Ciclos de Milankovitch

Introdução à Física Atmosférica - 2019

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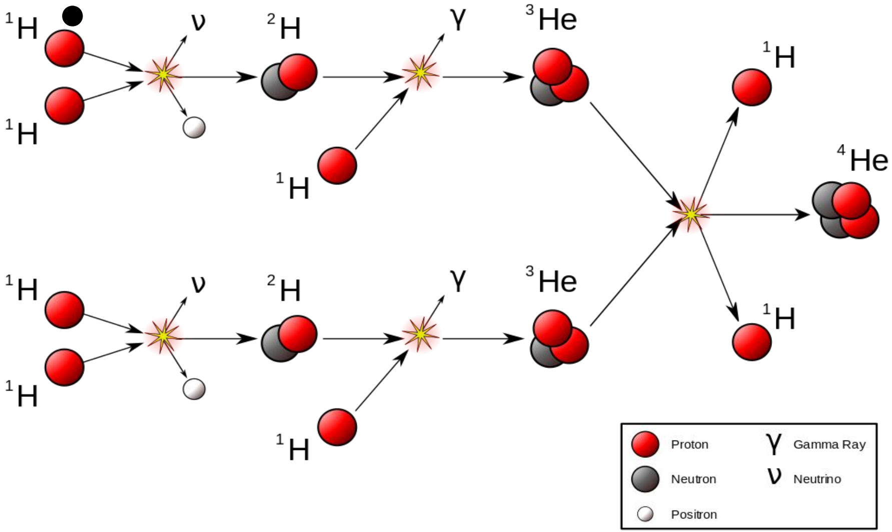
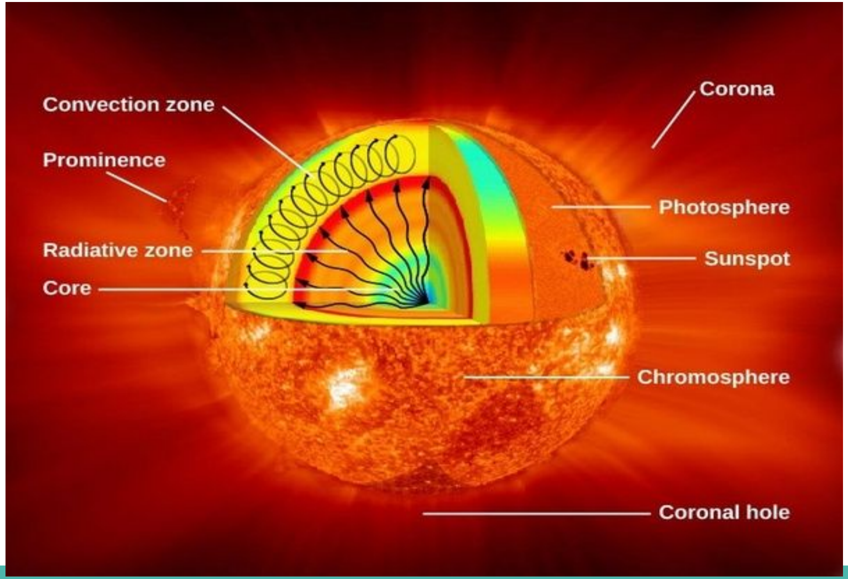
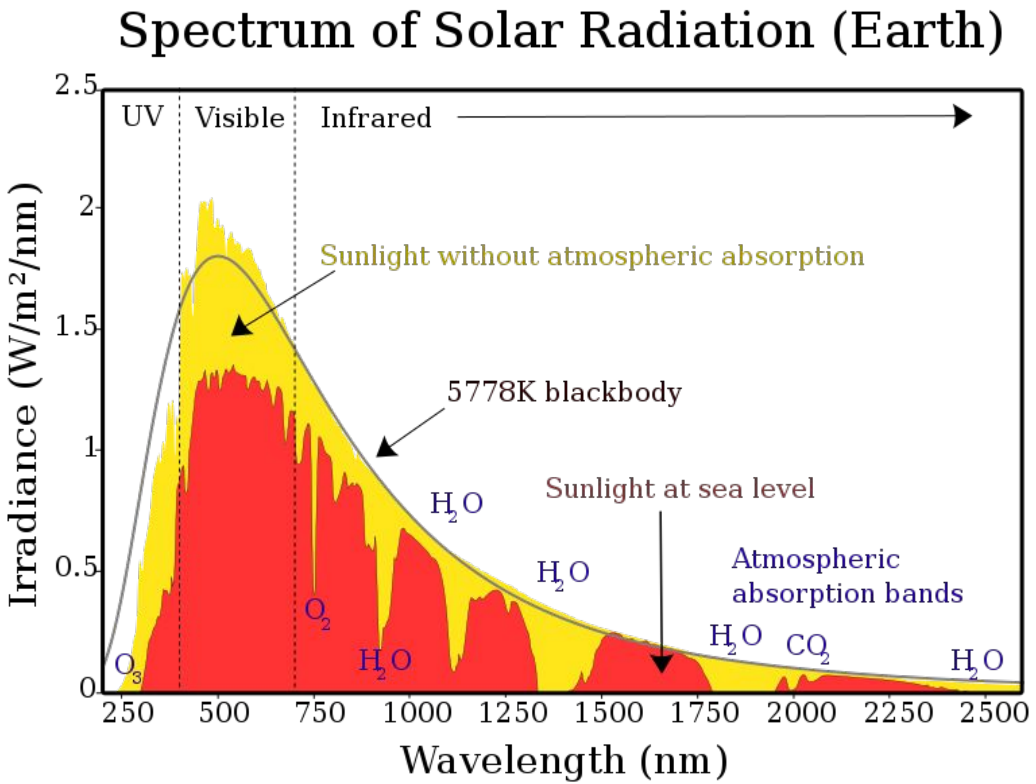
Produção de Radiação Solar

- Sol: 25% Hélio + 75% Hidrogênio; R=699.500.000 km
- Energia: reações nucleares no núcleo(25% do raio total)(99% de toda energia produzida)
- Núcleo: P=250 bilhões de atmosferas (25.33 trilhões kPa) e T=15.7x10^6 K
- Fotosfera: 500 km mais externos. Daqui vem quase toda energia
-





Emissão de Radiação Solar



Radiância Espectral de Corpo Negro

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda k_B T)} - 1}$$

Integrando sobre todos os ƛ:

$$j^\star = \sigma T^4$$ **Lei de Stefan-Boltzmann**

$$\sigma = 5,6697 \times 10^{-8} W m^{-2} K^{-4}$$

Ae = 4.π.r²

R=6.995×10^8 km

T=5800 K

P=3.95×10^26 W

Incidência da Radiação na Terra

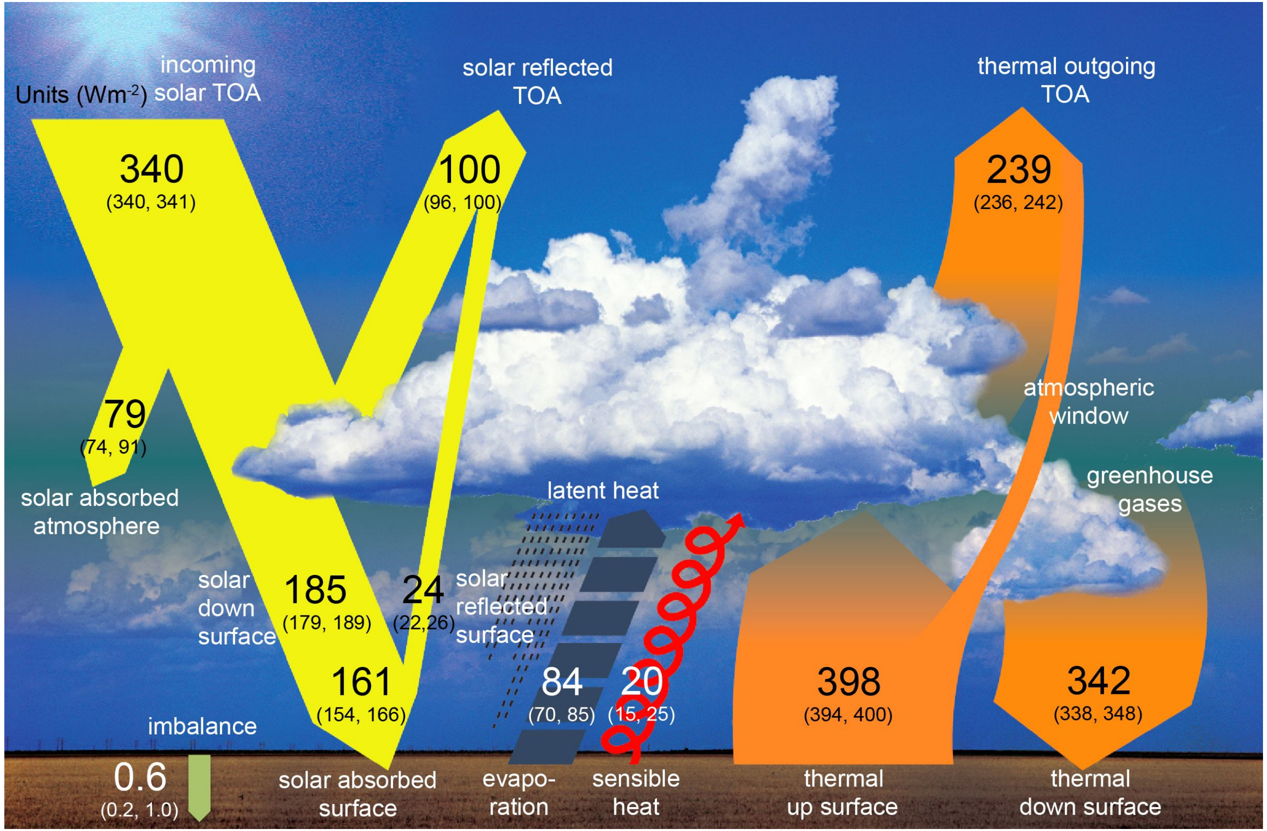
$\Delta E = \Omega / 4\pi \quad \Omega = \pi r^2 / R^2$

$\Delta E = \pi r^2 / 4\pi R^2$

$\Delta E = 342$ W/m²

$S_0 = 4 \times \Delta E = 1368$ W/m² (constante solar)

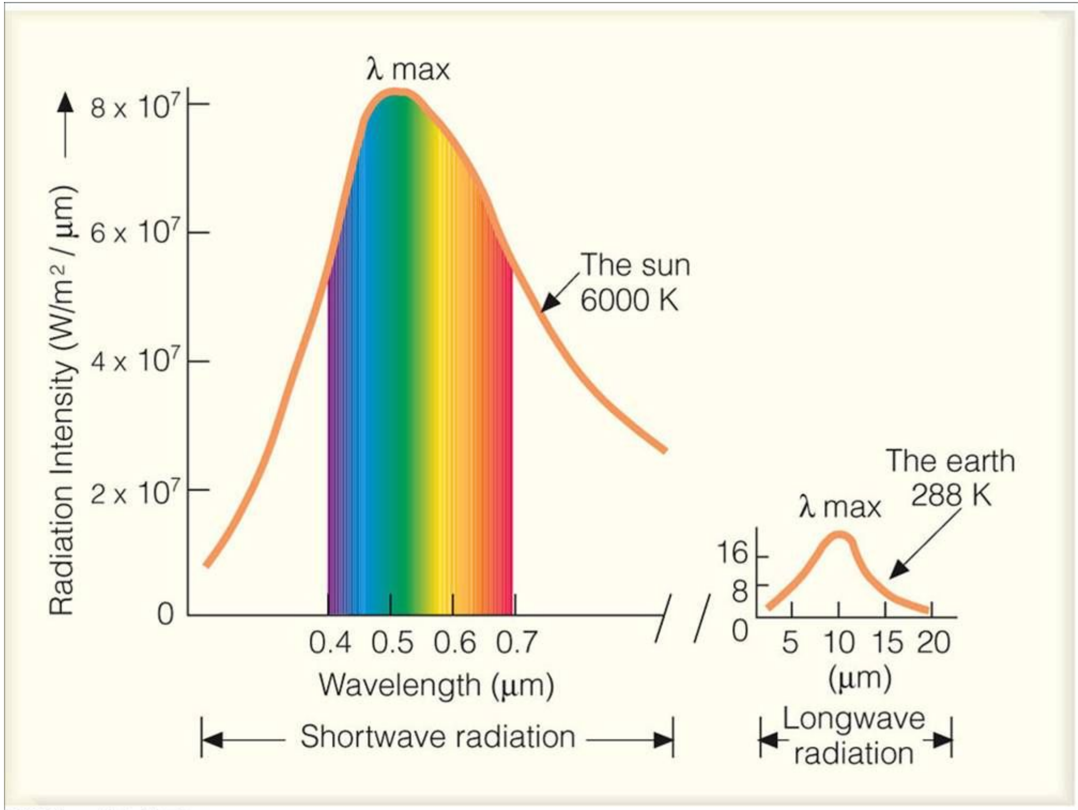
A Terra recebe 0,4 bilionésimos da energia emitida pelo Sol!



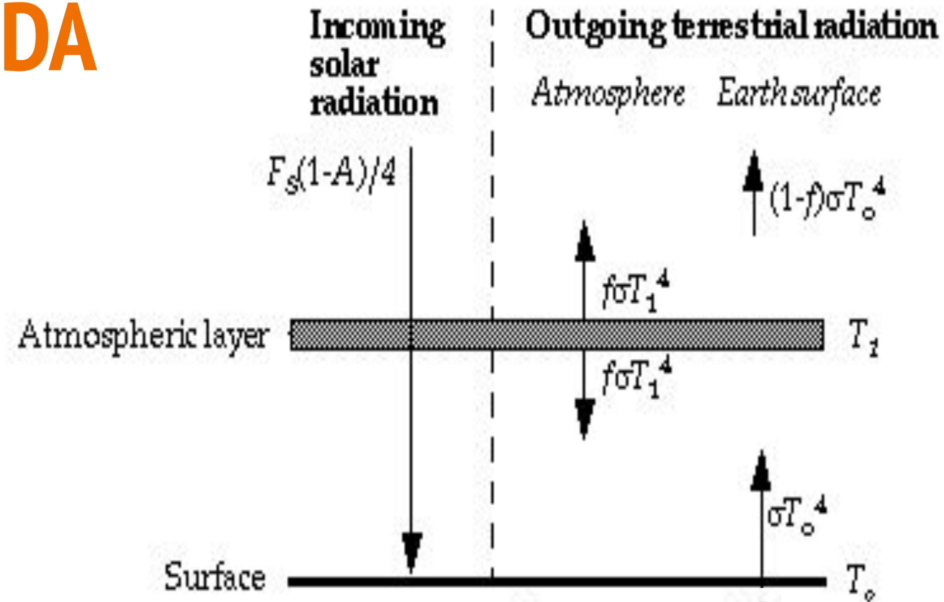
Temperatura de Equilíbrio do Sistema Terra-"Atmosfera"

- **F_s=S_0(1-A)/4**
- Igualando energia que vem do Sol com a emitida pela superfície da Terra(onda longa):
- **F_s=F_L=σ(T_{earth})^4**
  - para **A=0,3(atual):**
  T_{earth}=255K=-18ºC!

A superfície terrestre claramente não está tão fria!



Temperatura de Equilíbrio do Sistema Terra-Atmosfera CORRIGIDA



- Balanço do Sistema:

$$\frac{F_S(1-A)}{4} = (1-f)\sigma T_o^4 + f\sigma T_1^4$$

- Balanço para a atmosfera:

$$f\sigma T_o^4 = 2f\sigma T_1^4$$

- Substituindo:

$$\frac{F_S(1-A)}{4} = (1-f)\sigma T_o^4 + \frac{f}{2}\sigma T_o^4 = \left(1-\frac{f}{2}\right)\sigma T_o^4$$

$$T_o = \left[\frac{F_S(1-A)}{4\sigma\left(1-\frac{f}{2}\right)}\right]^{\frac{1}{4}}$$

Fonte: [9]

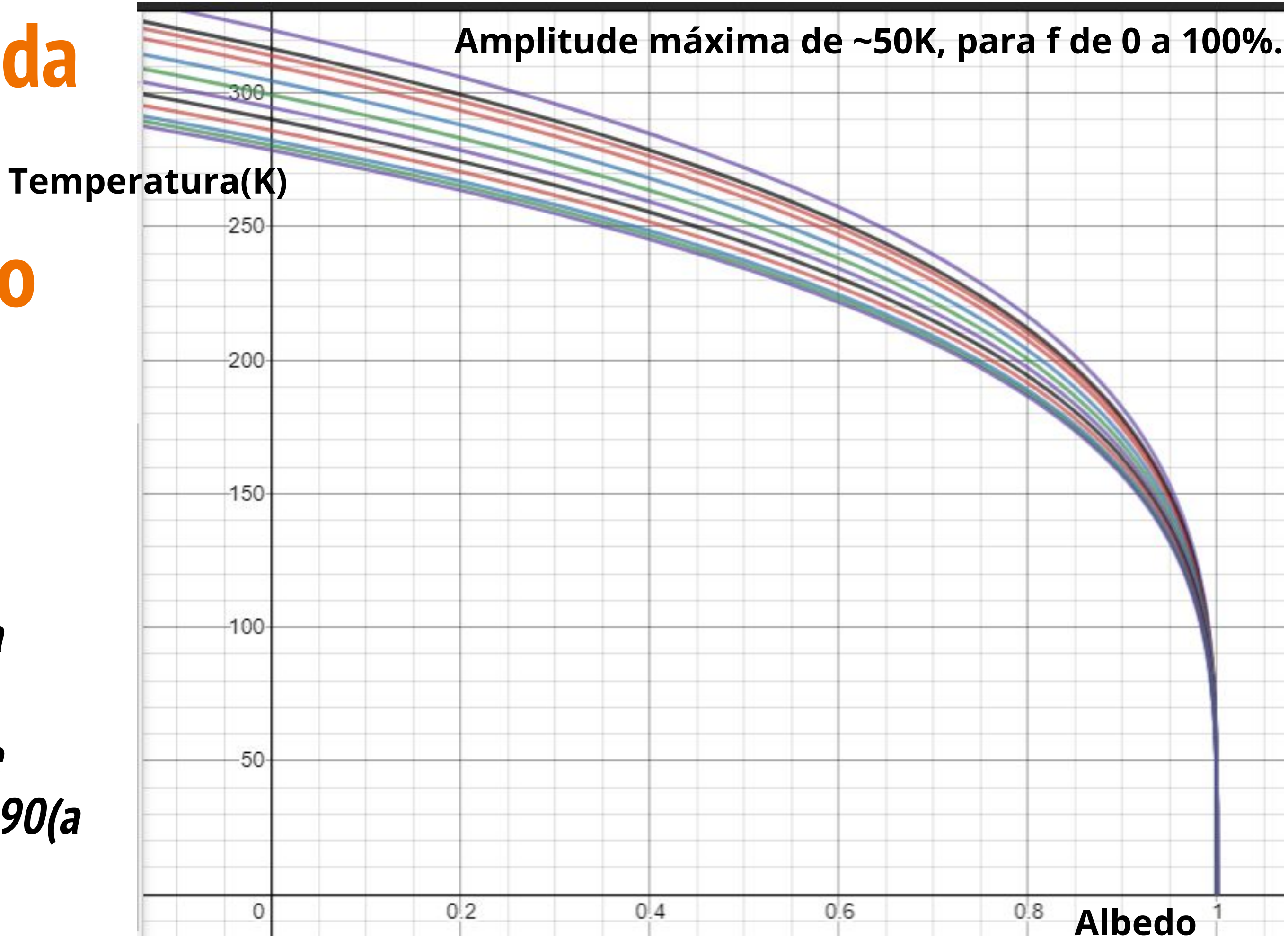
- T(superfície atual)=288K +
  Albedo(atual) =0,3
  f=0,77(fração de onda-longa absorvida pela atmosfera)

Scene type number	Scene type	Broadband albedo
1	Evergreen needle forest	0.1188
2	Evergreen broad forest	0.1300
3	Deciduous needle forest	0.1188
4	Deciduous broad forest	0.1726
5	Mixed forest	0.1443
6	Closed shrubs	0.2175
7	Open/shrubs (desert)	0.2314
8	Woody savanna	0.1620
9	Savanna	0.1818
10	Grassland	0.1841
11	Wetland	0.1147
12	Cropland	0.1496
13	Urban	0.1697
14	Crop mosaic	0.1583
15	Barren/desert	0.3551
16	Tundra	0.1697
17	Ocean water	0.0660

Surfaco	*albedo*
Snow	
fresh	0.80–0.95
old compacted/dirty	0.42–0.70
Ice	
glacier	0.20–0.40
Water	
calm, clear seawater	
solar elevation 60°	0.03
30°	0.06
10°	0.29
Soils	
dry, wind-blown sand	0.35–0.45
wet, wind-blown sand	0.20–0.30
silty loam (dry)	0.15–0.60
silty loam (wet)	0.07–0.28
peat	0.05–0.15
Plants	
short grass (0.02 m)	0.26
long grass (1.0 m)	0.16
heather	0.10
deciduous forest (in leaf)	0.20
deciduous forest (bare)	0.15
pine forest	0.14
field crops	0.15–0.30
sugar beet (spring)	0.17
sugar beet (early summer)	0.14
sugar beet (midsummer)	0.26
Man-made	
asphalt	0.05–0.20
concrete	0.10–0.35
brick	0.20–0.40

Temperatura da superfície da Terra x Albedo

$$T_e = \left[\frac{F_S(1-A)}{4\sigma\left(1-\frac{f}{2}\right)}\right]^{\frac{1}{4}}$$



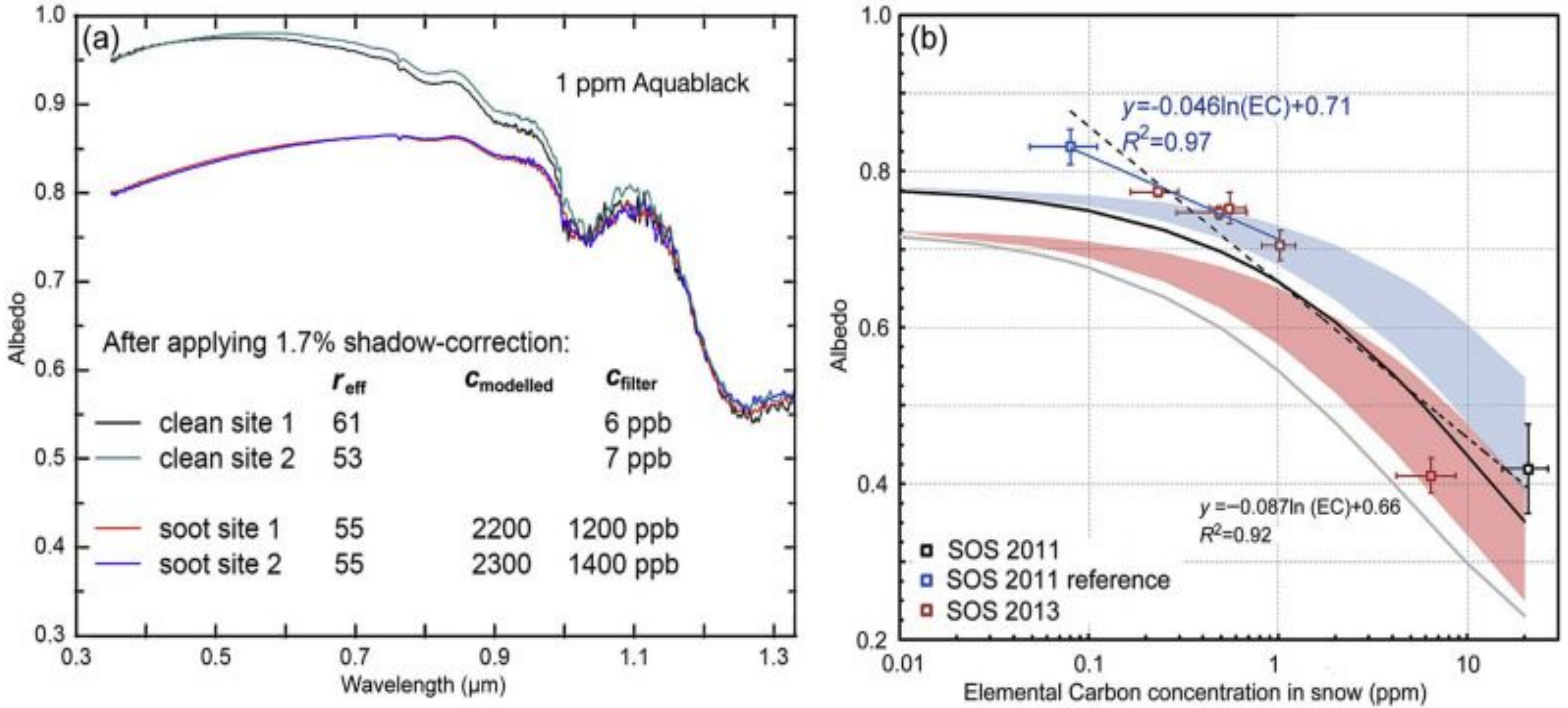
Cada curva representa a expressão acima com valores de f variando de 0,01(a mais baixa) a 0,90(a mais alta). Hoje f=0,77.

CO2 and Albedo feedback mechanisms

- **High albedo allows the polar ice sheets to slowly grow**
- Slowly **reflect more** and more incident sunlight in the process.
- And this ice-albedo **resist the next Great Summer when northern sunlight (insolation) is once again at a maximum**,
- **Great Summers produce no global warming whatsoever**."
- **Reduces the sun-strength in the northern hemisphere and allows ice sheets to grow.**
- As the ice sheets grow and the **seas cool, CO2 also reduces**.
- The concentration finally reaches the **critical 190 ppm** level where world **flora begins to die**, **steppe-lands turn into a true sand desert**.
- **Dust storms dump thousands of tonnes of dust onto the northern ice sheets** each year.
- **Dusty polar ice sheets can warm and melt and the next interglacial is born**

Fonte: [8]

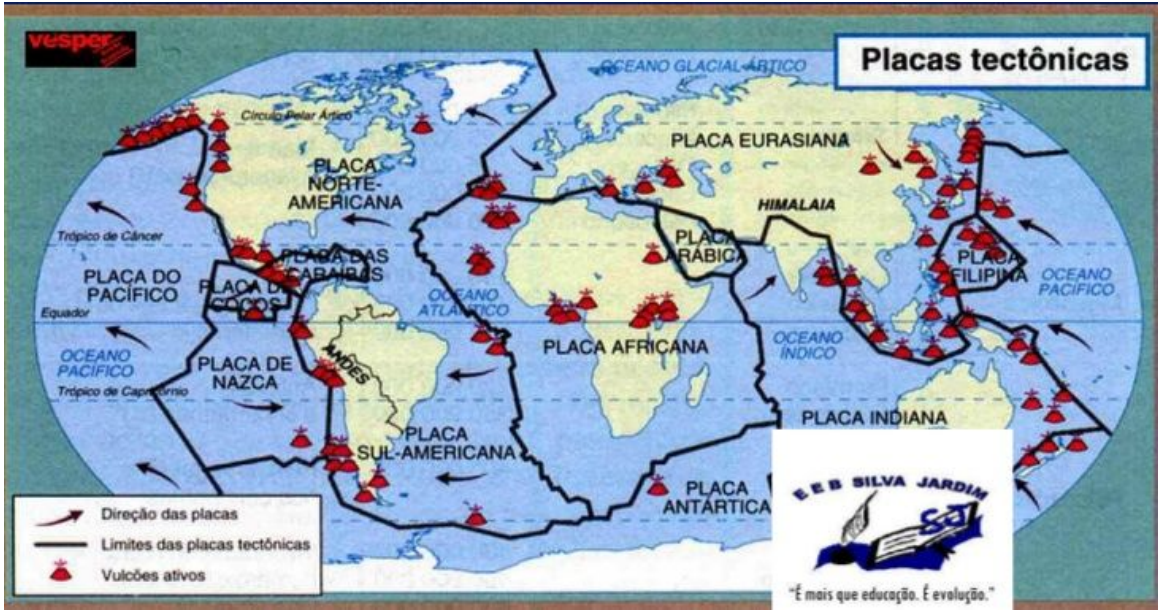
CO2 and Albedo feedback mechanisms

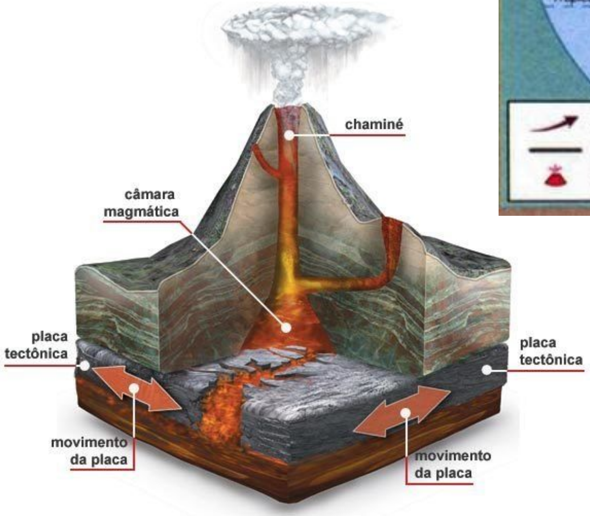


Fonte: [8]

Causas de alteração do sistema climático

1. Movimento tectônico
2. Vulcões
3. Composição atmosférica
4. Órbita terrestre
5. Forçante solar



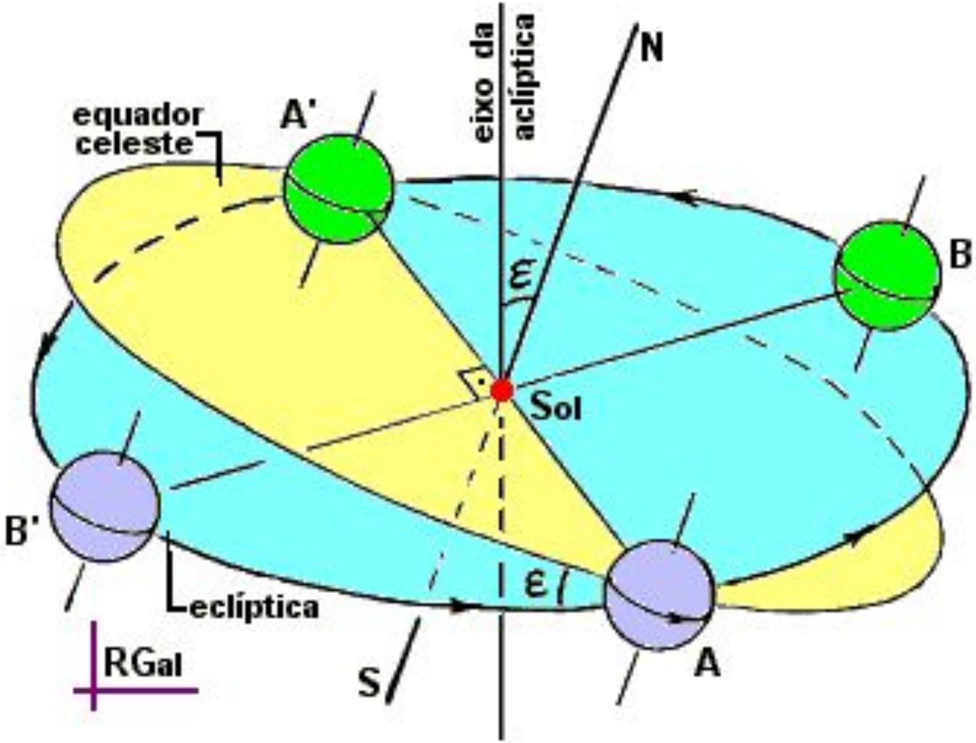


Fonte: [2]

Forçante solar

Variações do fluxo de radiação solar que atinge a Terra, devido aos movimentos:

- Excentricidade da órbita
- Precessão do eixo da Terra
- Obliquidade
- Precessão do Afélio
- Inclinação da Órbita



Fonte: [2]

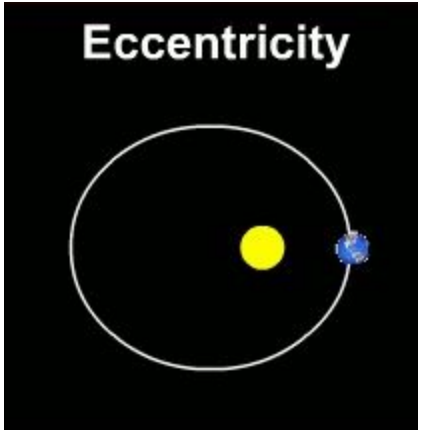
Excentricidade da Órbita

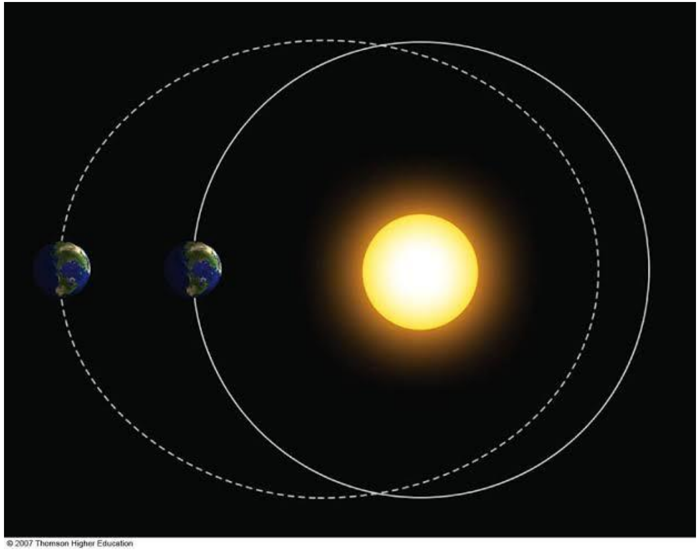
Atualmente

Diferença de 3% entre a maior (periélio) e menor aproximação (afélio).

Implica num aumento de 6% da radiação incidente entre Janeiro (periélio) e Julho (afélio).

- Período: 90.000-100.000 anos.
- Maior excentricidade: diferença de 20-30% entre o periélio e o afélio.



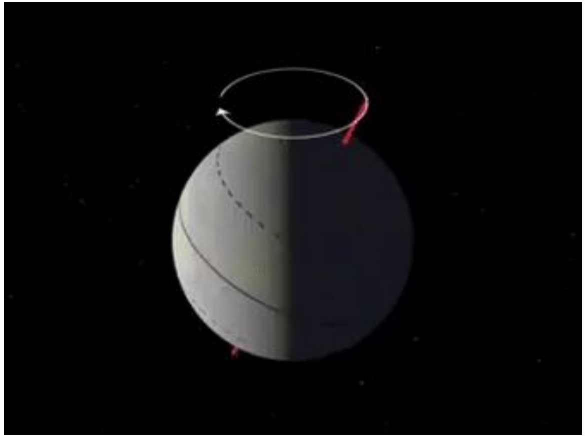


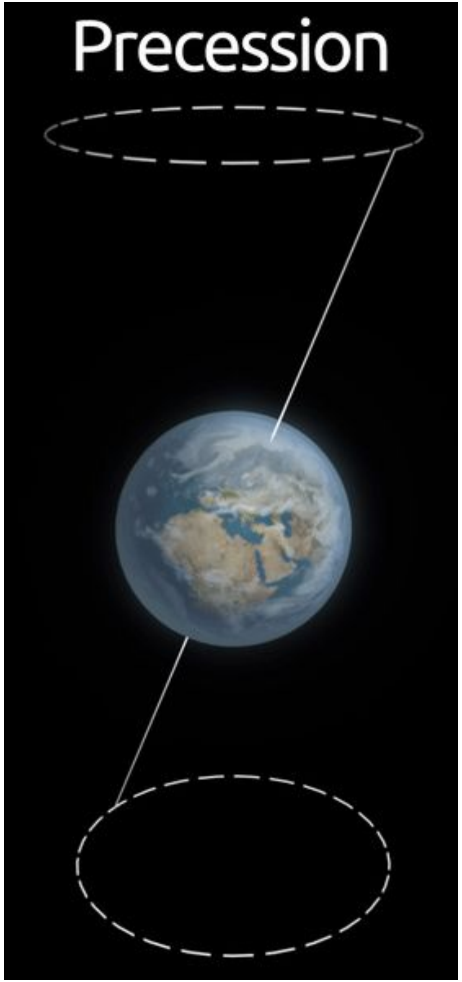
Fonte: [3]

Precessão da Terra

Período: ~26.000 anos

- Altera a orientação da Terra em relação ao afélio e periélio.





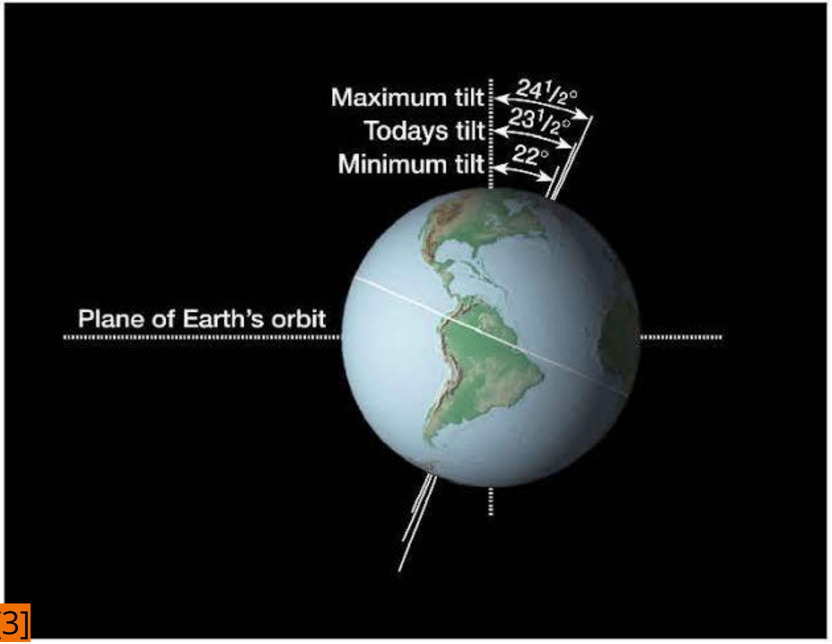
- Atualmente, o verão do hemisfério sul ocorre no periélio.

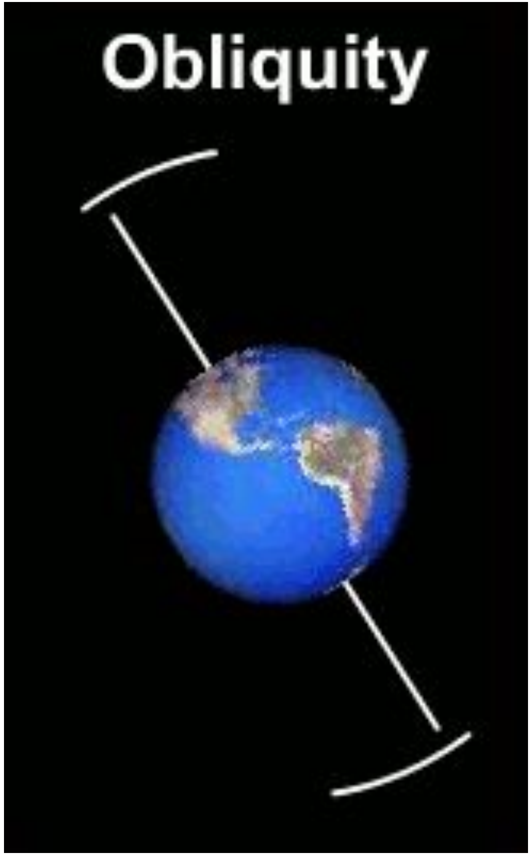
Fonte: [3]

Obliquidade

Período: ~41.000 anos.

Maior inclinação: estações mais severas.

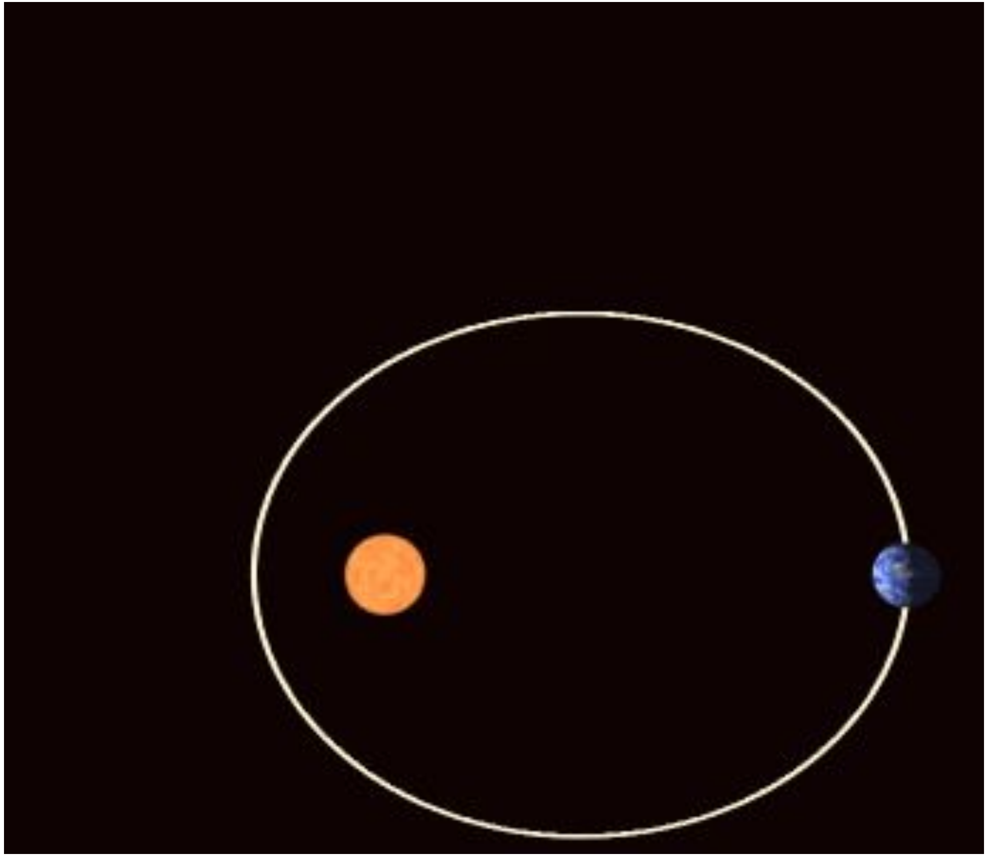




Fonte: [3]

Precessão do Afélio

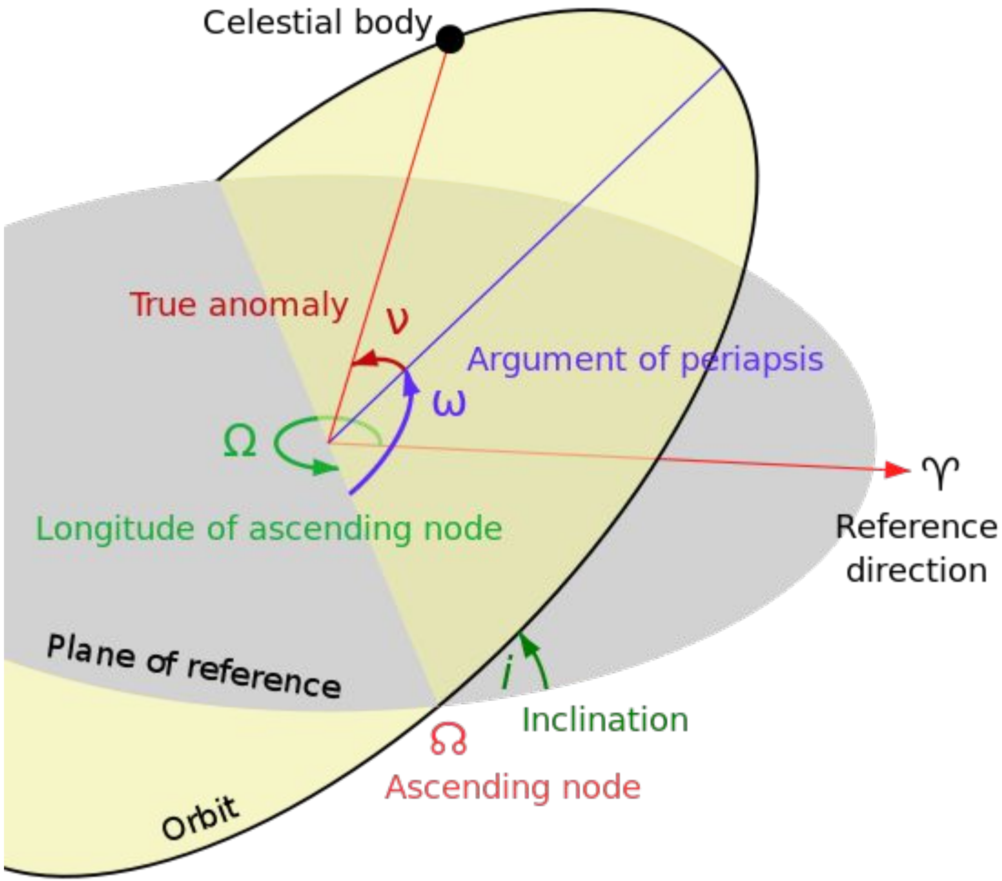
período: ~112.000 anos.



Fonte: [5]

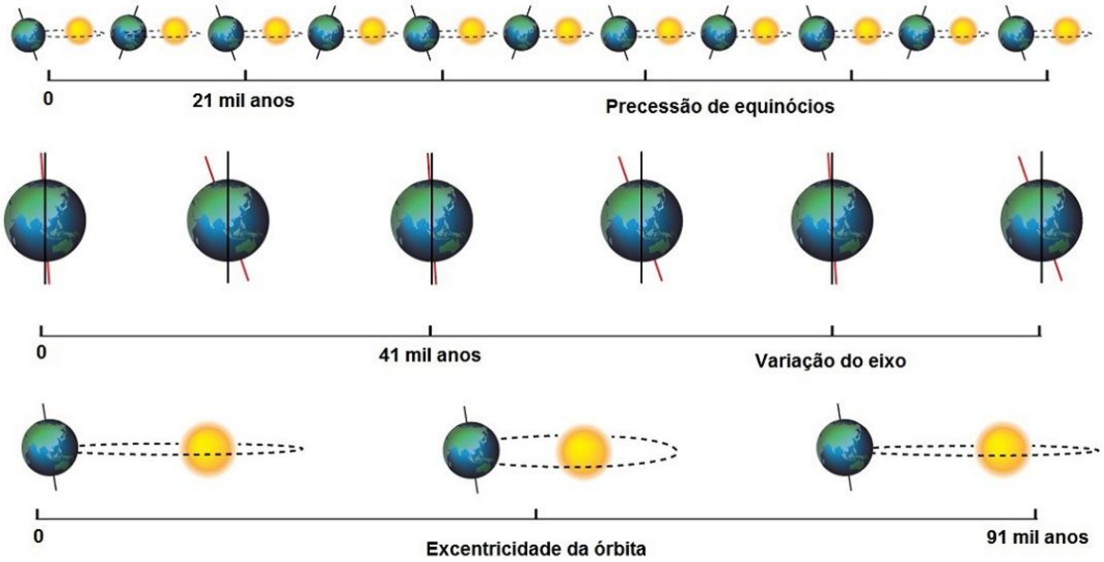
Inclinação da Órbita

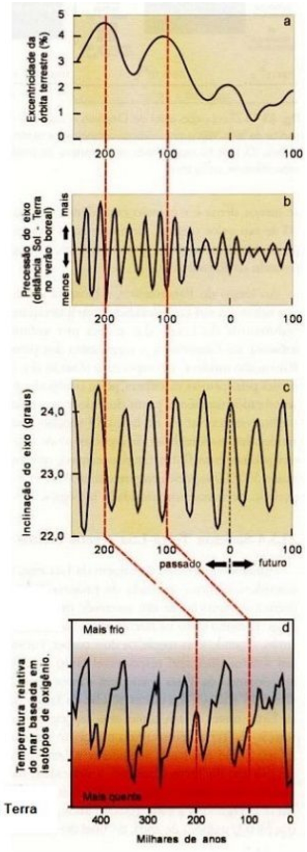
- Período: ~100.000 anos.



Fonte: [6]

Ciclos de Milankovitch



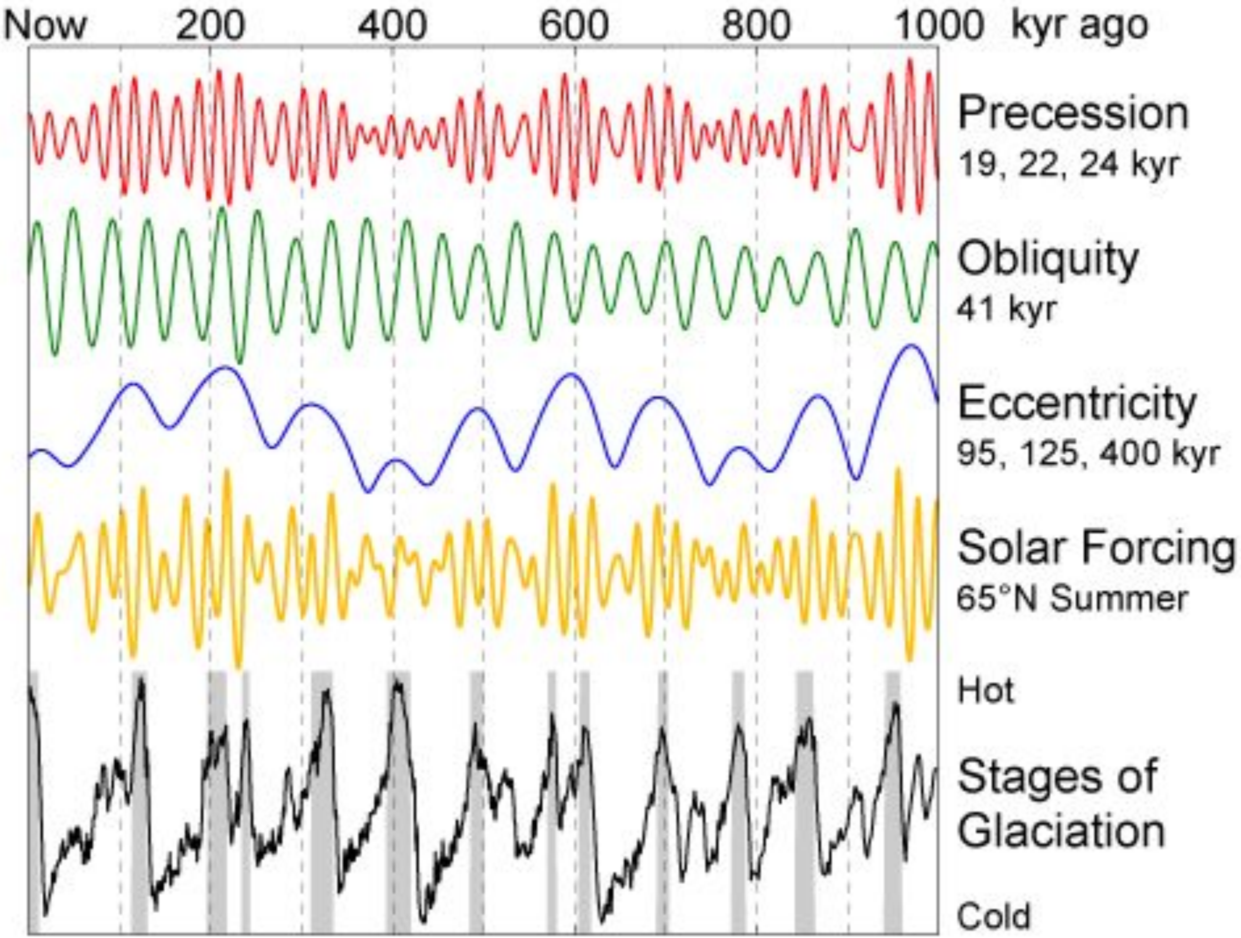


fonte: Decifrando a Terra

- (1983) Teoria que explica as eras glaciais e interglaciais a partir das variações dos 3 parâmetros orbitais.

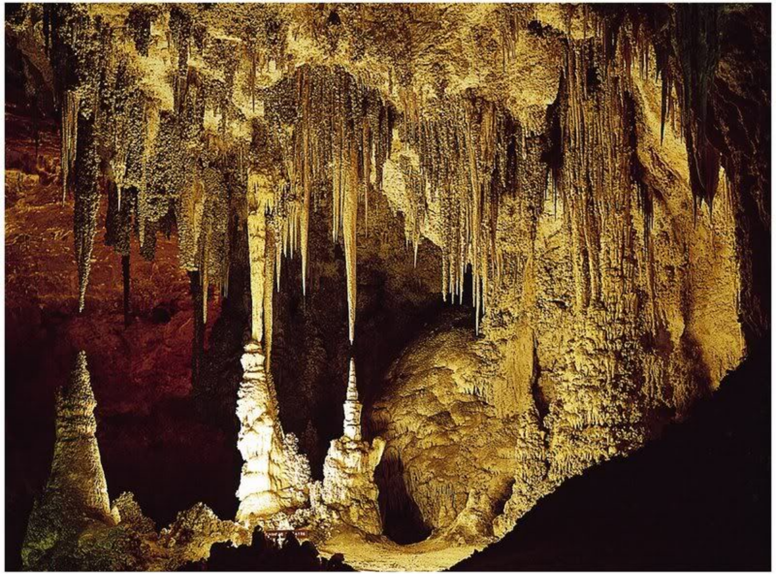
Fonte: [4]

- Combinação dos 3 modos de osciladores harmônicos = Forçante solar.
- Aumento suave, decaimento abrupto



Registros de mudanças climáticas

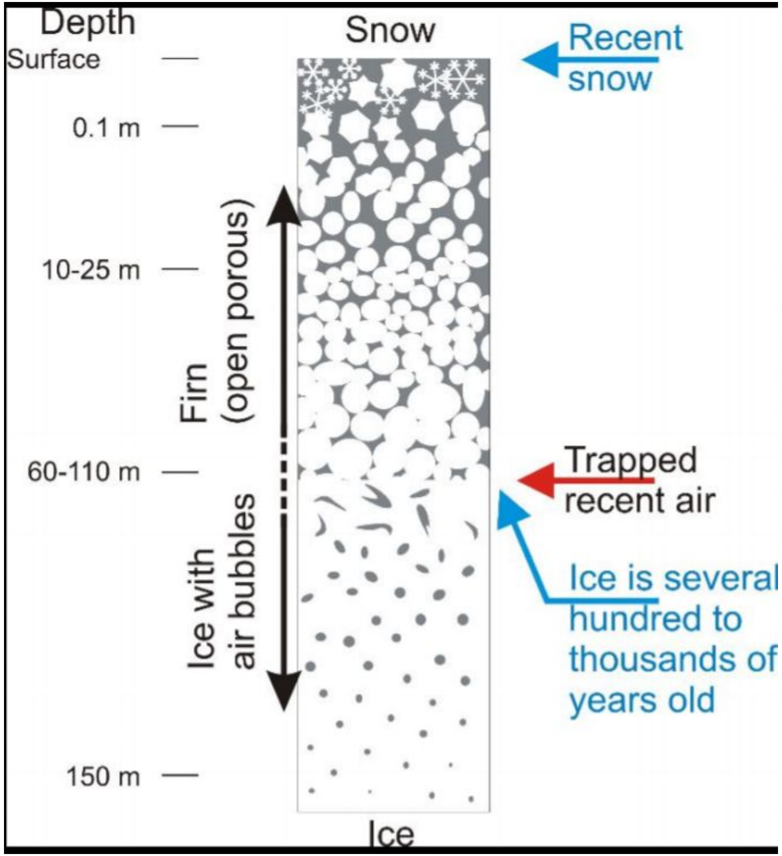
- Anéis de crescimento em árvores;
  - Câmbio vascular
- Sedimentos marinhos e lacustres
- Rochas e espeleotemas
- Testemunhos de gelo



Fonte: [2]

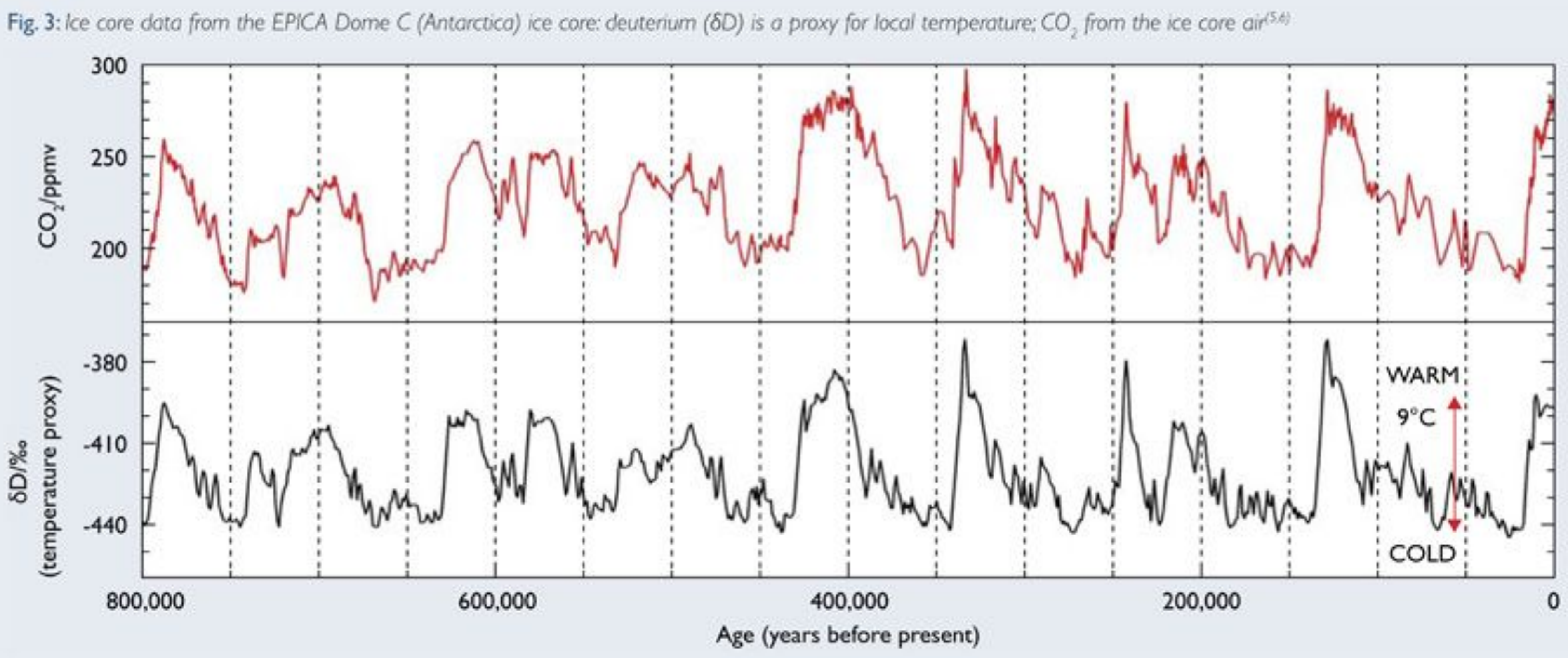
O registro paleoclimático em testemunhos de gelo

- Forma mais direta e detalhada;
- Bolhas de ar aprisionadas em geleiras;
- Análises das propriedades físicas e químicas ;
- Sujeito a difusão gasosa entre poros.

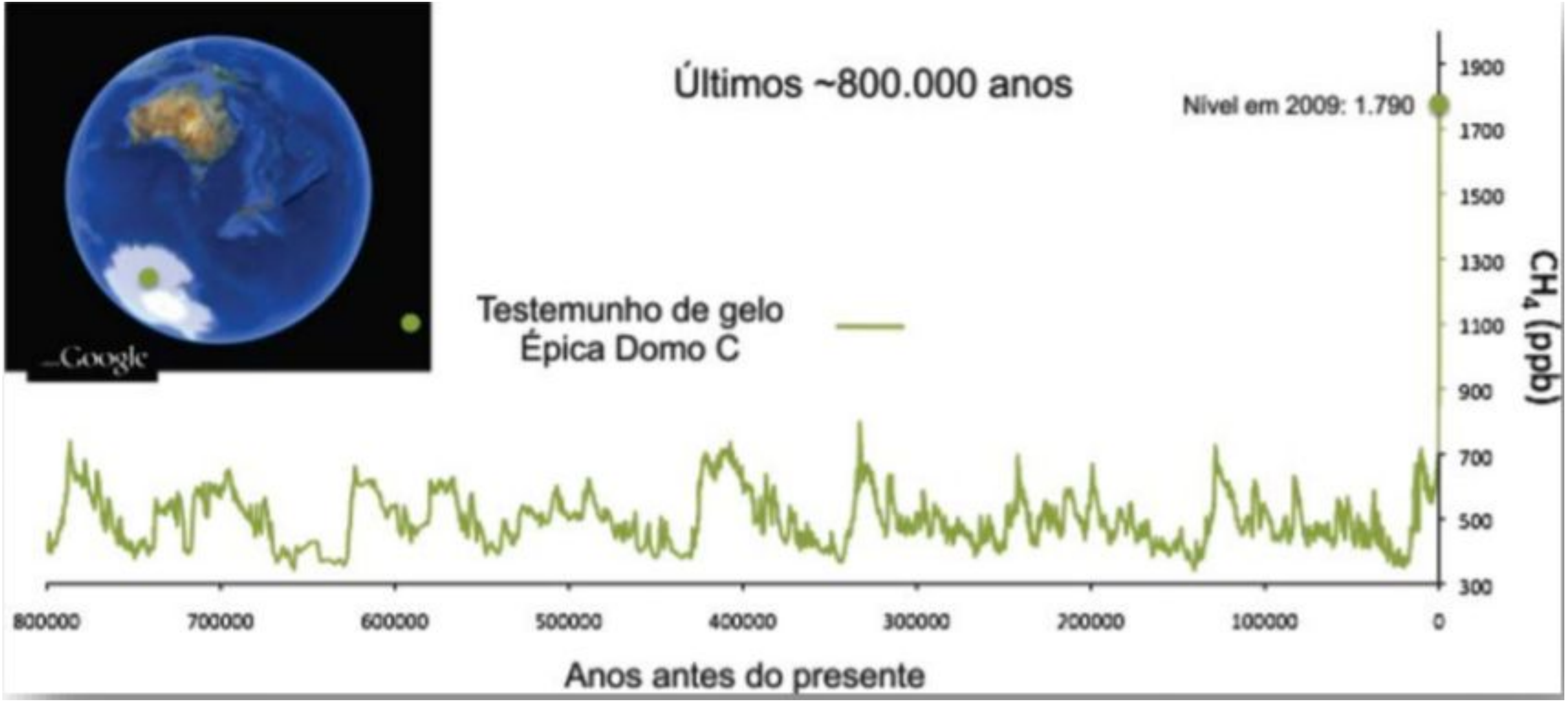


Fonte: [2]

Testemunho de gelo de Dome da Antártica



Testemunho de gelo de Dome da Antártica



Isótopos Estáveis

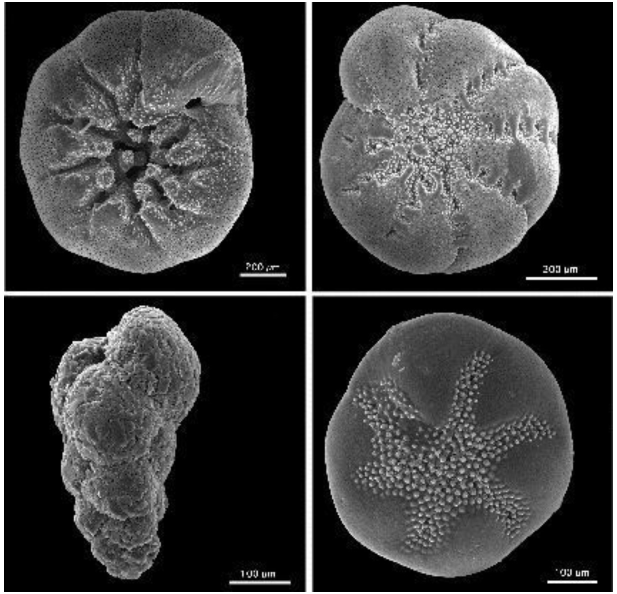
Eras Glaciais

$H_2{}^{18}O$ ⟶ gelo
$H_2{}^{16}O$ ⟶ oceanos

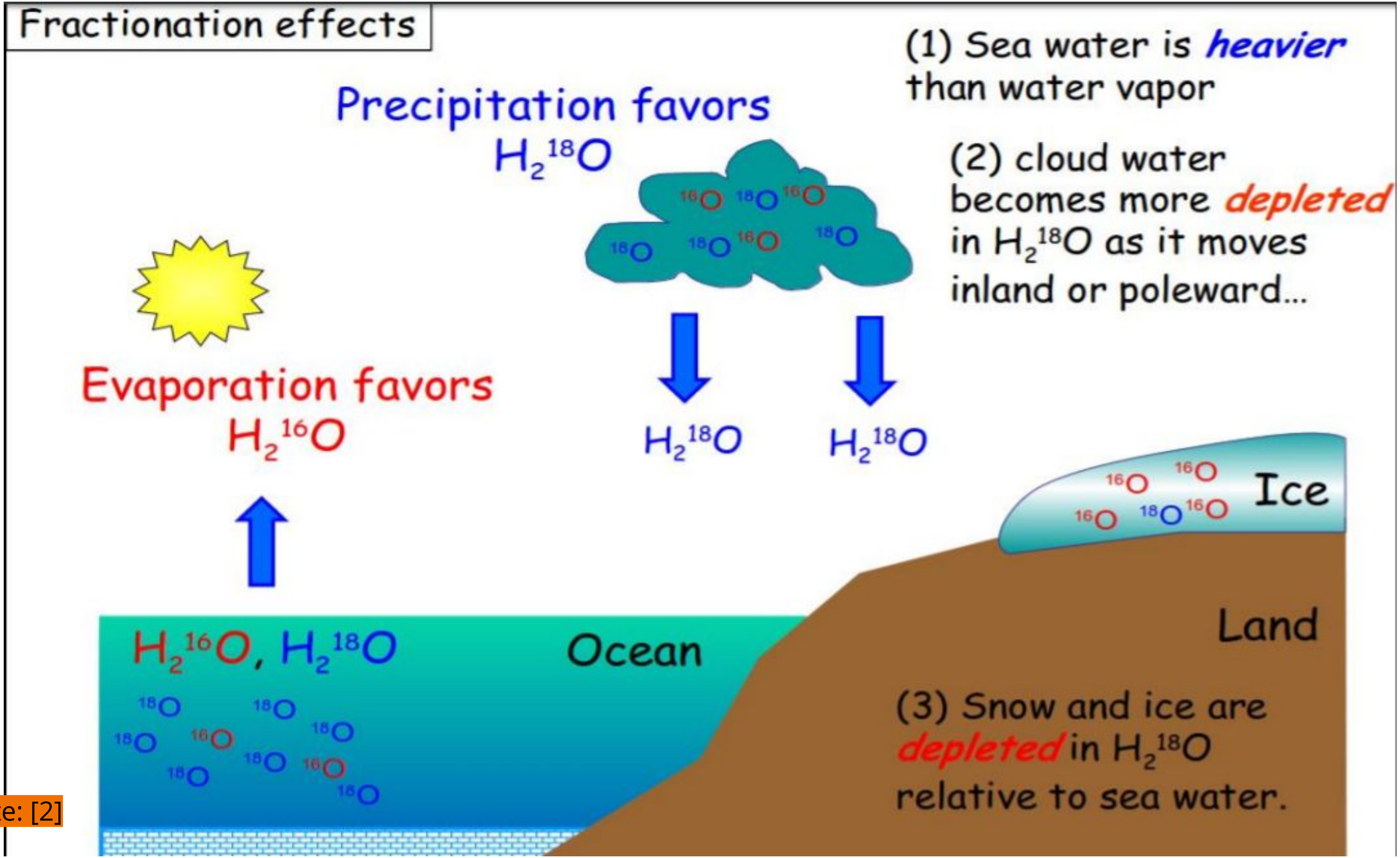
$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{amostra} - (^{18}O/^{16}O)_{referência}}{(^{18}O/^{16}O)_{referência}}$$

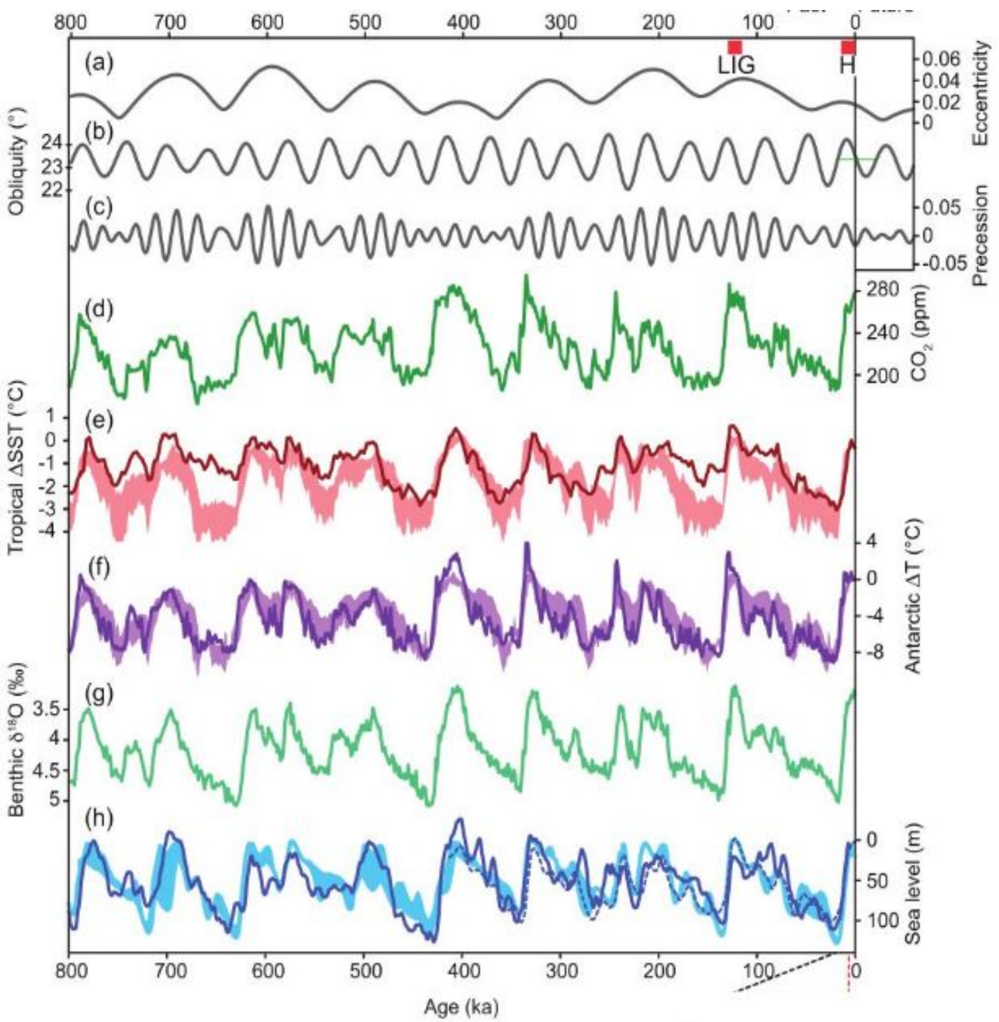
- água que evapora dos oceanos é, em maior quantidade, o $H_2{}^{16}O$ (mais leve).
- $H_2{}^{18}O$ que evaporou precipita mais rápido do que o $H_2{}^{16}O$
- $H_2{}^{18}O$ precipita antes da nuvem chegar no continente

- testemunhos de gelo;
- conchas de foraminíferos ($CaCO_3$).



Fonte: [7]

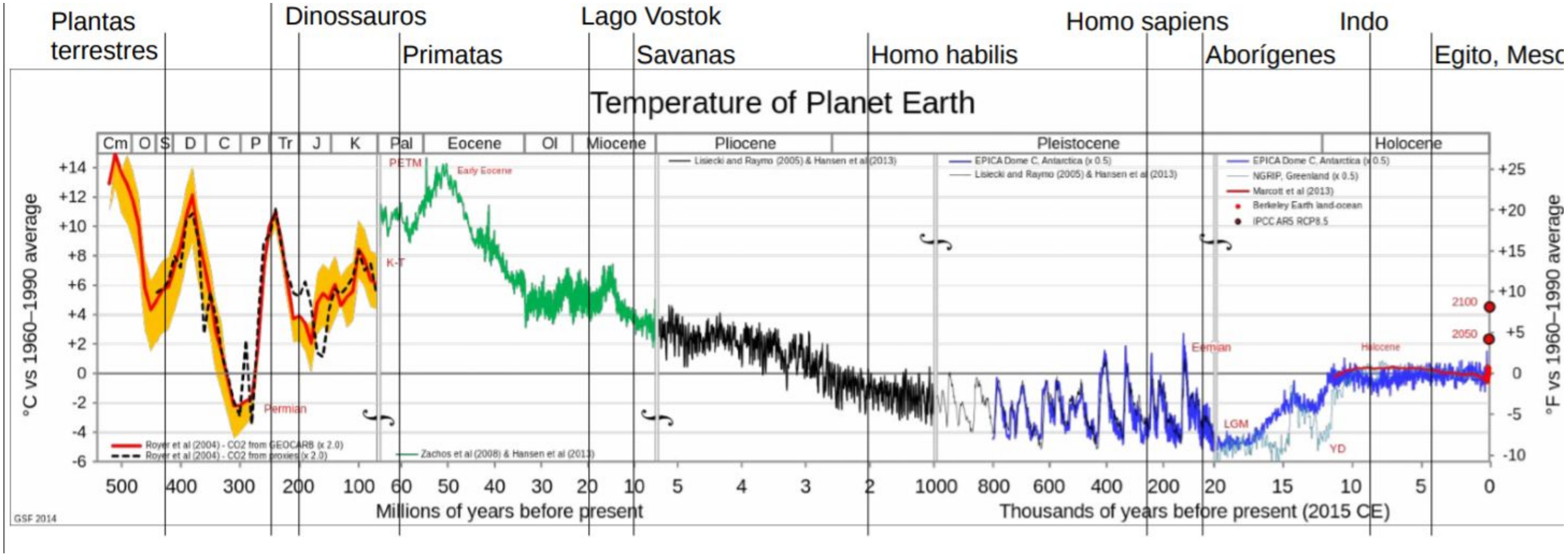

Fractionation effects
(1) Sea water is heavier than water vapor
Precipitation favors $H_2{}^{18}O$
(2) cloud water becomes more depleted in $H_2{}^{18}O$ as it moves inland or poleward...
16O 18O 16O
18O 18O 16O 18O
Evaporation favors $H_2{}^{16}O$
$H_2{}^{18}O$
$H_2{}^{18}O$
16O 16O
Ice
16O 18O 16O
Land
$H_2{}^{16}O$, $H_2{}^{18}O$
Ocean
18O 18O
18O 16O 18O
18O 16O
18O
18O
(3) Snow and ice are depleted in $H_2{}^{18}O$ relative to sea water.
Fonte: [2]



800
700
600
500
400
300
200
100
0
(a)
LIG
H
0.06
0.04
0.02
0
Eccentricity
Obliquity (°)
24
23
22
(b)
(c)
0.05
0
-0.05
Precession
(d)
280
240
200
CO2 (ppm)
Tropical ΔSST (°C)
1
0
-1
-2
-3
-4
(e)
(f)
4
0
-4
-8
Antarctic ΔT (°C)
Benthic δ18O (‰)
3.5
4
4.5
5
(g)
(h)
0
50
100
Sea level (m)
Age (ka)

Fonte: [2]

História da temperatura da Terra



Fonte: [2]

Gases do Efeito Estufa

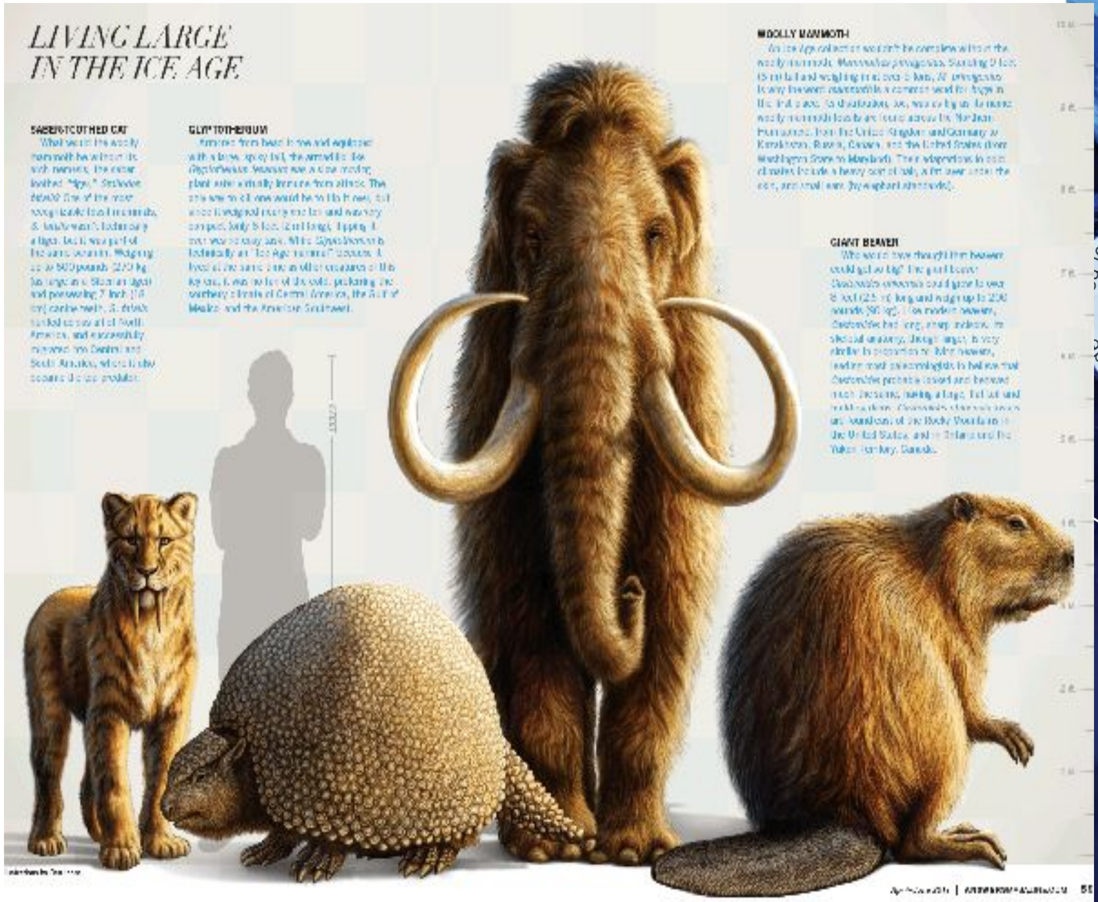
Table 9-1. Atmospheric Changes in Radiatively Active Species of Trace Gases

	Concentration			Twentieth Century	
Species	*Glacial*	*Pre-industrial**	*Current*	*Annual concentration change*	*Annual % change*
Carbon dioxide (CO_2)	200 ppmv	280–290 ppmv	365 ppmv	1.5 ppmv	0.4
Methane (CH_4)	300–400 ppbv	700 ppbv	1730 ppbv	10 ppbv	0.6
Carbon monoxide (CO)	—	90 ppbv	0.6 ppbv		0.7
Nitrous oxide (N_2O)	—	275	312 ppbv	0.8 ppbv	0.3
Chlorofluorocarbons (CFCs)	—	0.1–0.5 ppbv	0.01–0.02 ppbv		

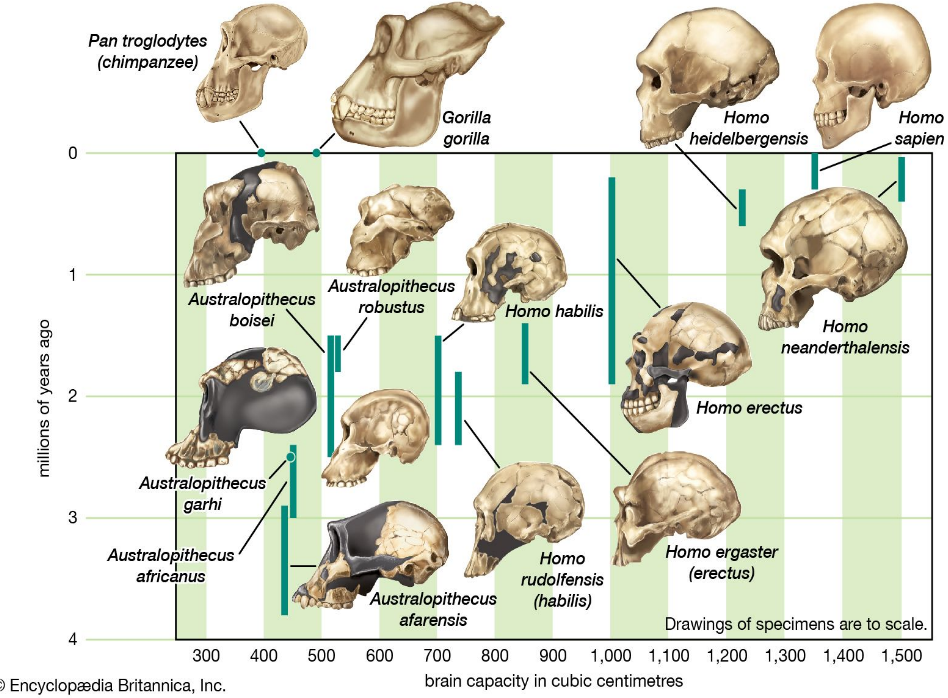
*"Pre-industrial" informally refers to the time before the late nineteenth century. Houghton et al. (1996) and other studies often plot trends since 1850 A.D.
Sources: Graedel and Crutzen (1993); Houghton et al. (1996); Battle et al. (1996)

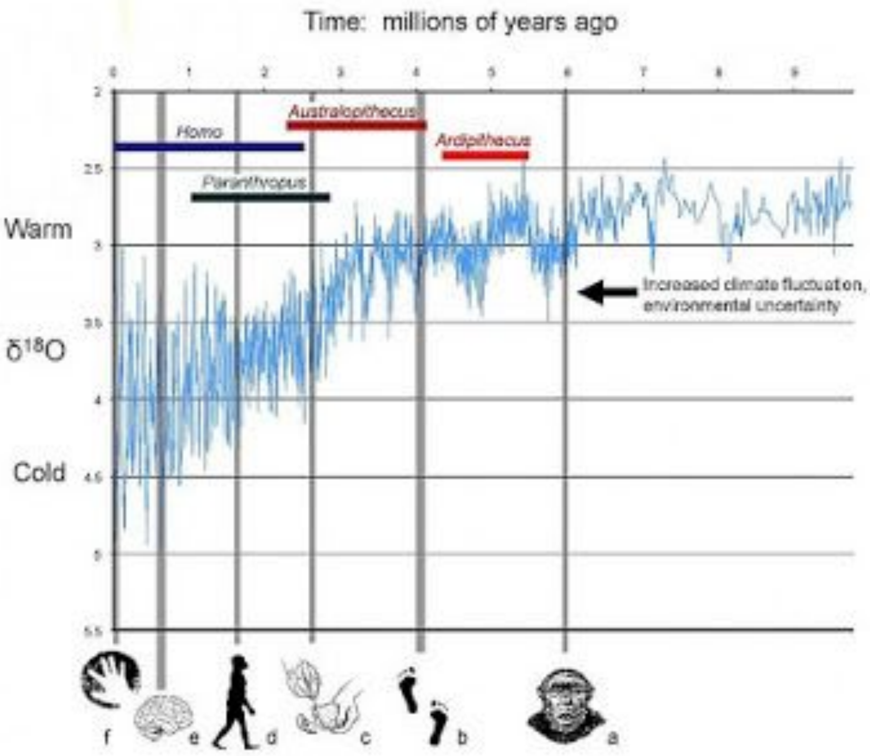
Fonte: [7]

A Era do Gelo(Pleistoceno)



Evolução Humana





Evolução Humana

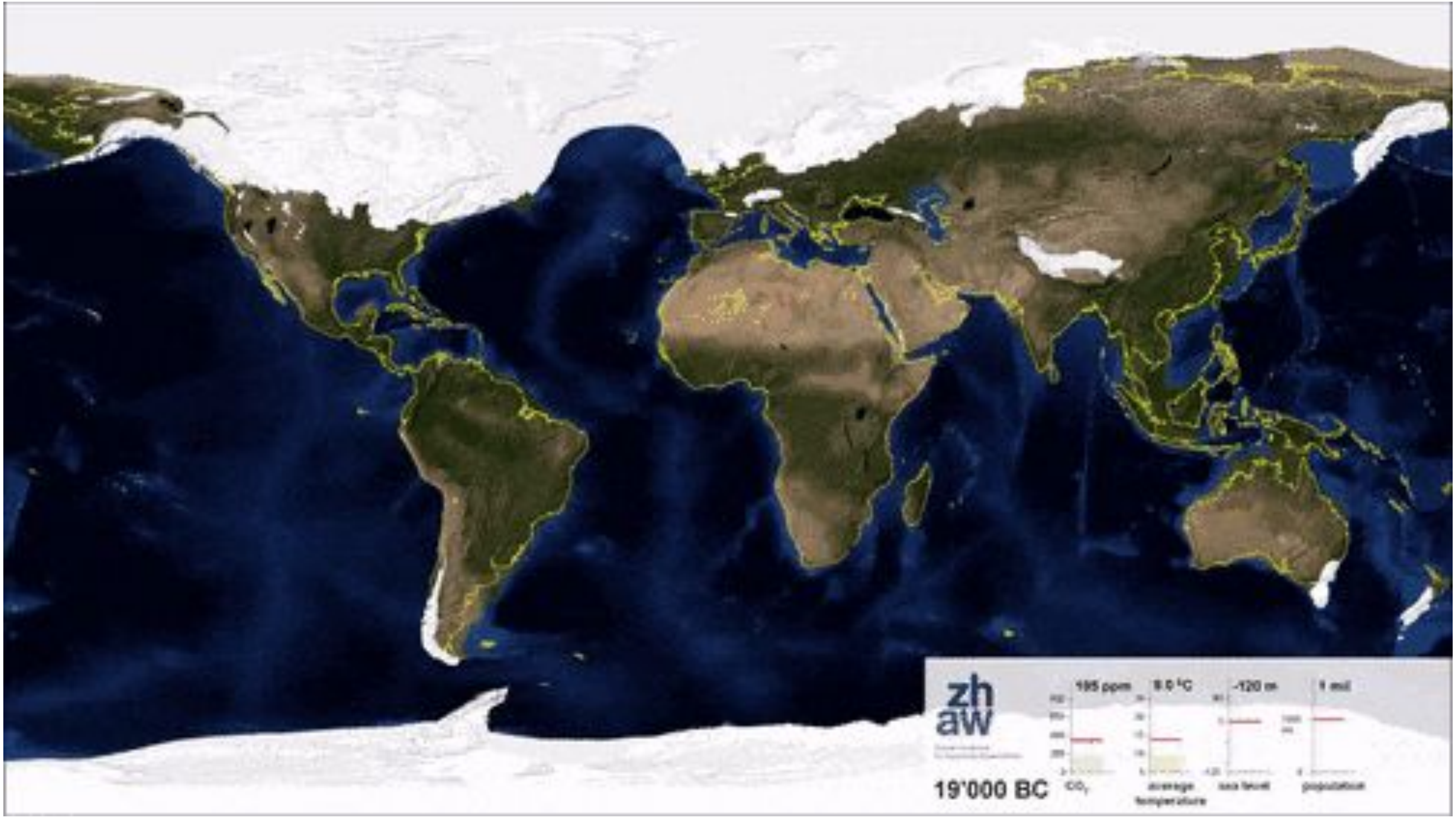
- “(...)Peter B. deMenocal of Columbia University's Lamont-Doherty Earth Observatory. But he and other researchers are exploring several lines of evidence, from **ancient teeth to seafloor sediments**(...)”
- “(...)two major evolutionary events can be linked to periods of climate instability”
- “Roughly **between 3 and 2.5 million years ago,** the lineage of ‘Lucy’ [*Australopithecus afarensis*] became extinct and the first members of **our own genus, *Homo*, appeared**. The first simple stone tools also appeared with those fossils, which featured some modern traits like **bigger brains**,” deMenocal says. “Then, **between 2 million and 1.5 million years ago, we see *Homo erectus*.**” That bigger-brained hominin had a **skeleton very much like our own**, more sophisticated tools like double-bladed axes and new behaviors that led early humans **out of Africa** for the first time. “
- “Africa was switching from **wooded areas to open grasslands** as the climate dried out.”
- **swings** between very **wet** and very **dry periods about every 20,000 years**. This follows a regular cycle, **governed by a wobble in Earth's orbit**, that increases and decreases the amount of available sunlight hitting the planet.”

- **”Fossil tooth analysis,** (...) what our ancestors were eating and drinking during these volatile periods(...) ,earlier peoples passively **fed on the expanding grasslands**, says deMenocal. This indicates that more successful **early humans sought diverse food options during variable periods** even as the African landscape was, in the long term, trending toward a more uniform grassland environment.”
- “it's plausible to theorize that our ancestors’ **brains might have expanded when the lakes were highly variable**, because hominins **had to become smarter** to **determine** where their **next meals** would come from, Maslin says.”

A piece of jawbone from an early human ancestor, found at a site in Spain that dates back about 1.2 million years.

“On the other hand, it could be that in **wet periods**, when there are **lots of resources, sexual selection kicks in** and the most clever females are saying, Whichever of the males is controlling the group, I'm having him as a partner.” Studies of later periods such as the Middle Stone Age (**about 80,000 to 40,000 years ago**) link rapid climate change that created wet conditions in South Africa to **innovations in language and cultural identity**, including symbolic engravings and shell jewelry.

Fonte: [10]

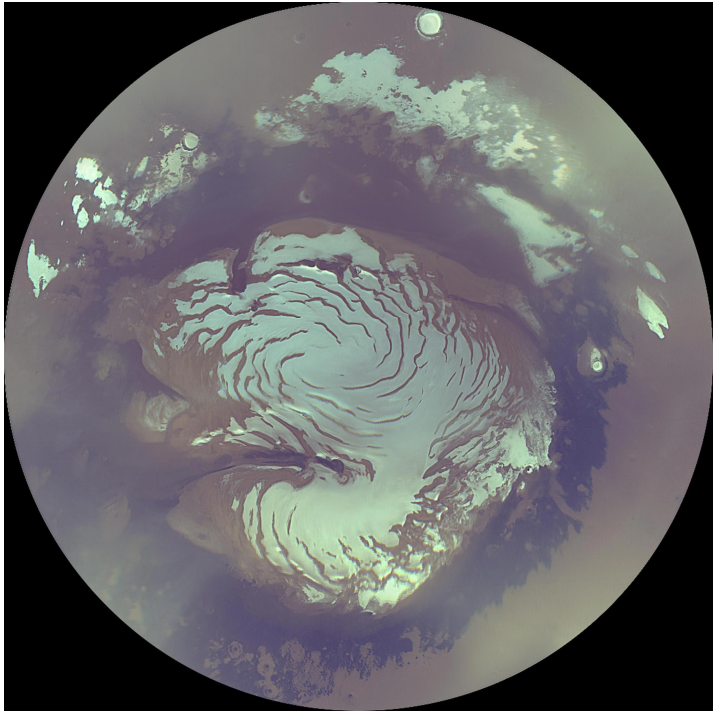

-120 m
19'000 BC

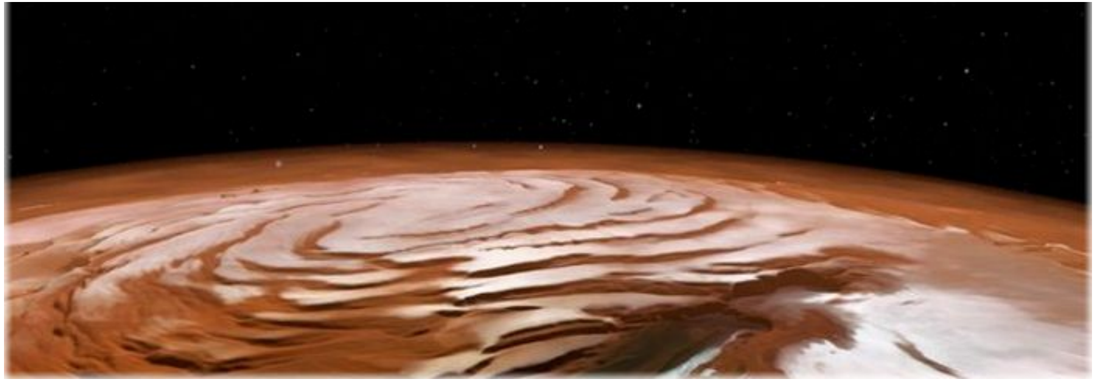
Ciclos de Milankovitch em outros planetas

- Não intensos e complexo como na Terra

MARTE

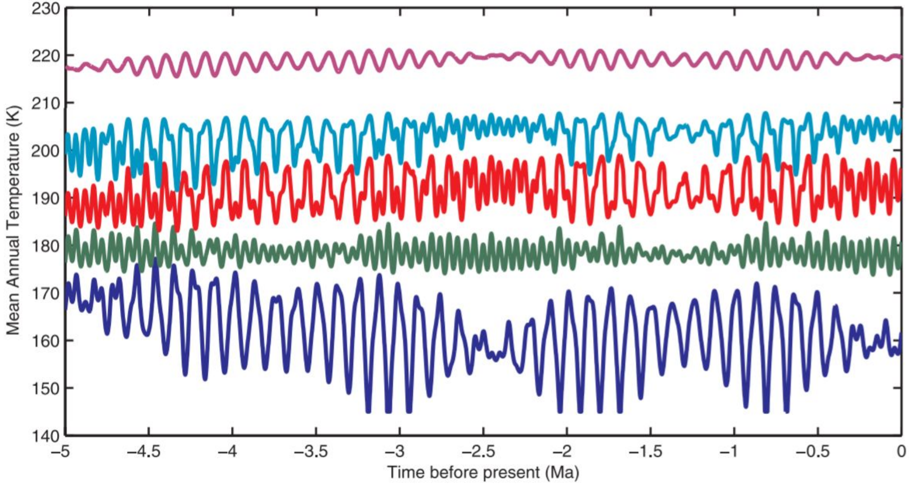
- Obliquidade: 120 ka, excentricidade: 95 ka e precessão de 51 ka;
- Extensão das calotas polares.
- Era glacial há ~370.000 anos;

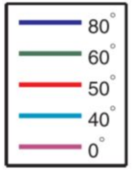




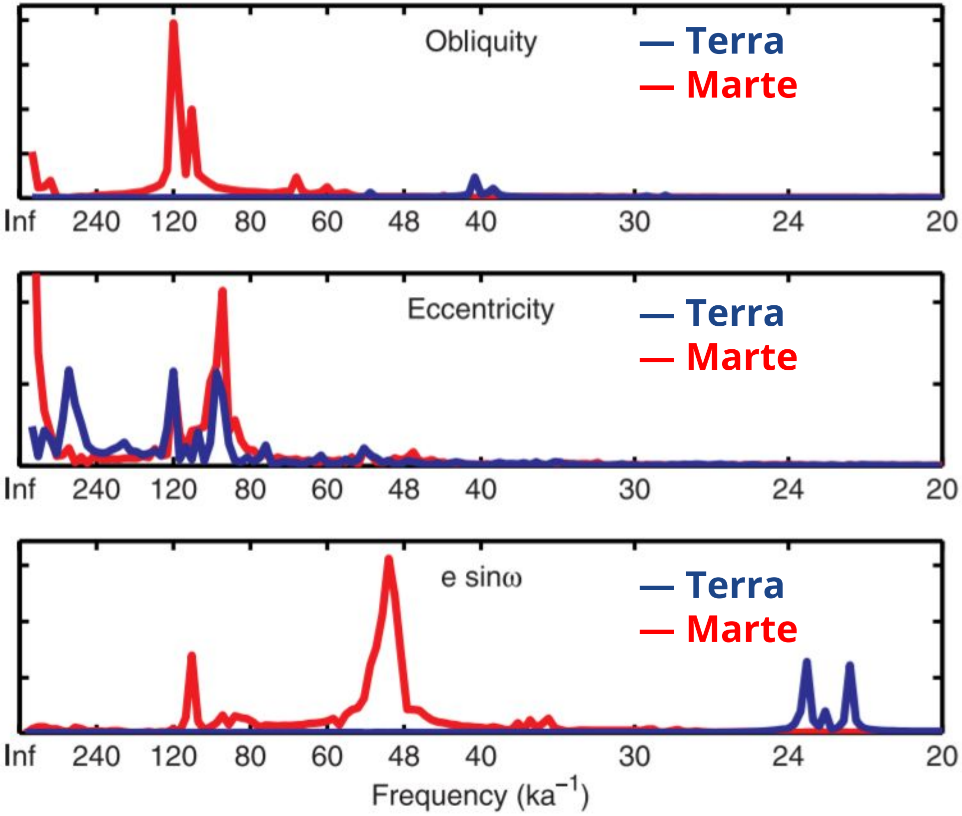
Ciclos de Milankovitch em outros planetas

MARTE





Modelo para planeta uniforme albedo de 0,2 e Patm = 5 mbar CO2.

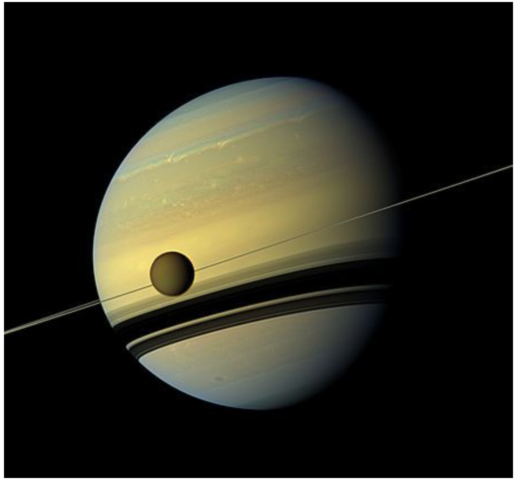


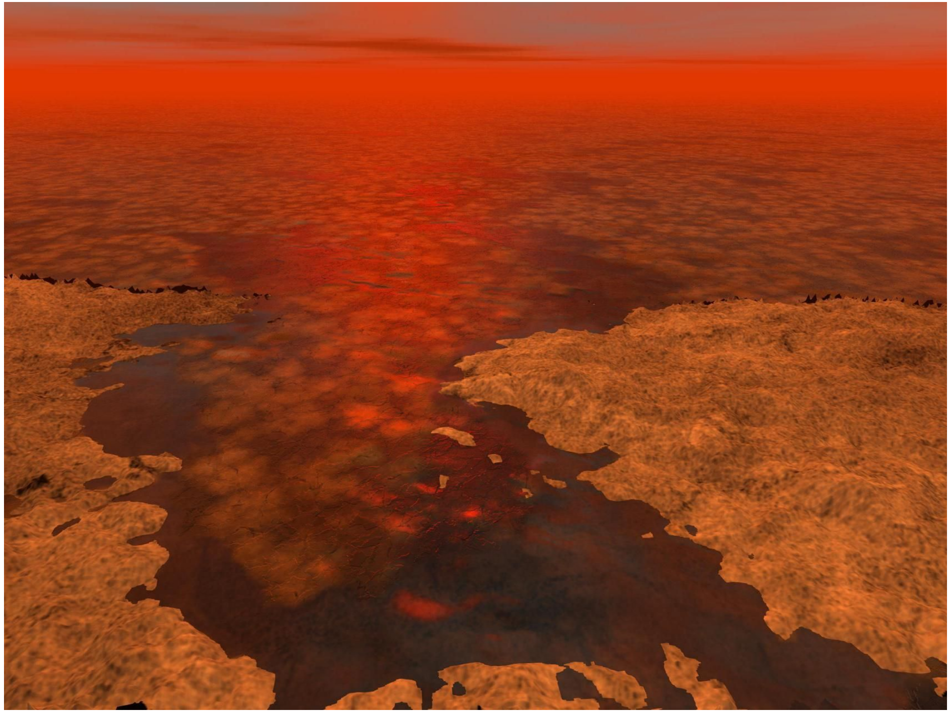
Fonte: [11]

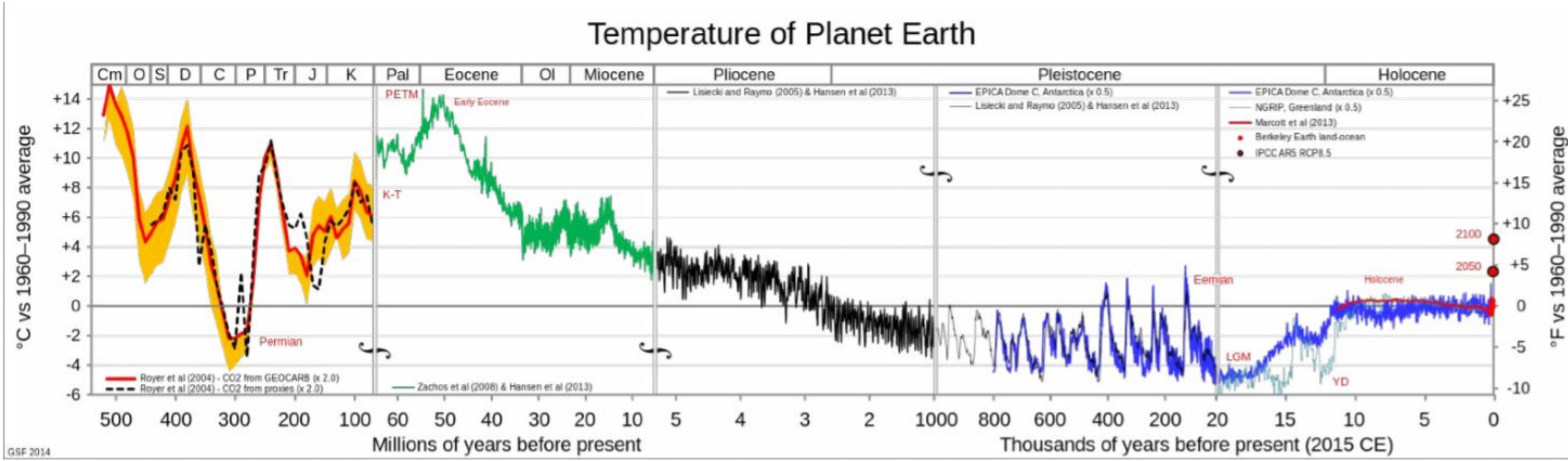
Ciclos de Milankovitch em outros planetas

SATURNO:

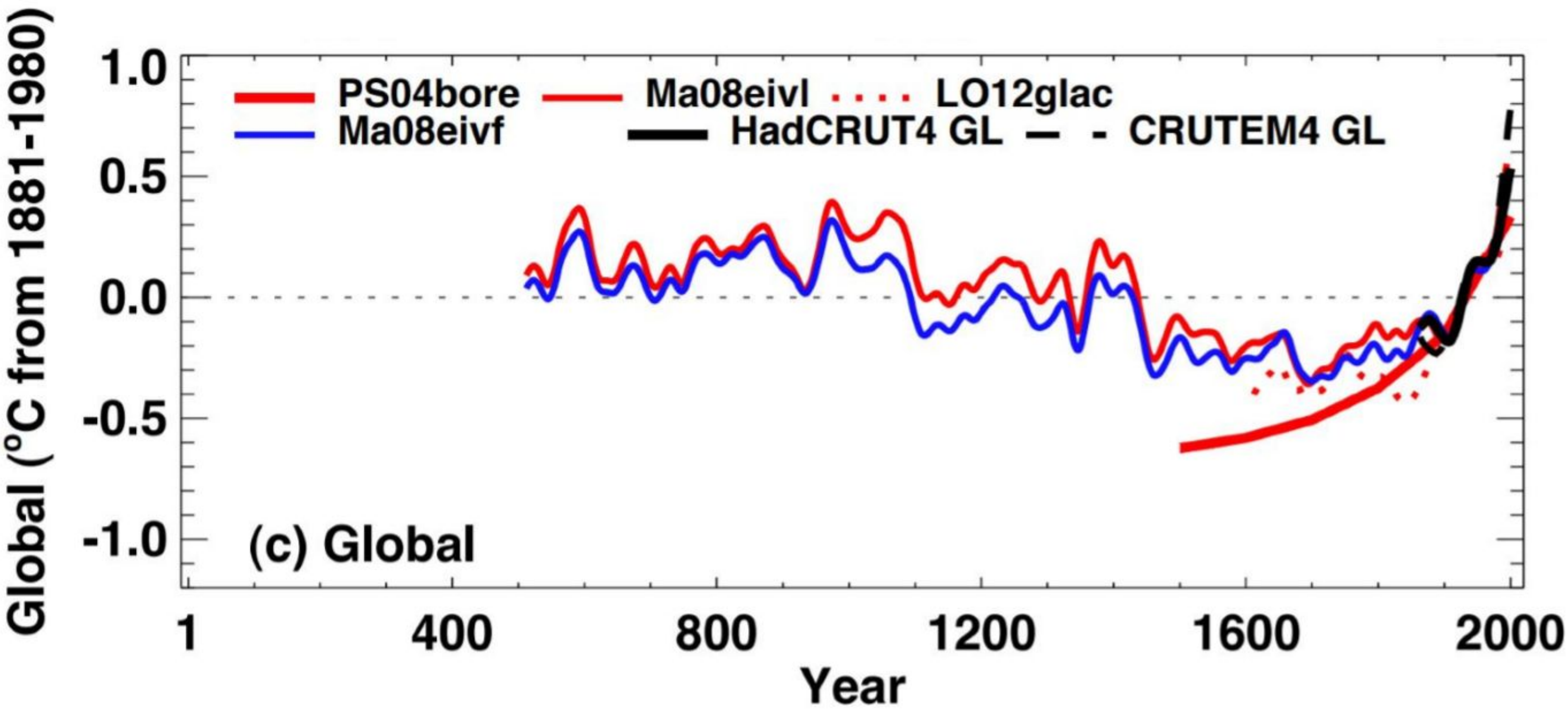
- Titã: 60.000 anos —> Lagos de Metano







Temperature of Planet Earth
Cm O S D C P Tr J K
Pal Eocene Ol Miocene
Pliocene
Pleistocene
Holocene
°C vs 1960–1990 average
°F vs 1960–1990 average
PETM
Early Eocene
K-T
Permian
Eemian
LGM
YD
Holocene
2100
2050
Royer et al (2004) - CO2 from GEOCARB (x 2.0)
Royer et al (2004) - CO2 from proxies (x 2.0)
Zachos et al (2008) & Hansen et al (2013)
Lisiecki and Raymo (2005) & Hansen et al (2013)
EPICA Dome C, Antarctica (x 0.5)
NGRIP, Greenland (x 0.5)
Marcott et al (2013)
Berkeley Earth land-ocean
IPCC AR5 RCP8.5
Millions of years before present
Thousands of years before present (2015 CE)
GSF 2014



PS04bore
Ma08eivl
LO12glac
Ma08eivf
HadCRUT4 GL
CRUTEM4 GL
(c) Global
Global (°C from 1881-1980)
1.0
0.5
0.0
-0.5
-1.0
1
400
800
1200
1600
2000
Year

Referências

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Obrigad@!