# Ce que le paléoclimat révèle des mutations du monde

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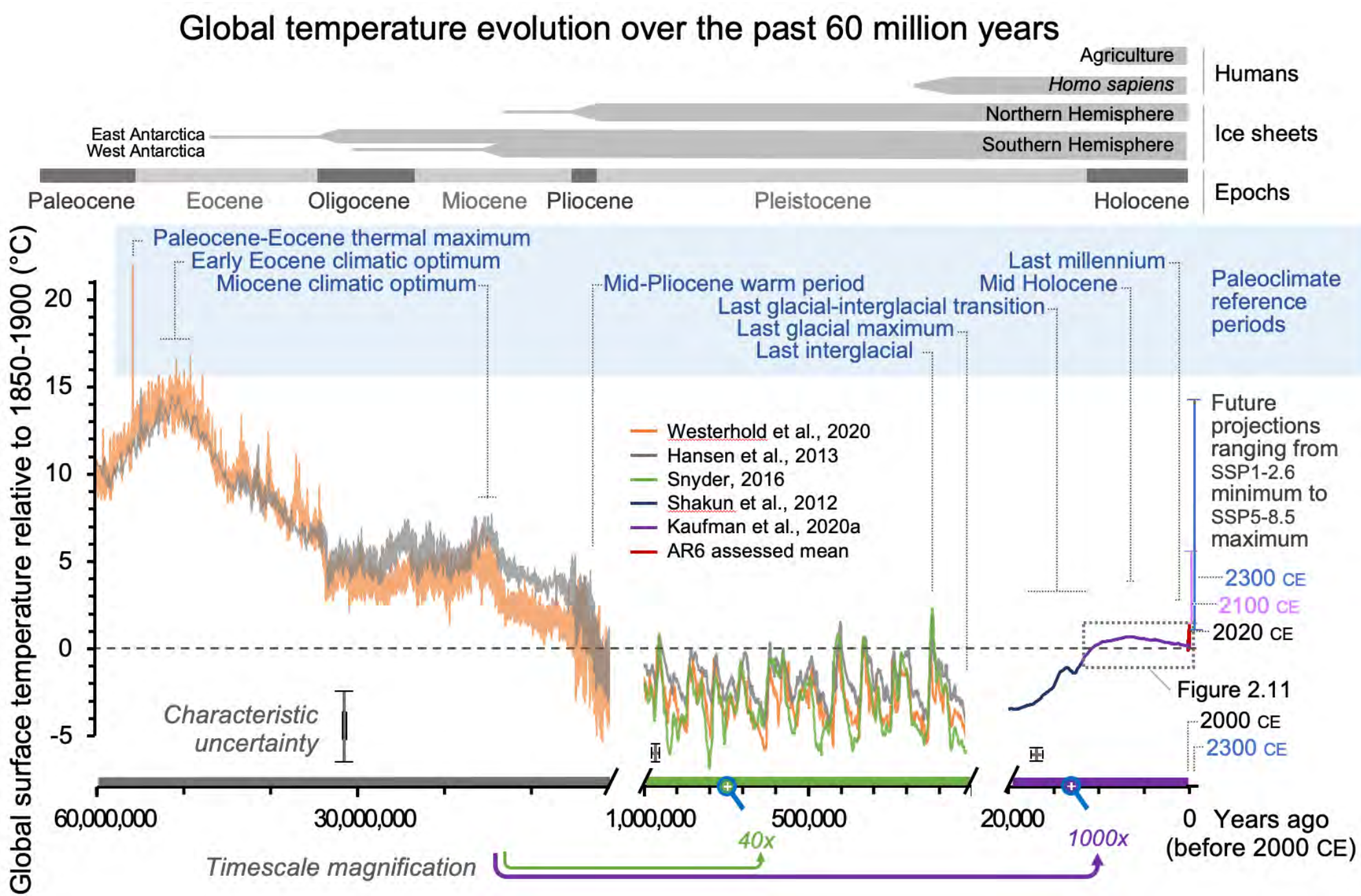
# Ce que le paléoclimat révèle des mutations du monde

Est-ce que notre réchauffement est réellement en dehors des fluctuations naturelles du climat ?

Est-ce que la planète a déjà été plus chaude ?

A quoi ressemble la planète Terre à 2°C de plus ?

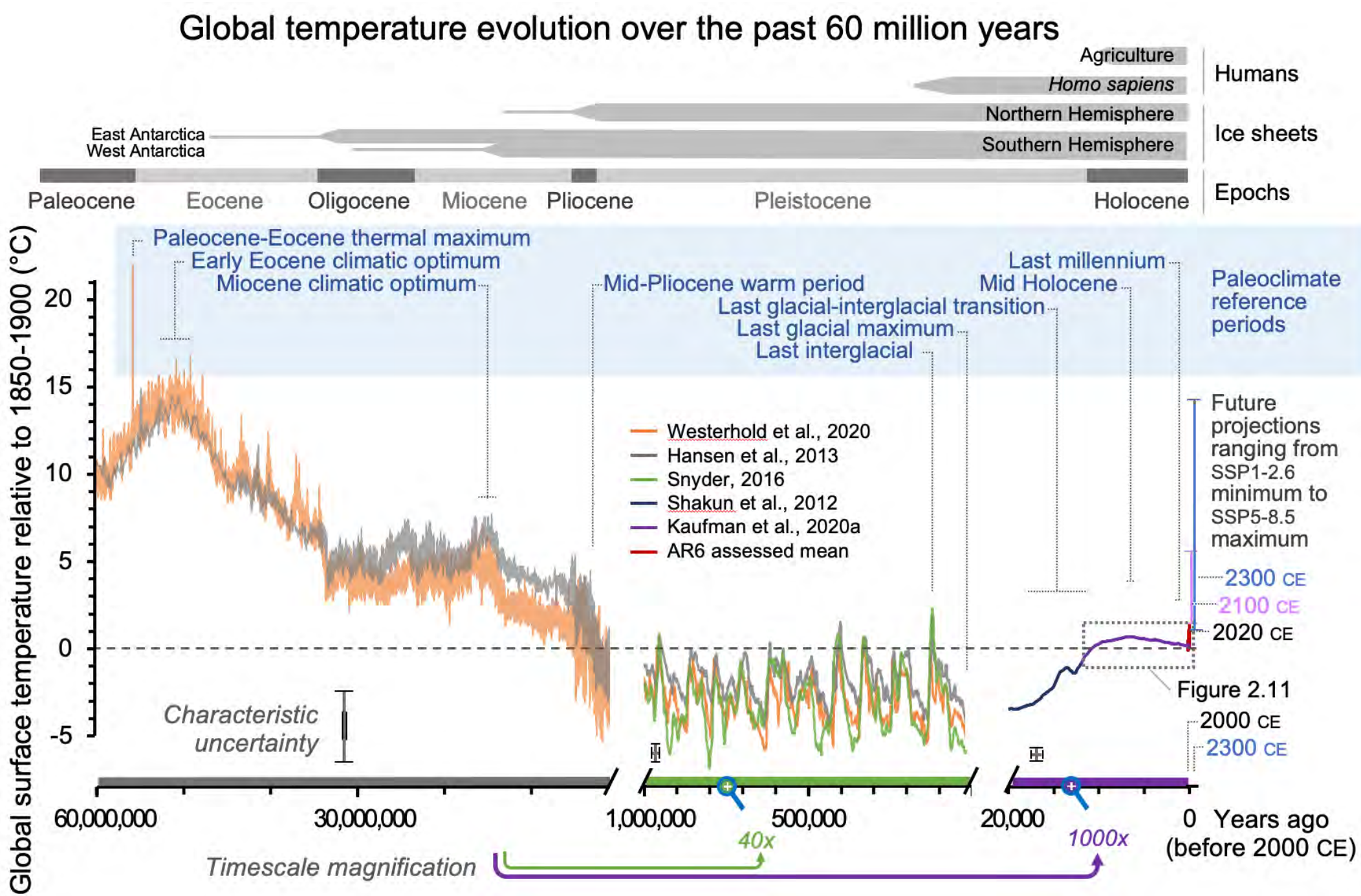
Comment comparer l'amplitude et la vitesse du réchauffement actuel aux fluctuations climatiques passées ?




IPCC AR6 WG1 Fig. 2.1

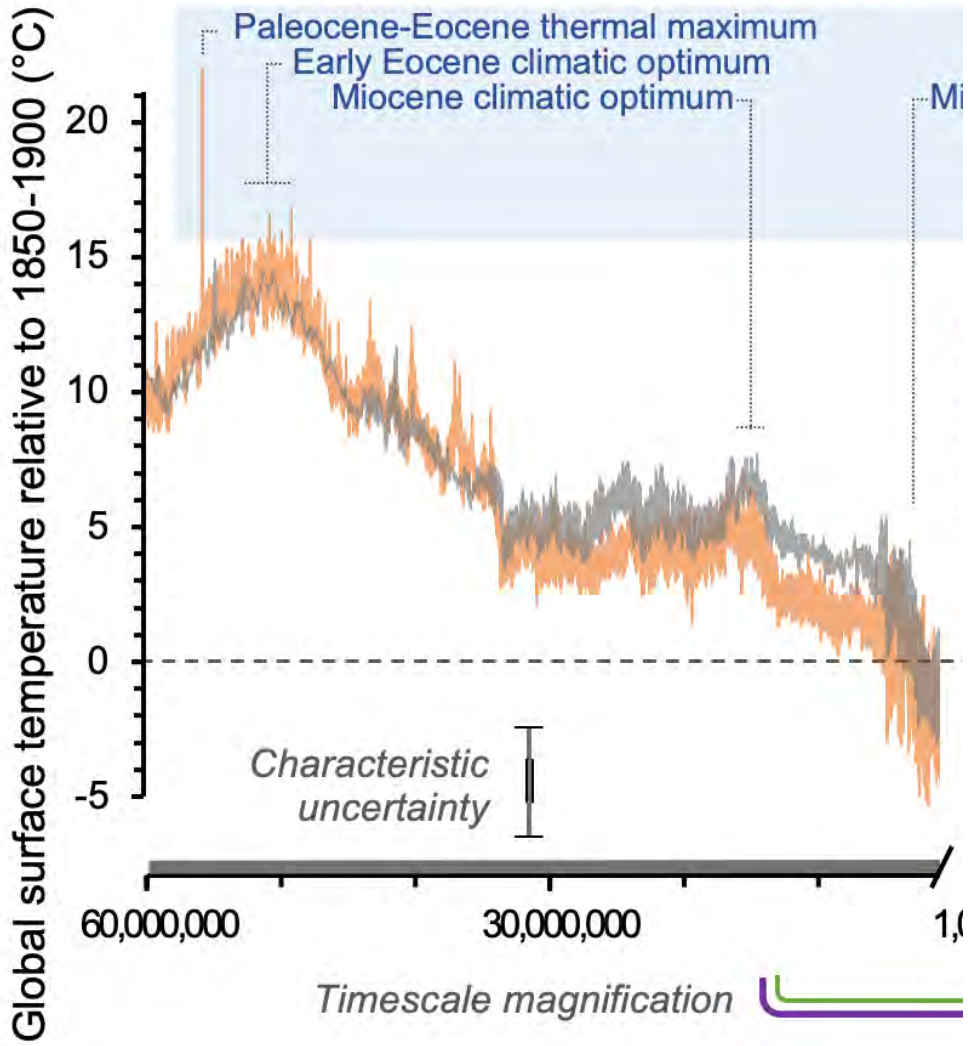
La Terre a été plus chaude par le passé,
Mais ce n'était pas la terre que l'on connait.

Biota of the Paleocene-Eocene Thermal Maximum 56 mya
National Geographic Magazine, October, 2011 - Artwork: Aldo Chiappe



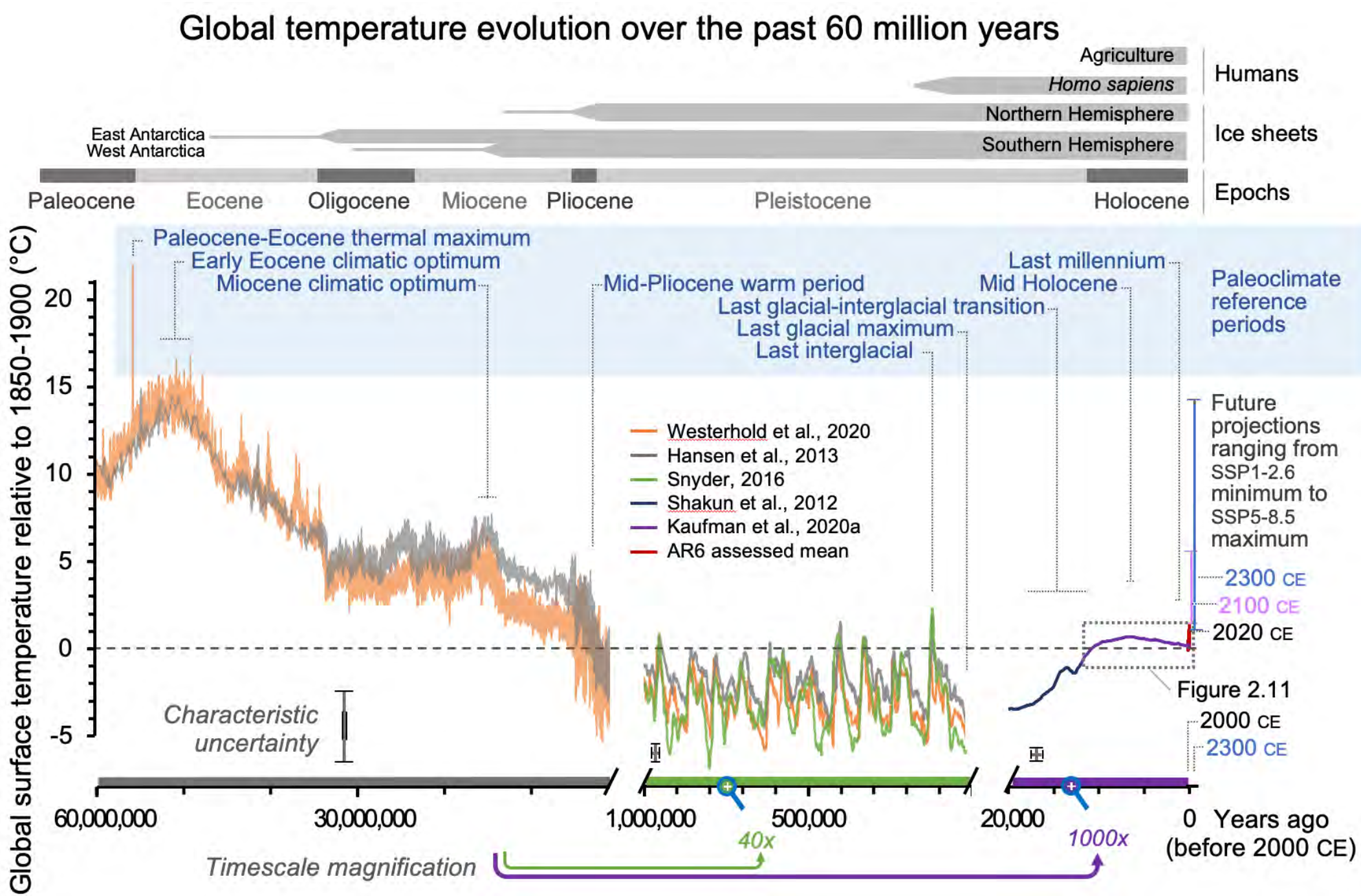

IPCC AR6 WG1 Fig. 2.1

# Depuis 50 Ma, le climat s'est refroidit




... À partir du moment ou l'Inde est entrée en collision avec l'Eurasie et les montagnes de l'Himalaya se sont formées.

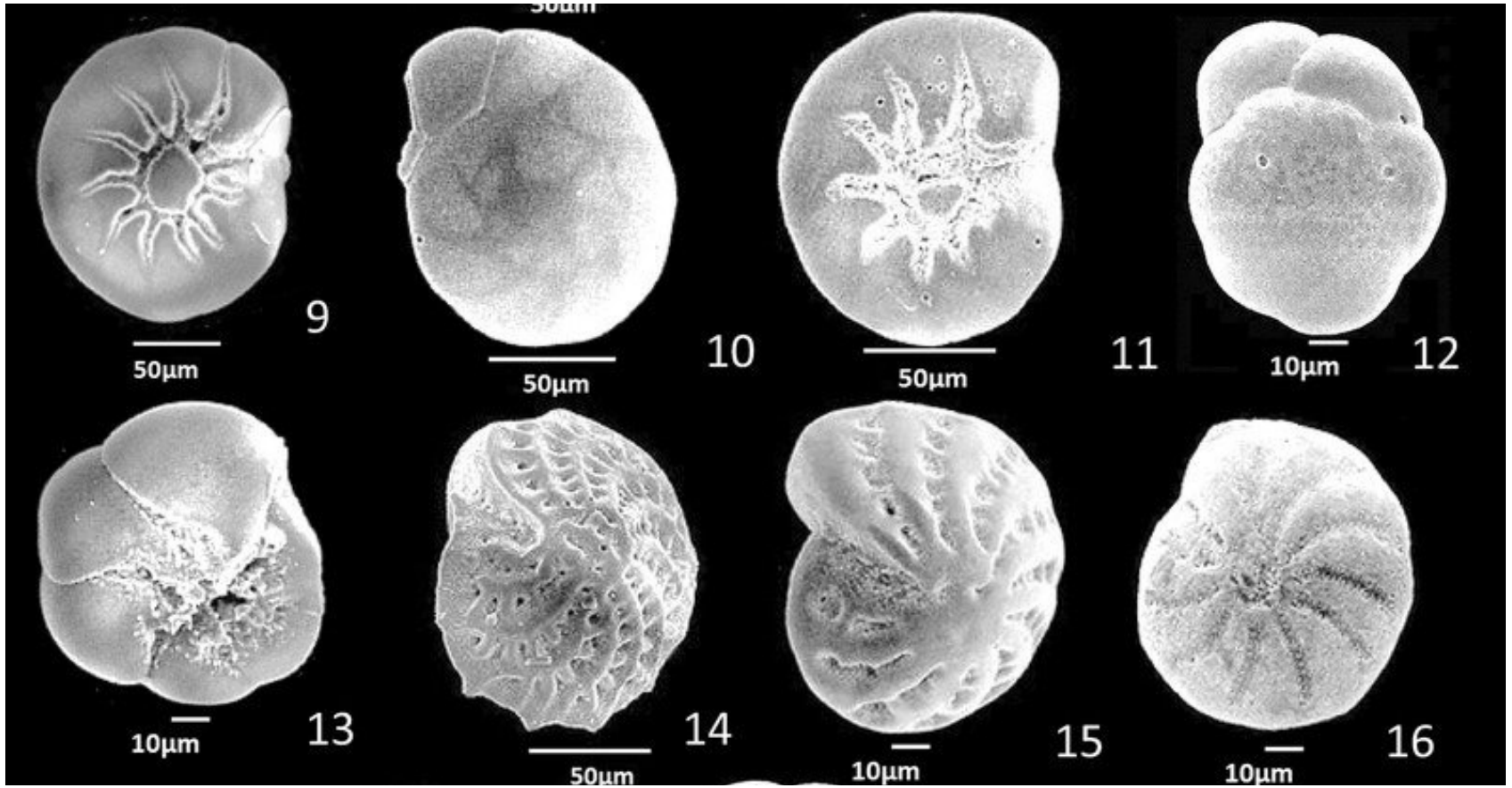

**=> Cause tectonique,** en interaction avec le cycle du Carbone.




IPCC AR6 WG1 Fig. 2.1

# Climate recorders: benthic foraminifera

Our best record of estimates of temperature (in this case deep ocean temperature) from the past ~70 million years come from the chemistry of shells preserved in the geological record.

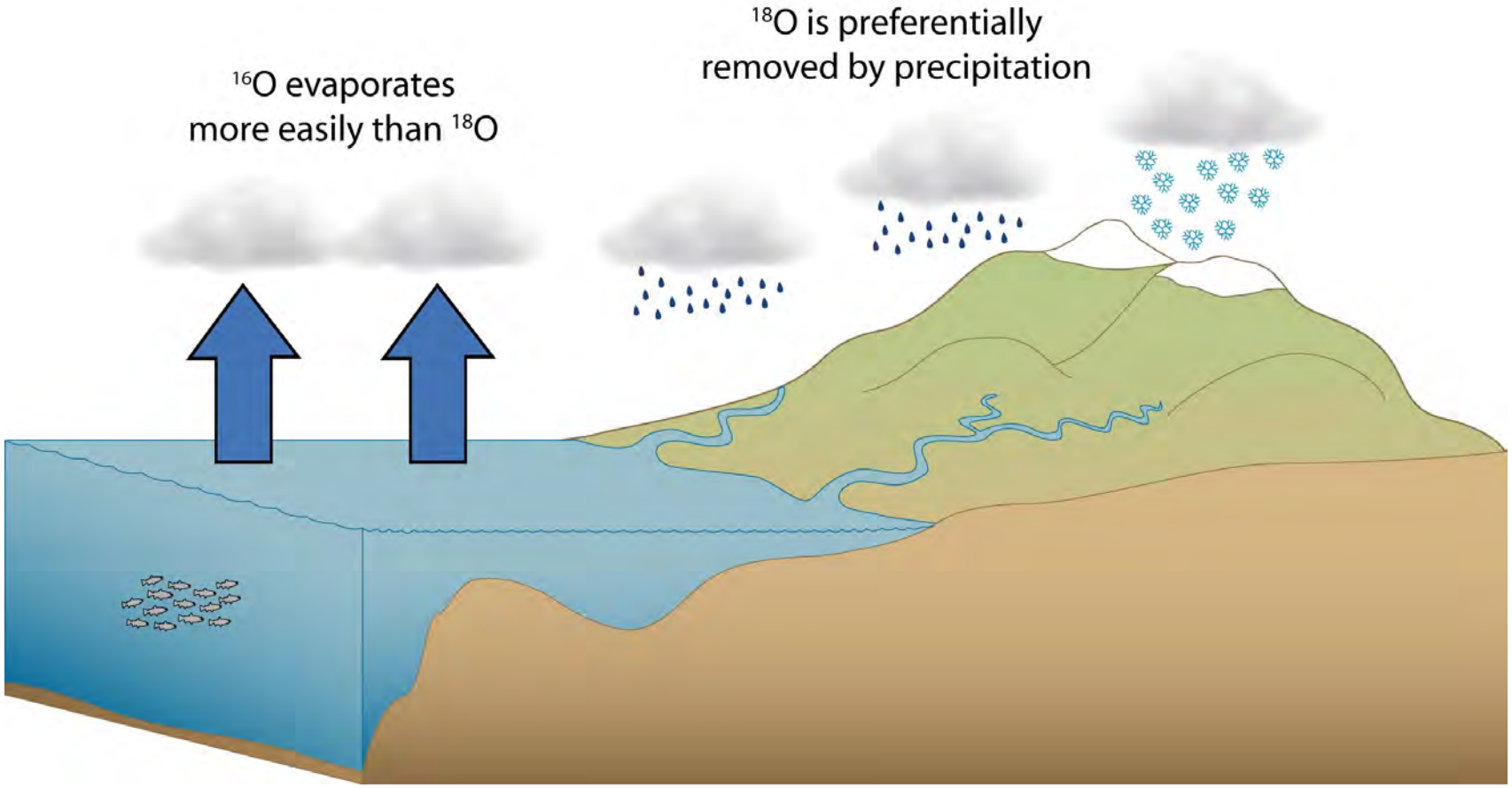



benthic foraminifera = single-celled organisms that live **on the sea floor** (benthic) and make shells out of calcium carbonate ($CaCO_3$)

# Water isotopes in the atmosphere

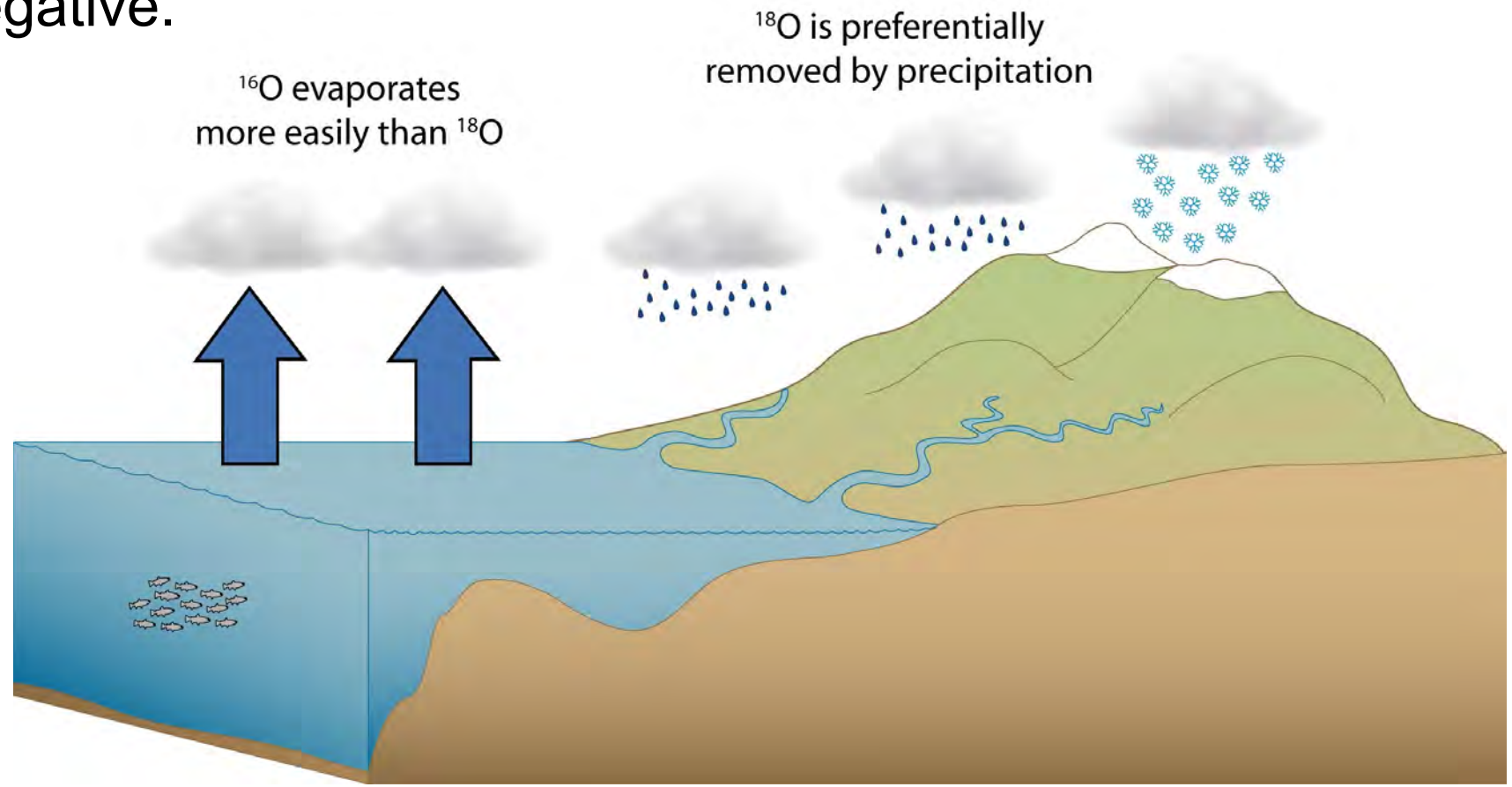
**Fractionation** during phase changes: heavy isotopes are concentrated in the more condensed phase:

- Water vapor will always be lighter than the ocean
- Heavy isotopes will be preferentially removed by precipitation, leaving the water vapor even lighter.



# Sea water $\delta^{18}O$ and evaporation

The light $^{16}O$ evaporates more readily than the heavy $^{18}O$.
As a result, $\delta^{18}O$ in water vapor (and subsequent precipitation) is always negative.




If I store a lot of precipitation on the ice sheets, what will happen to sea water $\delta^{18}O$?

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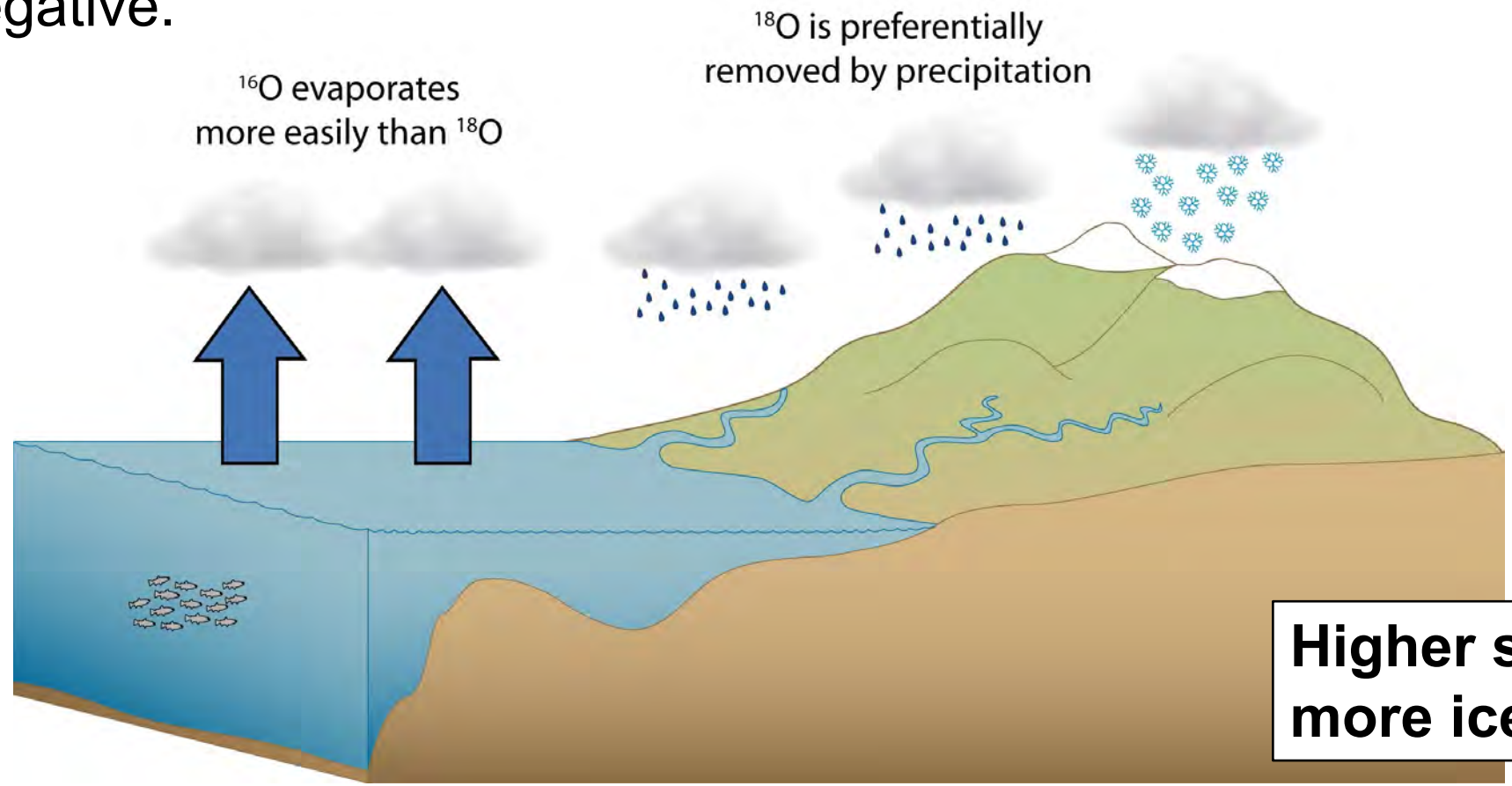


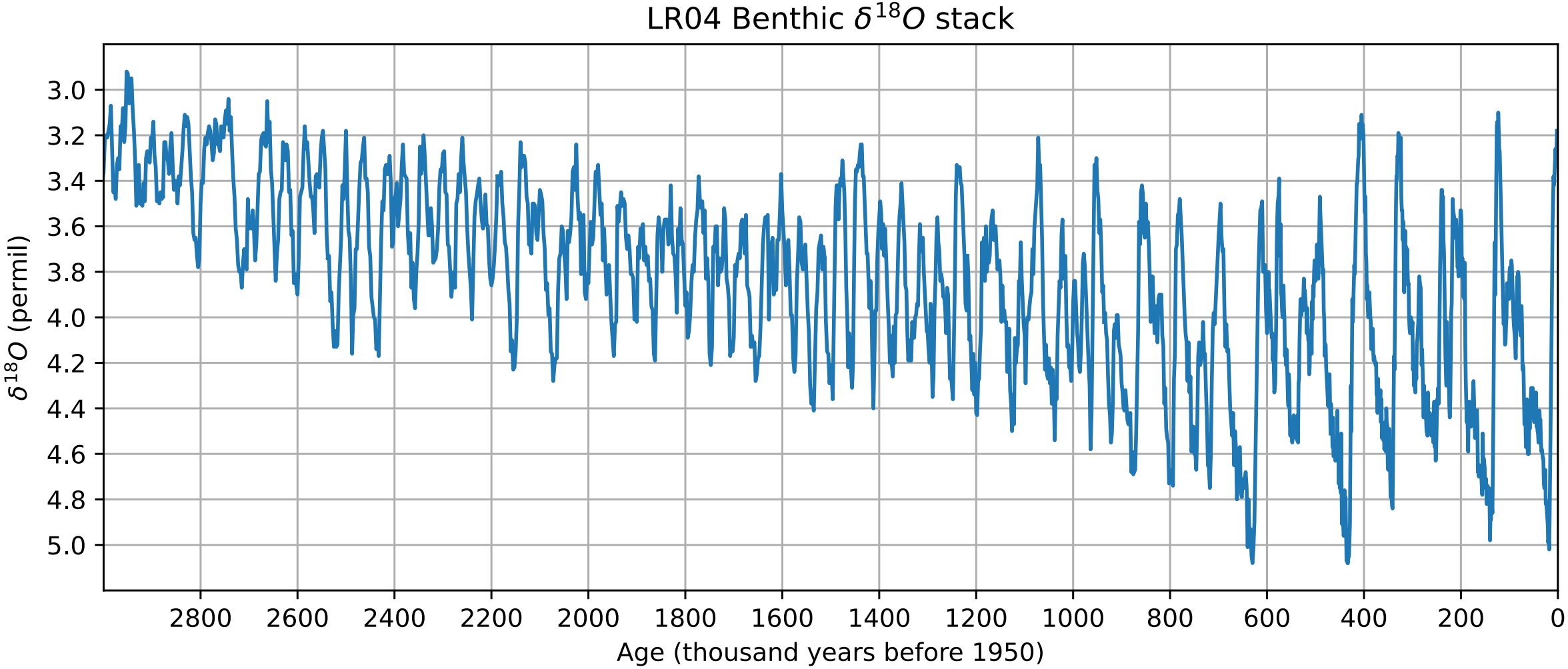

If I store a lot of precipitation on the ice sheets, what will happen to sea water $\delta^{18}O$?

**Higher sea water $\delta^{18}O$ = more ice volume**

# The benthic $\delta^{18}O$ record

Benthic foram $\delta^{18}O$ is sensitive to ice volume and temperature.

Higher $\delta^{18}O$ = more ice and colder : they go together (!! Inverted y-scale)



# The benthic $\delta^{18}O$ record – Q2

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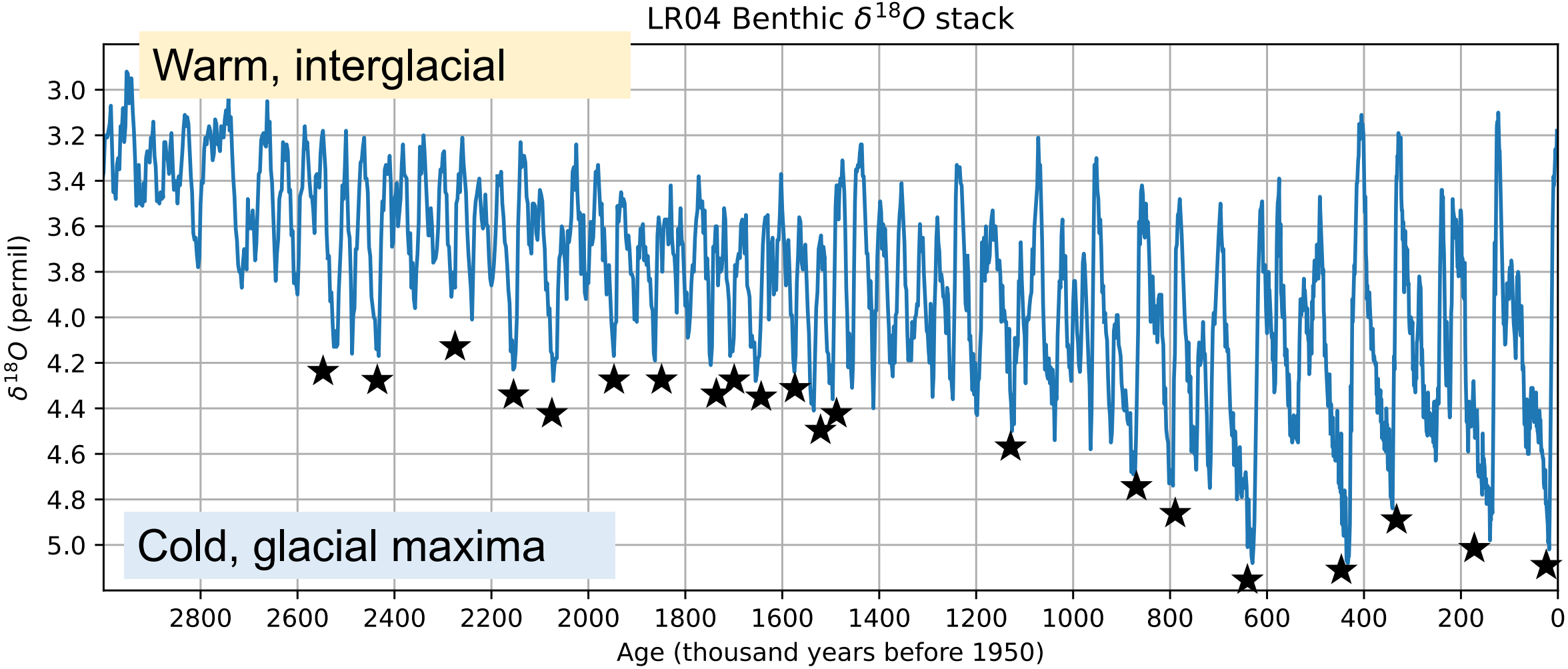
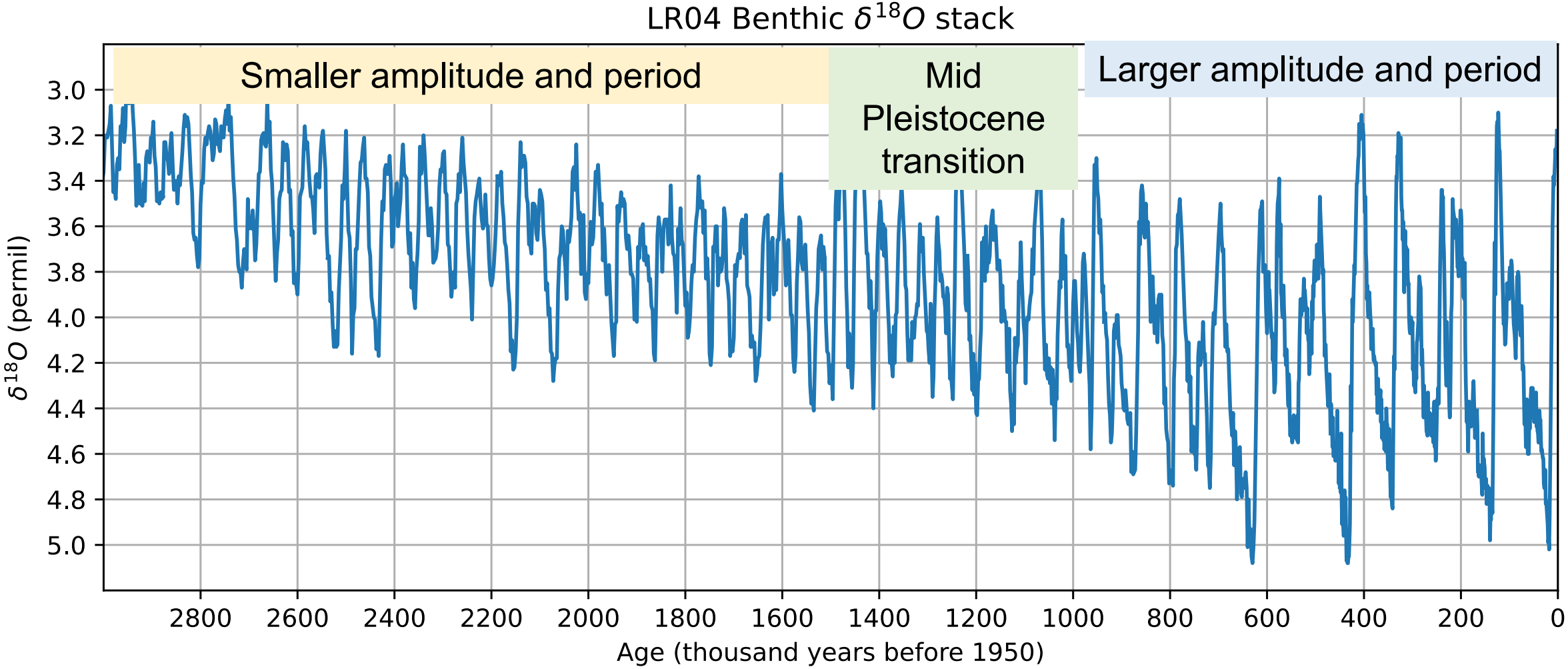


# The benthic $\delta^{18}O$ record

Ice age cycles become **colder**, **more intense** with time (amplitude doubles)
Their period becomes longer: from 41ka to 100ka.



# Lorraine Lisiecki made this graph

She is a professor at UC Santa Barbara, in California.
She made this canonical graph in 2005, when she was a PhD student.

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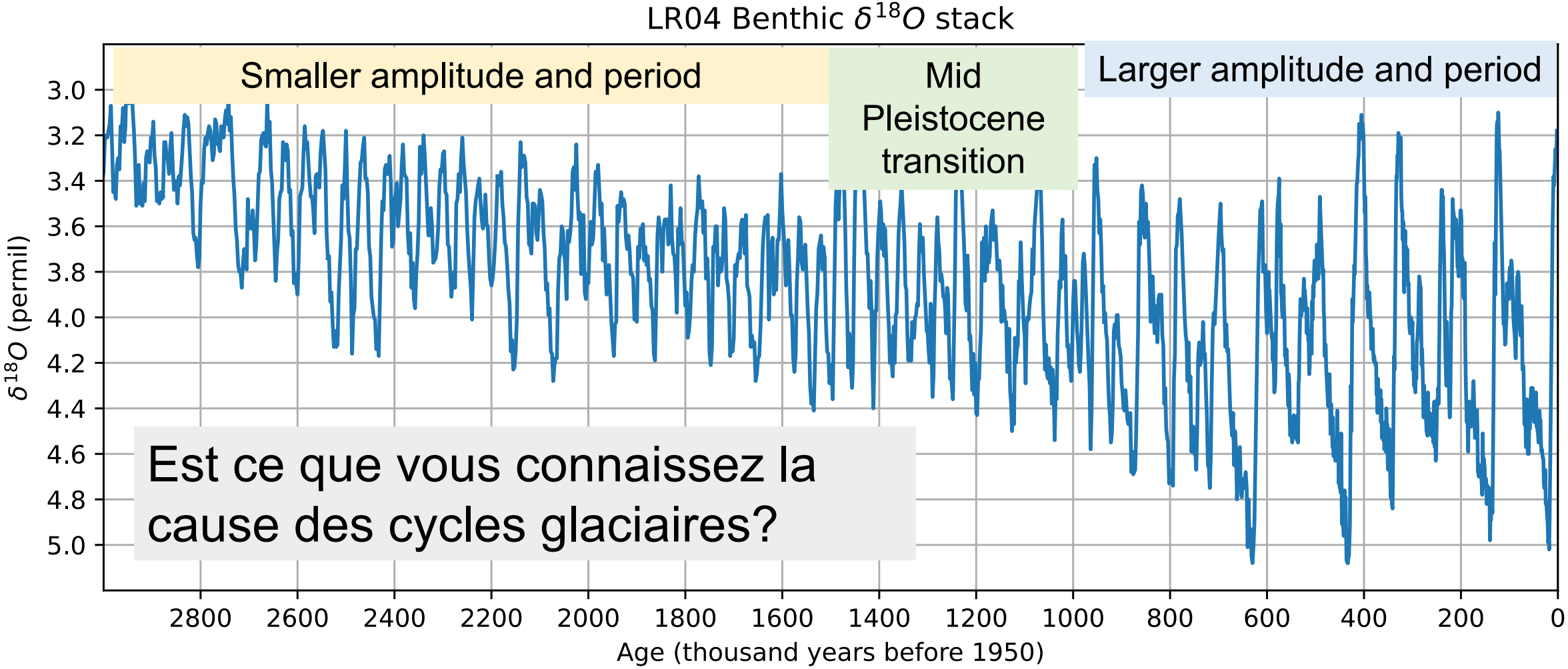
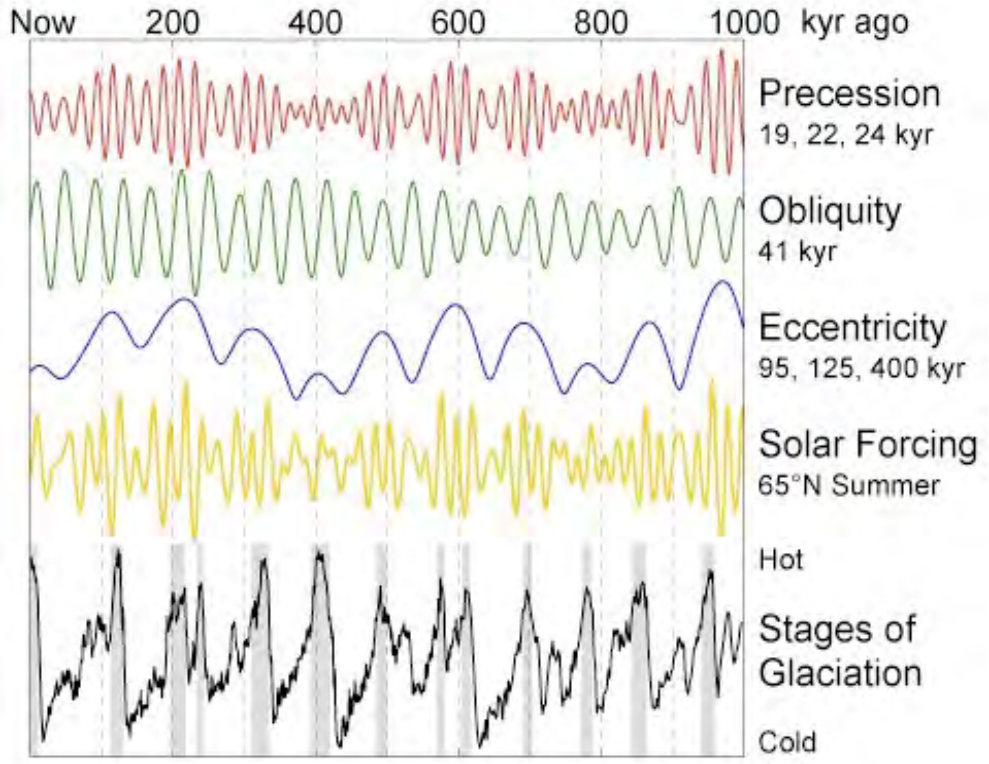


# The Astronomical theory of ice ages

The **Milankovitch theory** states that an ice age onset is triggered when solar radiation on **June 21st** at **65°N** falls below a threshold. Snow does not melt, which triggers the ice-albedo feedback and a full glaciation.




**Northern hemisphere is more important:** more continents, more potent ice-albedo feedback

**Summer is more important:** this is the season where we have melt/no melt.

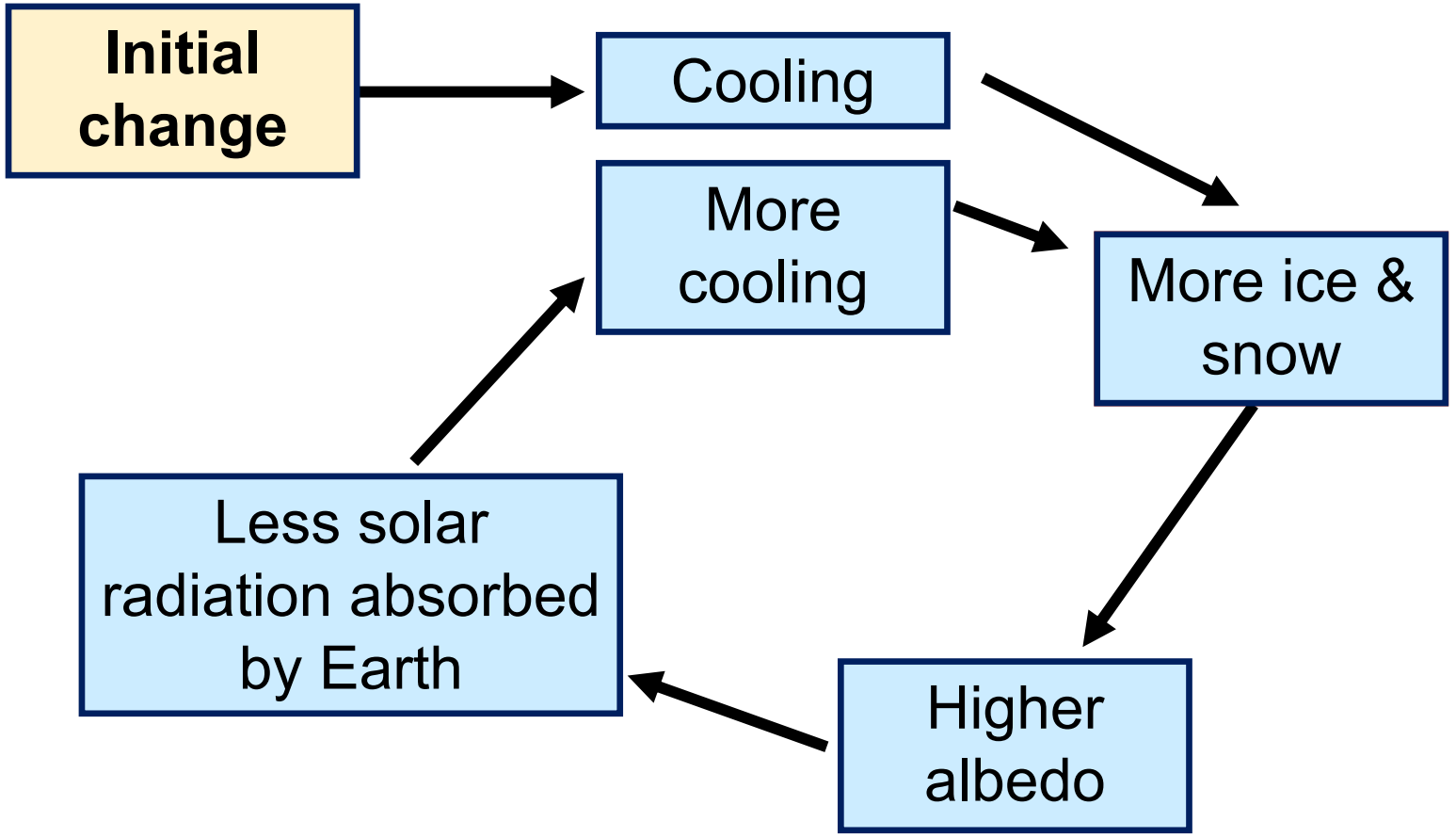
**Limits to Milankovitch theory:**

- Forcing is progressive but climate is in saw tooth
- There is no clear threshold.

# With the **ice-albedo feedback**, we can transform a small forcing into a big change

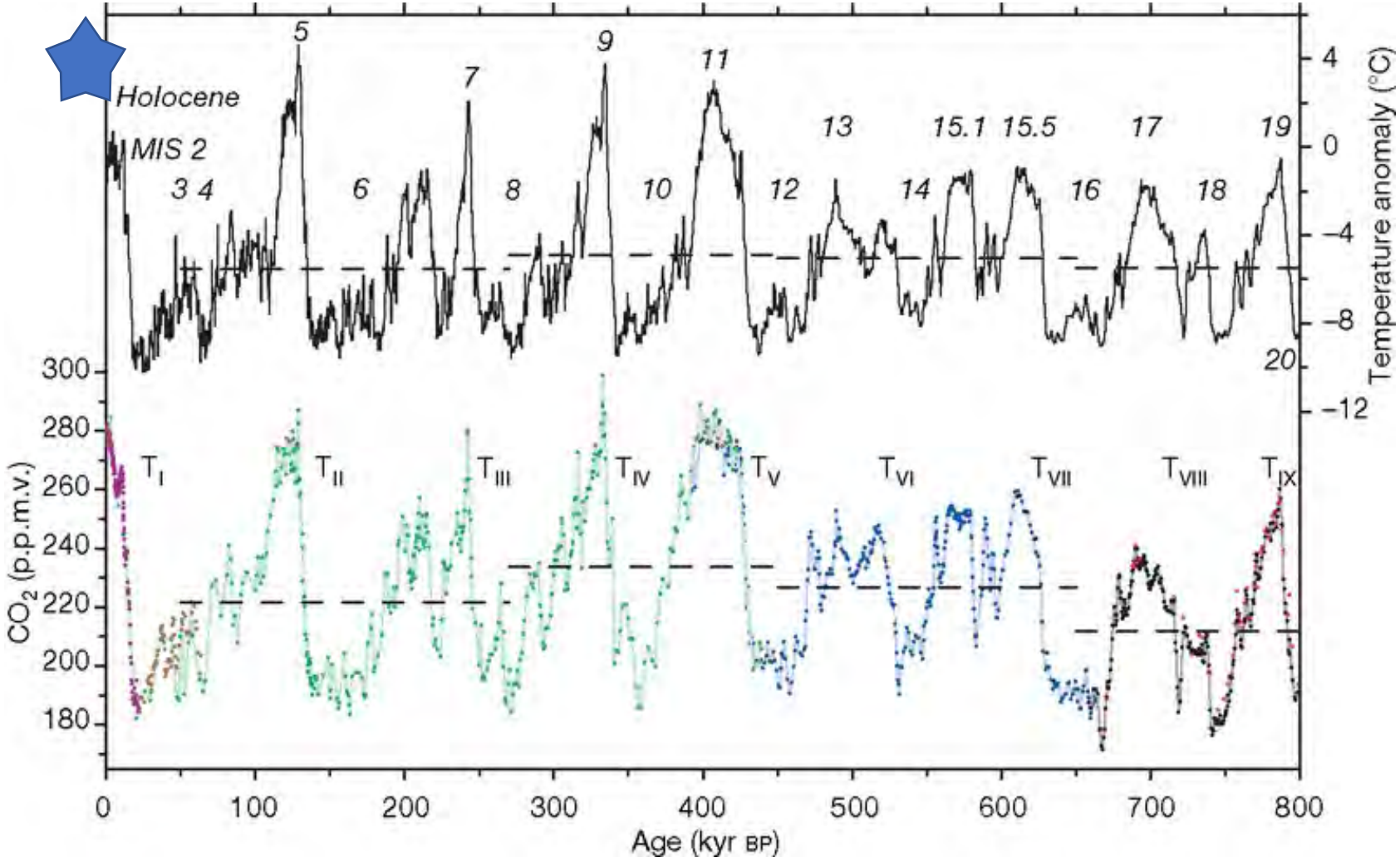
Les cycles glaciaires sont **forcés** par les changements d'insolation dus à l'orbite terrestre,

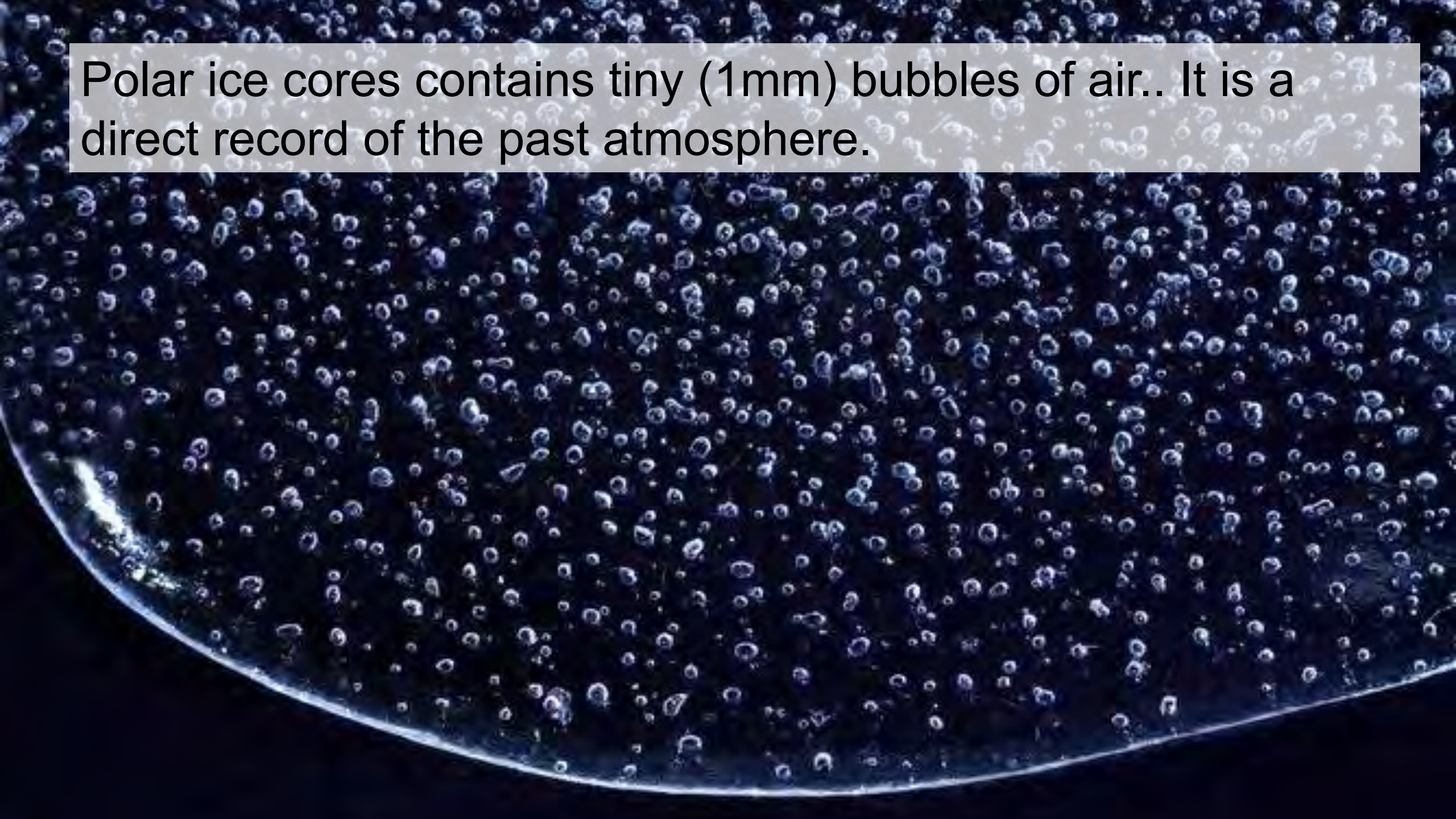
mais leur expression en terme de température à la surface dépend de **mécanismes internes** au système climatique qu'on appellle des **rétroactions**.



# Carottes de glace: couplage climat-$CO_2$

There is a remarkable correspondence between atmospheric $CO_2$ and temperature
It supports the idea of a direct link between greenhouse gas concentrations & climate in this period

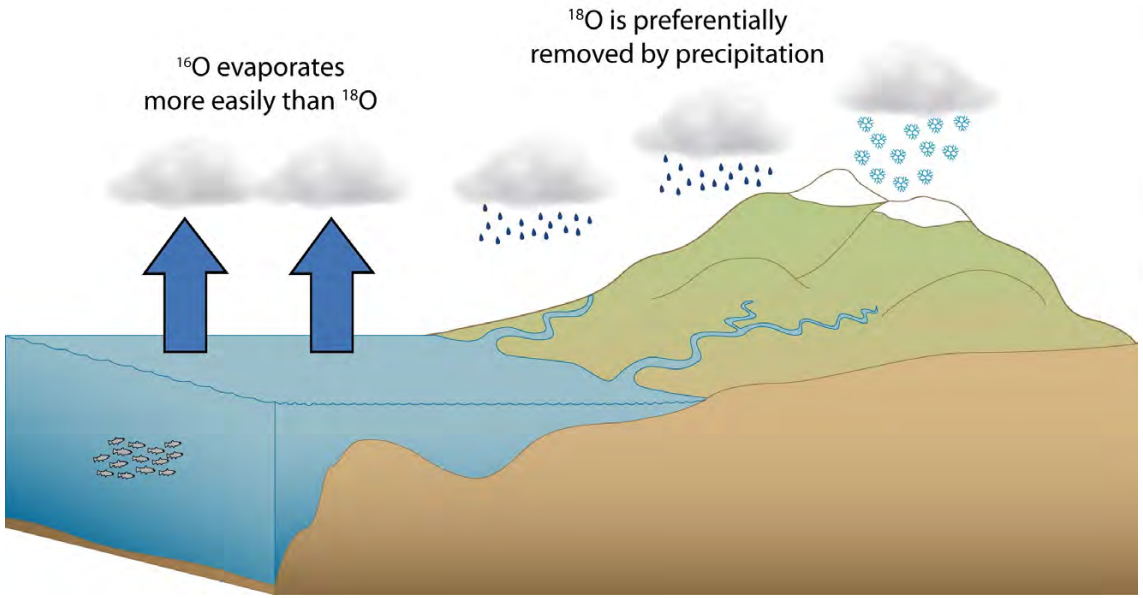


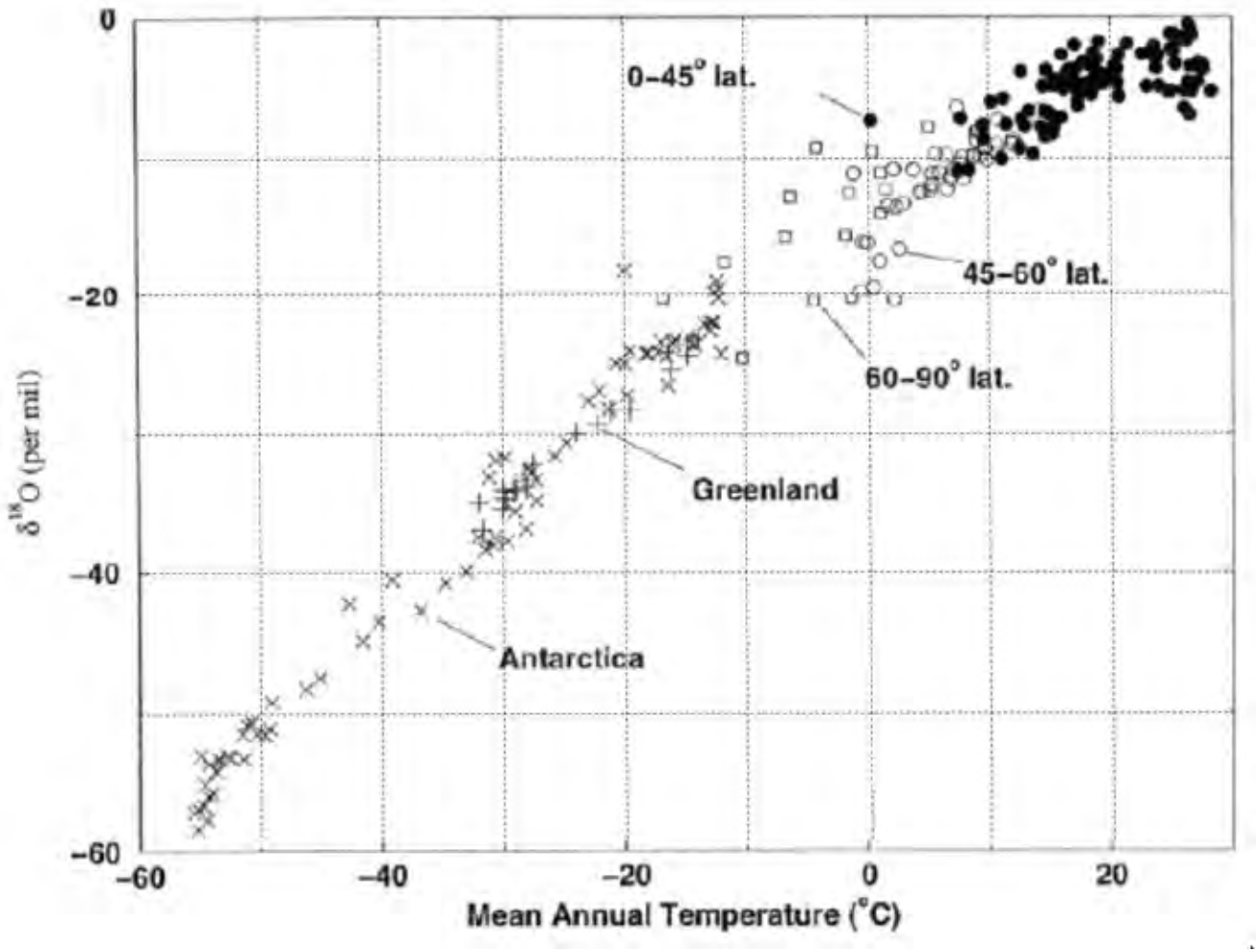



Polar ice cores contains tiny (1mm) bubbles of air.. It is a direct record of the past atmosphere.

# $\delta^{18}O$ in precipitation is a temperature proxy

A simple **Rayleigh distillation** model explains well the major feature of the relationship between $\delta^{18}O$ and temperature.



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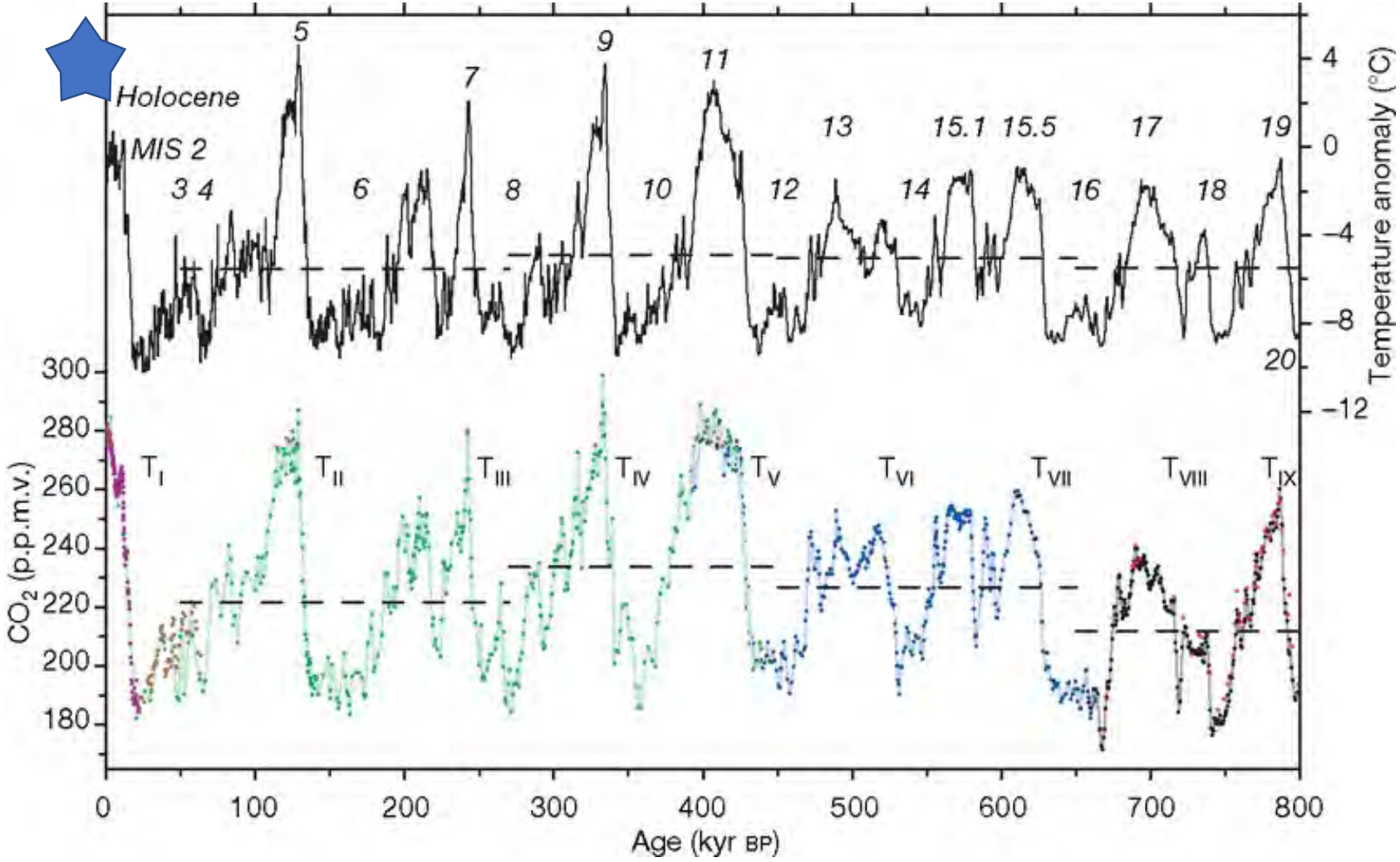
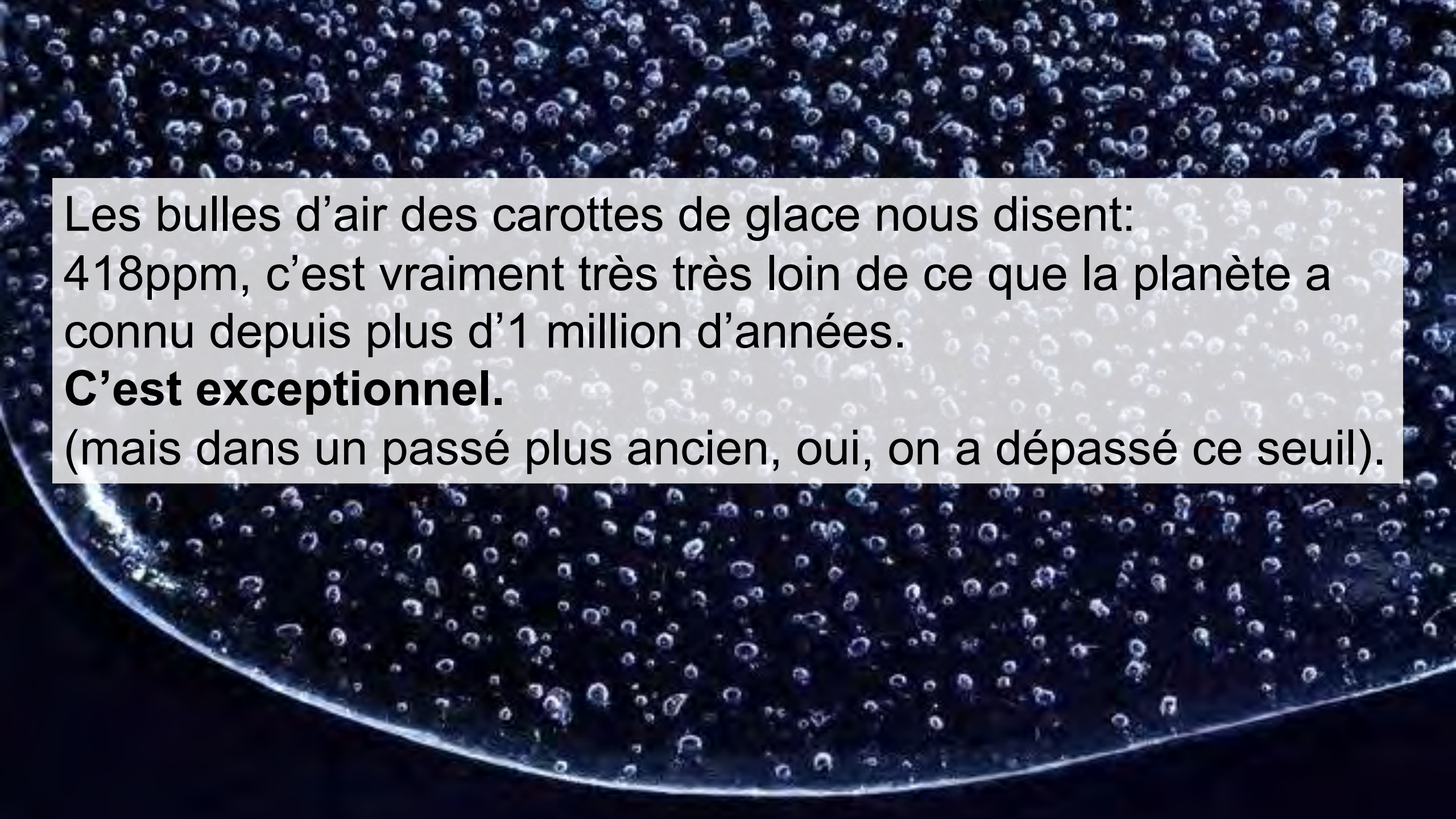
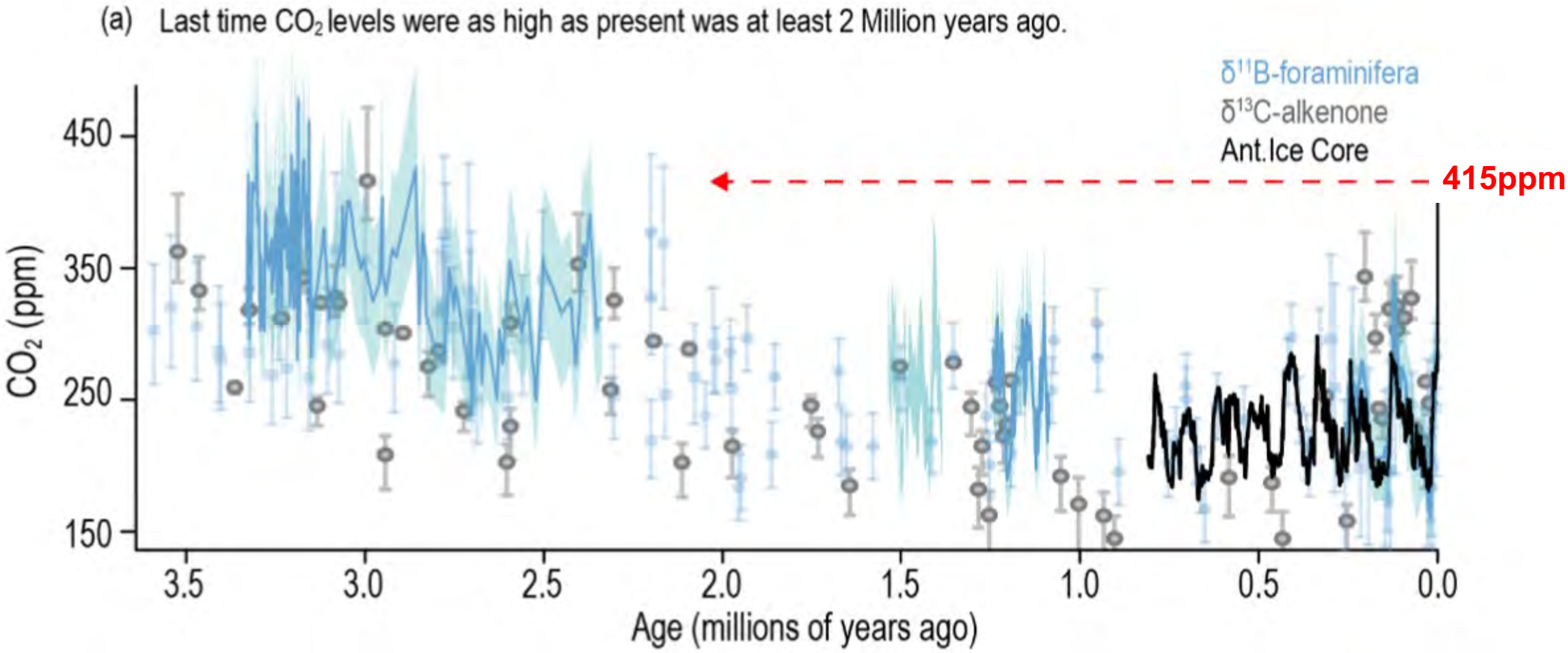


Les bulles d’air des carottes de glace nous disent:
418ppm, c’est vraiment très très loin de ce que la planète a connu depuis plus d’1 million d’années.
**C’est exceptionnel.**
(mais dans un passé plus ancien, oui, on a dépassé ce seuil).

# $CO_2$ over the last 3 million years – highest now than any time in the past 2 million years!

BG



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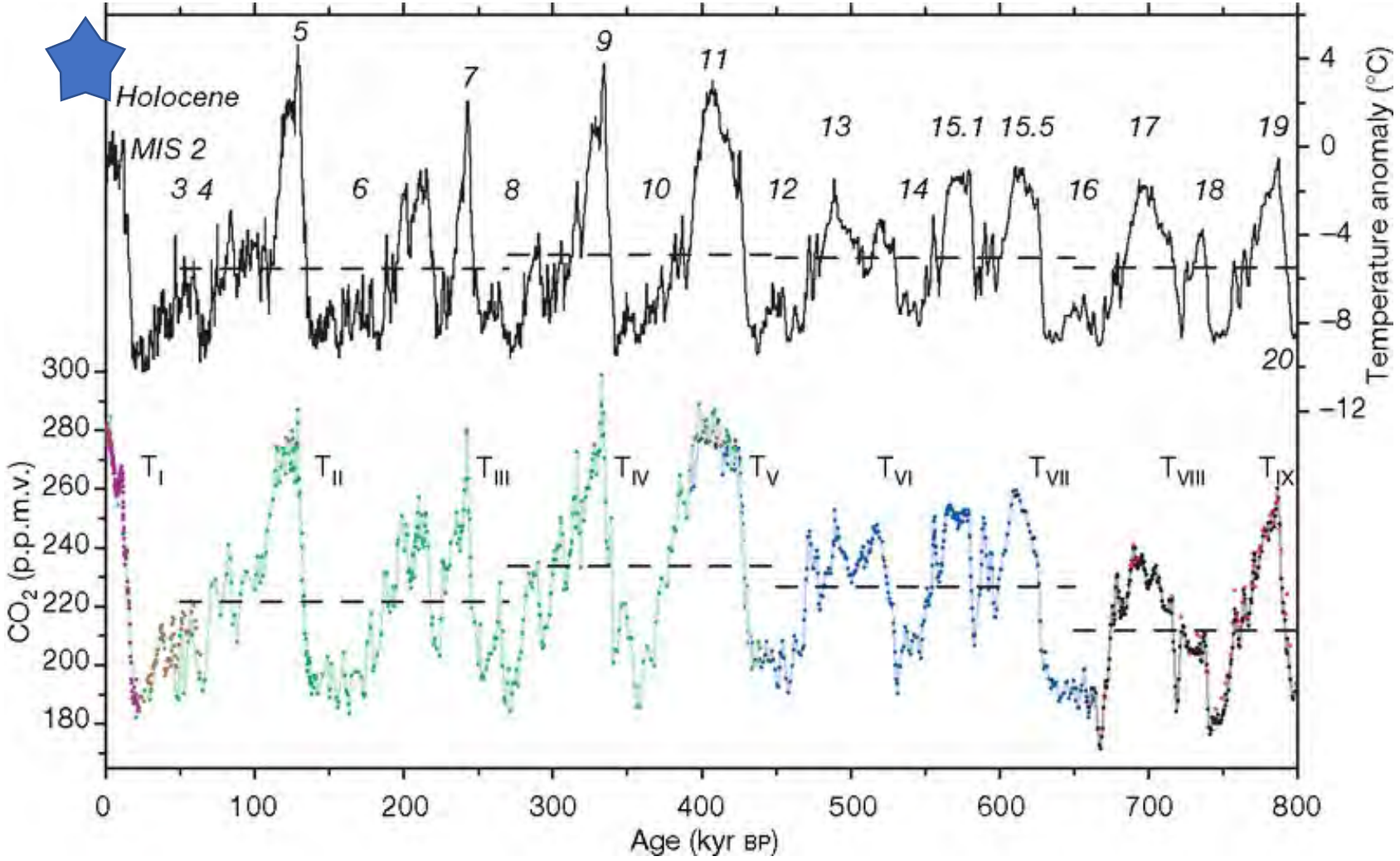
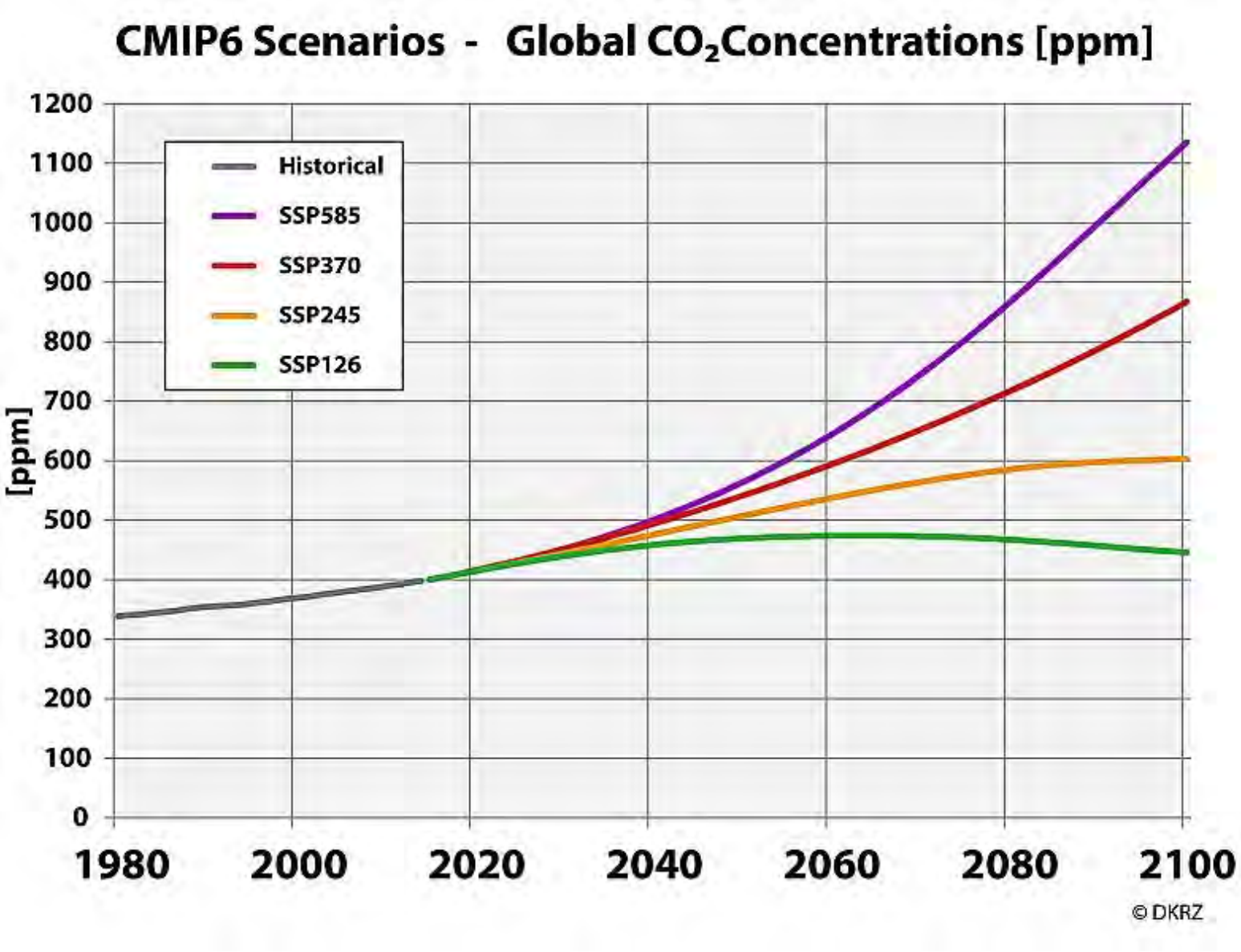



Aujourd'hui:
CO2 = 418ppm
**Exceptionnel**
**= 140ppm de plus que le préindustriel.**

Un cycle glaciaire, c'est 180-280 = 100ppm.

On modifie l'atmosphere du double de ce qui nous sépare d'une ère glaciaire.

# Scenarios




SSP5: fossil fuel development

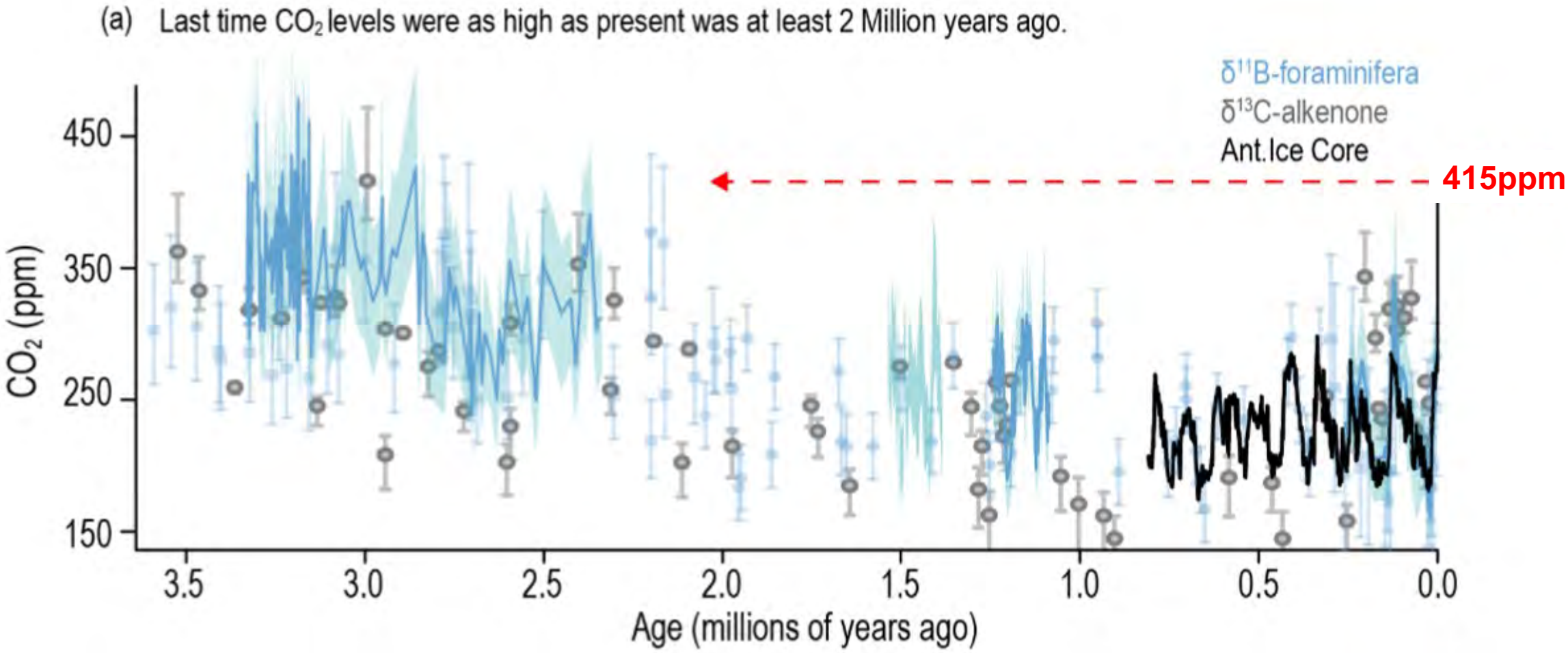
SSP3: regional rivalry

SSP2: middle of the road

SSP1: Sustainability – the green road

# $CO_2$ over the last 3 million years – highest now than any time in the past 2 million years!

BG



# Carottes de glace: Amplitude des cycles glaciaires

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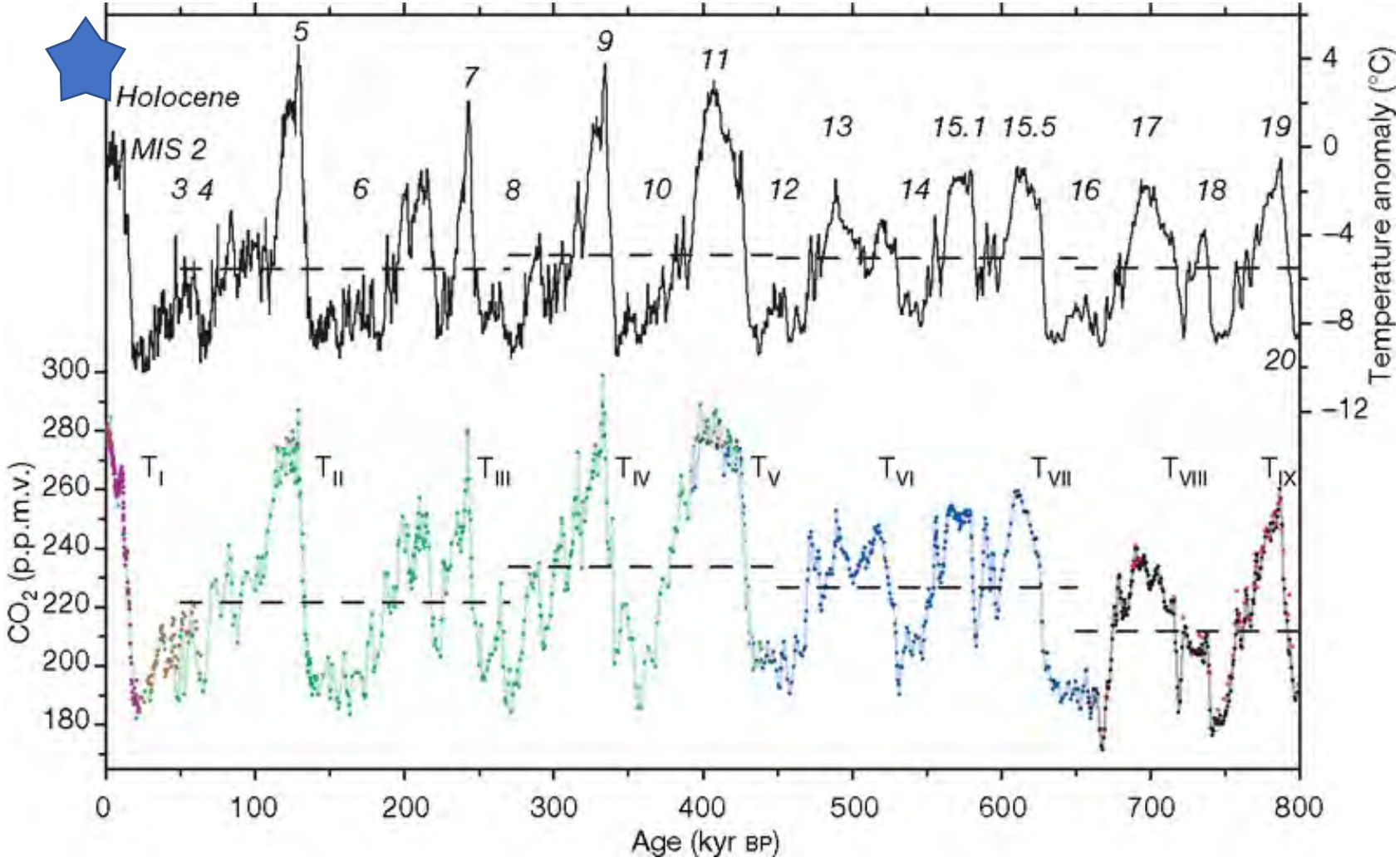
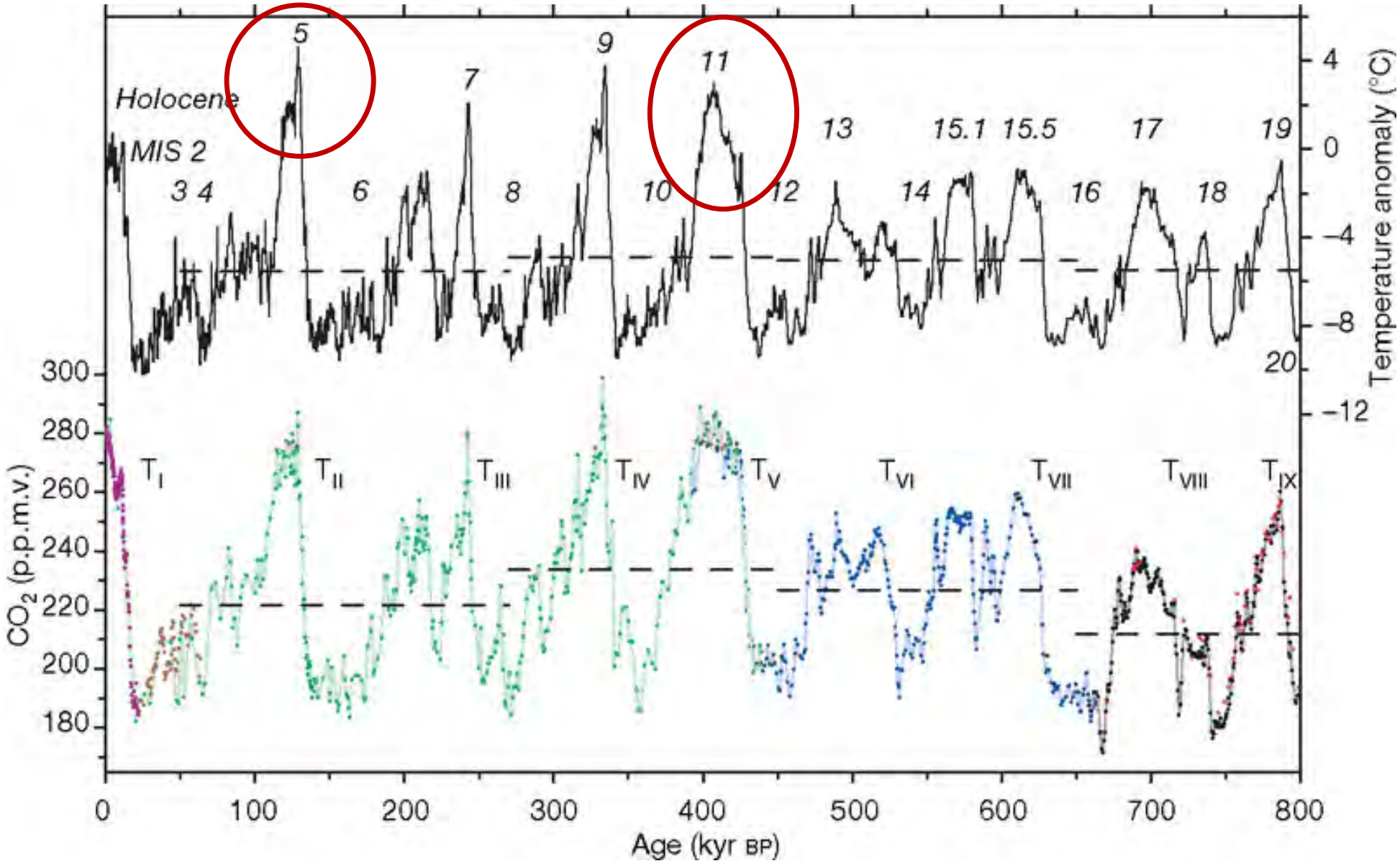


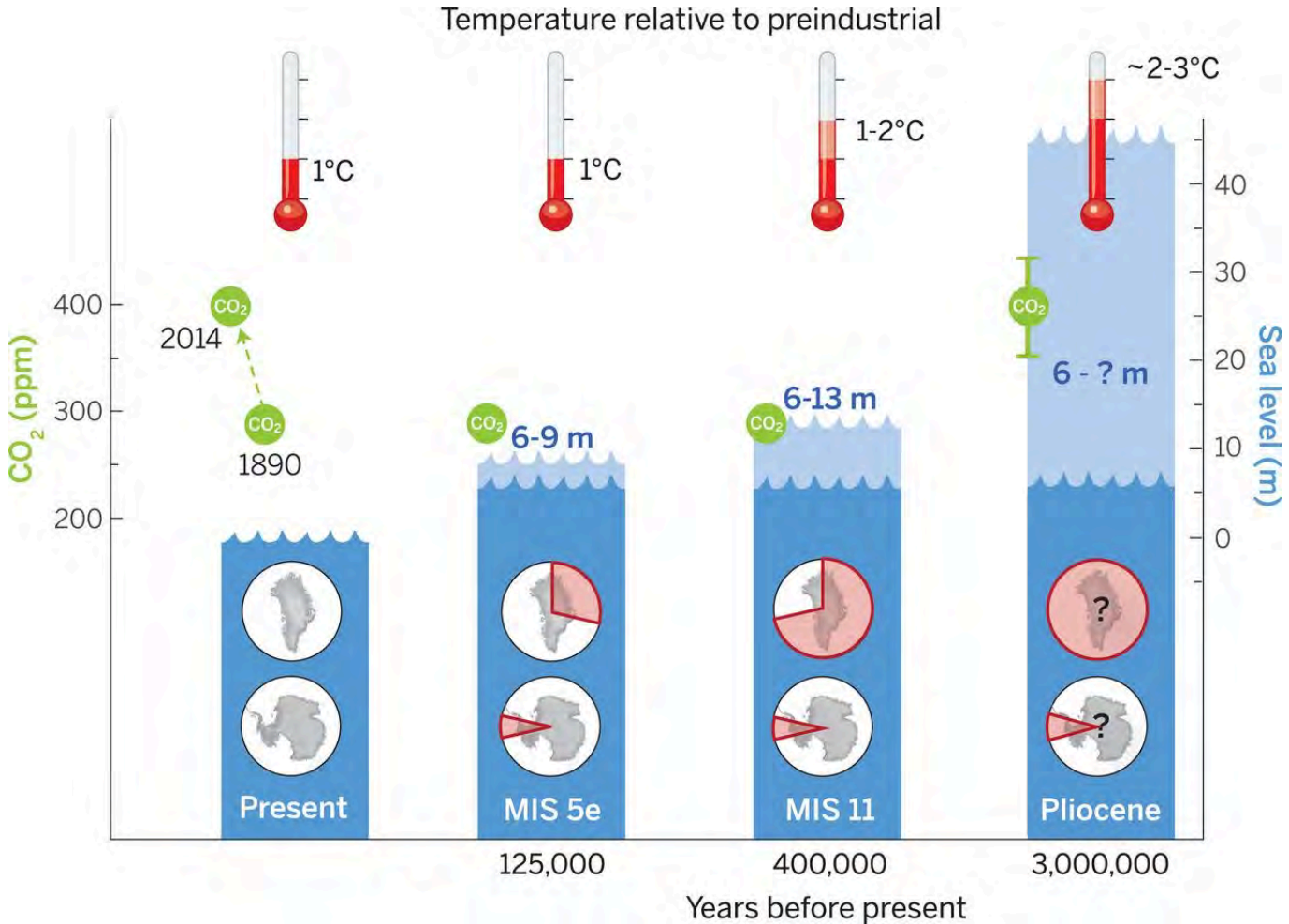

Amplitude des cycles glaciaires:
100ppm
10°C en Antarctique
5°C pour la planete
3°C pour les tropiques

# Les interglaciaires



# Niveau des mers dans les climats passés

Pendant le dernier interglaciaire (Eemien) il faisait 1-2°C plus chaud, le Groenland était 6°C plus chaud, et le niveau des mers 6-9m plus haut, mais seulement 2-4m viennent du Groenland.



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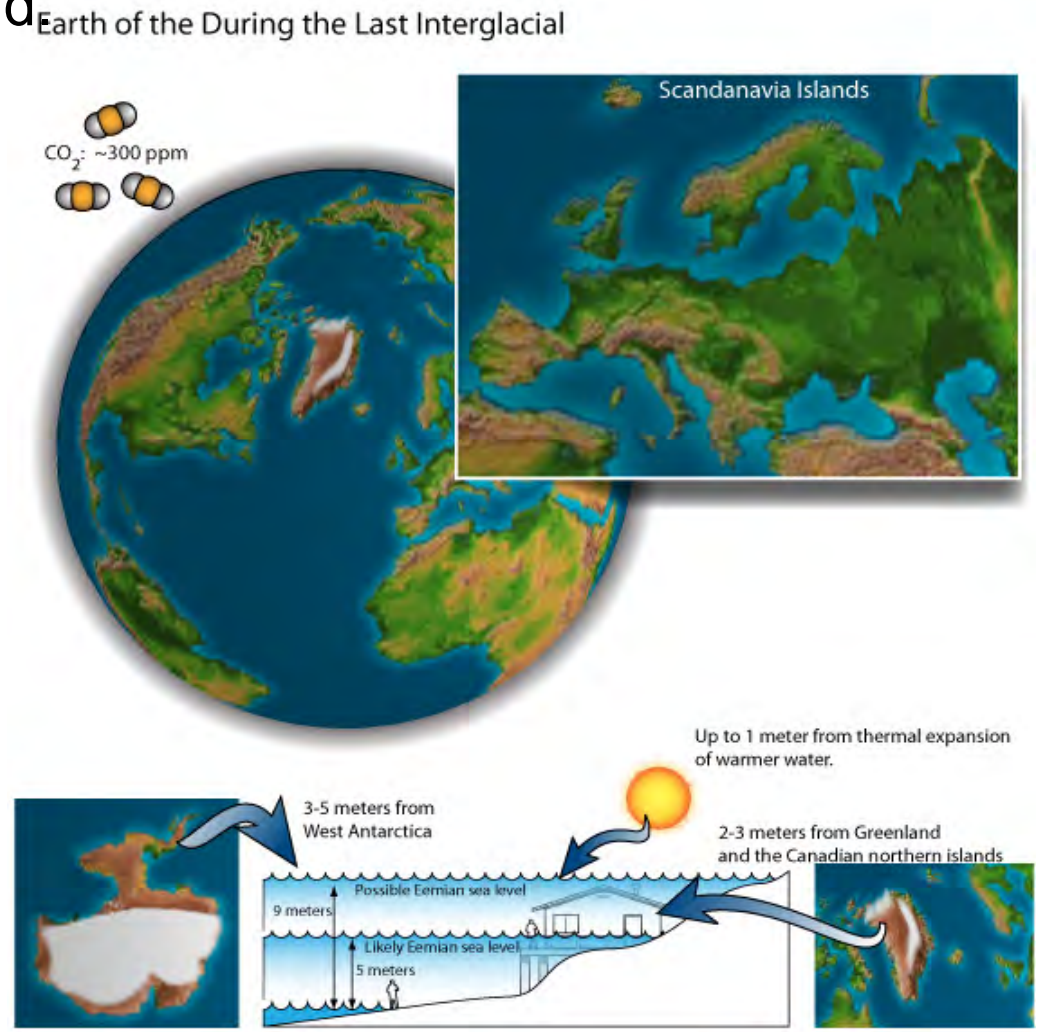



**Le risque majeur : les calottes basés sous le niveau de la mer, et l'antarctique de l'Ouest**

# Le risque majeur : les calottes basés sous le niveau de la mer

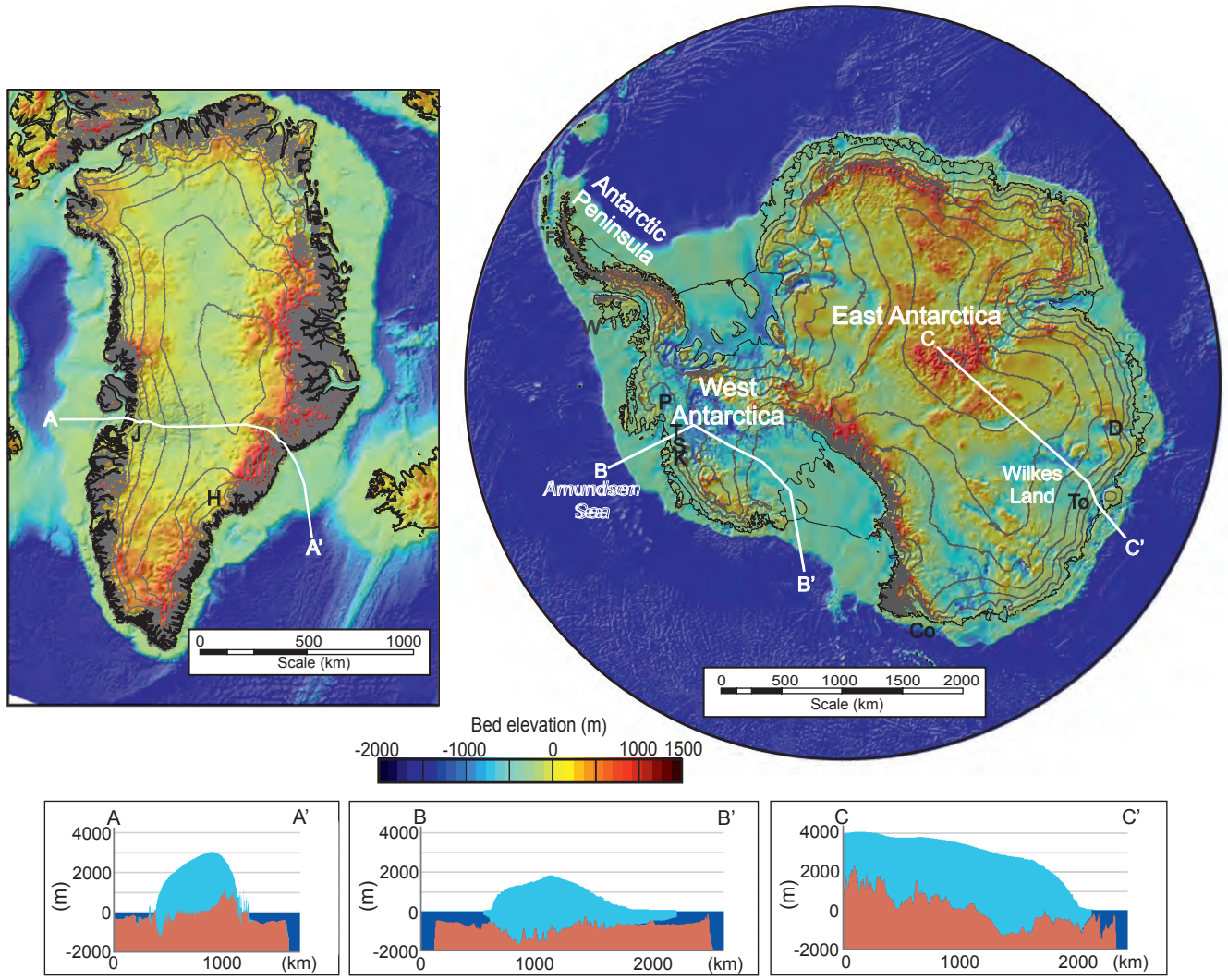
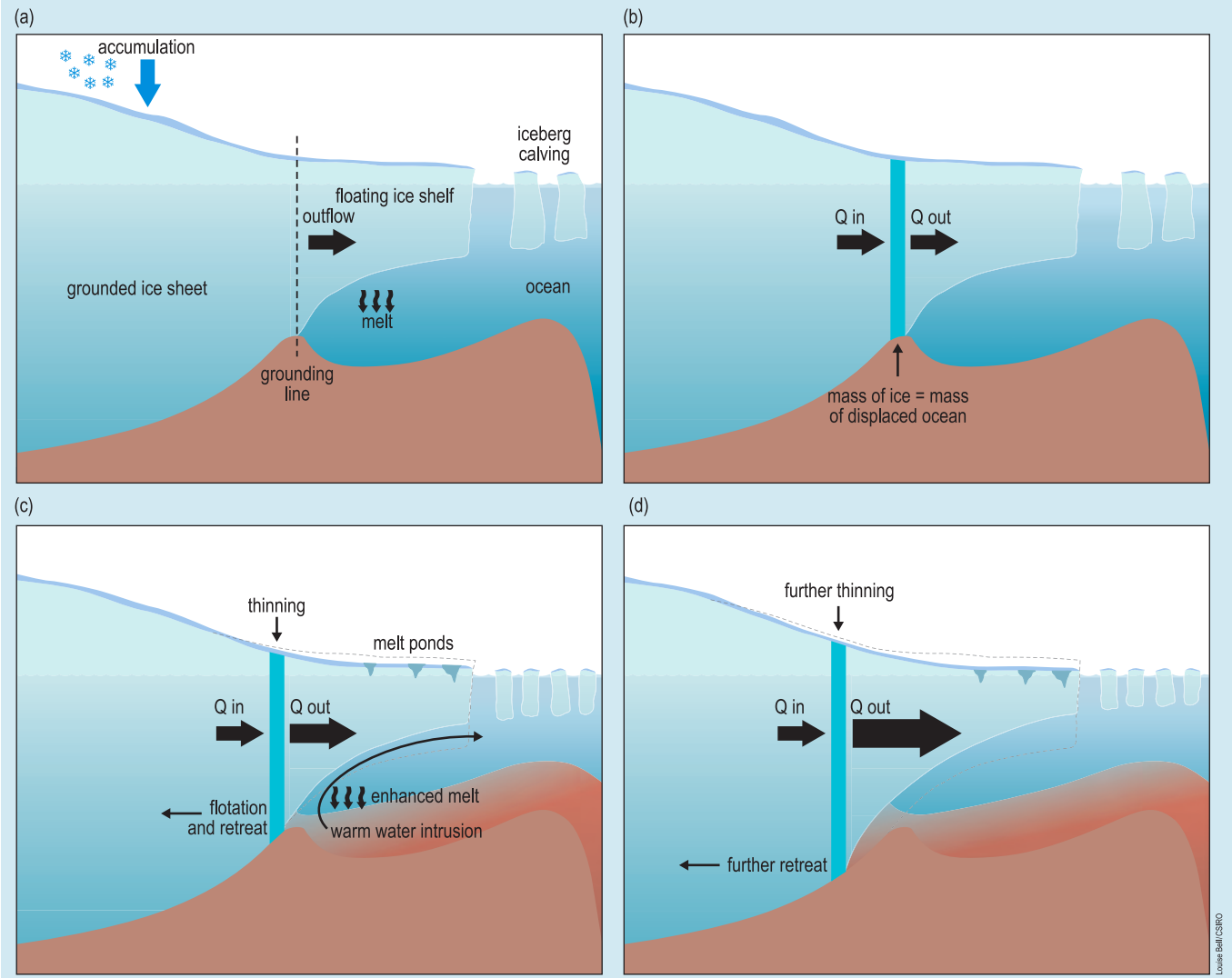


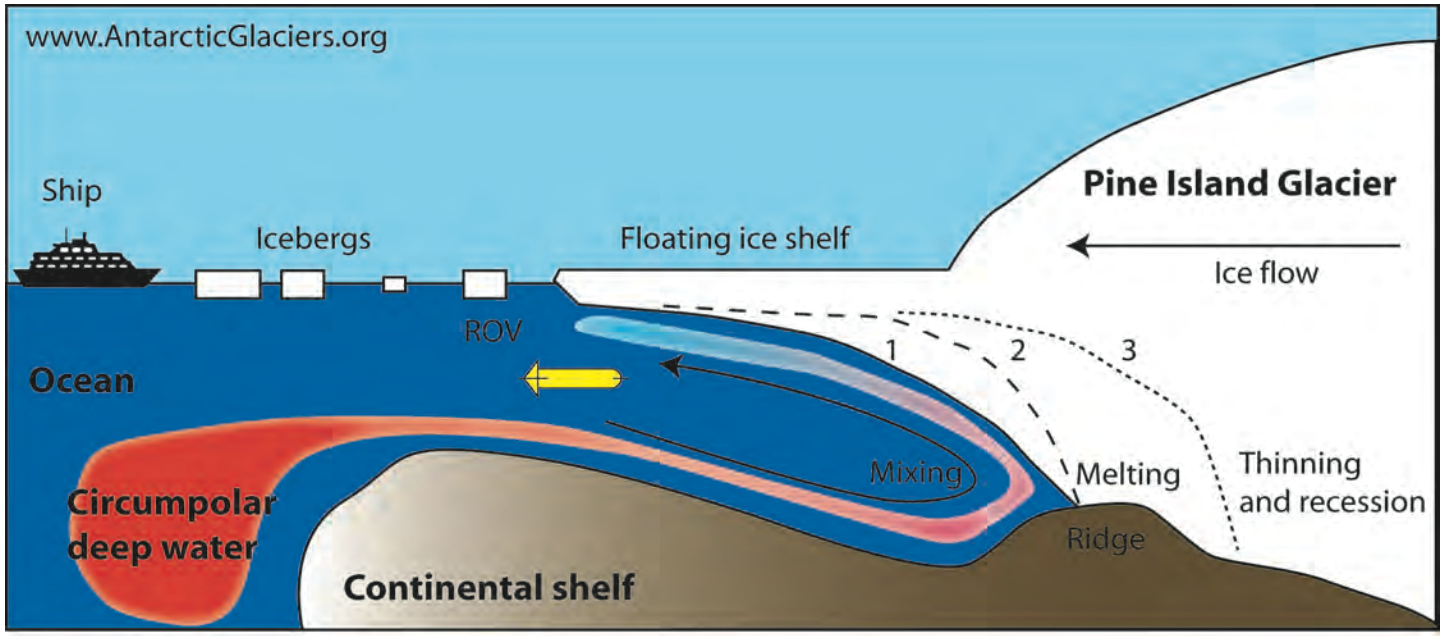

**Figure 4.18 |** Subglacial and seabed topography for Greenland and Antarctica derived from digital compilations (Bamber et al., 2013; Fretwell et al., 2013). Blue areas highlight the marine-based parts of the ice sheets, which are extensive in Antarctica, but in Greenland, relate to specific glacier troughs. Selected sections through the ice sheet show reverse bed gradients that exist beneath some glaciers in both ice sheets.

# Instabilité des calottes marines

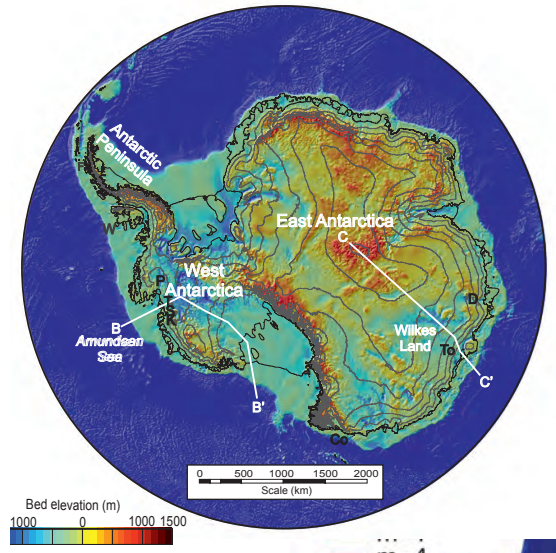


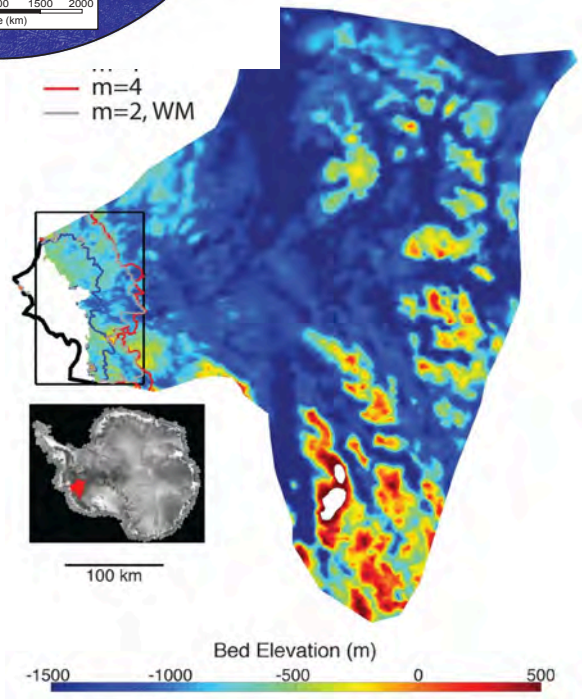

**Box 13.2, Figure 1 |** Schematic of the processes leading to the potentially unstable retreat of a grounding line showing (a) geometry and ice fluxes of a marine ice sheet, (b) the grounding line in steady state, (c) climate change triggering mass outflow from the ice sheet and the start of grounding line retreat and (d) self-sustained retreat of the grounding line.

# Zoom : Instabilité de l'Antarctique Ouest




1. Early 1970s. Pine Island Glacier is grounded at a bedrock ridge.
2. Warm, inflowing Circumpolar Deep Water melts the base of the glacier. The glacier steepens and accelerates.
3. Present day, observed by a remotely operated vehicle (ROV). Glacier is thinning and receding.



# Projections du niveau des mers

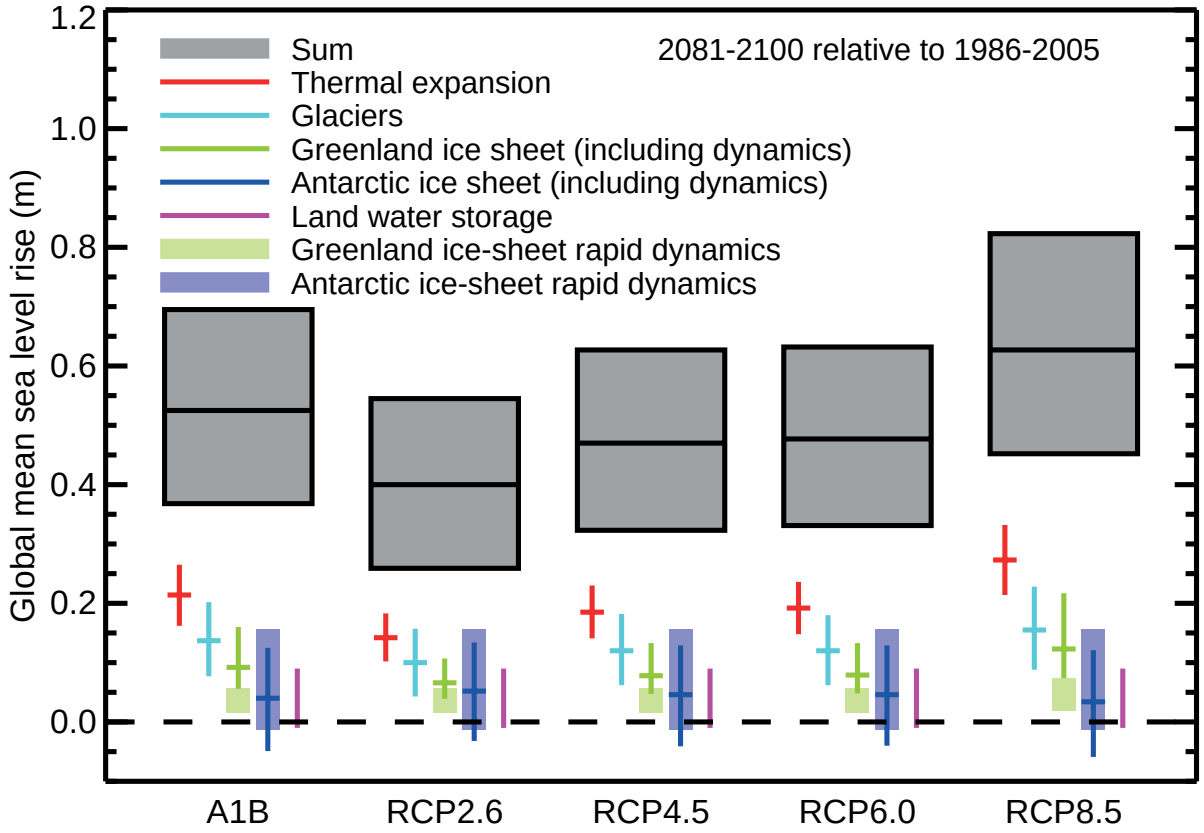
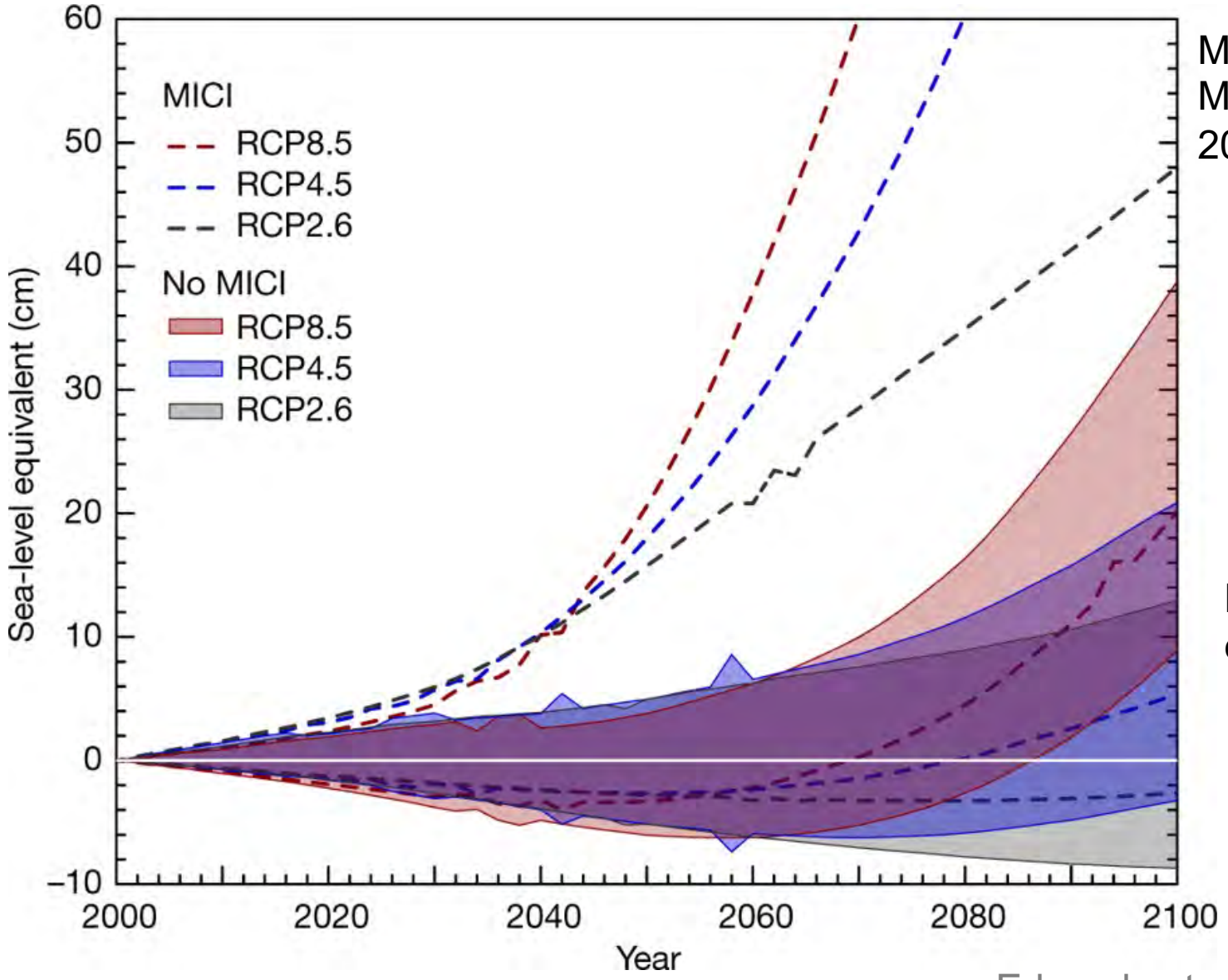



**Figure 13.10 |** Projections from process-based models with *likely* ranges and median values for global mean sea level rise and its contributions in 2081–2100 relative to 1986–2005 for the four RCP scenarios and scenario SRES A1B used in the AR4. The contributions from ice sheets include the contributions from ice-sheet rapid dynamical change, which are also shown separately. The contributions from ice-sheet rapid dynamical change and anthropogenic land water storage are treated as having uniform probability distributions, and as independent of scenario (except that a higher rate of change is used for Greenland ice-sheet outflow under RCP8.5). This treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. See discussion in Sections 13.5.1 and 13.5.3 and Supplementary Material for methods. Only the collapse of the marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level (GMSL) to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter of sea level rise.

# L’avenir de l’Antarctique est encore très incertain




Mécanisme MICI, De conto 2016

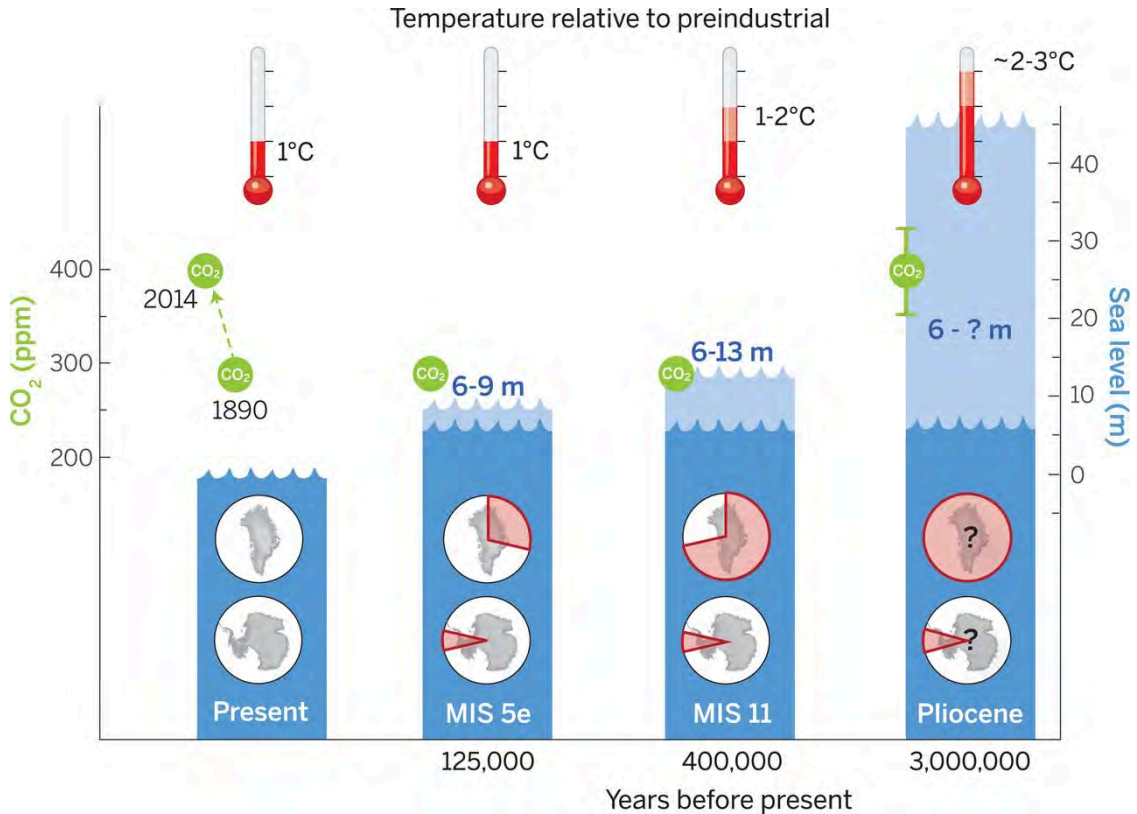
Nouvelles estimations

Edwards et al., Nature, 2019

# Conclusion sur les interglaciaires

Des “analogues” avec 2°C de réchauffement

Déjà, les conséquences sont importantes, notament pour le niveau des mers: 6-9m..



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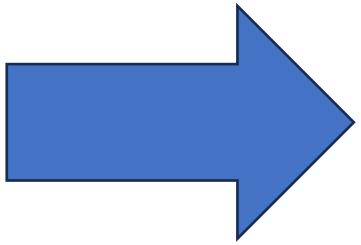
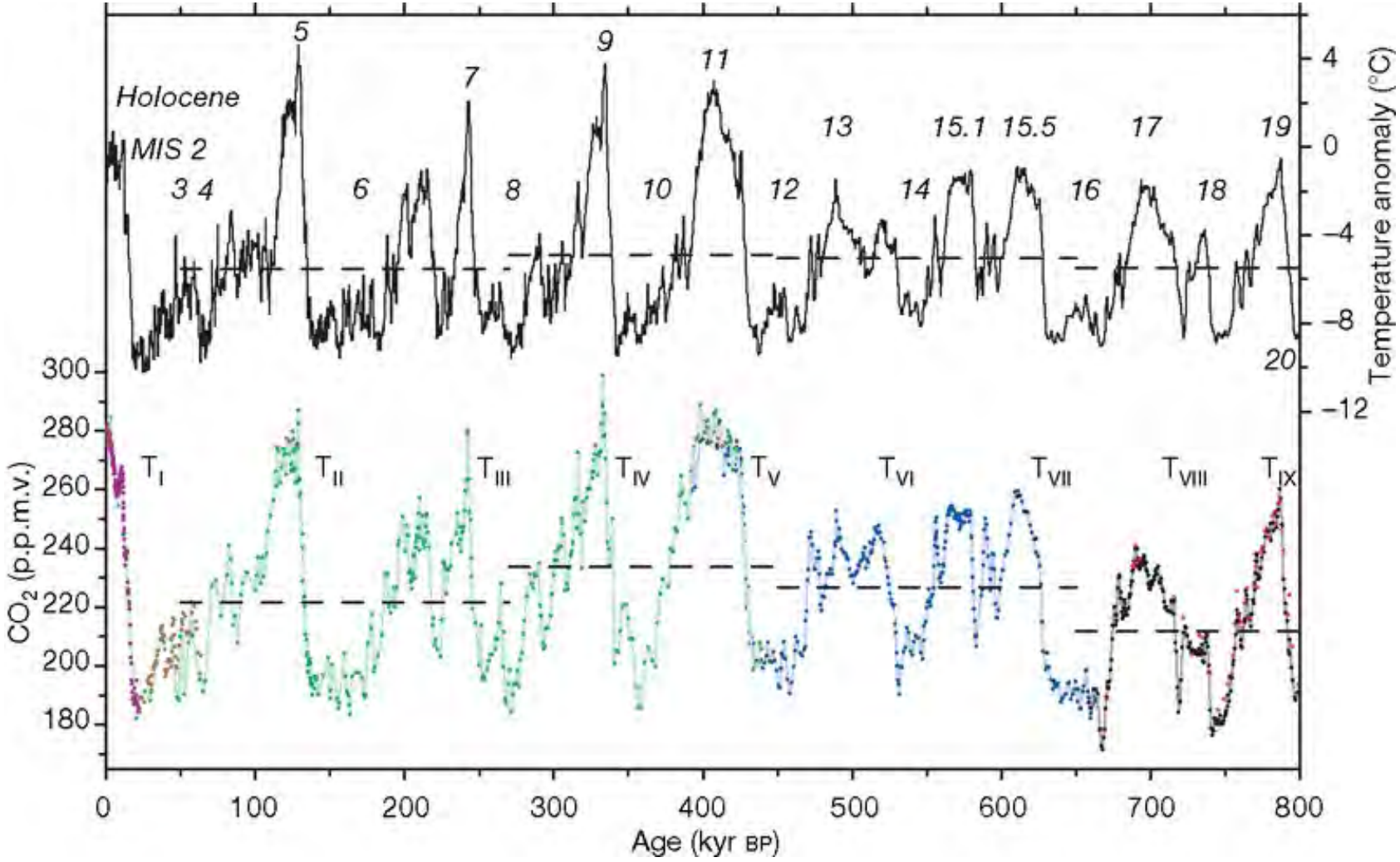


Mais on ne dit pas **à quelle vitesse** ces changements se sont produits.

# Vitesse du changement

- Les déglaciations sont plus rapides
- un cycle c'est 100ka, mais une déglaciation c'est 10ka




**Amplitude des cycles glaciaires:**
100ppm
10°C en Antarctique
5°C pour la planete
3°C pour les tropiques

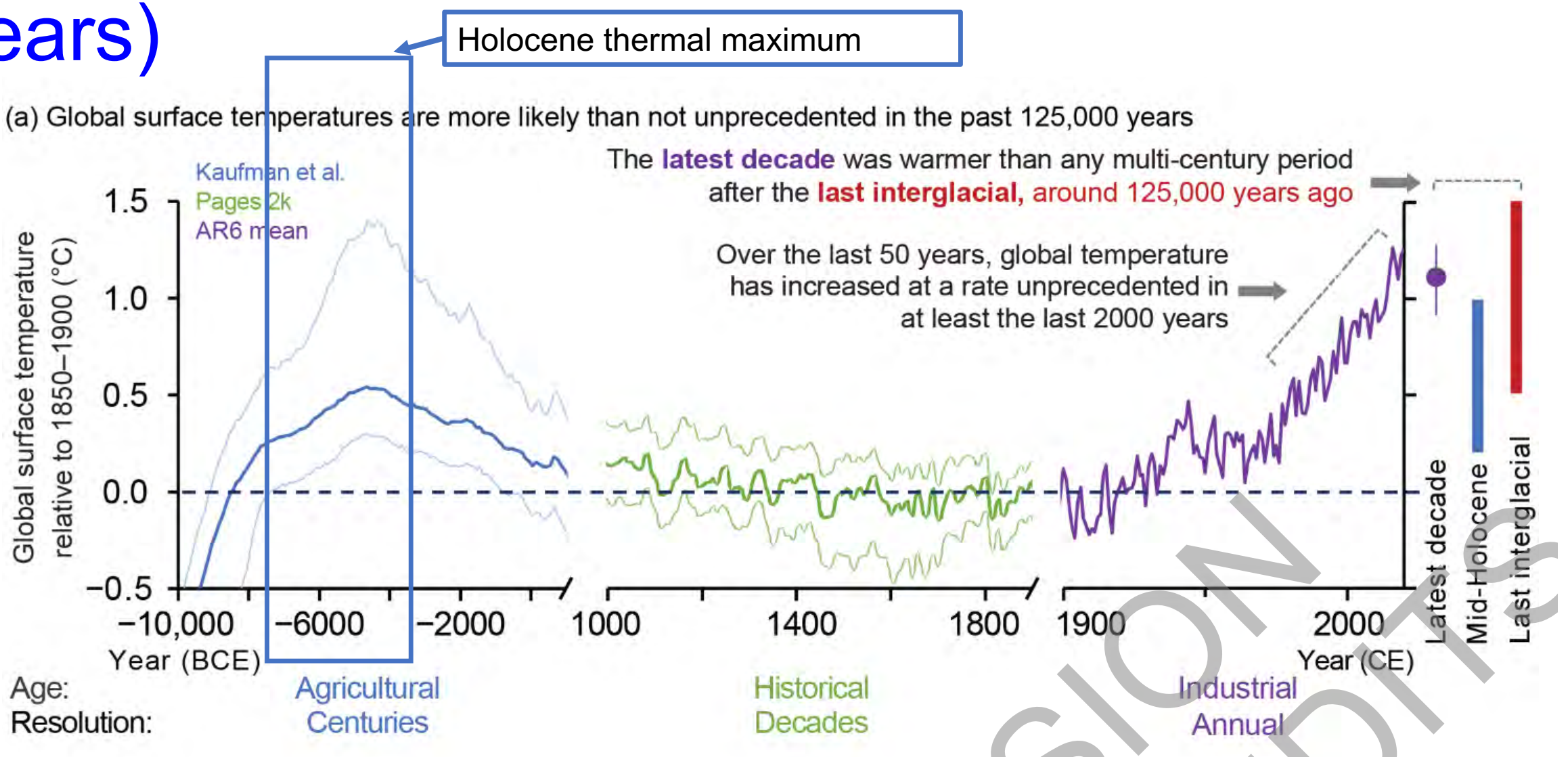
**Vitesse**:
5°C/10,000 ans

Aujourd'hui:
2-3°C/100 ans
**50 à 100x plus rapide!**

# Leçons de la glace:

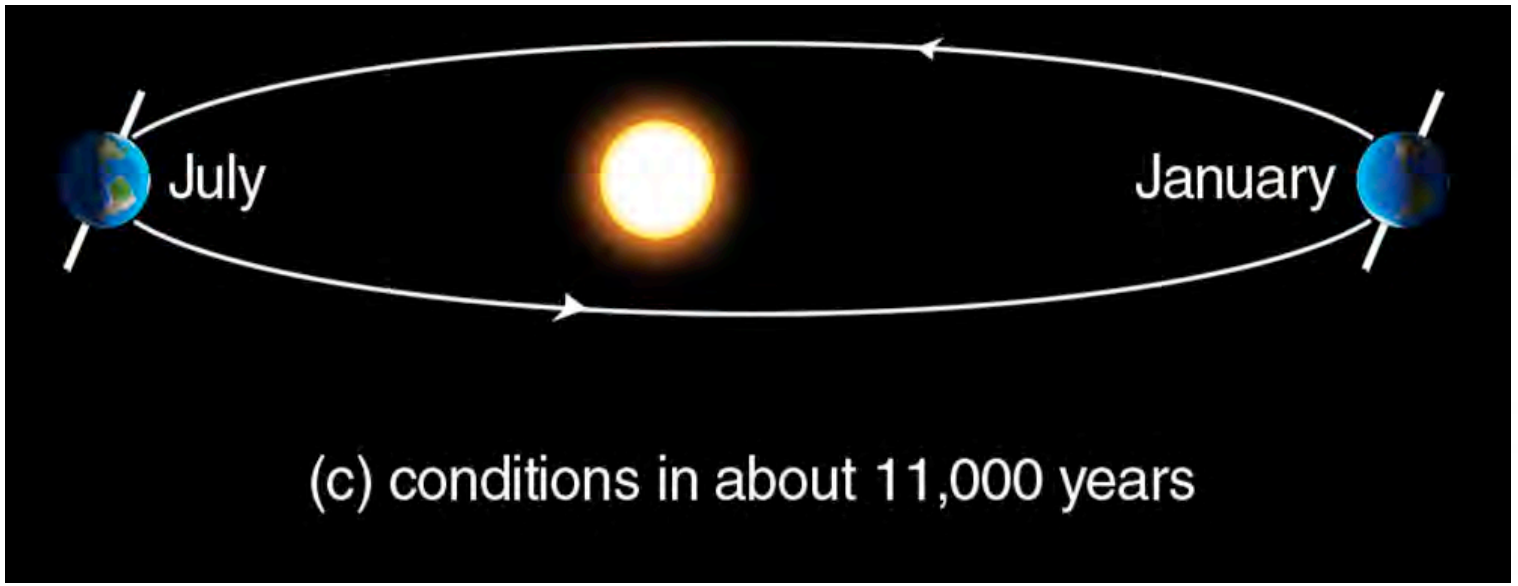
- Un cycle glaciaire c'est 100ppm, 10°C en Antarctique, 5°C pour la planete.
- La perturbation en $CO_2$ que nous imposons est déjà de 140ppm, et on parle de limiter à 200ppm. C'est énorme au vu du dernier million d'années.
- Le CO2 est important pour le climat: couplage climat carbone très fin.
- La planete a été 2°C plus chaude récement, et le niveau des mers était 6-9m au dessus du présent: 2°C, c'est déjà beaucoup! C'est une demi ère glaciaire
- La vitesse du réchauffement actuelle est 100x plus rapide que la vitesse du réchauffement pendant une déglaciation. Impacts sur les capacités d'adaptation de la biosphere.

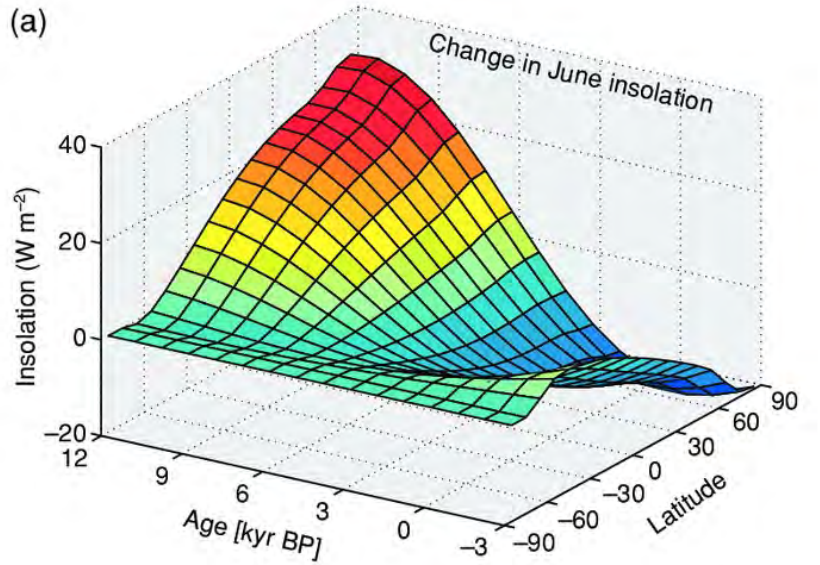
# Temperature of the **Holocene** (=last 10,000 years)

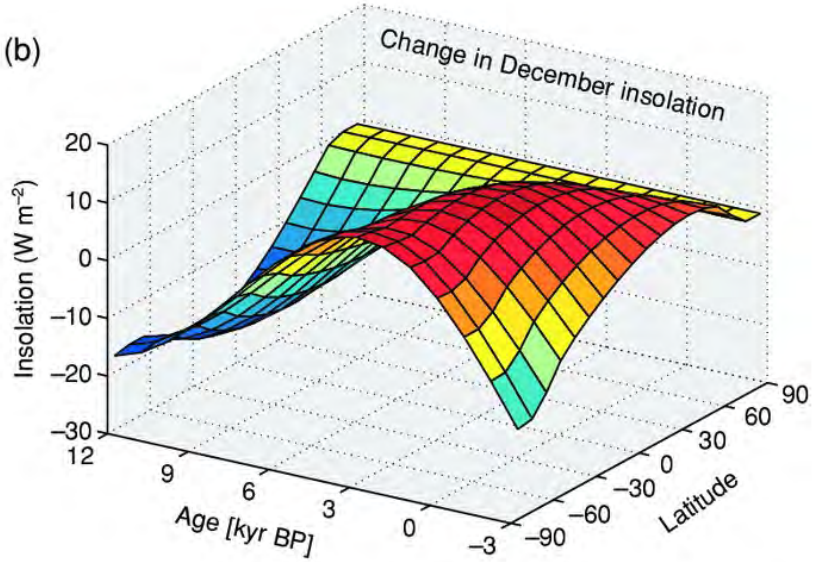


# Orbital forcing of Holcene climate variations

At the start of the Holocene, the orbital configuration made Northern Hemisphere seasons more intense.



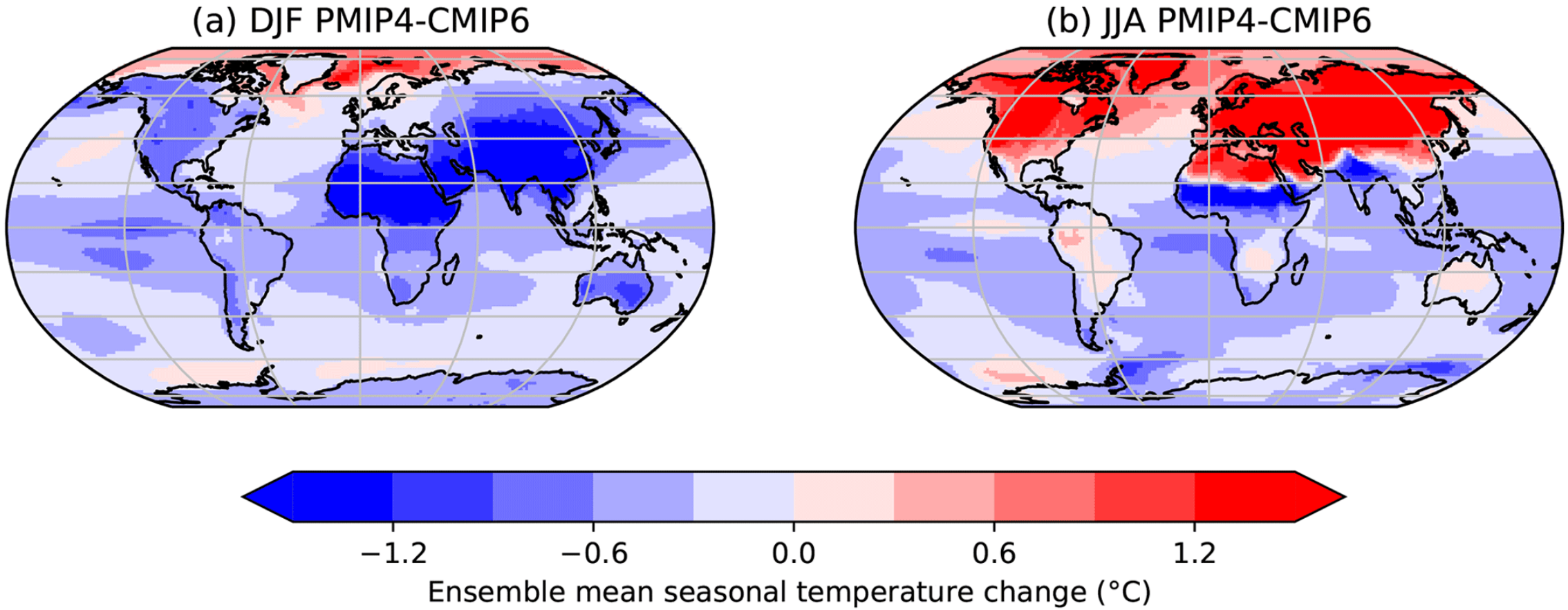



# Mid-Holocene temperature

Temperature change between the mid Holocene and the pre-industrial period.

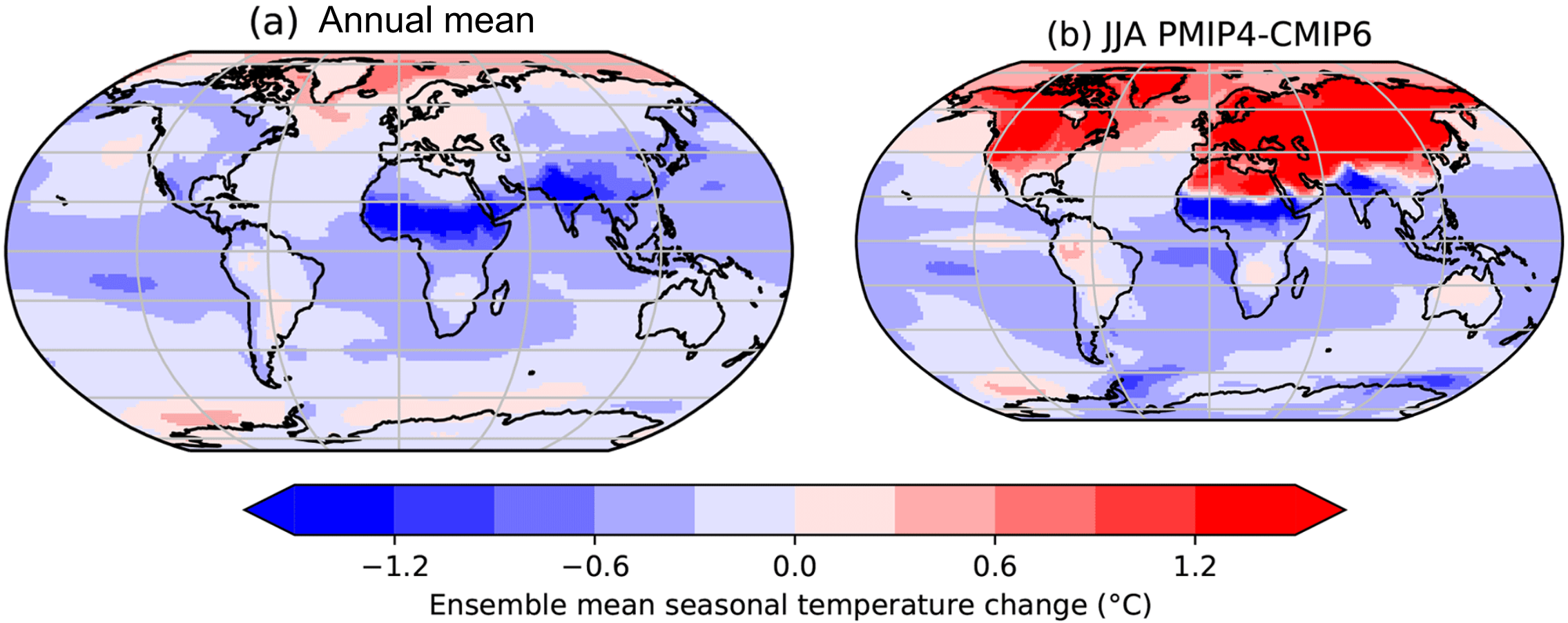
- Mostly Northern Hemisphere -> No homogeneous warming of the planet
- Mostly summer



# Mid-Holocene temperature

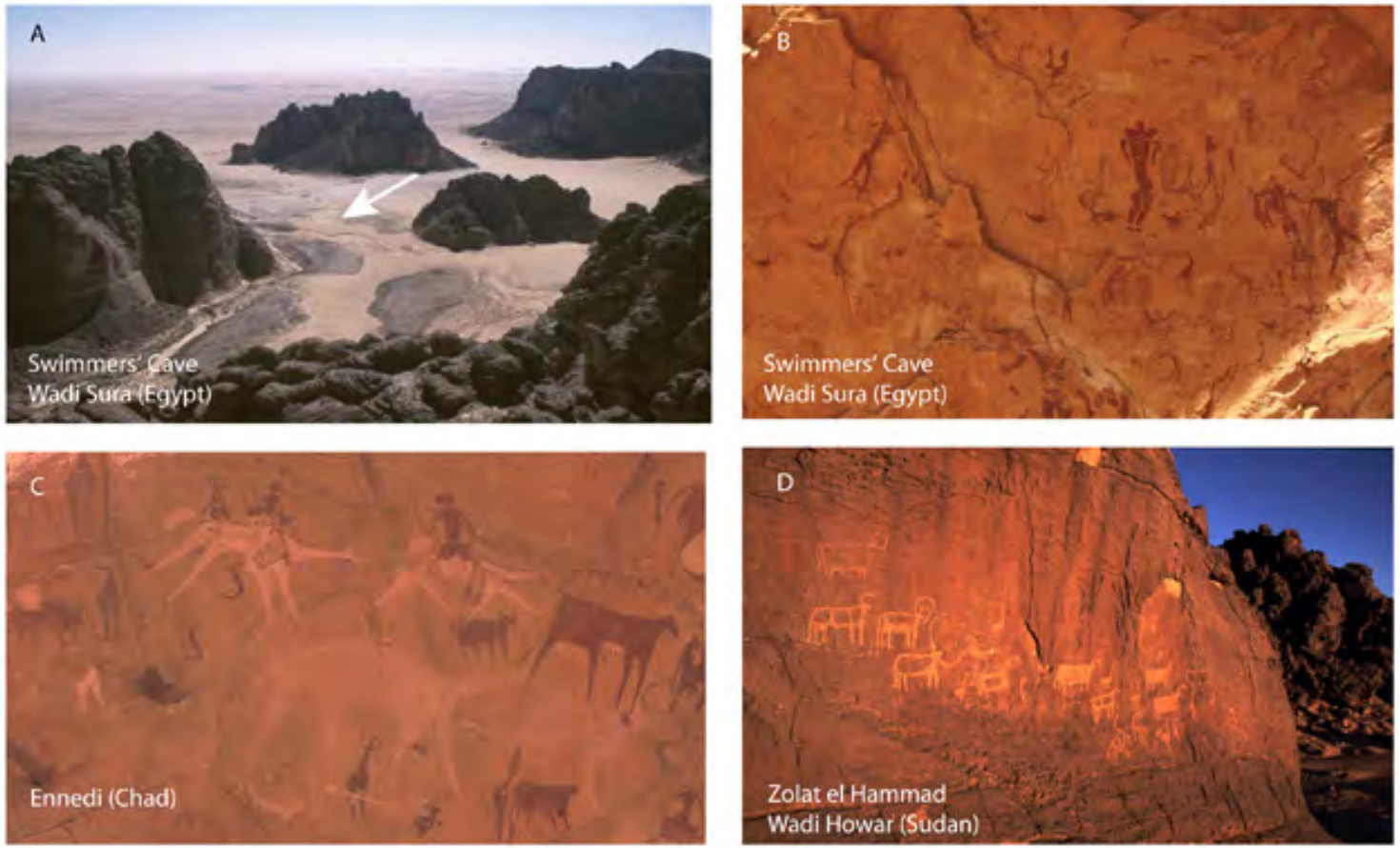
Temperature change between the mid Holocene and the pre-industrial period.

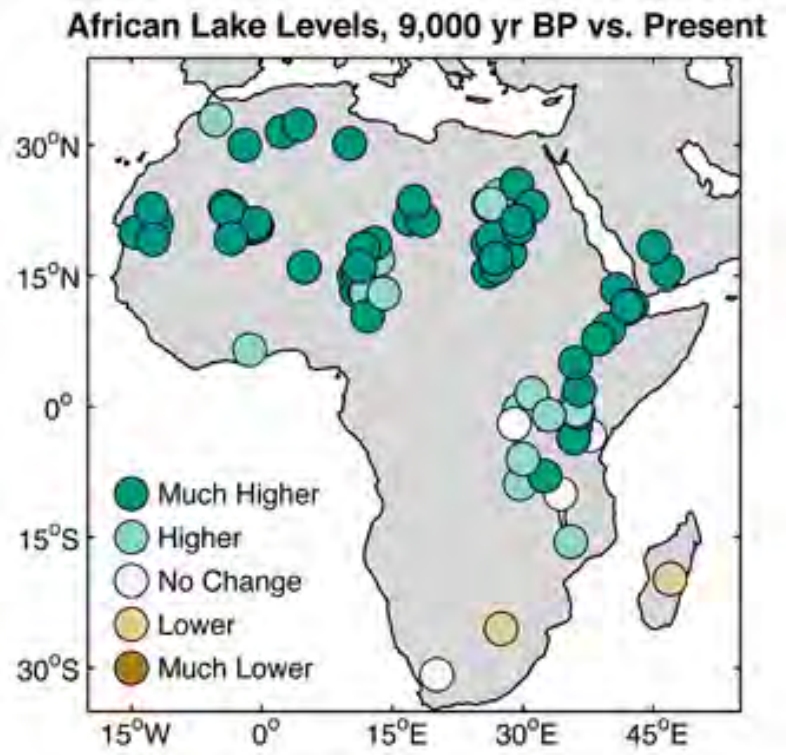
- Mostly Northern Hemisphere -> No homogeneous warming of the planet
- Mostly summer: on the annual mean, the effects are modest.



# The African Humid period

From about 10 to 5ka BP, the **Sahara desert was actually green**, with rivers, savanna.
This is due to the change in orbital parameters, that allowed the North African monsoon to reach further north.
Once it started, the vegetation albedo kicked in to prevent evaporation.



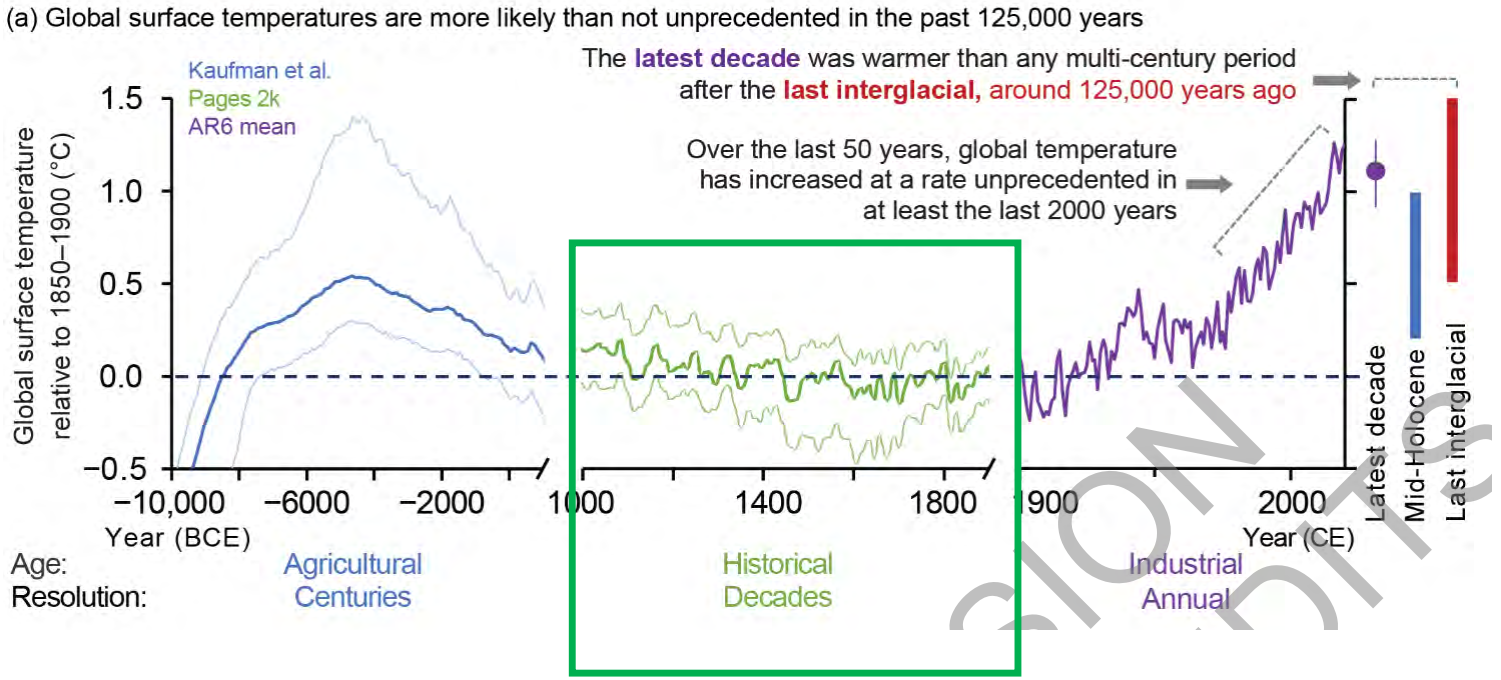

Distribution map of reconstructed lake levels across Africa, 9,000 years ago relative to today (Tierney et al., 2011)

https://www.nature.com/scitable/knowledge/library/green-sahara-african-humid-periods-paced-by-82884405/

Just 0.5°C of warming can have a dramatic impact on climate. Every half degree matters.

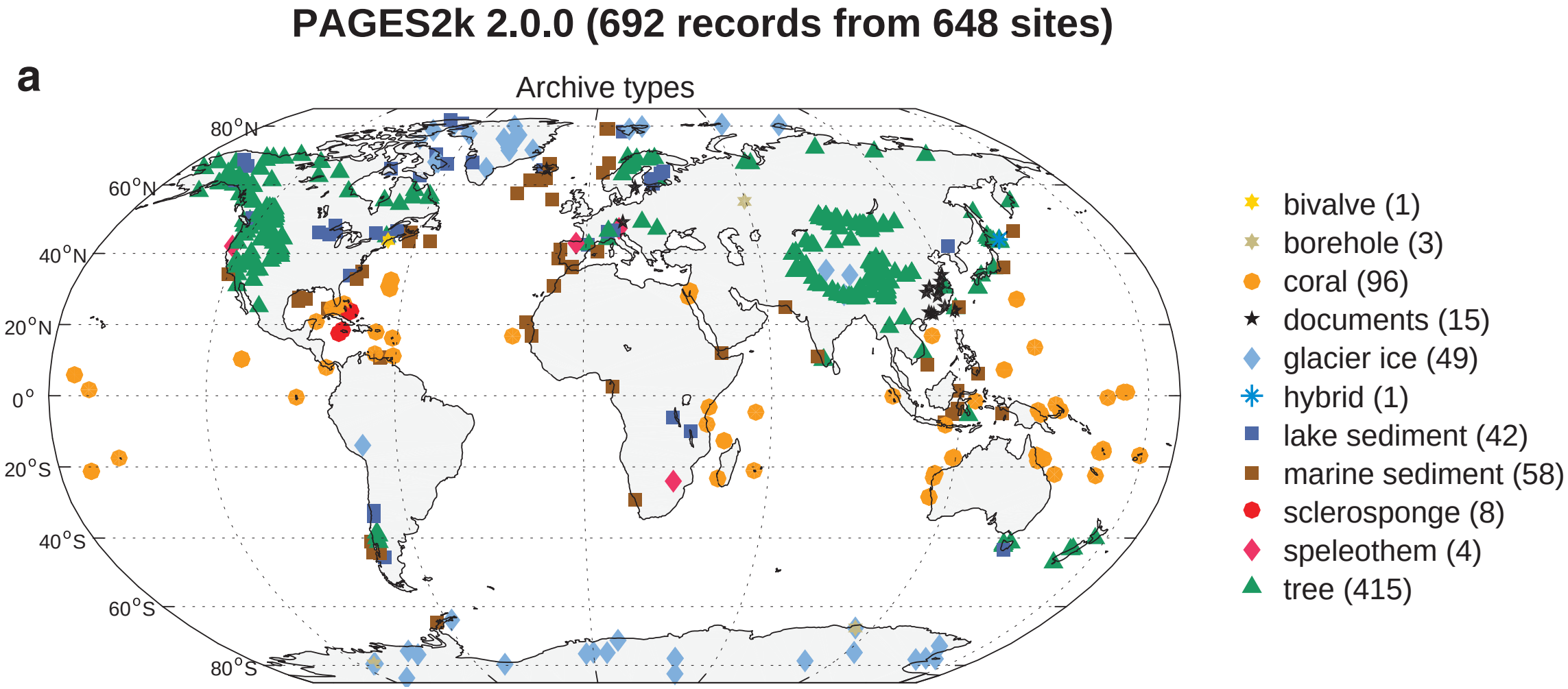
# Temperature of the early-mid **Holocene - summary**

- The early Holocene was warmer by 0.5°C on average. This warming was concentrated in Northern hemisphere summer, which was 1°C warmer than the preindustrial period.
- This trend is due to orbital forcing, with the precession cycle causing more intense NH season than now.
- The insolation forcing also explains the African humid period, when the Sahara desert was green.
- Since then, the Earth has been on a cooling trend that has recently reversed.



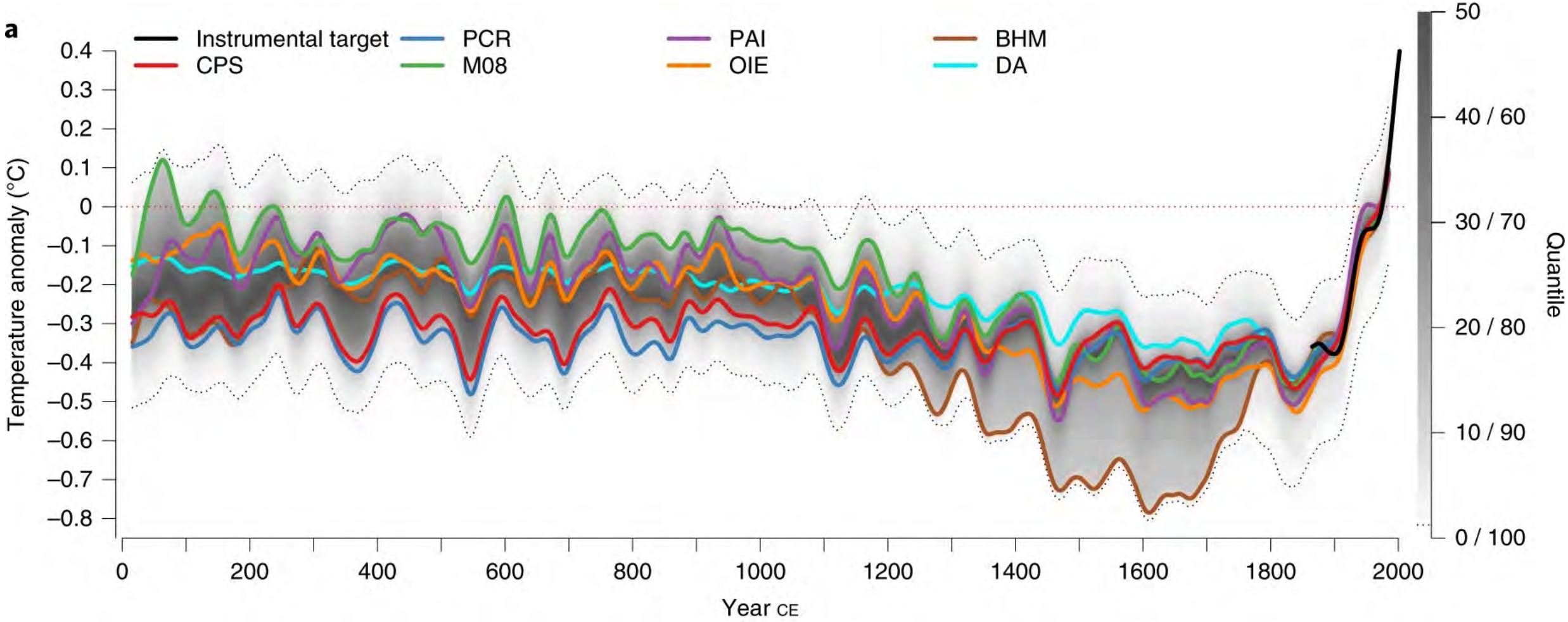
# Temperature over the last millennium

Better known than older periods: more proxies with annual resolution, especially tree rings



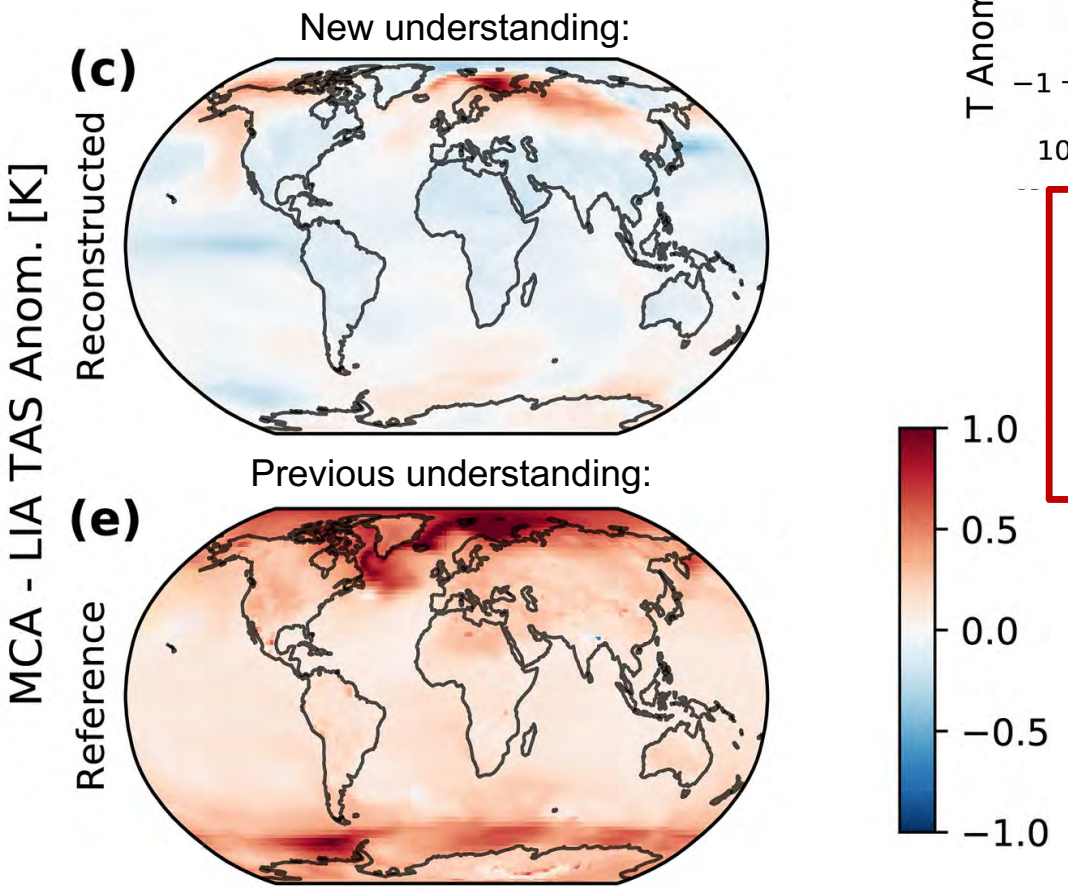
# Temperature over the last millennium

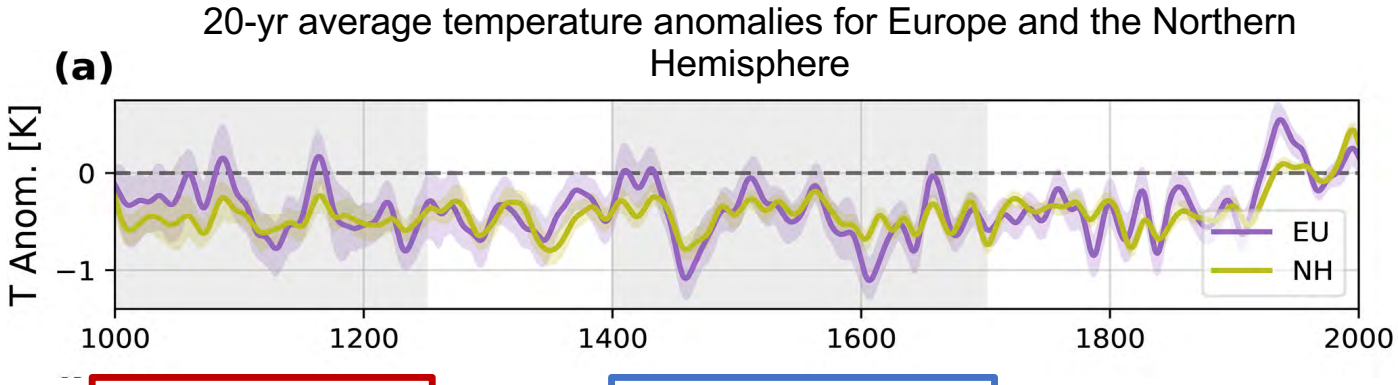
Little wiggles represent **internal variability :** the natural chaotic noise of the climate system.
When we average climate over a long time, this noise disappears, and the trends are more clear.
**The recent trend is clearly out of range of the envelope of internal variability.**



# Spatial patterns of temperature changes over the last 2000 years

Temperature anomaly between the MCA and the LIA




MCA:
The medieval climate anomaly
1000-1250

LIA:
The little ice age
1400-1800

- The terms MCA and LIA refer to “old” understanding, based on data from Europe. These terms are deprecated.
- Now we know that we did not have globally coherent warm and cold periods during the last millennium.
- The maximum difference between the warmest and coldest periods of the last millennium is on the order of **0.5°C.**

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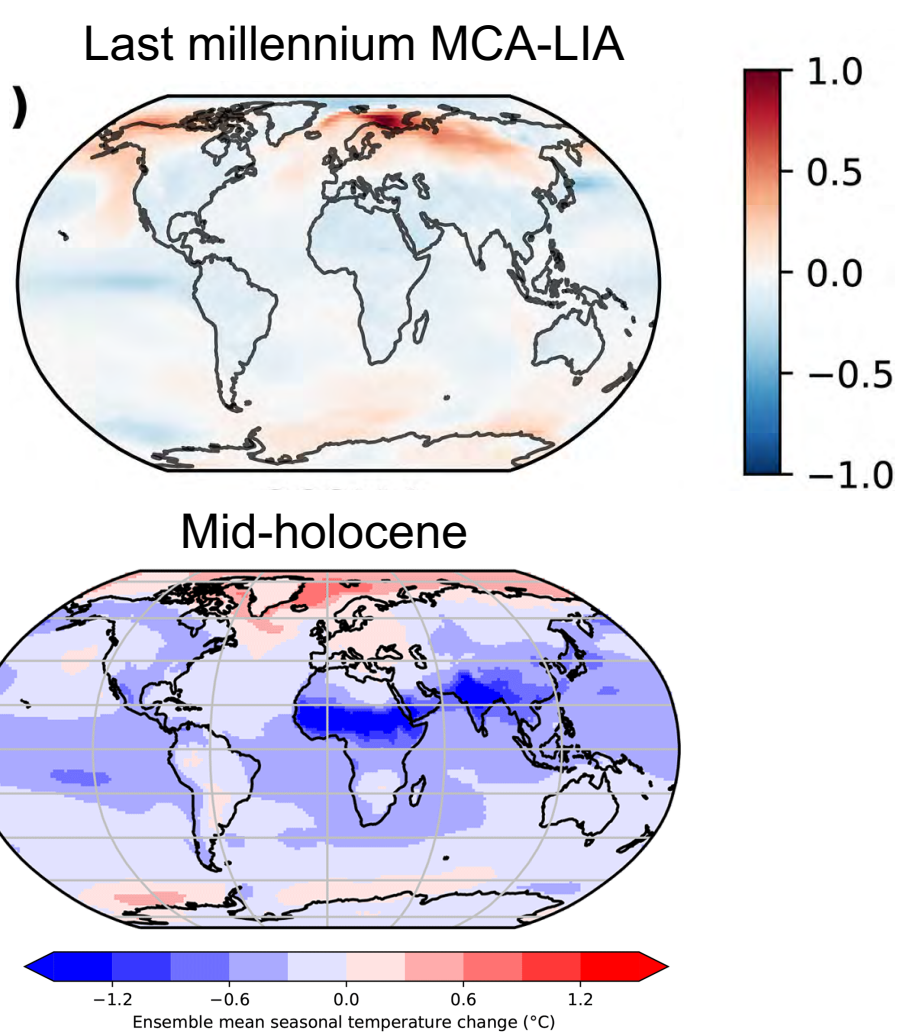
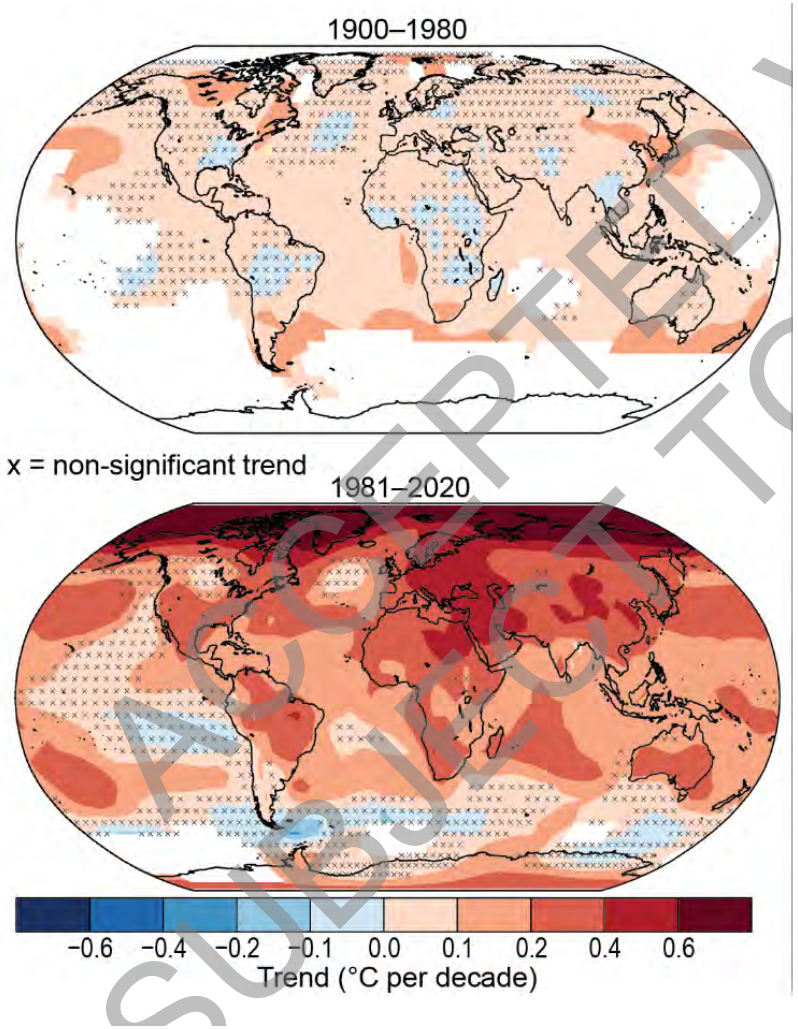
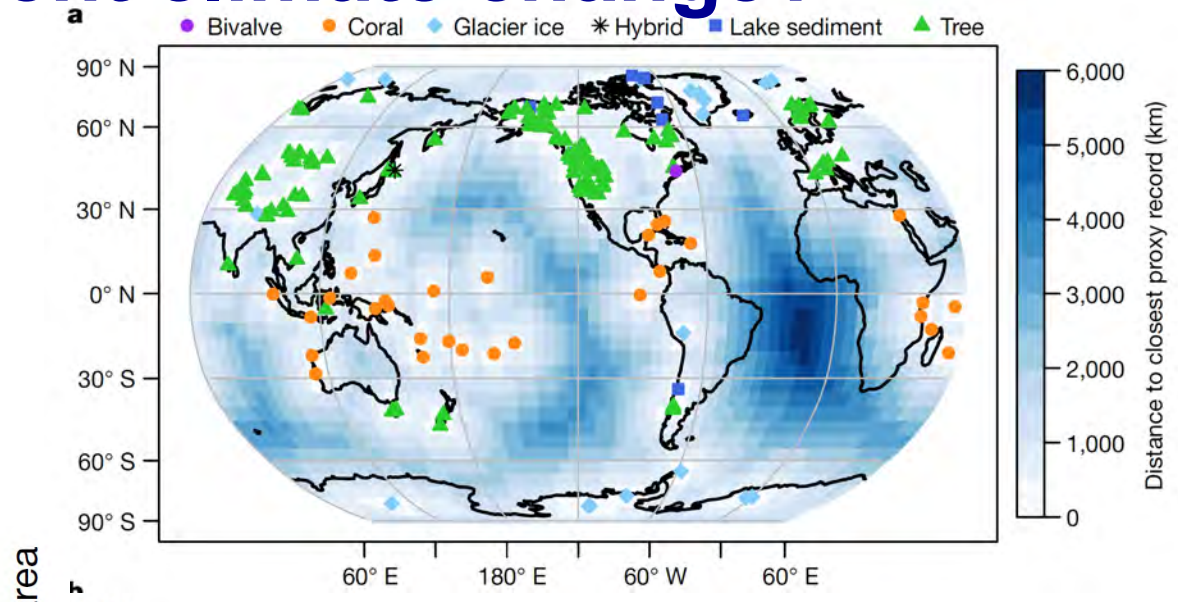
# The recent warming trend is more spatially homogeneous than any other warm interval

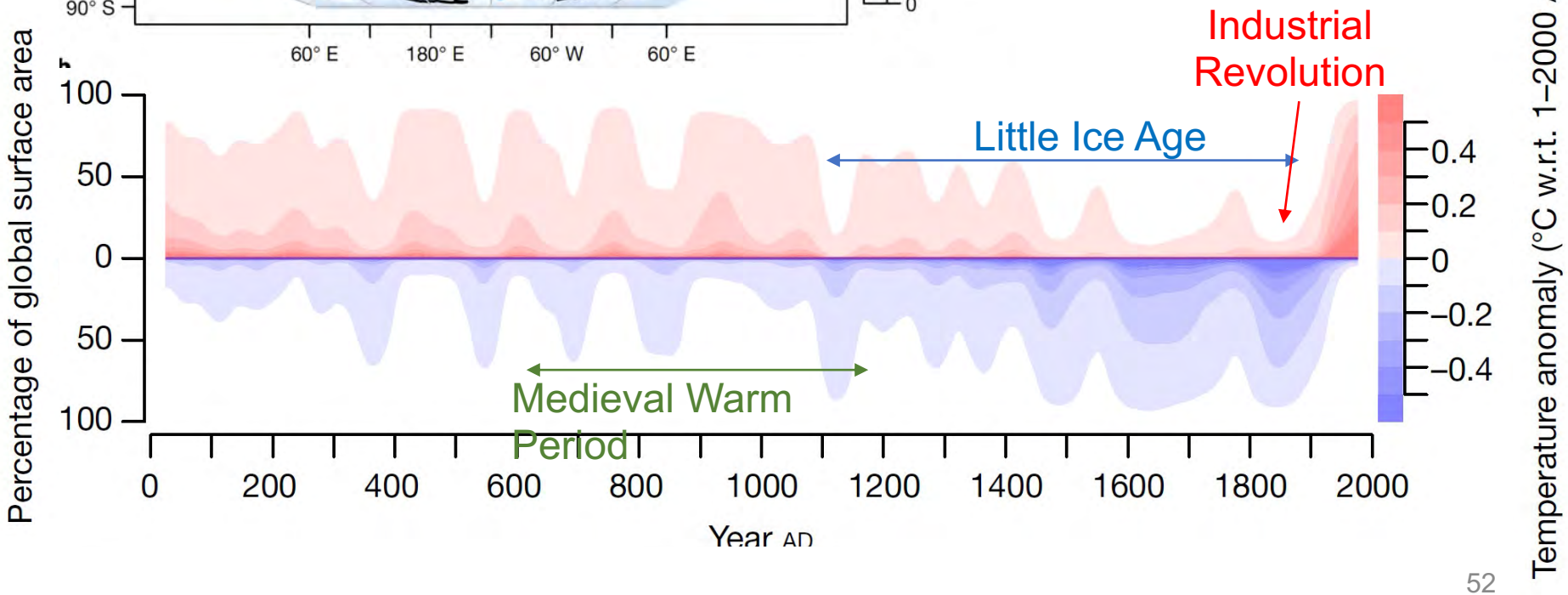


# What about the Medieval warm period as an analogue for recent climate change?




Only since the industrial revolution have temperatures been rising EVERYWHERE at the SAME TIME



# Leçons de l'Holocene

- L'holocene, les 10,000 dernières annés, est la période du développement de l'agriculture.
- Le climat a été particulièrement stable, variations <1°C.
- Le début de l'holocène était plus chaud dans l'hémisphere Nord, en été, là où nous avons des données..
- 0.5°C de différences, ca donne la période humide africaine, il y a 6ka.
- **=> Chaque demi degré compte!**
- Les 1000 dernières années sont utiles pour quantifier la variabilité interne du climat: la période récente est en dehors.
- Le réchauffement récent est la seule période avec un réchauffement cohérent entre les 2 hémisphere. Ca montre qu'il est forcé et non dominé par la variabilité interne.

# Ce que le paléoclimat révèle des mutations du monde

Est-ce que notre réchauffement est réellement en dehors des fluctuations naturelles du climat ?

Est-ce que la planète a déjà été plus chaude ?

A quoi ressemble la planète Terre à 2°C de plus ?

Comment comparer l'amplitude et la vitesse du réchauffement actuel aux fluctuations climatiques passées ?

# Ce que le paléoclimat révèle des mutations du monde

Le réchauffement climatique, ce n’est pas une blague.

Ne baissons pas les bras, chaque demi degré compte.

Et pensons sérieusement à l’adaptation. Il n’y a pas le choix.