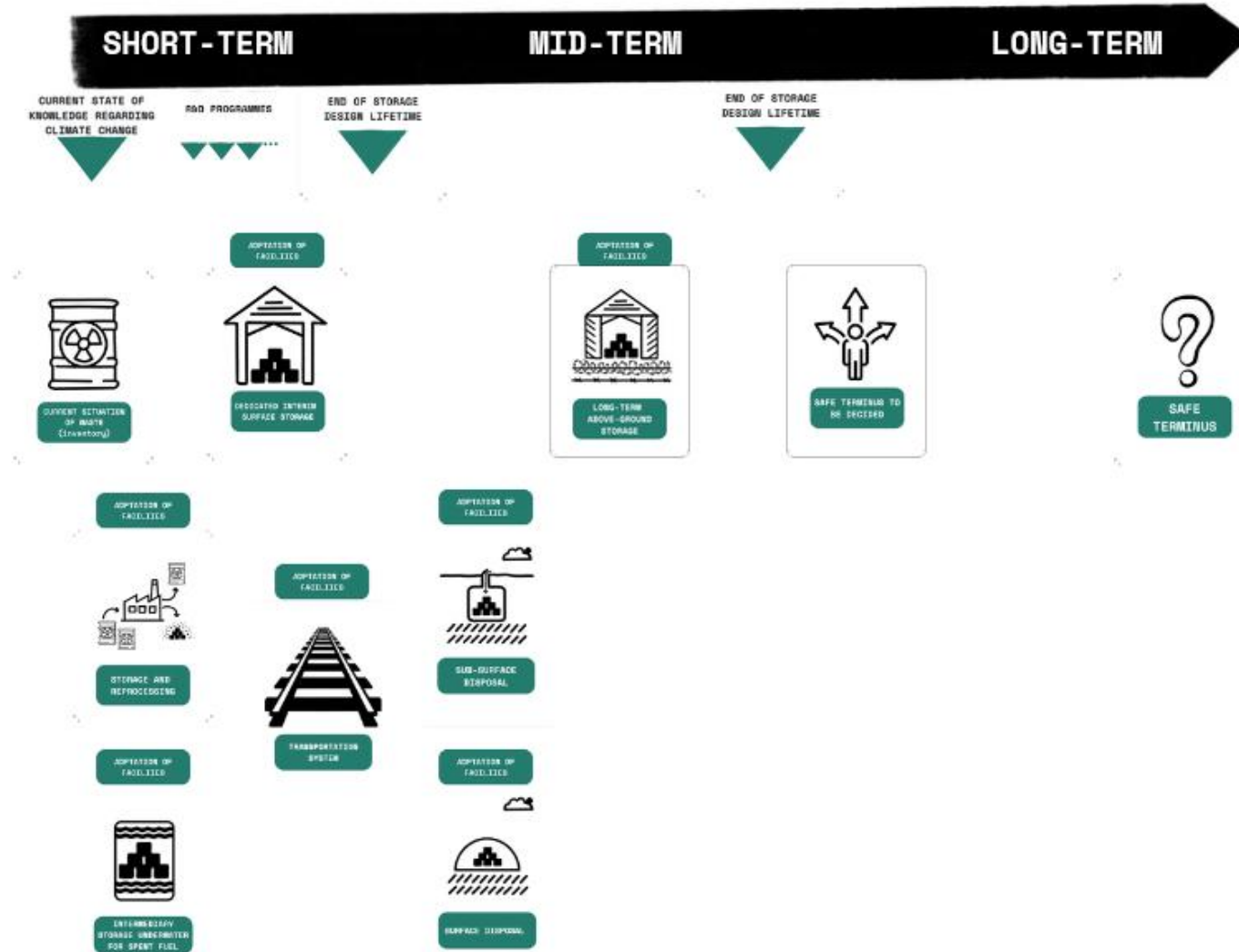


A PEP board game representing the driven pathway: reach the safe terminus as soon as possible

PEP - Pathway and Safe terminus

Pathway: strategy retracing the steps of a possible evolution from the current situation of RWM as a whole to a final state (ST).

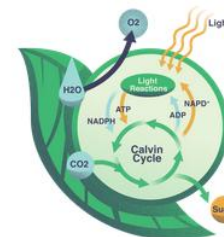
Safe Terminus: common goal - a safe situation of the waste for the Long term (protection of environment and health)



The **open pathway:** no safe terminus decided at the beginning - more time to perform research and discussions with stakeholders

How to to introduce the impacts of climate change in the pathway ?

CLIMATE CHANGE IMPACTS SHEETS



Rising air and water temperatures and ice melting

Rising air and ocean temperatures are driving widespread ice melt — including glaciers and ice caps — disrupting the water cycle and contributing to accelerating sea level rise.

- **Keywords:** temperature rise, perturbed water cycle, ice caps melting, glaciers melting, sea level rise, sea temperature rise

Increased frequency and intensity of extreme events

Climate change is leading to a measurable increase in the frequency, intensity, and duration of extreme weather and climate events, including heat waves, prolonged droughts, intense precipitation and flooding, stronger hurricanes, large-scale wildfires, and coastal submersion driven by storm surges and sea level rise.

- **Keywords:** heat waves, droughts, hurricanes, fires, floods, submersion, storms

Impacts on marine and terrestrial biodiversity

Climate change is profoundly affecting marine and terrestrial biodiversity through ocean temperature rise, ocean acidification, disruptions to calcification processes, shifts in species distributions and behavior, and the combined effects of local extinctions of some species and biological proliferations of others that alter ecosystem structure and functioning.

- **Keywords:** ocean acidification, calcification issues, biodiversity changes in behavior, disappearance and proliferations, biodiversity extinction

Positive feedback loop

Climate change carries a risk of runaway warming driven by positive feedback loops — such as the slowdown of ocean circulation or the thawing of permafrost — which amplify warming by weakening the Earth's natural regulatory systems

- **Keywords:** Gulf Stream slowing down, potential AMOC collapse, permafrost melting

Examples of impacts on RWM Rising air and water temperatures and ice melting

- Low-lying storage areas of a nuclear reprocessing and waste storage site located near the coast are submerged due to sea level rising.
- Storm surges cause flooding near the site.
- Saltwater intrusion in DGR could corrode steel waste containers and degrade concrete barriers.
- Coastal reprocessing plant at risk from North Atlantic storms.
- Decommissioned plant with dry cask storage near eroding cliffs.
- Floodings compromise retrievability of DG

Examples of impacts on RWM Increased frequency and intensity of extreme events

- Intense and long-lasting drought stresses the water resources needed for spent fuel facilities
- Two wildfires on the same month impact waste transportation
- A hurricane threatens the safety of a surface storage facility two months after a first one already damaged it
- The increase of duration and intensity of heat waves creates a higher risk of fire in data center of DGR.

Examples of impacts on RWM Impacts on marine and terrestrial biodiversity

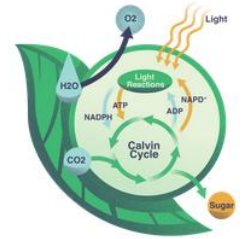
- Algae proliferation near site repeatedly alters cooling systems, delaying cooling time of spent fuel and altering safety.
- Several species near site are threatened by extinction and new environmental impact assessments are needed.
- New flora parasites jeopardize the biological protection envisaged for surface facilities.

Examples of impacts on RWM Positive feedback loop

- The sudden thaw of arctic permafrost multiplies GHG emission by two in only 10 years, accelerating all the CC processes.
- The changes in Atlantic climate systems cause glaciation to occur before the closure of DGR. Biodiversity crises severely decrease natural processes of CO₂ capture

How to to introduce the impacts of climate change in the pathway ?

CLIMATE CHANGE IMPACTS SHEETS



Impacts on humanity

Climate change is increasingly affecting human societies through the growing scarcity of water resources, declines in agricultural productivity and crop yields, heightened risks to human health, food insecurity and famine, the intensification of climate-induced migration, and the exacerbation of social tensions and armed conflicts.

- **Keywords:** Scarcity of water resources, crop yields loss, starvations, human health, climatic migrations, armed conflicts

Erosion and hydrological changes

Climate change is driving significant geomorphological and hydrological alterations, including accelerated soil and coastal erosion, shifts in groundwater flow patterns, changes in groundwater chemistry, and, in some regions, increased susceptibility to induced seismic activity.

- **Keywords:** geomorphological and geohydrological impacts - soil erosion, shore erosion, induced seismic activity, groundwater flows changes, groundwater chemical changes

Very long term impacts on planetary climates

Over very long timescales, climate change can perturb natural glaciation cycles and drive profound alterations of planetary landscapes, reshaping ecosystems and the distribution of sea, ice and landforms across the Earth. These impacts are specifically difficult to predict.

- **Keywords:** glaciation cycles perturbation, landscape changes, issues to predict

Examples of impacts on RWM Impacts on humanity

- Inhabitability of some places with RWM facilities / repositories, due to CC (extreme heat, floodings, coast erosion, desertification, etc.)
- Change in the use of the land due to new climate stresses (agriculture, new resources, etc.)
- Geopolitical changes linked with CC: migrations, borders change, conflicts
- Conflict in use of key stressed resources (water) for essential activities: cooling of RadWaste VS agriculture, etc
- Impact of CC on surrounding infrastructures (not directly linked with RWM) but essential for transportation or else

Examples of impacts on RWM Erosion and hydrological changes

- Loss of efficiency of the multi-layer cover in surface facilities as a consequence of erosion, leading to water infiltration
- Water entrance in DGR as a consequence of groundwater flow changes
- Damages to the repository due to CC-induced seismic activity
- Repository disruption as a consequence of shore erosion
- Decommissioned plant with dry cask storage near eroding cliffs.

Examples of impacts on RWM Very long-term impacts on planetary climates

- Repository disruption as a consequence of landscape development (valley creation after changes in river flow)
- Repository flooding as a consequence of severe sea level rise or long-term groundwater level increase
- Glaciation in areas where glaciation wasn't expected
- Delayed glaciation
- Seismic activity/instability/crack formation of DGR, after landscape developments



Events cards

Internal disruptions

- A1 WASTE INVENTORY CHANGES**
Unexpected shifts changes in the type or volume of waste challenge the pathway.
Examples
 - Plutonium stocks become unusable and require immobilization.
 - A national/regional national policy forces a site to accept greater or more complex waste streams than originally planned.
 - Changes in reactor operations produce new waste types with unexpected radiological or chemical properties.
- A2 TIME PRESSURE DELAYS**
Project delays or acceleration generate stress on logistics and safety.
Examples
 - Postponed spent fuel transfer.
 - A surface facility must shut down earlier than planned.
 - New technology reactors (e.g. SMRs) produce novel waste streams, requiring extended safety assessment and delaying disposal system integration.
- A3 OPERATIONAL MALFUNCTION**
Technical incidents disrupt safe functioning.
Examples
 - Control room demands urgent recovery.
 - Underground collapse blocks disposal operations.
 - Sensor failures create blind zones in monitoring systems.
 - A fire or unexpected chemical reaction involving incompatible waste materials or packaging occurs, threatening worker safety and waste containment.
- A4 SCIENTIFIC OR TECHNOLOGICAL INNOVATION / DISRUPTION**
New findings or breakthroughs unsettle initial assumptions for implementing the pathway.
Examples
 - Transmutation reduces the relevance of current plans.
 - Radioisotope migration proves faster than expected.
 - New knowledge (or information) contradicts previous safety assumptions.
 - Updated climate projections show higher coastal erosion risks, raising doubts about the site's long-term suitability.
- A5 EMERGENCY RESPONSE CHALLENGE**
Disruptive event exposes weaknesses in preparedness or emergency response capacity at radioactive waste management facility.
Examples
 - During a contamination incident, a conflict appears between the rules applying to safety and to security aspects.
 - New inhabited constructions close to facilities.

External shocks

- B1 SHIFTING PERSPECTIVES**
Environmental, territorial or economic changes alter risks' management plan or create new societal unplanned needs.
Examples
 - Groundwater scarcity increases pressure on long-term safety.
 - Strong interests re-emerge near the site.
 - A nearby urban expansion leads to land-use conflict.
 - Options for renewable energy infrastructure emerge near the site, creating new land-use tensions.
- B2 DELIBERATE ATTACKS**
Hostile actions target infrastructure or data.
Examples
 - Saboteurs destroy monitoring equipment.
 - Deliberate intrusion disrupts surface access to the site.
 - Cyberattacks corrupt real-time data or safety protocols.
 - Disinformation campaigns undermine trust in safety systems or emergency responses.
- B3 POLITICAL INSTABILITY**
Sudden geopolitical changes disrupt responsibilities or continuity of the project.
Examples
 - A new regime stops all nuclear programs.
 - Jurisdiction over a site is contested after regional secession.
 - Allies withdraw from a shared safety agreement.
 - Geopolitical conflicts disrupt recruitment, staff continuity, or access to key infrastructure.
- B4 CONTESTATION**
Public resistance challenges legitimacy or implementation.
Examples
 - A citizens' assembly denounces the project's ethics.
 - Disruptive movements halt construction through legal action.
 - Local referendums demand reassessment of site approval.
 - A transnational coalition of NGOs challenges regulatory plans in court based on intergenerational equity.
- B5 UNINTENTIONAL INTRUSION**
Unplanned or accidental human actions compromise site safety or integrity.
Examples
 - Construction work nearby damages underground infrastructure.
 - Minors unknowingly enter restricted zones due to signage failure.
 - Future land use changes ignore buried waste zones.
 - Records and markers fall over generations, leading to excavation or drilling at the site centuries later.
- B6 INTERNATIONAL DISRUPTION**
Cross-border or global changes destabilize national waste strategies or commitments.
Examples
 - A global energy crisis shifts national funding priorities away from waste programs.
 - International shipping routes close, preventing waste repatriation or shared facility use.
 - A partner country to a multinational repository withdraws, requiring unilateral action.

Governance challenges

- C1 INSTITUTIONAL BREAKDOWN**
Support of the safety systems or responsible actors collapse.
Examples
 - The waste management agency is dissolved.
 - Private operators declare bankruptcy mid-project.
 - Administrative reforms create gaps in oversight responsibility.
 - Budget cuts eliminate long-term monitoring or stakeholder engagement programs.
- C2 SAFETY INTEGRITY BREACH**
Regulatory review deems the project unsafe.
Examples
 - Uncertainty remains on hydrogeological modeling.
 - Earthquake risk exceeds thresholds despite mitigation.
 - External review fails to validate safety design parameters.
 - Safety case is deemed non-compliant with updated regulatory standards or international benchmarks.
- C3 LOSS OF CONTROL RISK**
Threats of misuse or instability prompt final closure.
Examples
 - Authorities enforce irreversible sealing to avoid future access.
 - Removal is prohibited due to proliferation risks.
 - Autonomous systems malfunction beyond human recovery.
 - A geopolitical event prompts the accelerated closure of the site under emergency conditions.
- C4 OBLIGATION OF REVERSIBILITY**
Democratic concerns call for long-term flexibility.
Examples
 - The system must allow full site dismantling if needed.
 - Legal frameworks demand proof of reversibility every decade.
 - Reversibility becomes enshrined in constitutional or human rights law.
 - Intergenerational ethics movements challenge the irreversibility of current decisions.
- C5 CORRUPTION OF THE REVIEW PROCESS**
Integrity of the review processes is undermined by political or private interests.
Examples
 - A conflict of interest leads to suppressed safety concerns.
 - Public trust collapses after leaked documents reveal concealed risks.
- C6**



Evaluate cards

Management of Risk

X1 **X1** EVALUATE

MANAGING RISKS PROACTIVELY

How are physical, environmental, digital and geopolitical risks identified, mitigated, prevented and continuously reassessed by the pathway throughout the process?

Examples

- shortage
- compensation
- cybersecurity
- risk delegation
- supply chain risk
- AI / autonomous system vulnerabilities

Management of Risk

X2 **X2** EVALUATE

STRATEGIC TIMING

Does the pathway allow for deliberate, timely decisions without being constrained by urgency or political pressure? Does the timing allow for learning from international experience before key decisions?

Examples

- alignment of technical milestones and political agendas
- flexible agendas
- contingency planning
- buffer periods
- synchronization of policy decisions with safety case development

Management of Risk

X3 **X3** EVALUATE

RESILIENCE AND ABANDONMENT RISK

How resilient is the pathway to shocks or deviations before reaching a Safe Terminus? Could it be abandoned in times of crisis in conditions compromising the safety?

Examples

- war
- pandemics
- institutional collapse
- loss of technical control

Management of Risk

X4 **X4** EVALUATE

ROBUSTNESS OF THE FACILITY SYSTEM

Is the system based on minimal, essential components (robust by simplicity) or advanced yet fragile technologies? Is the design fail-safe and tolerant of degradation?

Examples

- high-performance systems
- fail-safe design
- redundancy systems
- balance between engineered and natural barriers (multi-barrier concept)

Management of Risk

Governance Quality

Y1 **Y1** EVALUATE

INVOLVING PUBLICS

To what extent does the pathway enable meaningful participation by citizens and local actors at each step? Does participation influence real decisions or merely inform them?

Examples

- deliberative processes
- right to amend
- transparency
- citizen oversight
- stakeholder capacity-building (training, funding)
- independent advisory bodies or ethics committees

Governance Quality

Y2 **Y2** EVALUATE

INSTITUTIONAL CAPABILITY & STABILITY

Are the financial, human and institutional resources adequate and stable over time?

Examples

- budget resilience
- staff turnover
- expertise continuity
- political support
- scenario planning for institutional discontinuity

Governance Quality

Y3 **Y3** EVALUATE

INTEGRATING PLURAL KNOWLEDGE EXPERTISE

How are different types of knowledge and sensitivity (scientific, local, ethical) included in key decisions? How dissenting knowledge is addressed?

Examples

- expert dialogue
- social sciences
- local knowledge
- indigenous perspectives
- co-design of assessment frameworks, multi-criteria evaluation

Governance Quality

Y4 **Y4** EVALUATE

GLOBAL MONITORING

What forms of monitoring are foreseen, and how are they adapted to environmental, social and technical challenges?

Examples

- environmental surveillance
- public oversight
- long-term sensors
- citizen observations
- post-closure monitoring regimes
- early warning capabilities
- memory preservation strategies

Governance Quality

Y5 **Y5** EVALUATE

PUBLIC TRANSPARENCY

Does the pathway foster trust among stakeholders through shared values, transparency, and inclusion? Are mechanisms in place to repair trust if it is broken?

Examples

- trust-building rituals
- open data
- inclusive and responsive communication
- third-party audits, mediation
- distributional fairness and procedural justice

Governance Quality

Value & Ethics

Z1 **Z1** EVALUATE

FAIRNESS ACROSS GENERATIONS

What constraints or burdens does the pathway impose on future generations, and what capacities does it preserve? Does the pathway leave room for future decision-making?

Examples

- debts
- provisos choices
- open options
- legacy infrastructures
- sustainability
- intergenerational dialogue

Value & Ethics

Z2 **Z2** EVALUATE

MANAGING UNCERTAINTY ETHICALLY

How does the pathway balance the precautionary principle with the need to act under uncertainty? How is ignorance, not just uncertainty, addressed?

Examples

- scenario planning
- sensitive decisions
- adaptive design
- ethical review boards
- iterative decision-making
- ethical trade leaving
- culture economic leaving

Value & Ethics

Z3 **Z3** EVALUATE

CLIMATE AND ENVIRONMENTAL COMPATIBILITY

How does the pathway impact climate resilience and ecological integrity?

Examples

- carbon footprint of operations, maintenance, and closure
- green-house gas emissions
- ecosystem impact
- land use
- resource consumption

Value & Ethics

Z4 **Z4** EVALUATE

CULTURAL & SPIRITUAL DIMENSIONS

Does the pathway acknowledge the symbolic or ethical significance of deep time, land, or the act of disposal itself?

Examples

- sacredness of land
- interfaith rituals
- cultural legacy
- ancestral heritage
- symbolic forms of memory transmission
- rituals of closure

Value & Ethics

Z5 **Z5** EVALUATE

ETHICAL CONSIDERATIONS

Does the pathway align with ethical principles and values? Are there any ethical dilemmas or trade-offs? How are these addressed?

Examples

- ethical frameworks
- stakeholder engagement
- transparency
- accountability
- ethical review boards
- iterative decision-making
- ethical trade leaving

Value & Ethics

eurad2

10

Example of a PEP scenario



Rising air and water temperatures and ice melting

Rising air and ocean temperatures are driving widespread ice melt — including glaciers and ice caps — disrupting the water cycle and contributing to accelerating sea level rise.

- **Keywords:** temperature rise, perturbed water cycle, ice caps melting, glaciers melting, sea level rise, sea temperature rise



C2 **EVENT**

SAFETY INTEGRITY BREACH

Regulatory review deems the project unsafe.

Examples

- Uncertainty remains on hydrogeological modeling.
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Governance challenges



X1 **EVALUATE**

MANAGING RISKS PROACTIVELY

How are physical, environmental, digital and geopolitical risks identified, mitigated, prevented and continuously reassessed by the pathway throughout the process?

Examples

- sabotage
- contamination
- cybersecurity
- risk delegation
- supply chain risk
- AI / autonomous system vulnerabilities

Management of Risk



When?

25 years after closure



Short story:

A surface disposal close to shore is getting submerged by saline water due to a sea level rise faster than expected. What could be done in order to manage the situation and reduce risks ?

Organisation of the discussion

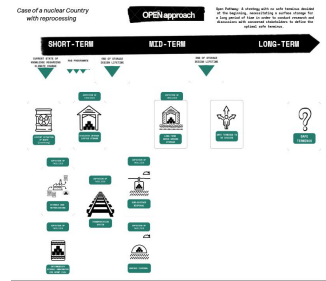
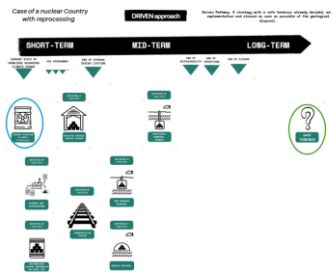


- Small groups of 5-6 participants with a facilitator
- Participants elaborate the scenarios. To start the discussion, one participant suggest a scenario to be discussed with the other participants.
- **The participants will speak one after the other, and will not interrupt the participant who is speaking (equality of time)**
- They will prepare their views on post-it notes (3 minutes to write ideas before to share orally)
- **First turn of discussion:** each participant will give its views on the issues raised by the scenario (Is it credible ? Will the pathway be robust to solve the issue ? On what conditions ? Etc...?) with a focus on the question (evaluate card) chosen for the scenario
- **Second turn of discussion:** each participant have an opportunity to give complementary views according to what he/she heard during the first turn.

2 rounds of evaluation and a synthesis round



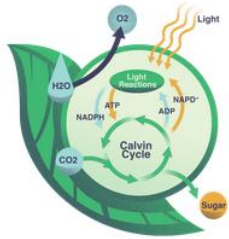
- 2 pathways evaluated successively in 2 rounds of 60 minutes.
- At the end of each round, each participant have an opportunity to give its views on the issues raised during a final roundtable of evaluation of the discussed pathway.



- After discussing the two pathways, a last round of 30 minutes is organised : a synthesis round



4 main questions to be answered during the round of evaluation



A. Climate processes: Which climate processes concerned you the most in terms of impacts on RWM?



B. Safety issues: Which aspects of RWM seem most vulnerable to climate change regarding safety issues?



C. Mitigation of CC impact on RWM: How can we improve the mitigation of CC impact on RWM?



D. PEP experience: What struck you the most ?



PEP update after the first test (on-going work)

The PEP was tested during the **second CLIMATE Workshop (28-29 January 2026)**. After discussions, some update are planned:

- Convert the climate change impacts sheets into event cards to simplify the game
- Review the existing cards to ensure they are relevant (remove them if they are not) and simplify the text, which is sometimes too dense: limit to a maximum of two examples per card.
- Simplify boards (pathways): create two boards one for HL waste facilities and one for other facilities.
- To highlight differences in timeframes, create two “Time Horizon” cards : Short Term (ST) and Long Term (LT), providing a non-exhaustive list of short-term and long-term effects and Include ST and LT examples on the event cards.
- Reverse the order of elements in scenario construction: start by defining the time horizon before selecting the event.



Useful links:



- **Sitex network website:** <https://www.sitex.network/activities/experimental-forms-of-pluralistic-engagement/pathway-evaluation-process-pep/>
- **Canva tool demo online of the PEP tool on Climate change:**
<https://www.canva.com/design/DAHJc7yUp0k/raWQuIb2XYSph6cCYxNwdA/edit>

THANK YOU!

CLIMATE CHANGE IMPACT ON MULTI-LAYER COVERS: HEAVY RAINFALL AND EROSION

Olivier Stab¹, Jean-Louis Grimaud¹

¹ MINES Paris - FRANCE

Training session

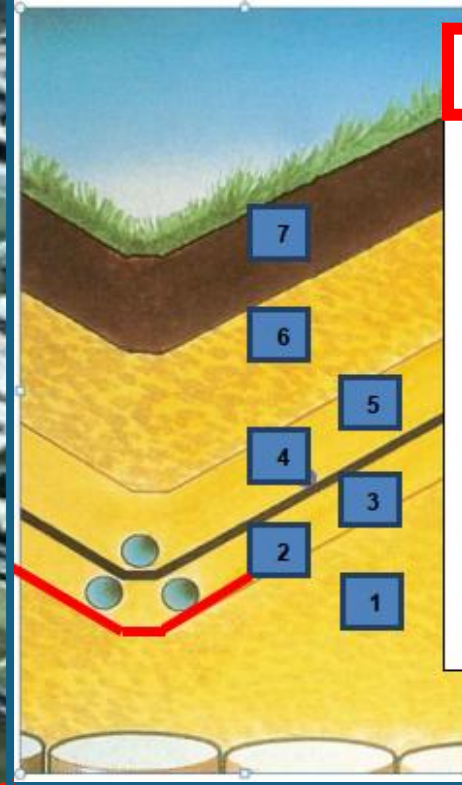


Co-funded by the European Union under Grant Agreement n° 101166718

HEAVY RAINFALL AND EROSION INCLUDING EXTREMES

1. Layered design of surface disposal facility
2. Erosion processes caused by rain
3. Physic of a raindrop
4. Rainfall erosivity (R factor)
5. Rainfall erosivity for future climate
6. Universal Lois Soil Equation (USLE)
7. Exercise : Sensitivity analysis using RUSLE equation – Given these sensitivities of the system, how would you design a cover?
8. Extreme rainfall events prediction & experimental approach to quantify its erosion impact

CSM MULTILAYER COVERAGE EFFICIENCY



- 7 : Top soil**
- 6 : Sandy silt**
- 5: Sand + Drainage**
- 4: Upper geomembrane**
- 3 : Sand + Drainage**
- 2 : Lower geomembrane**
- 1 : Sandy silt**



Layers	Function
7 : Top soil	Natural cover
6 : Sandy silt	Barrier to prevent human and animal intrusion
5: Sand + Drainage	Drainage layer above the geomembrane
4: Upper geomembrane	Waterproof barrier
3 : Sand + Drainage	Drainage layer in case of geomembrane leaks
2 : Lower geomembrane	Control layer for geomembrane leaks
1 : Sandy silt	Subgrade layer

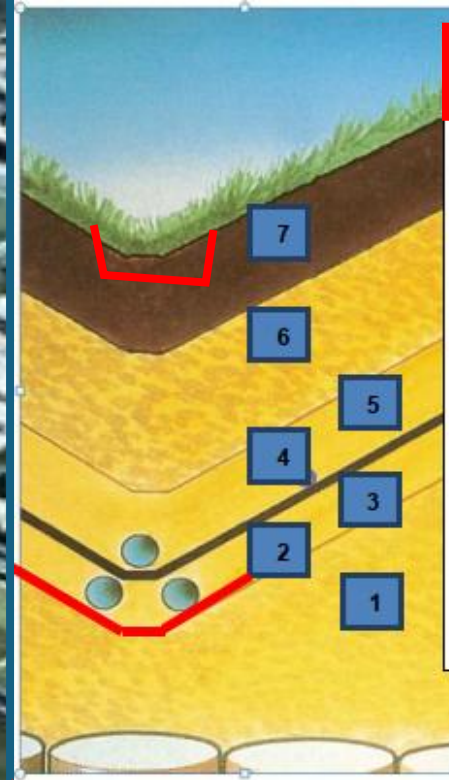
CSM MULTILAYER COVERAGE EFFICIENCY

Rainfall

~300 years

<30m

33% (18°)



7 : Top soil

6 : Sandy silt

5 : Sand + Drainage

4 : Upper geomembrane

3 : Sand + Drainage

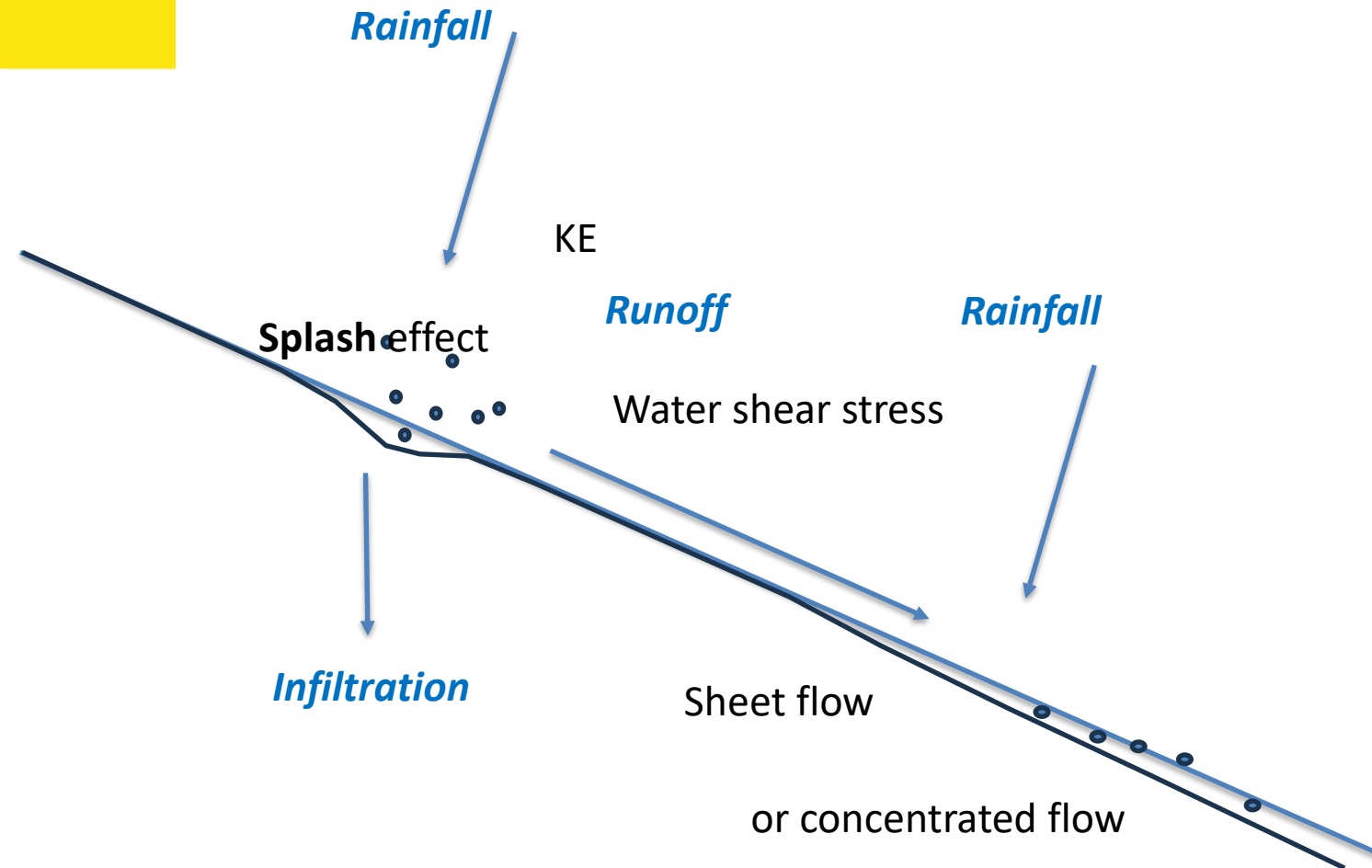
2 : Lower geomembrane

1 : Sandy silt

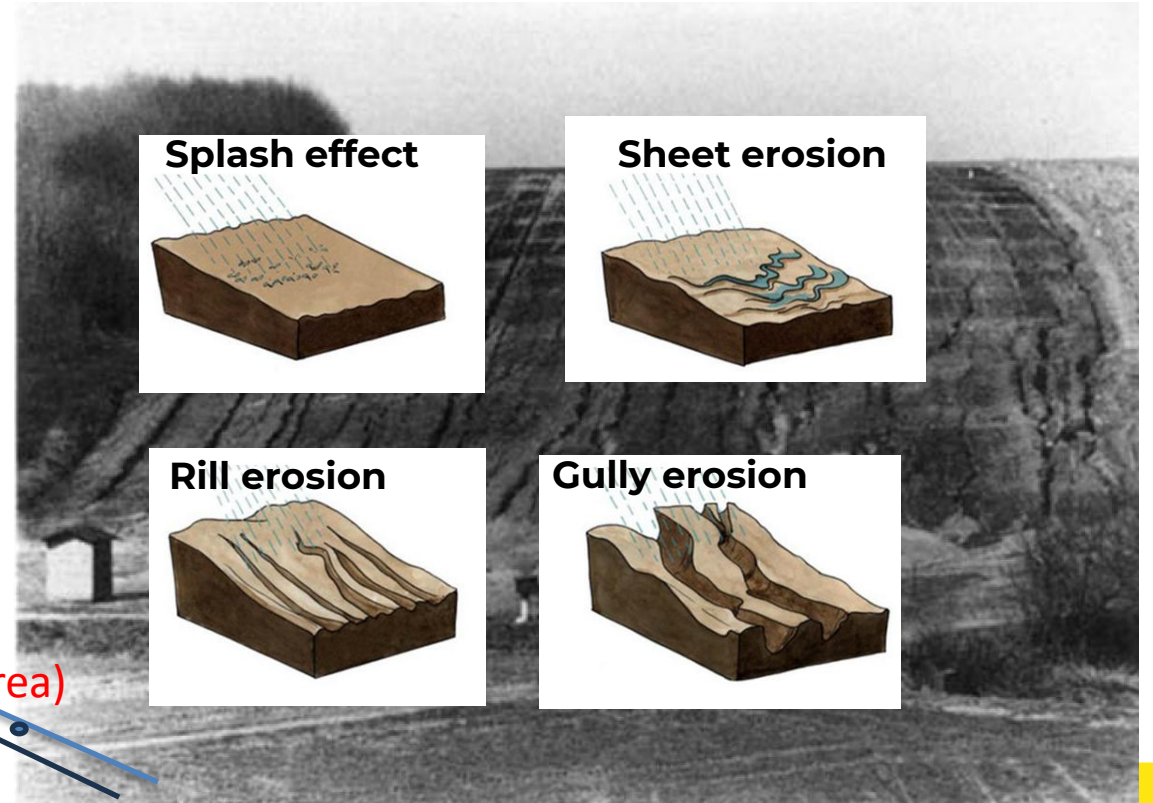
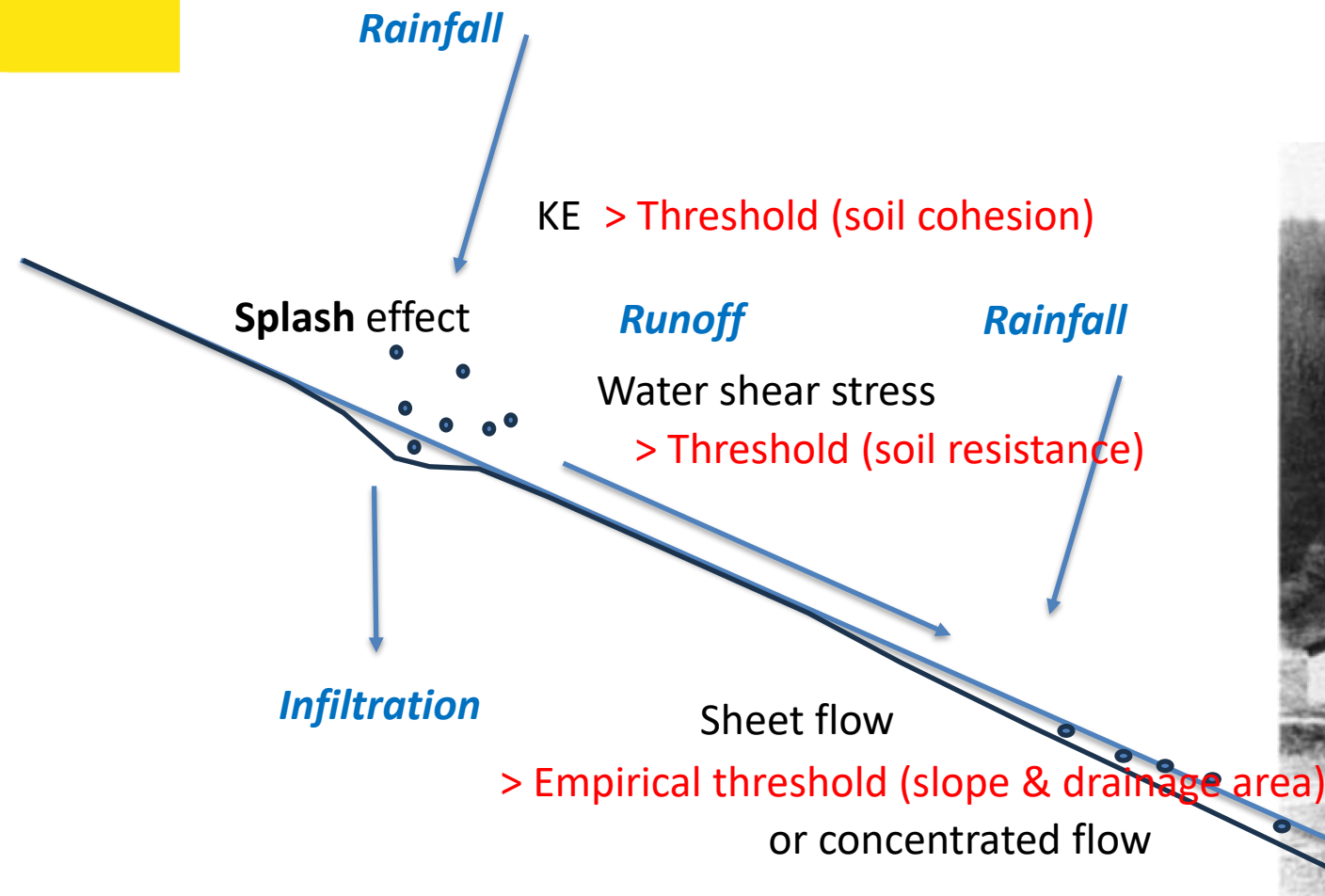


Layers	Function
7 : Top soil	Natural cover
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3 : Sand + Drainage	Drainage layer in case of geomembrane leaks
2 : Lower geomembrane	Control layer for geomembrane leaks
1 : Sandy silt	Subgrade layer





- Thresholds



Flow concentration (in rills)

o Thresholds

Rainfall erosivity

R factor

Rainfall

Vegetation

C factor

$KE > \text{Threshold (soil cohesion)}$

Splash effect

Runoff

Rainfall

Water shear stress

$> \text{Threshold (soil resistance)}$

Topography
LS factor

Infiltration

Sheet flow

$> \text{Empirical threshold (slope \& drainage)}$
or concentrated flow

Soil erodability

K factor

The erosion rate depends on :

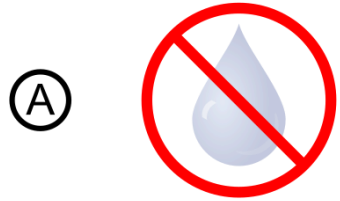
Rainfall characteristics (intensity, drops...) → rainfall erodability (R)

Soil characteristics (permeability, cohesion...) → soil erodability (K)

Slope (runoff) → Length and slope factor (LS)

Vegetation type and density → protective cover (C)

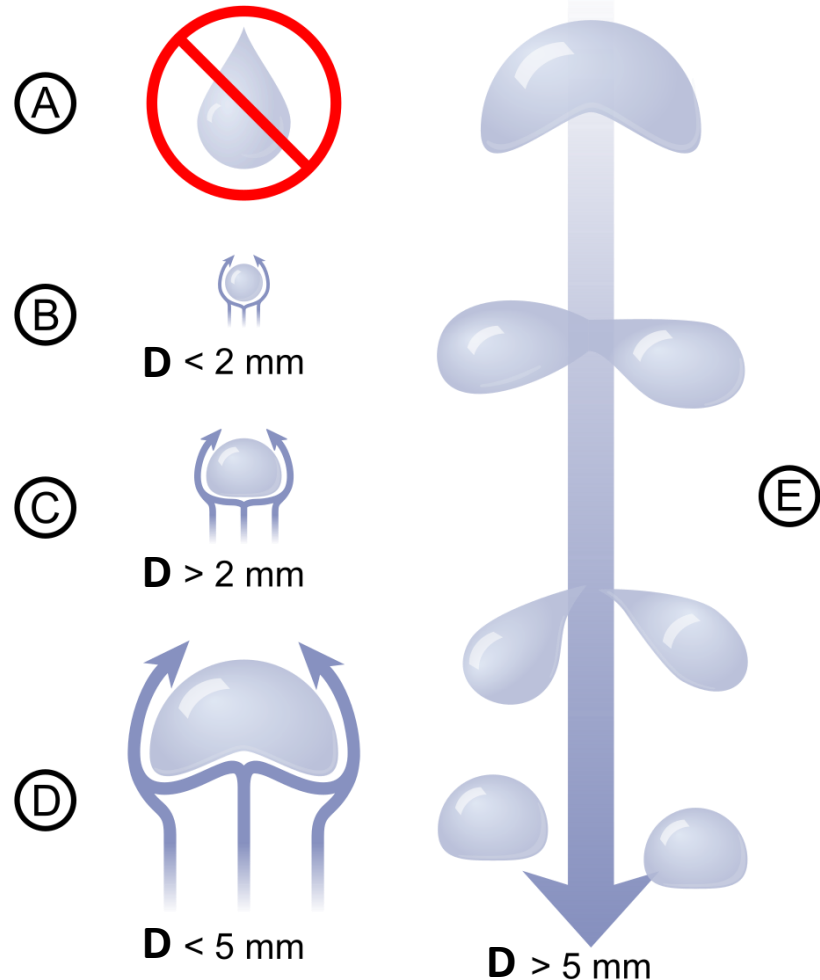
$$\text{USLE : MER} = \mathbf{R} \times K \times \text{LS} \times C$$



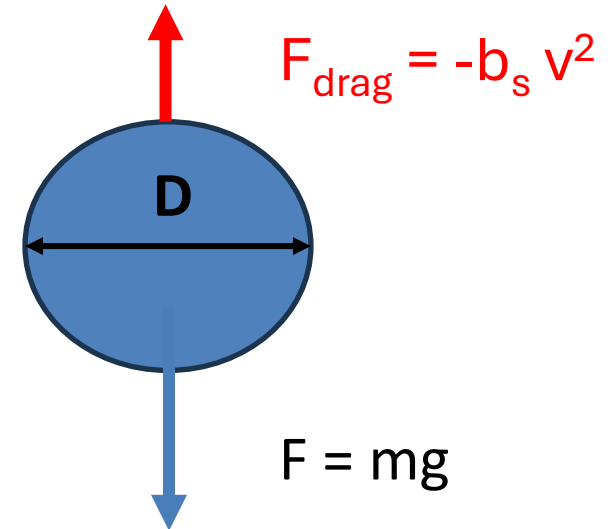
Physics of a rain drop

Shape, Terminal Velocity and Kinetic Energy

A drop speed limit : terminal velocity



Drop splitting



Theoretical terminal velocity

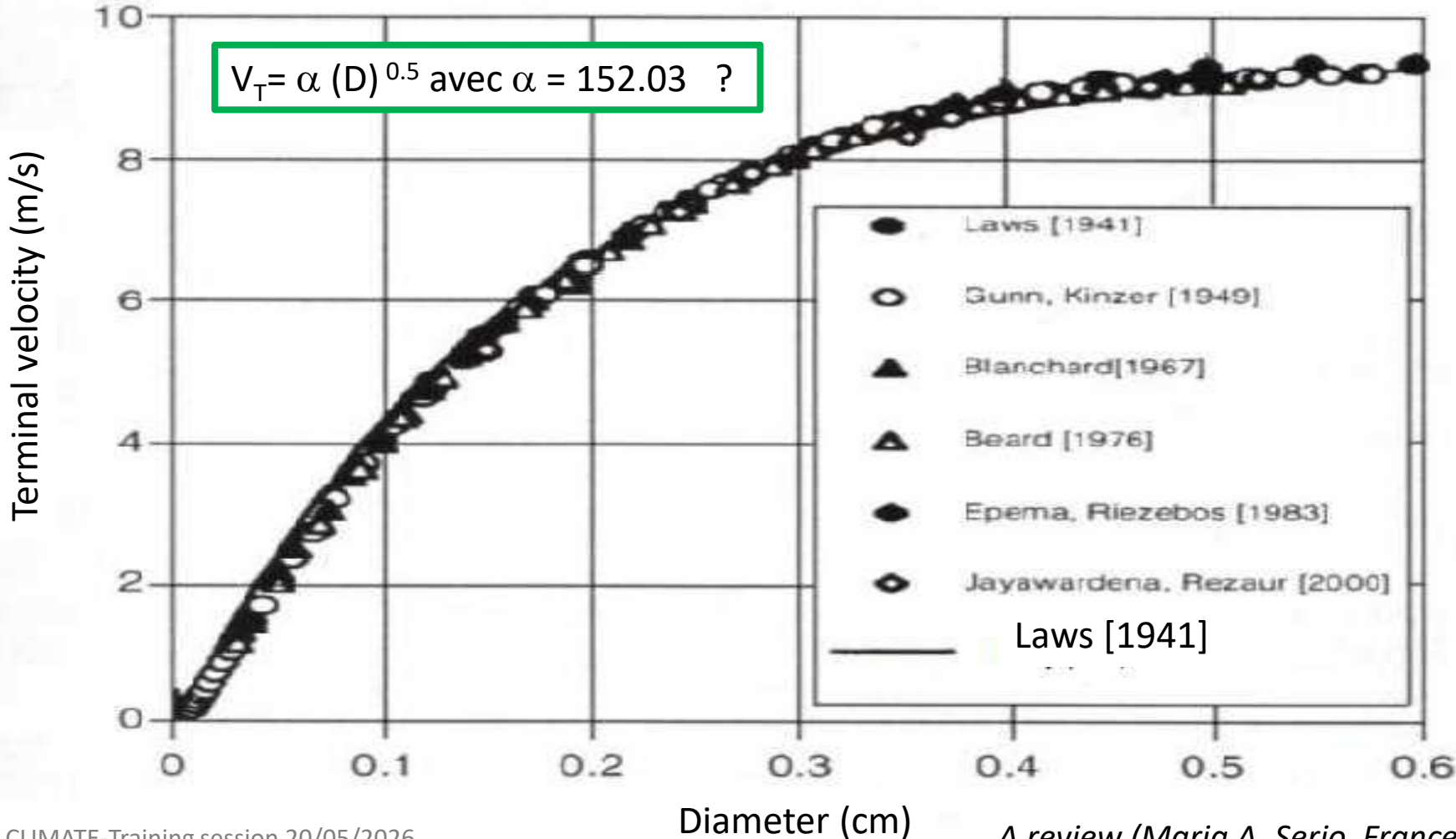
$$V_T = \alpha (D)^{0.5} \quad \text{with } \alpha = 152.03$$

where b_s is the resistance factor due to air friction (kg/m) $b_s = \frac{1}{2} \rho_a c_d A$
 With $A = \pi (D/2)^2$ and ρ_a (kg/m^3) air density and $c_d \approx 0.47$ (Mhaske 2019)

“Empirical TV law ” (Laws 1941 ...):

$$VT(D) = V_{\max} (1 - \exp(-a_n D))$$

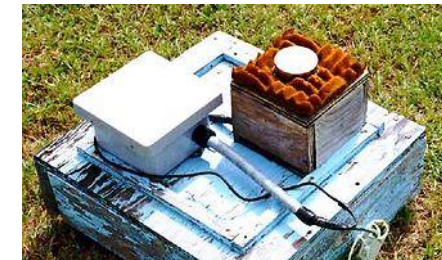
a_n changes with H, and D drop diameter (in cm) for H=20 : $V_{\max} = 9.5\text{m/s}$ et $a_n = 6\text{cm}^{-1}$



Lab experiments in still air



Laser disdrometer

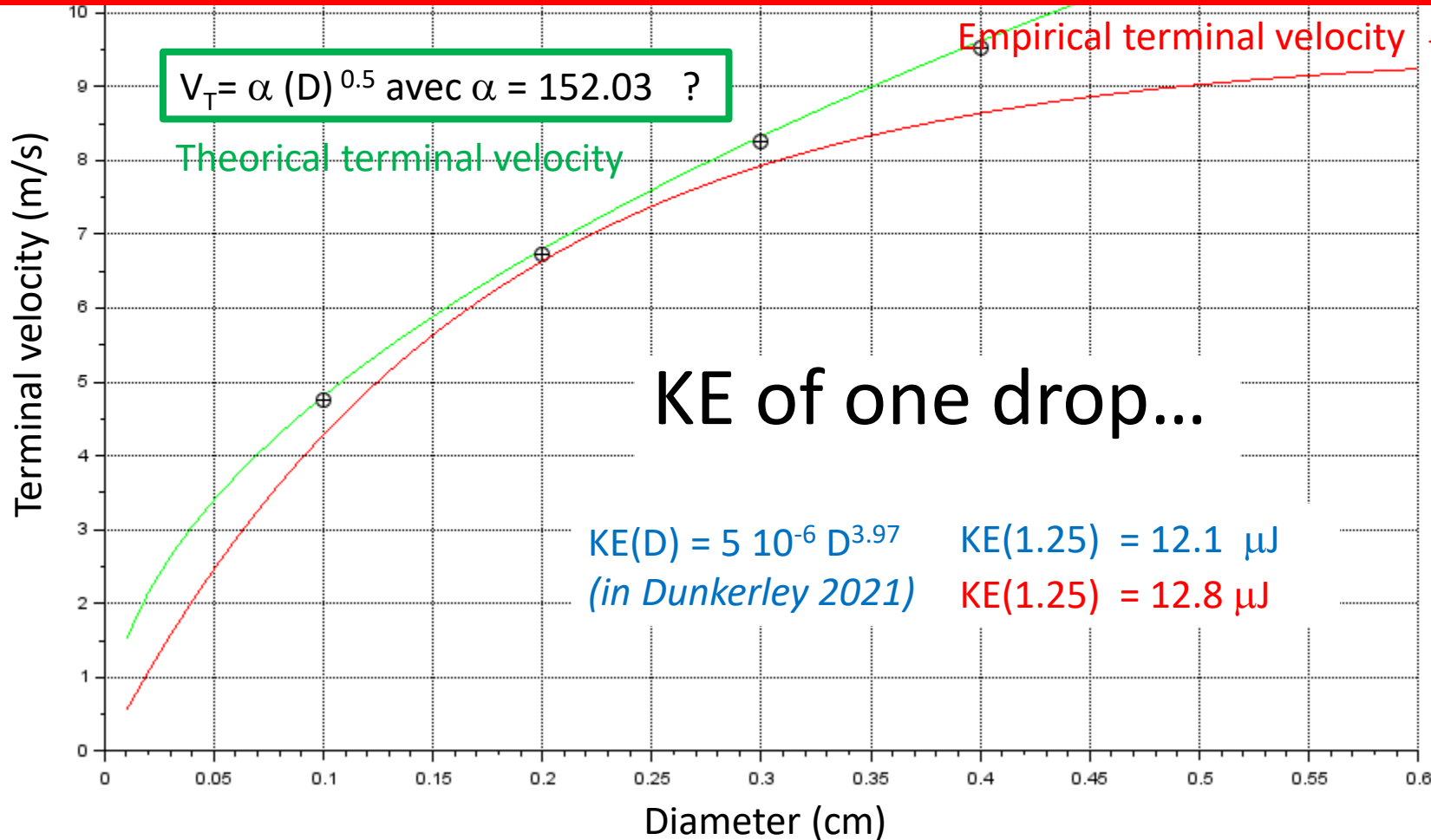


Impact disdrometer

“Empirical TV law ” (Laws 1941 ...):

$$VT(D) = V_{\max} (1 - \exp(-a_n D))$$

a_n changes with H, and D drop diameter (in cm) for H=20 : $V_{\max} = 9.5\text{m/s}$ et $a_n = 6\text{cm}^{-1}$



KE of one drop...

$KE(D) = 5 \cdot 10^{-6} D^{3.97}$ (in Dunkerley 2021) $KE(1.25) = 12.1 \mu\text{J}$
 $KE(1.25) = 12.8 \mu\text{J}$

9.5m/s
Lab experiments in still air



Laser disdrometer



Impact disdrometer

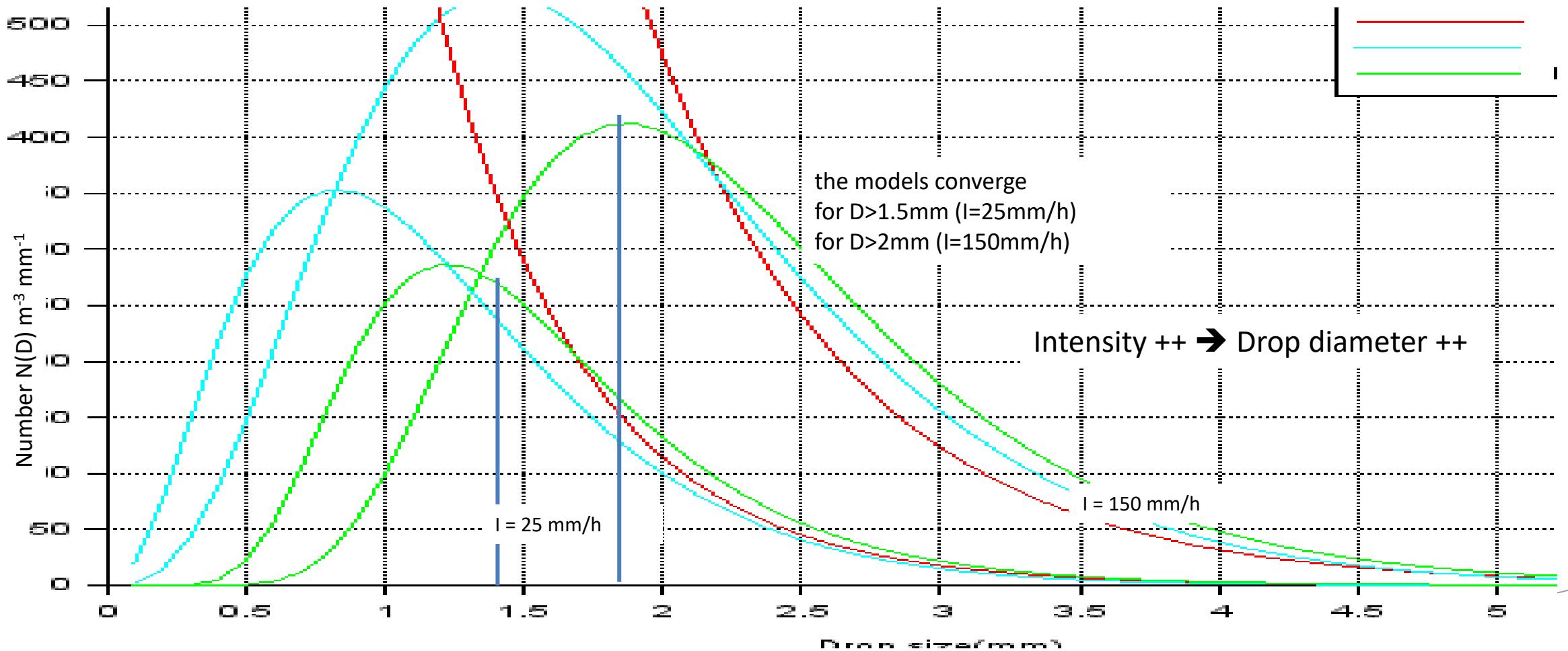
Exponential law : $N(D) = N_0 \exp(-\Lambda D)$

Gamma law : $N(D) = N_0 D^\alpha \exp(-\Lambda D)$

Lognormal law : $N(D) = N_T / (2\pi \sigma D)^{0.5} \exp(-1/2 (\ln(D/D_g)/\sigma)^2)$

Rainfall Intensity (« I » in our notation)

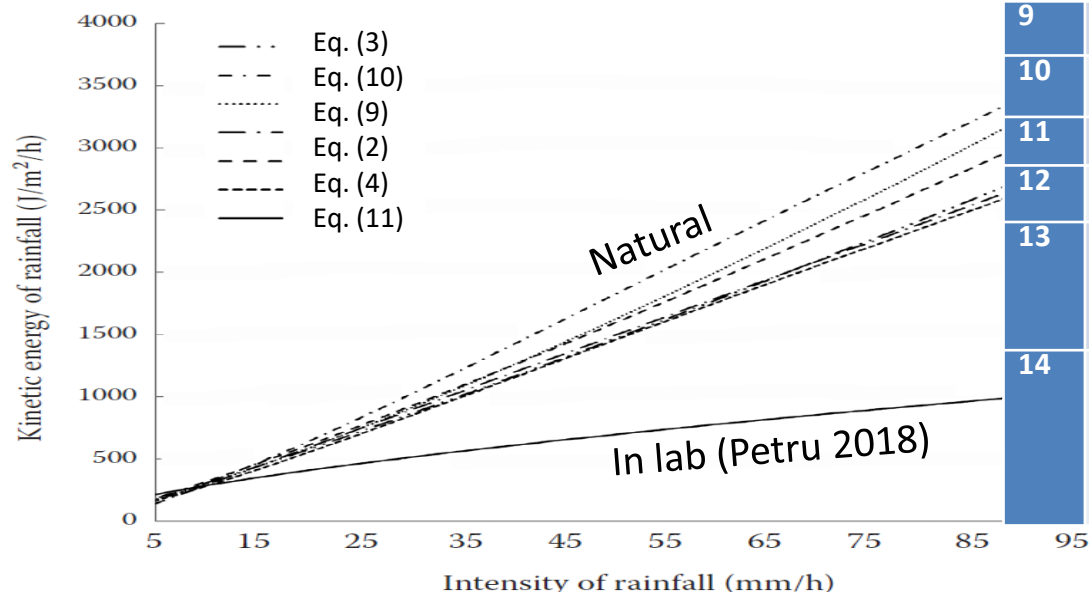
Exponential	Gamma	Lognormal
$N_0 = 2.32 \times 10^3 R^{0.22}$	$N_0 = 8.80 \times 10^3 R^{-0.13}$	$N_T = 194 R^{0.30}$
$r^2 = 0.61$	$r^2 = 0.27$	$r^2 = 0.83$
$\Lambda = 3.32 R^{-0.18}$	$\alpha = 1.27 R^{0.19}$	$D_g = 0.630 R^{0.23}$
$r^2 = 0.95$	$r^2 = 0.74$	$r^2 = 0.97$
	$\Lambda = 4.05 R^{-0.11}$	$\sigma^2 = 0.191 - 1.1 \times 10^{-2} \ln R$
	$r^2 = 0.72$	$r^2 = 0.72$



$$P_n = KE_{\text{time}} = (\pi/12) (10^{-6}) (3600/t) (1/A) \sum N(D_i) D_i^3 v_{Di}^2$$

where:

- P_n - is the time-specific kinetic energy in $J/m^2/h$
- A – sampling area of the LPM (0.005 m^2)
- t – rainfall duration (60 s)
- $N(D_i)$ number of drops in the class of diameter D_i
- D_i – drop class diameter (mm)
- v_{Di} – fall velocity of drops (m/s) of the diameter D_i (mm)



	Authors	$KE_{\text{Time}} = f(\text{Intensity})$	Location
1	Laws et Parsons 1943		
2	Hudson 1965	$KE = 29.86 (I - 4.29)$	Zimbabwe
3	Wischmeier & Smith 1978	$KE = I (11.87 + 8.73 \log_{10}(I))$ $I < 76 \text{ mm/h}$ $KE = 28.3(I)$ $I \geq 76 \text{ mm/h}$	North America – Washington - USA USLE
4	Zanchi & Torri 1980	$KE = I (9.81 + 11.25 \log(I))$	Italy central
5	Kinnel 1981		
6	Brown & Foster 1987	$KE = 29.0 (I) (1 - 0.72 \exp(-0.050 I))$	Southern USA R-factor RUSLE
7	Coutinho & Tomas 1995	$KE = 35.9 (I) (1 - 0.559 \exp(-0.034 I))$	South Portugal
8	Cerro et al . 1998	$KE = 38.4 (I) (1 - 0.528 \exp(-0.029 I))$	Spain Barcelone
9	Steiner & Smith 2000	$KE = 11 (I)^{1.25}$	Northern Mississippi
10	Jayawardena & Rezaur 2000	$KE = 36.8 (I) (1 - 0.691 \exp(-0.038 I))$	Hong Kong
11	Van Dijk 2002	$KE = 28.3 (I) (1 - 0.52 \exp(-0.042 I))$	World
12	Foster 2004	$KE = 29.0 (I) (1 - 0.72 \exp(-0.082 I))$	RUSLE 2
13	Petru & Kalibová 2018	$KE = 50.633 (I)^{0.656}$ $KE_{\text{time}} = -1195.7 + 483.181 \ln(I)$	In Lab
14	Fornis 2005	$KE = 1288.17 m^{-1.34} I^{(1+1.34 b)}$ M and b depend on the type of storm : if it is convective or stratiform	

Empiric relationship between KE and intensity (I)

o R factor in USLE & RUSLE models

$$R = \frac{1}{n} \sum_{j=1}^n \sum_{k=1}^{m_j} (EI_{30})_k \quad (\text{MJ mm /ha /h})$$

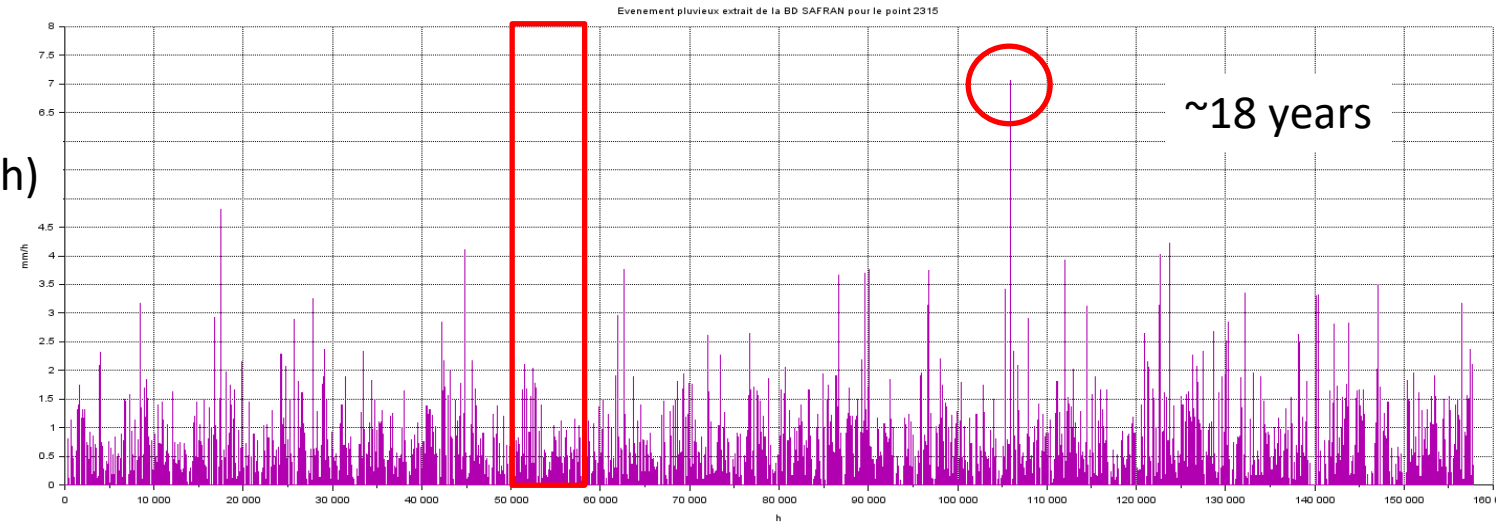
- n number of years of recording
- m_j number of rainfall during year j

For each rainfall event :

$$EI_{30} = \left(\sum_{r=1}^R KE_r v_r \right) I_{30}$$

(MJ/ha)
(mm/h)

- I_{30} : the max intensity over 30min samples (mm h^{-1}),
- v_r : « volume » (mm) during the measure



A rainfall event → rain intensity > 1.27mm for 6h

« Kinetic energy » of a sample « r » (Brown & Foster 1987):

$$KE_r = 0.29 (1 - 0.72 \exp(-0.05 i_r))$$

- KE_r : kinetic energy per mm of rain during the sampling ($\text{MJ ha}^{-1} \text{mm}^{-1}$)
- i_r rainfall intensity (mm/h)
- r a sample

o R factor in USLE & RUSLE models

$$R = \frac{1}{n} \sum_{j=1}^n \sum_{k=1}^{m_j} (EI_{30})_k \quad (\text{MJ mm /ha /h})$$

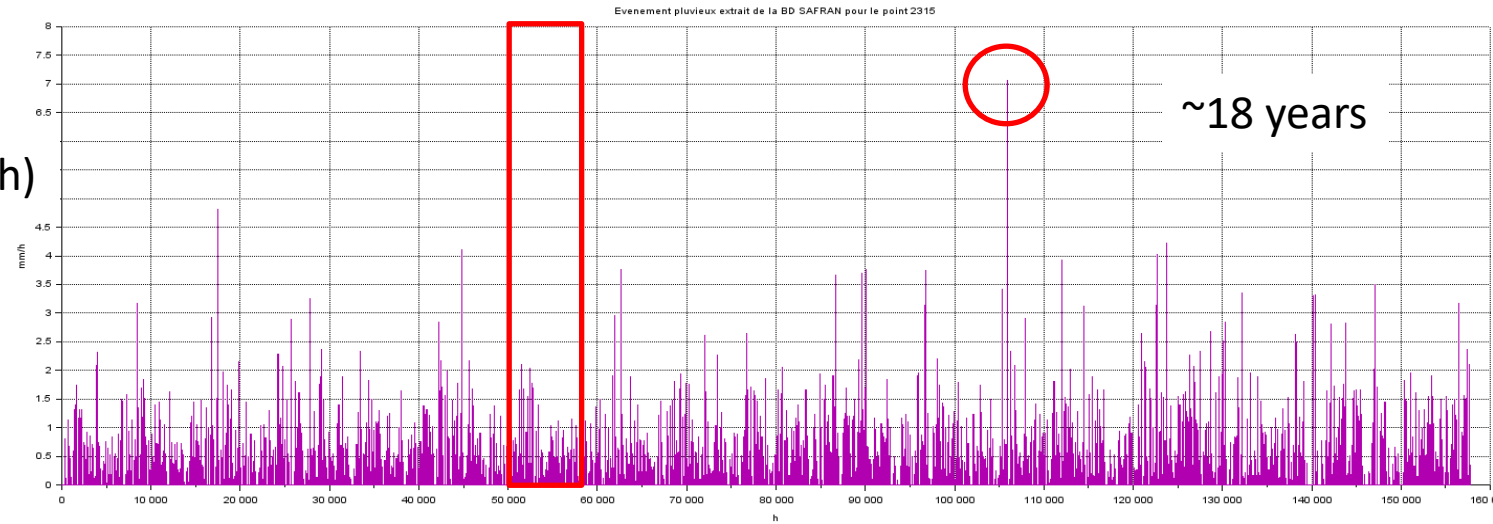
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Kinetic energy of a sample « r » (Brown & Foster 1987):

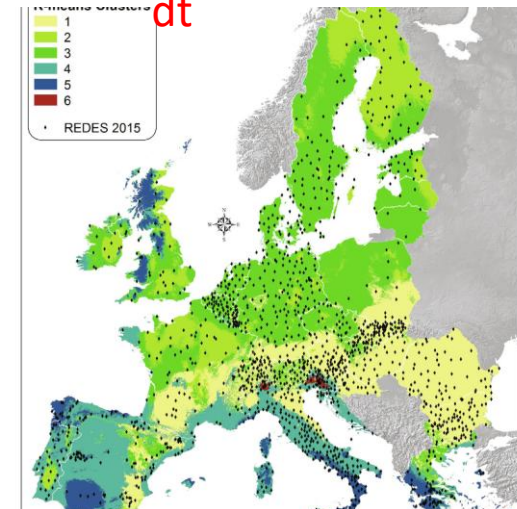
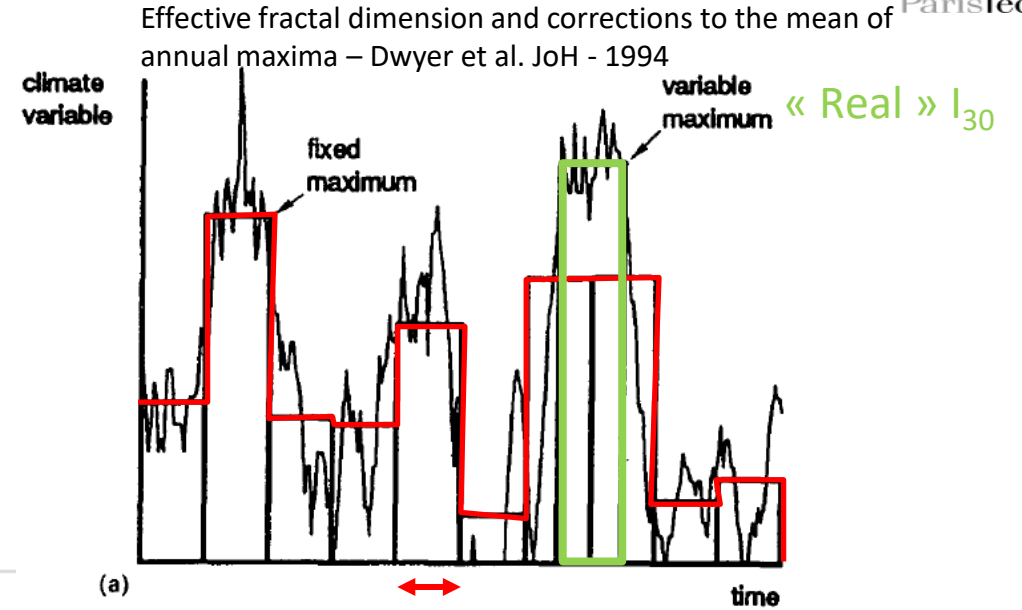
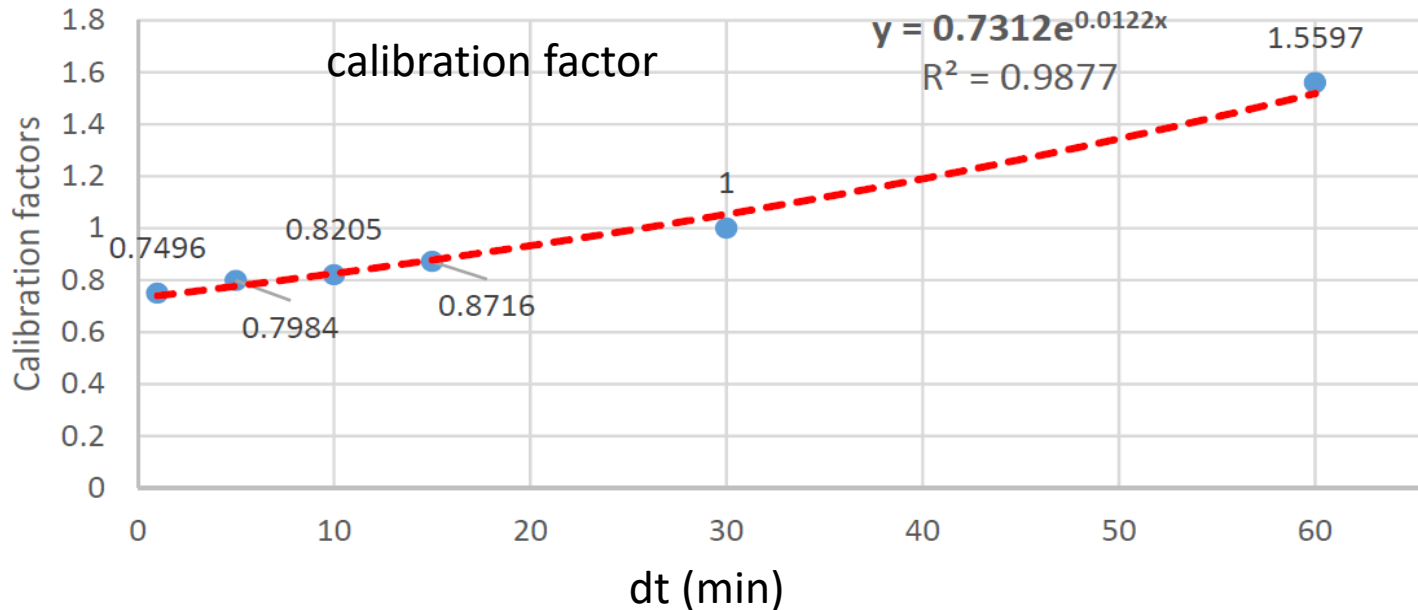
$$KE_r = 0.29 (1 - 0.72 \exp(-0.05 i_r))$$

- e_r : kinetic energy per mm of rain during the sampling ($\text{MJ ha}^{-1} \text{mm}^{-1}$)
- i_r rainfall intensity (mm/h)
- r a sample

KE_r and I_{30} values rely on the frequency of the sampling (ie. their duration).

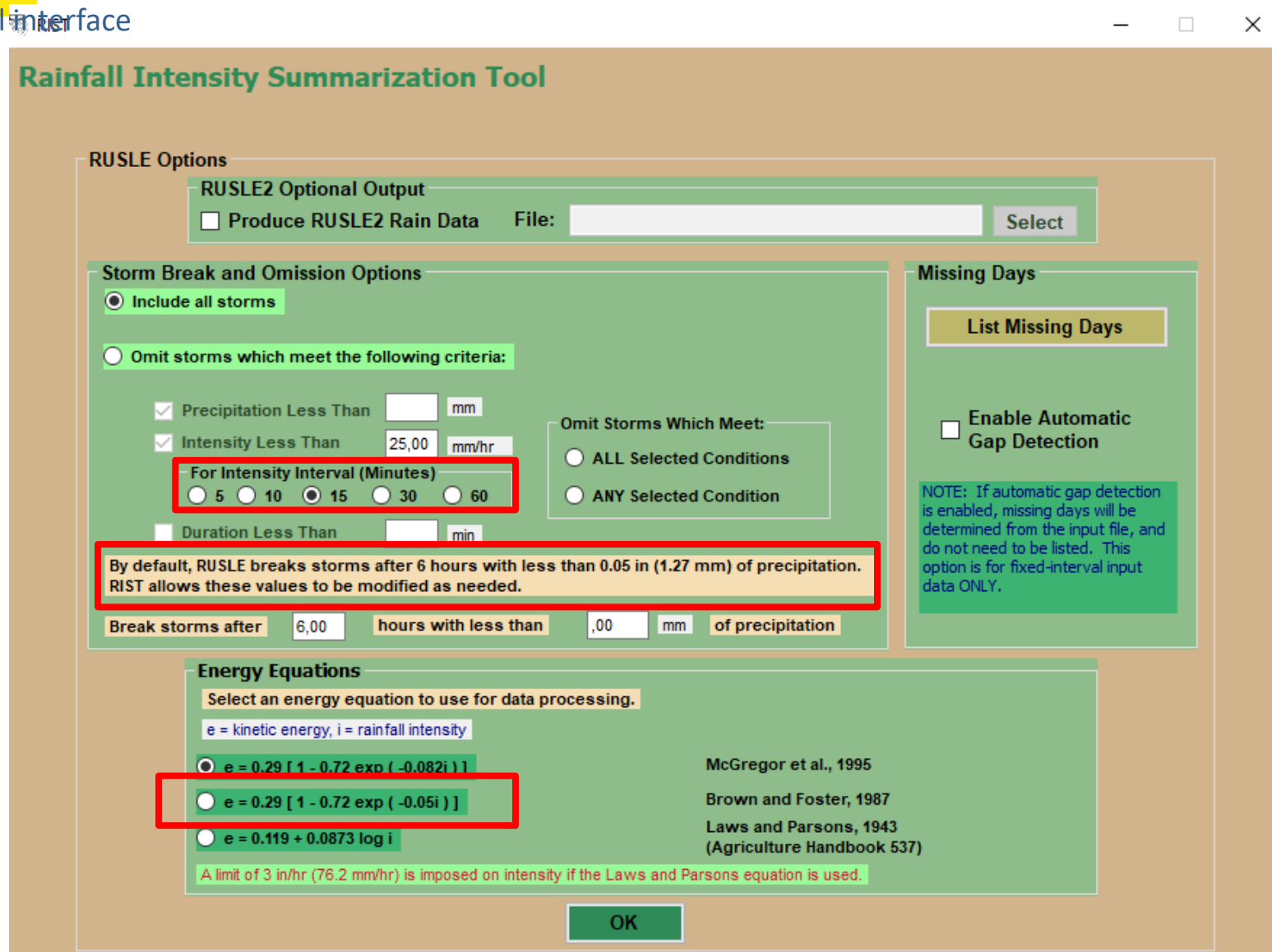
$$E(I_{30}) = \left(\sum_{r=1}^R KE_r v_r \right) I_{30}$$

$$KE_r = 0.29 (1 - 0.72 \exp(-0.05 i_r))$$



REDES ~1700 stations

o RIST graphical interface



Rainfall Intensity Summarization Tool

RUSLE Options

RUSLE2 Optional Output

Produce RUSLE2 Rain Data File: Select

Storm Break and Omission Options

Include all storms

Omit storms which meet the following criteria:

Precipitation Less Than mm

Intensity Less Than 25,00 mm/hr

For Intensity Interval (Minutes)

5 10 15 30 60

Duration Less Than min

Omit Storms Which Meet:

ALL Selected Conditions

ANY Selected Condition

By default, RUSLE breaks storms after 6 hours with less than 0.05 in (1.27 mm) of precipitation. RIST allows these values to be modified as needed.

Break storms after 6,00 hours with less than .00 mm of precipitation

Missing Days

List Missing Days

Enable Automatic Gap Detection

NOTE: If automatic gap detection is enabled, missing days will be determined from the input file, and do not need to be listed. This option is for fixed-interval input data ONLY.

Energy Equations

Select an energy equation to use for data processing.

e = kinetic energy, i = rainfall intensity

$e = 0.29 [1 - 0.72 \exp (-0.082i)]$ McGregor et al., 1995

$e = 0.29 [1 - 0.72 \exp (-0.05i)]$ Brown and Foster, 1987

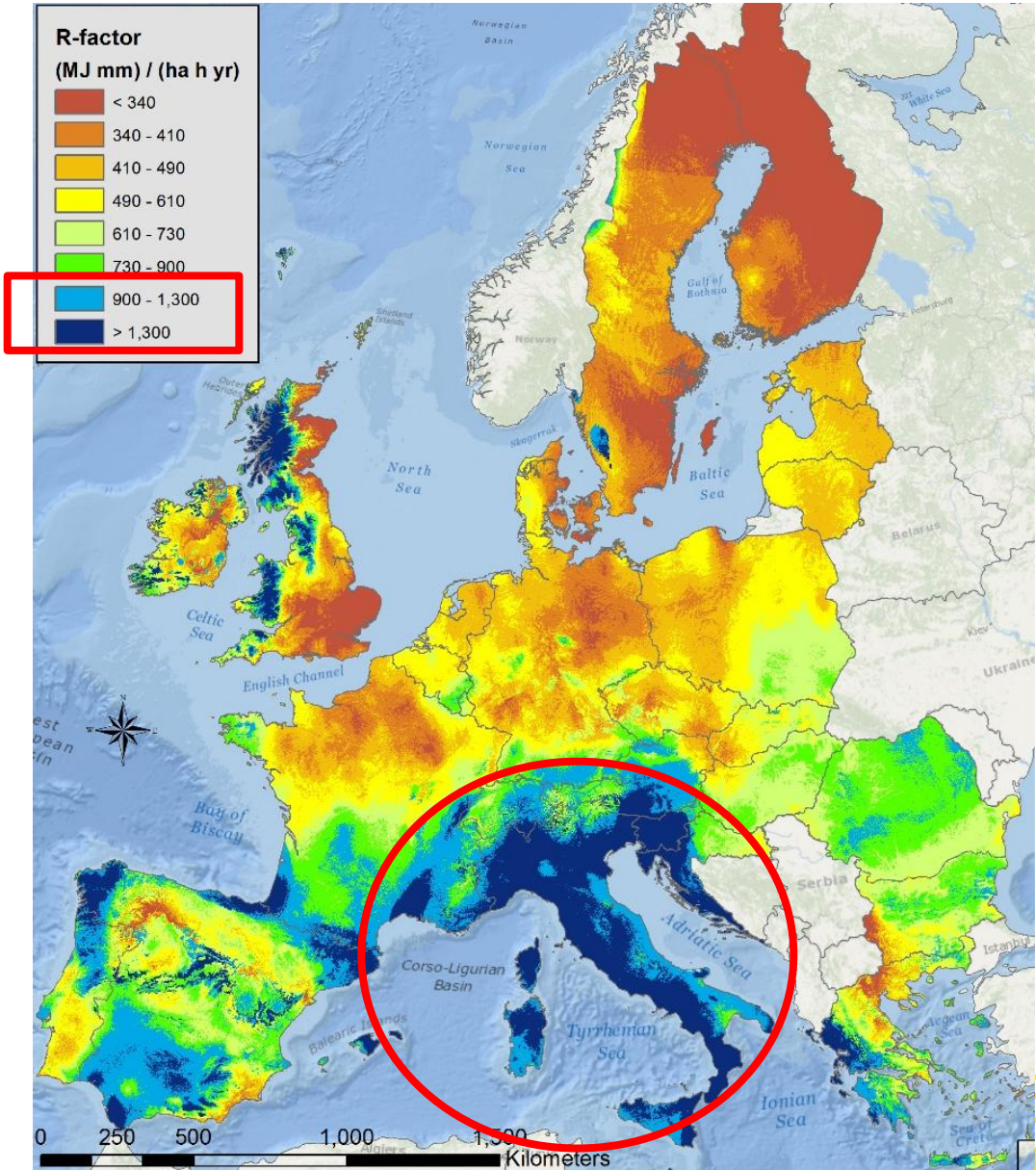
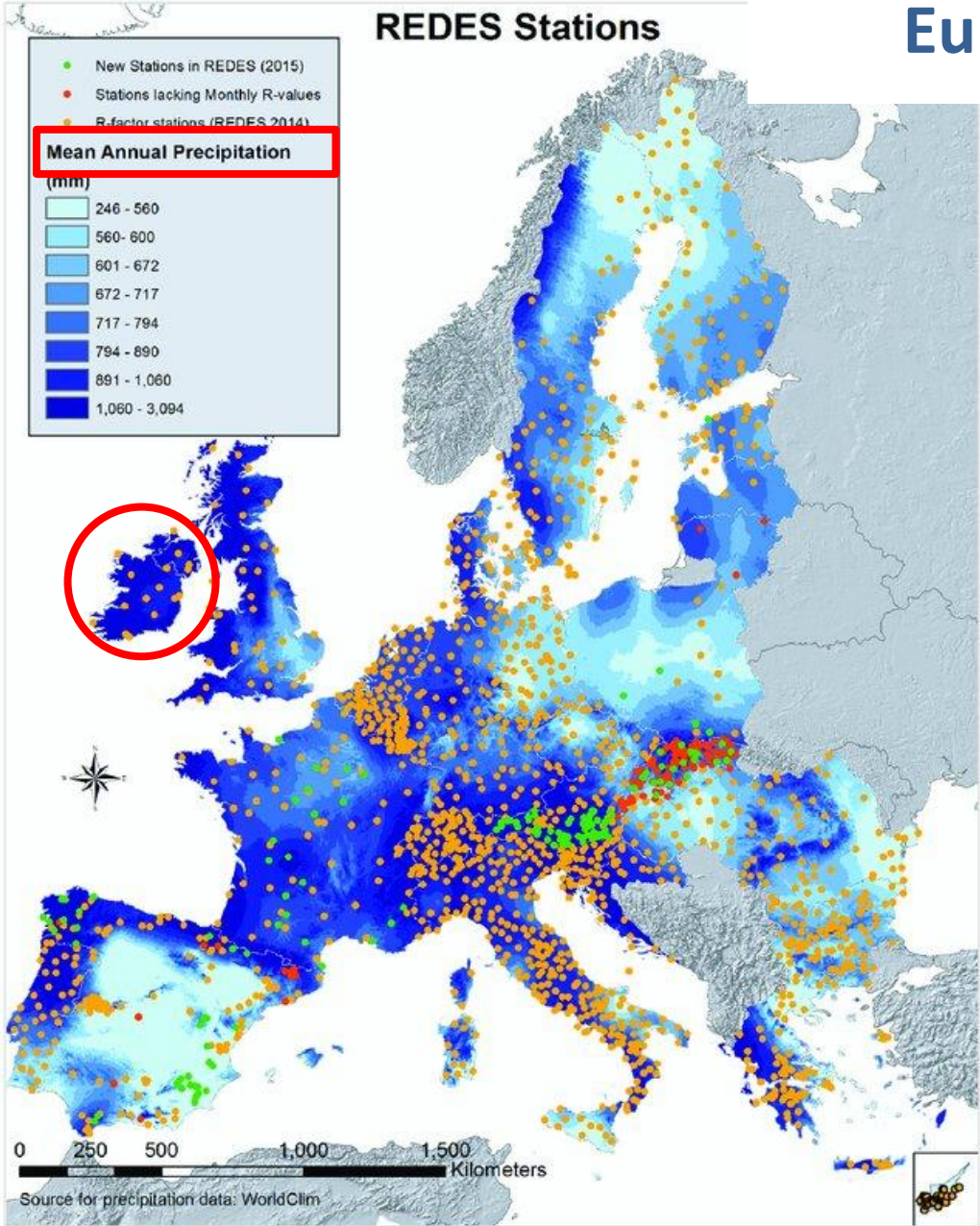
$e = 0.119 + 0.0873 \log i$ Laws and Parsons, 1943 (Agriculture Handbook 537)

A limit of 3 in/hr (76.2 mm/hr) is imposed on intensity if the Laws and Parsons equation is used.




















OK

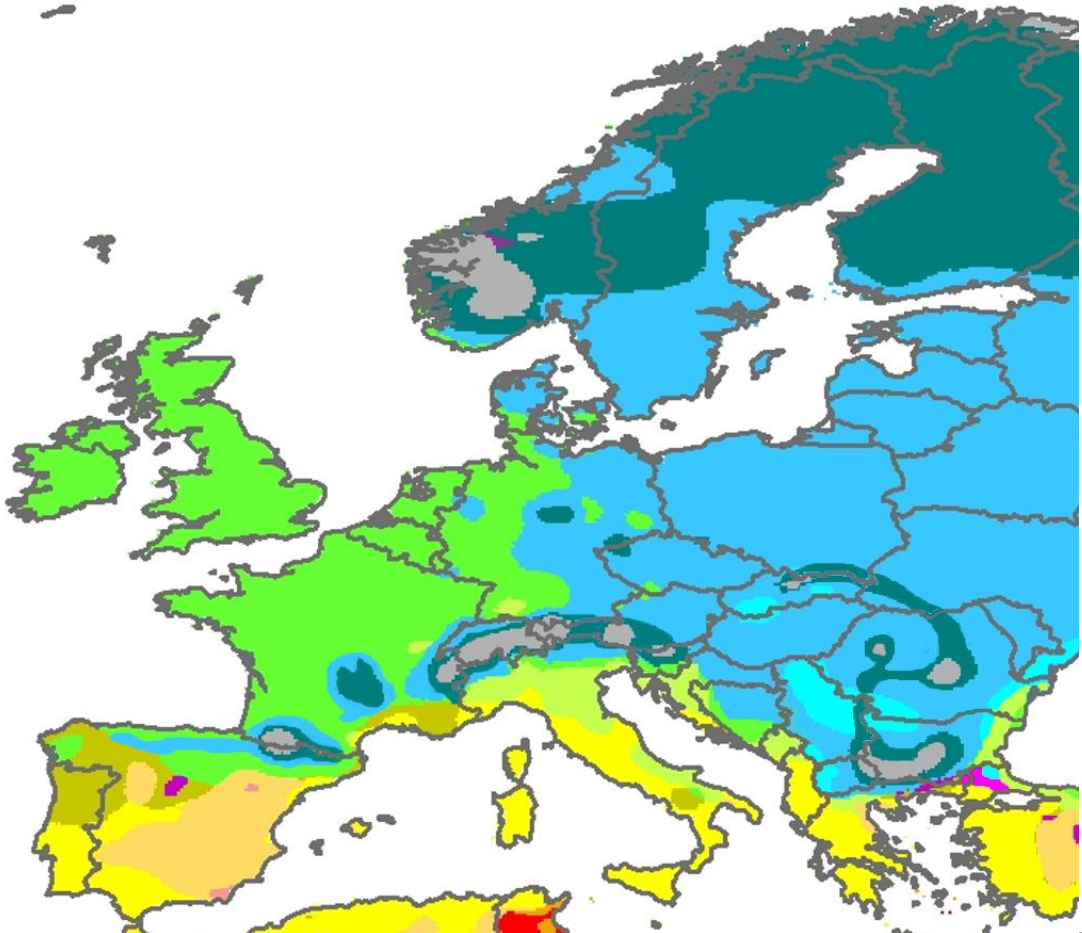
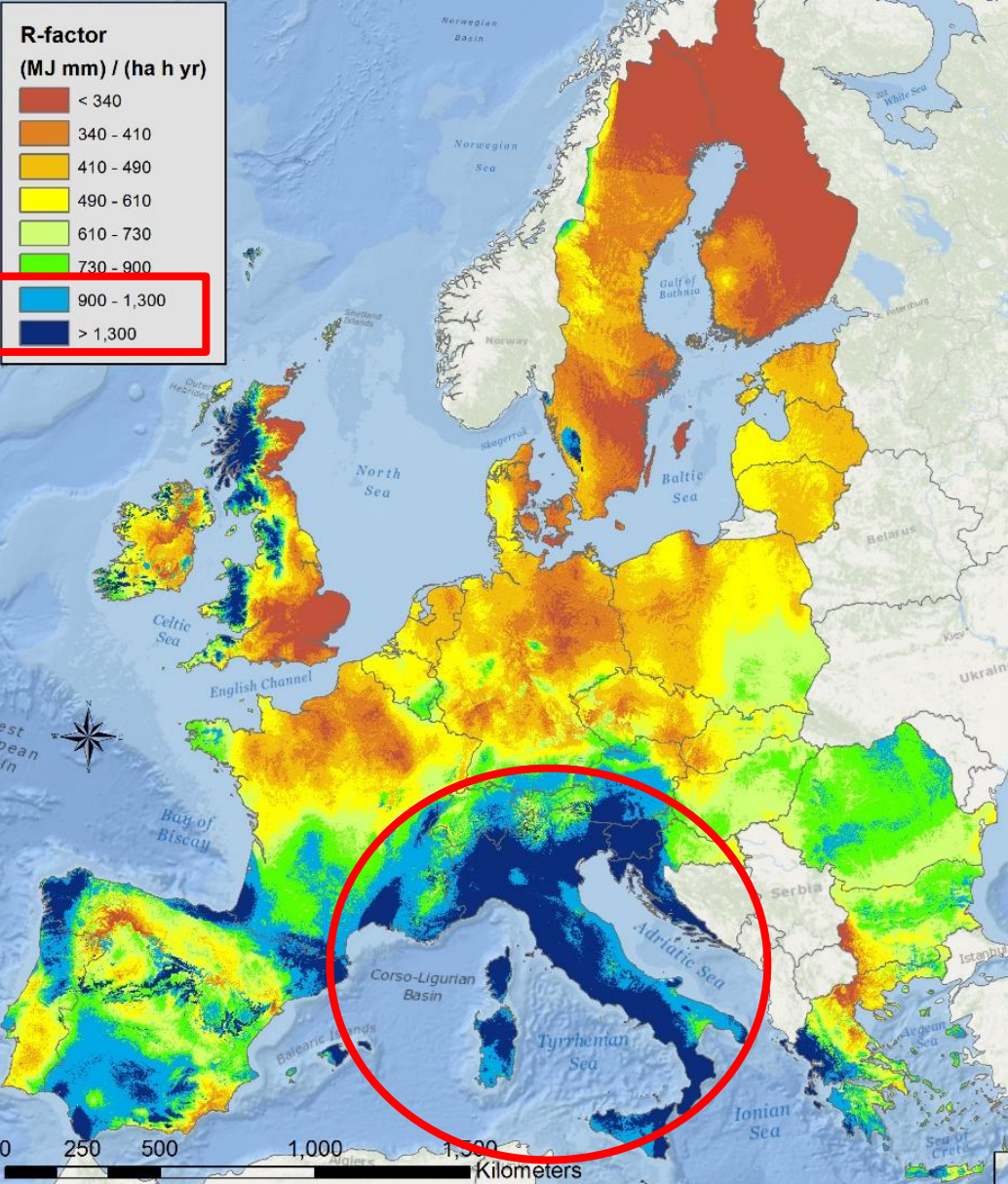
Wildly used (by ESDAC for ex)

European rainfall erosivity by ESDAC (2010)

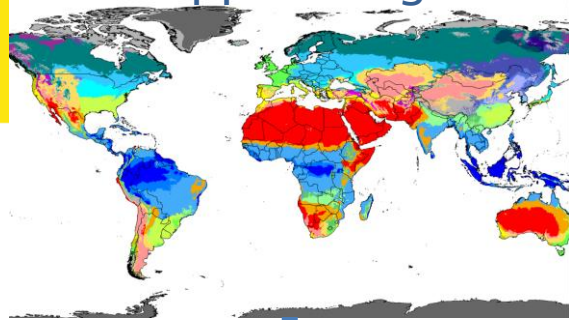


European rainfall erosivity by ESDAC (2010)

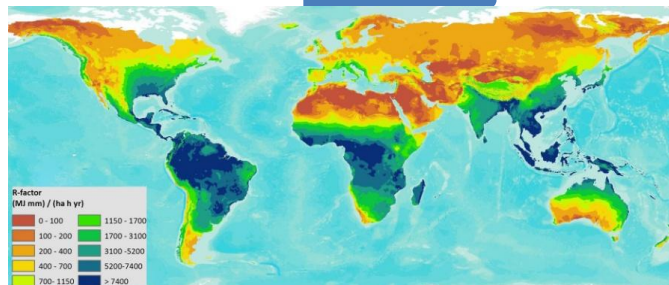
 Af	 BWh	 Csa	 Cwa	 Cfa	
 Am	 BWk	 Csb	 Cwb	 Cfb	
 Aw	 BSh		 Cwc	 Cfc	
	 BSk				



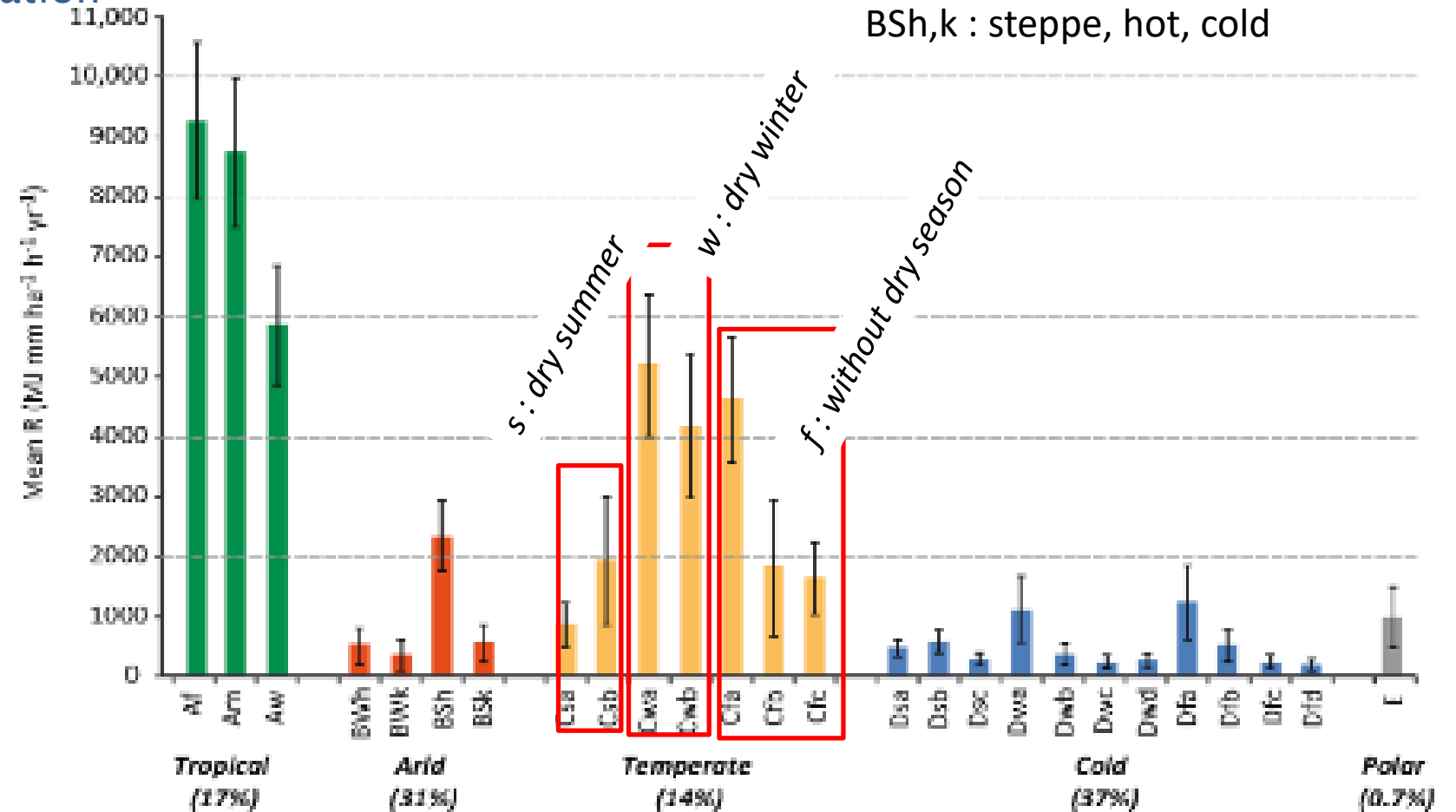
Köppen-Geiger classification



Global KG Climate map



Global Rainfall Erosion map



a, b, c, d : hot, warm, cold, very cold
BSh,k : steppe, hot, cold

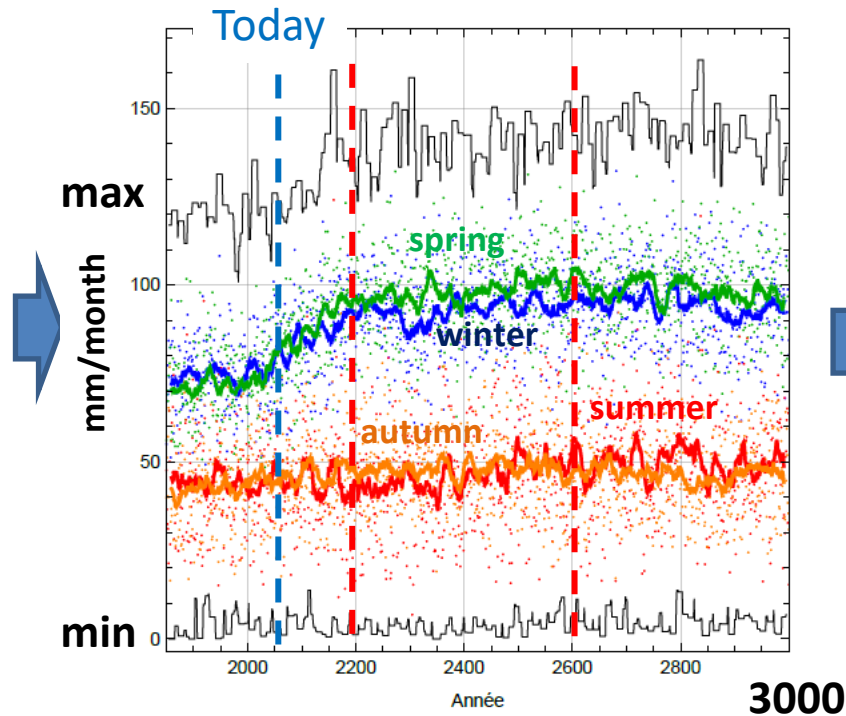
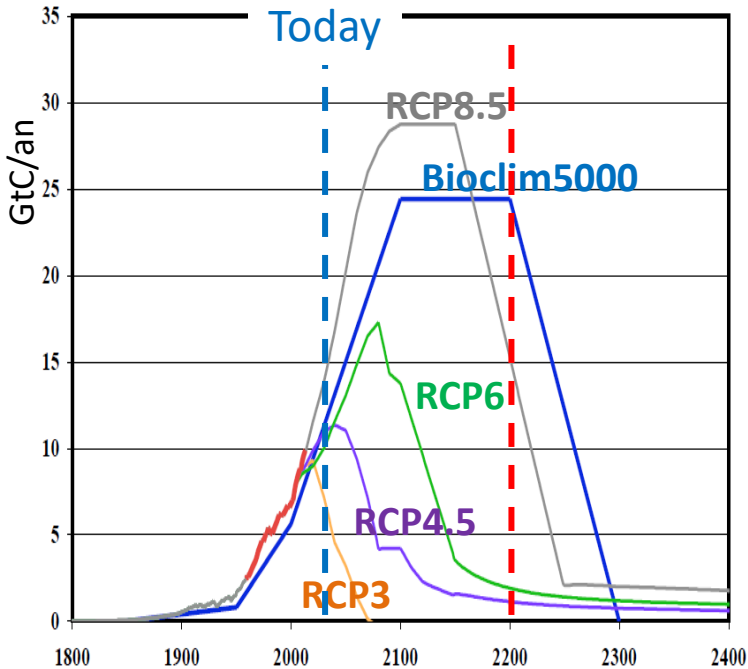
A = tropical, **B = Arid**, **C = temperate**, **D = cold**, **E = polar**

Panagos, Panos, Pasquale Borrelli, Katrin Meusburger, et al. 2017. « Global Rainfall Erosivity Assessment Based on High-Temporal Resolution Rainfall Records ». *Scientific Reports* 7 (1): 4175. <https://doi.org/10.1038/s41598-017-04282-8>.

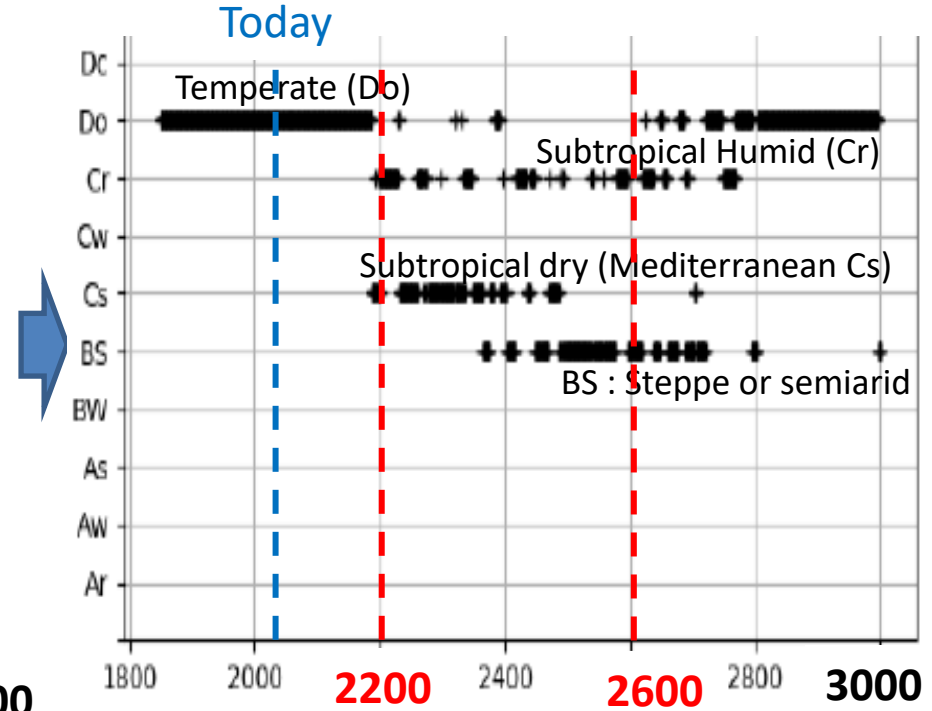
Climate simulation for short term evolution

o iLOVECLIM - LSCE 2020 climatic evolution scenario for Bioclim5000 greenhouse gas hypotheses

Greenhouse gas scenarios



Monthly Precipitation computed by iLOVECLIM (LSCE-2020)

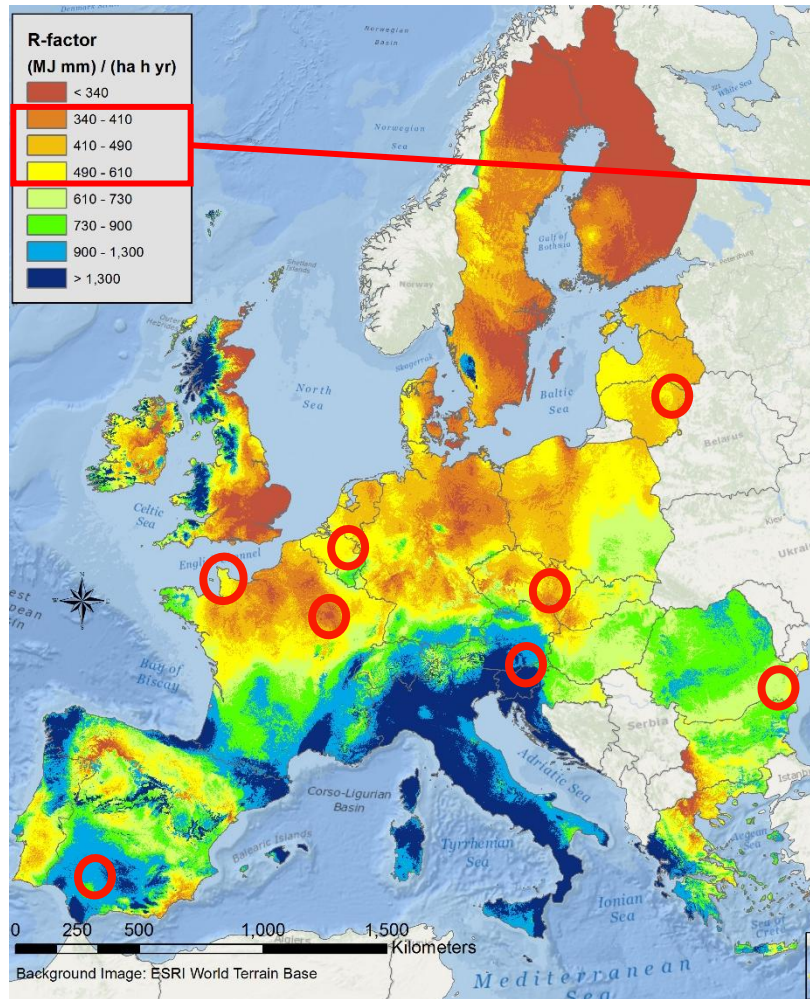


Rainfall intensity and temperature scenarios are converted into a succession of climatic types (Köppen-Trewartha)

Rainfall erosivity evolution from 2010 to 2050 (ESDAC)

○ RAINFALL EROSIVITY (RUSLE R factor evolution)

“TODAY” (2010)

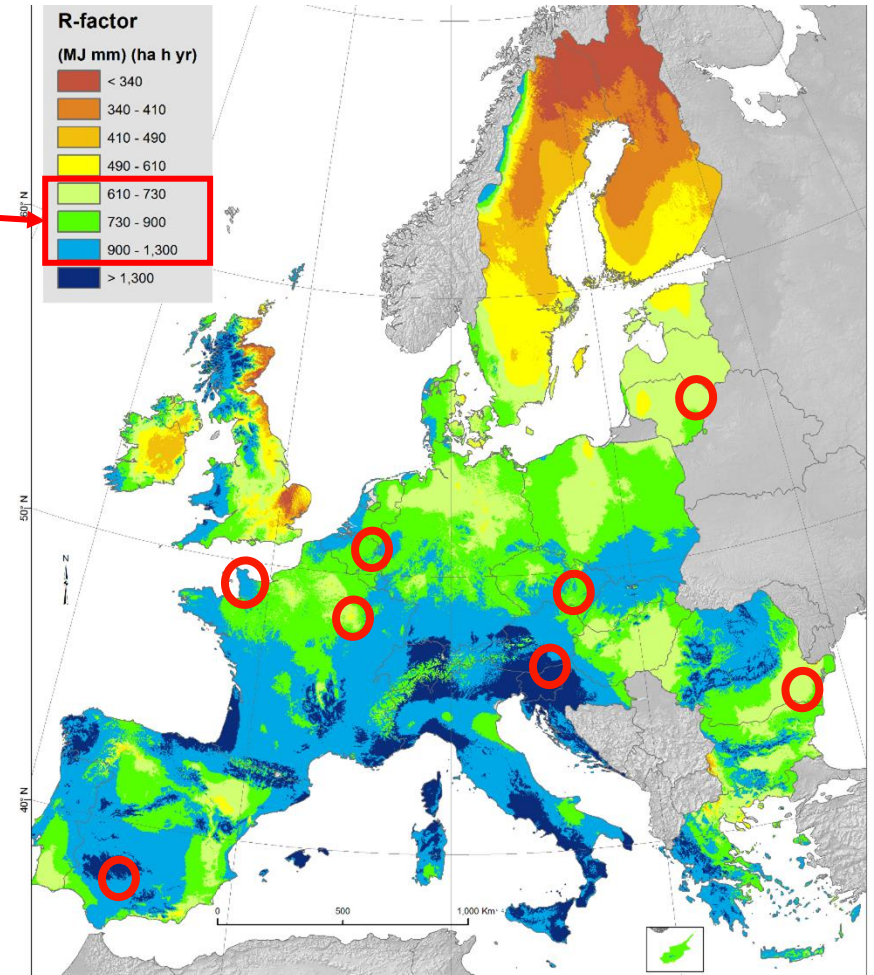


R factor map in 2015 (Panagos & al., 2015)

~x2

RCP 4.5

« TOMORROW » (2050)



R factor map in 2050 (Panagos & al., 2017)

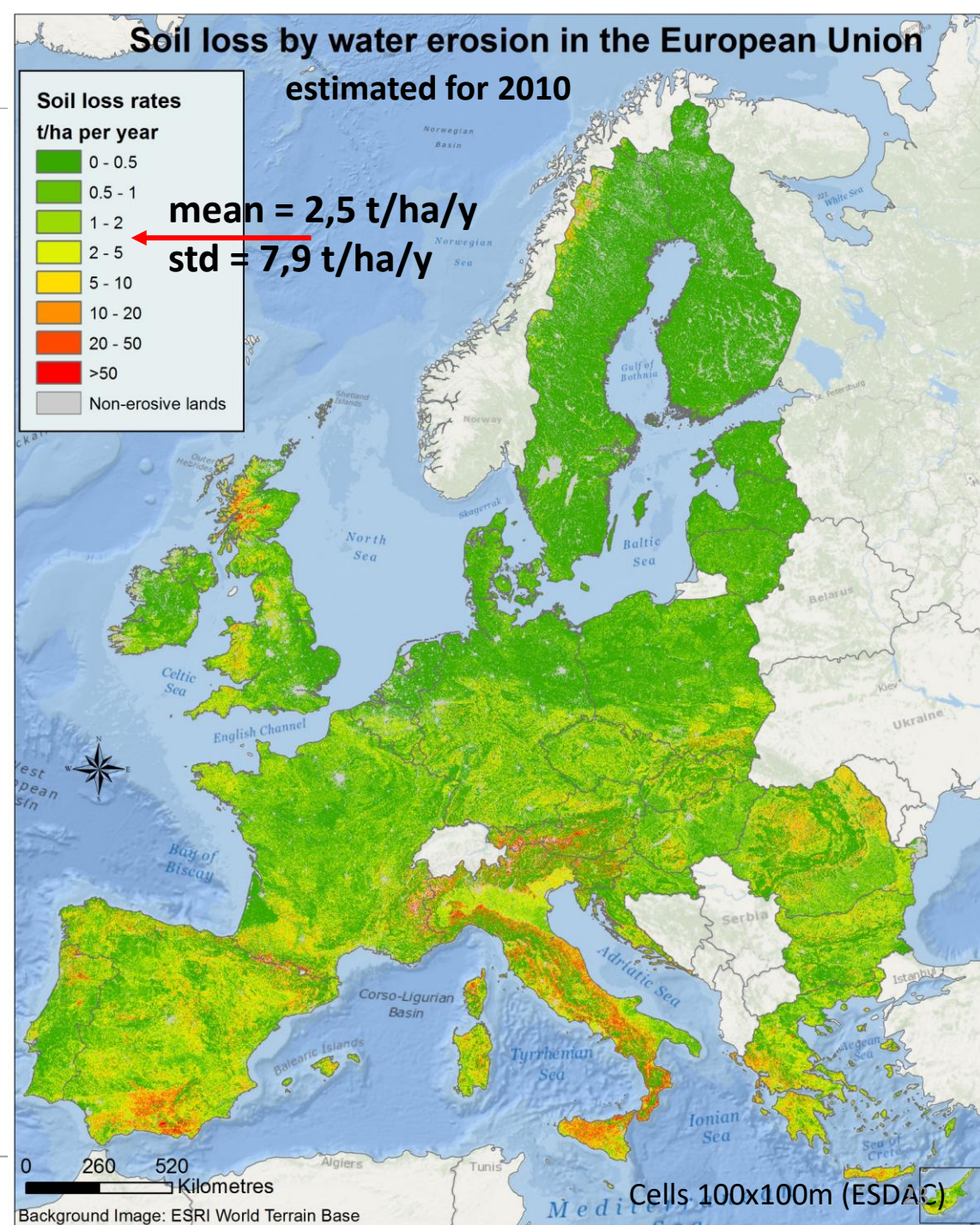
Mean erosion rate - USLE – ESDAC results

Mean erosion rate :

$$\text{MER} = R \times K \times LS \times C \text{ (t/ha/y)}$$

- R : Rainfall erosivity (MJ mm /ha /h),
- K : Soil erodability (t h / (MJ mm)),
- SL : topography contribution (drainage) (-),
- C : vegetation Cover (%)

<https://esdac.jrc.ec.europa.eu/themes/soil-erodibility-europe>



o Wischmeier equation

$$K = \frac{(K1 + K2 + K3)}{100} \times 0,1317$$

$$K1 = 2,1 \times 10^{-4} \times M^{1,14} \times (12 - OM) \quad [0; 91] \sim 40$$

$$K2 = 3,25 \times (s - 2) \quad \text{with } s \text{ in } [1-4] \quad [-3.25; 7.5]$$

$$K3 = 2,5 \times (p - 3) \quad \text{with } p \text{ in } [1-6] \quad [-5; 7.5]$$

Correction factor
[-5; 7.5]

$$M = (PC_{\text{silt}} + PC_{\text{vfs}}) \times (100 - PC_{\text{clay}})$$

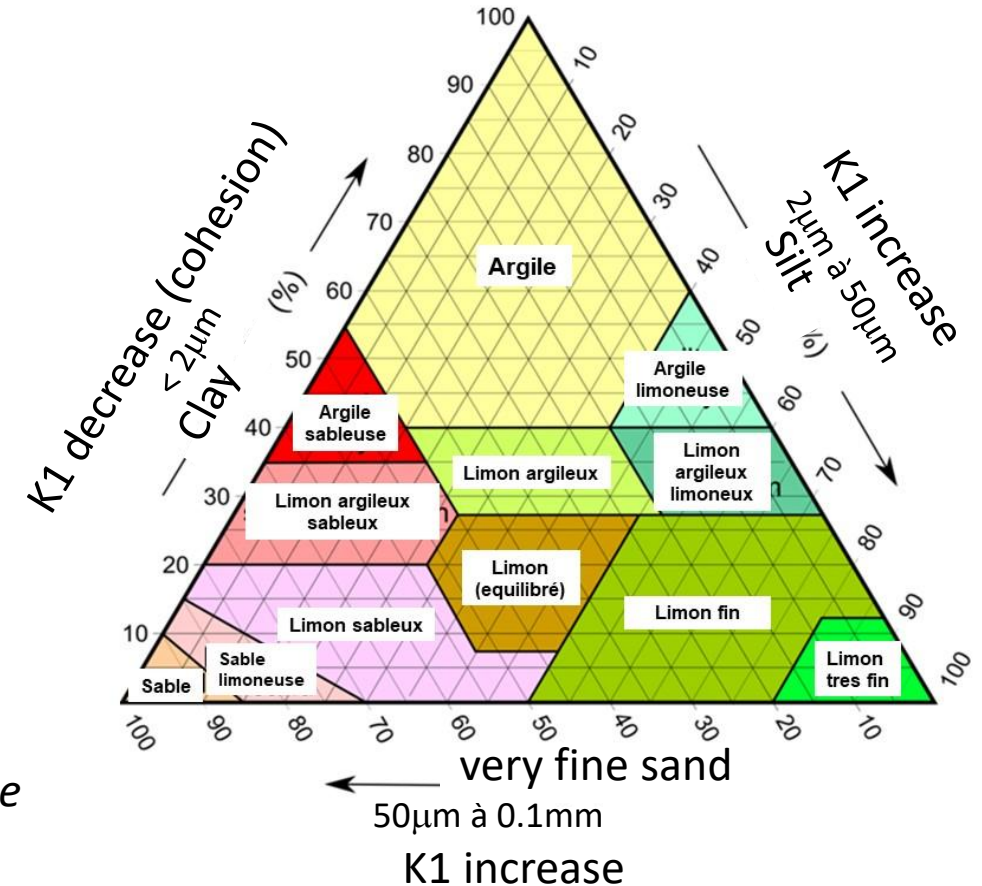
OM Organic Mater (%)

PC pourcentage of :

- vfs (very fine sand) : 50µm à 0.1mm
- clay : < 2µm
- silt : 2µm à 50µm

Order of magnitude

$$\text{mean}(K, \text{Europa}) \sim 0,03 \text{ t ha h} / (\text{ha MJ mm})$$



K1

Classes of soil structure derived the European Soil Database.

Structure class (s)	European Soil Database
1 (very fine granular: 1–2 mm)	G (good)
2 (fine granular: 2–5 mm)	N (normal)
3 (medium or coarse granular: 5–10 mm)	P (poor)
4 (blocky, platy or massive: > 10 mm)	H (humic or peaty top soil)

p index	permeability	texture	Hydraulic conductivity (mm/h)
1	Fast, very fast	Sand	>61.0
2	Moderately fast	Sandy silt, silty sand	20.3--61.0
3	moderate	Silt, fine silt	5.1--20.3
4	Moderately slow	Sandy loam, clay loam	2.0--5.1
5	Slow	Fine clay loam, sandy clay	1.0--2.0
6	Very slow	Silty clay, clay	<1.0

Vegetation cover : standard C factor values for RUSLE model

Corine Land Cover

Group	CLC class	Detailed class	Description	C_{type}
Permanent crops	221	Vineyards	Areas planted with vines	0.15–0.45
	222	Fruit trees & berry plantations	Parcels planted with fruit trees or shrubs: single/mixed fruit species, fruit trees associated with permanently grassed surfaces.	0.1–0.3
Pastures	223	Olive groves	Areas planted with olive trees	0.1–0.3
	231	Pastures	Dense, predominantly graminoid grass cover, of floral composition, not under a rotation system. Mainly used for grazing.	0.05–0.15
Heterogeneous agricultural areas	241	Annual crops associated with permanent crops	Non-permanent crops (arable land or pasture) associated with permanent crops on the same land parcel	0.07–0.35
	242	Complex cultivation patterns	(non-associated annual crops represent less than 25%) Juxtaposition of small parcels of diverse annual crops, pasture and/or permanent crops (arable land, pasture and orchards each occupy less than 75% of the total surface area of the land unit)	0.07–0.2
	243	Land principally used for agriculture, with significant areas of natural vegetation	Areas principally used for agriculture, interspersed with significant natural areas (agricultural land occupies between 25 and 75% of the total surface of the land unit)	0.05–0.2
	244	Agro-forestry areas	Annual crops or grazing land under the wooded cover of forest species	0.03–0.13
Forests	311	Broad-leaved forest	Vegetation formation composed principally of trees, including shrub and bush understories, where broadleaved species predominate	0.0001–0.003
	313	Mixed forest	Vegetation formation composed principally of trees, including shrub and bush understories, where broadleaved and coniferous species co-dominate.	0.0001–0.003
Scrub and/or herbaceous vegetation associations	321	Natural grasslands	Low productivity grassland. Often situated in areas of rough and uneven ground	0.01–0.08
	322	Moors and heathland	Vegetation with low and closed cover, dominated by bushes, shrubs and herbaceous plants (heath, briars, broom, gorse, laburnum)	0.01–0.1
	323	Sclerophyllous vegetation	Bushy sclerophyllous vegetation. Includes maquis (dense vegetation composed of numerous shrubs) and garrige (oak, arbutus, lavender, thyme, cistus)	0.01–0.1
	324	Transitional woodland-shrub	Bushy or herbaceous vegetation with scattered trees. Can represent either woodland degradation or forest Regeneration/colonisation.	0.003–0.05
Open spaces with little or no vegetation	331	Beaches, dunes, sands	Beaches, dunes and expanses of sand or pebbles in coastal or continental areas	0
	332	Bare rocks	Scree, cliffs, rocks and outcrops	0
	333	Sparsely vegetated areas	Includes steppes, tundra and badlands. Scattered high-altitude vegetation	0.1–0.45
CLIMATE-Training session 20/05/2026	334	Burnt areas	Areas affected by recent fires, still mainly black	0.1–0.55
	335	Glaciers and perpetual snow	Land covered by glaciers or permanent snowfields	0

$$C_{factor} = \min(C_{type}) + [\max(C_{type}) - \min(C_{type})] (100 - PC_{cover})$$

P. Panagos et al. / Land Use Policy 48 (2015) 38–50

$$LS = (l/22.13)^m (65,41 \sin^2 \theta + 4,56 \sin \theta + 0,065)$$

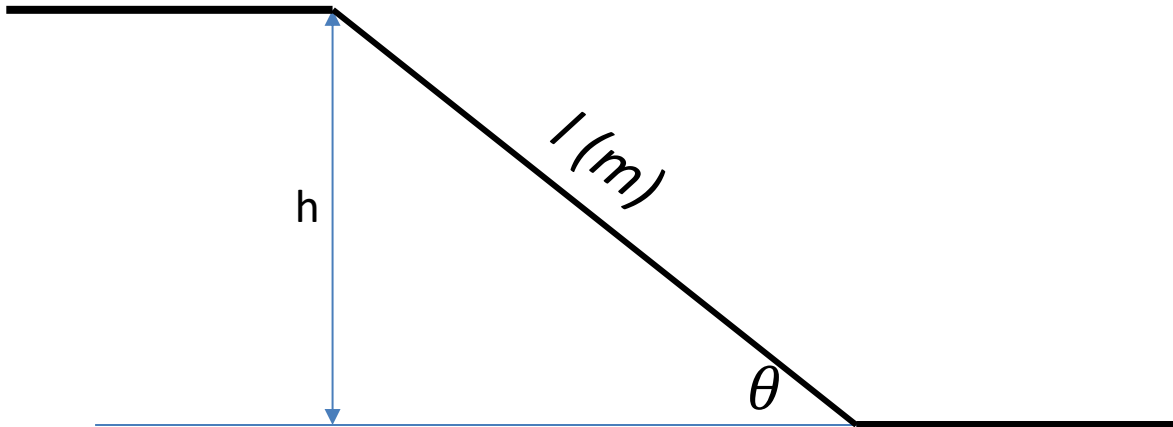
$$LS = L \cdot S$$

$$L = (l/22.13)^m$$

$$S = 65,41 \sin^2 \theta + 4,56 \sin \theta + 0,065$$

With

$m = 0.65$	for	$9.74^\circ < \theta < 16.04^\circ$
$m = 0.6$	for	$5.1^\circ < \theta < 9.74^\circ$
$m = 0.5$	for	$2.9^\circ < \theta < 5.1^\circ$
$m = 0.4$	for	$1.7^\circ < \theta < 2.9^\circ$
$m = 0.3$	for	$0.6^\circ < \theta < 1.7^\circ$
$m = 0.2$	for	$\theta < 0.6^\circ$



Wischmeier, Walter H. 1978. « Predicting rainfall erosion losses ». USDA agricultural research services handbook 537.

H7 fx $= (65,41 * \text{PUISSANCE}(E7;2) + 4,56 * E7 + 0,065)$

	A	B	C	D	E	F	G	H	I
1	Topography (LS factor)	length of the slope (m)	slope	Slope in degree (°C)	sin	h	L	S	LS
2	test 1 values	Cells to fill with your values			0,0000	0,0000	0,00	0,07	0,00
3	test 2 values				0,0000	0,0000	0,00	0,07	0,00
4	test 3 values				0,0000	0,0000	0,00	0,07	0,00
5	your selected value				0,0000	0,0000	0,00	0,07	0,00
6	Default (typical) values	Length of the slope (m)	slope	Slope in degree (°C)	sin	h	L	S	LS
7	example 1	30,40	1:3	18,00	0,3090	9,3941	1,17	7,72	9,05
8	example 2	40,00		13,58	0,2349	9,3941	1,34	4,74	6,38
9	example 3	50,00		10,83	0,1879	9,3941	1,50	3,23	4,86

topography (LS) | Soil erodability (K) | Rainfall erosivity (R) | Vegetation cover (C) | mean rate erosion (RUSLE) | +

LS factor

Exercise : spreadsheet principle on LS factor example

Formula are already programmed but can be changed

H7

	A	B	C	D	E	F	G	H	I
1	Topography (LS factor)	length of the slope (m)	slope	Slope in degree (°C)	sin	h	L	S	LS
2	test 1 values	Cells to fill with your values			0,0000	0,0000	0,00	0,07	0,00
3	test 2 values				0,0000	0,0000	0,00	0,07	0,00
4	test 3 values				0,0000	0,0000	0,00	0,07	0,00
5	your selected value				0,0000	0,0000	0,00	0,07	0,00
6	Default (typical) values				Length of the slope (m)	slope	Slope in degree (°C)	sin	h
7	example 1	30,40	1:3	18,00	0,3090	9,3941	1,17	7,72	9,05
8	example 2	40,00		13,58	0,2349	9,3941	1,34	4,74	6,38
9	example 3	50,00		10,83	0,1879	9,3941	1,50	3,23	4,86

topography (LS) Soil erodability (K) Rainfall erosivity (R) Vegetation cover (C) mean rate erosion (RUSLE)

Final LS factor Reported in the last sheet

LS factor

K factor

R factor

C factor

=

Product of the 4 factors

H7

	A	B	C	D	E	F	G	H	I
1	Topography (LS factor)	Length of the slope (m)	slope	Slope in degree (°C)	sin	h	L	S	LS
2	test1 values				0,0000	0,0000	0,00	0,07	0,00
3	test2 values				0,0000	0,0000	0,00	0,07	0,00
4	test3 values				0,0000	0,0000	0,00	0,07	0,00
5	your selected value				0,0000	0,0000	0,00	0,07	0,00
6	Default (typical) values	Length of the slope (m)	slope	Slope in degree (°C)	sin	h	L	S	LS
7	example 1	30,40	1:3	18,00	0,3090	9,3941	1,17	7,72	9,05
8	example 2	40,00		13,58	0,2349	9,3941	1,34	4,74	6,38
9	example 3	50,00		10,63	0,1879	9,3941	1,50	3,23	4,86

topography (LS) | Soil erodability (K) | Rainfall erosivity (R) | Vegetation cover (C) | mean rate erosion (RUSLE)

EXERCISE

Find the climate that will face your facility in near future
and optimise it :
play with K and LS (and C to a lesser extend)

$$\text{MER} = \boxed{\text{R}} \boxed{\text{K}} \boxed{\text{LS}} \boxed{\text{C}}$$

H7 X ✓ fx =(65,41*PUISSANCE(E7;2)+4,56*E7+0,065)

	A	B	C	D	E	F	G	H	I
1	Topography (LS factor)	Length of the slope (m)	slope	Slope in degree (°C)	sin	h	L	S	LS
2	test1 values				0,0000	0,0000	0,00	0,07	0,00
3	test2 values				0,0000	0,0000	0,00	0,07	0,00

The file is in .odt
But decimal are

CTRL+H and substitute « , » by « . »

Options Excel

- Générales
- Formules
- Données
- Vérification
- Enregistrement
- Langue
- Accessibilité
- Options avancées**
- Personnaliser le ruban
- Barre d'outils Accès rapide
- Compléments
- Centre de gestion de la confidentialité

Options avancées pour travailler avec Excel

Options d'édition

- Déplacer la sélection après validation
 - Sens : Bas
- Décimale fixe
 - Place : 2
- Activer la poignée de recopie et le glisser-déplacer des cellules
 - Alerter avant remplacement
- Modification directe
- Étendre les formules et formats de plage de données
- Activer la saisie automatique de pourcentage
- Saisie semi-automatique des valeurs de cellule
 - Utiliser automatiquement le remplissage instantané
- Zoom avec la roulette IntelliMouse
- Avertir l'utilisateur lorsqu'une opération potentiellement longue est lancée
 - Lorsque cette quantité de cellules (nombre en milliers) est affectée : 33 554
- Utiliser les séparateurs système
 - Séparateur de décimale : .
 - Séparateur des milliers :
- Déplacement du curseur :
 - Logique
 - Visuel
- Ne pas créer un lien hypertexte automatique de la capture

Couper, copier et coller

OK Annuler

15 min exercise...

And questions...

- What does RUSLE estimation tell us ?

Order of magnitude on a « standard » example:

With $K \sim 0.04$ and $LS \sim 8$ ($\rho = 1.3 \text{ t/m}^3$)

Scenario/local characteristics : **R in 500 to 6300 (x12.6)**

With $C = 0.01$ (dense grassland) → MRE = 1.2cm/century to 15.cm/century

With $C = 0.08$ (sparse grassland) → MRE = 9.6cm/century to 1.2m/century

With $C = 0.55$ (little VG) → MRE = 66.cm/century to 8.3m/century

With $C = 1$ (bare soil) → MRE = 1.2m/century to 15.m/century

- What does RUSLE estimation tell us ?

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With $C = 0.55$ (little VG) → **MRE = 66.cm/century to 8.3m/century**

← 1m soil thickness, 3 centuries

With $C = 1$ (bare soil) → **MRE = 1.2m/century to 15.m/century**

→ K and LS can be optimized (with gravel 20% → $K/20$) and by lowering the slope but consequences remain limited

RUSLE estimation tell us that → zone of uncertainty (because of vegetation cover) → increase accuracy...

- Scenario and associate R (and C) must be investigated (to be more accurate)
 - Scenarios with P (and T) evolution must be proposed for the site
 - R must be calculated with these local values
 - C must be estimated (how? Drought probability?...)

What does RUSLE estimation tell us not?

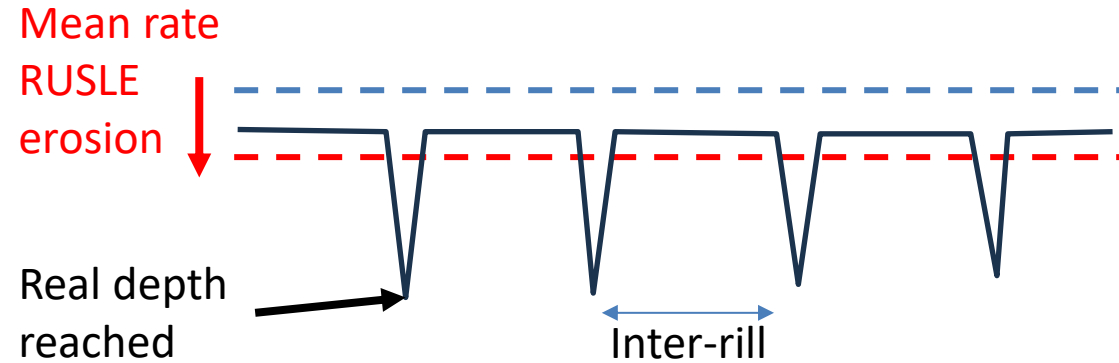
1) Rills and gullies dynamic

Rill depth = 3 x MER ?

- Soil cohesion
- Slope &
- Drainage area...

2) Extreme events (rainfall, drought...)

The cover must resist rare events : millennial or decamillennial rainfall...

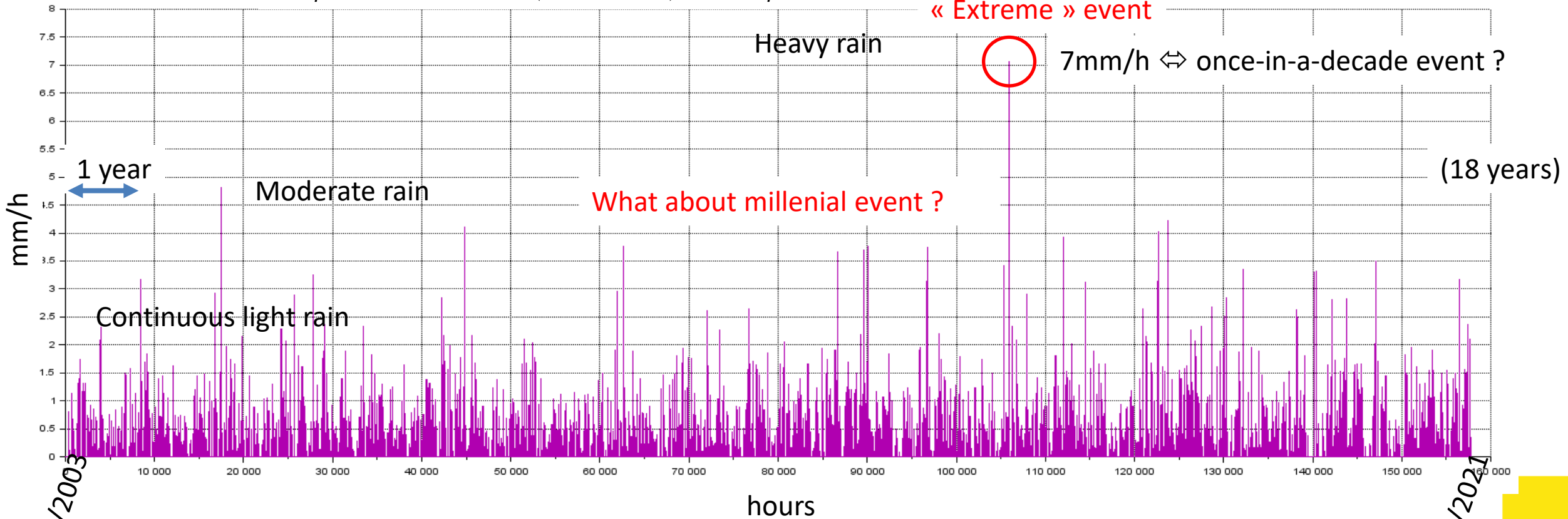


→ need of a new approach, or new models...

Continuous light rain	1 to 3 mm per hour
Moderate rain	4 to 7 mm per hour
Heavy rain	8 mm per hour and more

Qualitative assessment of precipitation in lowland areas of mainland France (based on data from Météo-France)

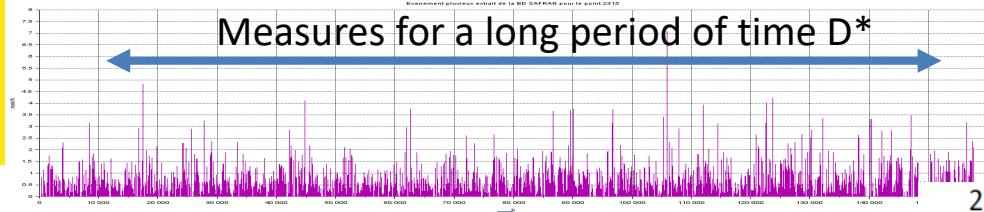
Rainfall events at SAFRAN (Météo-France) n° 2315 point.



01/08/2003

eurad
31/07/2021

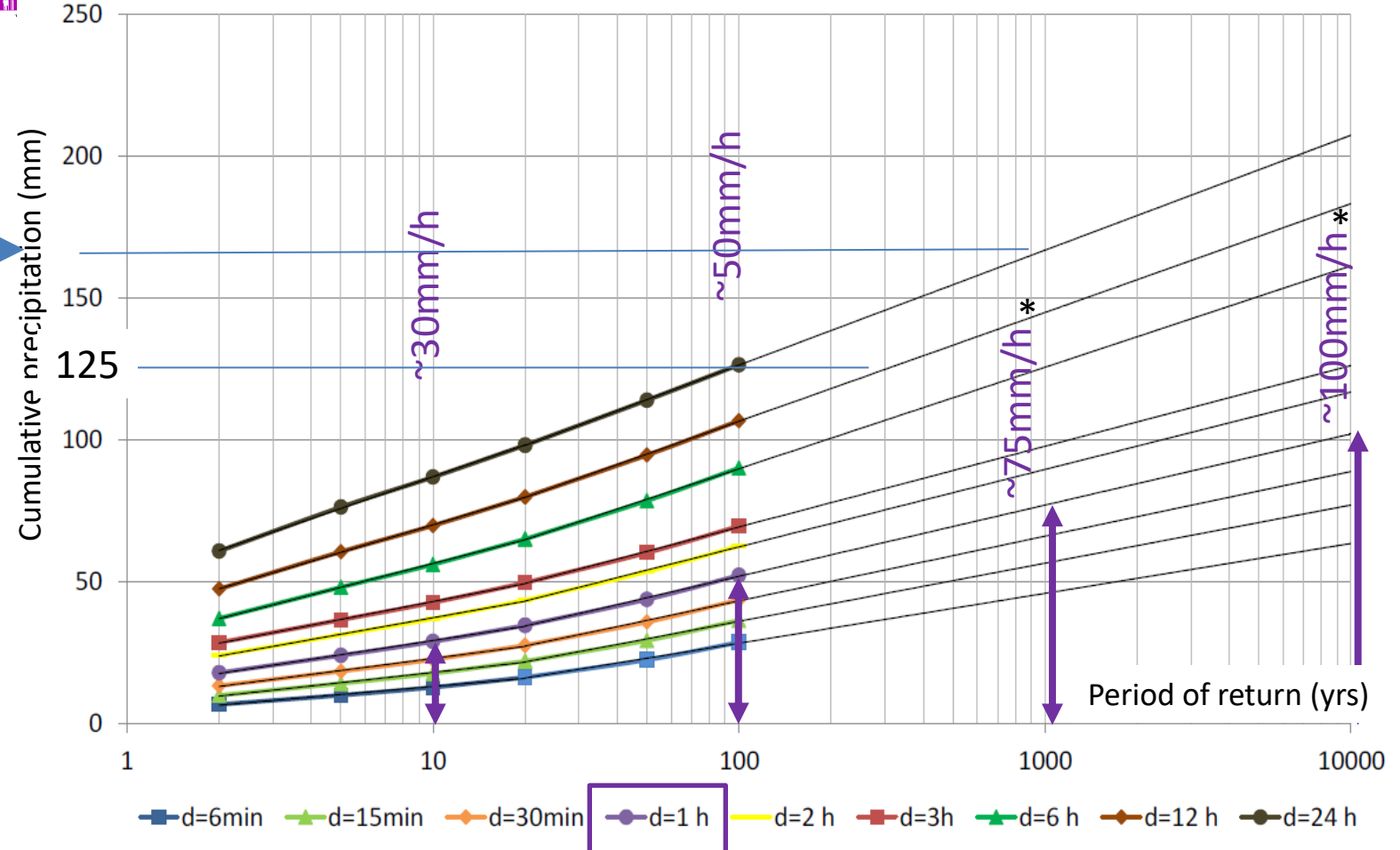
Frequency of extreme rainfalls : calculation of the return period



Frequency analysis (of the maximum over d) and fitting to a (GEV) distribution

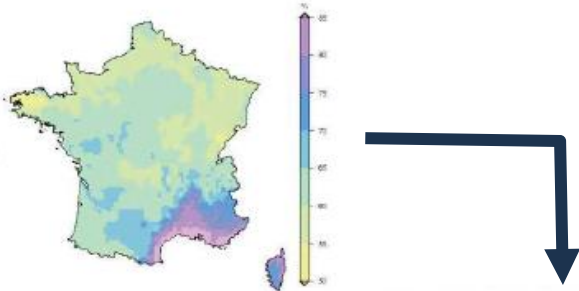
Rainfall variability

Reference quantiles for rainfall events ranging from 6 minutes to 24 hours (return periods of 2 to 100 years) and extrapolation for return periods of 100 to 10,000 years

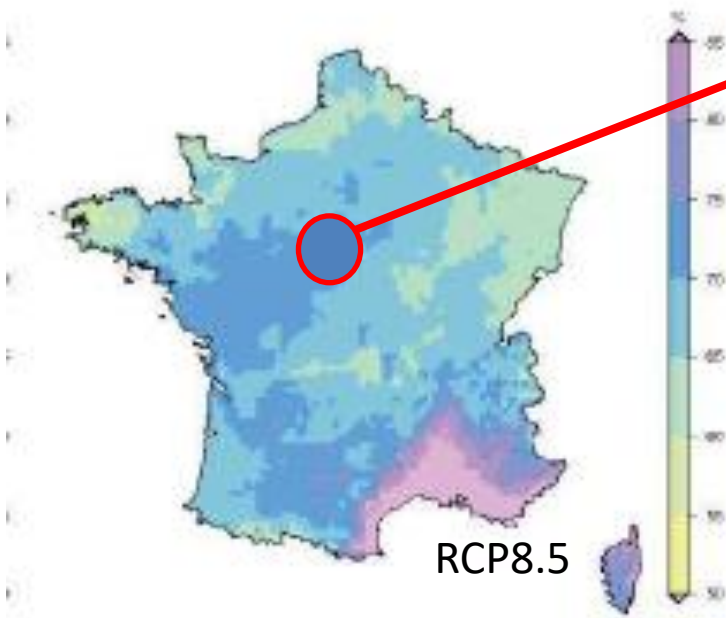


*The return time must be less than four times the duration of the measurements (IRSN/ASNR, Nov. 2013)

Hist – 1976-2005

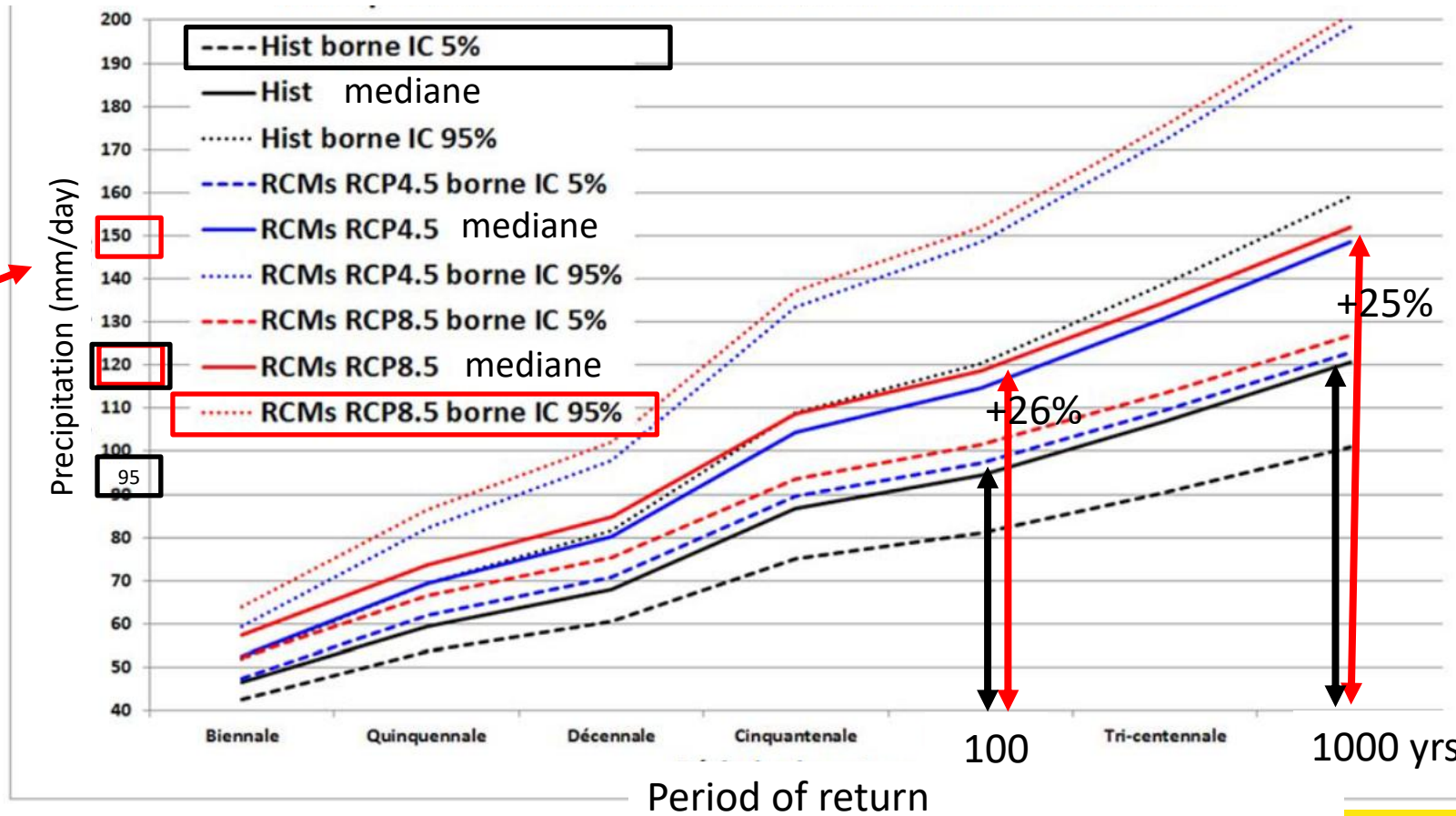


Simulation 2071-2100



RCP8.5

Rainfall values and the 5% and 95% confidence intervals estimated using the **Gumbel** method applied to the average of future rainfall projections from six RCMs for the RCP4.5 and RCP8.5 scenarios for the **period 2071–2100**



EXPERIMENTAL DEVICE



EXPERIMENTAL DEVICE

Rainfall

Presurized Rainfall simulator (100mm/h)
 2 to 7 presurized nozzles (QPHA-10W) 5.2/5.6 bars
 Uniformity : $95\% < CUC < 98\%$
 Kinetic Energy : DSD, VT



Soil

$0.335\text{m}^3 \Leftrightarrow \sim 16\text{cm}$ soil depth on gravel
 (Almost) Same composition (same K)
 Same conditions ($\rho=1.6$)

Slope

18° (Max CSM site slope)



AN EXEMPLE OF SOIL EROSION IN THE LAB

Initial dry soil (10%)



After 1 hour of 100mm rainfall



CLIMATE CHANGE EFFECTS ON ENGINEERED BARRIERS FOR LOW-LEVEL WASTE STORAGE FACILITIES

AMPHOS²¹
an **RSK** company

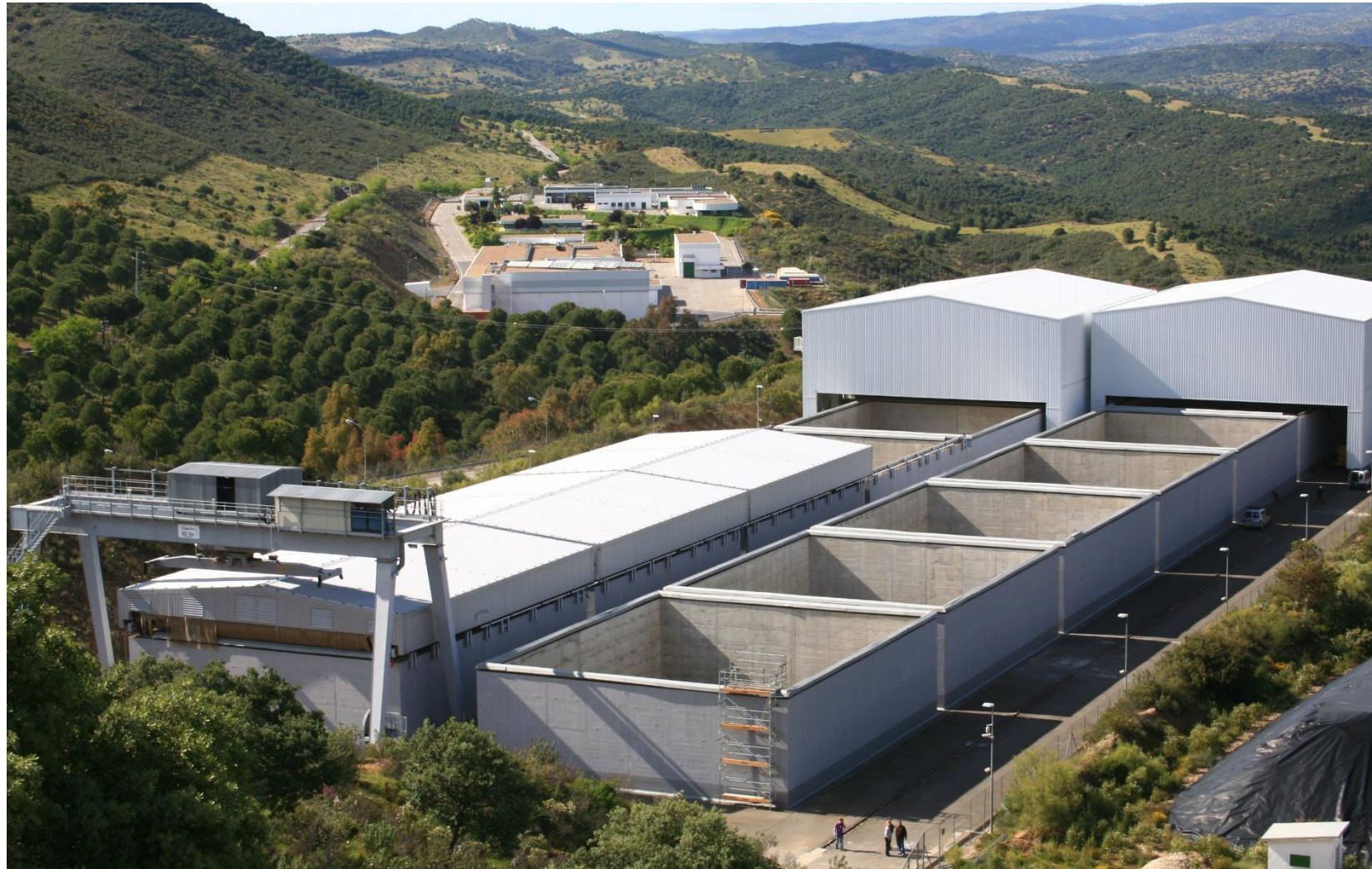


Co-funded by the European Union under Grant Agreement n° 101166718

Climate change effects on low-level waste storage facilities

Assessing how changing climatic conditions may influence the performance of engineered barriers, with a focus on multilayer soil covers during operational period.

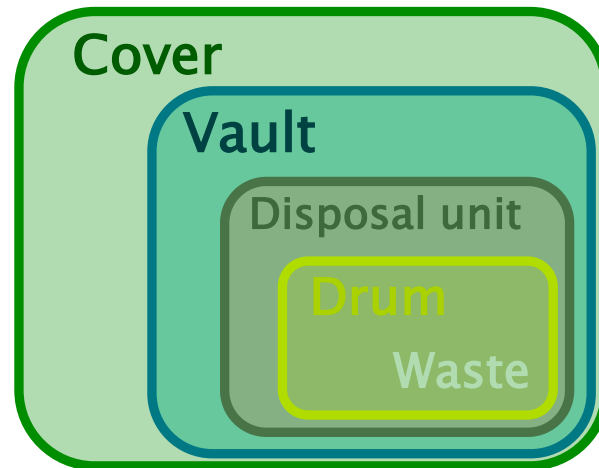
Case study: numerical modelling of a multilayer cover in Spain.

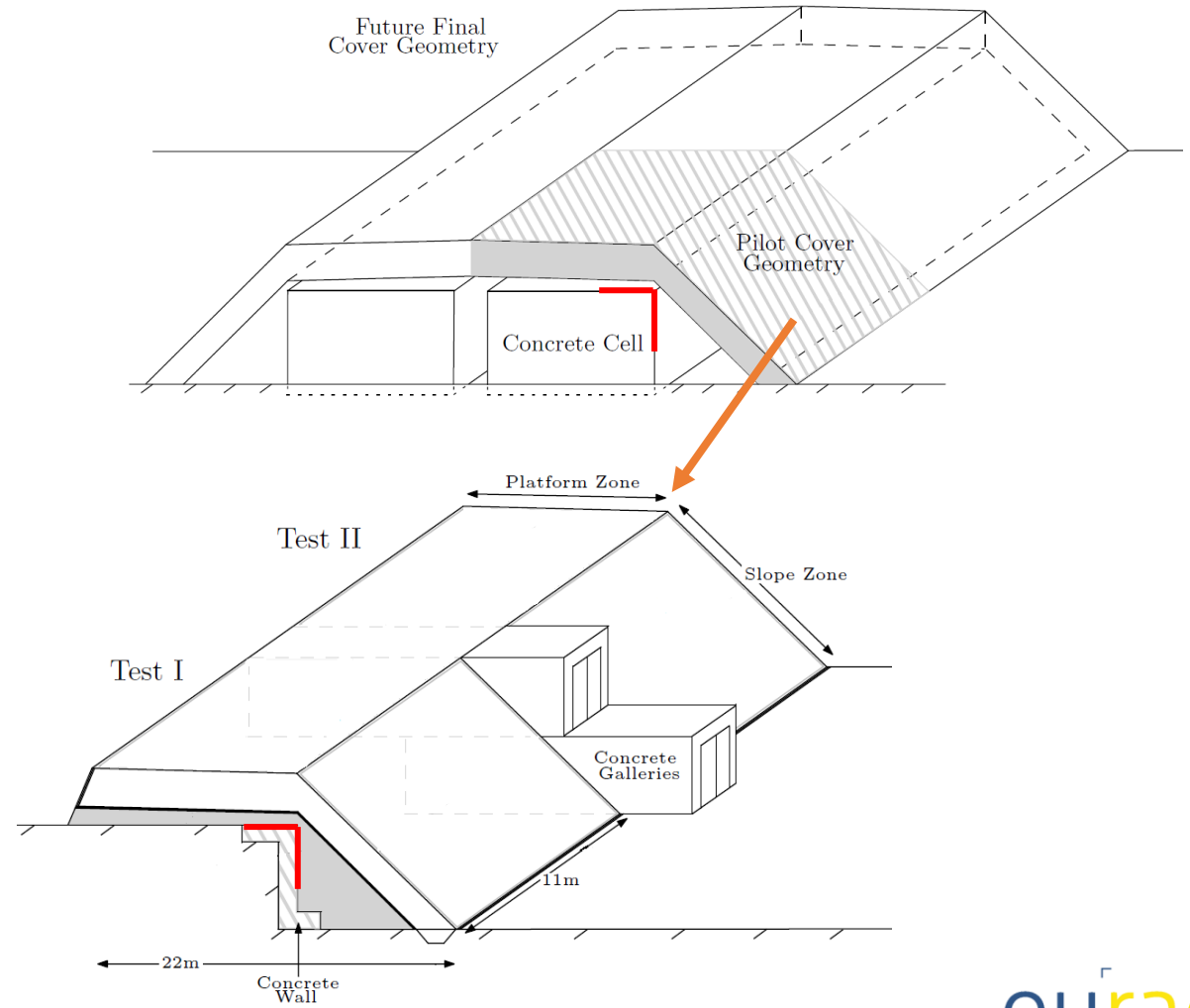


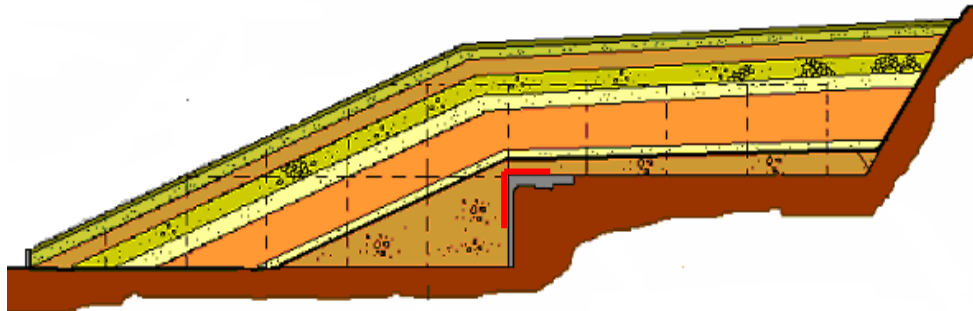
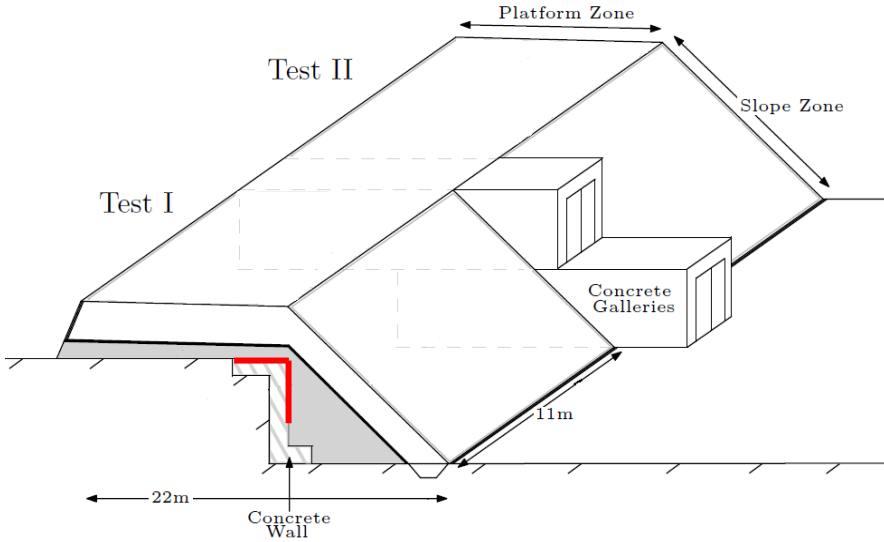
El Cabril is the intermediate, low, and very low-level waste storage facility managed by Enresa and located in Córdoba, Spain.



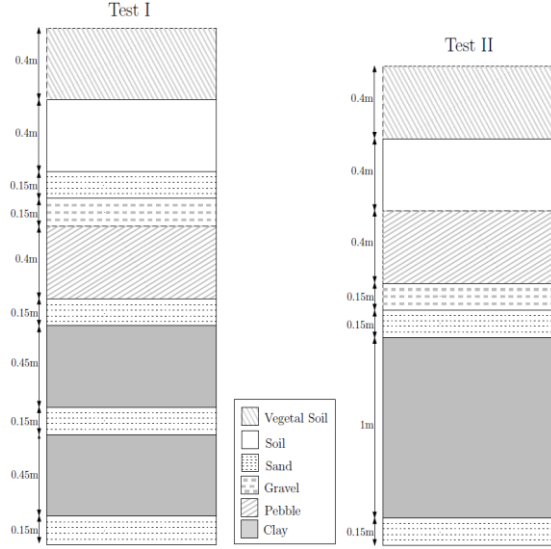
Multibarrier system







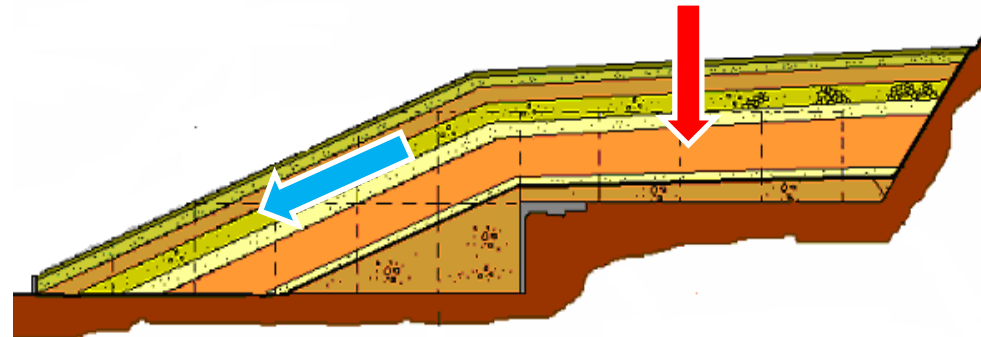
2 different multilayer cover designs in the same test



Its **objectives** are to:

- Reduce erosion
- Protect against biointrusion
- Minimise vertical water flow to limit infiltration
- Promote lateral water flow to facilitate drainage of infiltrating water

All of this is designed for an expected operational lifetime of at least 300 years.



Mechanisms and processes to be reproduced:

- Water retention available for evapotranspiration
- Capillary barrier to limit infiltration
- High-permeability drainage layers
- Evaporation/condensation processes
- Flow varying between saturated and unsaturated conditions
- Water flow in both liquid and vapour phases, and energy flow

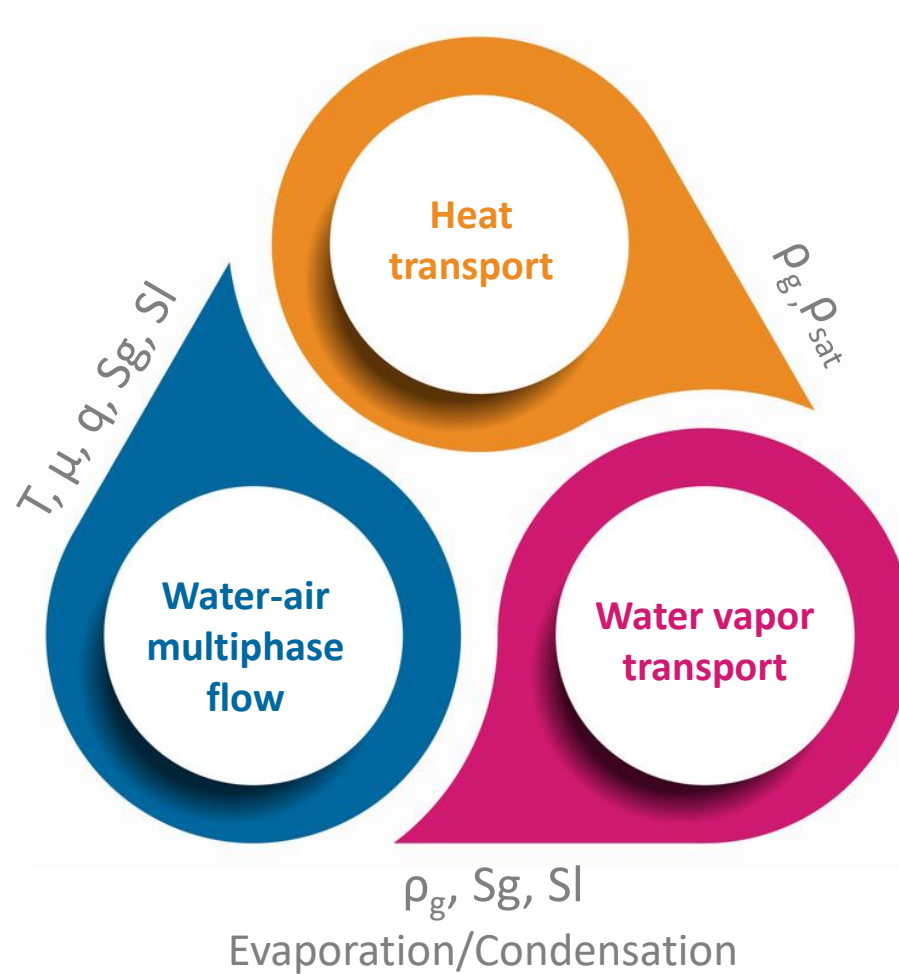


Need of well-defined materials' hydraulic properties



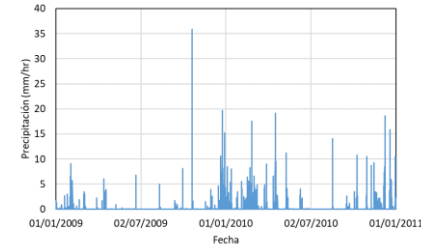
Multiphase flow and heat transport

The numerical model must include **three physically coupled processes**:

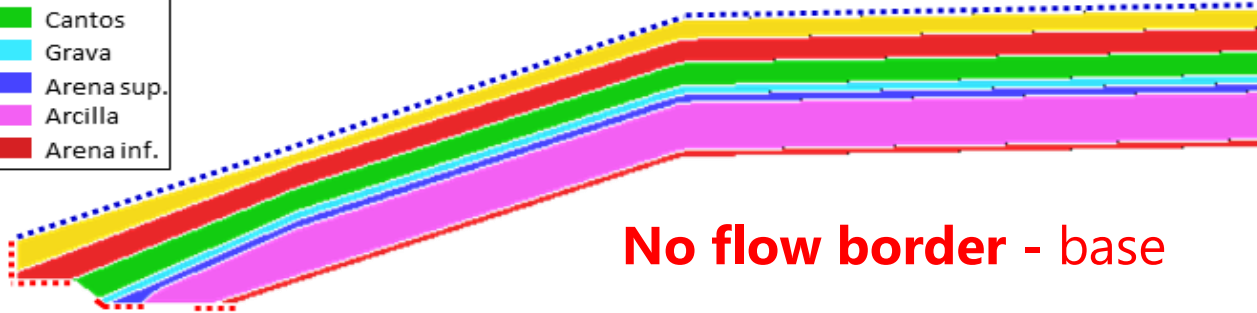


Geometry, materials and boundary conditions (bc)

Atmospheric bc - surface

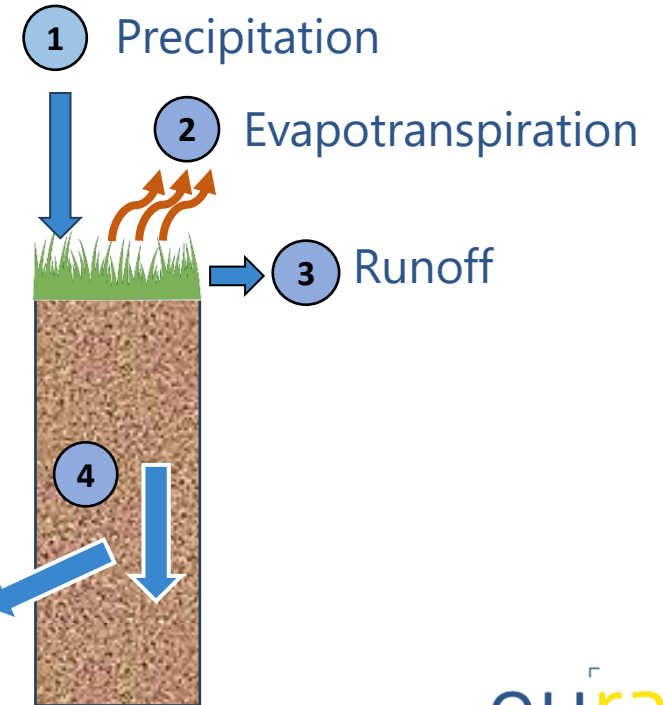


- Tierra V.
- Suelo
- Cantos
- Grava
- Arena sup.
- Arcilla
- Arena inf.



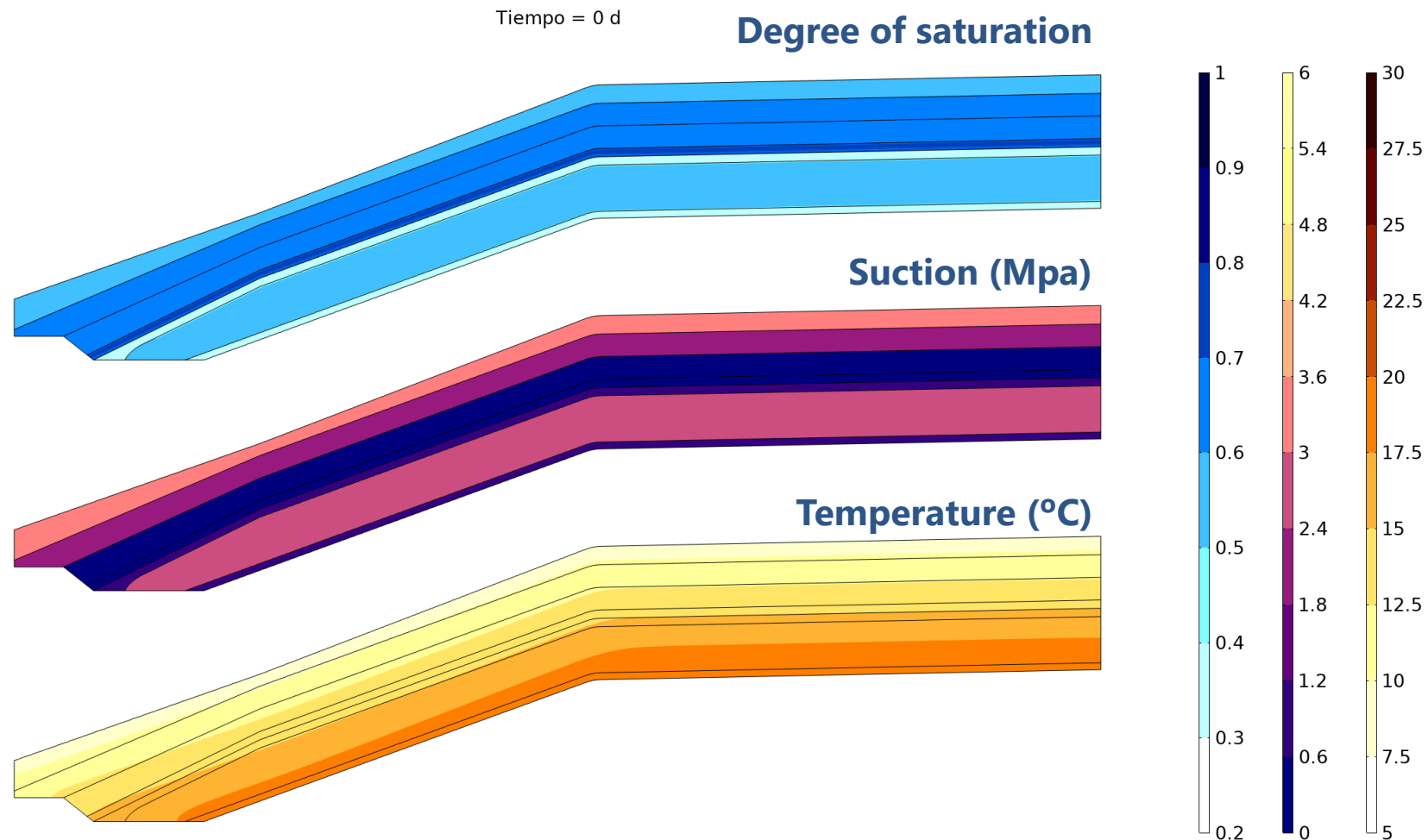
No flow border - base

Mixed bc - outflux



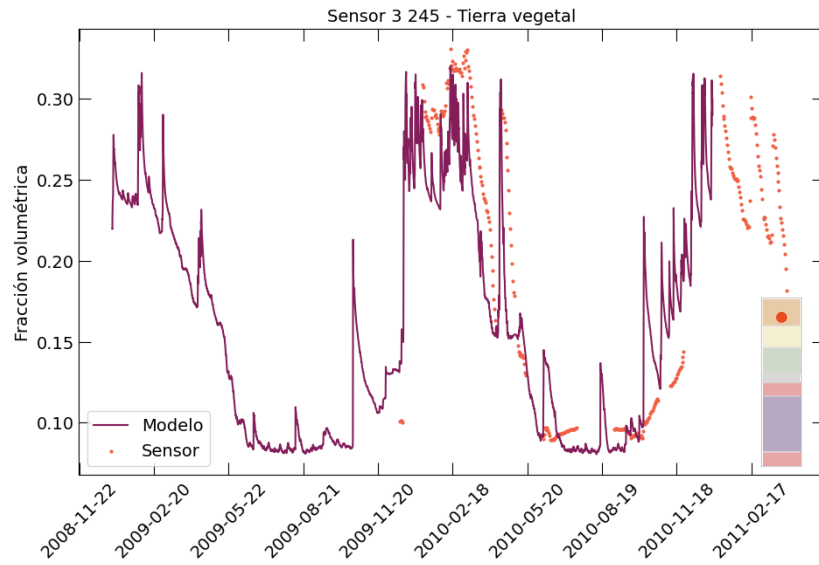
Water mass balance at the surface

2 years of simulation

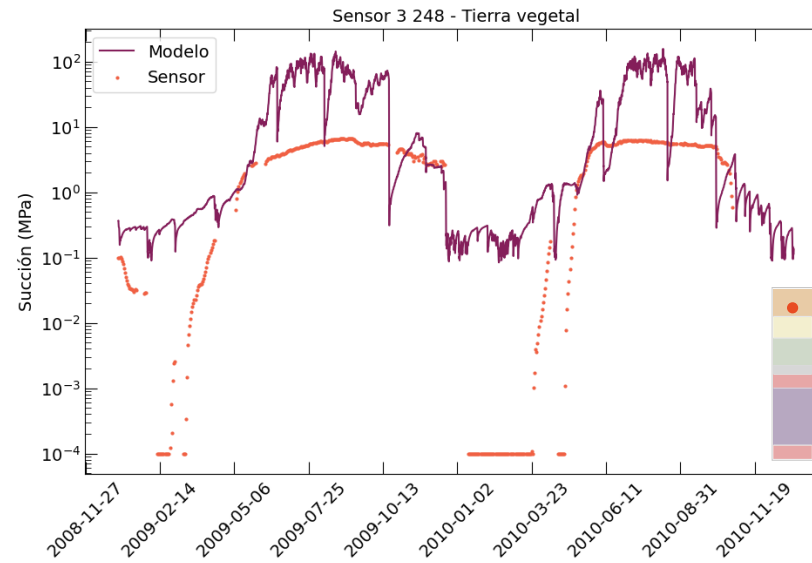


Hydraulic behaviour of the superficial layer

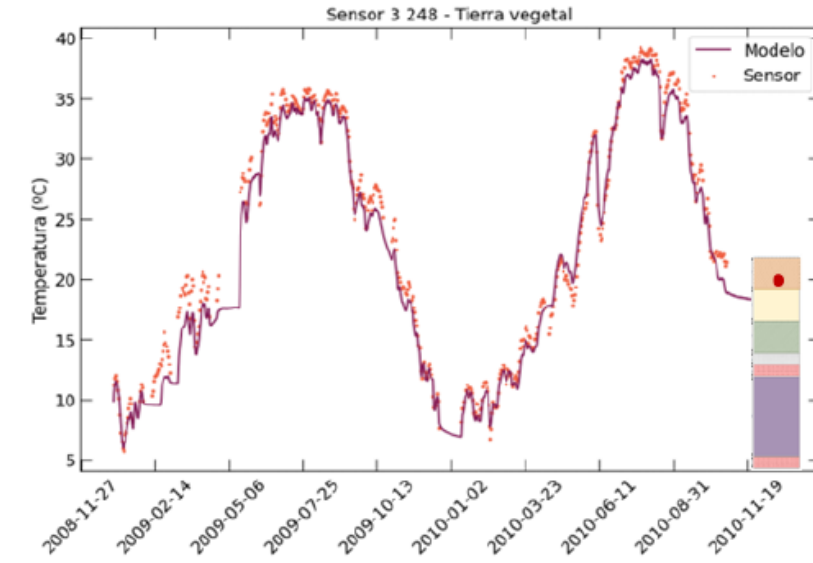
Volumetric water content



Suction (MPa)



Temperature (°C)

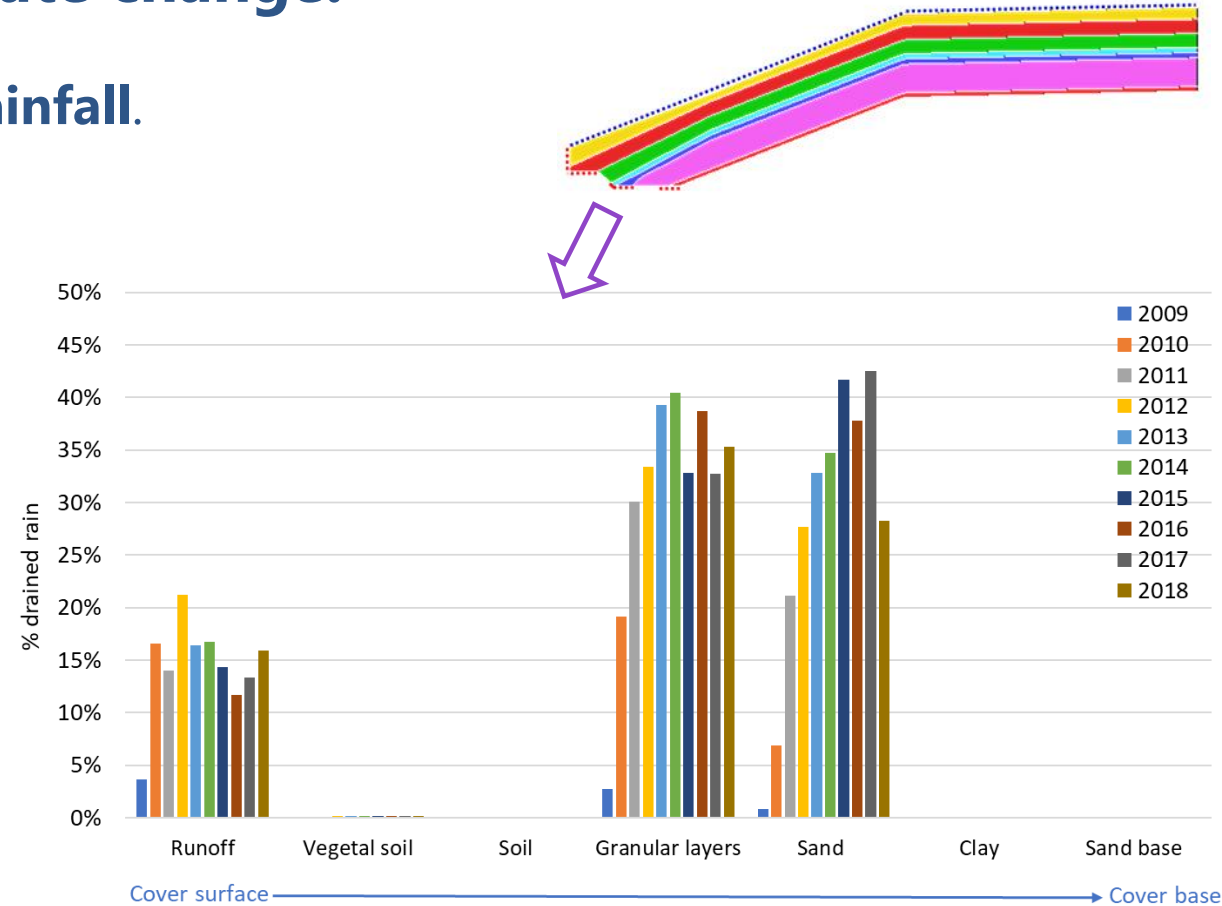
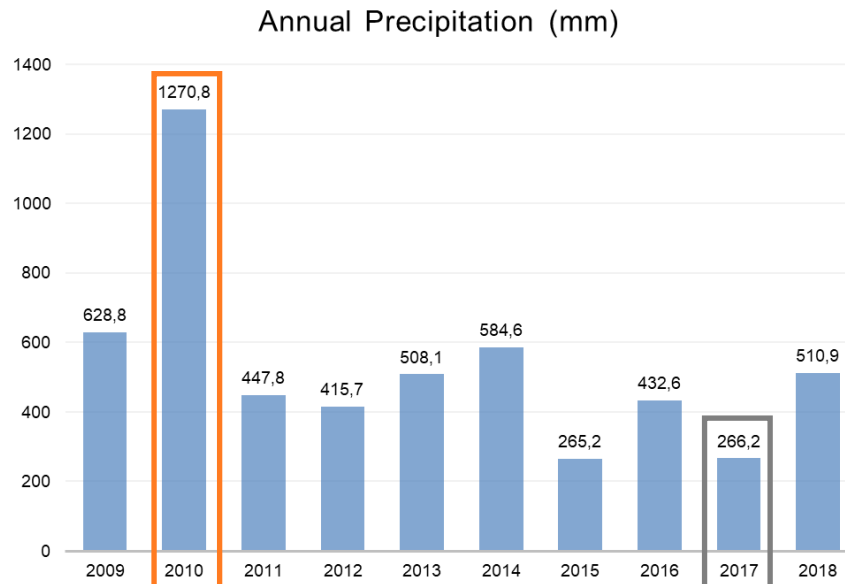


Potential scenarios due to climate change:

- **Reduction** of the **average annual rainfall**.
- **More droughts**: temperature's increase leads to higher evapotranspiration + lower precipitation -> drier soil -> cracking, loss of vegetation and **structural degradation of the superficial layer**.
- **Greater seasonal concentration of rain** (drier springs, drier and longer summers and more variable autumns alternating dry years with heavy rains).
- **Longer dry periods followed by stormy precipitation events**.

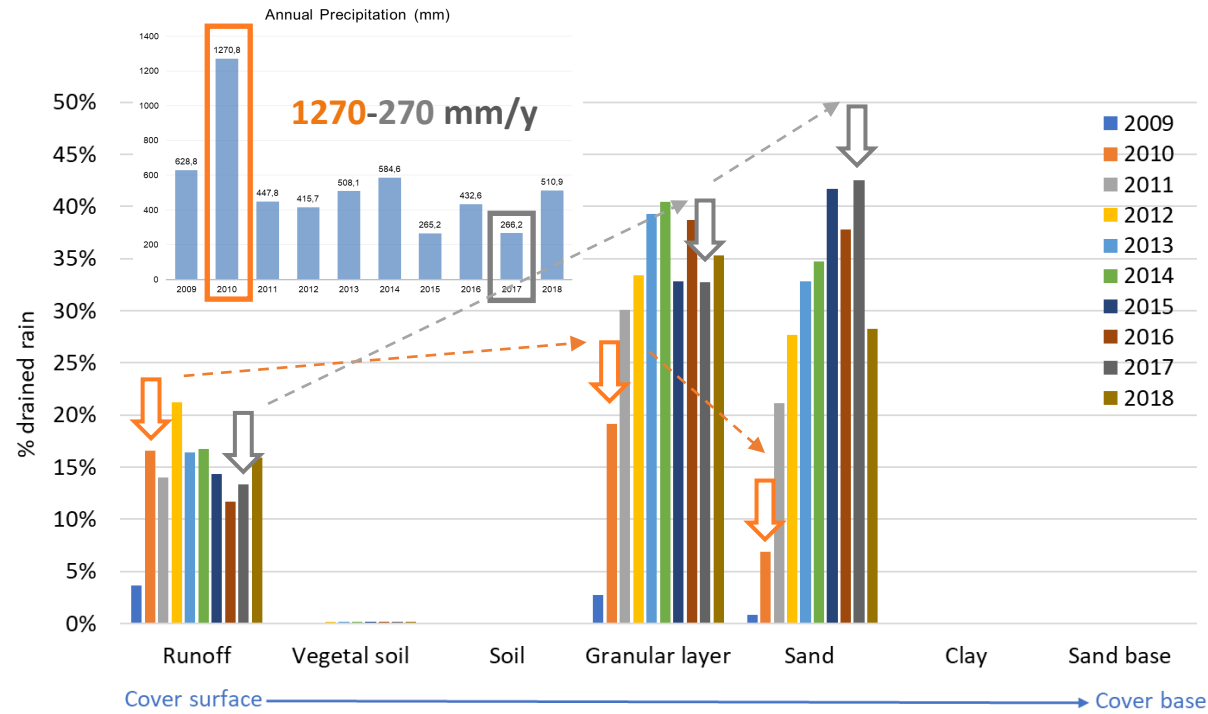
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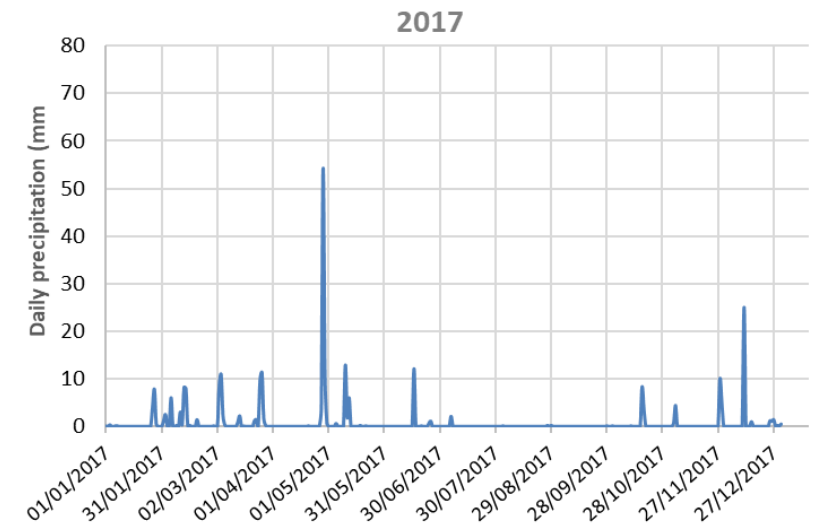
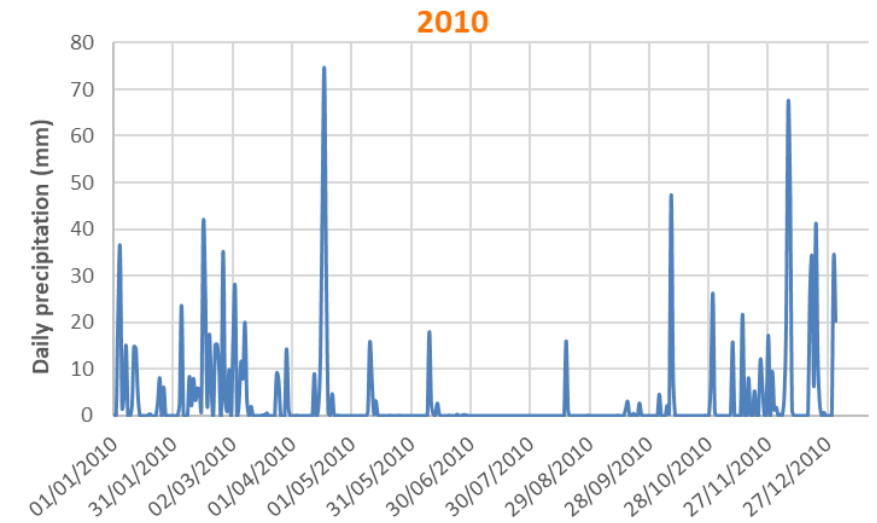
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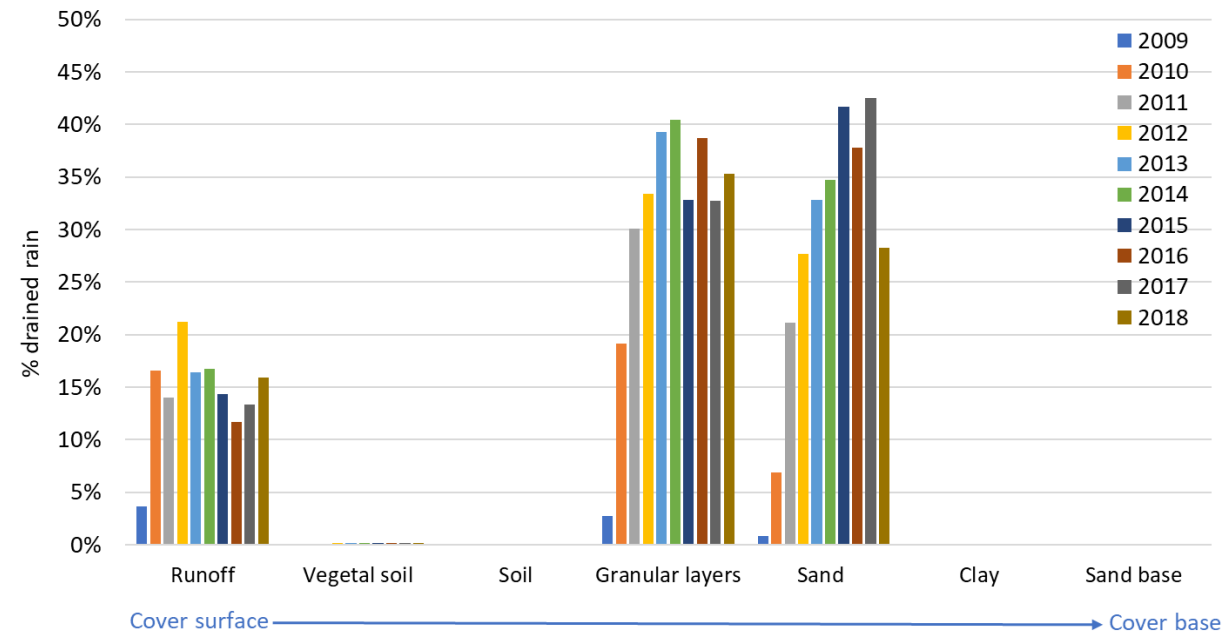
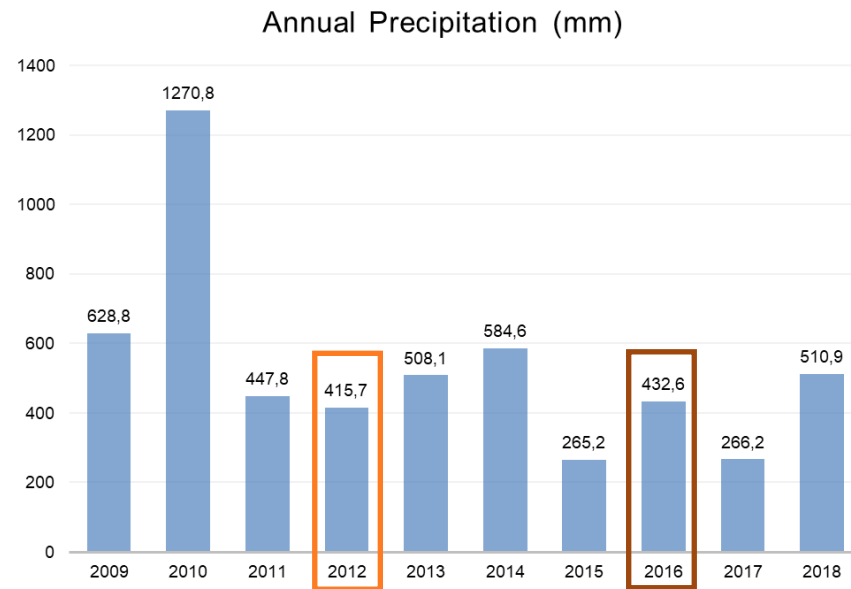
Lower average annual rain (2017):

- Lower runoff
- Higher infiltration deeper into the cover



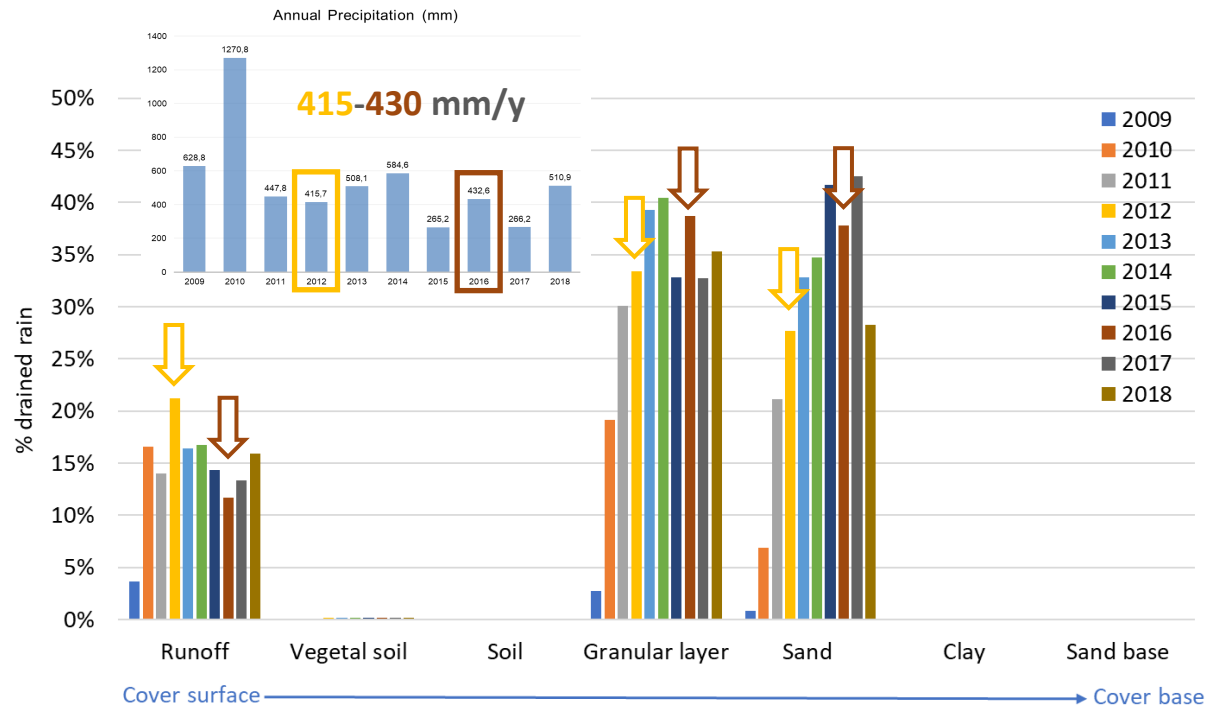
Potential scenarios due to climate change (3sc climate group):

- Dry period followed by stormy events.



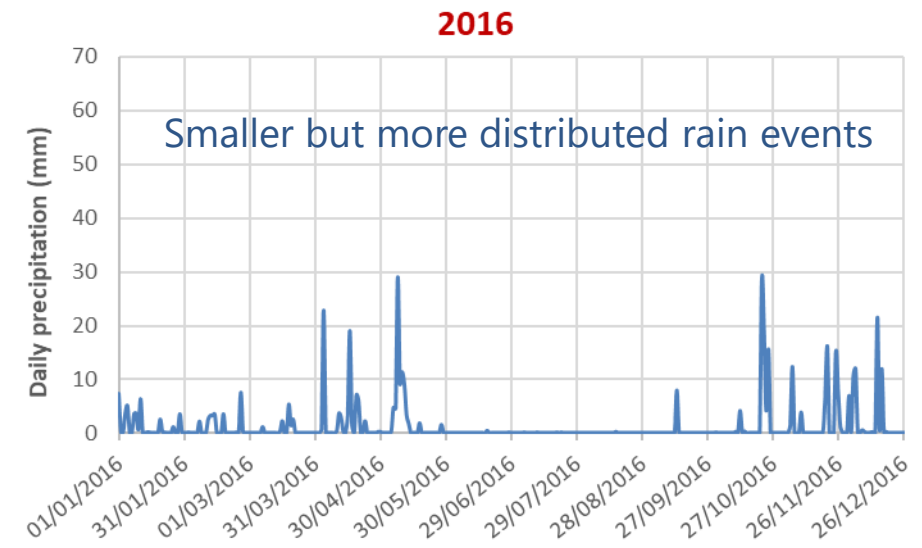
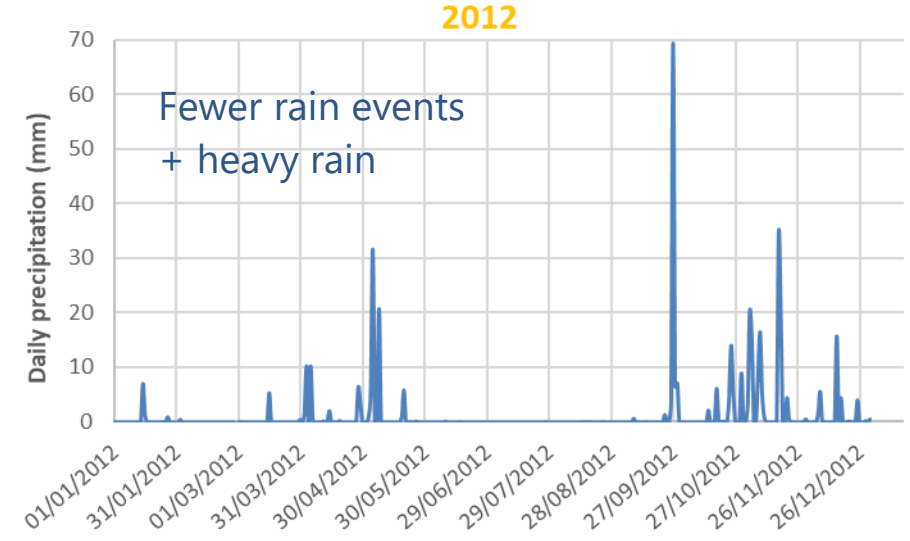
Potential scenarios due to climate change:

- Dry period followed by stormy events



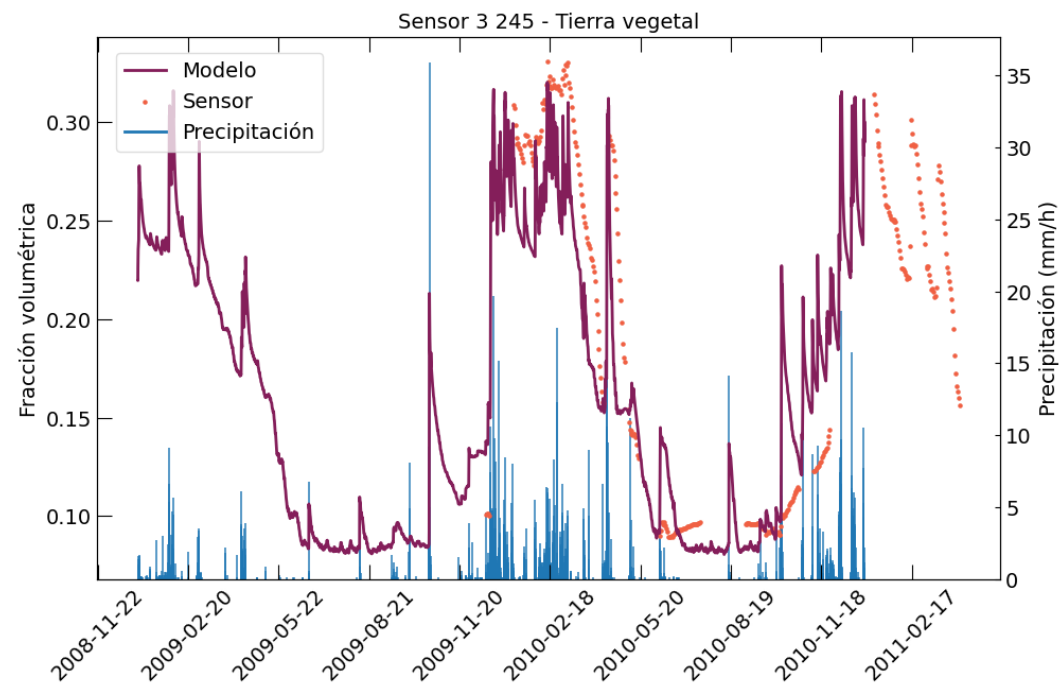
Dryer soil + heavy rain (2012):

- Higher runoff
- Lower infiltration values



Potential scenarios due to climate change:

- Dry period followed by stormy events



Dryer soil + heavy rain (2012):

- Higher runoff
- Lower infiltration values

Potential scenarios due to climate change:

- **Reduction of the average annual rainfall.** → Lower average annual rain:
 - Lower runoff
 - Higher infiltration deeper into the cover
 - **More droughts:** temperature's increase leads to higher evapotranspiration + lower precipitation -> drier soil -> cracking, loss of vegetation and **structural degradation of the superficial layer.** → + Droughts (increase in temp)
- Potential loss of vegetation -> increase of erosion
- **Greater seasonal concentration of rain** (drier springs, drier and longer summers and more variable autumns alternating dry years with heavy rains). → Longer dry periods and more concentrated rain:
 - Higher runoff
 - Lower infiltration
 - **Longer dry periods followed by stormy precipitation events.**



First conclusions on how climate change could affect the performance of the Spanish multilayer cover:

- **Reduction of the average annual rainfall** and/or longer dryer periods combined with **more concentrated rain** periods **don't lead to a significant increase of infiltration.**
- The potential **loss of vegetation due to drought** risks the integrity of the cover (**erosion increase**), which would be worst if combined with more intense rains.



Study of the effect of losing the vegetation in the water mass balance.

Study the effect of losing the integrity of the first layer.

CLIMATE CHANGE EFFECTS ON ENGINEERED BARRIERS FOR LOW-LEVEL WASTE STORAGE FACILITIES

AMPHOS²¹
an RSK company



Co-funded by the European Union under Grant Agreement n° 101166718

CLIMATE CHANGE IMPACT ON GROUNDWATER FLOW DYNAMICS AND RADIONUCLIDE TRANSPORT

SKB'S SFR SAFETY ASSESSMENT CASE

AMPHOS²¹
an RSK company



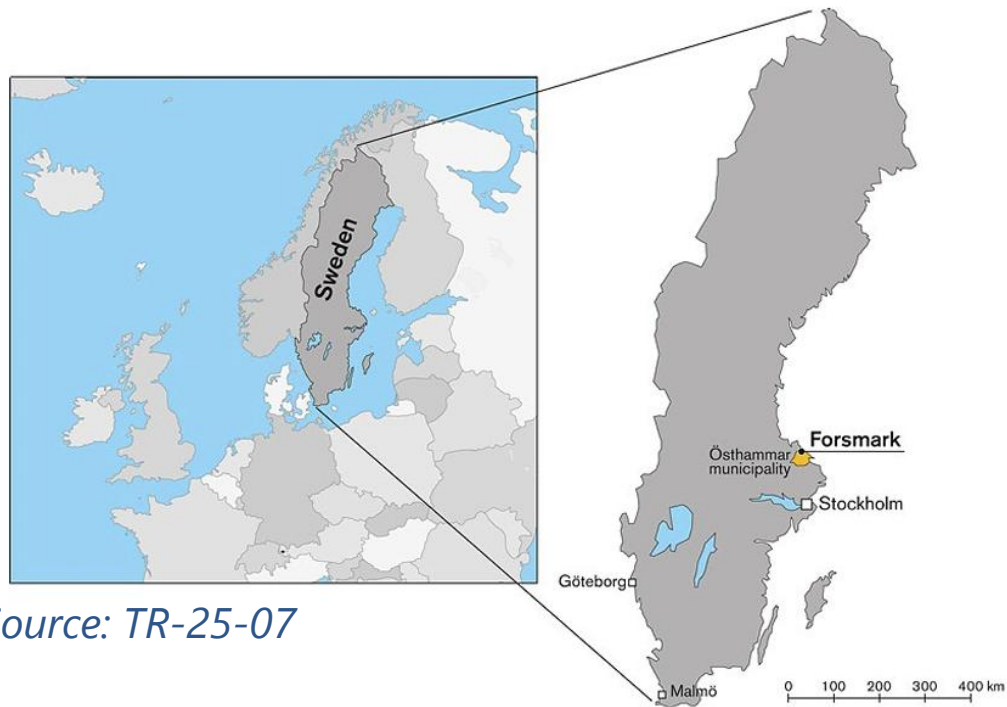
Co-funded by the European Union under Grant Agreement n° 101166718

Climate change effects on geological waste storage facilities

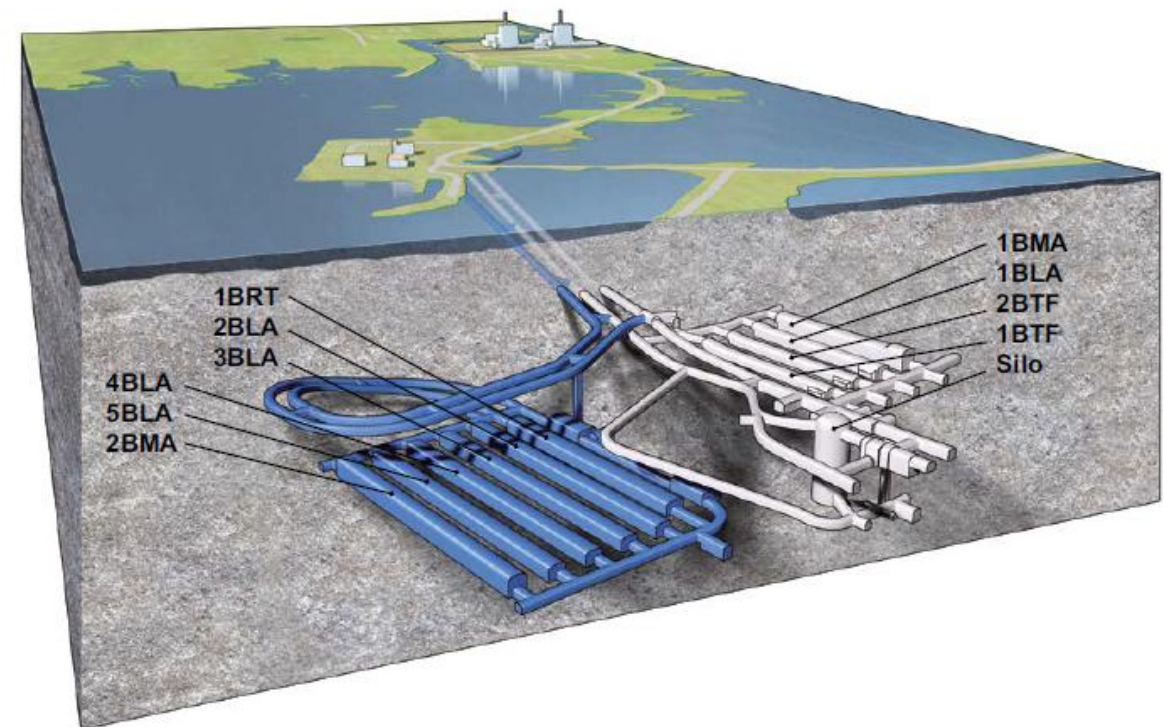
- Assessing how changing climatic conditions may influence groundwater flow and repository safety during **post closure** period.
- **Near-surface** repository case, focus on how climate change affects **surface drivers**, such as precipitation, evapotranspiration and infiltration.
- **Geological repository case**, focus on long-term **climate-related processes**, such as shoreline displacement and permafrost.
- Case study: numerical modelling for **Safety Assessment on SFR repository, Sweden (SKB)**.

SFR:

- Repository for low- and intermediate-level radioactive waste
- Located in Forsmark, Sweden
- Existing facility: **SFR1** (60 m depth)
- Planned extension: **SFR3** (120 m depth)



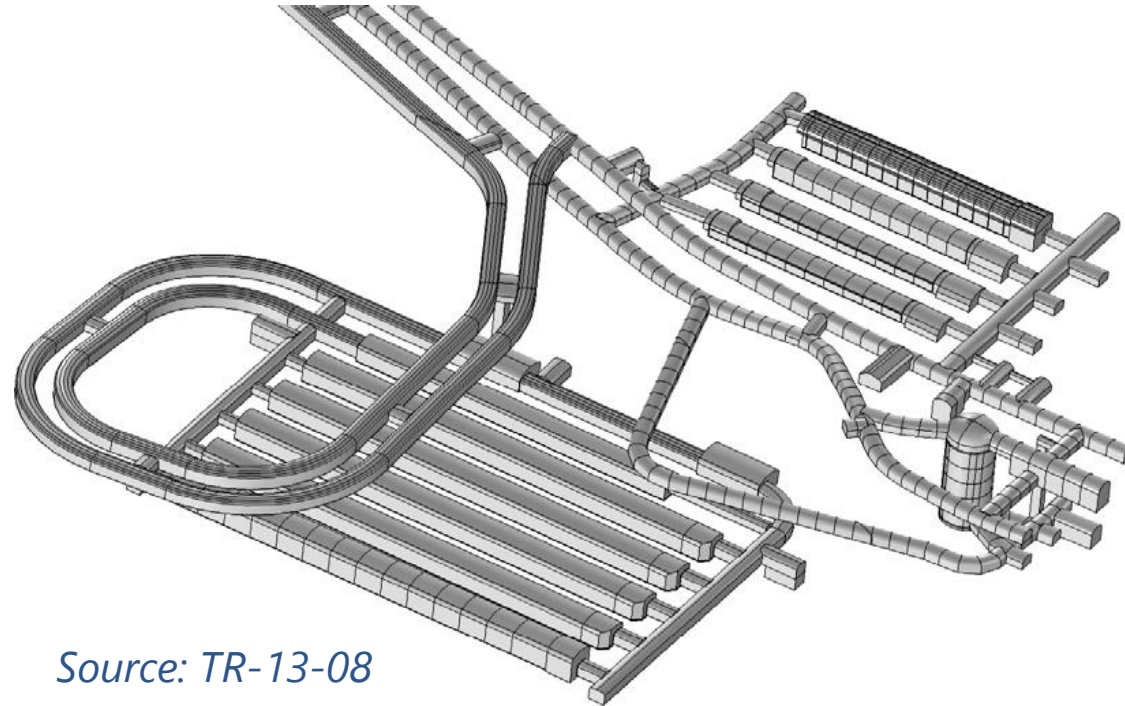
Source: TR-25-07



Source: TR-14-09

SFR:

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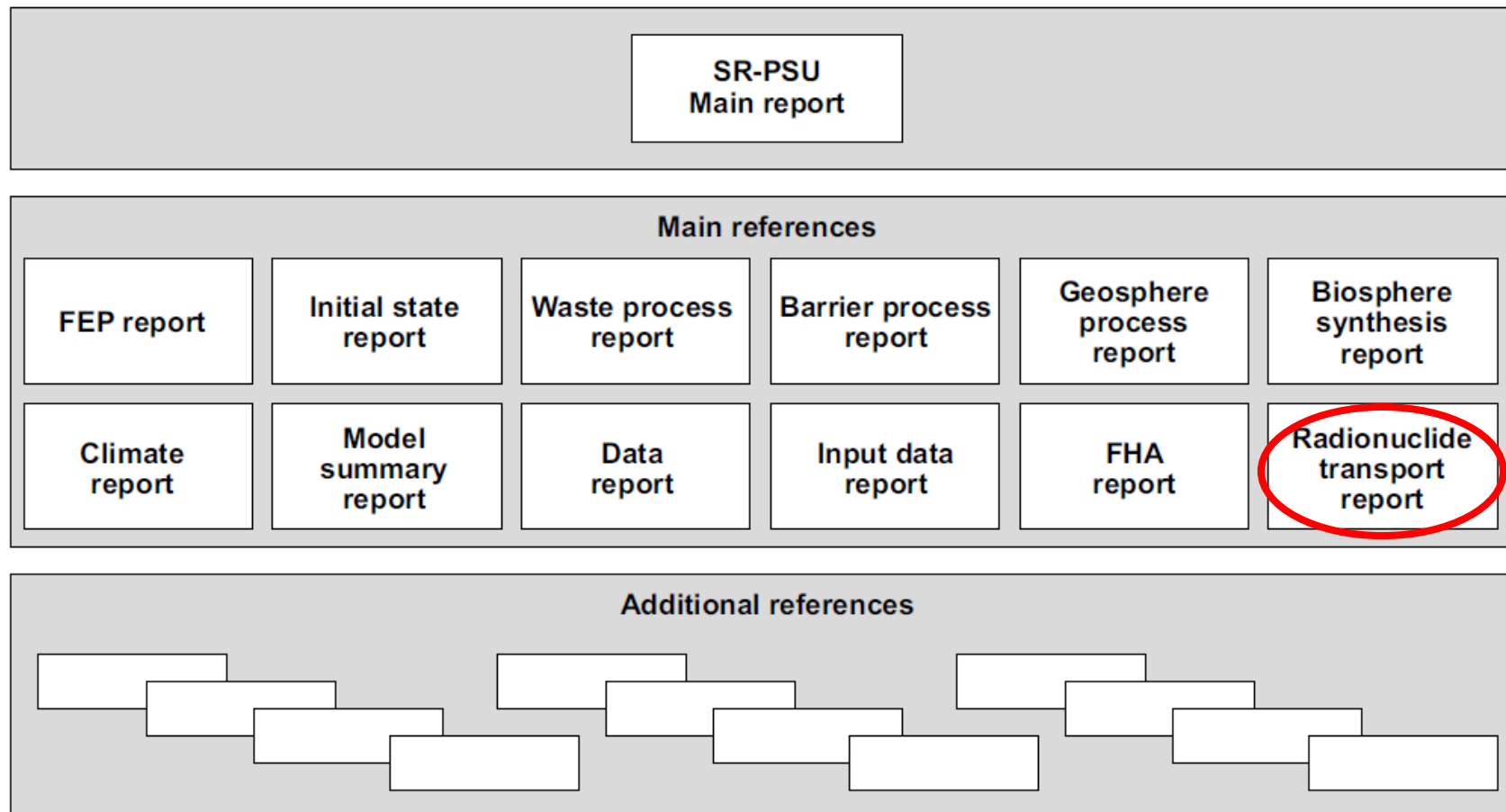


Source: TR-13-08

Post-closure Safety Assessment

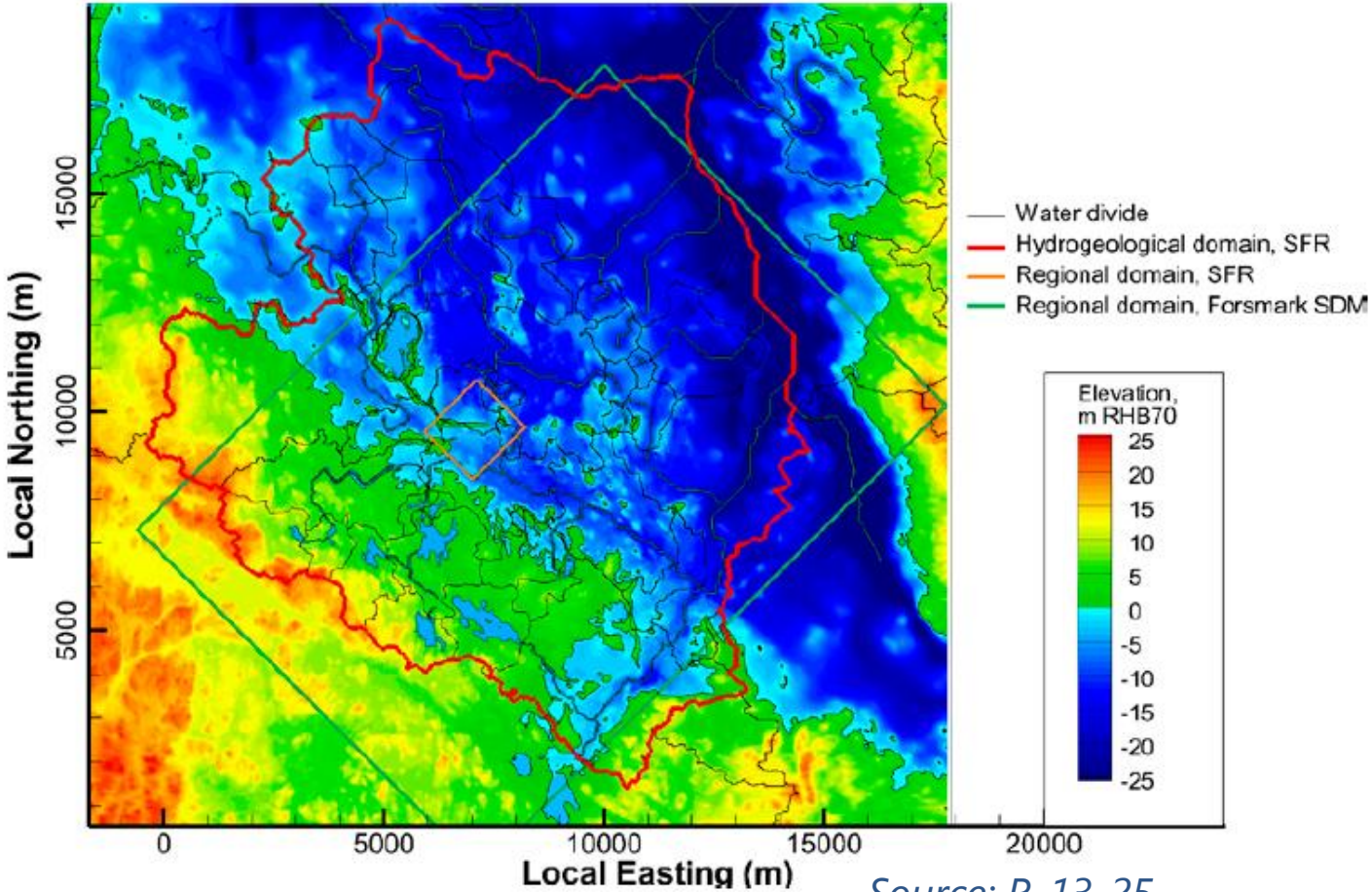
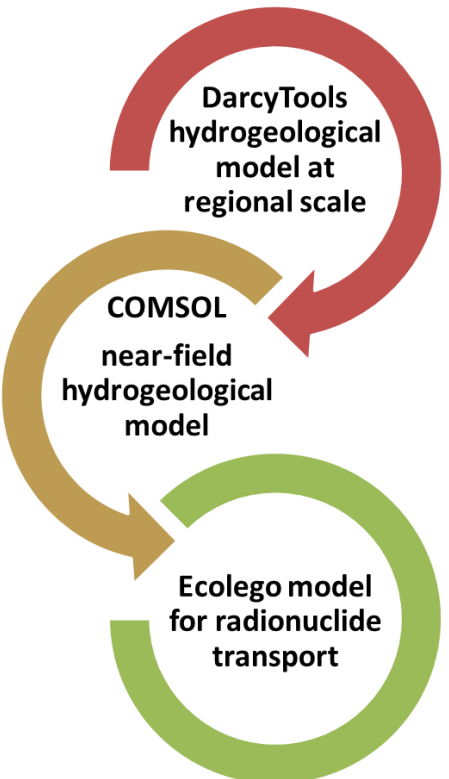
- Show that the **repository remains radiologically safe after closure**
- It does not predict one exact future
- It evaluates safety over long timeframes
 - **100 kyr for SFR**
 - 1 Myr for the spent fuel repository

- **Groundwater flow** is one of the key inputs
 - How much groundwater can flow through the repository, and how does that evolve over time?



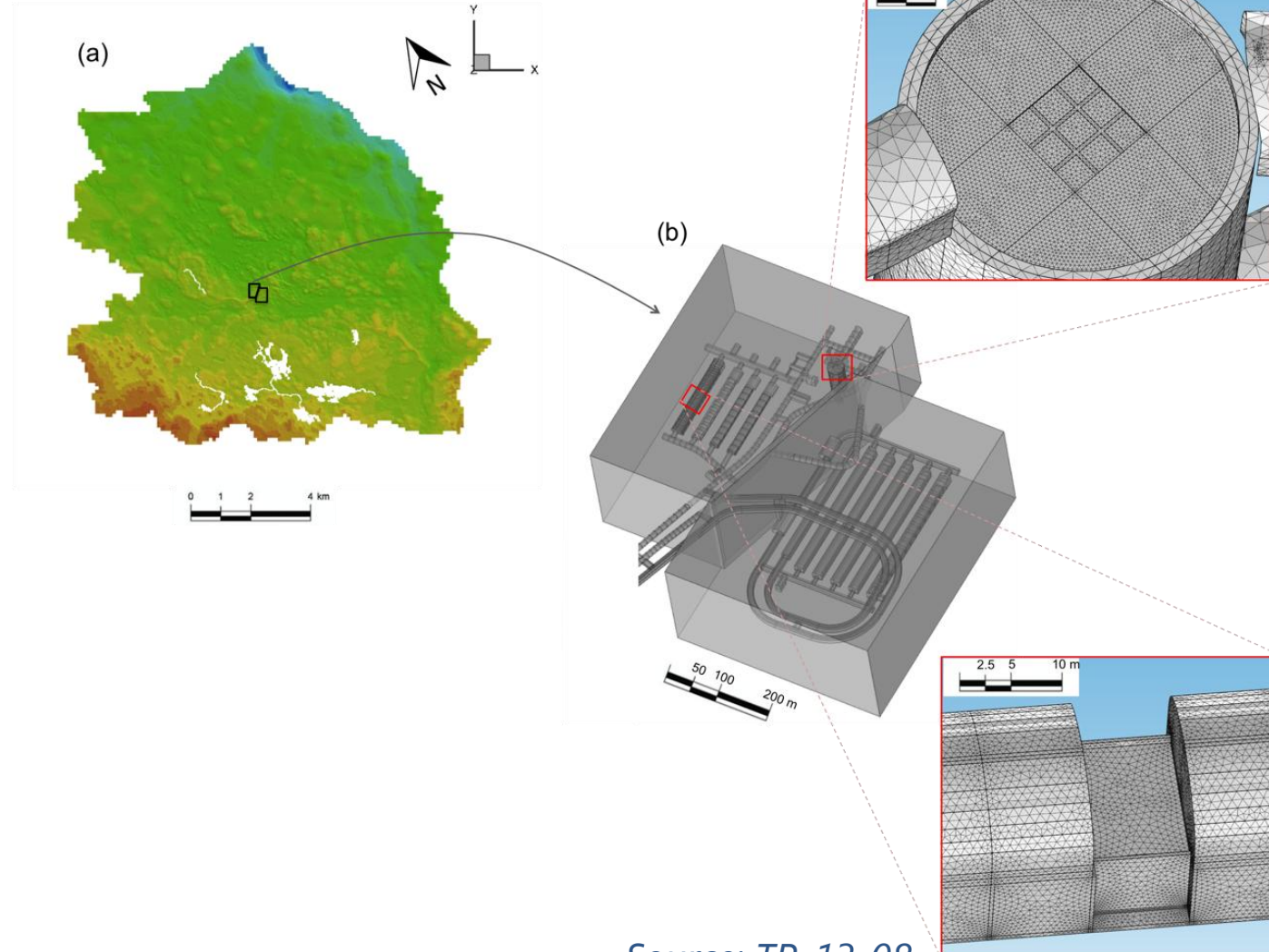
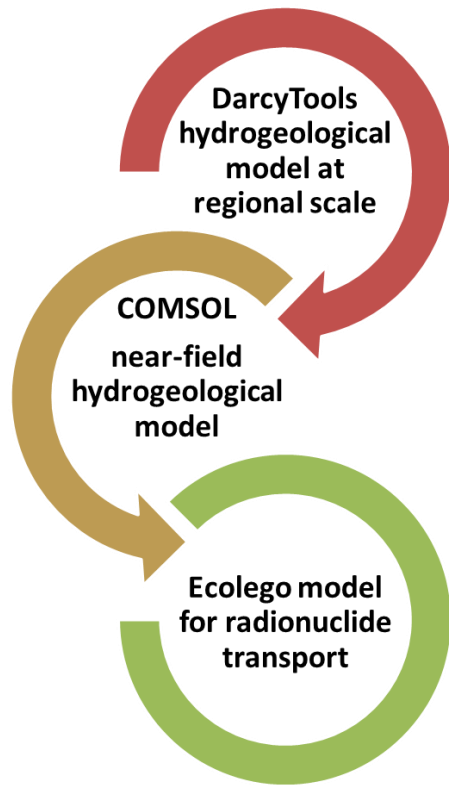
Source: TR-14-01

Chain of models



Source: R-13-25

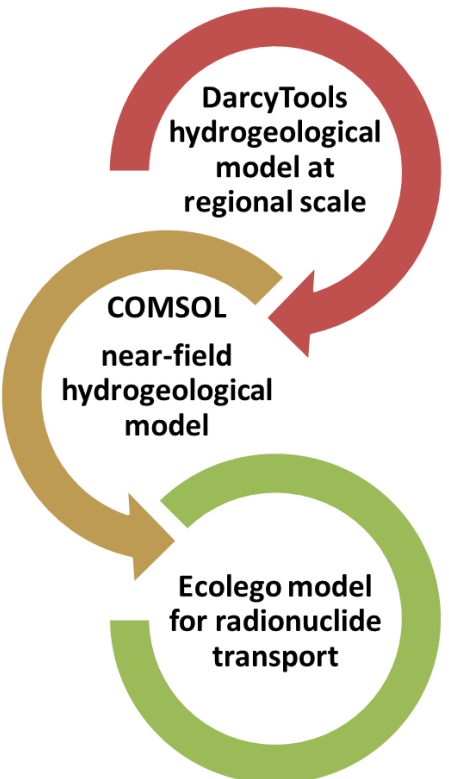
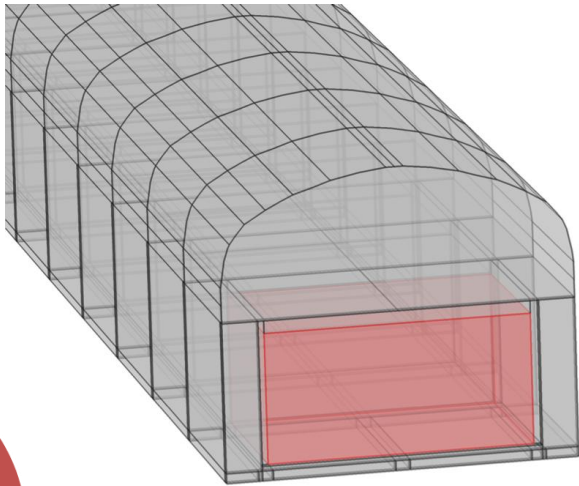
Chain of models



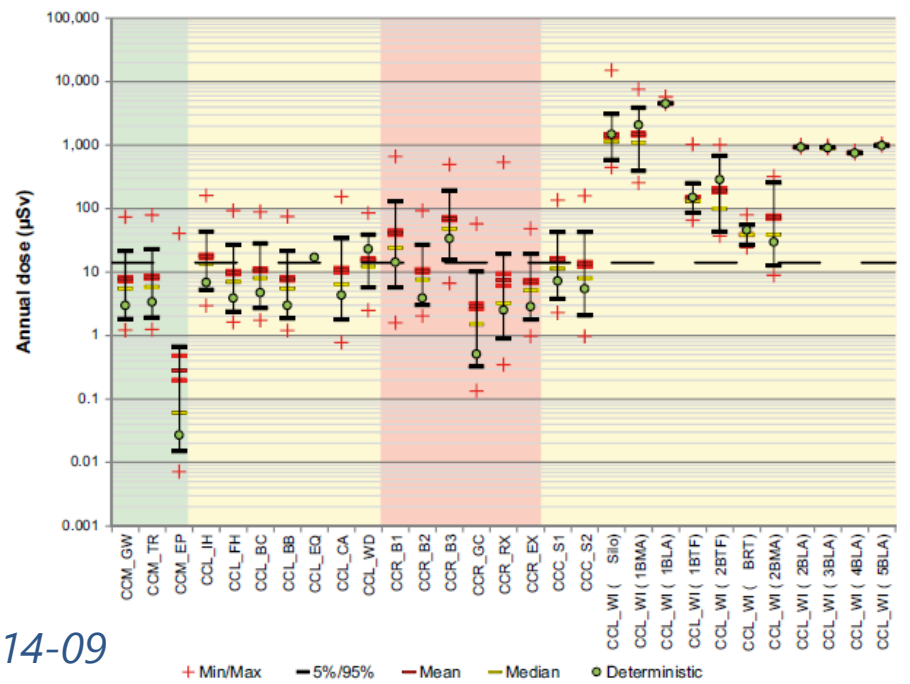
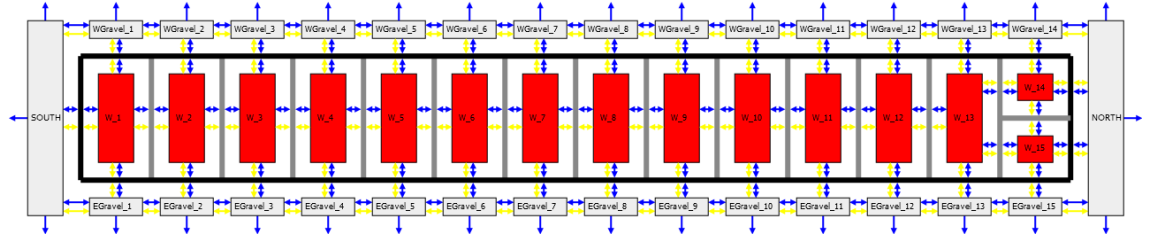
Source: TR-13-08



Chain of models



Source: TR-13-08



Source: TR-14-09

Groundwater flow model

- Two separate repository-scale models: SFR 1 and SFR 3
- Repository and bedrock properties
- Initial and boundary conditions from regional scale model
- Calculates flow rates through vaults, waste domains, and control volumes

Dimensions SFR 1 model:

X : 370 m [6255, 6625]

Y : 485 m [9850, 10335]

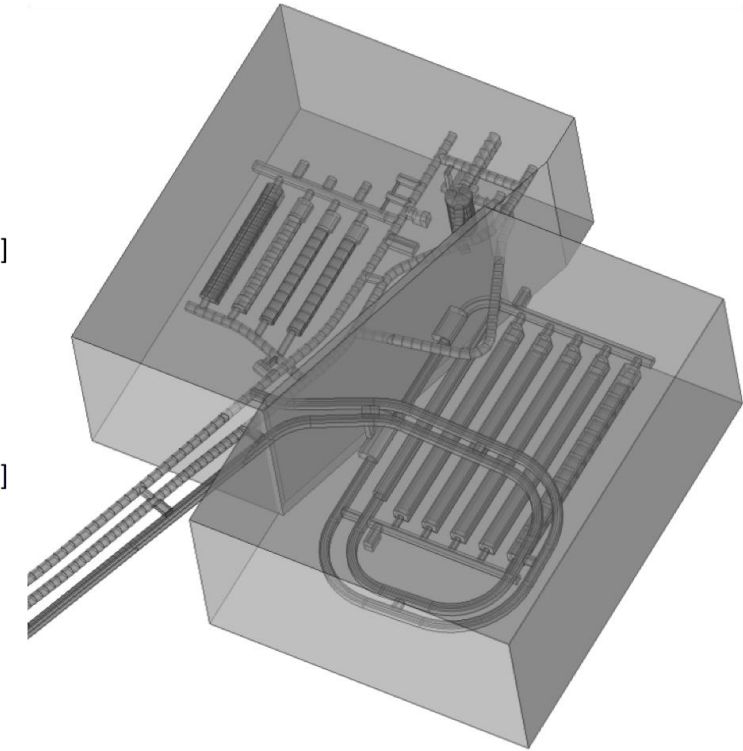
Z : 205m [-25, -230]

Dimensions SFR 3 model:

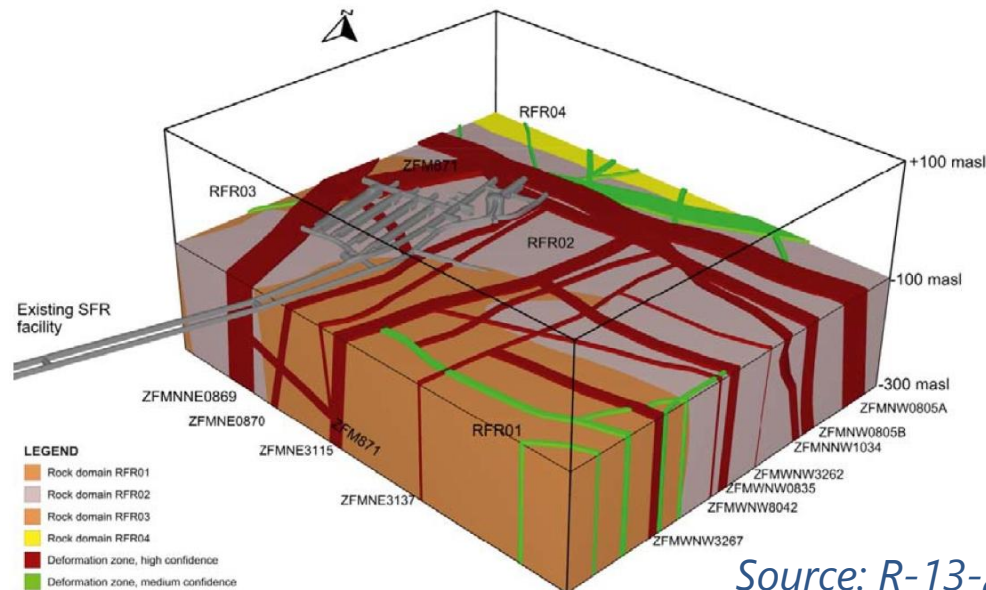
X : 400 m [6490, 6890]

Y : 500 m [9690, 10190]

Z : 205m [-25, -230]



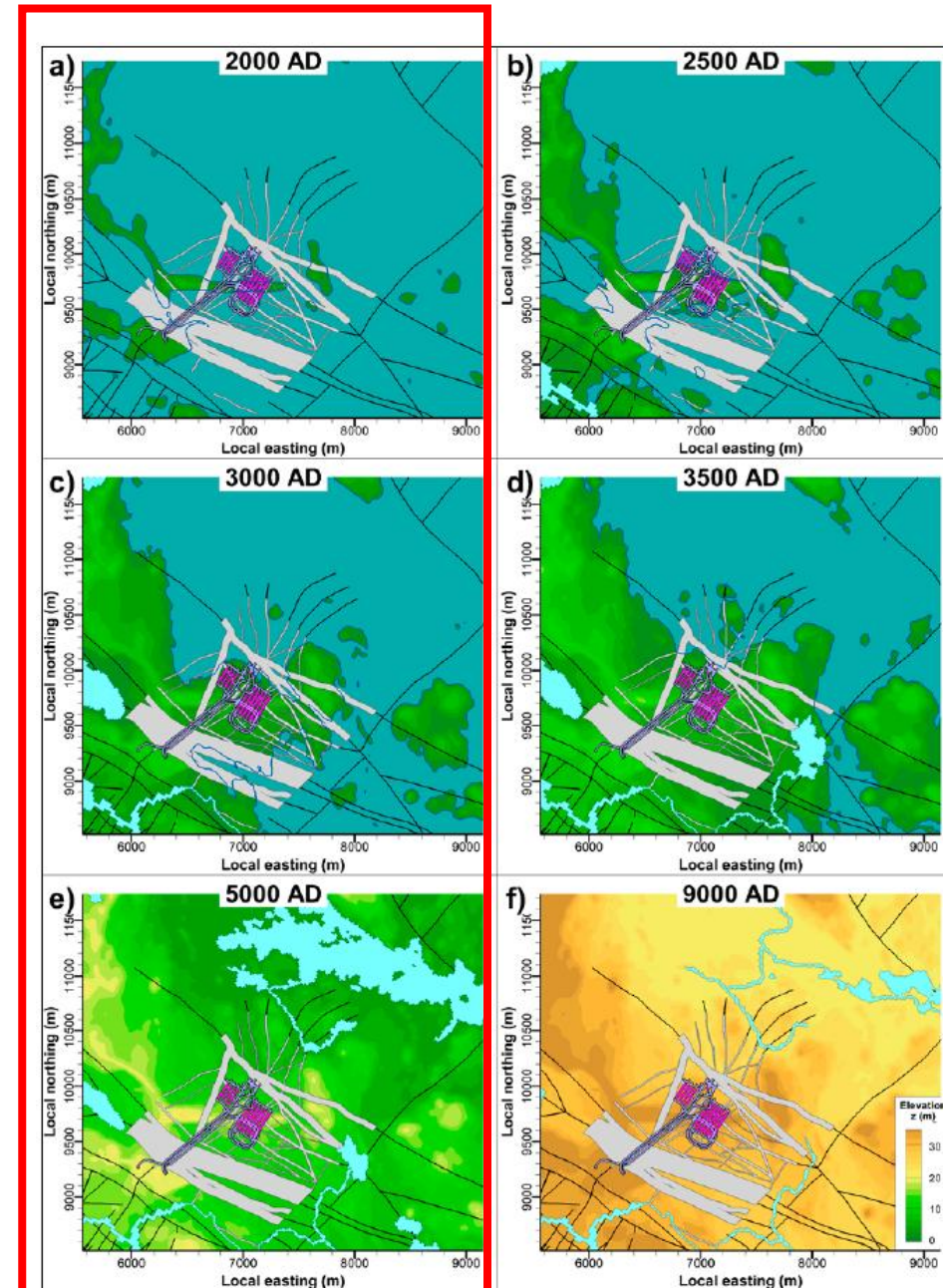
Source: TR-13-08



Source: R-13-25

Climate related cases

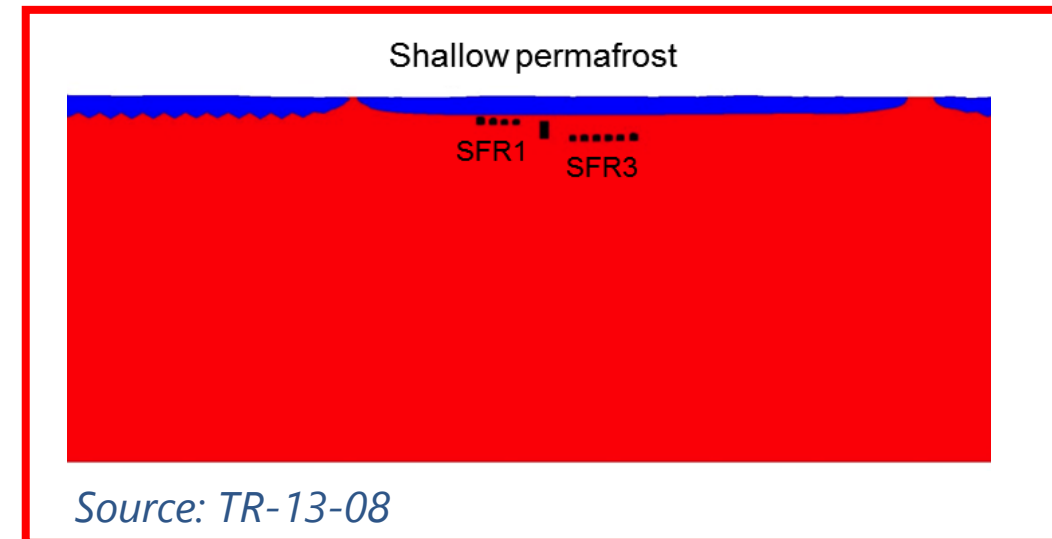
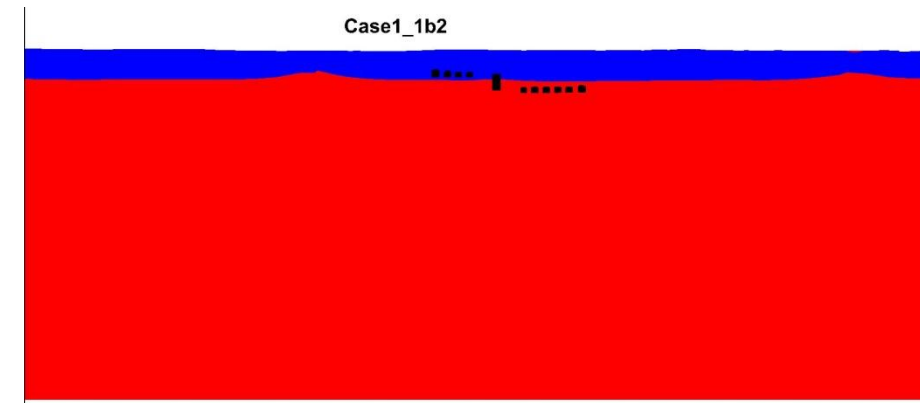
- Stationary cases
- Global warming climate case
 - Relative **shore-line positions**



Source: R-13-25

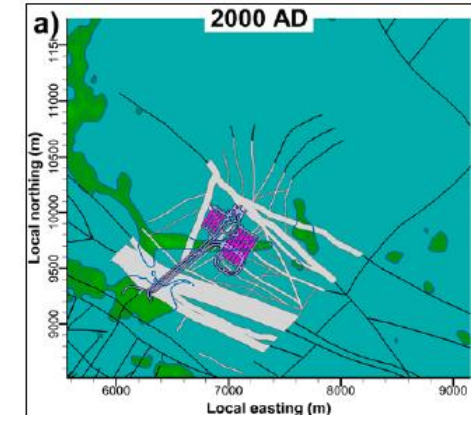
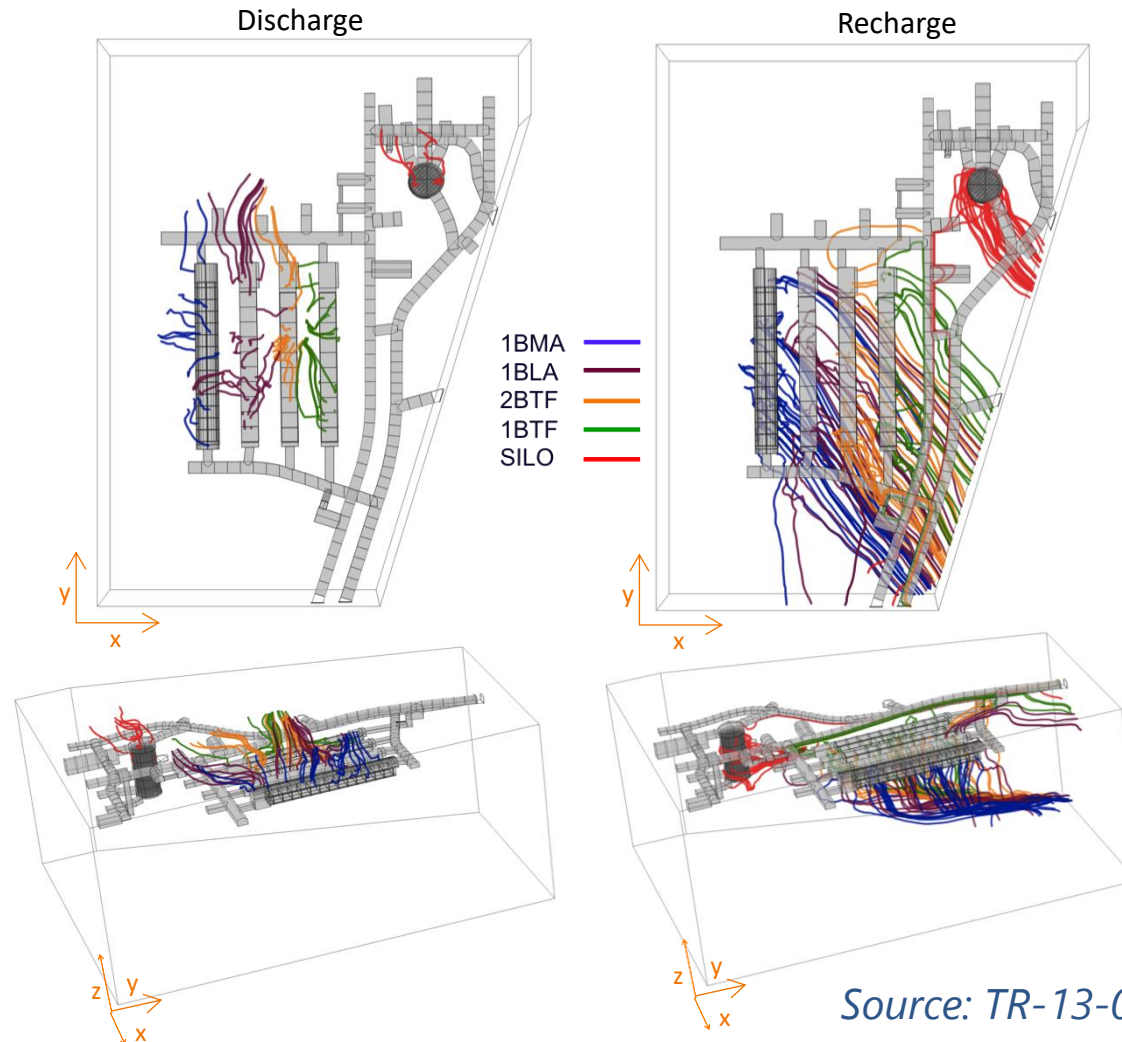
Climate related cases

- Stationary cases
- Global warming climate case
 - Relative **shore-line positions**
- Periglacial climate case
 - Different **permafrost depths**
 - Presence and locations of taliks



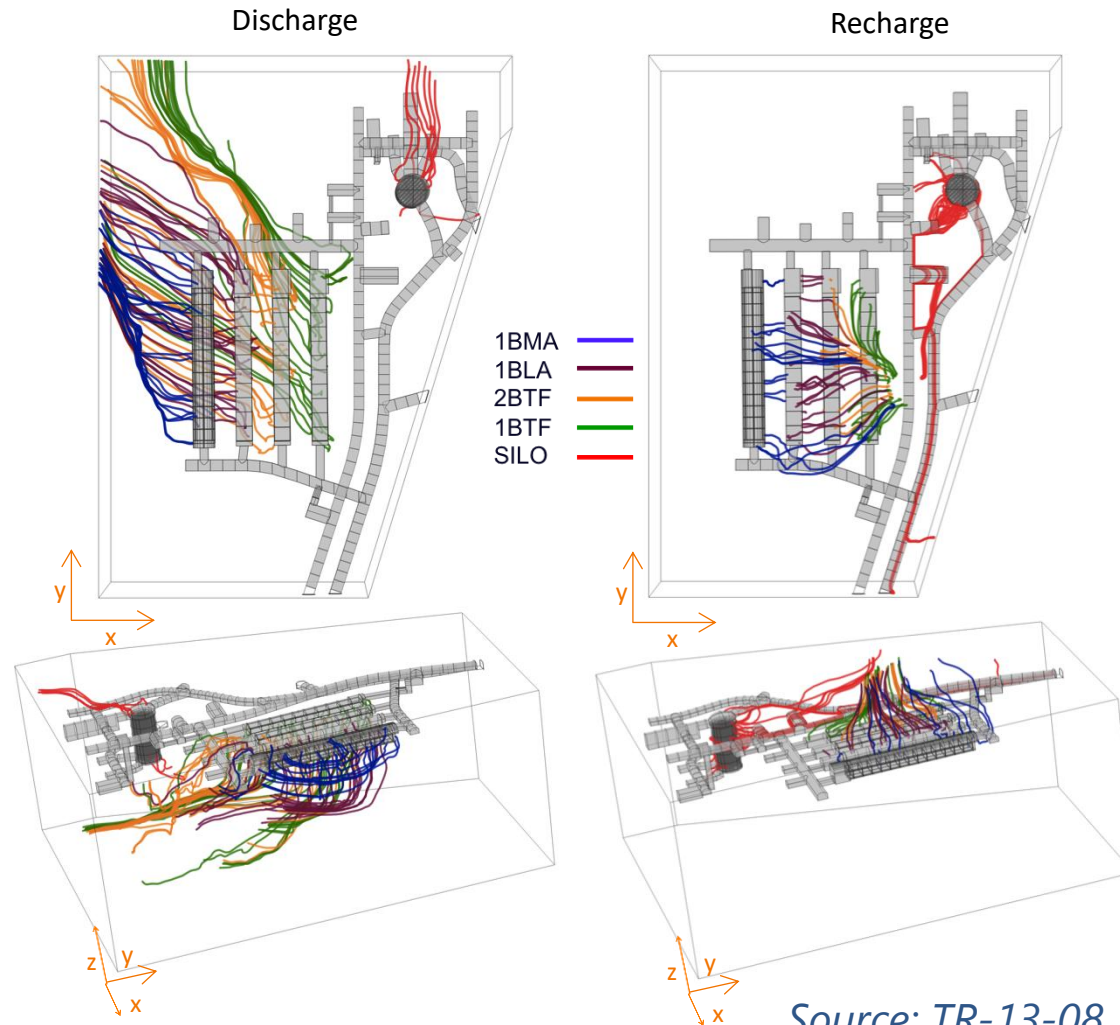
Climate related cases

- Relative shore-line positions

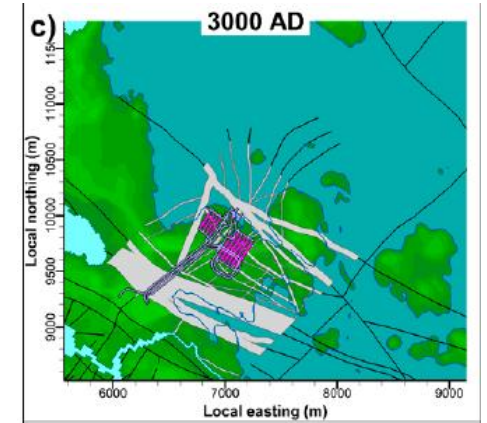


Climate related cases

- Relative shore-line positions

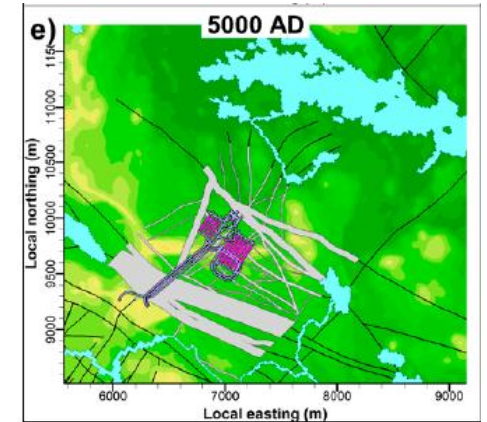
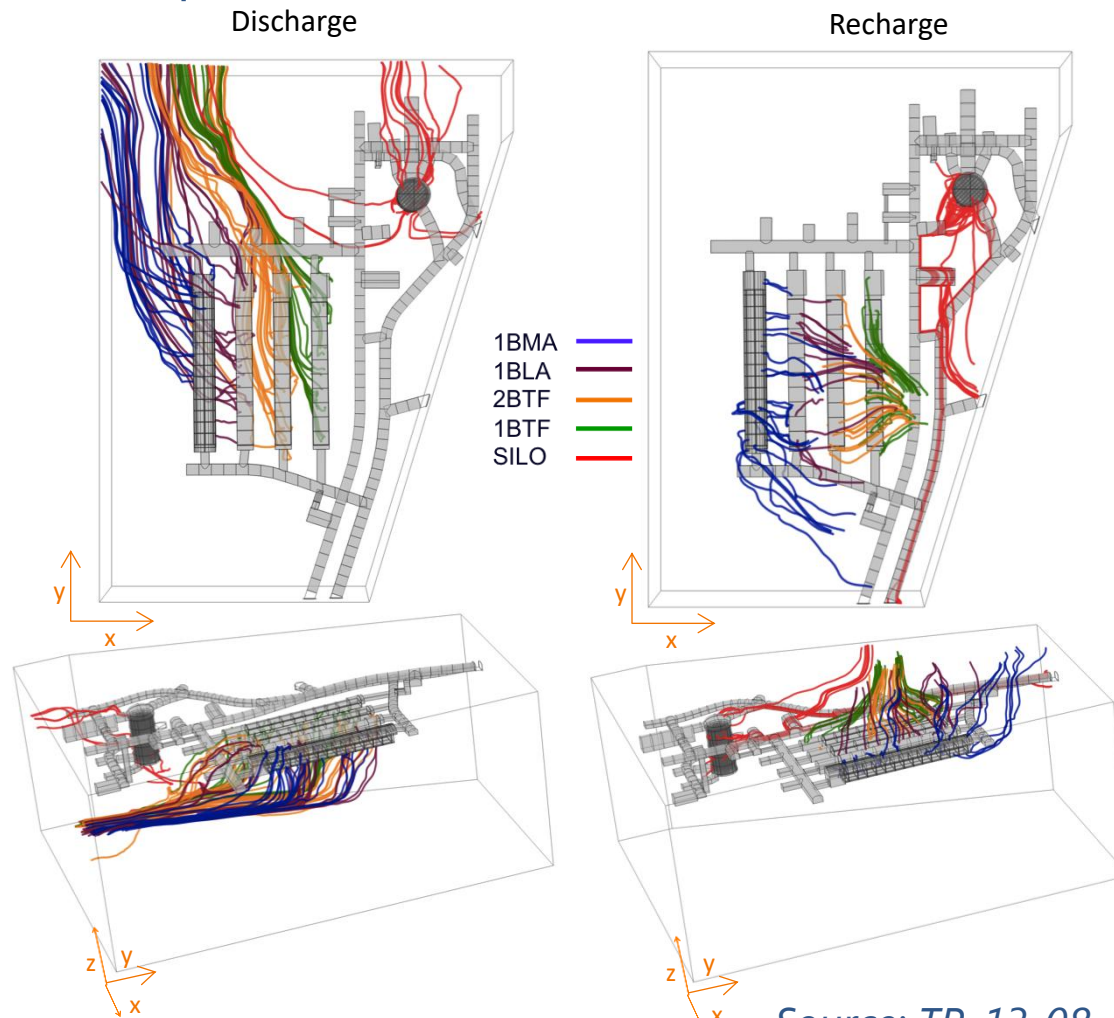


Source: TR-13-08



Climate related cases

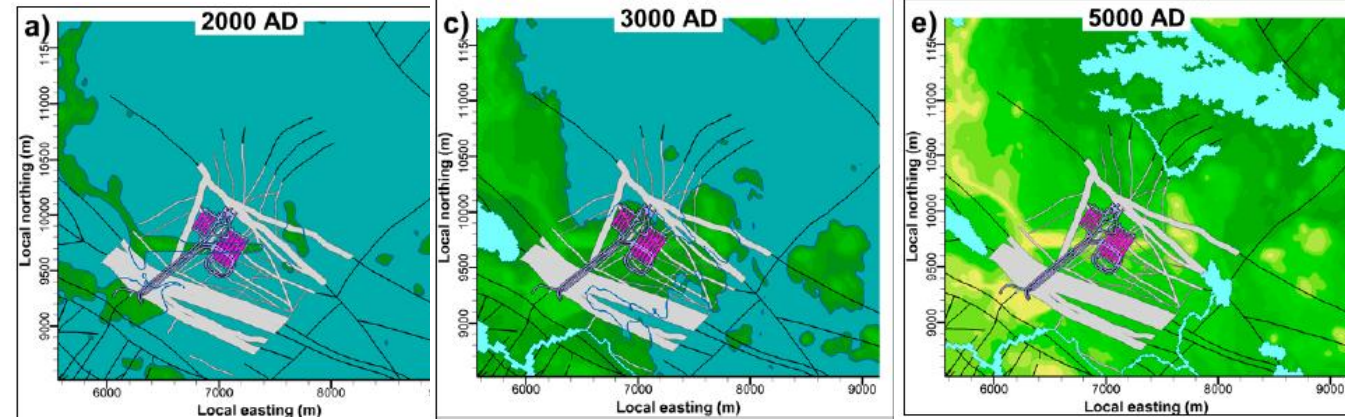
- Relative shore-line positions



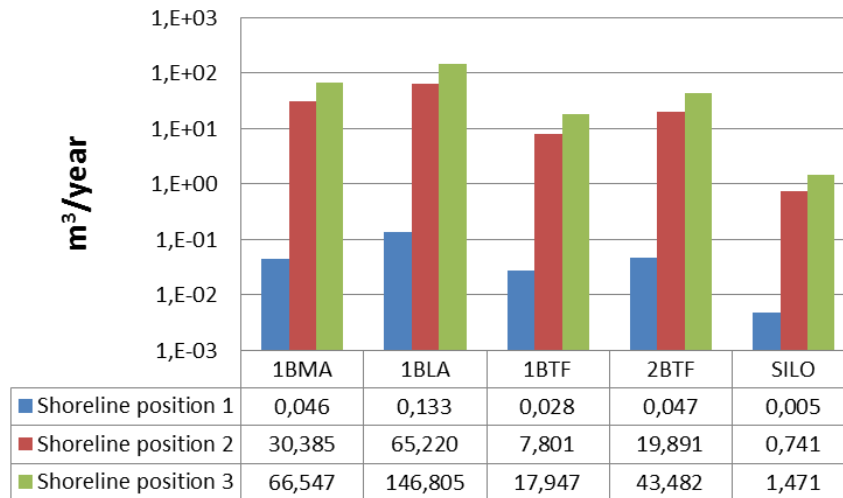
Source: TR-13-08

Climate related cases

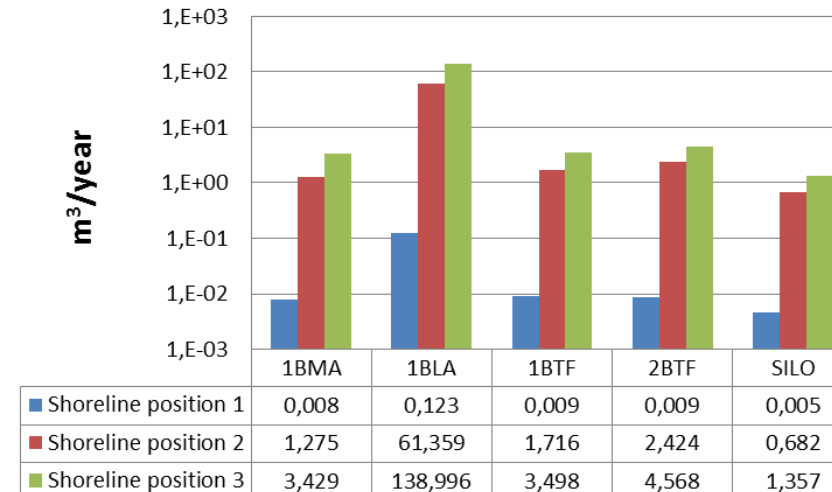
- Relative shore-line positions



(a) Total flow per vault (m³/year)



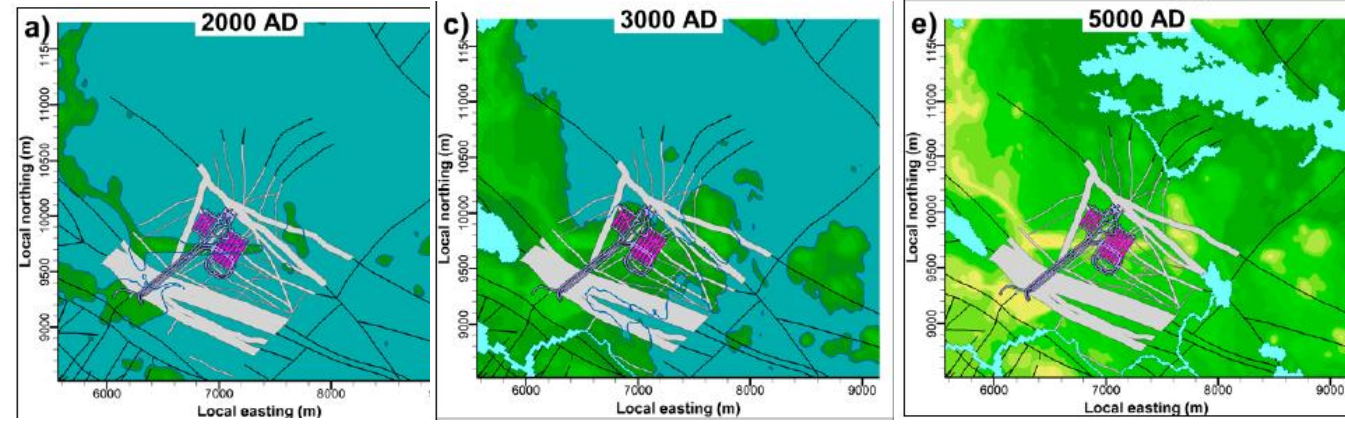
(b) Total flow per waste (m³/year)



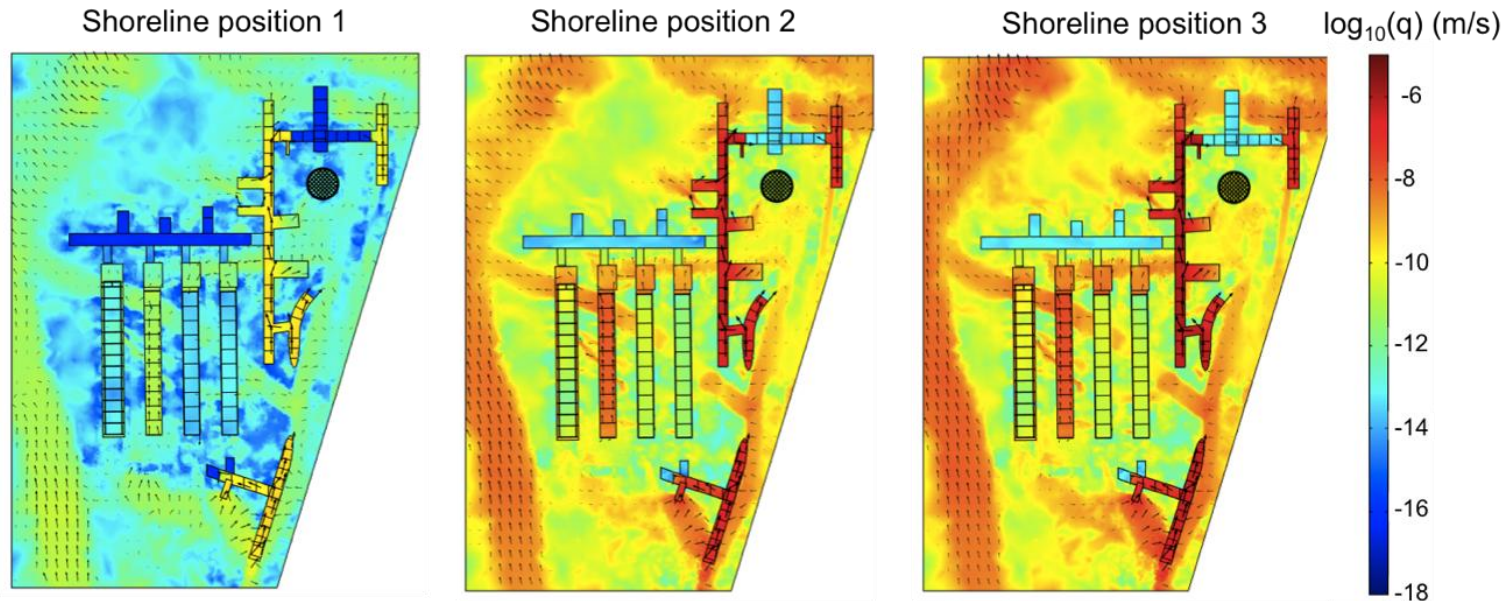
Source: TR-13-08

Climate related cases

- Relative shore-line positions

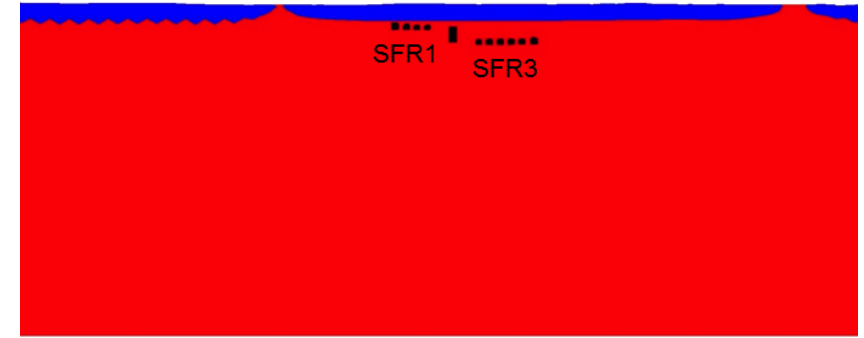


Darcy velocity (m/s) and velocity vectors on a xy plane at z= -82.5 m.



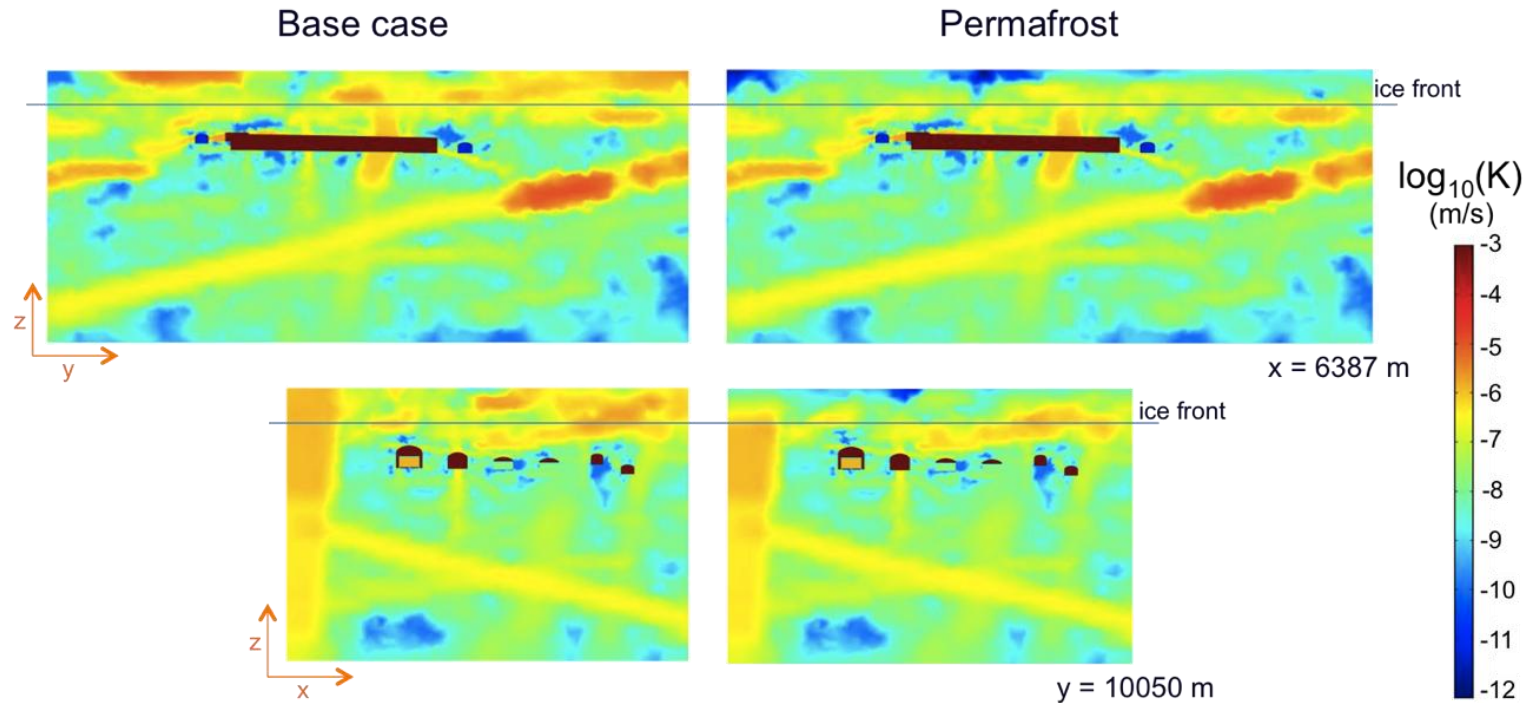
Source: TR-13-08

Shallow permafrost



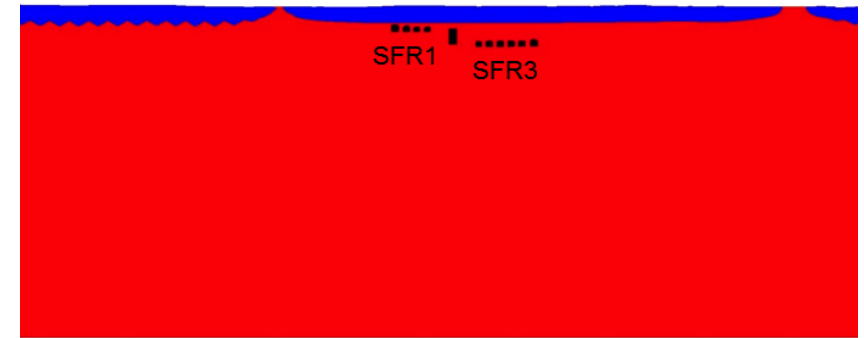
Climate related cases

- Shallow permafrost (depth -59 m)
- 2 taliks



Source: R-13-25

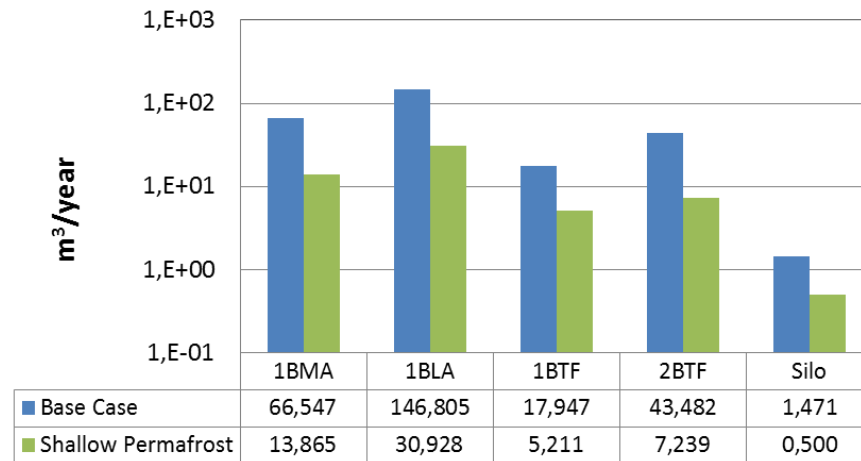
Shallow permafrost



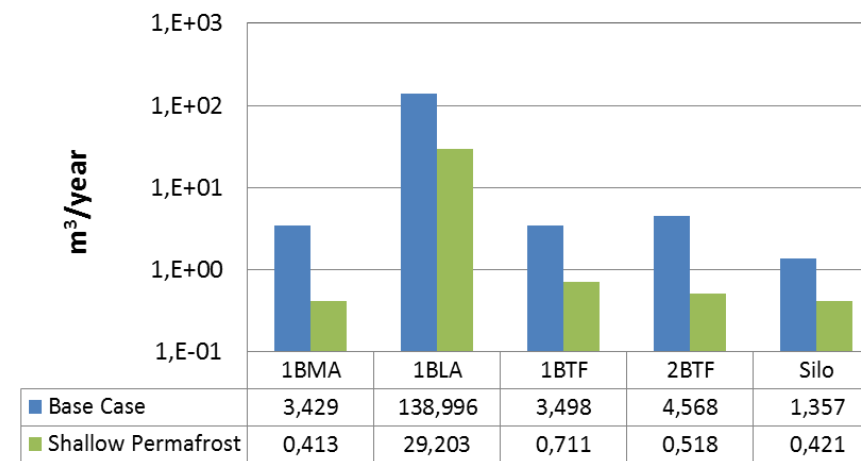
Climate related cases

- Shallow permafrost (depth -59 m)
- 2 taliks

(a) Shallow Permafrost - Total flow per vault

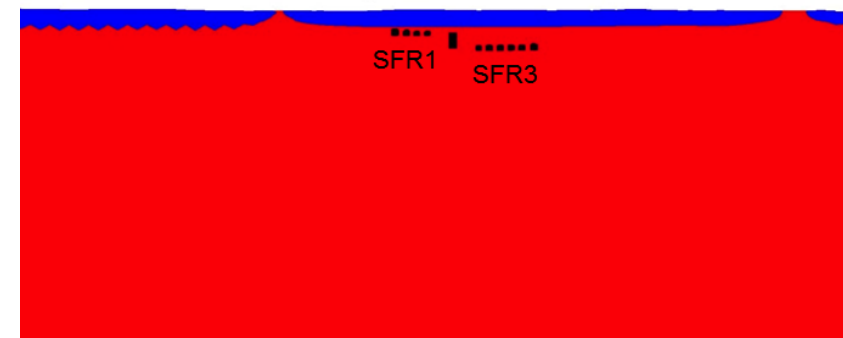


(b) Shallow Permafrost - Total flow per waste



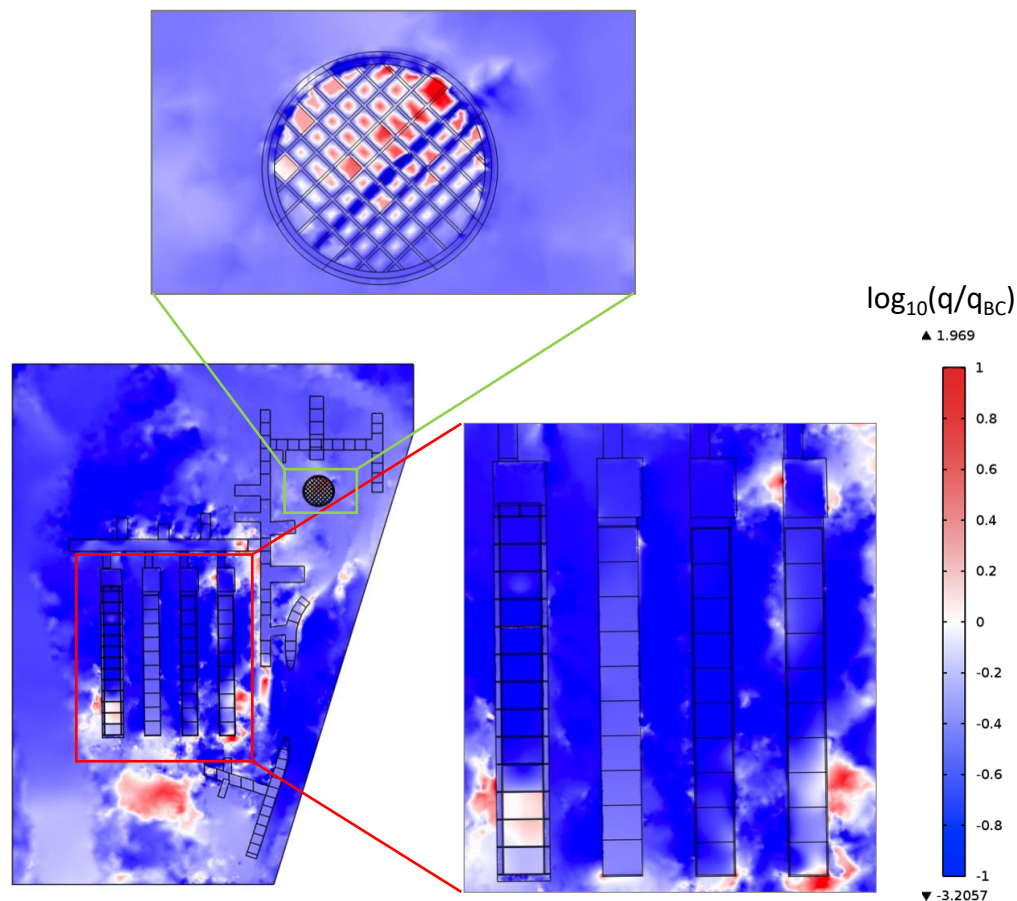
Source: TR-13-08

Shallow permafrost



Climate related cases

- Shallow permafrost (depth -59 m)
- Presence of taliks



Ratio of the Darcy velocity magnitude between the Shallow permafrost case and the Base case for the shoreline position 3 in a xy plane at $z = 82.5$ m.

Source: TR-13-08

- For a **coastal geological repository**, long-term climate change is best understood as a change in hydrogeological **boundary conditions**.
- As the **shoreline retreats**, the repository evolves from a submerged discharge setting to shoreline-controlled and then land-dominated recharge conditions, which changes both the **direction and the intensity of groundwater flow**.
 - The largest conceptual shift occurs when the **shoreline passes over the repository**. The **flow field inverts** from predominantly upward discharge to a more local recharge-driven system.
- A shallow **permafrost** front above the repository **reduces overall flow** and makes the **flow pattern more horizontal**. In the SFR studies, average flow reductions were about 78% for SFR1 and about 40% for SFR3 relative to the corresponding base case.

- **Groundwater flow** is a central input to post-closure **safety assessment**.
- **Groundwater modelling** is a necessary step because its outputs feed the radionuclide transport assessment (and other processes).
 - Multiscale hydrogeological modelling is essential.
- For long-term safety, the key issue is **not one exact future**, but a set of **climate-driven hydrogeological states**.

CLIMATE CHANGE IMPACT ON GROUNDWATER FLOW DYNAMICS AND RADIONUCLIDE TRANSPORT

SKB'S SFR SAFETY ASSESSMENT CASE

AMPHOS²¹
an RSK company



Co-funded by the European Union under Grant Agreement n° 101166718

CLIMATE CHANGE IMPACT ON LONG-TERM LANDSCAPE EVOLUTION AT VARIOUS SPATIAL AND TEMPORAL SCALES AND IMPLICATIONS FOR SAFETY

WP CLIMATE training session 2 – Wednesday 20 May 2026

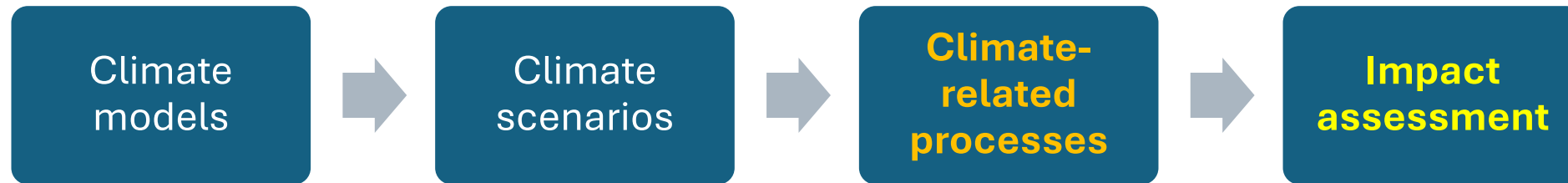
Koen Beerten SCK CEN



Co-funded by the European Union under Grant Agreement n° 101166718

SCOPE OF THIS PRESENTATION

- How can output from climate models (numerical or conceptual) be used to build relevant climate scenarios to **assess the impact** of **climate-related processes**





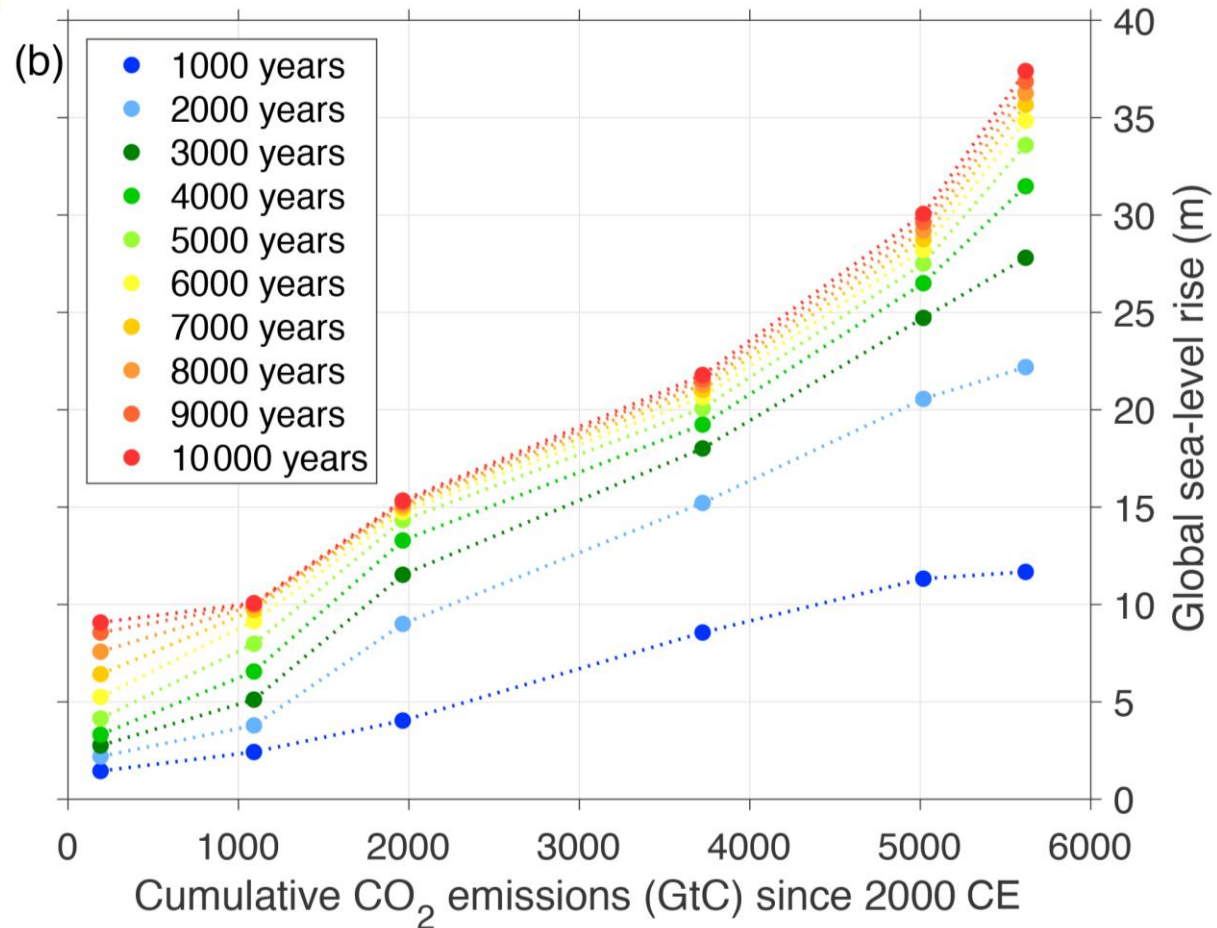
SCOPE

- **Many scenarios and future climate states from session 1 (Tuesday)**
- **Now: how do these modify 'the landscape', in the broadest sense**
 - Topography
 - Hydrography
 - Vegetation
 - Vadose zone (usually upper few meters)
- **Non-exhaustive**
- **Link to safety functions, mostly isolation**

GLOBAL WARMING

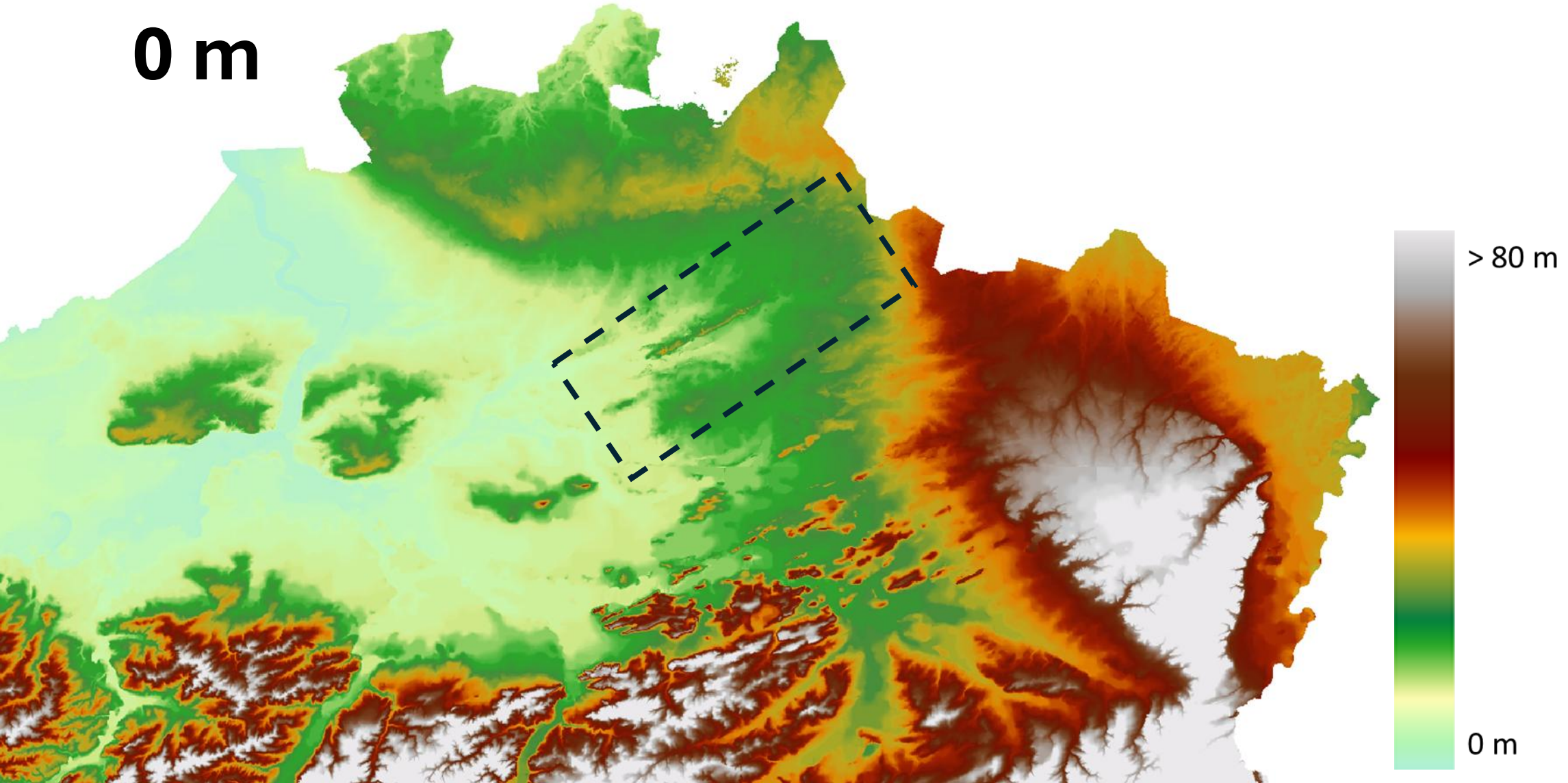
- **All evidence points to a long interglacial ahead (up to 50,000 years)**
 - Insolation and natural CO₂
 - Anthropogenic forcing
- **Local: climate transitions (by 2100)**
 - Köppen-Geiger Dfb → Dfa or Cfb
 - Köppen-Geiger Cfb → Csb/Csa
 - Köppen-Geiger Csa → BSh/BSk
- **See yesterday's presentation by Johan**
 - In a state of equilibrium, doubling of CO₂ concentration leads to ca. 2-4 °C global warming by 10 ka AP (10,000 years after present)
 - This is not even the worst case
- **Global: sea-level rise**
 - Marine/estuarine erosion
 - Geochemical changes
 - Groundwater flow dynamics

COMMITTED SEA-LEVEL RISE



Van Breendam, J., Goelzer, H., & Huybrechts, P. (2020). Semi-equilibrated global sea-level change projections for the next 10 000 years. *Earth System Dynamics*, 11, 953–976.

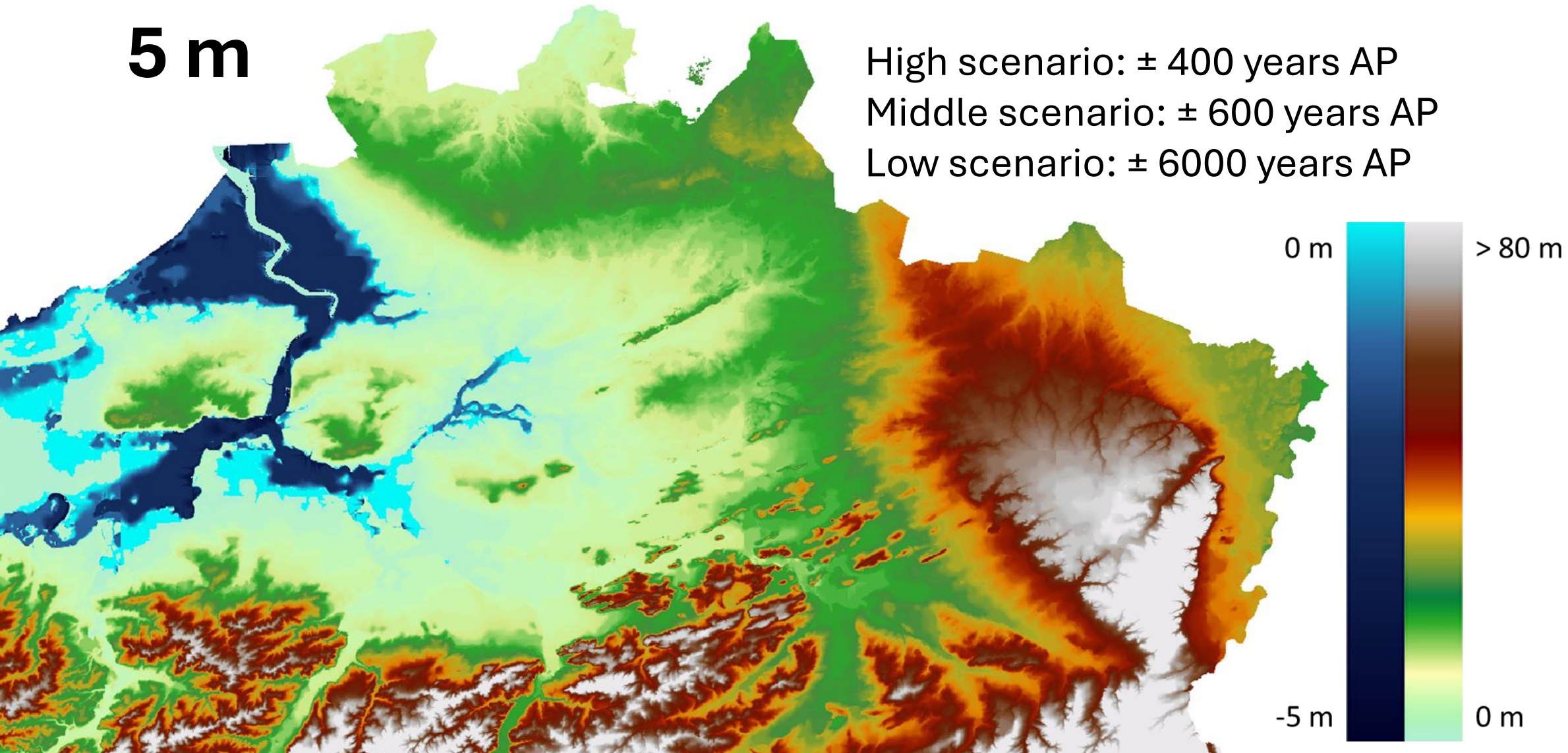
0 m



Unpublished.

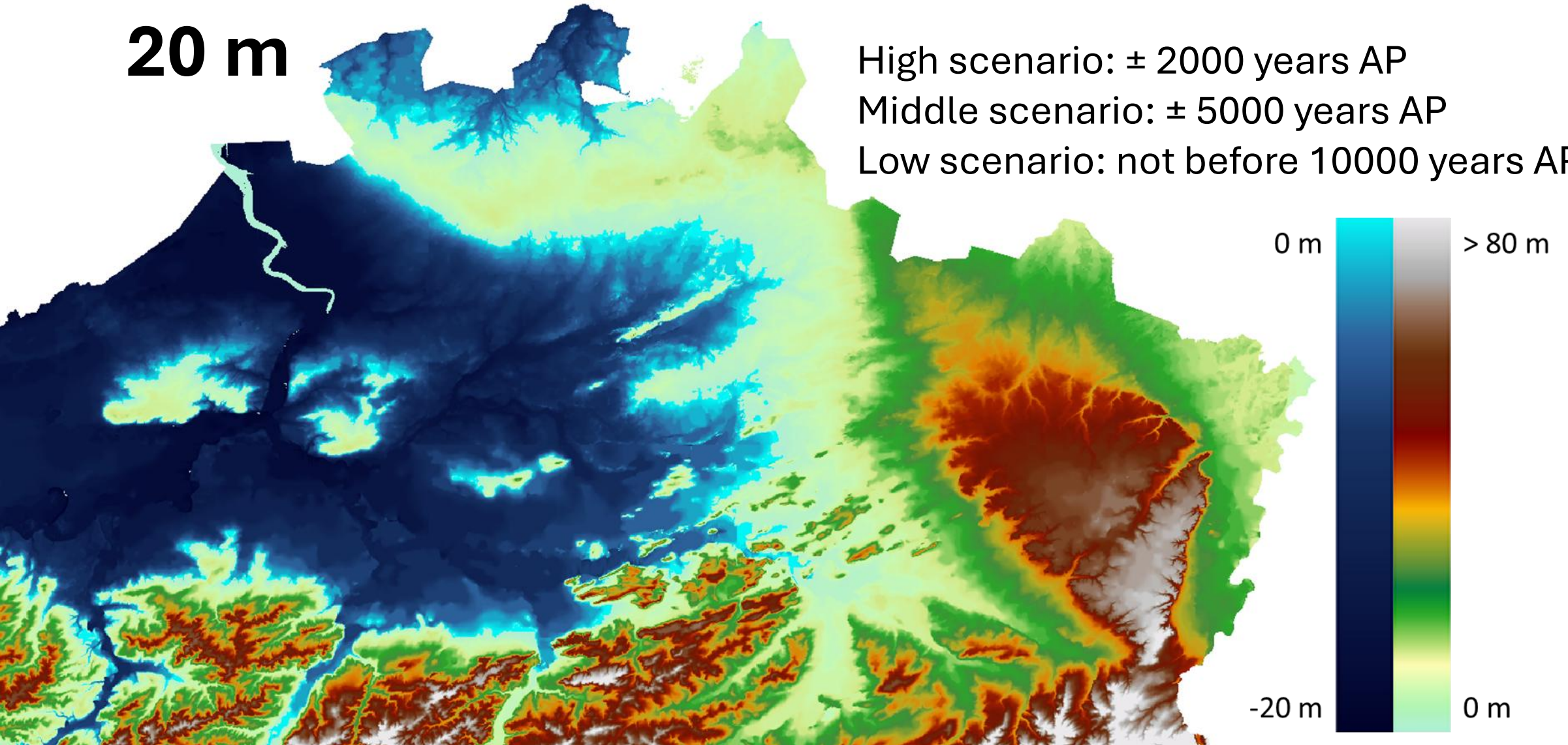
5 m

High scenario: ± 400 years AP
Middle scenario: ± 600 years AP
Low scenario: ± 6000 years AP



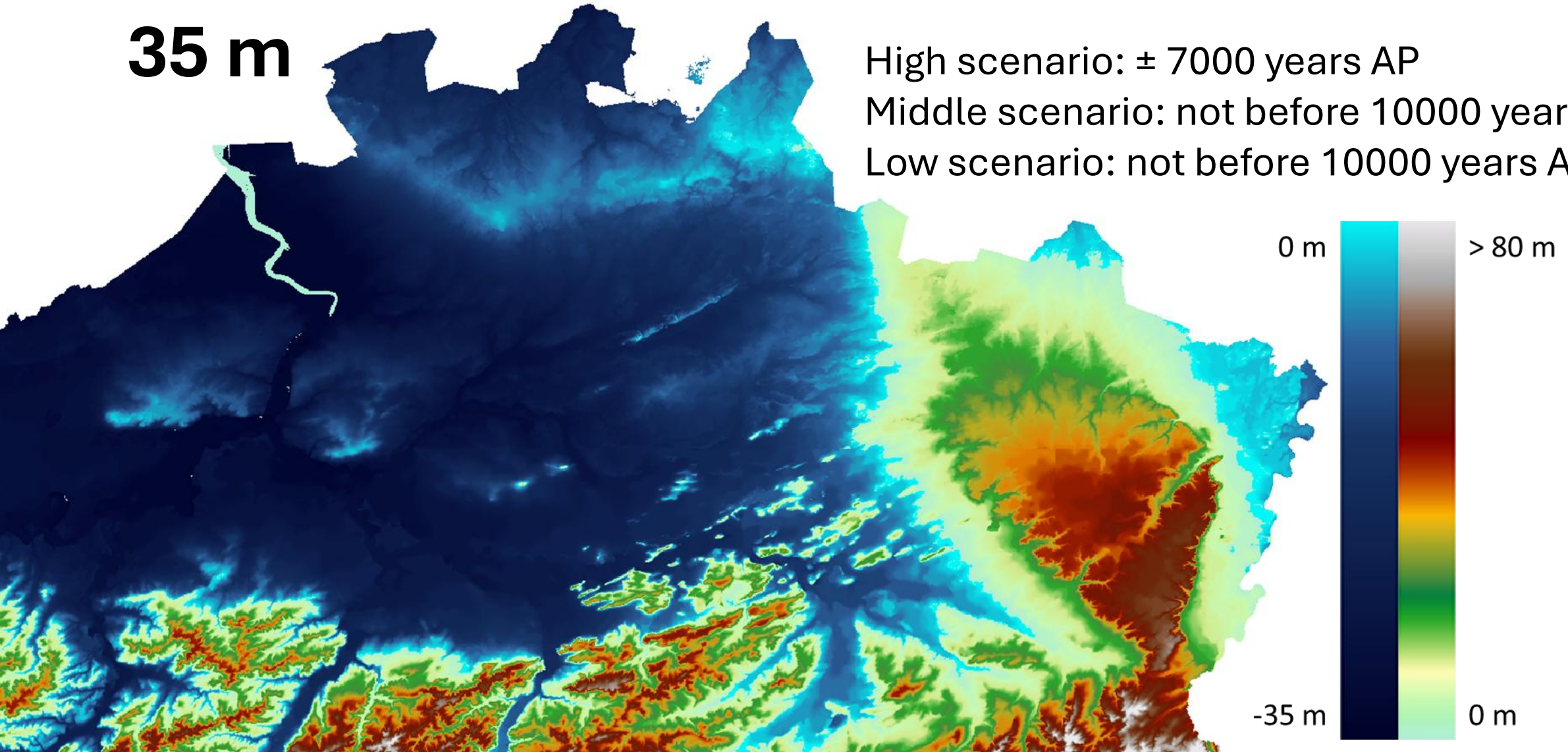
20 m

High scenario: ± 2000 years AP
Middle scenario: ± 5000 years AP
Low scenario: not before 10000 years AP



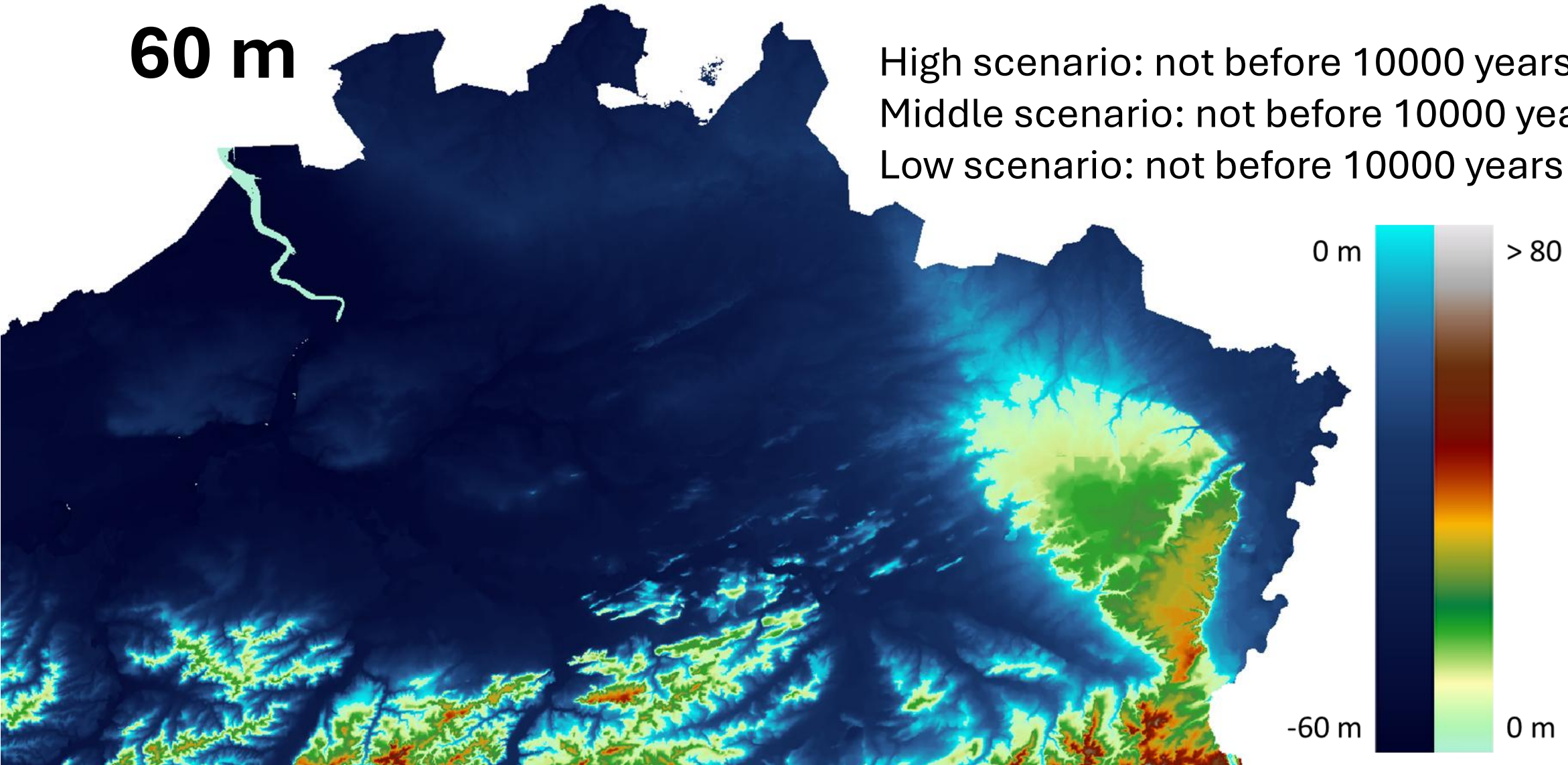
35 m

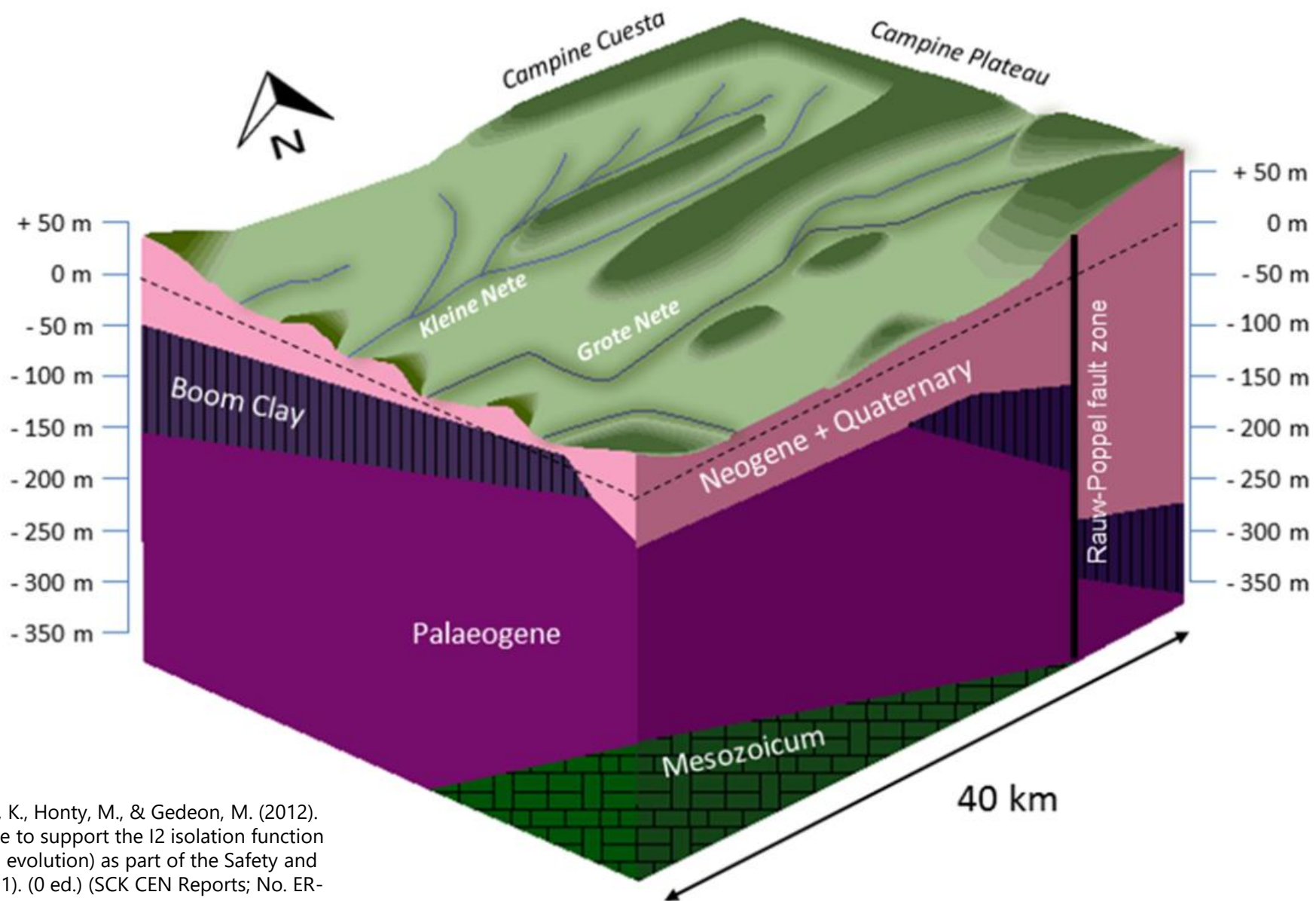
High scenario: ± 7000 years AP
Middle scenario: not before 10000 years AP
Low scenario: not before 10000 years AP



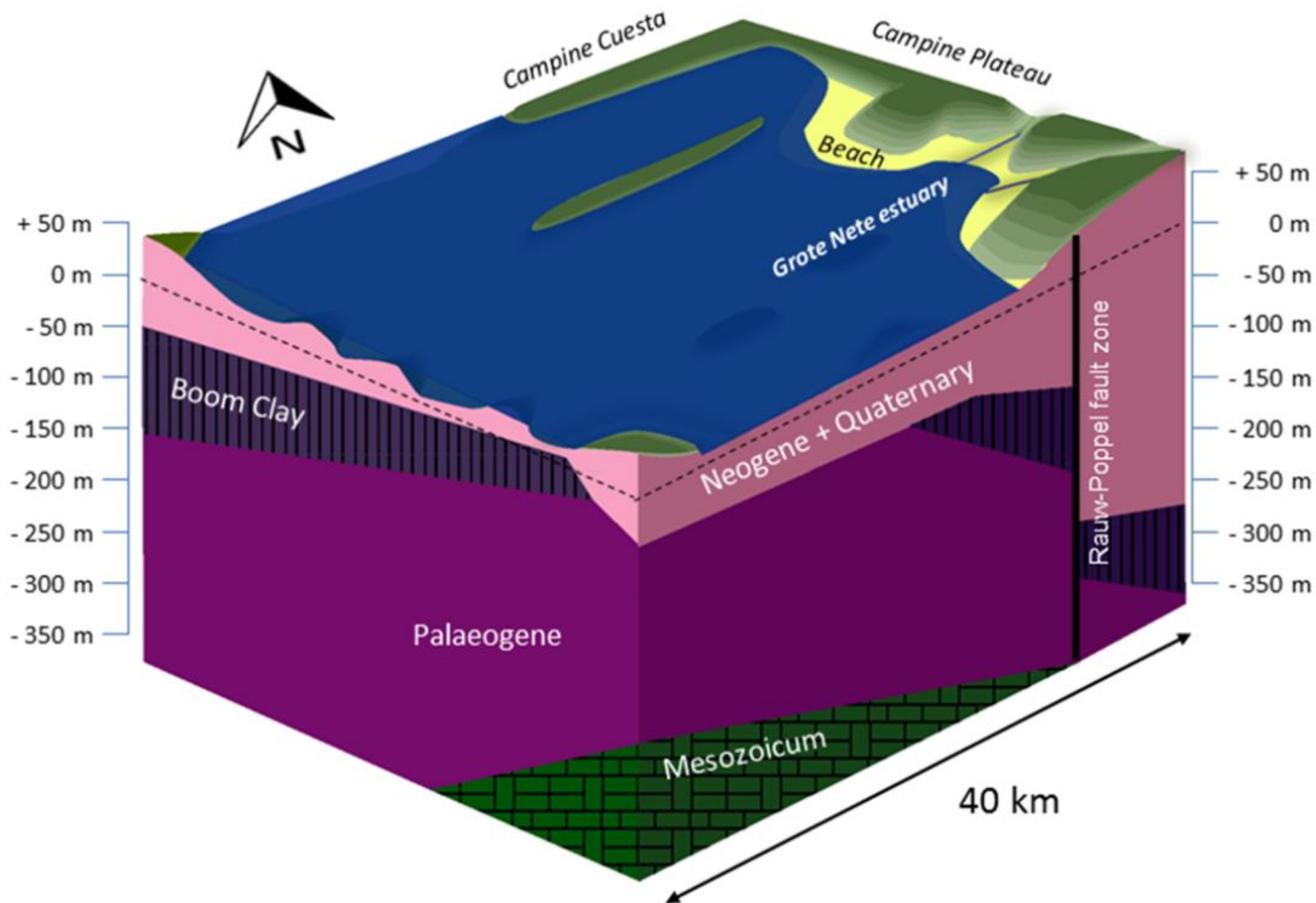
60 m

High scenario: not before 10000 years AP
Middle scenario: not before 10000 years AP
Low scenario: not before 10000 years AP

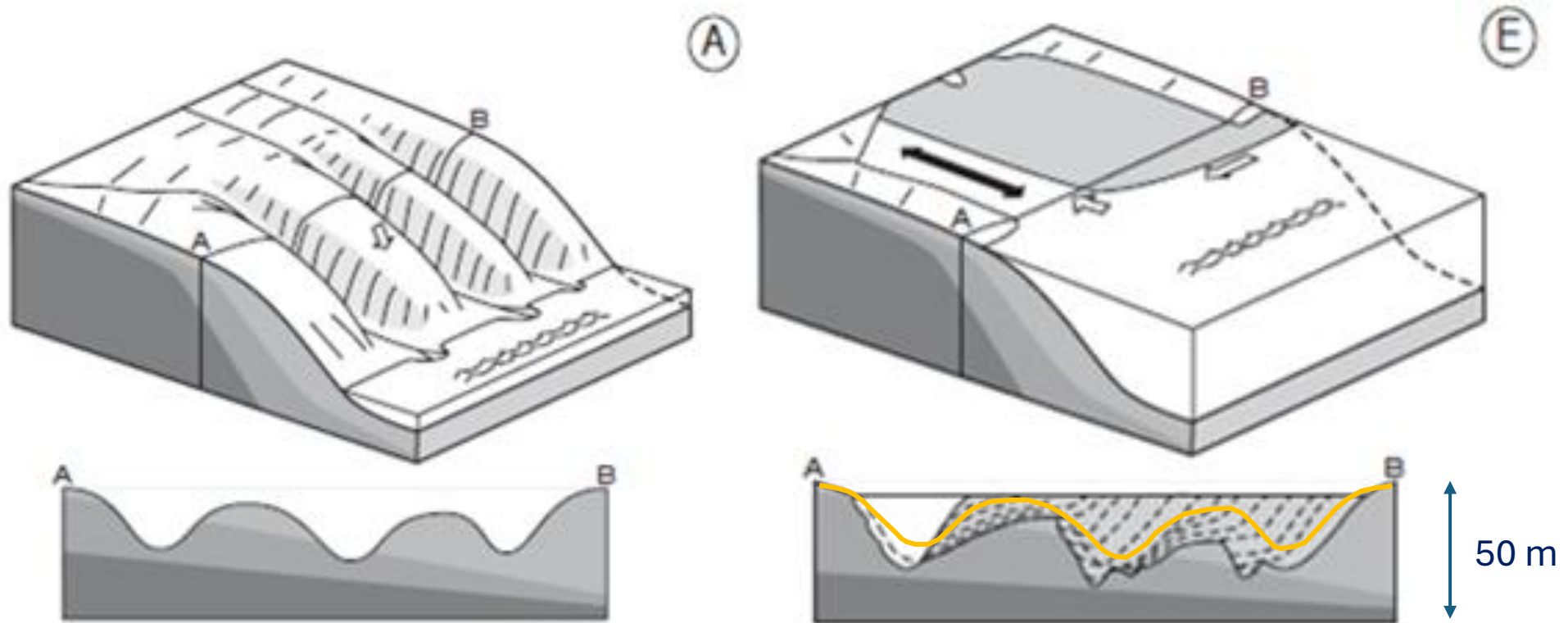




De Craen, M., Beerten, K., Honty, M., & Gedeon, M. (2012). Geo-scientific evidence to support the I2 isolation function (geology & long-term evolution) as part of the Safety and Feasibility Case 1 (SFC1). (0 ed.) (SCK CEN Reports; No. ER-184). SCK CEN.

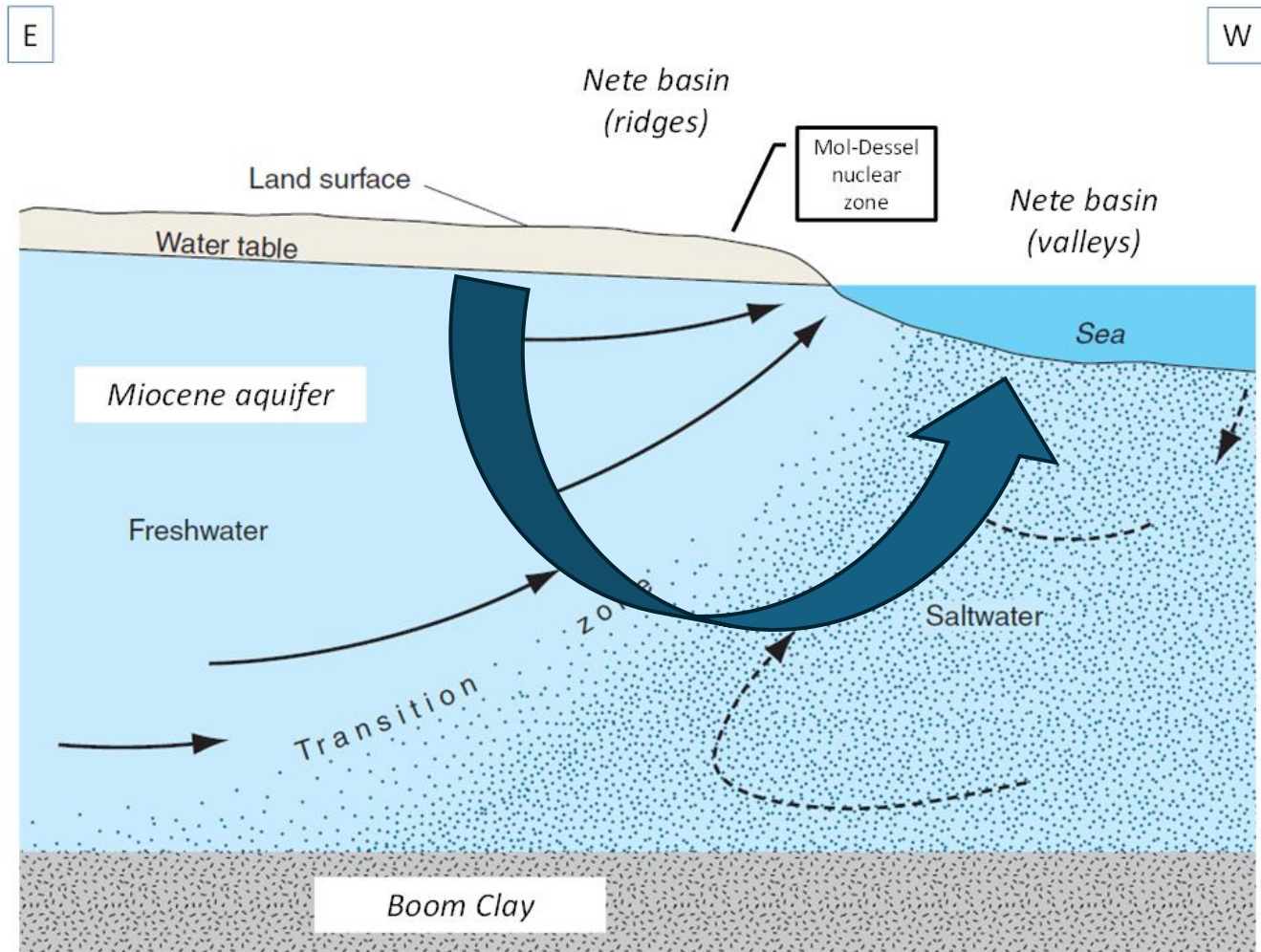


ESTUARINE/MARINE EROSION: NATURAL ANALOGUE FROM THE EOCENE



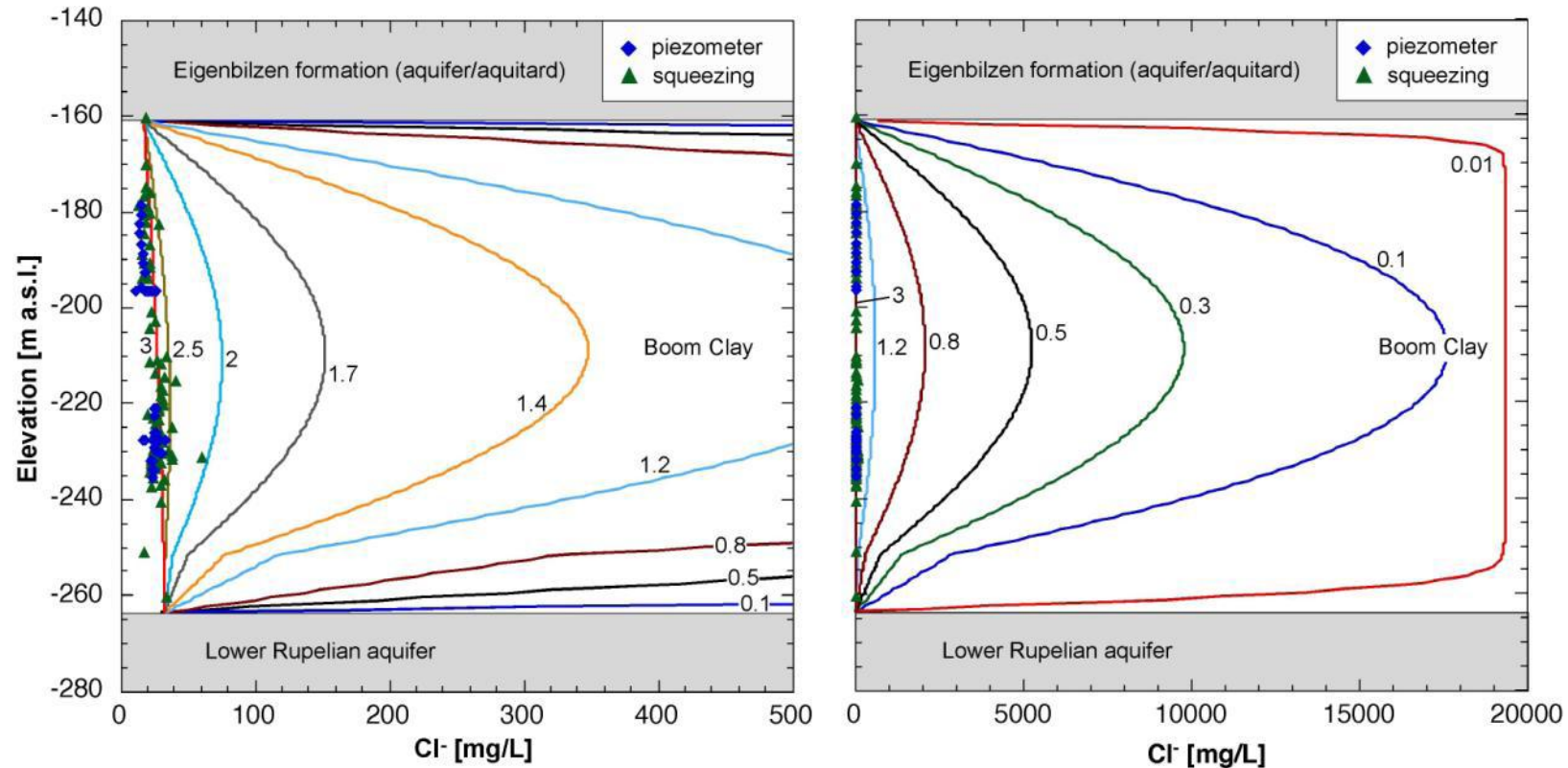
Houthuys, R., 2011. A sedimentary model of the Brussels Sands, Eocene, Belgium. *Geologica Belgica* 14, 55-74.

FLOW DYNAMICS



Barlow, P.M., 2003. Groundwater in Freshwater-Saltwater Environments of the Atlantic Coast. Circular 1262. U.S. Department of the Interior, U.S. Geological Survey. Modified.

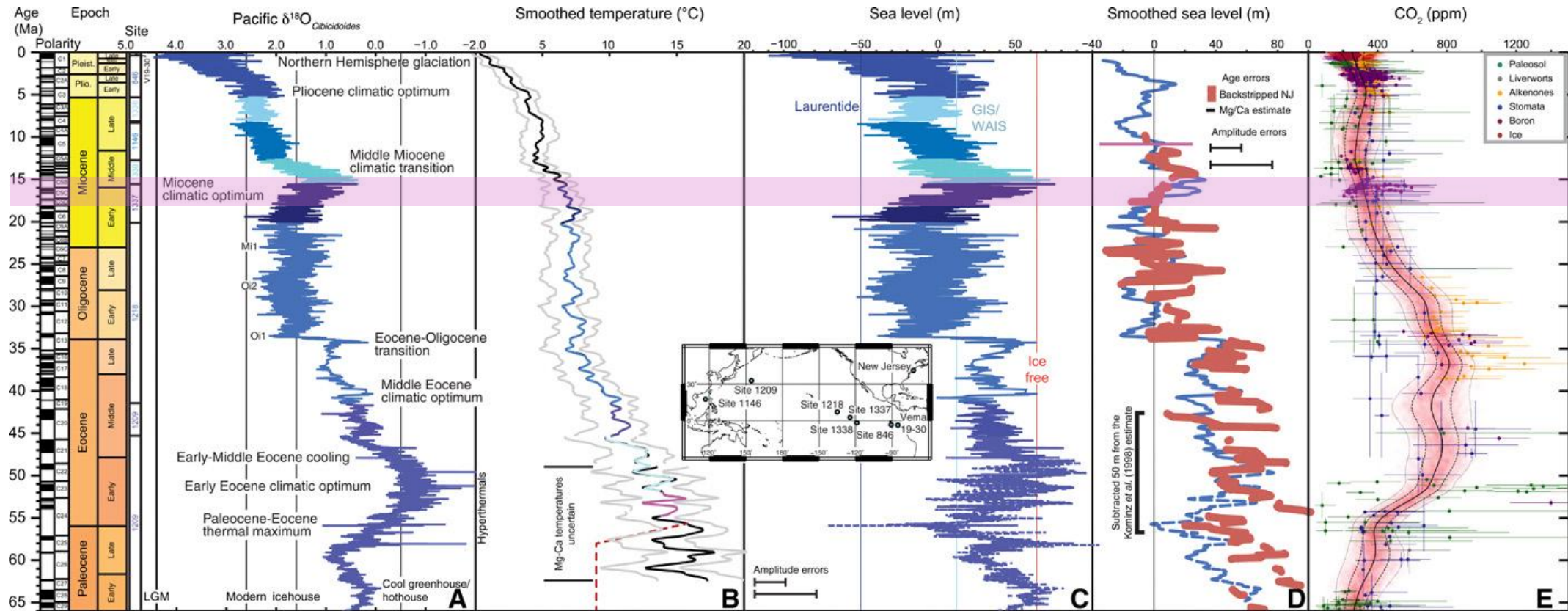
PORE WATER: REVERSE PROCESS OF FRESHENING



Mazurek, M., Alt-Epping, P., Bath, A., Gimmi, T., Waber, H.N., 2008. Natural Tracer Profiles Across Argillaceous Formations: Review and Synthesis. CLAYTRAC Project, NEA No. 6253.

A WARM FUTURE BY 10 KA AP: HOW WOULD IT LOOK LIKE ONSHORE?

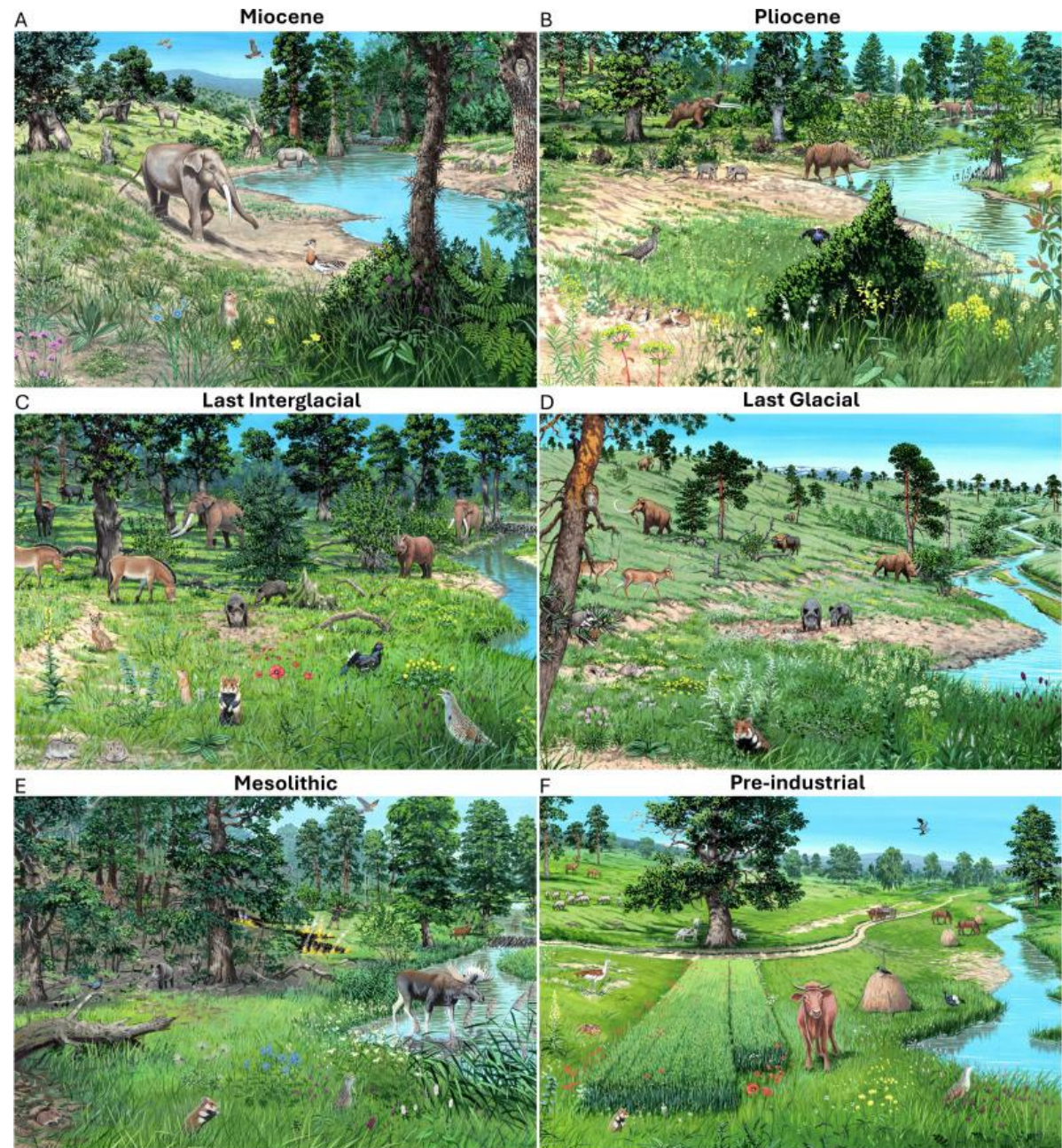
- Earlier we said: doubling of CO₂ concentration, up to 4°C warmer : put in geological perspective



RETURN TO MIOCENE AND PLIOCENE CLIMATES AND LANDSCAPES?

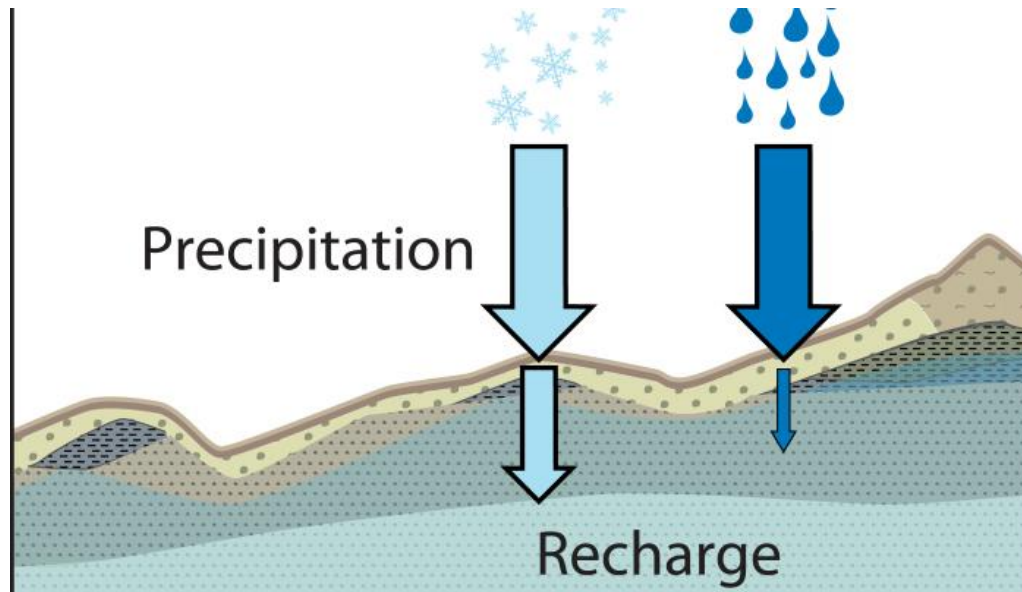
- Artistic palaeo-reconstructions of ecosystem states in Central Europe over the last 23 million years

Szymon Czyżewski, Skjold Alsted Søndergaard, Ábel Péter Molnár, Matthew Roy Kerr, Jeppe Aagaard Kristensen, Joe Atkinson, Jonas Trepel, Maciej Sykut, Paweł Radzikowski, Signe Sangill Termansen, Karol Wałach, Elena A. Pearce, Sean E.H. Pang, Bartłomiej Zajac, Juraj Bergman, Emil Sloth Thomassen, Ninad Mungi, Camilla Fløjgaard, Rasmus Ejrnæs, Robert Buitenwerf, Jens-Christian Svenning, Revisiting Europe's temperate forests: Palaeoecological evidence for an herbivory-driven woodland-grassland mosaic biome, *Biological Conservation*, Volume 316, 2026, 111749, ISSN 0006-3207, <https://doi.org/10.1016/j.biocon.2026.111749>



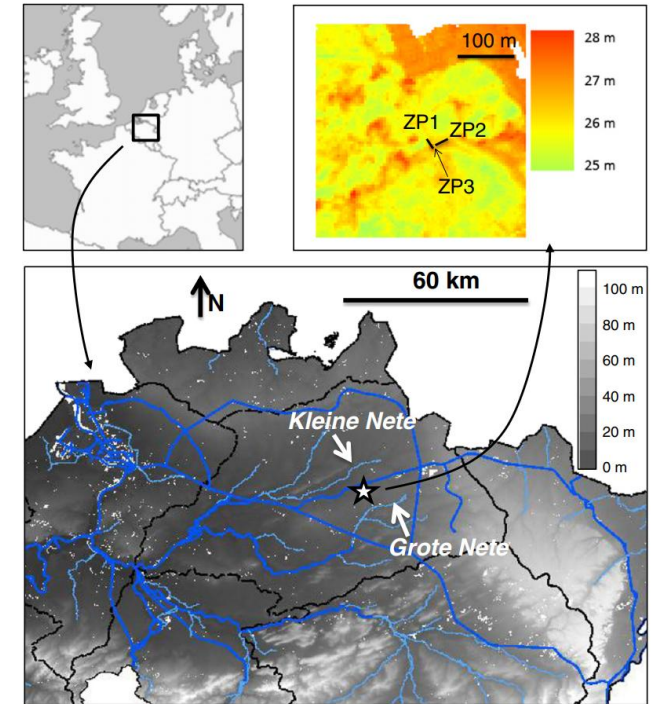
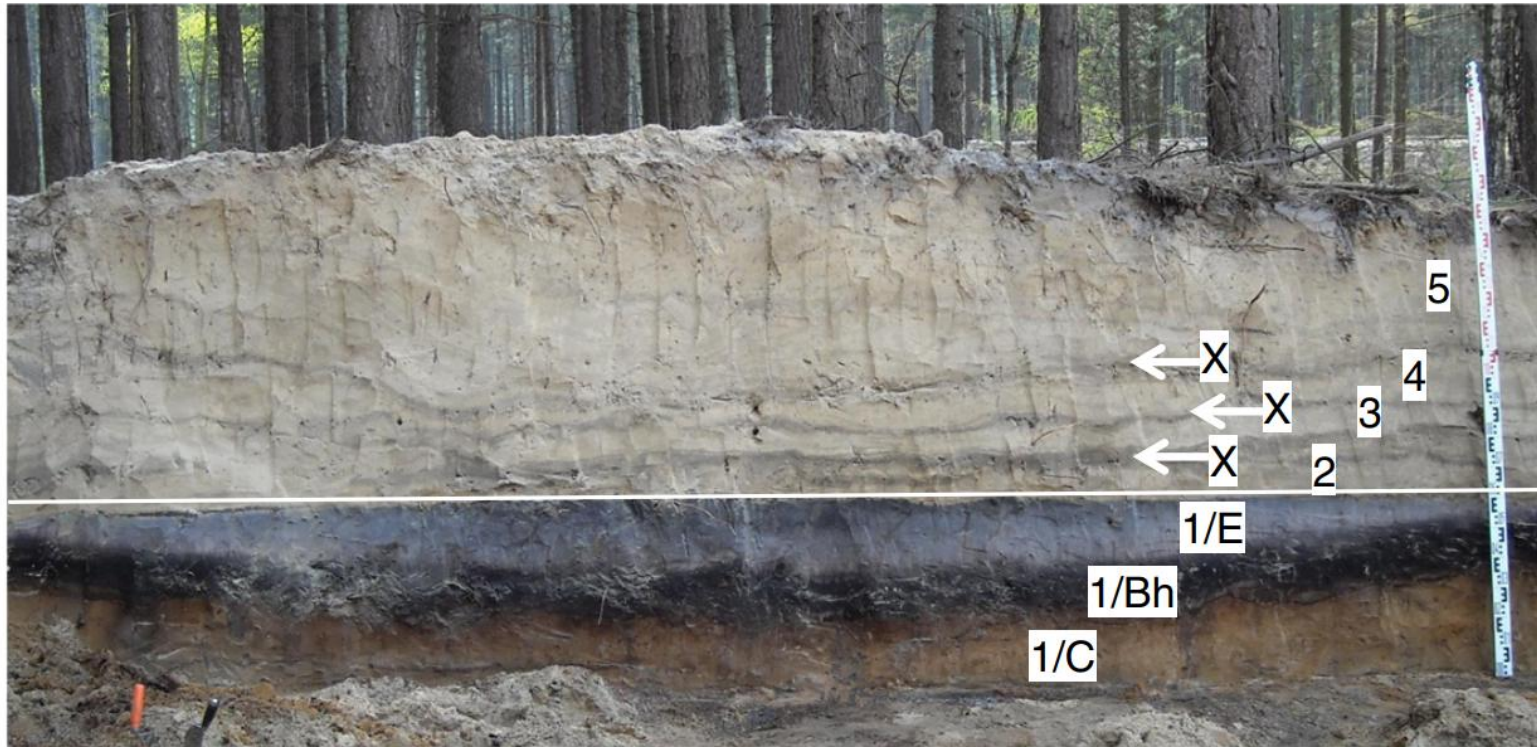
PROJECTIONS INCLUDE APPEARANCE OF B-CLIMATE CONDITIONS OVER THE NEXT MILLENIA IN CURRENT Cfb AND Csa CLIMATES

- How does this impact soil properties, land use and vegetation?
 - Evapotranspiration, infiltration, discharge to aquifer



<https://blogs.egu.eu/network/water-underground/2015/07/19/when-it-snows-it-pours-into-aquifers-recharge-seasonality-around-the-world/>

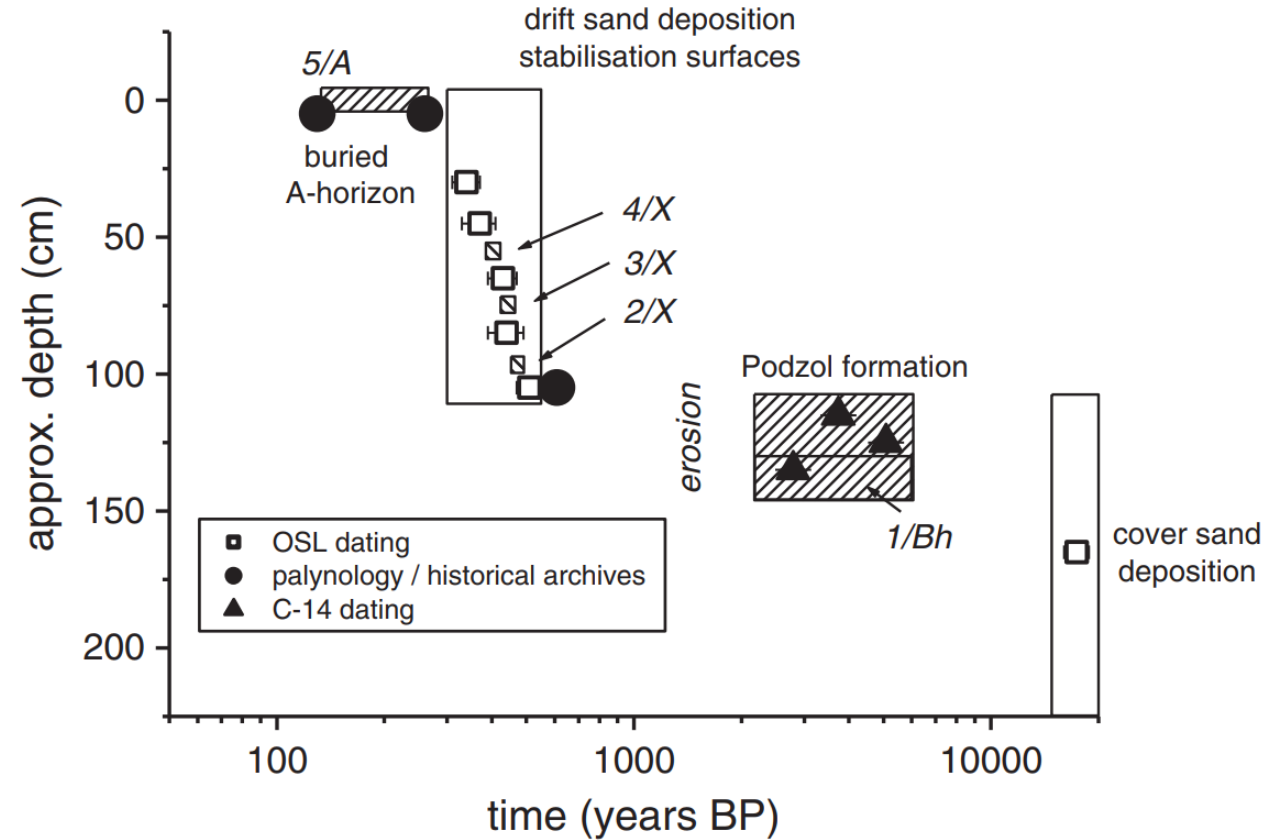
PODZOLS IN SANDY TERRAINS UNDER Cfb CLIMATE



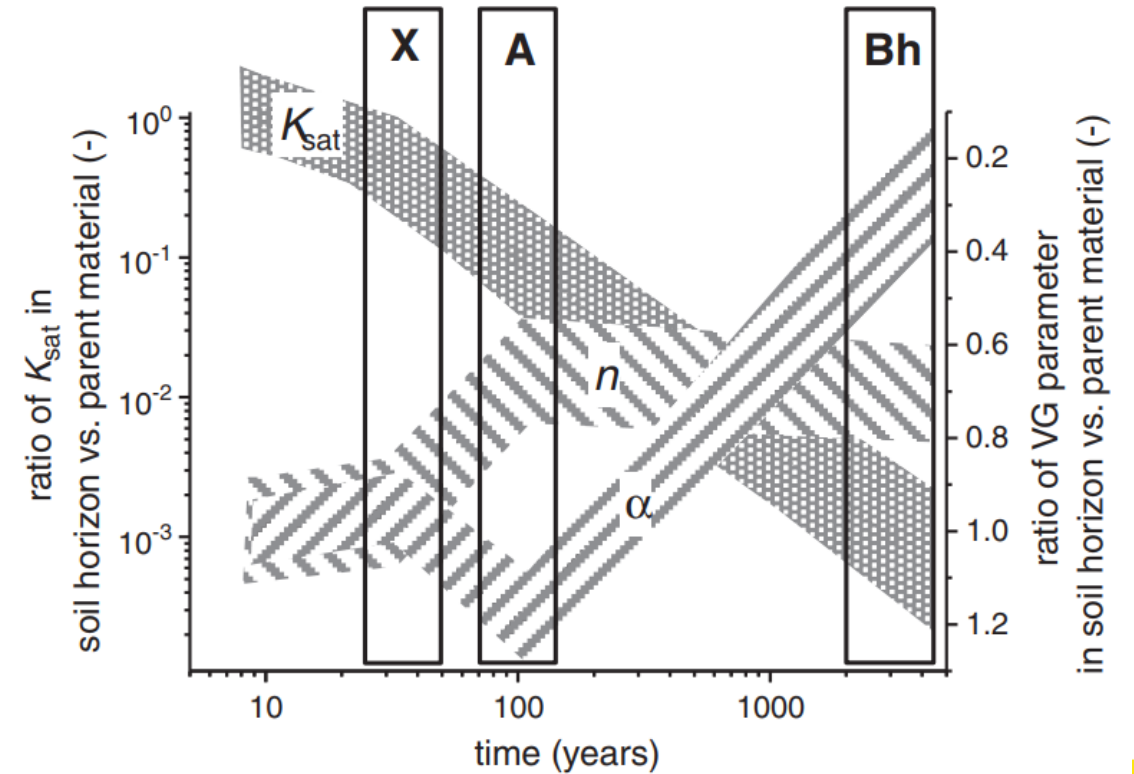
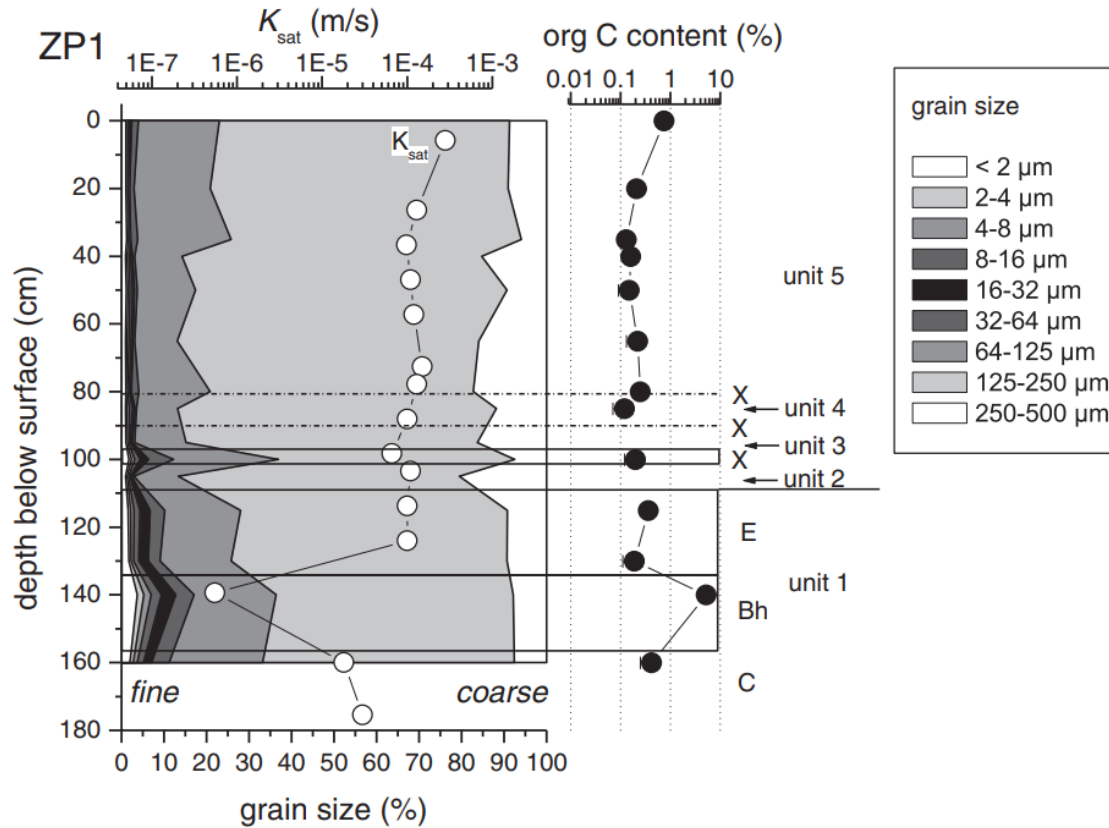
K. Beerten, K. Deforce, D. Mallants,
 Landscape evolution and changes in soil hydraulic properties at the decadal, centennial and millennial scale: A case study from the Campine area, northern Belgium, CATENA, Volume 95,
 2012, Pages 73-84, ISSN 0341-8162, <https://doi.org/10.1016/j.catena.2012.03.005>

PODZOLS ARE TYPICAL SOILS FOR SANDY TERRAINS IN Cfb CLIMATES

- **Mature podzols develop in several millenia**
 - Under vegetation
 - Precipitation surplus $P > ET$



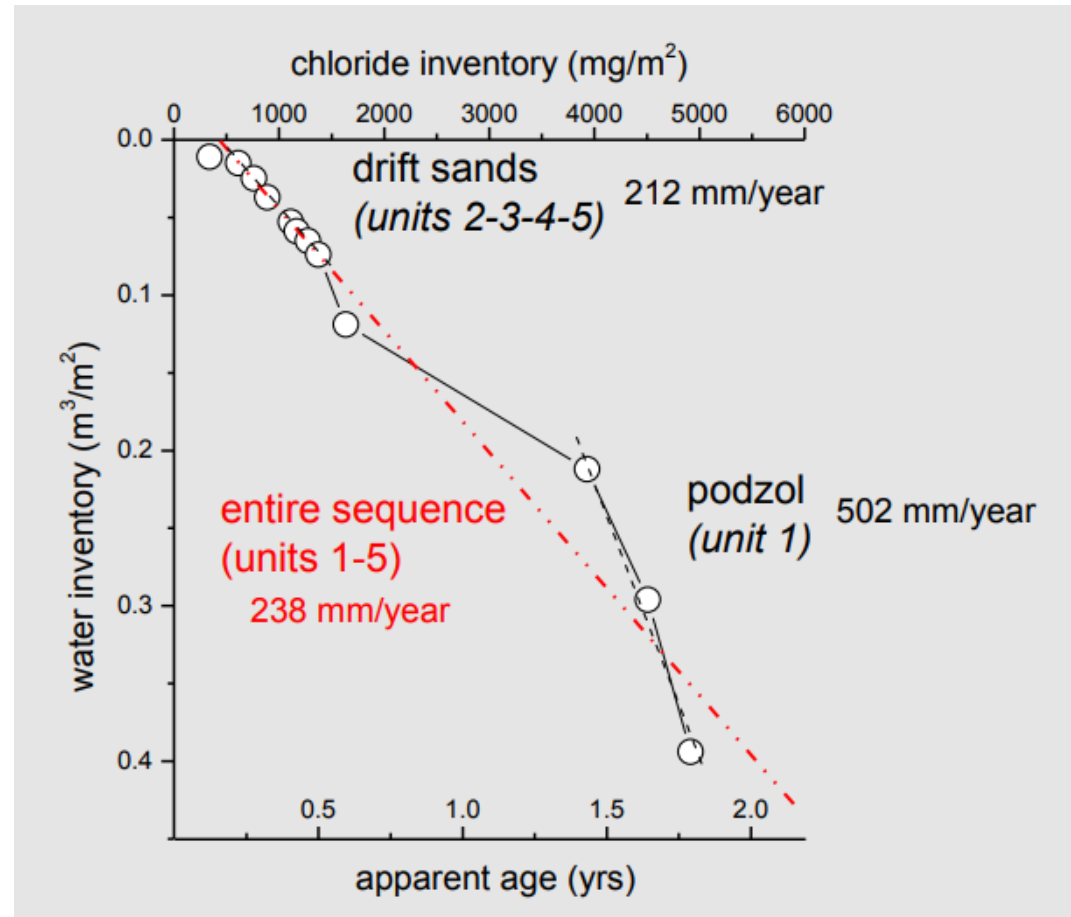
EVOLUTION OF SATURATED HYDRAULIC CONDUCTIVITY OF A PODZOL IN A Cfb CLIMATE



RECHARGE TO AQUIFER

- **This will change**

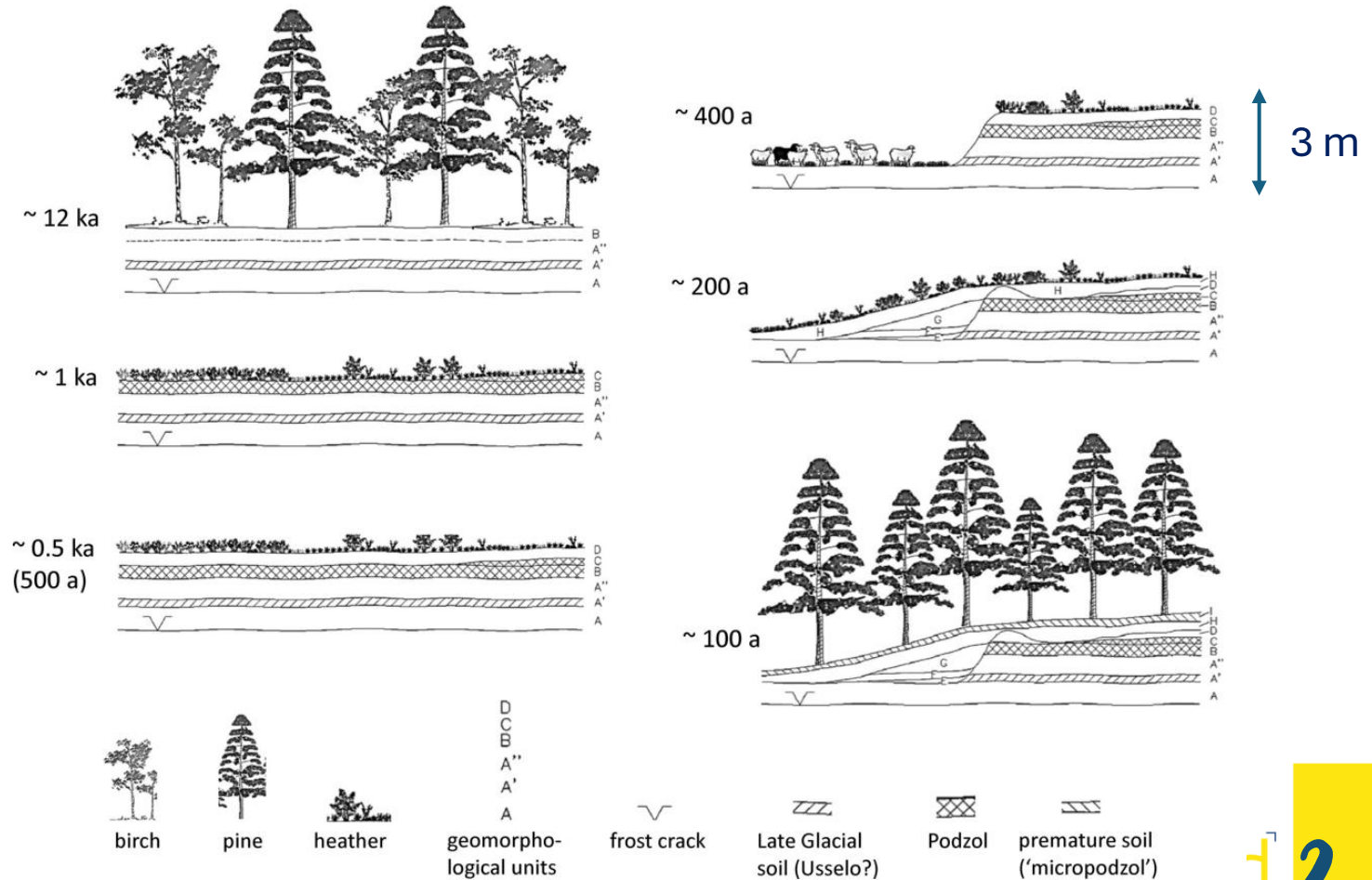
- Not only because of changing P and ET
- Also because of changing vegetation and hydraulic properties
- *Podzolisation is hardly observed in Csa climates*



Beerten, K., & Mallants, D. (2011). Geomorphology and hydrology of a sediment-soil sequence in Dessel: studying natural analogues for engineered earth covers. (0 ed.) (SCK•CEN Reports; No. ER-180). SCK CEN.

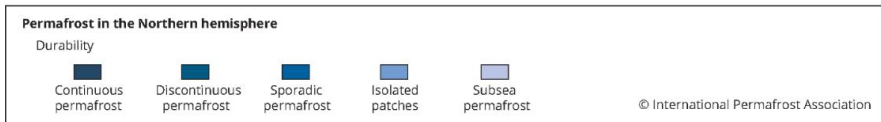
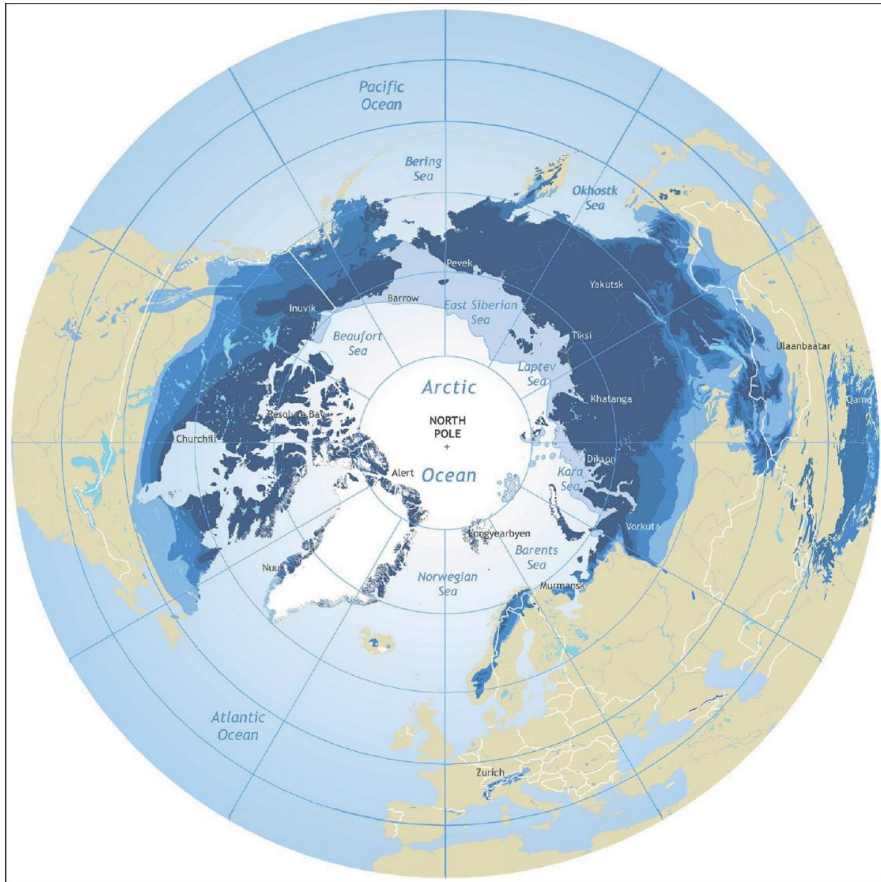
AEOLIAN DEFLATION IN SANDY TERRAIN UNDER Cfb CLIMATE

- Human-induced aeolian erosion due to deforestation and intensive land-use during the last couple of centuries
- Now these landscapes are stable
- Will they become unstable again in a B-climate?
 - Less vegetation
- Will modify vadose zone characteristics and thus recharge to aquifer



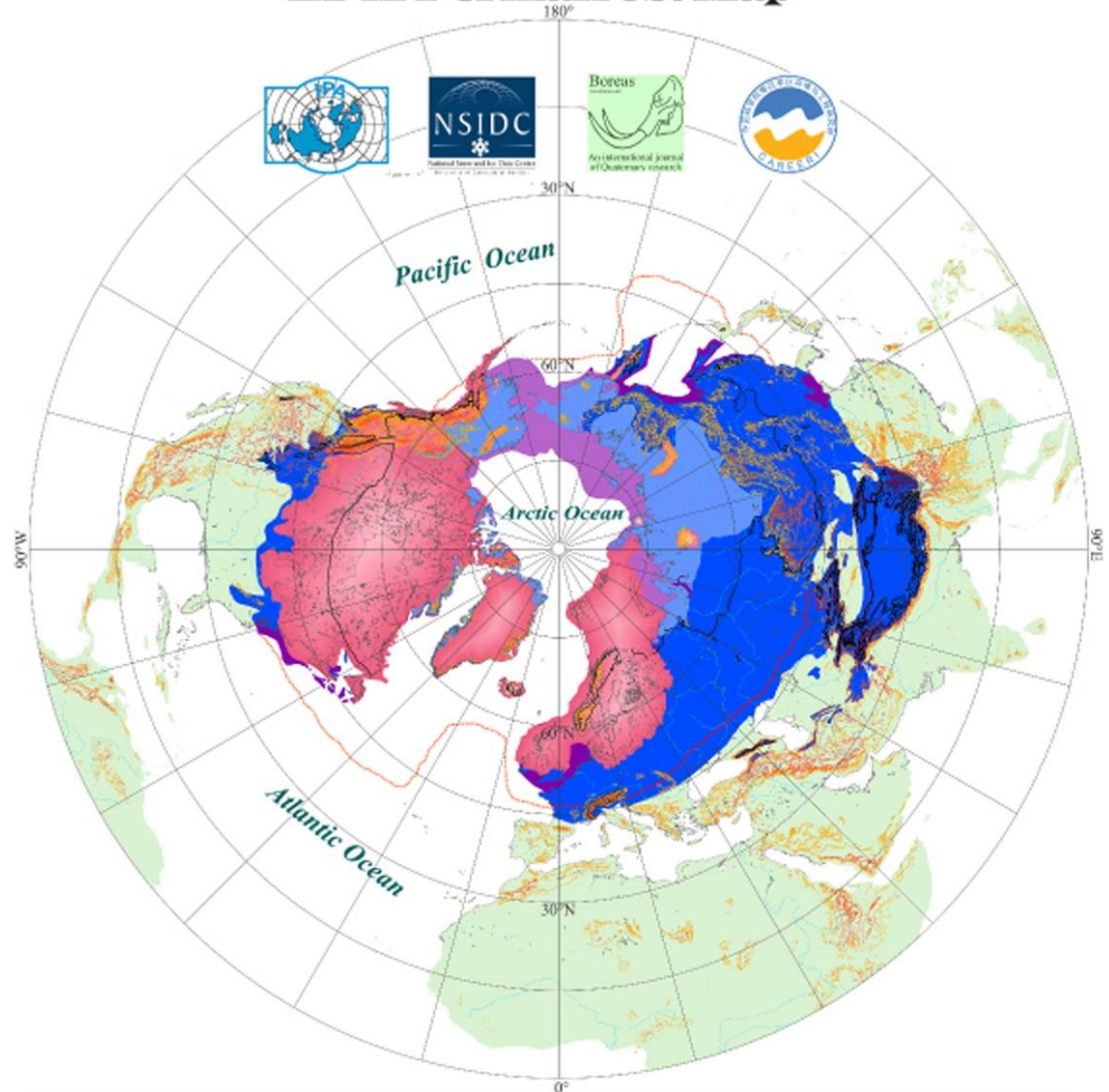
BEERTEN, K., VANDERSMISSEN, N., DEFORCE, K. and VANDENBERGHE, N. (2014), Late Quaternary (15 ka to present) development of a sandy landscape in the Mol area, Campine region, north-east Belgium. J. Quaternary Sci., 29: 433-444. <https://doi.org/10.1002/jqs.2713>

COLD CLIMATE WITH PERMAFROST



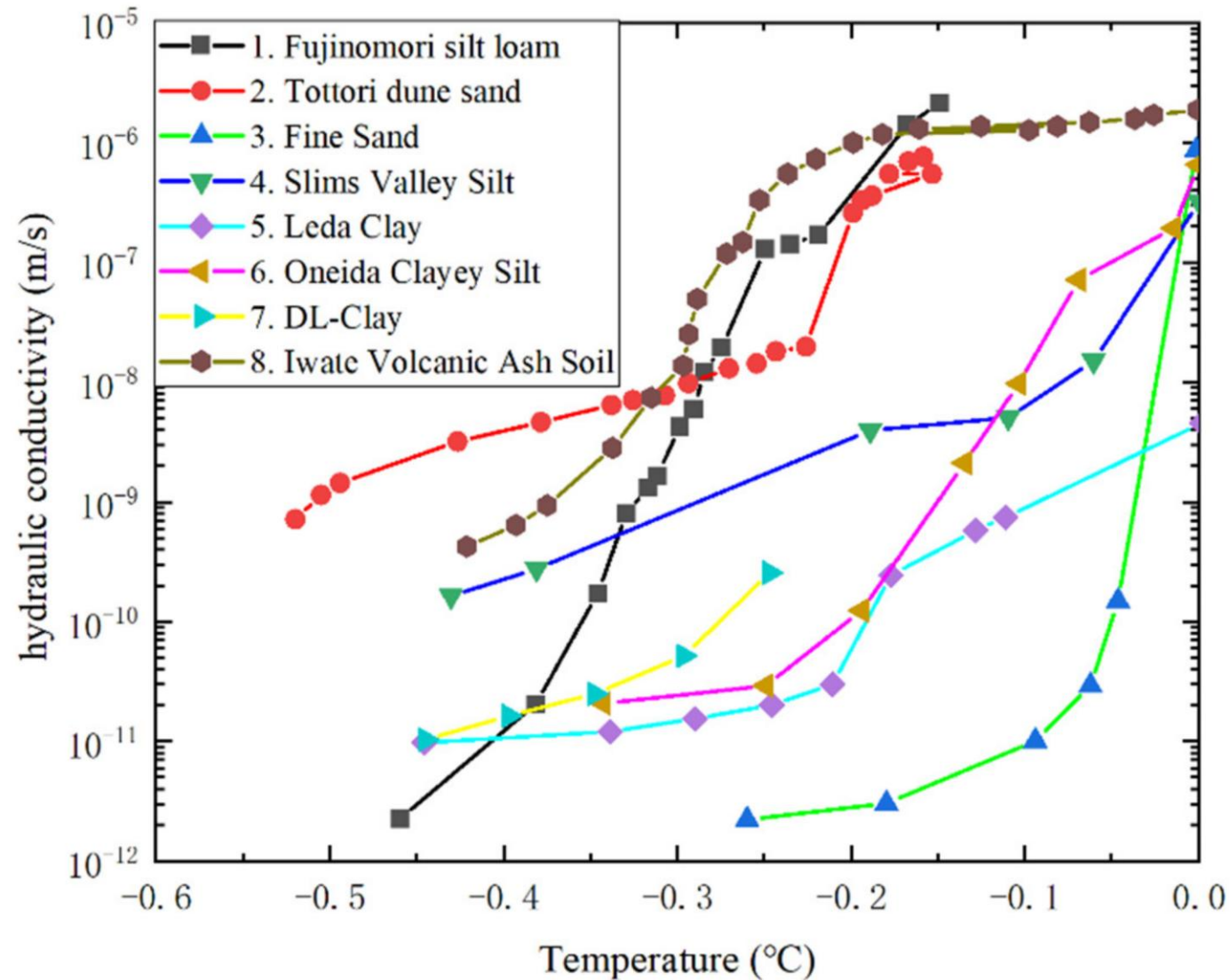
<https://www.eea.europa.eu/data-and-maps/figures/permafrost-in-the-northern-hemisphere/>

LPM Permafrost Map



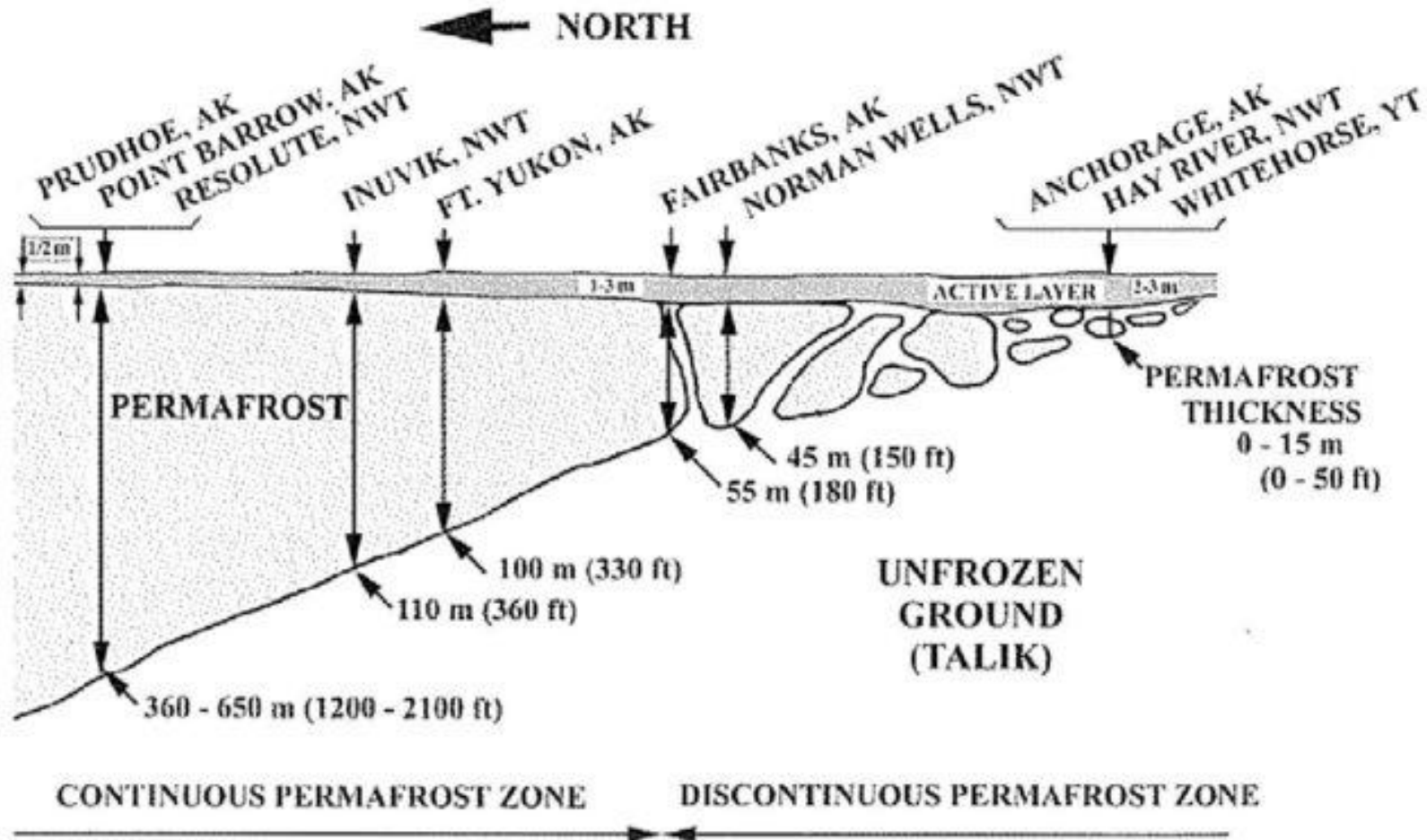
Vandenberghe et al., 2014

WHY IS THIS IMPORTANT?



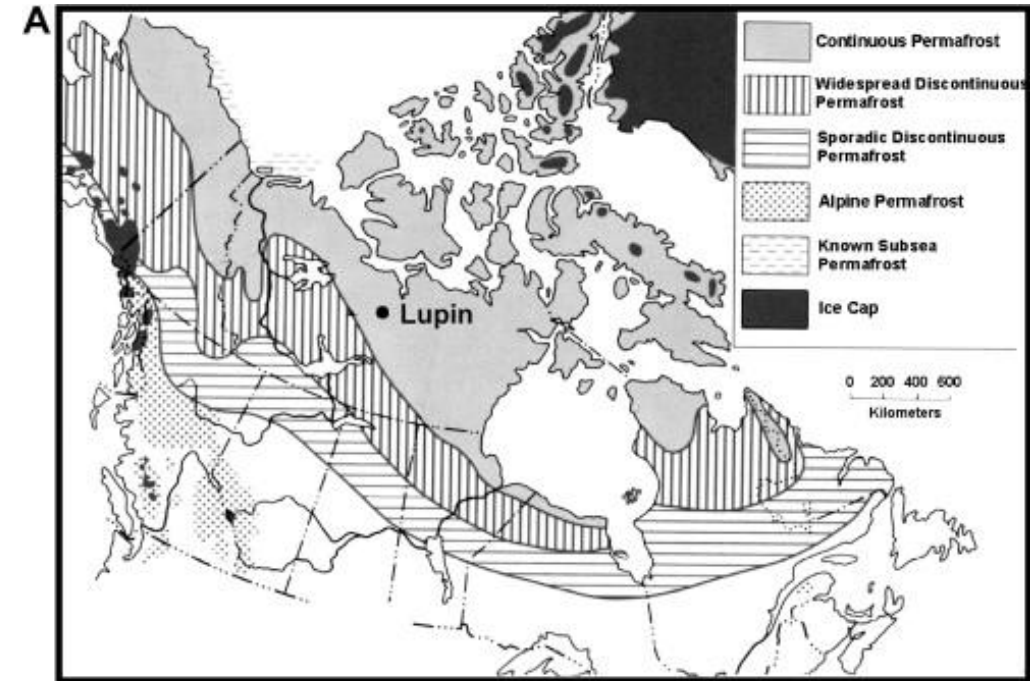
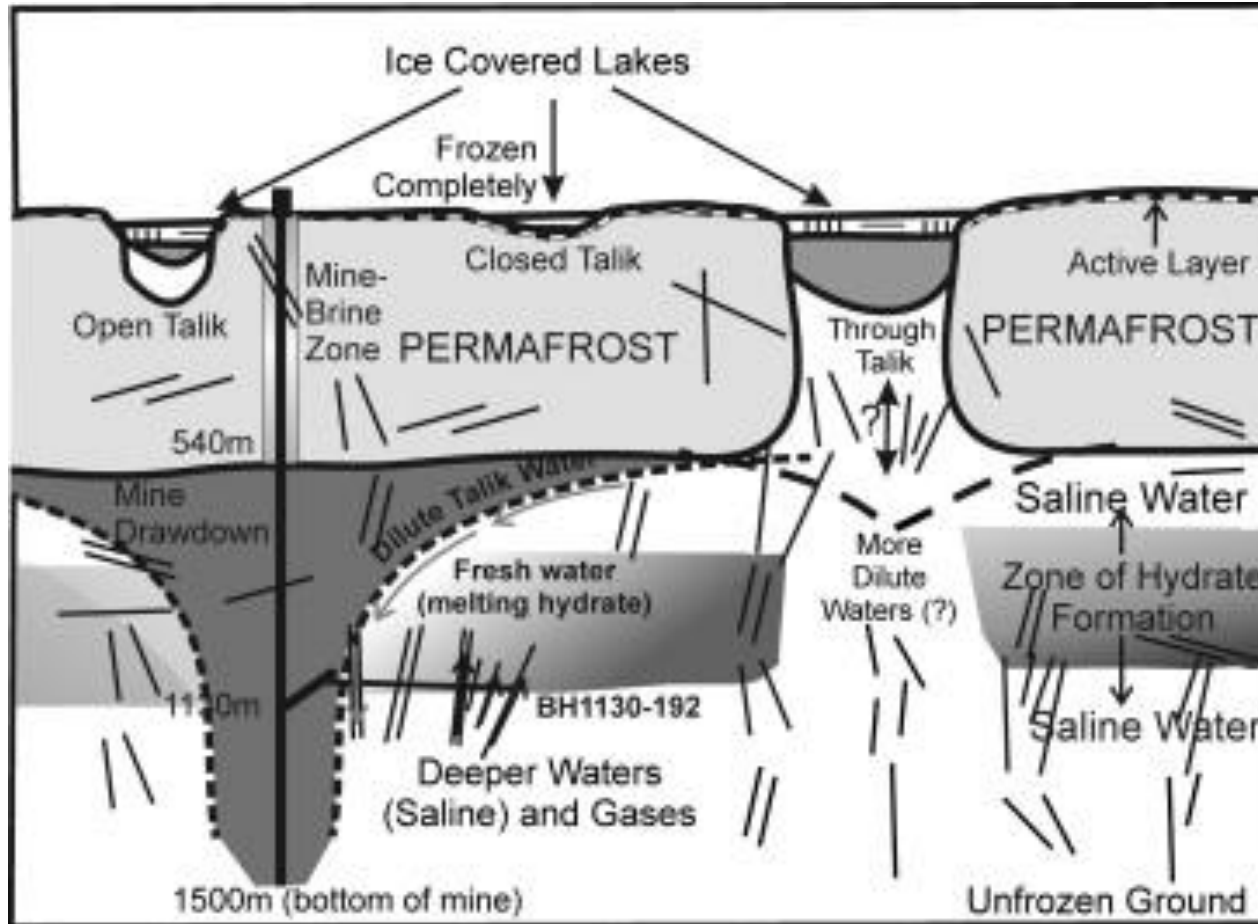
Jin H, Huang Y, Bense VF, Ma Q, Marchenko SS, Shepelev VV, Hu Y, Liang S, Spektor VV, Jin X, et al. Permafrost Degradation and Its Hydrogeological Impacts. *Water*. 2022; 14(3):372. <https://doi.org/10.3390/w14030372>

TODAY'S PERMAFROST IN NORTHERN AMERICA: DIFFERENT TYPES



Davis, 2001

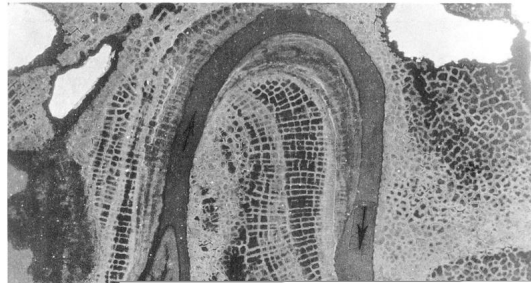
PERMAFROST THAT DEVELOPED OVER THE LAST 8000 YEARS AFTER ICE-SHEET COLLAPSE



Stotler et al., 2009

SUCH CONDITIONS CAN ALSO (RE-)APPEAR IN CURRENT TEMPERATE CLIMATES

Alaska, today



Lachenbruch, 1962

GEOL. SOC. AM., SPECIAL PAPER 70

LACHENBRUCH, PL. 1

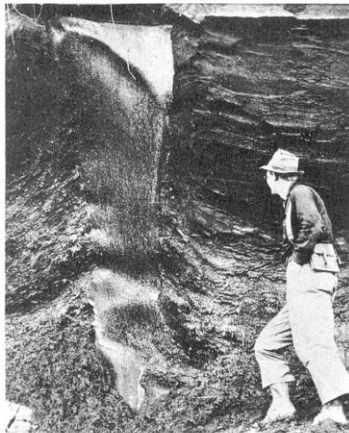
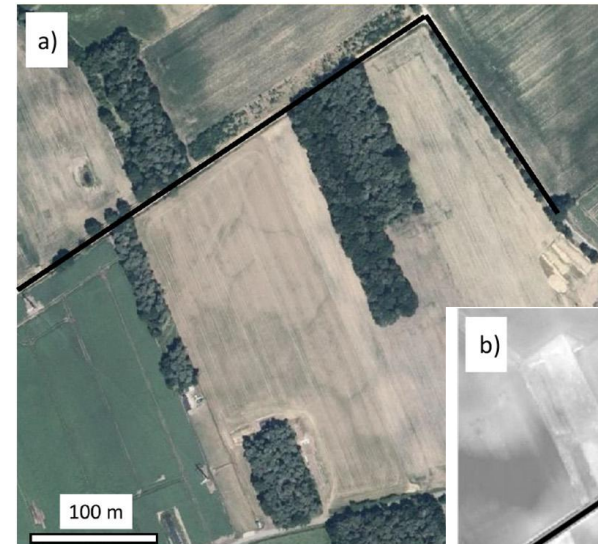


FIGURE 1

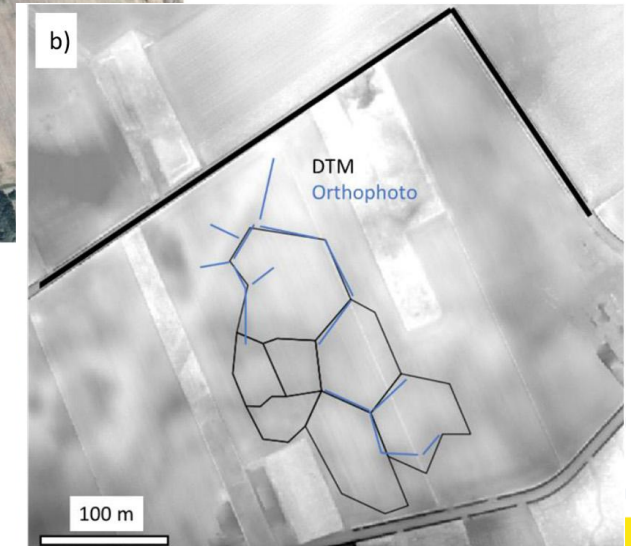


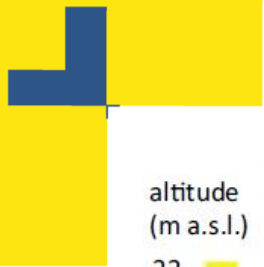
FIGURE 2

Northern Belgium, last glacial

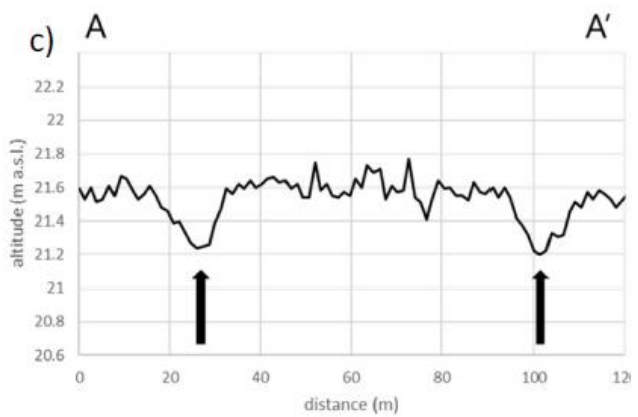
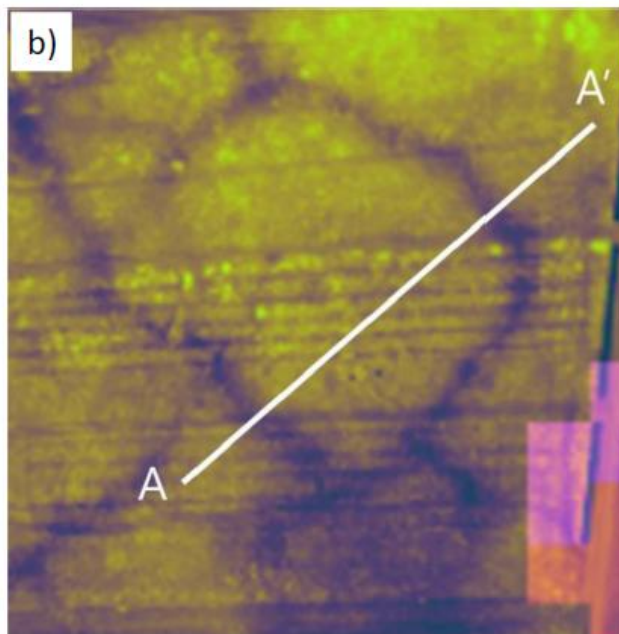
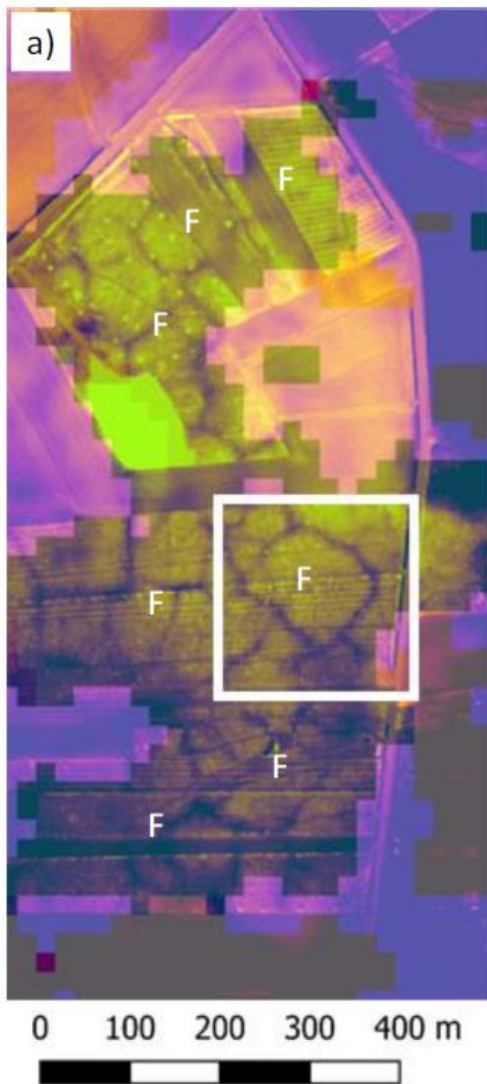


Beerten et al., 2021





altitude
(m a.s.l.)
22
21



Date

Event

WHICH TYPE OF PERMAFROST FITS WITH THESE SURFACE FEATURES? SPITSBERGEN IS A POTENTIAL ANALOGUE

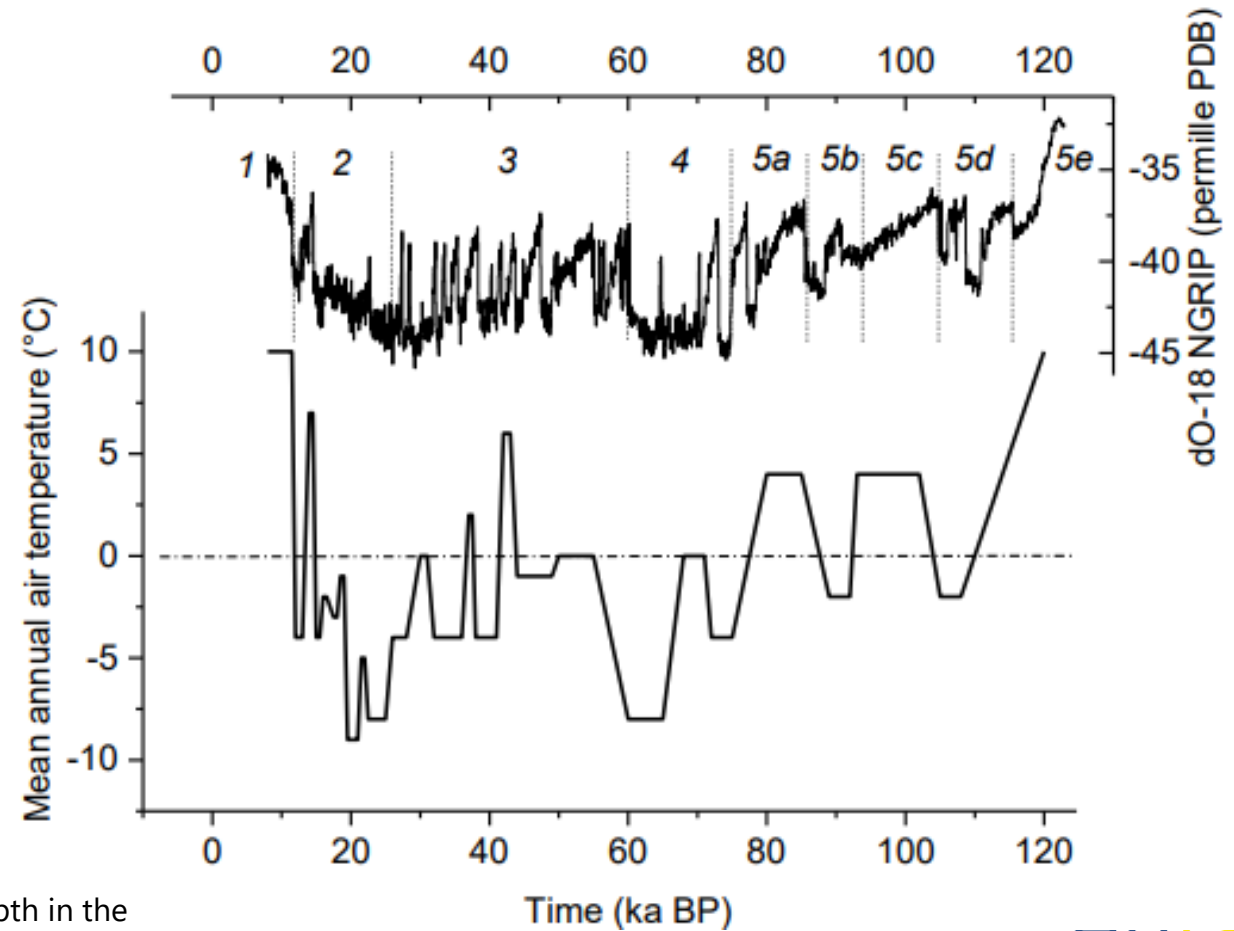
Table 2

Metrics of the analogue networks (present-day and fossil): number of polygons (N), mean area (MEAN), median area (MEDIAN), relative standard deviation (RSD), minimum area (MIN), maximum area (MAX), total number of counted intersections (N_i), percentage of 4-ray intersections (4RAY), and percentage of orthogonal intersections (ORTHO) (n/d = not determined; n/a = not applicable). For comparison, a summary of the Campine data is also included.

Site	Polygon type	N	MEAN (m ²)	MEDIAN (m ²)	RSD (%)	MIN (m ²)	MAX (m ²)	N_i	4RAY (% 4-ray inter-sections)	ORTHO (% orthogonal intersections)
Devon Island	Oriented orthogonal	93	397	386	38	119	836	112	55	97
Axel Heiberg Island	Random orthogonal	78	153	130	62	20	580	117	13	32
Barrow	Irregular mixed	135	310	274	57	93	1049	112	12	65
Prudhoe Bay	Random orthogonal	9	204	198	24	121	291	50	28	74
Sugluk Inlet, Hudson Bay, D4	Random orthogonal	17	80	59	63	30	191	33	21	79
Sugluk Inlet, Hudson Bay, D1	Random orthogonal	22	150	131	53	33	329	23	30	78
Sugluk Inlet, Hudson Bay, G5	Random orthogonal	17	173	124	83	8	504	26	11	69
Garry and Richards Island upland	Random ortho/hexagonal	21	743	723	63	214	1764	27	26	63
Garry and Richards Island lowland	Random ortho/hexagonal	53	373	307	52	166	1093	83	15	66
Svalbard Adventdalen AD1	Pentagonal, hexagonal	185	340	268	77	51	2029	n/a	10	n/a
Svalbard Adventdalen AD2	Pentagonal, hexagonal	241	771	594	69	70	3329	n/a	4	n/a
Svalbard Adventdalen AD3	Pentagonal, hexagonal	103	559	447	68	85	2101	n/a	7	n/a
Svalbard Adventdalen AD4	Hexagonal on dry terrace and orthogonal down the slope	159	507	83	65	75	1786	n/a	9	n/a
West Flanders	Mixed	145	104	58	112	4	760	178	18	46
France	n/d	n/d	179	n/d	n/d	63	380	n/a	n/a	n/a
Campine	Mixed	210	3128	2912	54	454	9401	243	20	31

FROM PRESENT-DAY AND PAST ANALOGUES TO FUTURE PERMAFROST DEVELOPMENT (THE NETHERLANDS)

- MIS5: pollen data
- MIS4: periglacial deformation phenomena in the subsoil
- MIS3: periglacial features + pollen data
- MIS2: periglacial features

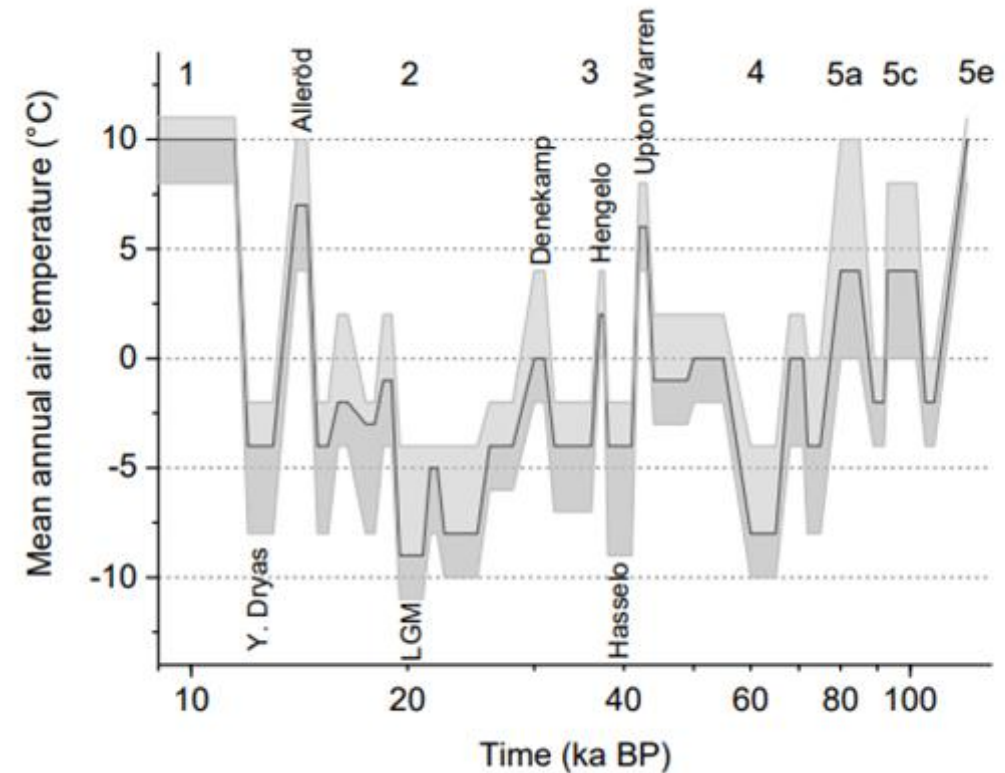


Govaerts, J., Beerten, K., & ten Veen, J. (2016). Weichselian permafrost depth in the Netherlands: a comprehensive uncertainty and sensitivity analysis. *The Cryosphere*, 10, 2907-2922. <https://doi.org/10.5194/tc-10-2907-2016>

PAST GLACIAL CYCLE AS AN ANALOGUE FOR PERMAFROST EVOLUTION DURING A NEXT GLACIAL PHASE: UPPER AND LOWER BOUNDS

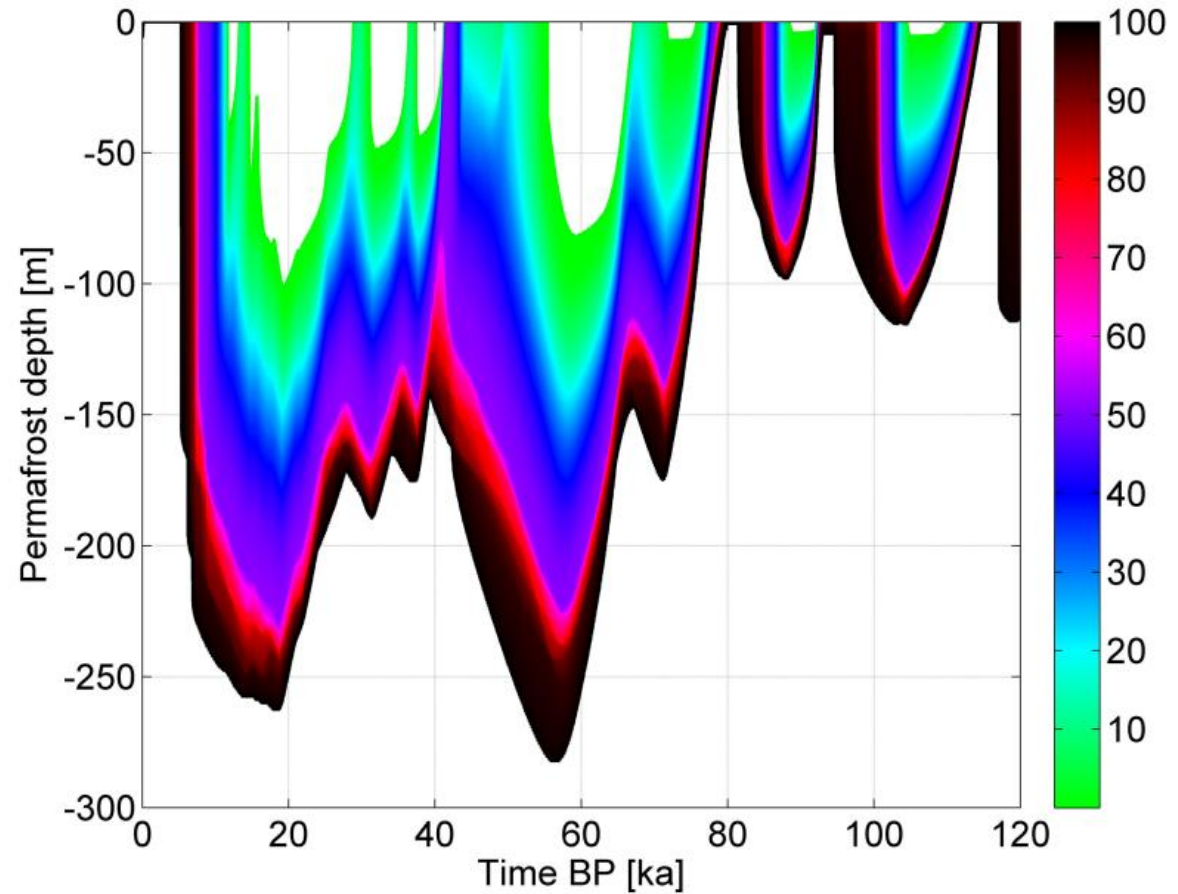
- **Different sources of uncertainty**

- reliability of the palaeotemperature proxy
- transferability towards a future glacial climatic cycle
- temperature gradients across the country
- atmosphere–soil temperature coupling



STOCHASTIC UNCERTAINTY ANALYSIS OF NATION-WIDE PERMAFROST PENETRATION DEPTH

- Upper boundary condition: temperature
- Lower boundary condition: geothermal heat flux
- Subsoil properties
 - Density
 - Porosity
 - Specific heat
 - Thermal conductivity



NORTHERN LATITUDES

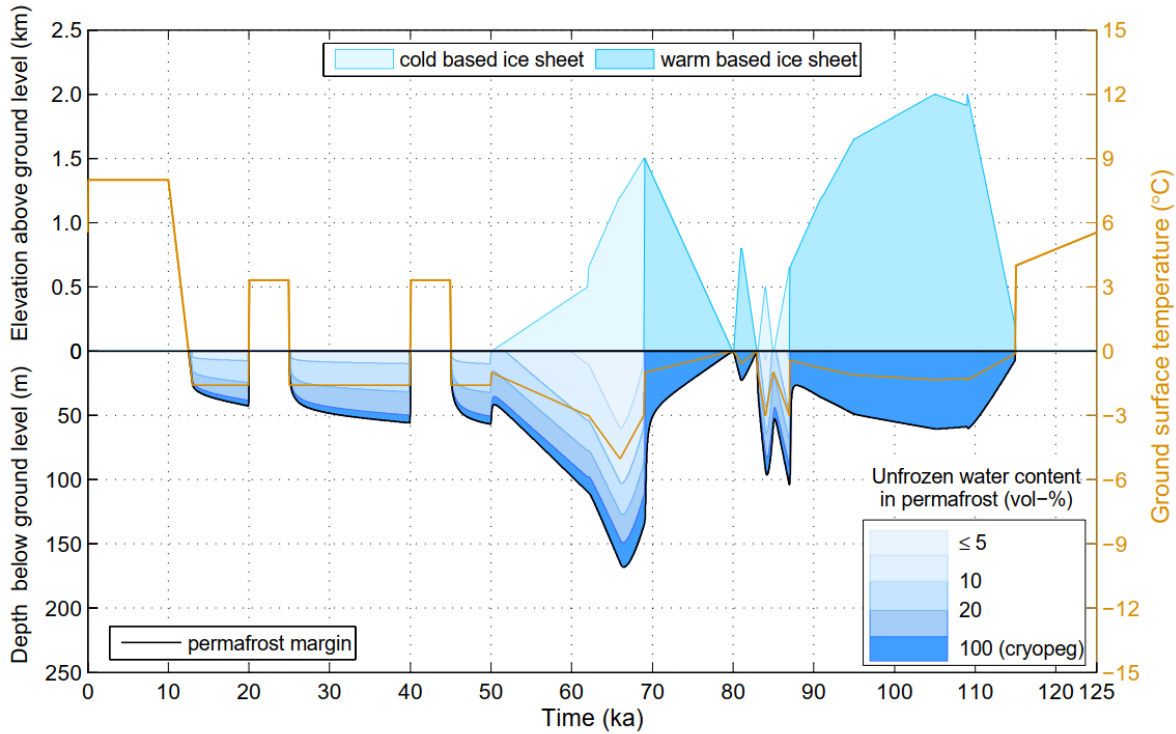


Figure 4-1. Evolution of permafrost and unfrozen water content in the permafrost at Olkiluoto calculated for the Weichselian-R scenario considering vegetation and snow cover.

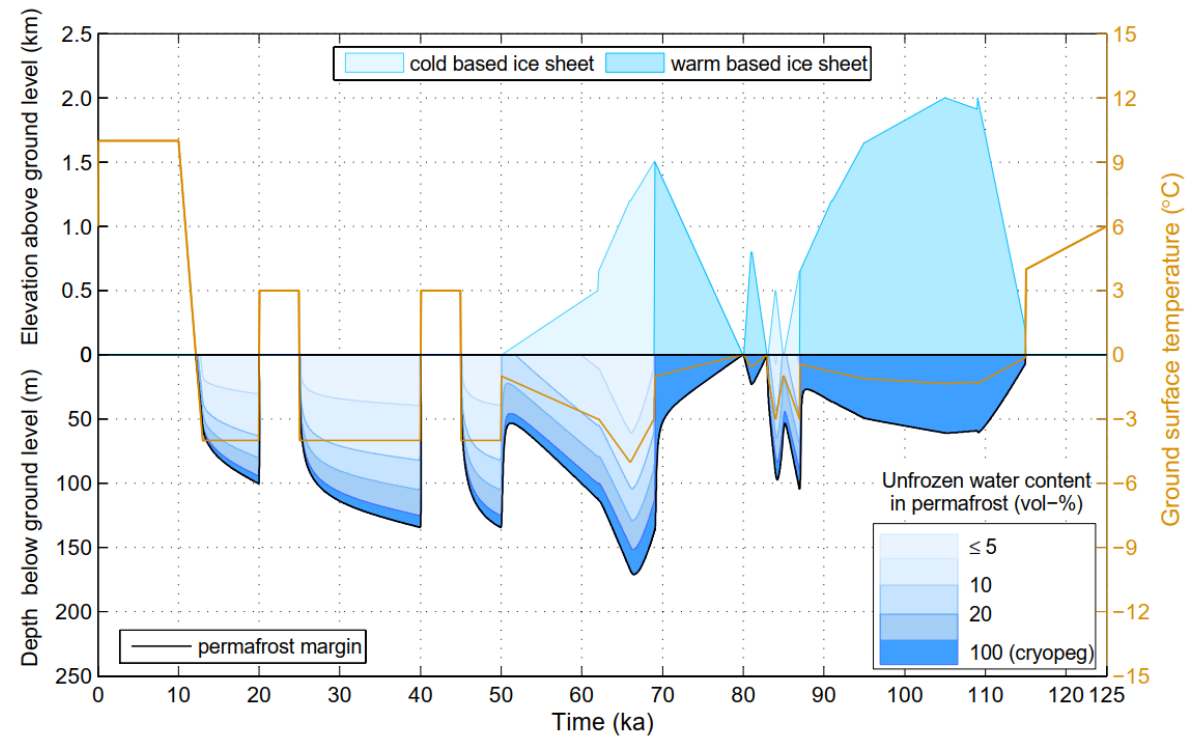
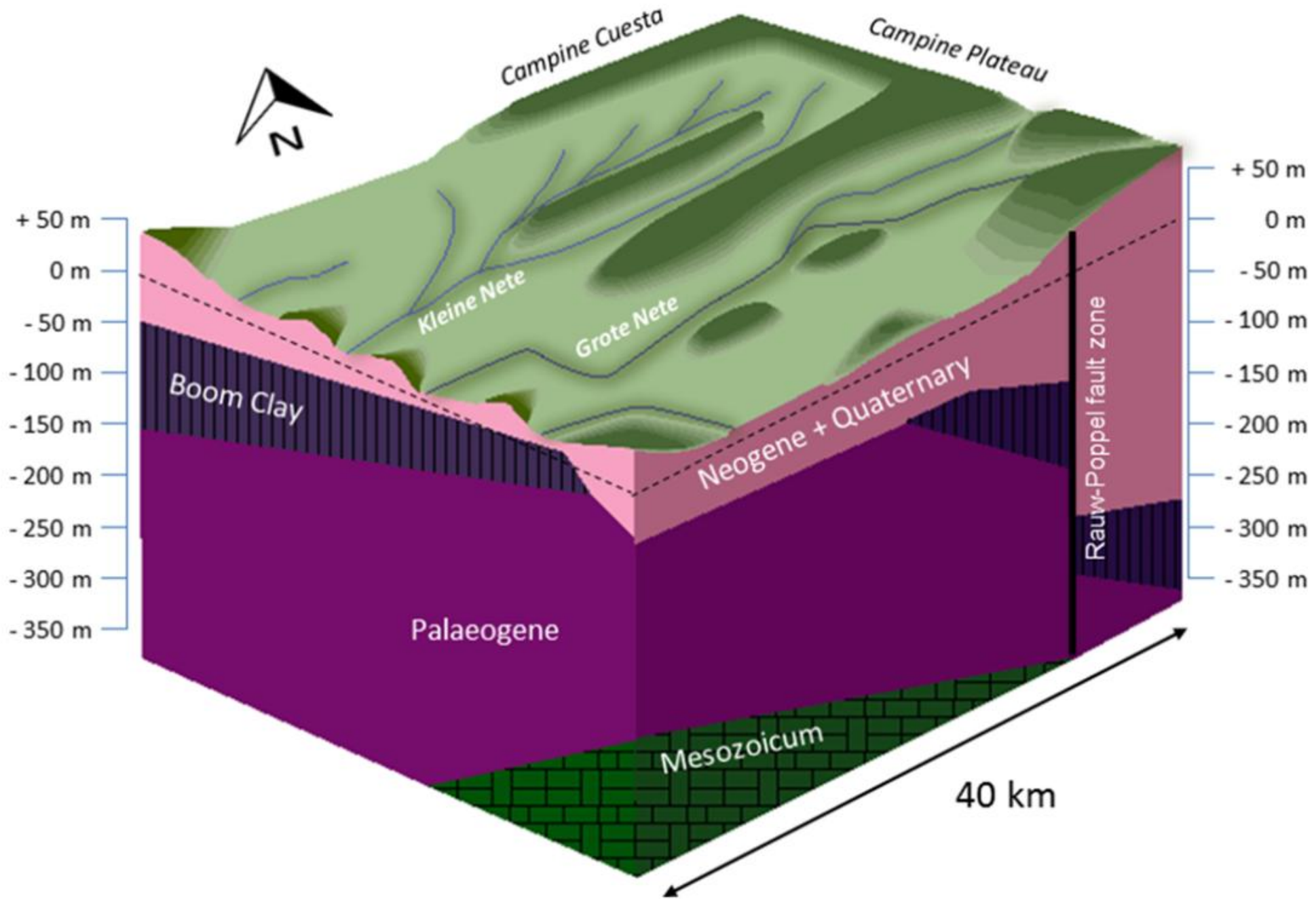
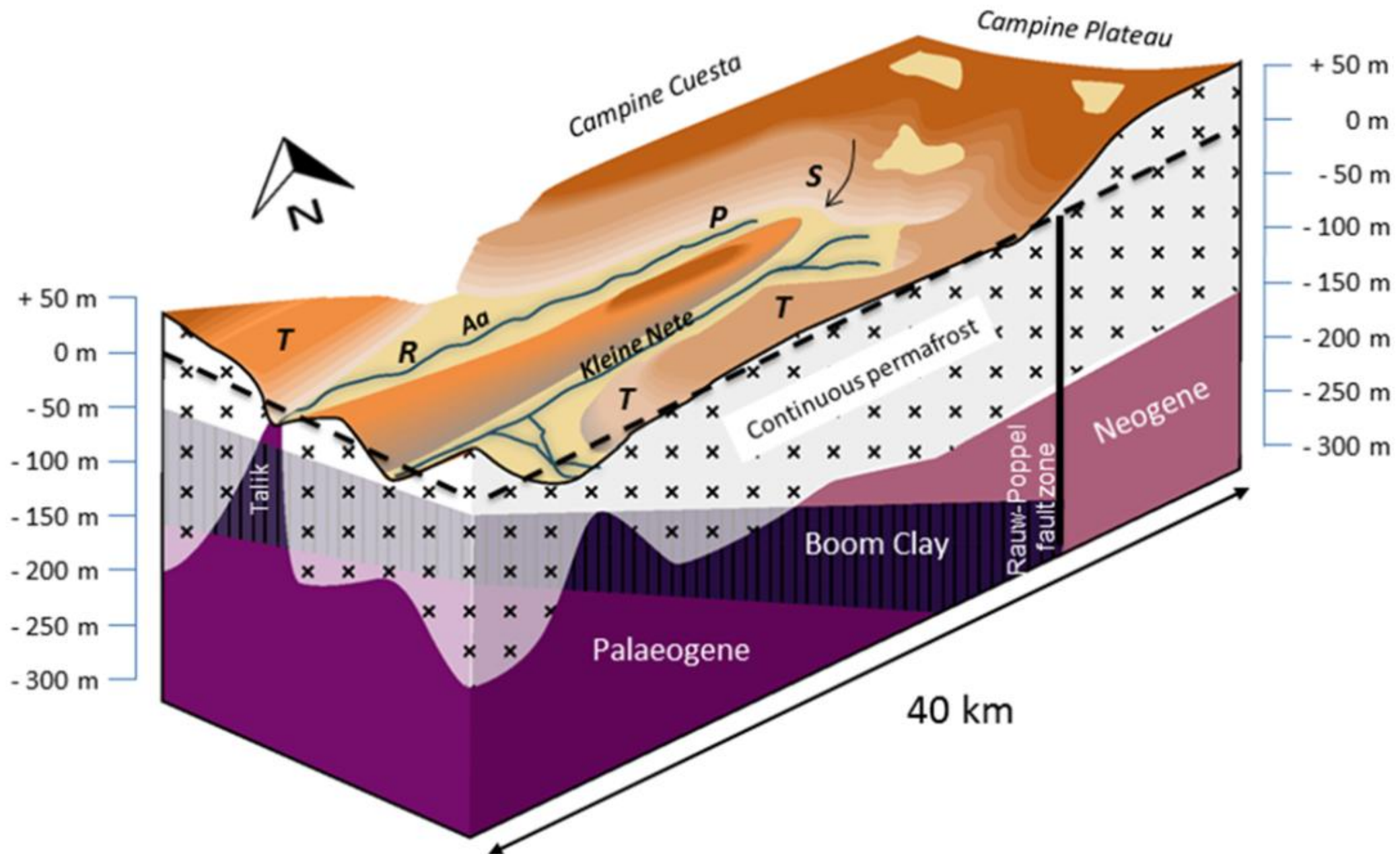


Figure 4-2. Evolution of permafrost and unfrozen water content in the permafrost at Olkiluoto calculated for the Weichselian-R scenario considering no vegetation and no snow cover.

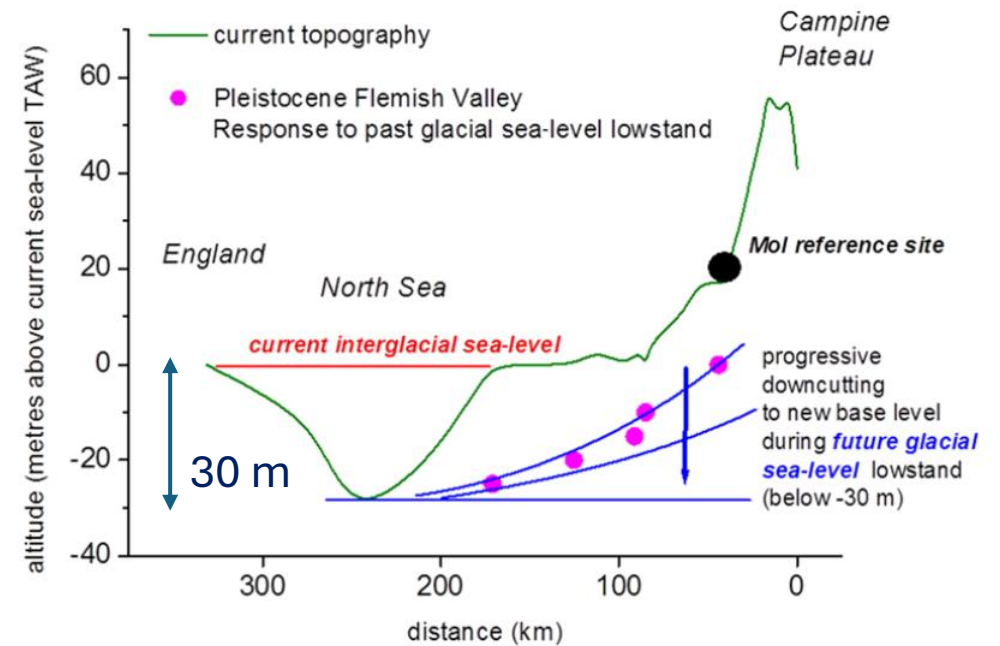
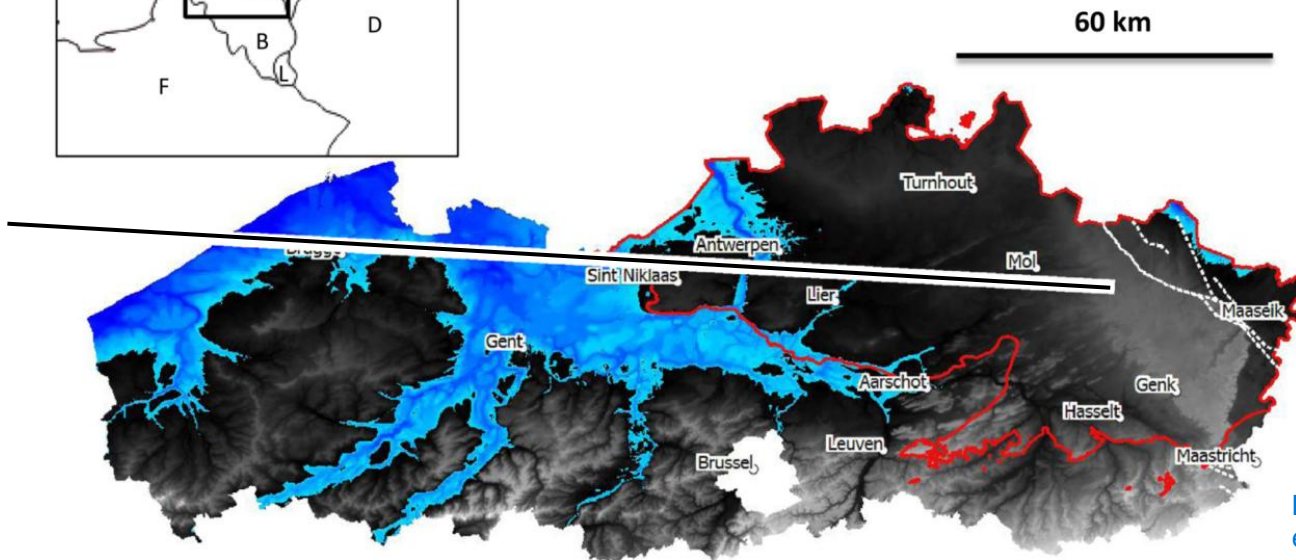
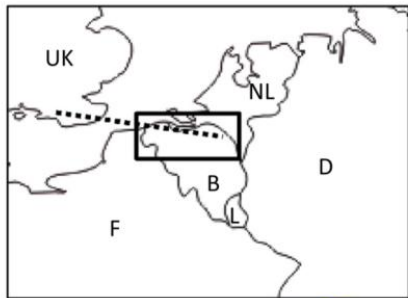
Hartikainen, 2006. POSIVA.





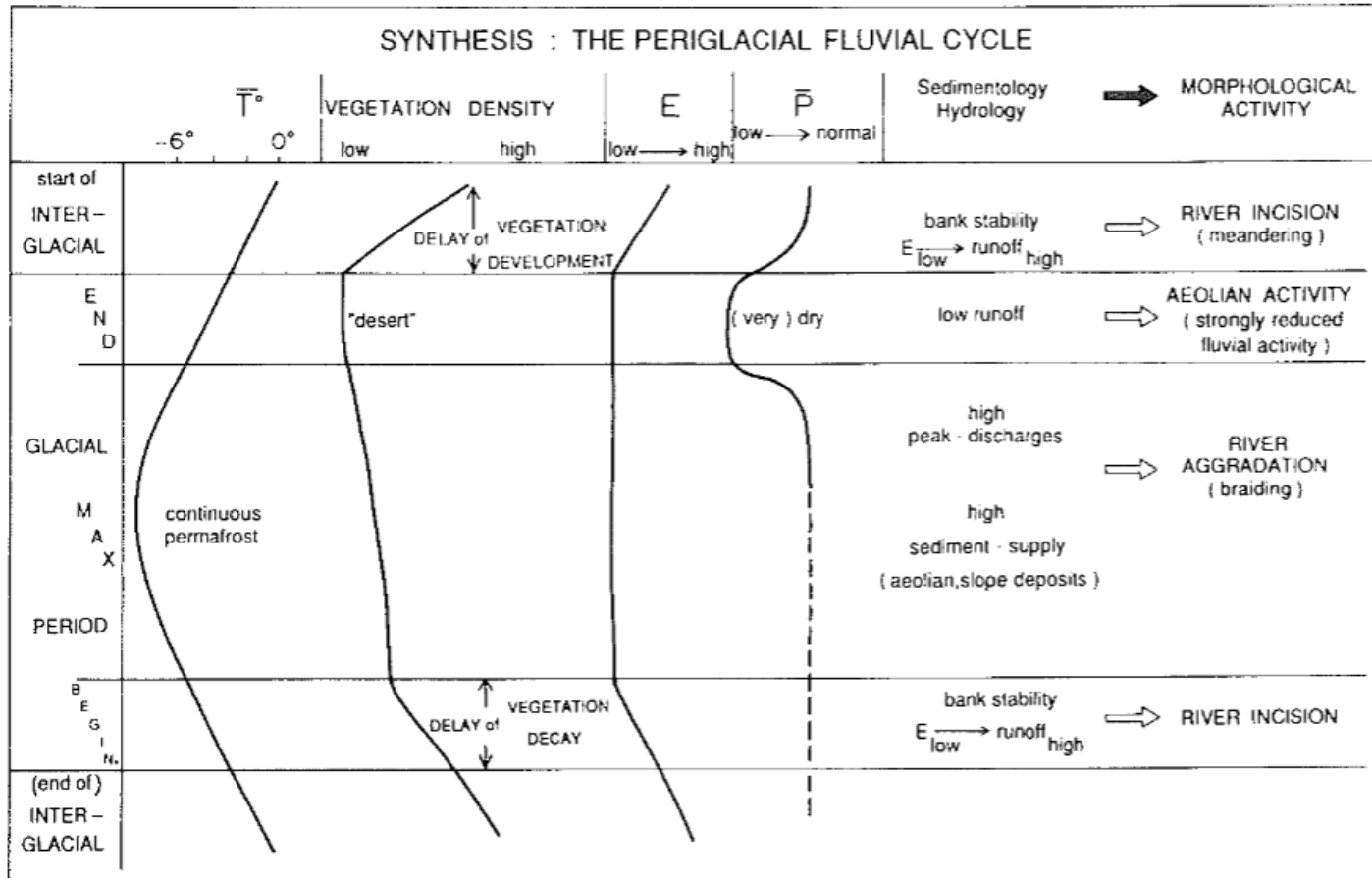
IN THIS AREA, NON-GLACIAL (FLUVIAL) EROSION CAN NOT GO DEEPER THAN -30 M BELOW CURRENT SEA LEVEL → THIS IS THE SEA FLOOR OF THE ENGLISH CHANNEL

- Safety function: isolation



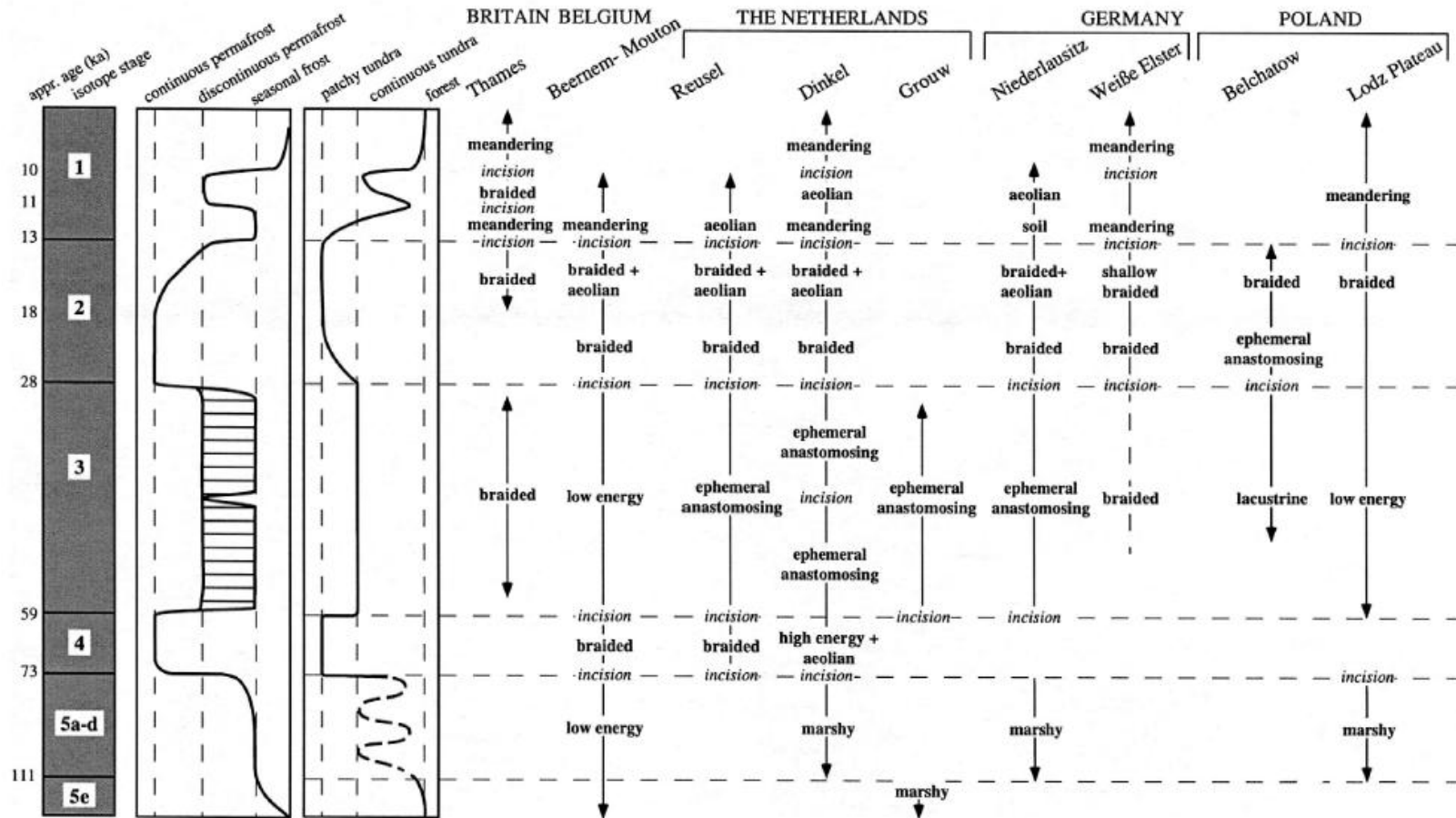
Beerten, K., De Craen, M., & Leterme, B. (2014). Long-term evolution of the surface environment of the Campine area, northeastern Belgium: first assessment. *Journal of the Geological Society*, 400, 33-51. <https://doi.org/10.1144/SP400.23>

HOW DO RIVERS ERODE IN WARM-COLD-WARM CYCLES? (NOT FOR THE NEXT 50,000 YEARS?)



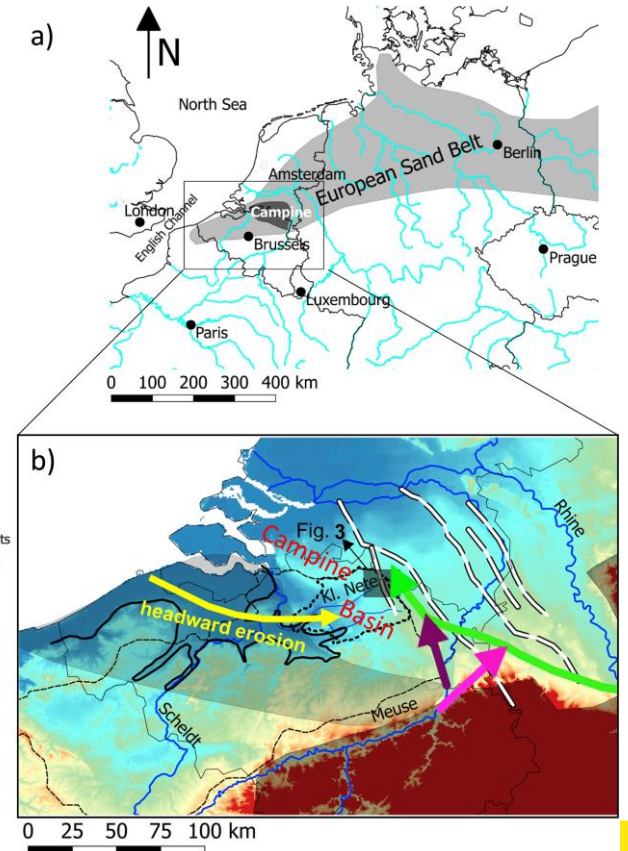
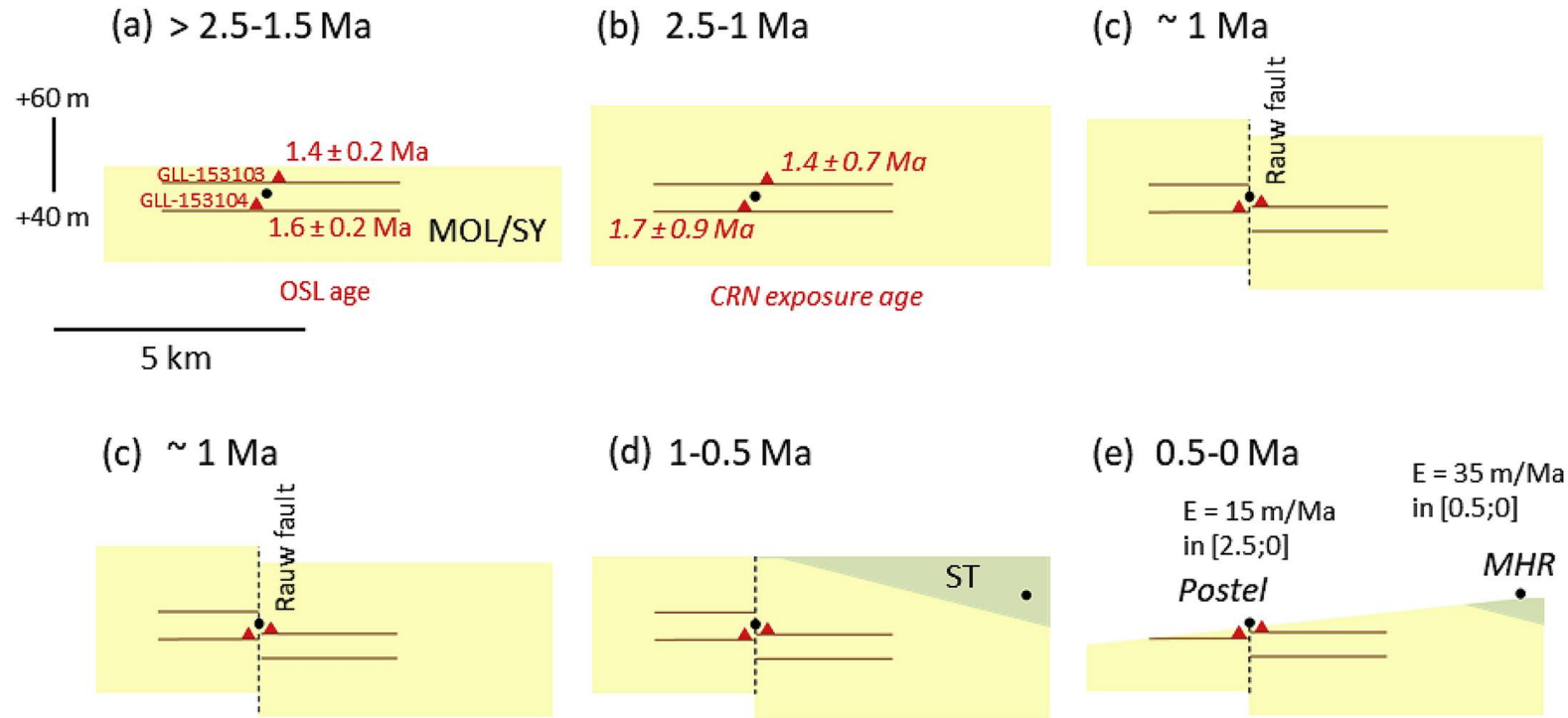
Vandenbergh, J., 1993

THIS LANDSCAPE INSTABILITY AT COLD-WARM AND WARM-COLD TRANSITIONS IS SEEN EVERYWHERE IN LOWLAND EUROPE



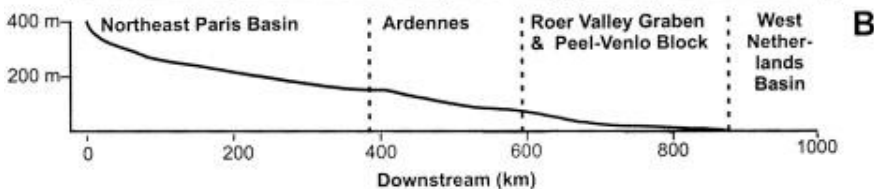
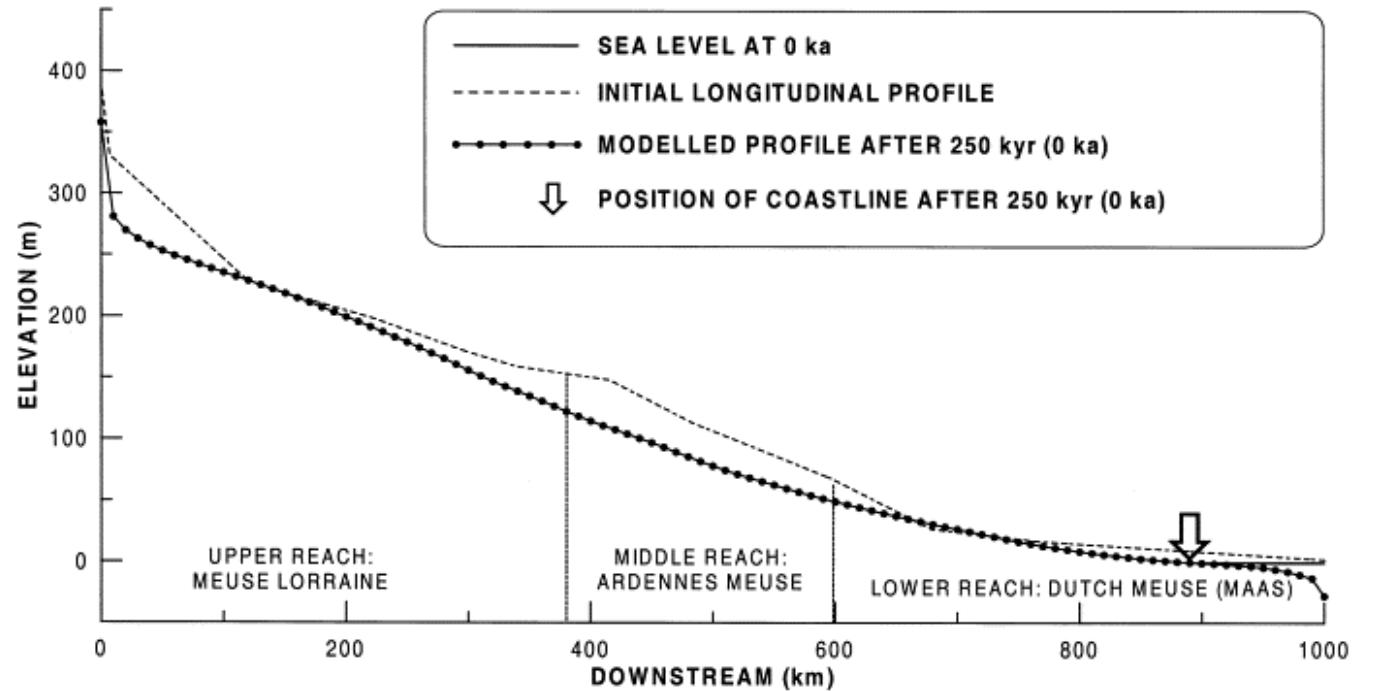
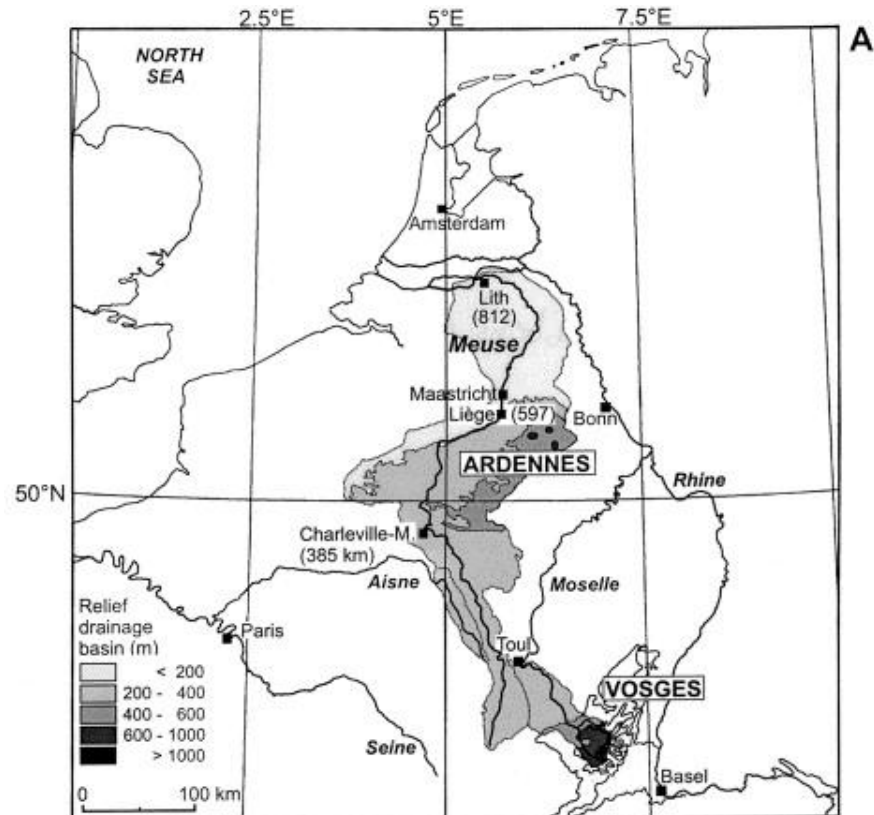
Mol et al., 2001

LARGE-SCALE NON-GLACIAL DENUDATION: HOW FAST?

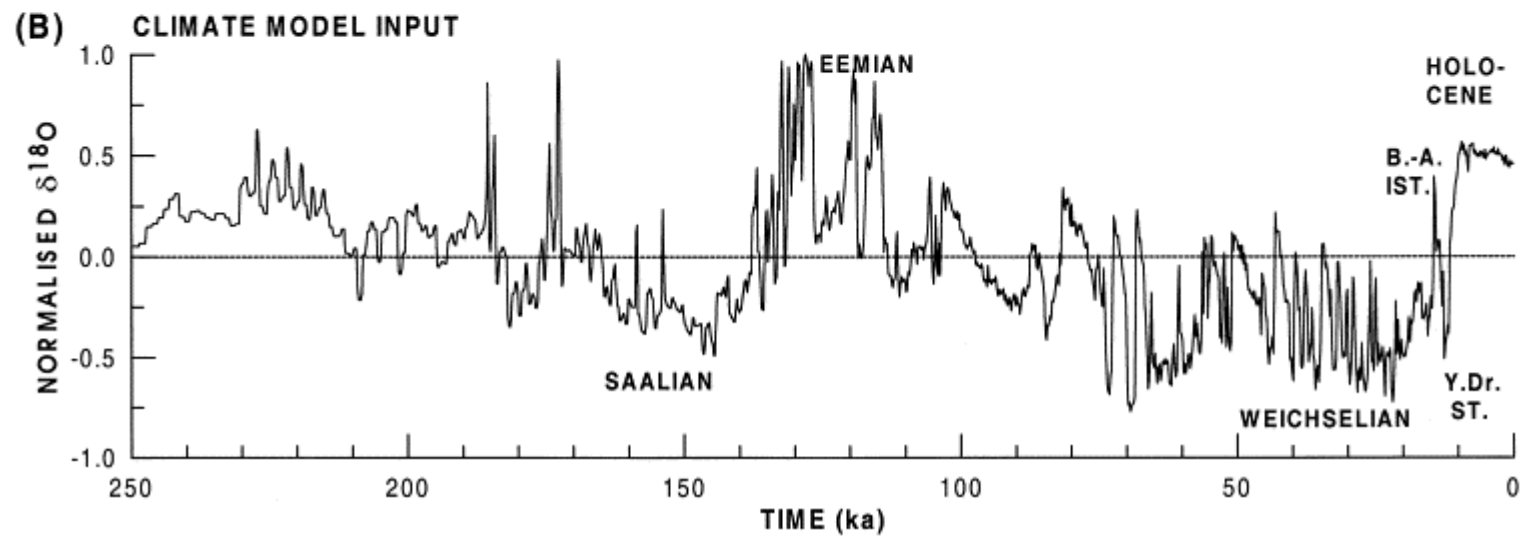
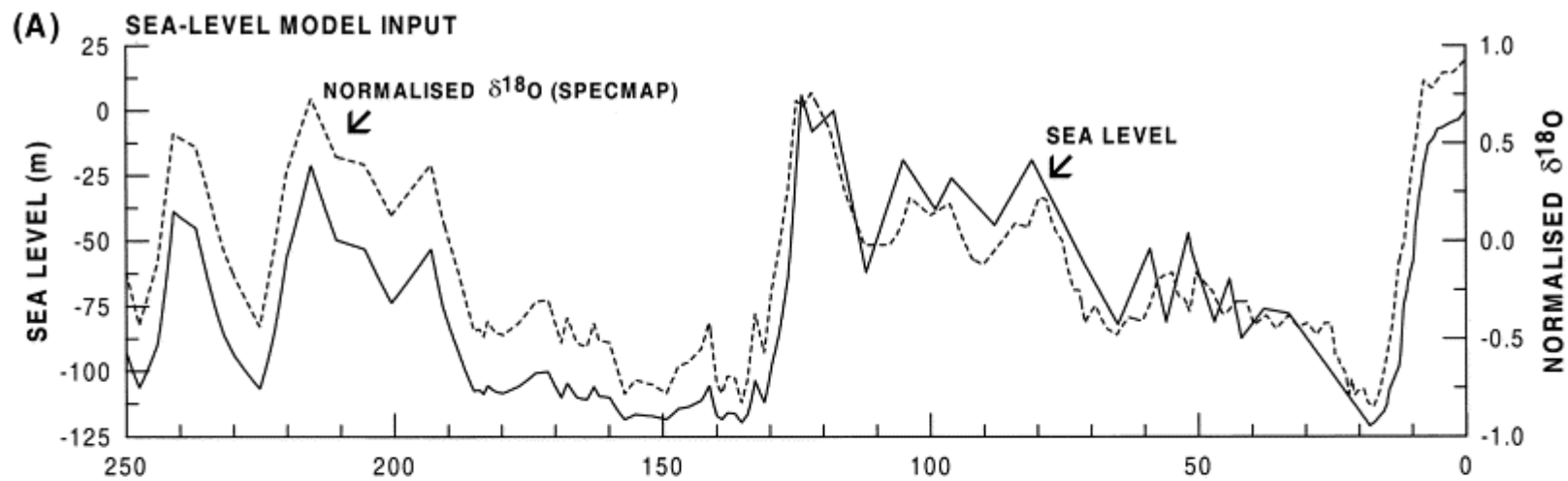


Koen Beerten, Koen Verbeeck, Eric Laloy, Veerle Vanacker, Dimitri Vandenberghe, Marcus Christl, Johan De Grave, Laurent Wouters, Electron spin resonance (ESR), optically stimulated luminescence (OSL) and terrestrial cosmogenic radionuclide (TCN) dating of quartz from a Plio-Pleistocene sandy formation in the Campine area, NE Belgium, Quaternary International, Volume 556, 2020, Pages 144-158, ISSN 1040-6182, <https://doi.org/10.1016/j.quaint.2020.06.011>

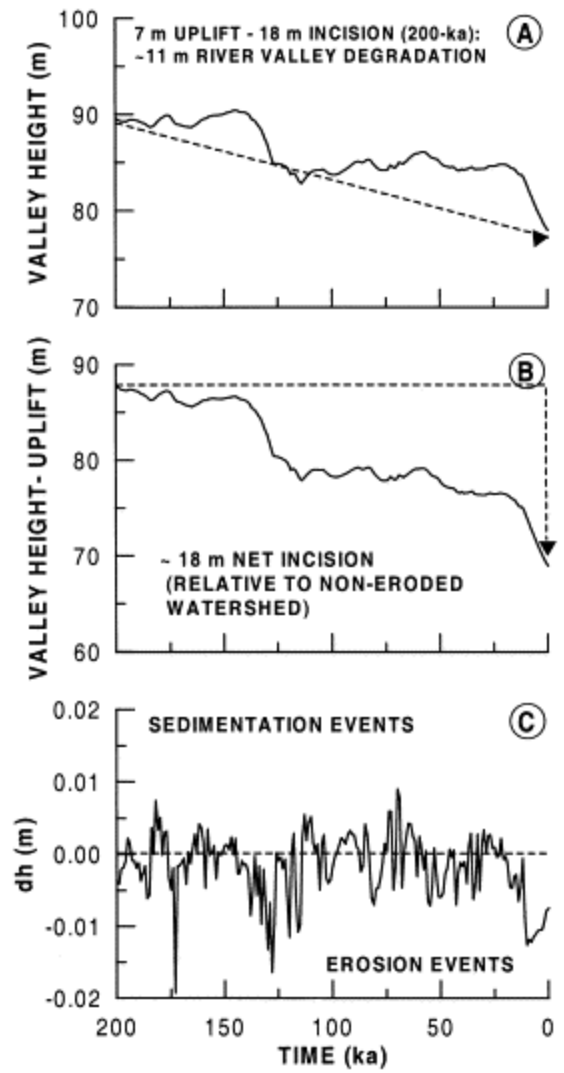
DEVELOPMENT OF RIVER PROFILES UNDER CLIMATE AND SEA-LEVEL CHANGE



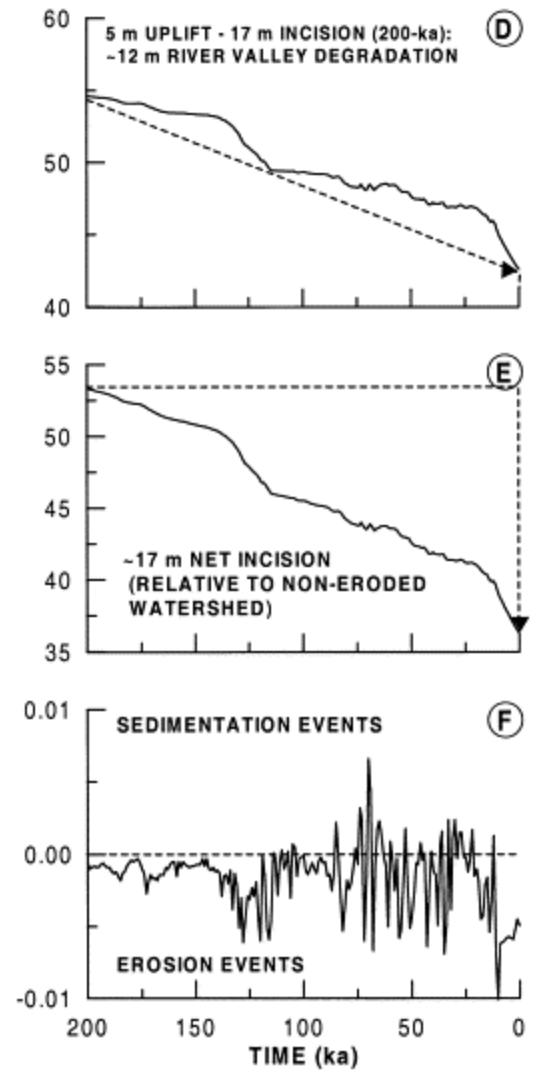
L.A. Tebbens, A. Veldkamp, J.J. Van Dijke, J.M. Schoorl,
 Modeling longitudinal-profile development in response to Late
 Quaternary tectonics, climate and sea-level changes: the River Meuse,
 Global and Planetary Change,
 Volume 27, Issues 1–4,
 2000, Pages 165-186



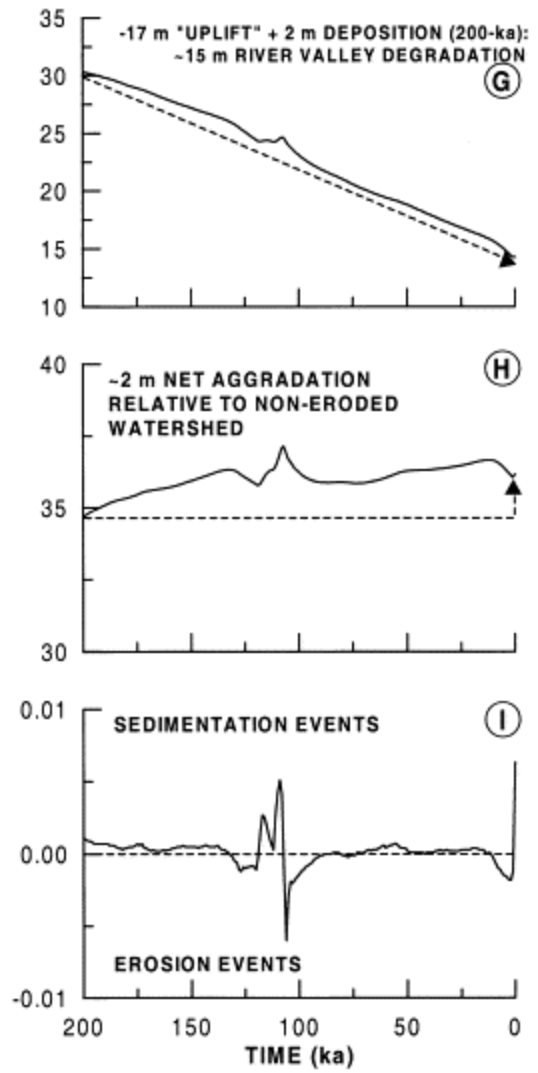
CENTRAL ARDENNES AREA (500-km)

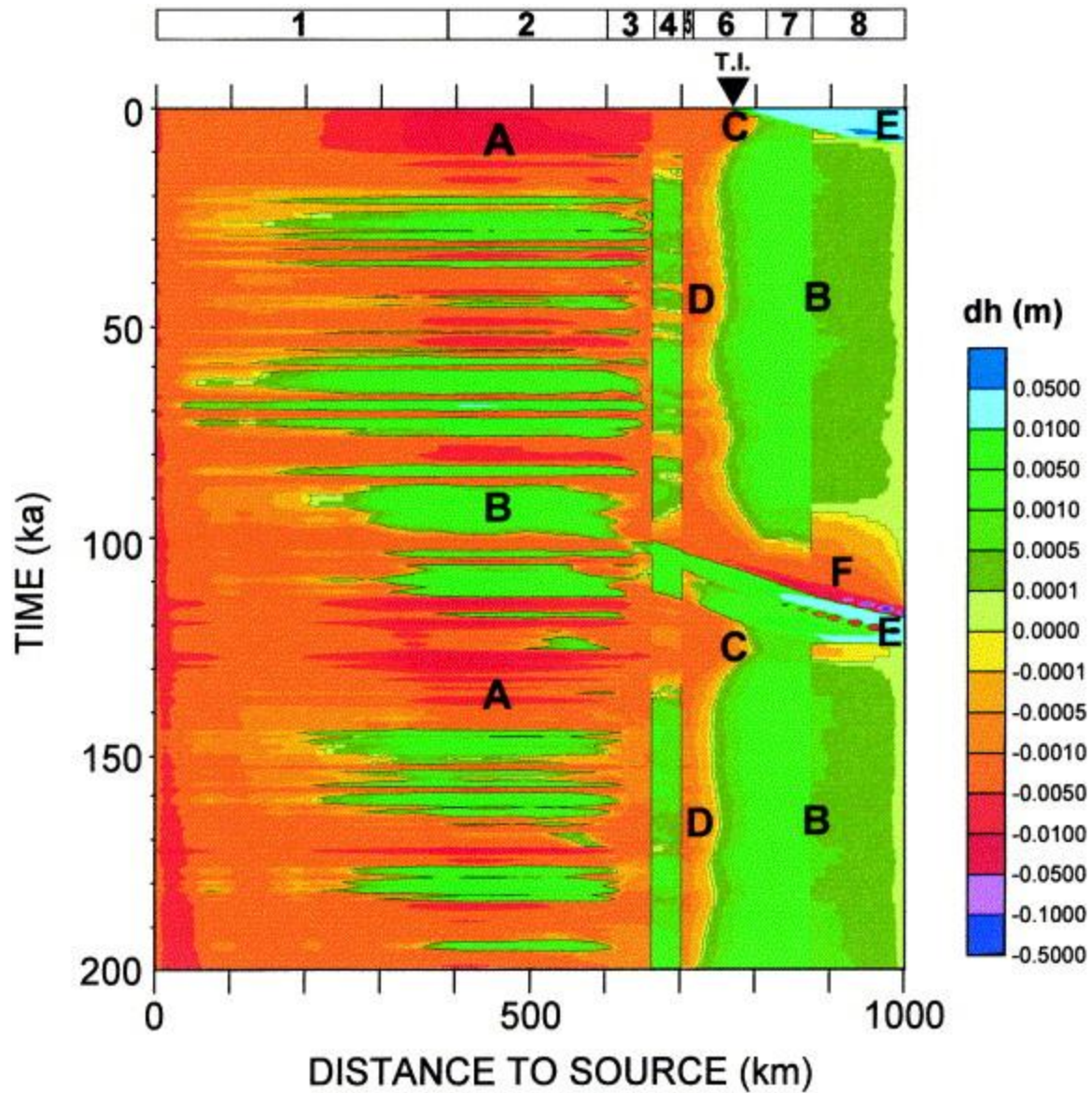


TERRACE FLIGHT AREA (627-km)



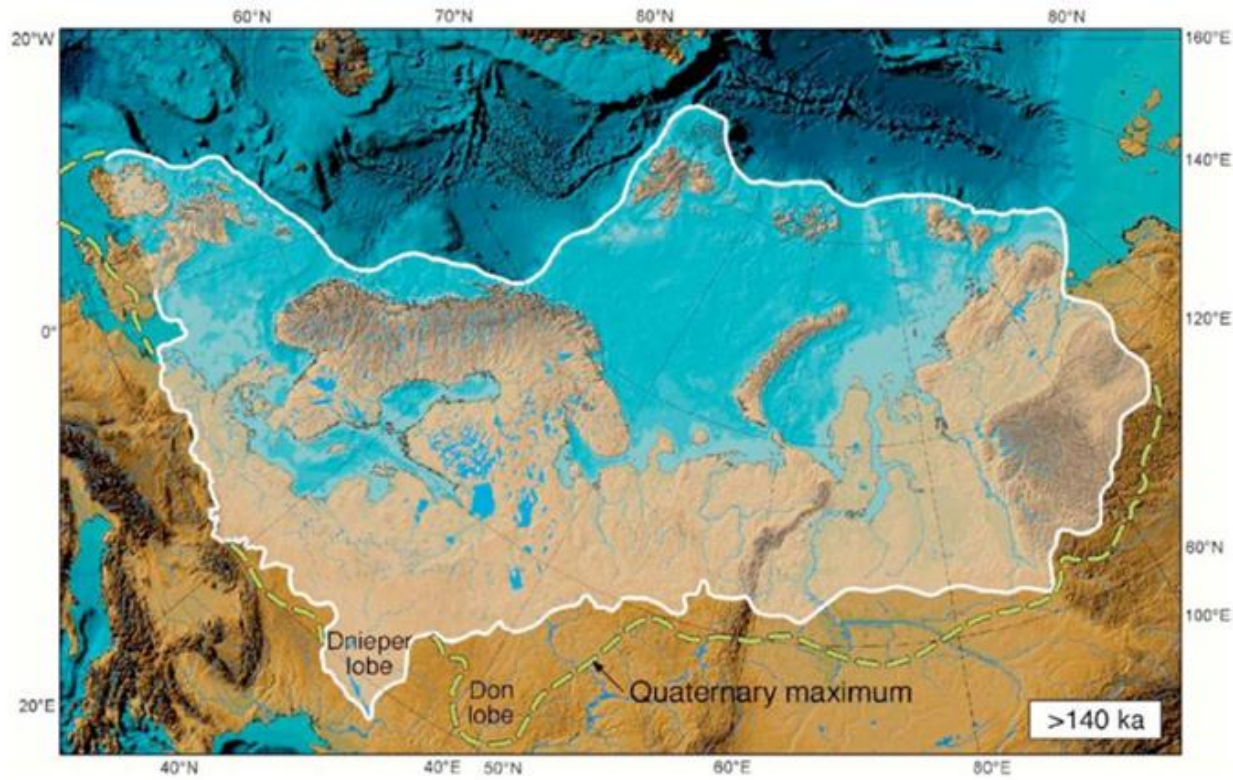
VENLO BLOCK AREA (762-km)



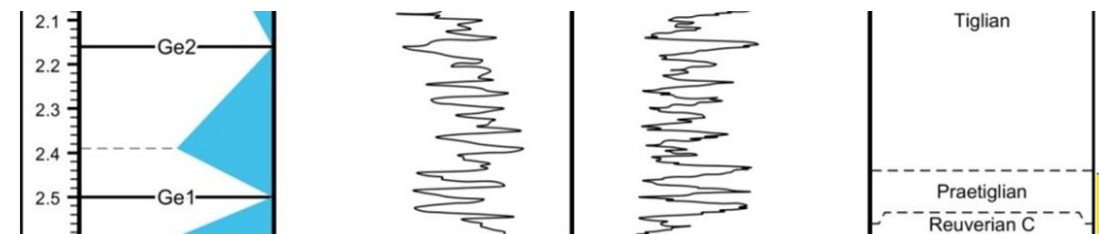
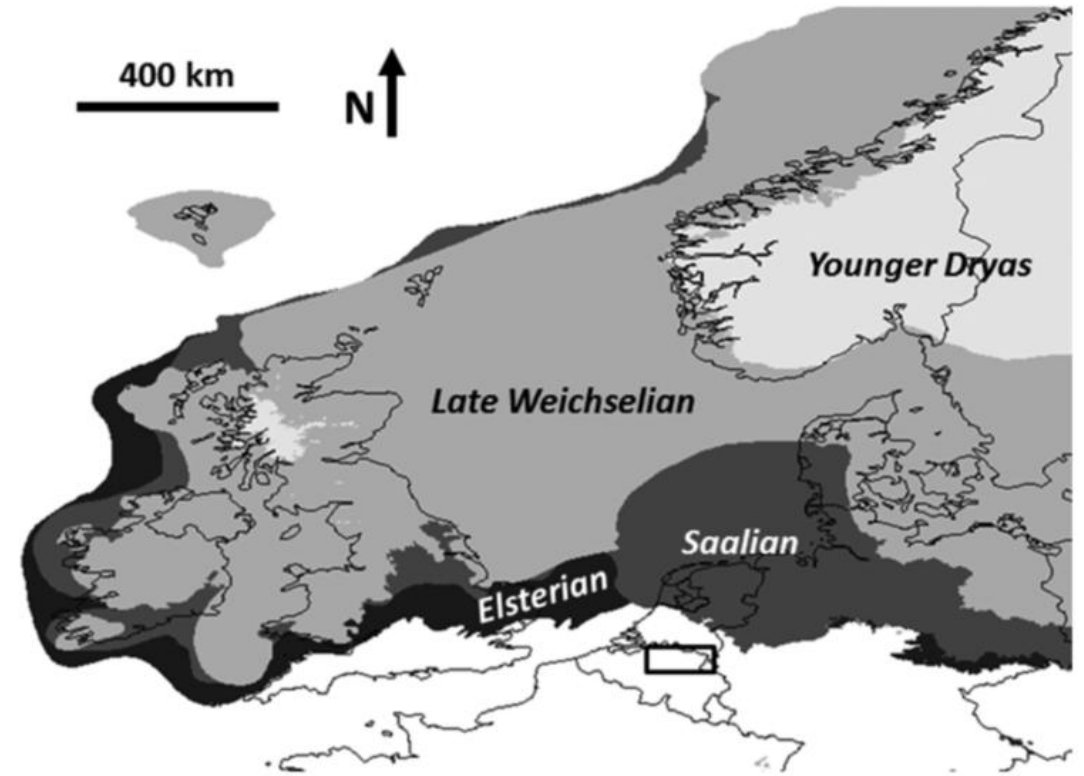
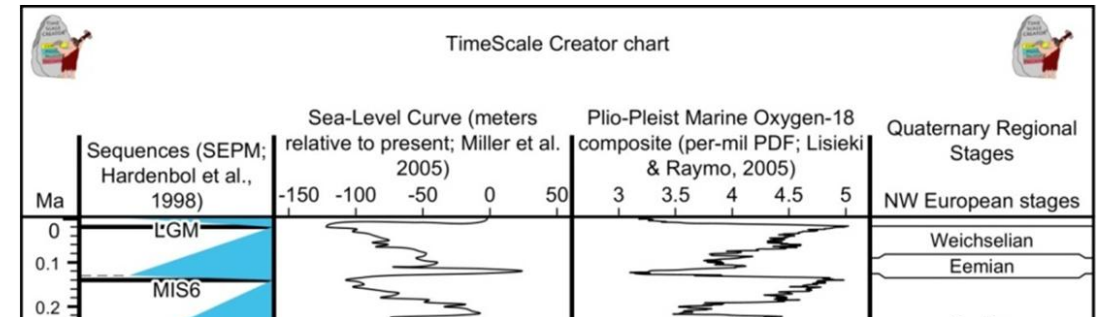




COLD CLIMATE WITH GLACIAL ADVANCE

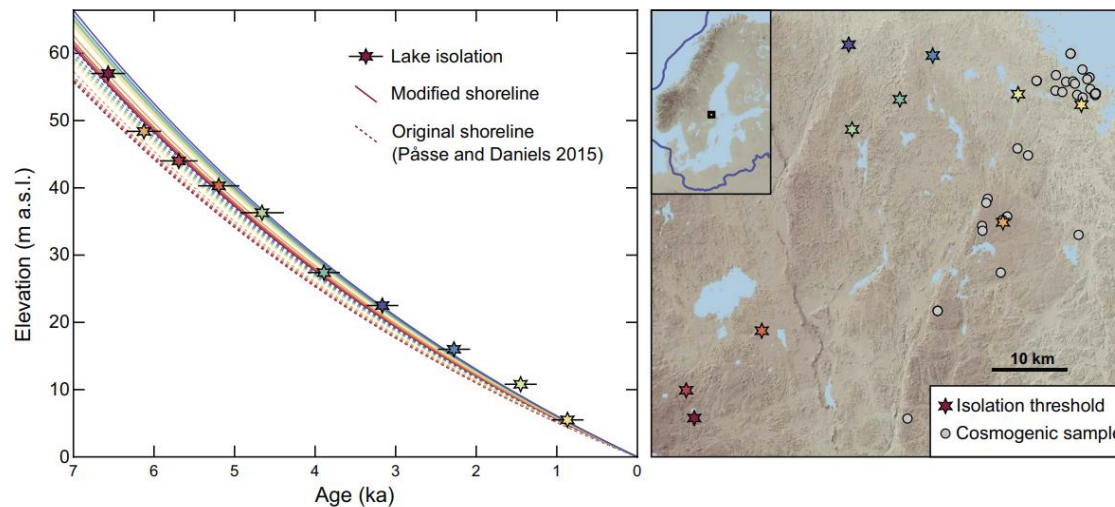


Svensson, 2004

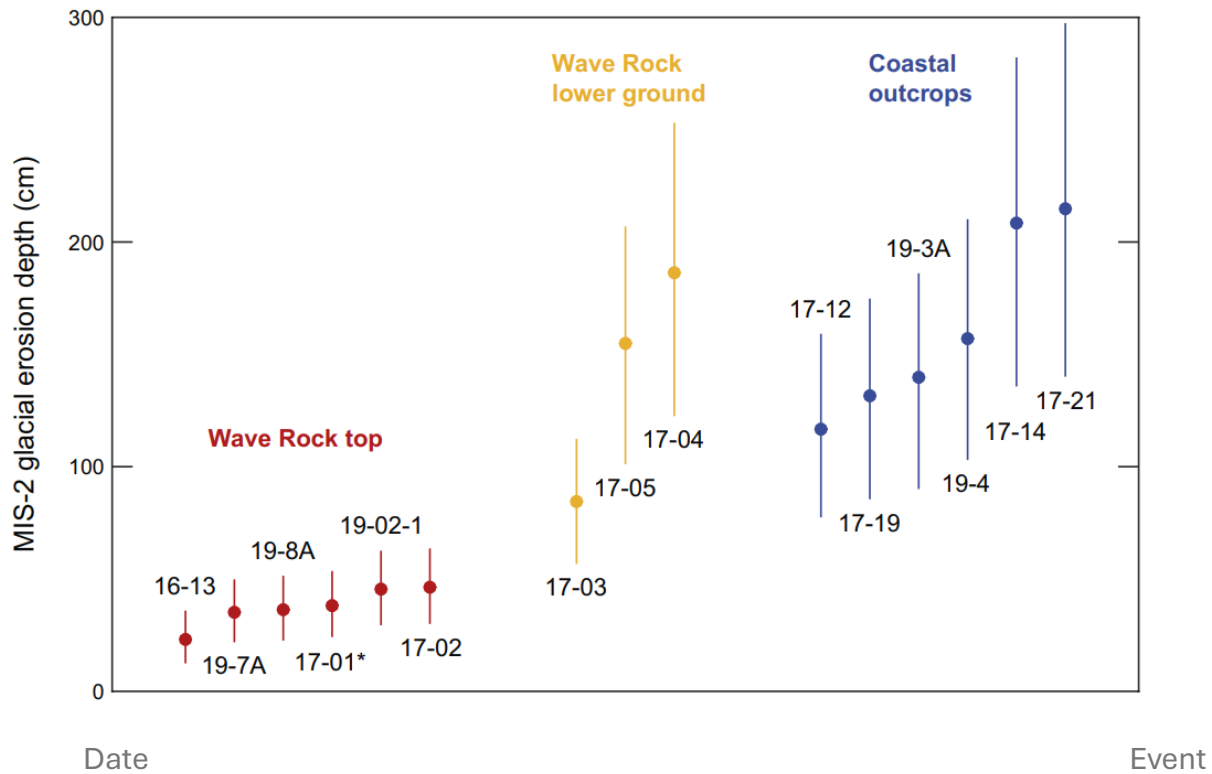
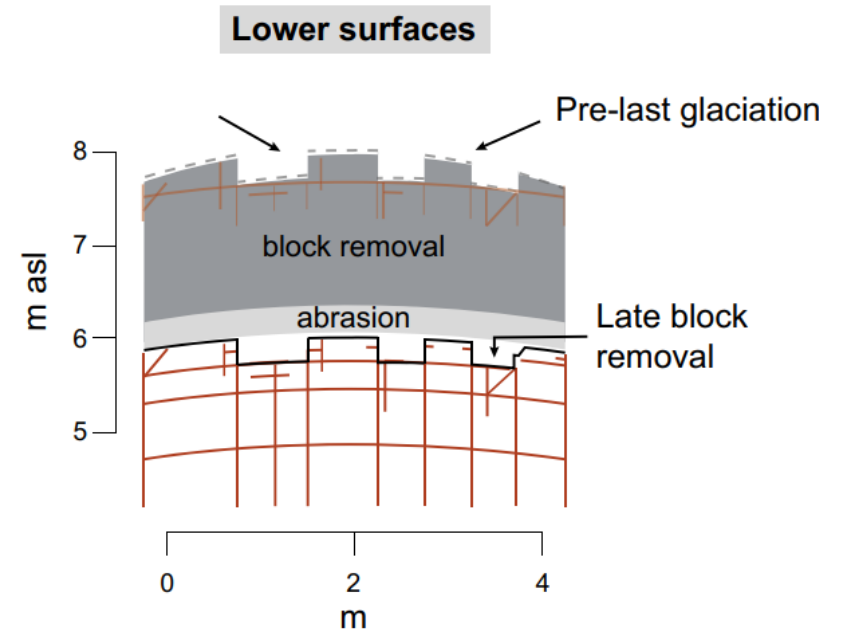
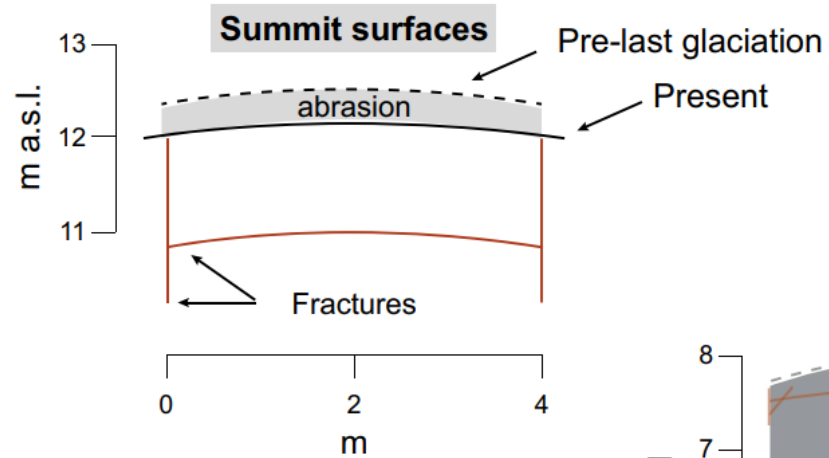


GLACIAL EROSION IN CRYSTALLINE ROCK

- Coastal rock outcrops and low elevation rock surfaces at Wave Rock have relatively high fracture densities and carry glacial microforms indicating erosion by combined abrasion and block removal; glacial erosion depth estimates for the last glaciation between 35.4 ka BP and 10.8 ka are 84–215 cm
- Summit rock surfaces at Wave Rock have low fracture densities and carry only abrasion microforms; glacial erosion depth estimates for the last glaciation are 23–46 cm and are interpreted to represent abrasion only



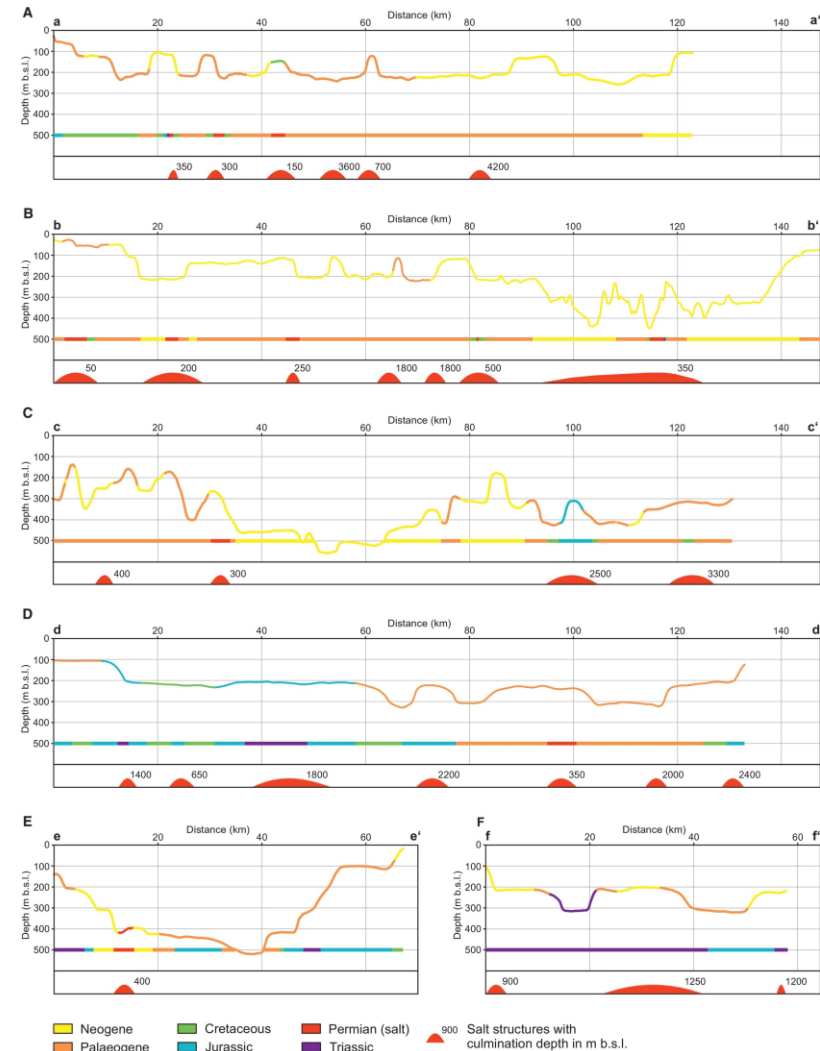
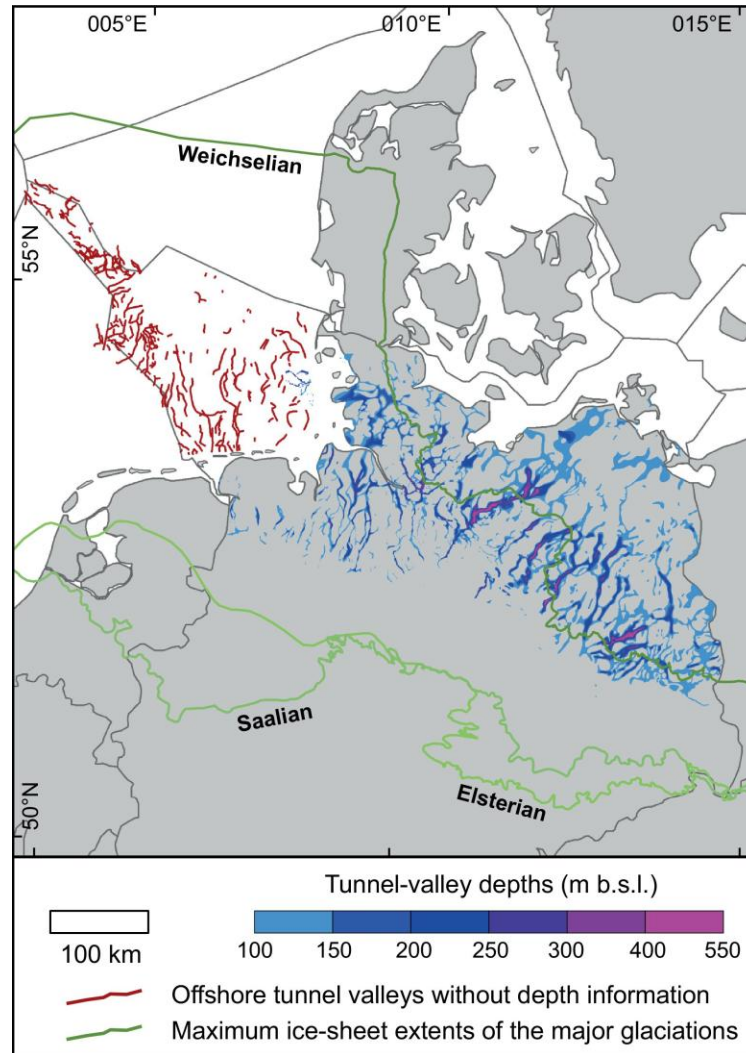
Hall, A. M., Heyman, J. & Hein, A. S. 2023: Glacial erosion rates at Forsmark derived from Terrestrial Cosmogenic Nuclides: additional results. Svensk Kärnbränslehantering AB. SKB-TR-23-21, 34 pp.



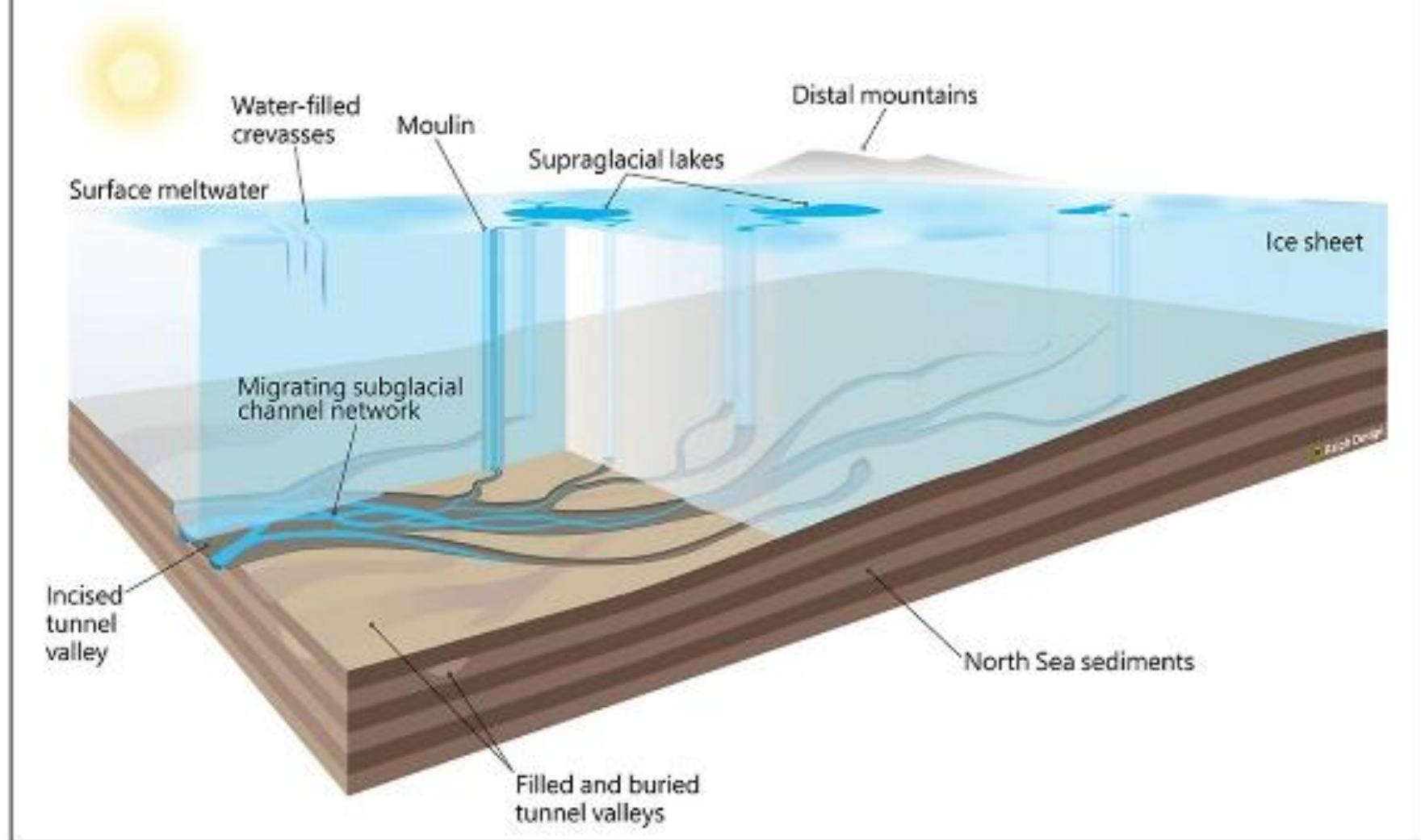
Hall, A. M., Heyman, J. & Hein, A. S. 2023

GLACIAL EROSION IN SEDIMENTARY BASINS: TUNNEL VALLEYS

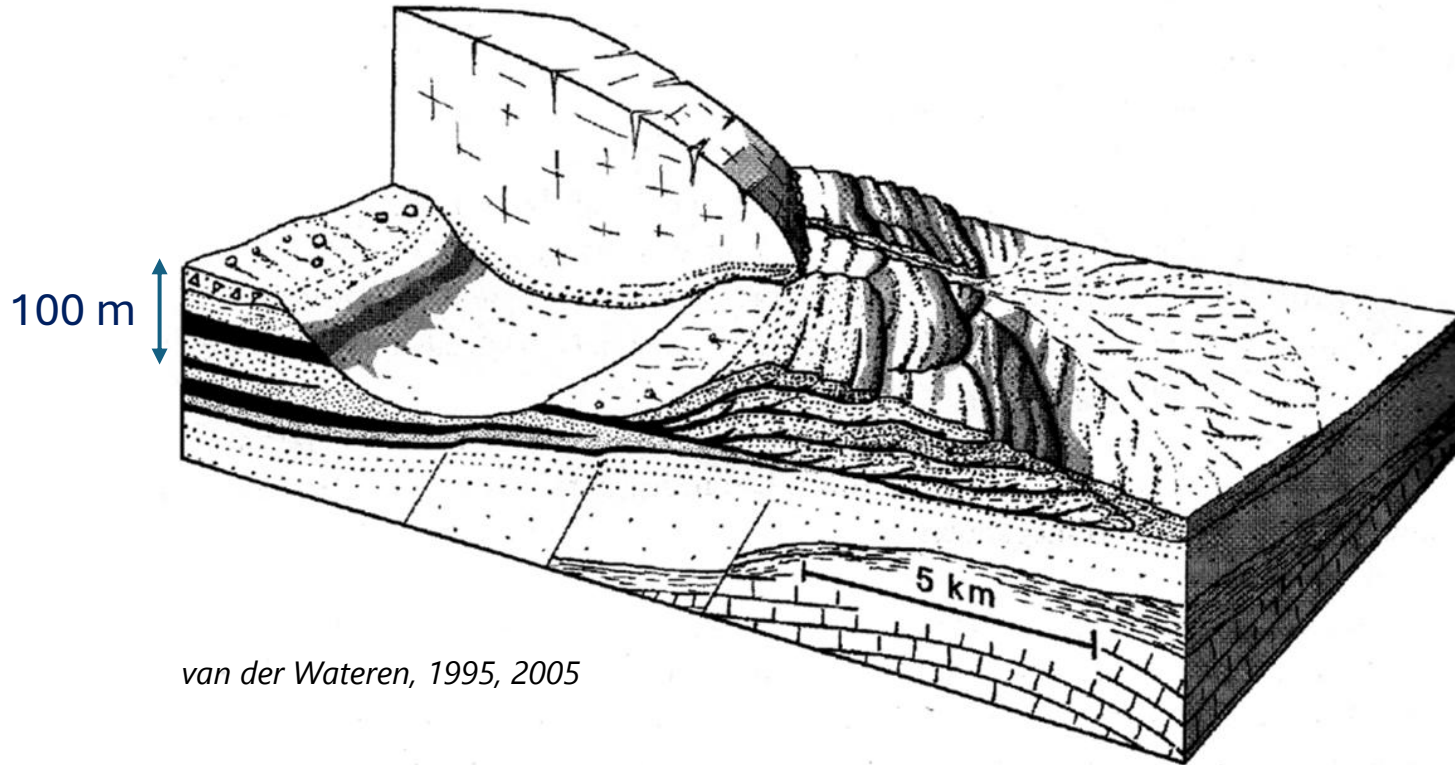
Lang, J., Bebiolka, A., Noack, V., Schütze, J., Weihmann, S. and Breuer, S. (2025), The impact of the structural framework of the North German Basin on Pleistocene tunnel-valley formation. *Boreas*, 54: 542-566. <https://doi.org/10.1111/bor.12694>



Migrating channels fed by seasonal surface meltwater can erode tunnel valleys within 100s to 1000s of years during deglaciation.



GLACIOTECTONIC DEFORMATION



van der Wateren, 1995, 2005

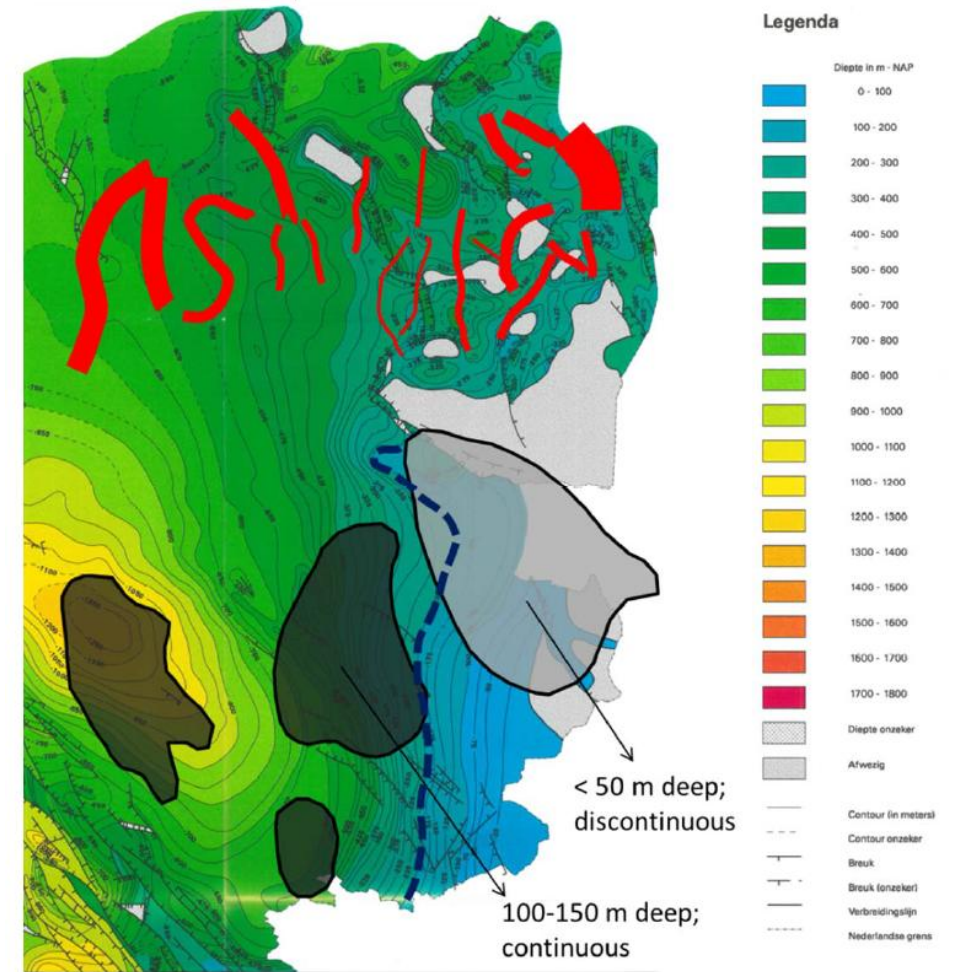


Figure 11 – Depth of the top of Rupelian clay in the Netherlands (meters below sea level), and distribution of glacial basins (dark grey: continuous and up to 150 m deep; light grey: discontinuous small basins less than 50 m deep) and tunnel valleys (red lines). The 200 m depth contour line is accentuated by the hatched dark blue line. Isohyps map from Rijks Geologische Dienst (1996), distribution of tunnel valleys and glacial basins from Zagwijn (1975).

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WHY SO LITTLE GLACIAL EROSION IN NORDIC CRYSTALLINE BEDROCK, IN CONTRAST TO DEEP EROSIONAL FEATURES OBSERVED IN THE RATHER SOFT SEDIMENTARY ENVIRONMENT OF THE SOUTHERN NORTH SEA BASIN?

- Erosion-resistant crystalline material (gneiss, granite) <-> sedimentary formations (sand, clay)
- Cold-based ice-sheets inhibit glacial erosion: pre-existing permafrost in front of the advancing ice
- Warm-based sliding conditions are probably very brief

QUESTION

- Give an estimate (order of magnitude) of the expected erosion rate for a hypothetical location at an altitude of 30 m in a current Cfb climate at 50°N.
- X or 0

Type of erosion	Timeframe	Several meters	Up to 10-20 meters	Up to 100 meters	More than 100 meters
Aeolian deflation	Within the next 1,000 yrs	X			
Marine/estuarine erosion	Within the next 10,000 yrs		X		
Fluvial erosion	Within the next 100,000 yrs		X		
Glacial tunnel valleys	Within the next 1,000,000 yrs				X