GREENHOUSE CLIMATE

Source images: Ruddiman, 2007 (Chapter 5)

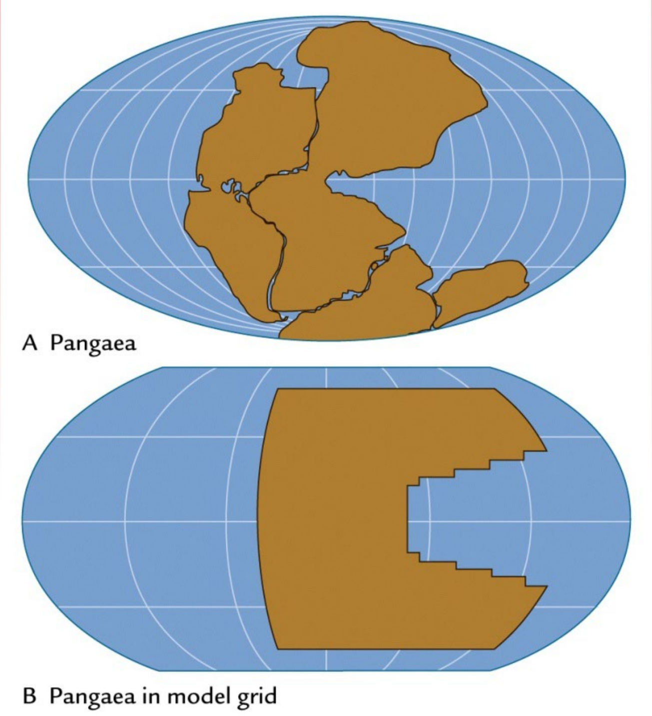
SUPERCONTINENT PANGEA MODELLING

Pangea = supercontinent (250-180 Myr ago)

Model GCMs

BOUNDARY CONDITION

(1) The symmetry between the northern and southern hemisphere
(2) The sea level is similar to the present one
(3) Distribution of topography (plateau of 1000m)
(4) CO_2 levels. CO_2 levels are not known directly. The model uses a value of 1650 ppm



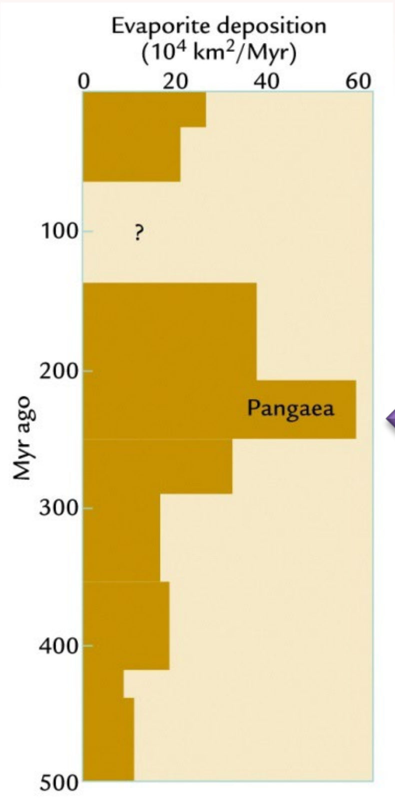
KNOWN INFORMATION (INDEPENDENT GEOLOGIC DATA)

- The sun was weaker (-1%)
- There was no geological evidence of ice at the poles (mild climate).
- Fossil vegetation suggests a freezing limit at ~40°N, higher than the present day (30°N).

MODEL RESULTS - 1

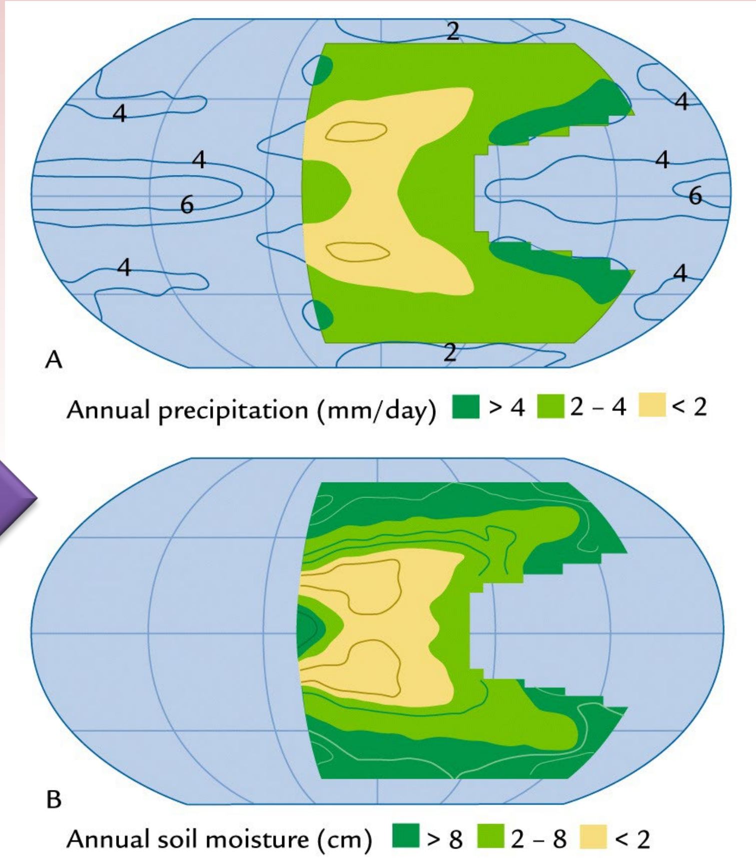
The arid climate in Pangea's interior stems from extensive tropical land expansion, caused by:

- Trade winds releasing moisture as they cross the continent
- Shifts in the Hadley cell



MODEL

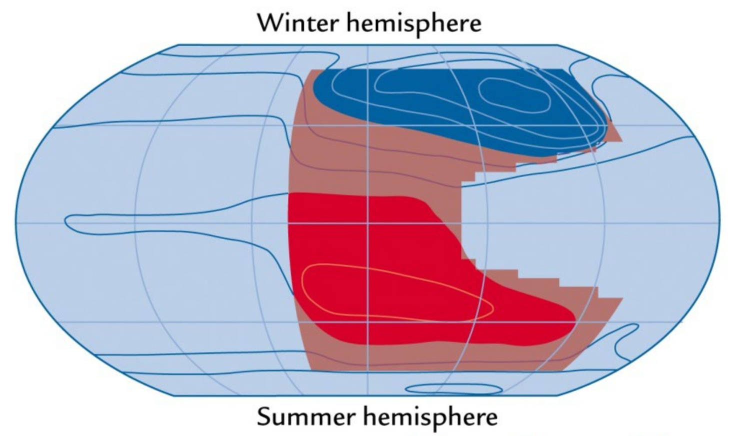
INDIPENDENT GEOLOGIC DATUM

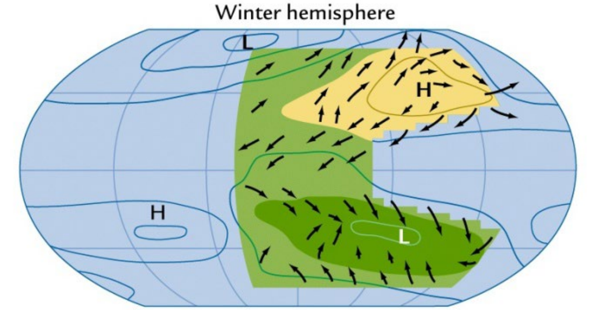


The geological record supports the models: widespread evaporites indicate an arid climate (evaporation > precipitation).

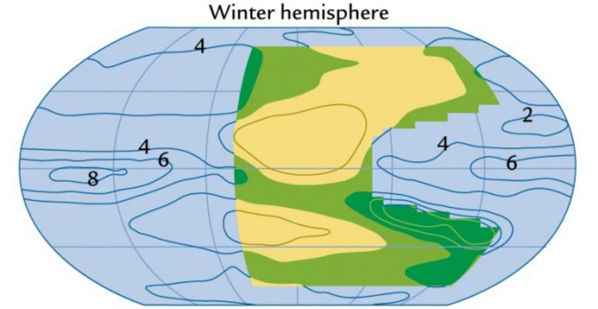
MODEL RESULTS - 2

The model predicts s**trong seasonal contrasts**, with severe winters and snow accumulation, followed by extremely hot summers that melt the snow. It projects freezing conditions at 40°N.





A Seasonal pressure and winds



B Seasonal precipitation (mm/day)

The model predicts a "**SUPERMONSOONIC**" regime driven by shifts in pressure and wind direction.

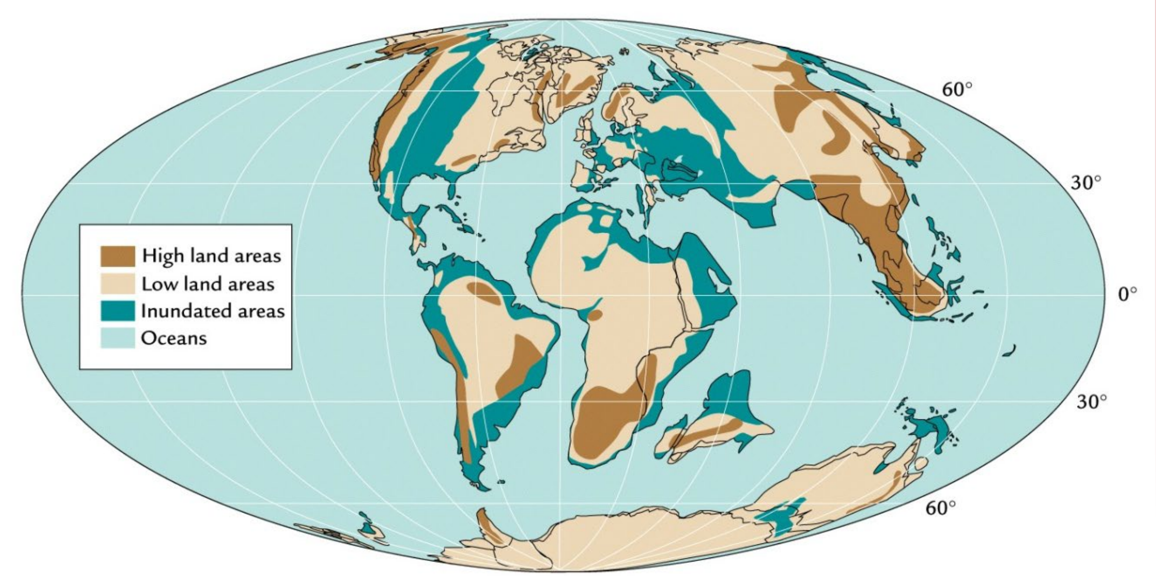
Rainfall:
Dry/arid conditions in continental winters
Humid conditions in continental summers

THE WORLD 100 MILLION YEARS AGO

PALEOGEOGRAPHY:

•Most modern continents were already separated.

•Sea level was 100 meters higher than today.



PALEOCLIMATE:

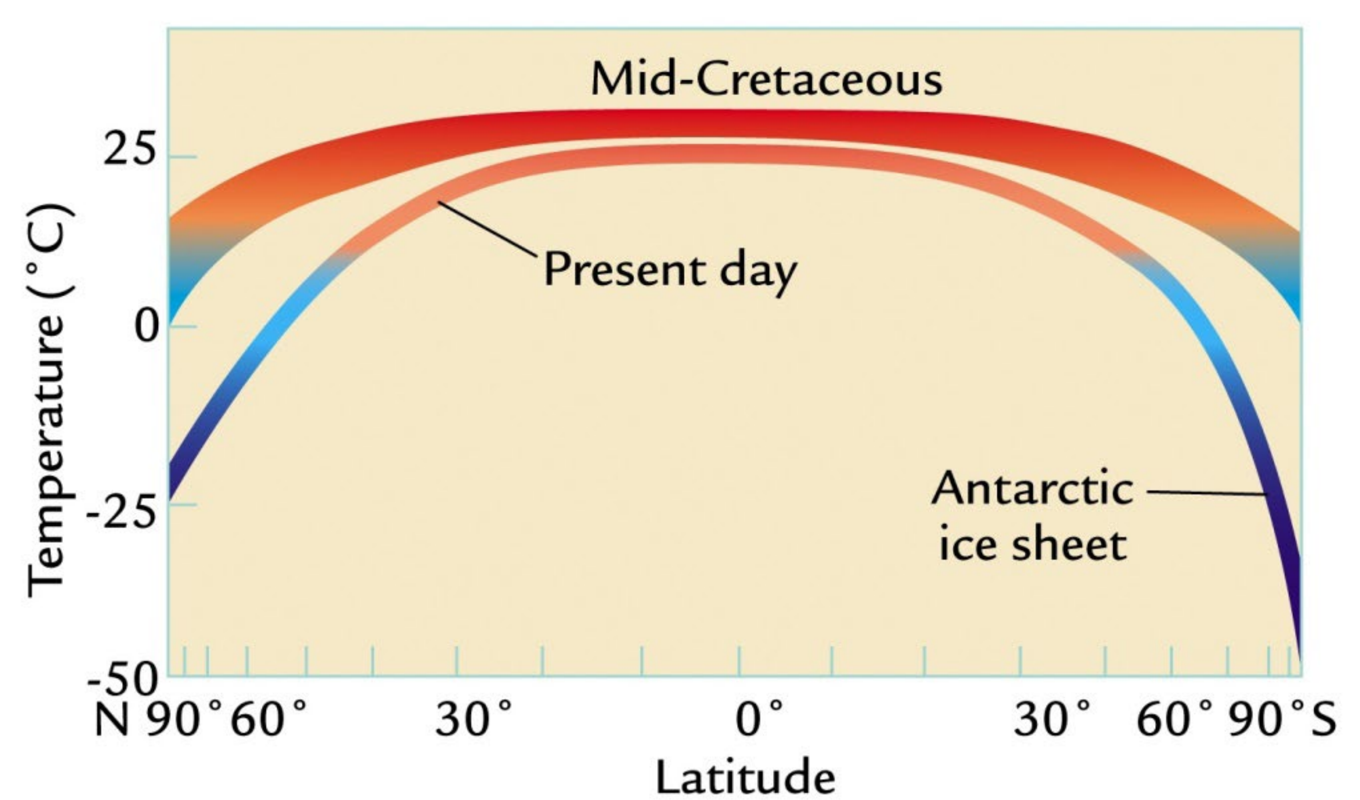
•Warm-adapted plants and animals thrived beyond the Arctic Circle.

•Hermatypic corals, usually within 30°, lived up to 40° outside the tropical zone.

Artocarpus altilis

Dinosaurs

TEMPERATURE MODELS FOR CRETACEOUS

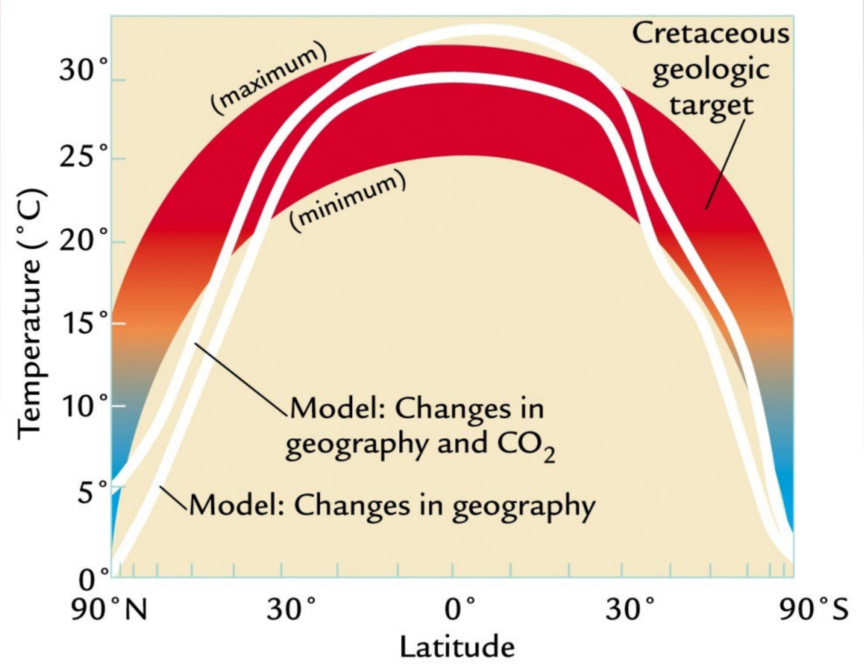


adapted from Barron and Washington, 1985

CRETACEOUS TARGET CURVE vs PRESENT CONDITIONS

Climate scientists have used geologic data (faunal, floral, and geochemical) to compile an estimate of temperatures 100 Myr ago. Temperatures were warmer than they are today at all latitudes, especially in polar regions.

TEMPERATURE MODELS FOR CRETACEOUS



adapted from Barron and Washington, 1985

MODEL vs TARGET SIGNAL

Target signal = Independent temperature estimation based on geological data

Model 1 => Cretaceous geography (boundary condition).
CO_2 = pre-industrial levels
Model 2 => Cretaceous geography (boundary condition).
CO_2 = 4x pre-industrial levels

DISCREPANCIES BETWEEN DATA AND MODELS - 1

Discrepancies Between Data and Models may arise from two categories of issues:

•**Problems with Model Assumptions**

1. Primitive 0-GCMs
2. Ocean heat transport hypothesis
3. Deep water masses formation
4. Other issues

•**Problems with Data Obtained from the Geological Record**

1. Diagenetic overprint

DISCREPANCIES BETWEEN DATA AND MODELS - 2

PROBLEMS WITH MODEL ASSUMPTIONS

(1) **PRIMITIVE 0-GCMs:**
In 1985, the development of the 0-GCMs models were at a very primitive stage and did not involve important processes such as upwelling and deep circulation.

DISCREPANCIES BETWEEN DATA AND MODELS – 2

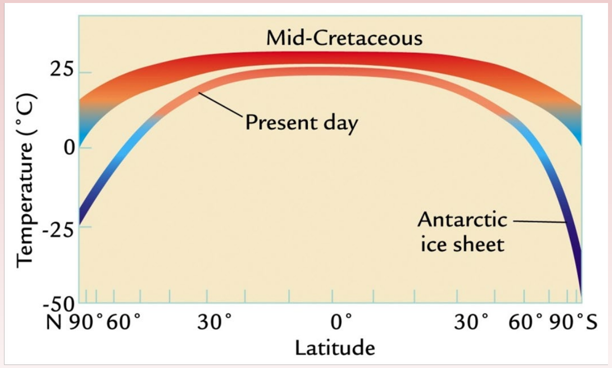
(2) **OCEAN HEAT TRANSPORT HYPOTHESIS**

(Covey & Barron, 1988; Barron et al., 1993)

Some scientists proposed that during the Cretaceous, ocean circulation transported twice as much heat to the poles as it does today, unlike the current 50/50 heat distribution between ocean and atmosphere.

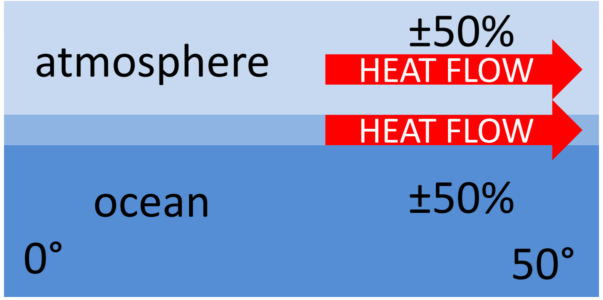
This could explain colder poles and a warmer equator in models based on modern circulation.

However, recent models suggest increased heat transport is unlikely in a warmer climate with lower latitudinal gradients.

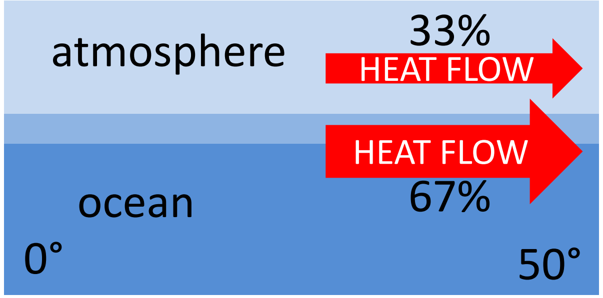


adapted from Barron and Washington, 1985

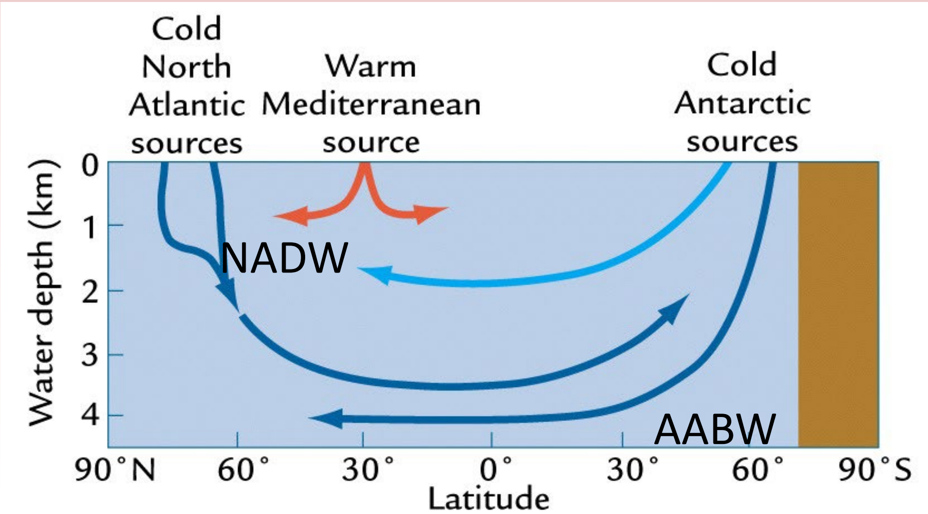
TODAY



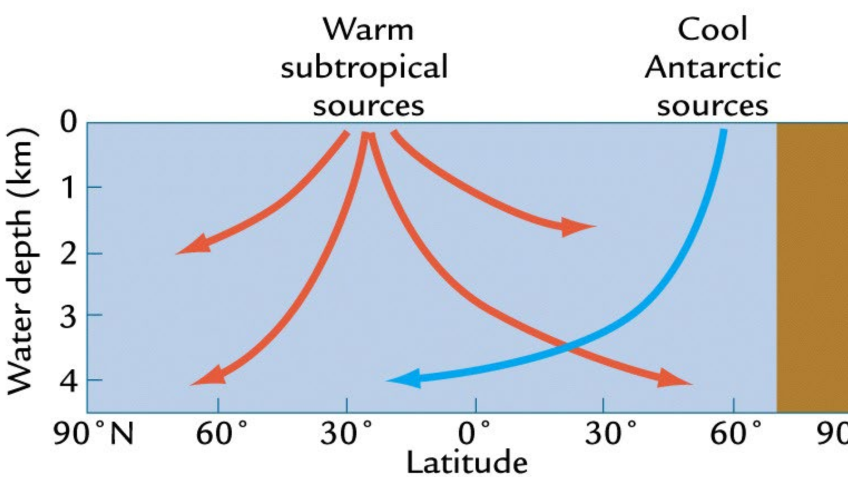
GREENHOUSE



DISCREPANCIES BETWEEN DATA AND MODELS - 3



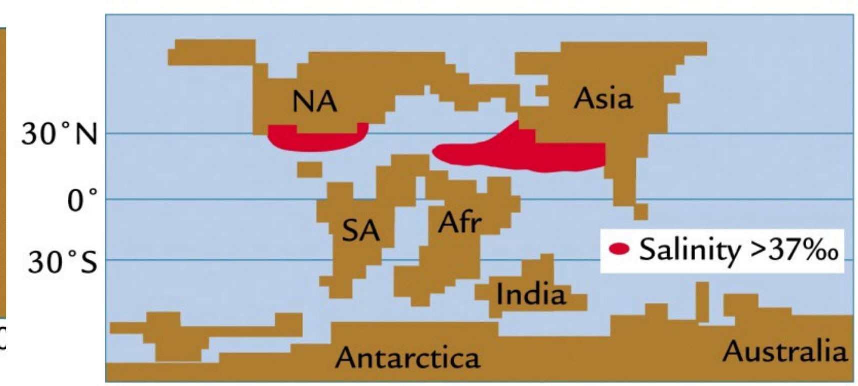
A Modern deep-water flow



B Mid-Cretaceous deep-water flow

(3) **DEEP WATER MASS FORMATION**

To explain this discrepancy, other scientists hypothesized that waters formed in the **northern hemisphere's subtropical regions** (not at the poles as today) due to **the sinking of warm, salty waters** (37‰, dense from salinity).



DISCREPANCIES BETWEEN DATA AND MODELS - 3

(4) **OTHER ISSUES**
Geological data from mid-high latitudes, like palm tree fossils, contradicts the model's prediction of winter freezing in continental interiors. Even with warm Arctic Ocean boundary conditions, the model still simulates freezing. The heat loss over continents in winter seems too great to offset.

PROBLEMS WITH DATA OBTAINED FROM THE GEOLOGICAL RECORD

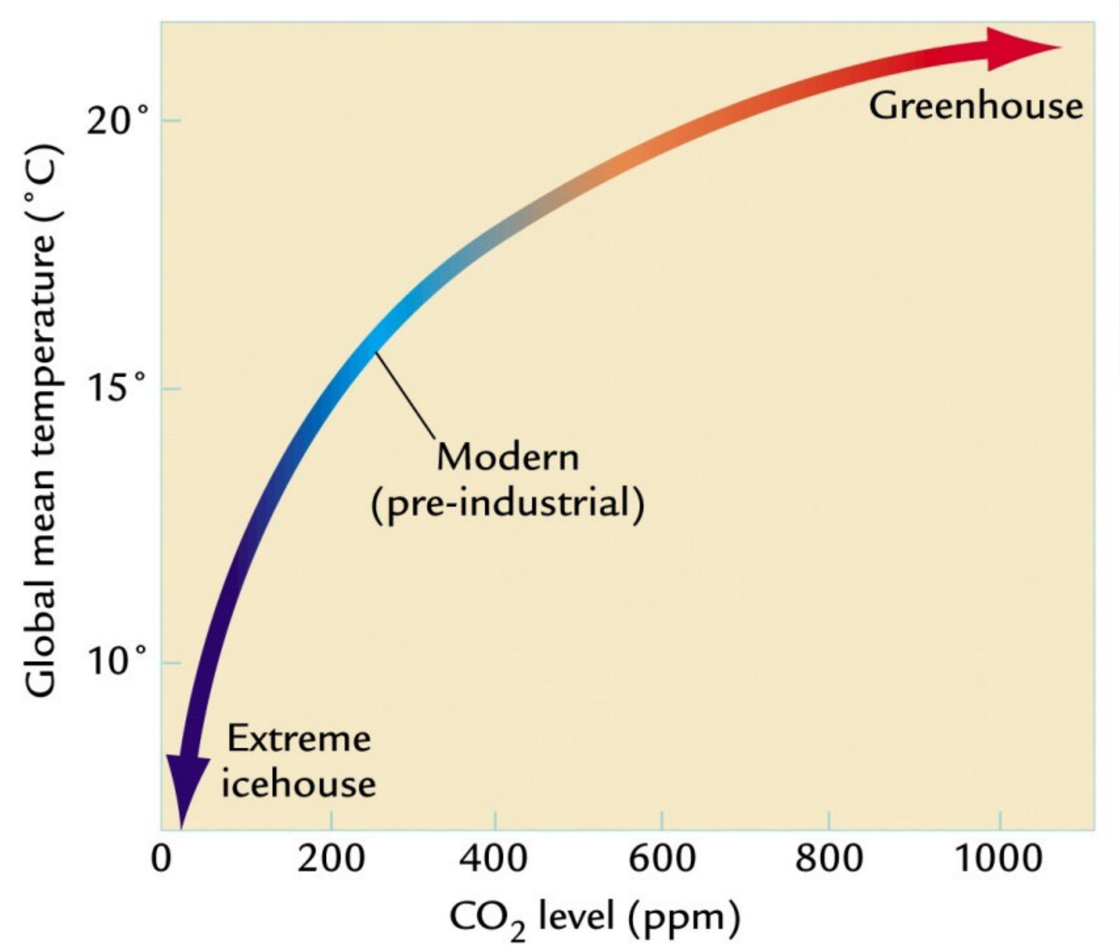
(1) **DIAGENETIC OVERPRINTING:** Temperatures obtained from isotope analyzes on planktonic foraminifera could have a diagenetic overprinting (dissolution, recrystallization). Data acquired from unaltered material return cooler temperature at low latitudes.

CRETACEOUS AS AN ANALOG OF THE PRESENT – sensitivity

GCM CO_2 Sensitivity Test

Simulations with CO_2 levels from 100-1000 ppm, using current geography as the boundary condition, show **temperature increases with CO_2, but nonlinearly.**

Temperature changes are more pronounced at lower CO_2 levels
=> **doubling of pCO_2.**



Sensitivity Test: Altering only one condition (pCO_2).

CRETACEOUS AS AN ANALOG OF THE PRESENT – sensitivity

What factors influence the relationship between CO_2 and temperature?

1) Albedo positive feedback

2) The band (CO_2) saturation effect: The greenhouse effect

3) The positive feedback of water vapour

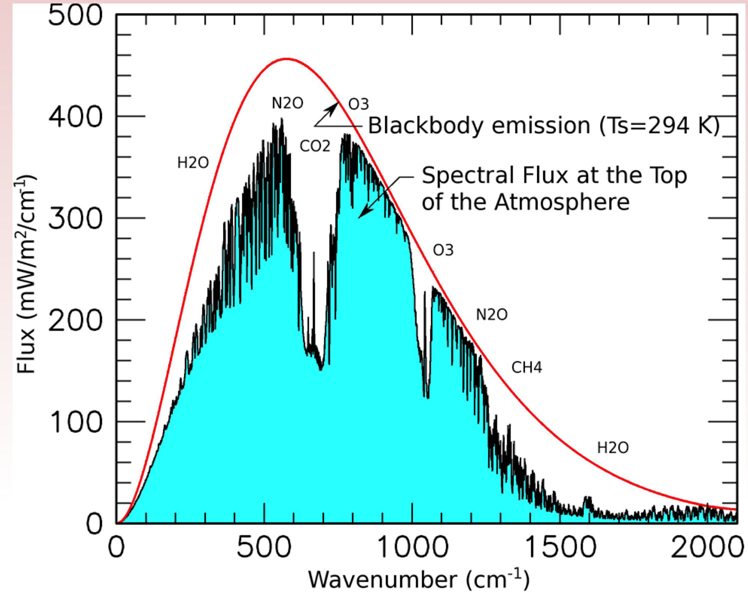
(1) Albedo positive feedback (attenuated at high CO_2 values)

At CO_2 levels below 200 ppm, snow is abundant, and small CO_2 changes greatly impact snow cover (albedo). At higher CO_2 levels (1000 ppm), snow is minimal, reducing albedo and system sensitivity.

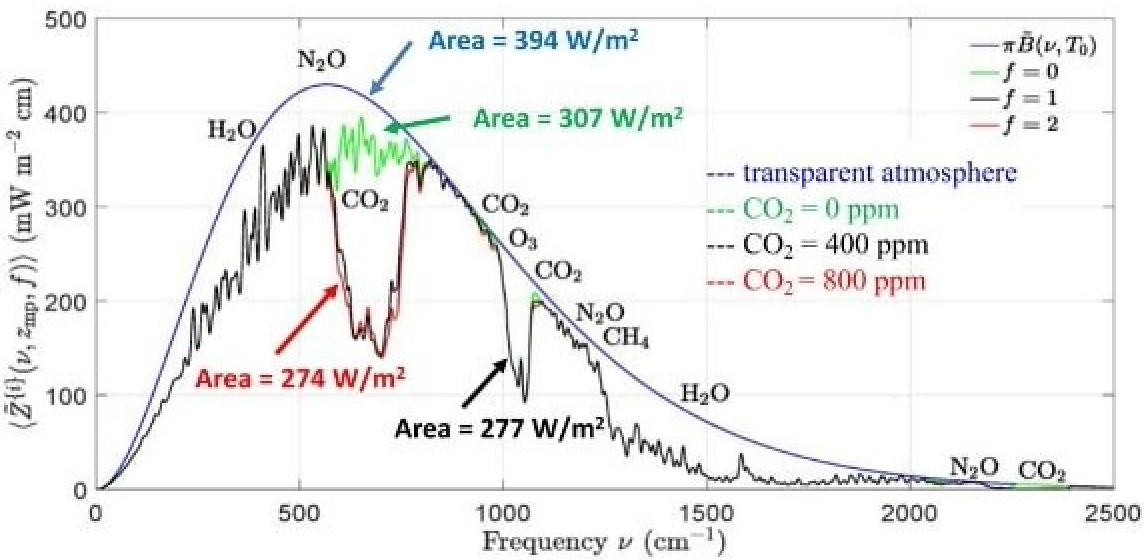
CRETACEOUS AS AN ANALOG OF THE PRESENT – sensitivity

(2) The band (CO_2) saturation effect: The greenhouse effect

As the CO_2 concentration increases, the atmosphere reaches a saturation point where further increments in CO_2 become less effective in trapping the Earth's emitted radiation back into space.



Outgoing spectral radiance at the top of Earth's atmosphere showing the absorption at specific frequencies and the principle absorber. For comparison, the red curve shows the flux from a classic "blackbody" at 294°K (≈21°C ≈ 69.5°F).

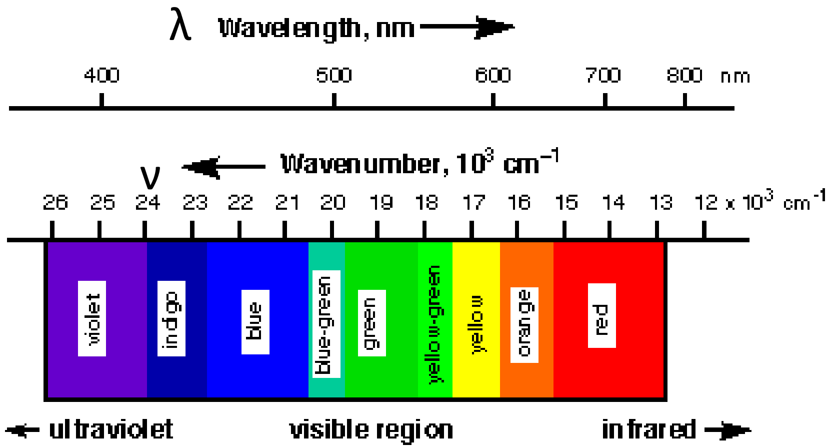


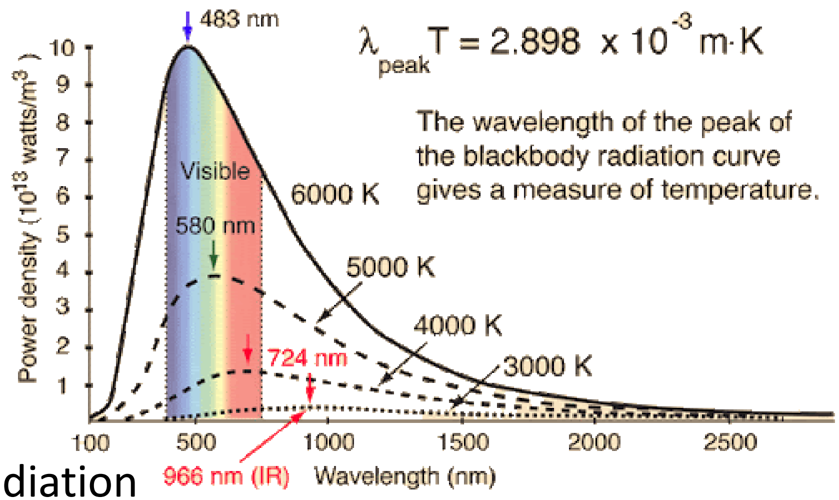
Emission spectrum of a black body compared to the emission spectrum of planet Earth at different pCO_2 scenarios.

CRETACEOUS AS AN ANALOG OF THE PRESENT – sensitivity

A black body is an idealized object that absorbs all incident electromagnetic radiation, regardless of wavelength, and re-emits energy based solely on its temperature.

Its emission spectrum follows Planck's law (bell shape), with higher temperatures shifting the peak emission to shorter wavelengths, as described by Wien's law.



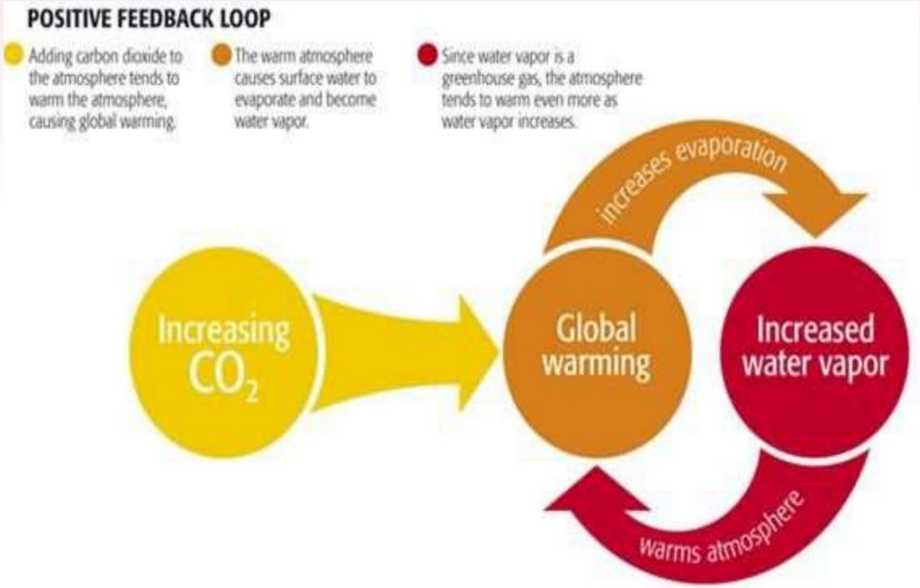


It serves as a model to understand radiation and energy distribution in physics and climate science.

CRETACEOUS AS AN ANALOG OF THE PRESENT – sensitivity

(3) The positive feedback of water vapour

High CO_2 levels increase atmospheric water vapor, strengthening the greenhouse effect and raising temperatures.



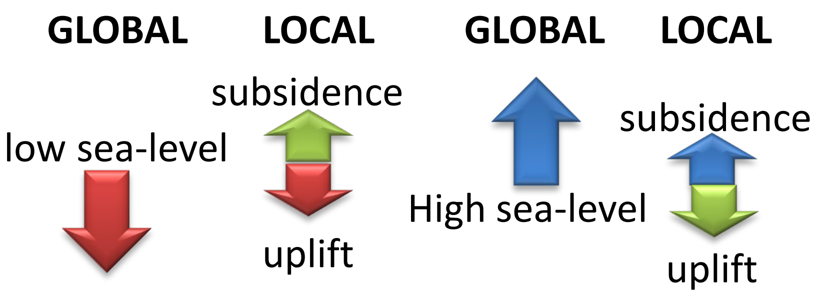
Future Projections Models predict that in the next 200 years, CO_2 concentrations could reach 550-1000 ppm, similar to levels estimated for the Cretaceous period.

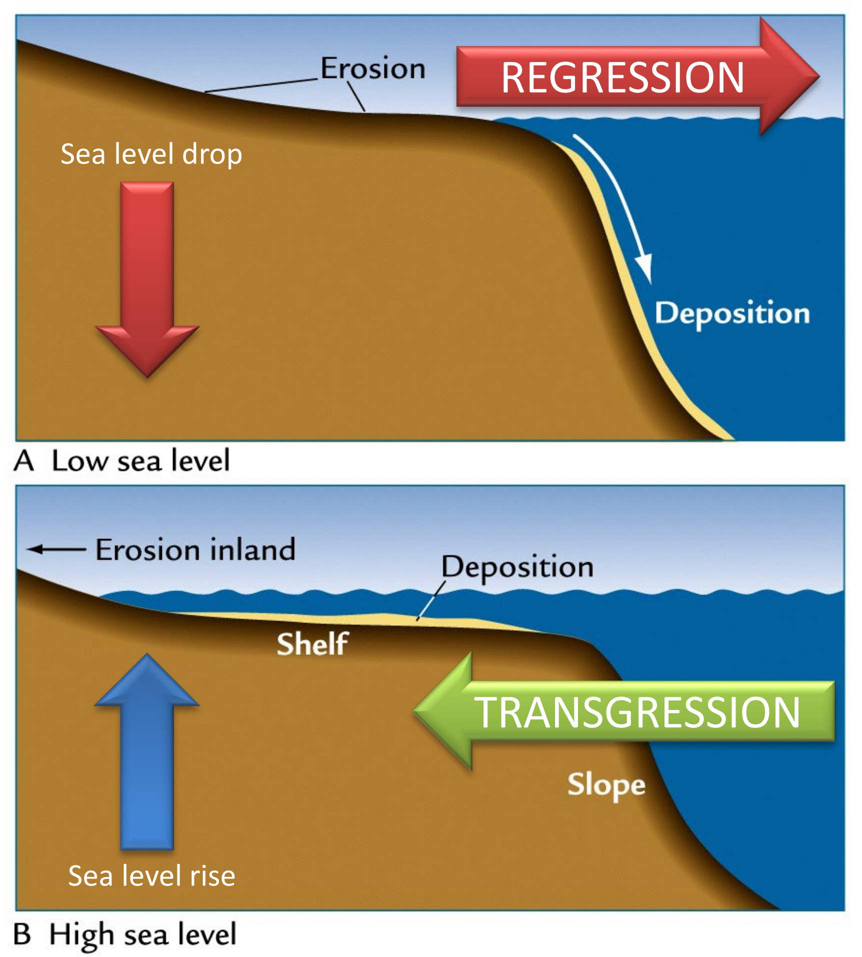
SEA LEVEL VARIATIONS IN THE CRETACEOUS

Possible relationships with climatic variations

CHANGES IN SEA LEVEL AND CLIMATE - 1

Global eustatic sea level changes arise from glacial ice volume, seawater thermal expansion, and shifts in land water storage.
Relative sea level changes are due to local tectonics (**subsidence**, **uplift**).
Regressions and transgressions can expose or submerge marginal areas.



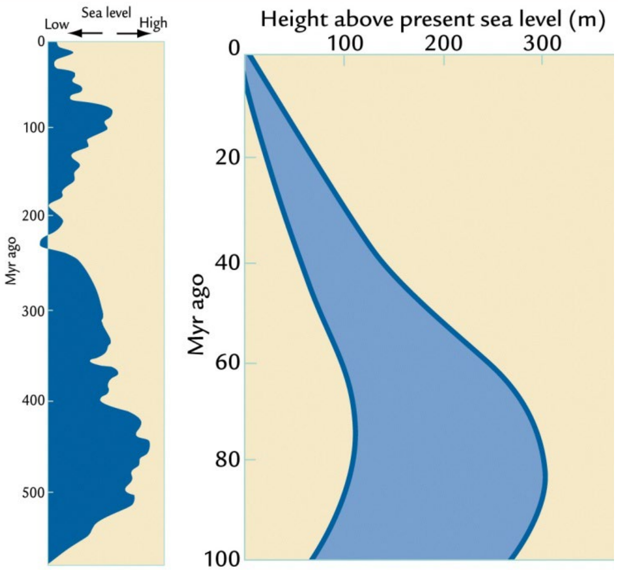


Past sea level reconstructions are based on the deposition of marine sediments at continental margins: paleoshore lines.

CHANGES IN SEA LEVEL AND CLIMATE - 2

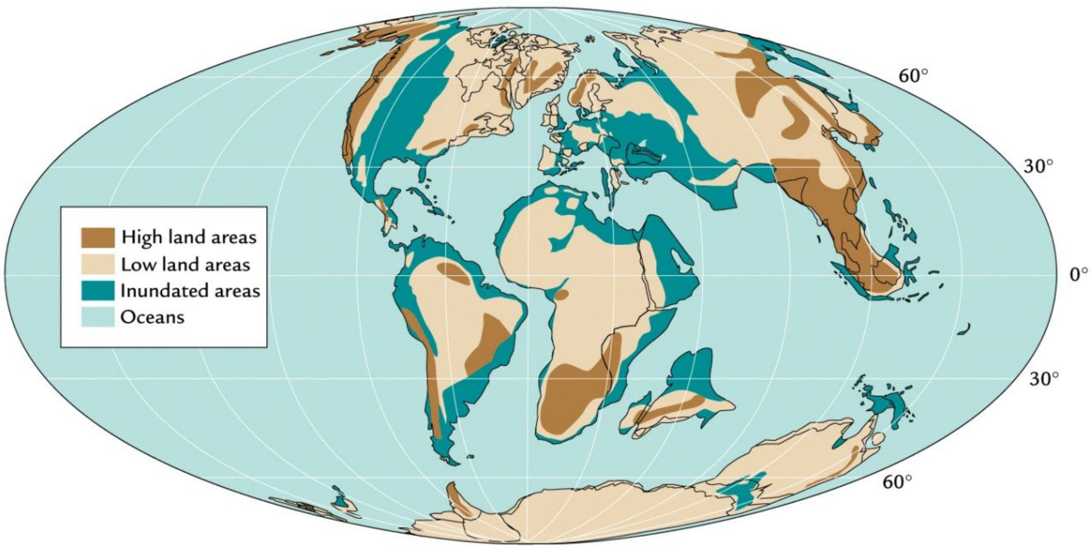
Around 100 million years ago, sea levels were about 100-300 meters higher than today. Exact estimates are difficult due to **sediment compaction** and **rock subsidence**.
Large areas, including coastal regions, Southern Europe, North America, and the Arctic Ocean, were submerged.

Sea level changes



modified after Vail et al. (1977) and Haq et al. (1987)

Consequences of sea level changes

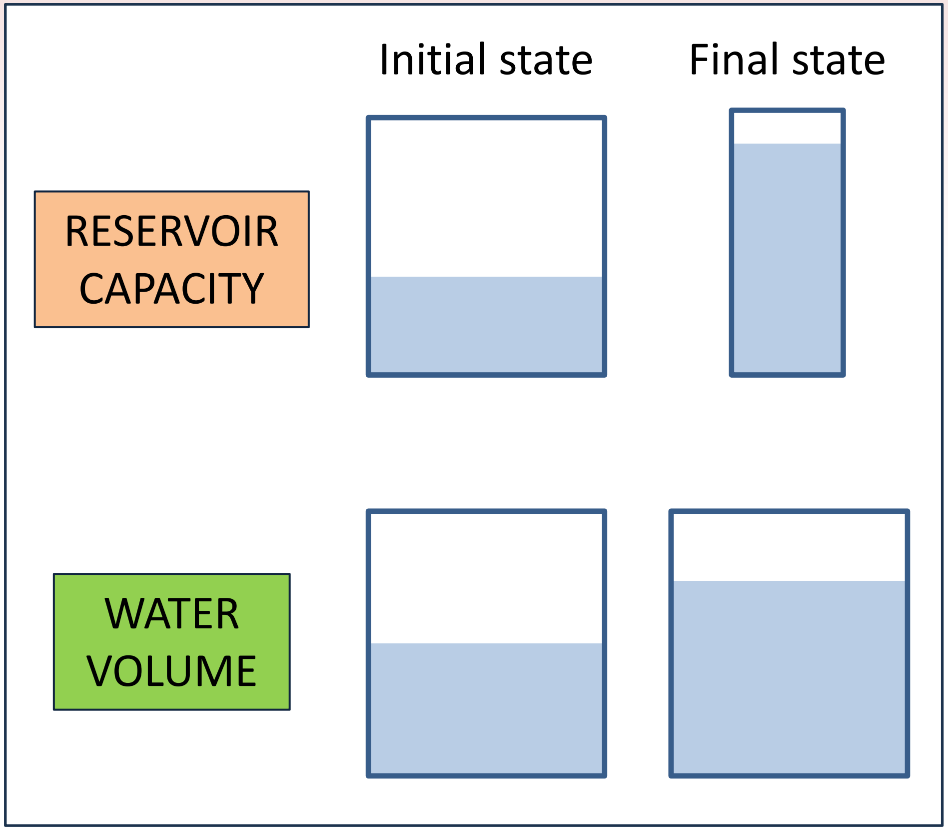


CAUSES OF SEA LEVEL VARIATIONS

The sea level is mainly controlled by two orders of factors:

TECTONICS →
linked to changes in the volume of ocean basins, leading to a variation in the capacity of the basin itself.

CLIMATE →
linked to changes in the volume of water contained in ocean basins.

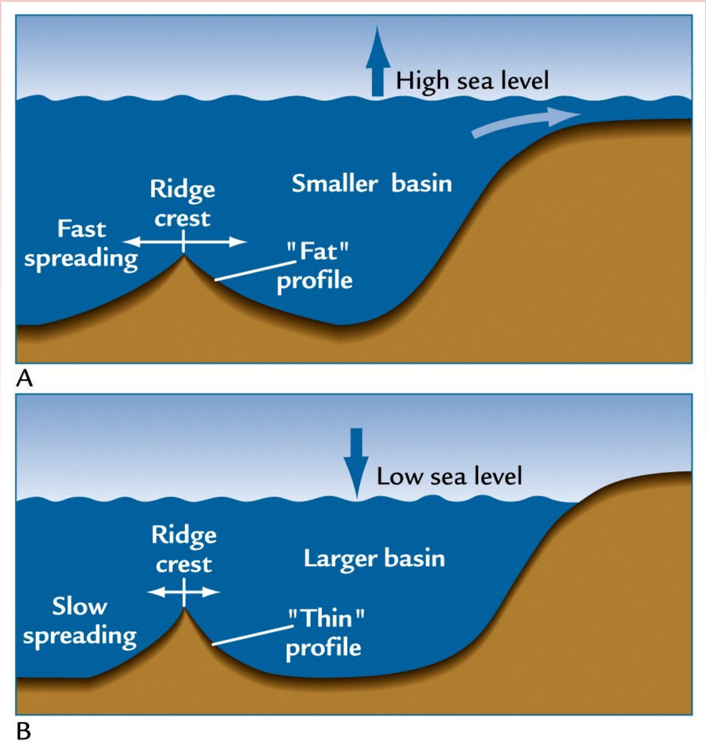


CHANGES IN BASIN VOLUME – tectonics - 1

(1) Δ in mid-ocean volumes (spreading rates)

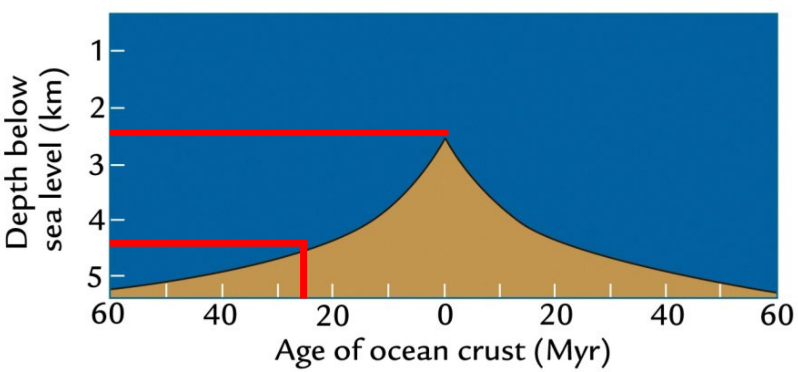
High spreading rate→
"fat" profile→
SMALLER BASIN
high sea level

Slow spreading rate→
"thin" profile →
LARGER BASIN low sea level



Rigde depth = 2500 m + 350 $\sqrt[2]{crustal\ age}$
(in meters) (at O age) (in Myr)

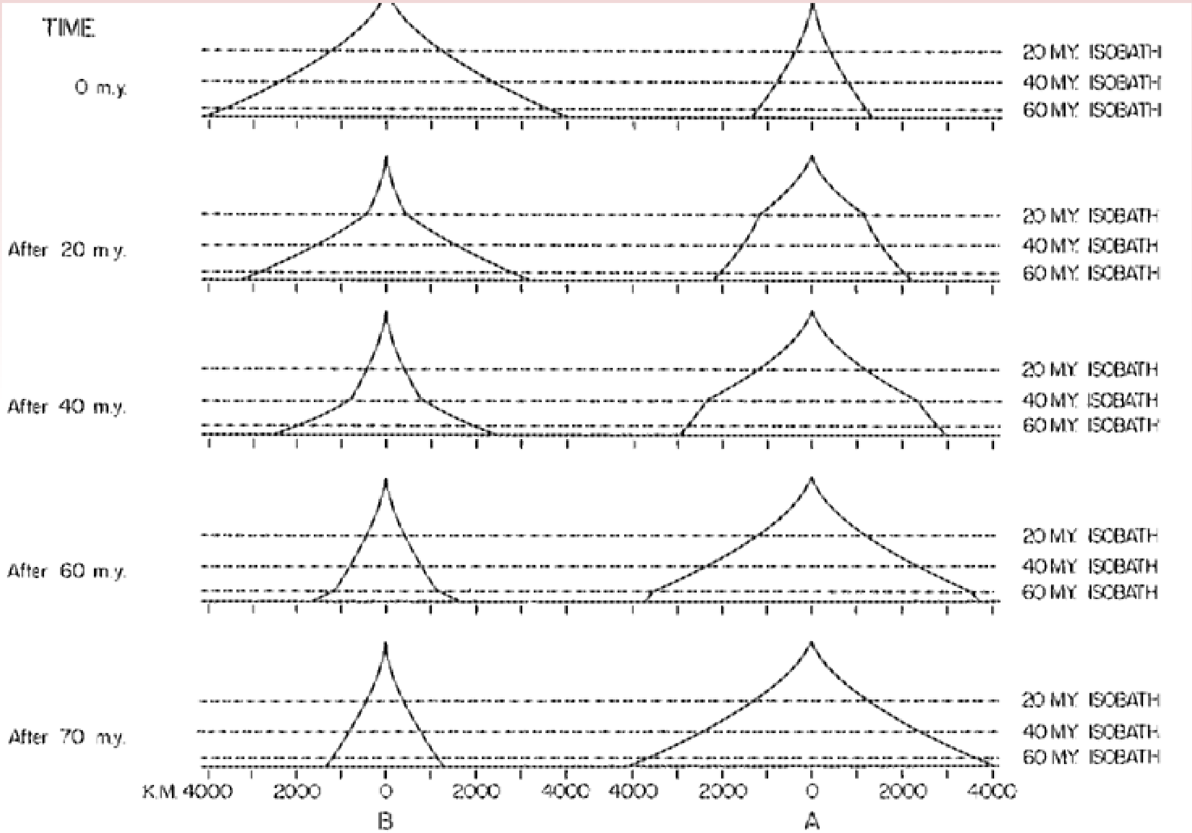
Rigde depth = 2500 m + 350 $\sqrt[2]{25}$
2500 m + 350 x 5 m
2500 m + 1750 m = 4250 m



CHANGES IN BASIN VOLUME – tectonics - 2

low spreading rate 2 cm/yr

high spreading rate 6 cm/yr



THIN PROFILE **FAT PROFILE**

Figure 2 (from Pitman, 2013)

A, top shows profile of ridge that has been spreading at 2 cm/yr for 70 m.y. At time 0 m.y., spreading rate is increased to 6 cm/yr. Sequential stages in consequent expansion of ridge profile are shown: first at 20 m.y. after spreading rate change, at 40 m.y., then at 60 m.y., and finally at 70 m.y. after spreading-rate change. At 70 m.y., ridge will be at a new steady-state profile; cross-sectional area at this time will be three times what it was at 0 m.y.

B, top is profile of ridge that has spread at 6 cm/yr for 70 m.y. At 0 m.y., spreading rate is reduced to 2 cm/yr. Sequential stages in subsequent contractions of ridge are shown. At 70 m.y., after change in spreading rate, ridge will be at a new steady-state profile; cross-sectional area will be one-third what it was at 0 m.y.

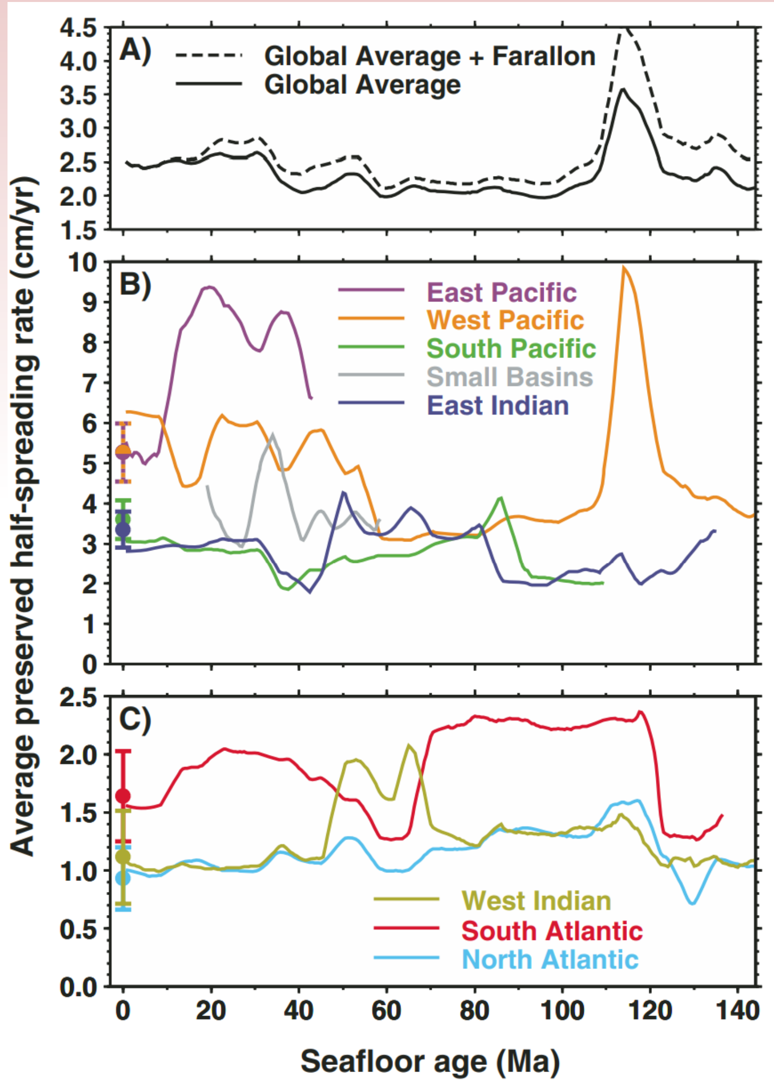
CHANGES IN BASIN VOLUME – tectonics - 3

Estimates of average spreading rates from 80-100 Ma are higher (3.5-4.5 cm/year) than today's (2.5-3 cm/year) but are highly uncertain.

Reasons for Uncertainty:
•Not all paleobasins, like the Tethys, are preserved.
•Some spreading rate estimates have been revised and lowered.

Note: While some scientists believe increased ocean crust spreading could raise sea levels by up to 200 m, others limit or negate this effect.

EFFECT ON SEA LEVEL: +50/150 m



(Conrad & Lithgow-Bertelloni, 2007)

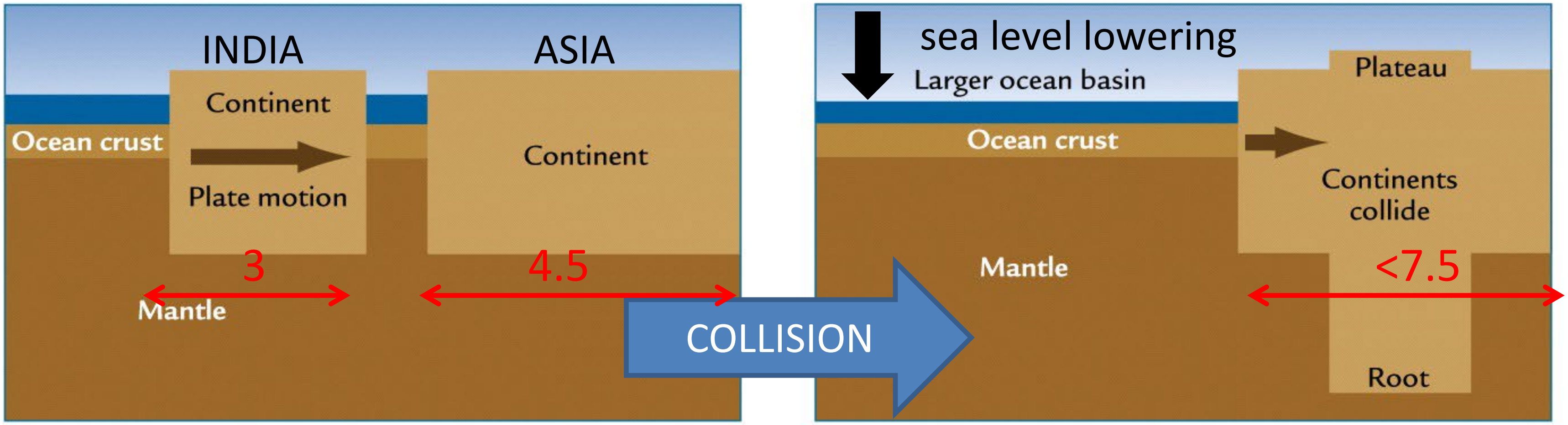
CHANGES IN BASIN VOLUME – tectonics - 3

(2) Continental collision

The formation (at ridges) and consumption (at trenches) of ocean basins do not cause net changes. Instead, ocean basin area changes occur through continental collisions.

When continents collide, the less dense crust "floats," creating a high plateau with deep roots (70 km). **This reduces continental area, expanding ocean basins and lowering sea levels.**

The India-Asia collision around 50 million years ago lowered sea level by approximately 10 meters (**EFFECT ON SEA LEVEL: +10 m**).



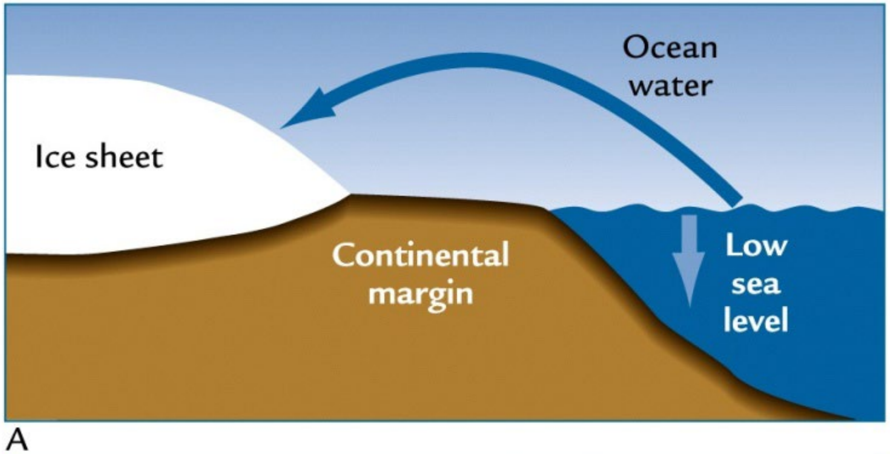
CHANGES IN THE VOLUME OF BASINS – climatic -1

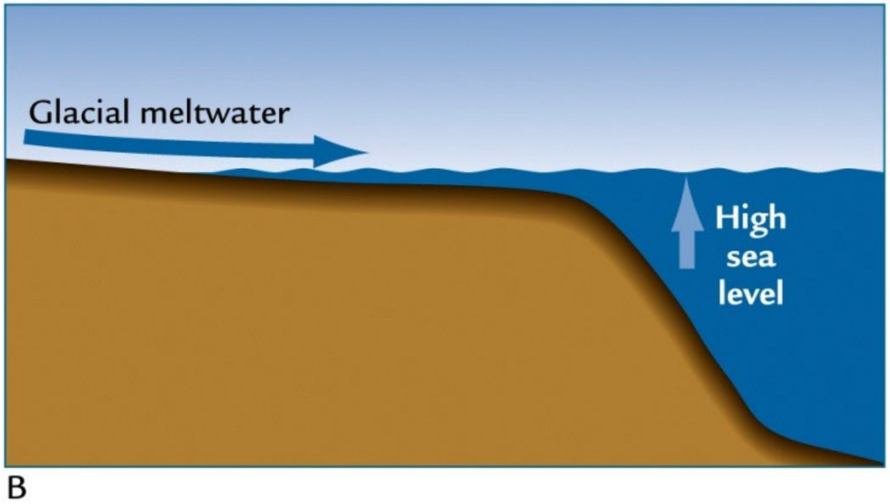
(1) Δ OF THE VOLUME OF WATER TRAPPED IN ICE CAPS

Ice caps, spanning thousands of kilometers and several kilometers thick, can temporarily store large amounts of H_2O.

While there's no evidence of permanent ice caps at the poles during the Cretaceous, over the last 35 million years, beginning in Antarctica and then Greenland, about 72 meters (66 +6) of sea level equivalent has been stored.

EFFECT ON SEA LEVEL: +72m





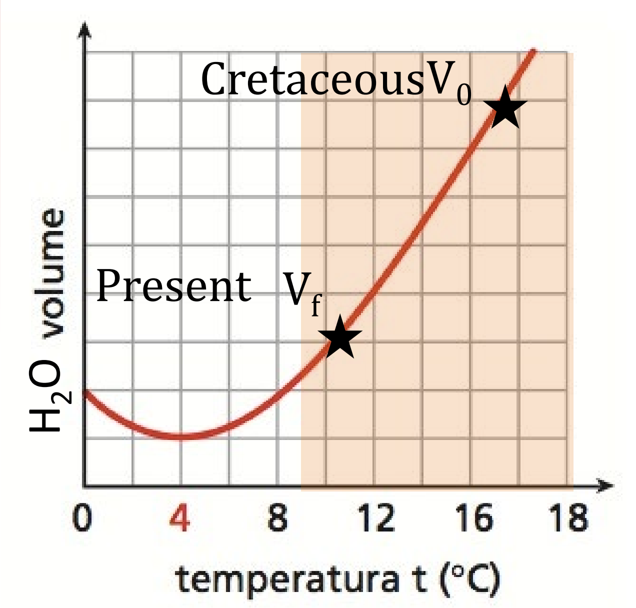
CHANGES IN THE VOLUME OF BASINS – climatic -2

THERMAL CONTRACTION/EXPANSION OF SEA WATER

Water contracts/expands as the temperature changes.

$\Delta V = K * "V0" * \Delta T$

ΔV = change in volume (m^3)
K = coefficient of expansion ($°C^{-1}$)
V_0 = initial volume (m^3)
ΔT = temperature variation



V_0 = initial volume (m^3)
V_f = final volume (m^3)

The cooling that took place from the Cretaceous to today has therefore produced a decrease in the volume of water.

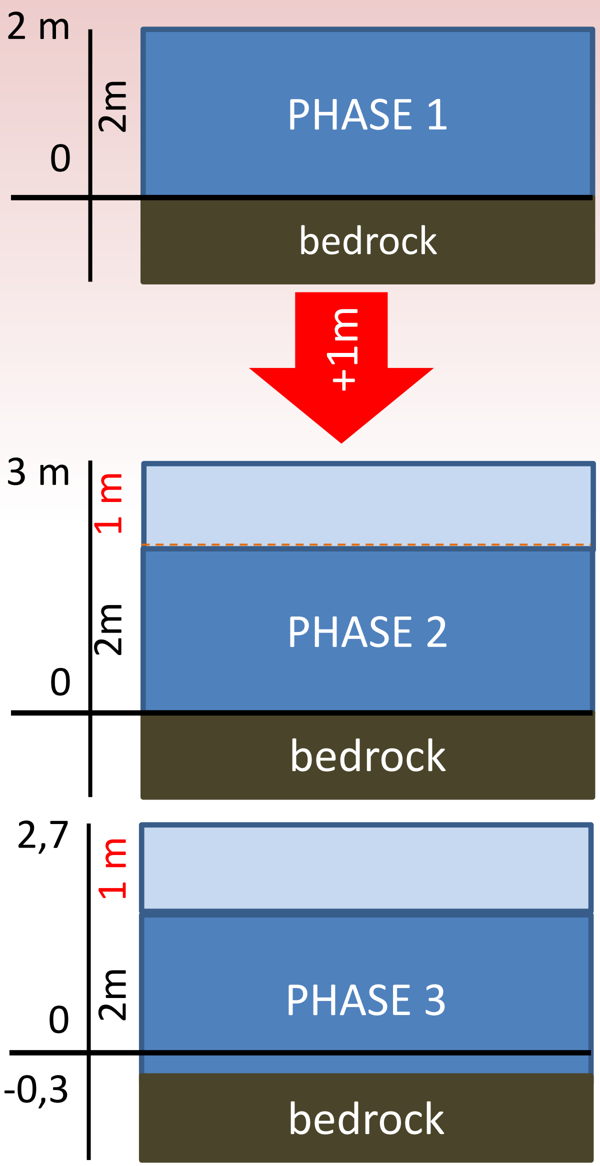
EFFECT ON SEA LEVEL: +7m sea level

OTHER COMPLICATIONS

ICE CAP MELTING/GROWTH SIDE EFFECT

Water transferred between continents and oceans adds (or removes) weight on the seafloor rock or sediment.

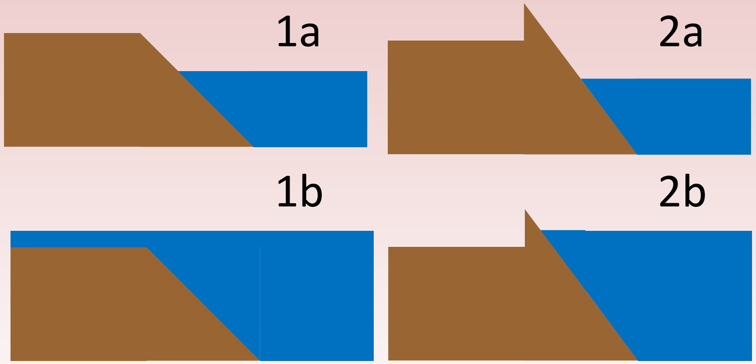
Example:
Adding water to oceans raises sea levels, placing a load that depresses the underlying rock. About 30% of sea level rise from ice cap inflow is offset by isostatic loading from the water, as **bedrock response dampens sea level changes**.



OTHER COMPLICATIONS

VARIABILITY IN COASTAL PROFILES

The complex nature of coastlines means that water influx can cause varied sea level changes due to highly variable coastal profiles. While accurate reconstructions are possible today, estimating this factor for past coastlines is challenging.



sandy coast rocky coast

sandy coast

rocky coast

CRETACEOUS RECORD and PHYSICAL MODELS

All factors examined in understanding the underlying physical mechanisms suggest a sea level variation of +120 to +220 meters, consistent with observations in the Cretaceous geological record.

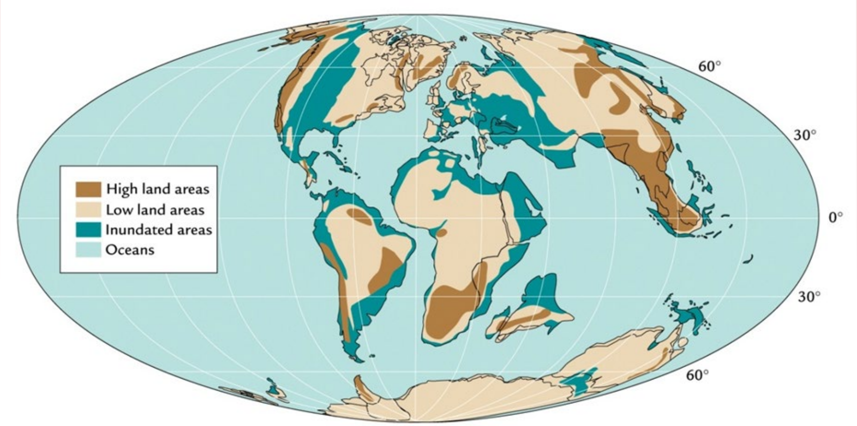
Factors Contributing to Higher Sea Levels 100 to 80 Million Years ago	
Cause of sea level change	**Estimated changes (meters)**
Decrease in ocean ridge volume	+50 to +150
Collision of India and Asia	+10
Water stored in ice sheet	+72 (66 +6)
Thermal contraction of seawater	+7
All factors	**+120 to +220**

EFFECTS OF SEA LEVEL CHANGES ON CLIMATE

The main climate impact of sea level variations is due to the differing thermal responses of oceans and land; water has a higher heat capacity.

If sea level is high (e.g., Cretaceous), previously subaerial areas are submerged, leading to:

- **Mitigation of climate extremes** (cooler summers, milder winters)



If sea level drops:

- **Stronger seasonal contrasts** (hotter summers, cooler winters)

CAN EUSTATIC CHANGES BE THE CAUSE OF THE SWITCH FROM A GREENHOUSE REGIME TO AN ICEHOUSE REGIME?

Could the sea level drop observed from the Cretaceous to the present have caused the switch from a Greenhouse to an Icehouse regime?

https://app.wooclap.com/events/PCCM24/0

What's wrong?

THEORY

The main issue with this theory is that ice sheet expansion and retreat are driven by summer melting, not winter temperatures.

Low sea levels cause water to recede from inland seas, resulting in hot summers and cold winters; a harsh winter can still be offset by a hot summer that melts accumulated snow.

Conversely, **high sea levels** (like during the Cretaceous) lead to cooler summers and milder winters, **promoting polar ice cap formation**

GEOLOGICAL RECORD

At high sea levels (Cretaceous) => NO ice cap.

CONCLUSION

Increased landmass exposure leads to greater seasonal extremes, with colder winters but especially hotter summers. These intense summer temperatures would cause ice sheets to melt, making it difficult for them to persist, thus preventing the transition to a stable Icehouse regime.