上海交通大学海洋学院

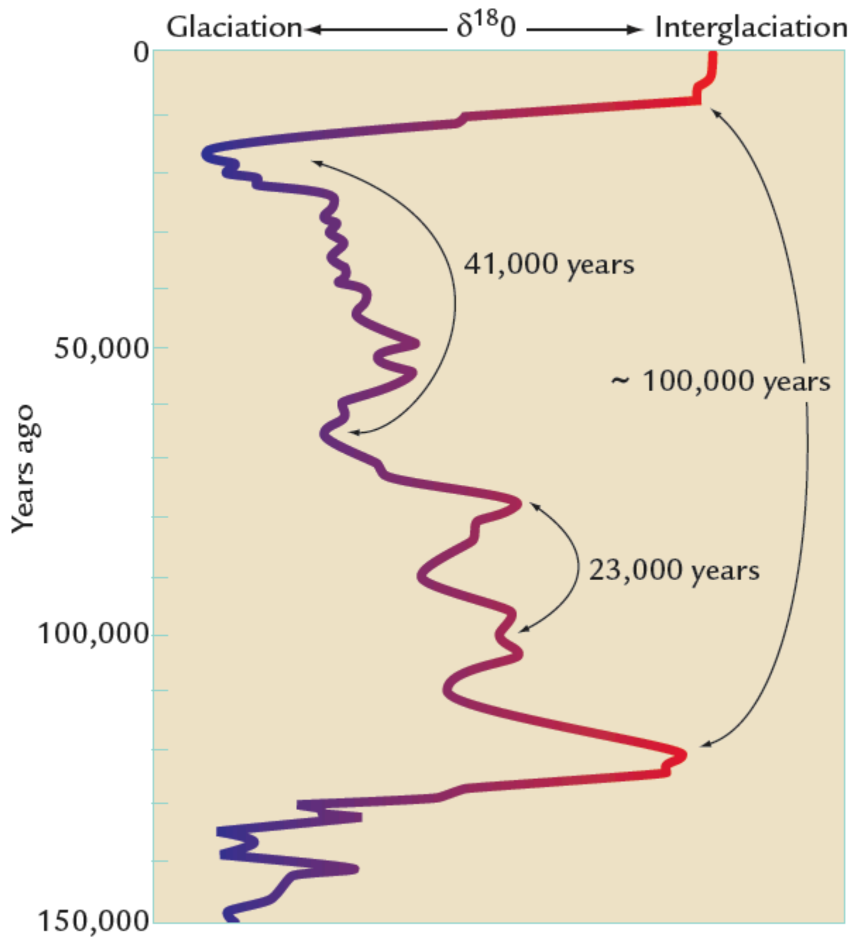
气候学与全球变化
Climate and Global Change

2022.05.06

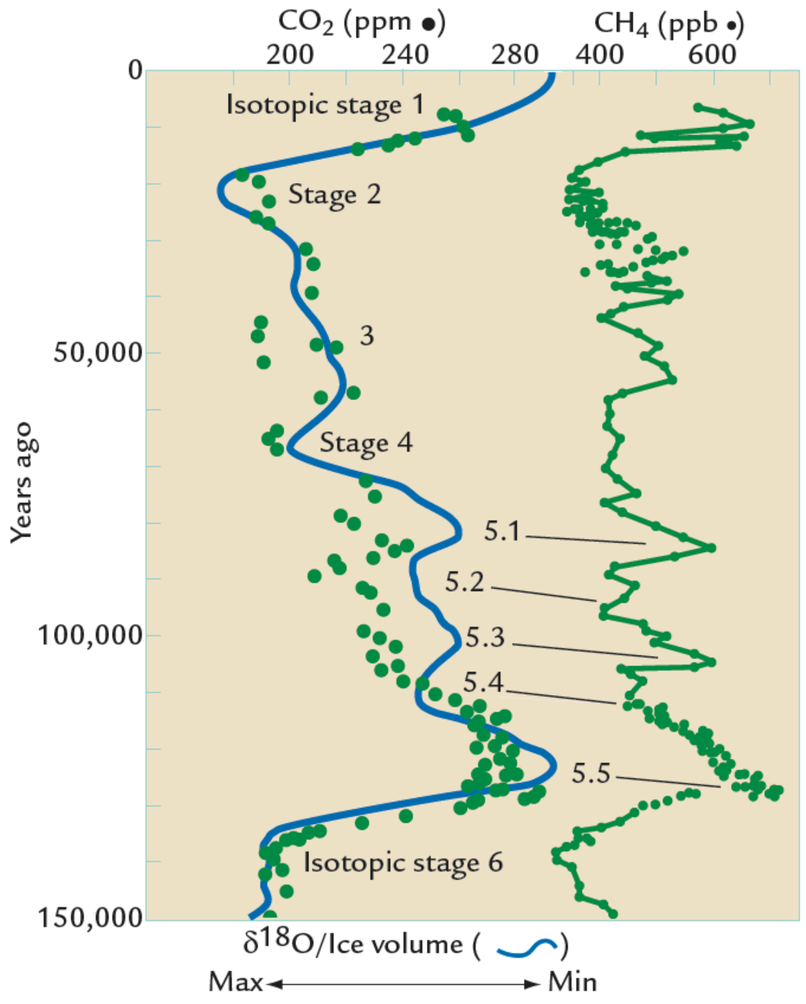
SCHOOL OF OCEANOGRAPHY
SHANGHAI JIAO TONG UNIVERSITY
上海交通大学 海洋学院

9.2.2 轨道尺度 (orbital scale)

轨道变化的气候影响： 冰川的变化

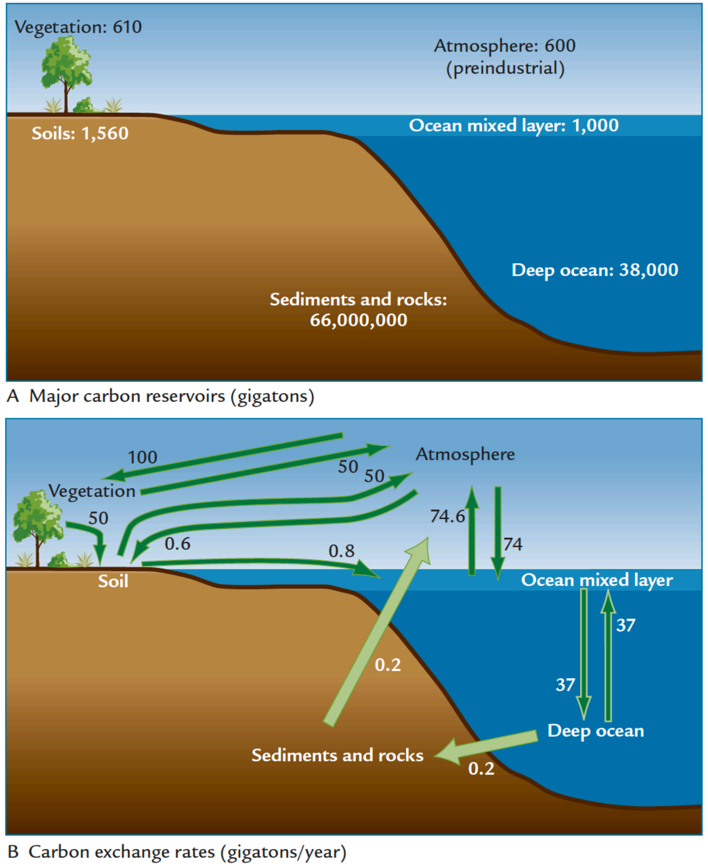


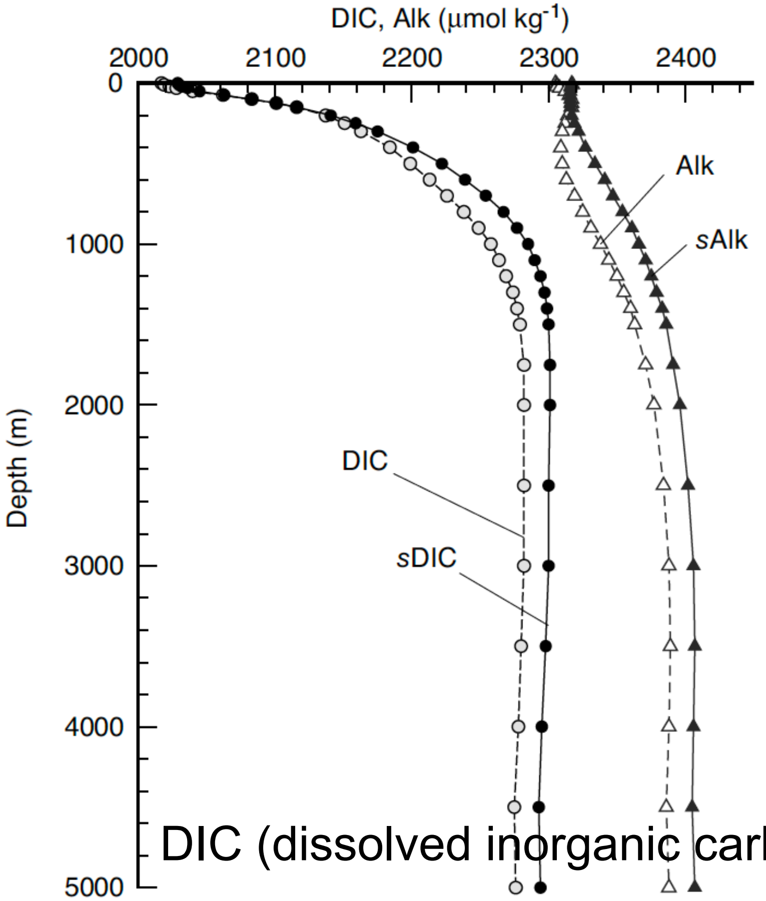
CO_2 和 CH_4的变化



Ocean carbon pumps

Deep Ocean as "active" carbon reservoir





DIC (dissolved inorganic carbon): $DIC = [H_2CO_3^*] + [HCO_3^-] + [CO_3^{2-}]$

Mechanism to maintain the vertical gradient (different pumps):

- **gas exchange pump (physical pump), including the solubility pump**
- **soft-tissue pump**
- carbonate pump

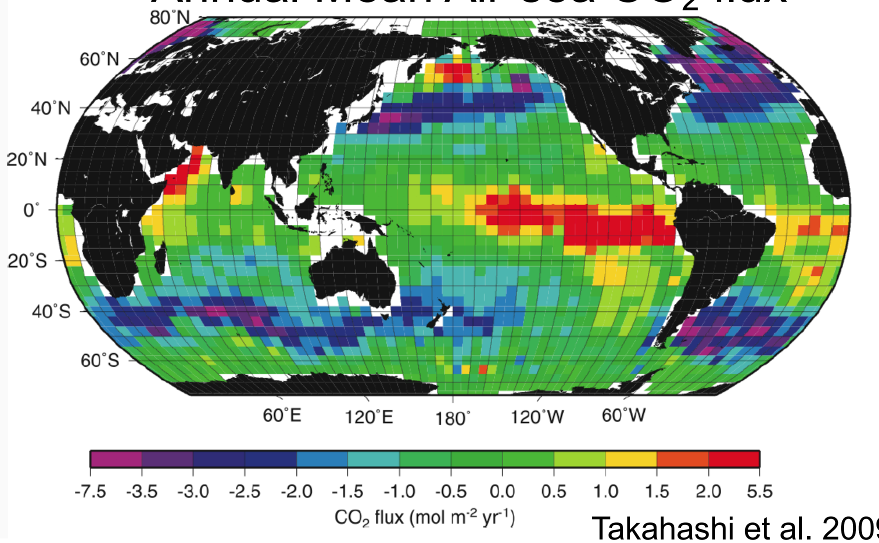
Ocean carbon pumps

Gas exchange pump

$$pCO_2^{ocn} \approx \frac{K_2}{K_0 K_1}\frac{(2DIC-ALk)^2}{Alk-DIC}$$

(K_0 solubility dominates!)

Annual Mean Air-sea CO_2 flux



Takahashi et al. 2009

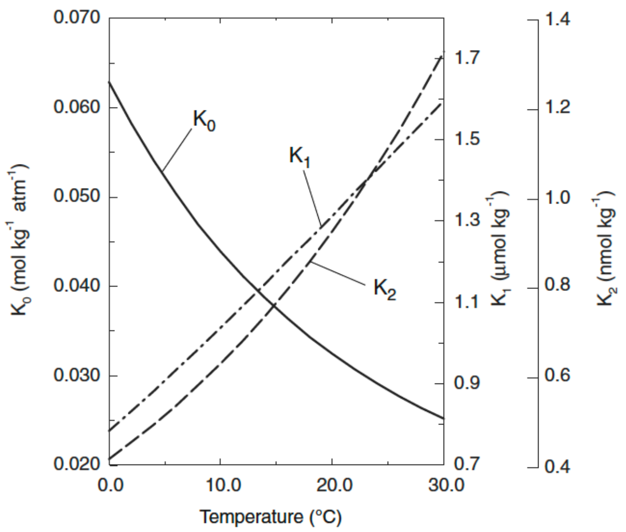


FIGURE 8.3.2: Plot of the CO_2 solubility (K_0), and of the first and second dissociation constants of carbonic acid (K_1 and K_2) as a function of temperature.

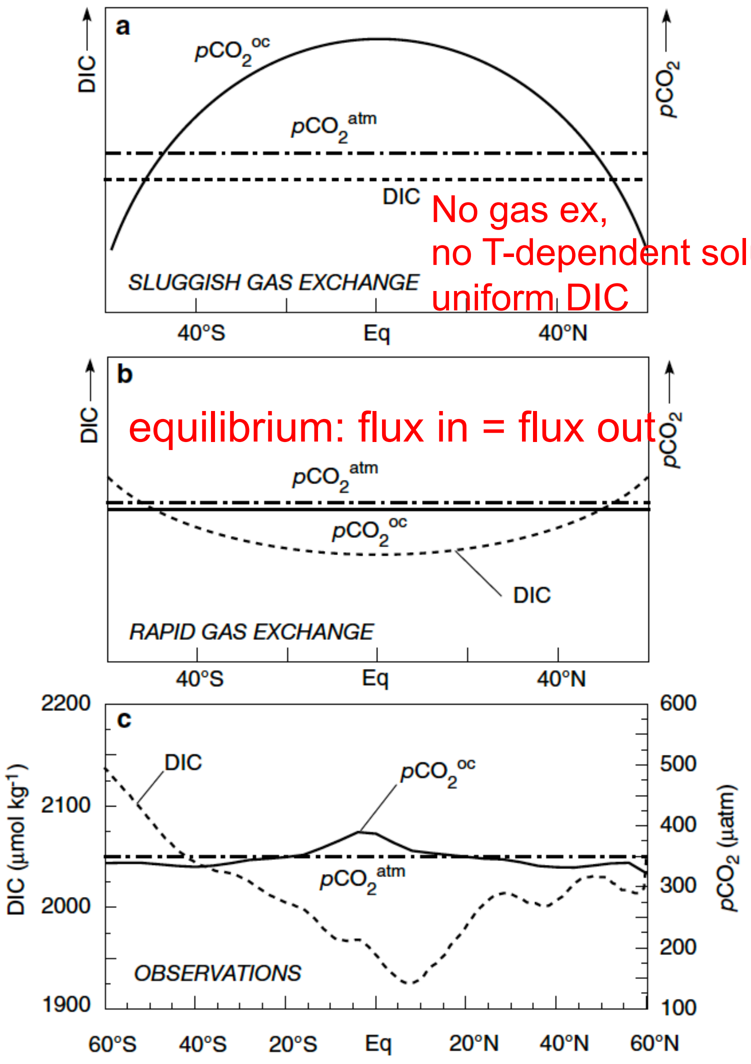


FIGURE 8.3.3: Hypothetical and observed meridional variations of pCO_2 and *DIC* in the surface ocean. (a) Hypothetical distribution in a case where gas exchange is very slow. It is assumed that no biological processes take place and that therefore *Alk* remains constant [*Broecker and Peng*, 1982]. (b) As in (a), but for a case with very rapid gas exchange. (c) Observed zonal mean variations of pCO_2 and *DIC*. Based on the pCO_2 climatology of *Takahashi et al.* [2003] and the GLODAP climatology of *Key et al.* [2004].

$pCO_2^{ocean} > pCO_2^{atm}$: outgassing

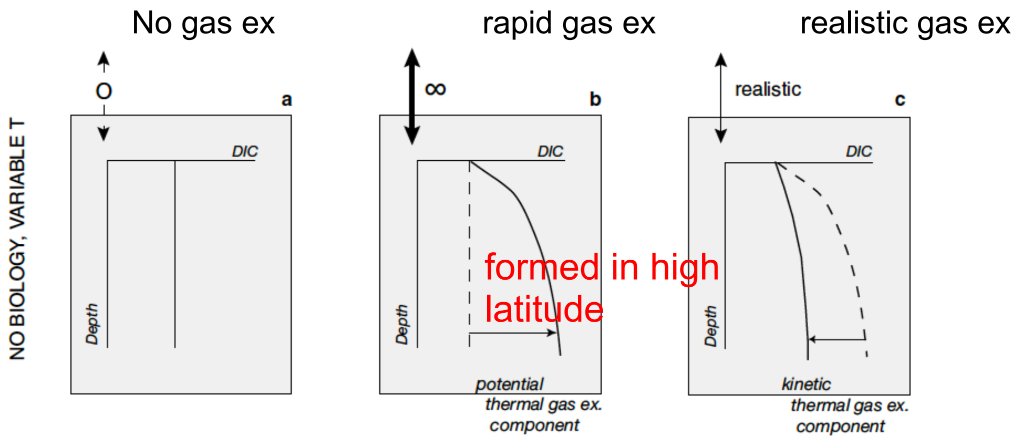
$$CO_2(gas) + H_2O \rightleftharpoons H_2CO_3^* \quad k_0 = \frac{[H_2CO_3^*]}{pCO_2^{ocn}}$$

$$H_2CO_3^* \rightleftharpoons H^+ + HCO_3^- \quad k_1 = \frac{[H^+][HCO_3^-]}{[H_2CO_3^*]}$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{2-} \quad k_2 = \frac{[H^+][CO_3^{2-}]}{[HCO_3^-]}$$

Ocean carbon pumps

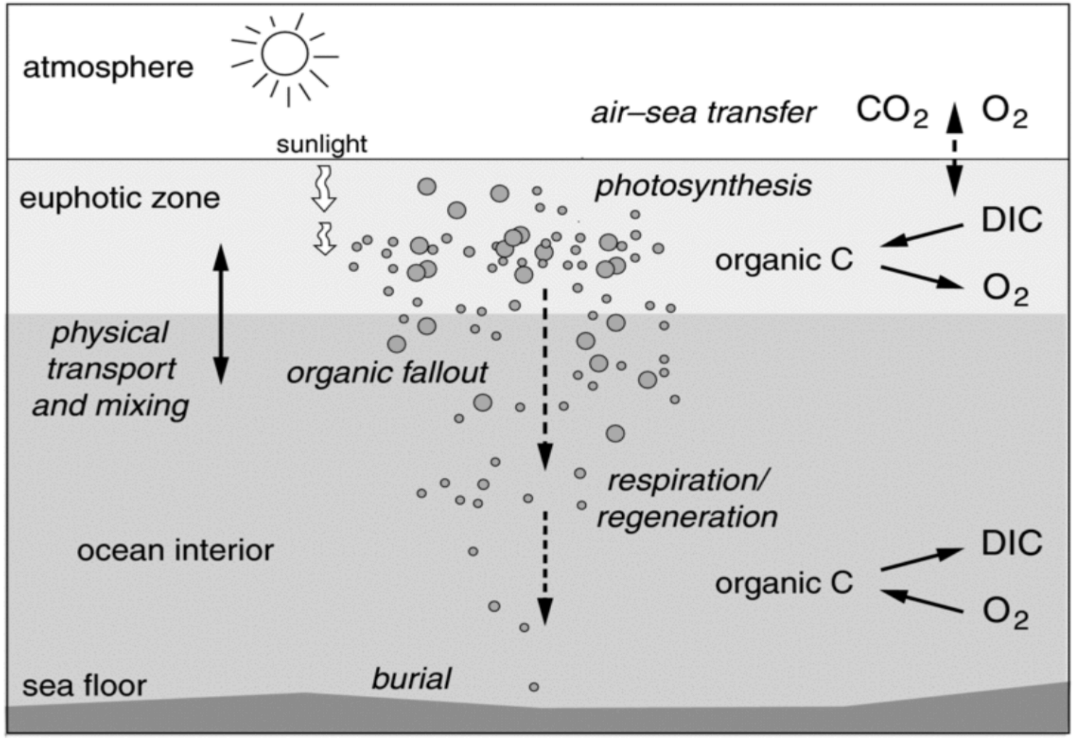
Understanding the different pumps hypothetically



potential: fully equilibrated

Ocean carbon pumps

Soft-tissue pump

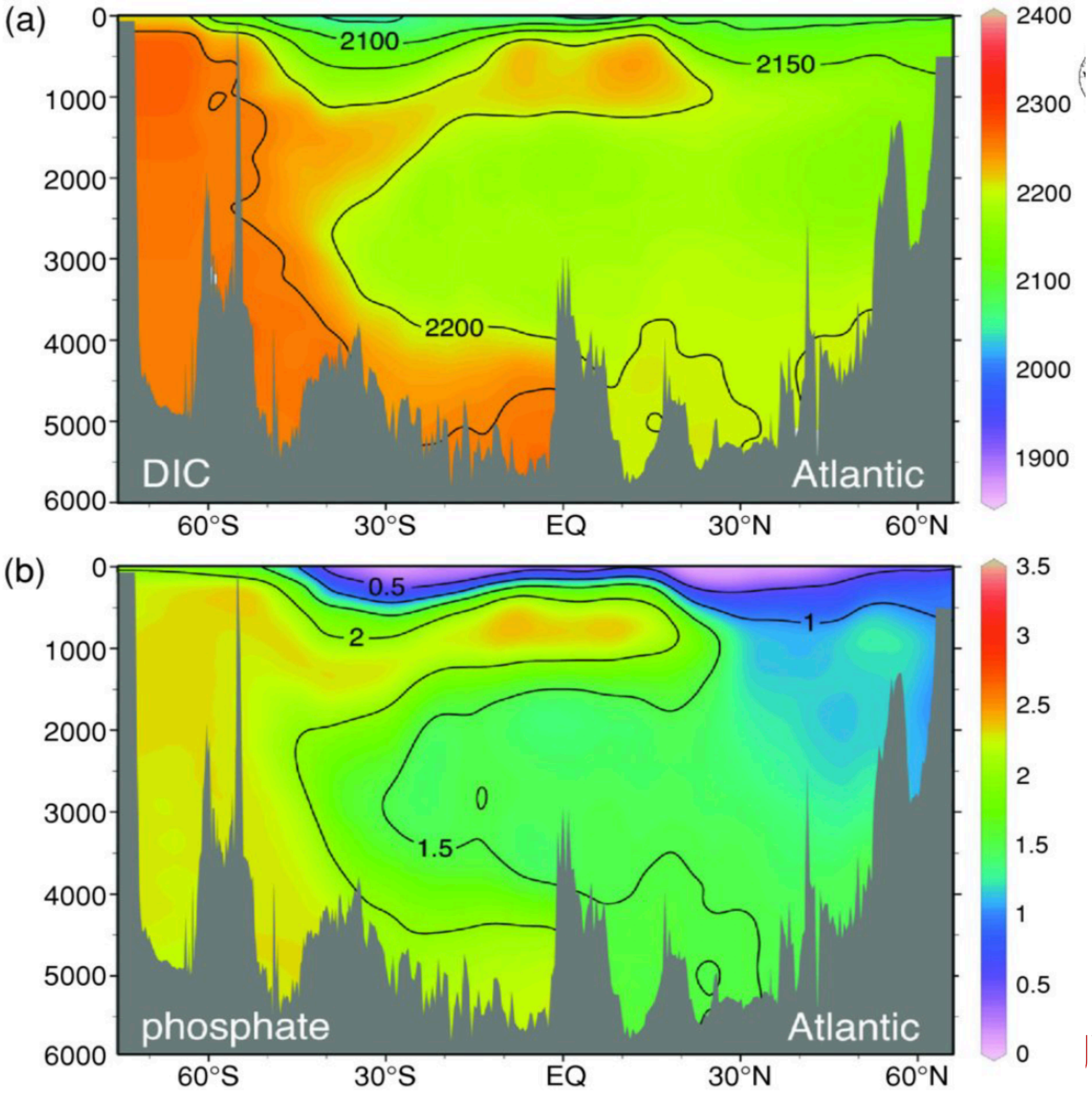


Redfield ratio

$$106CO_2 + 16NO_3^- + HPO_4^{2-} + 78H_2O + 18H^+$$

$$\rightleftharpoons C_{106}H_{175}O_{42}N_{16}P + 150O_2$$

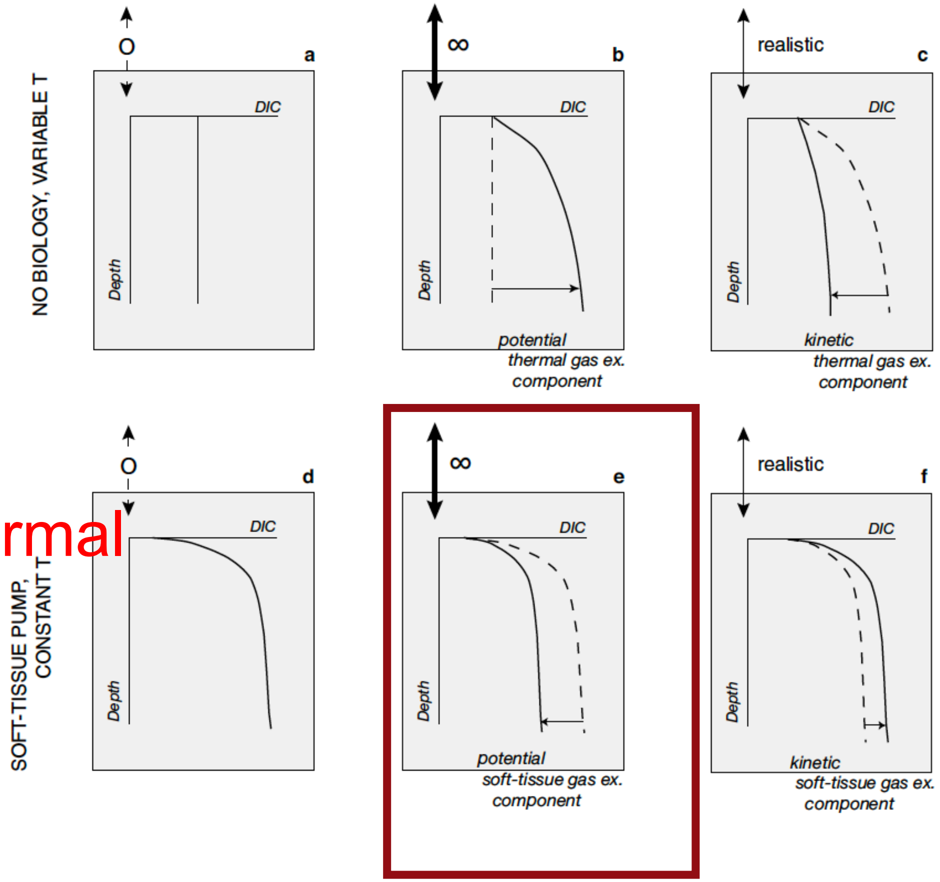
$$\Delta C_{soft} = r_{c:p}([PO_4^{3-}] - [PO_4^{3-}]^{ref})$$



Ocean carbon pumps

Understanding the different pumps hypothetically

isothermal



$$pCO_2^{ocn} \approx \frac{K_2}{K_0K_1}\frac{(2DIC - ALk)^2}{Alk - DIC}$$

With gas ex:

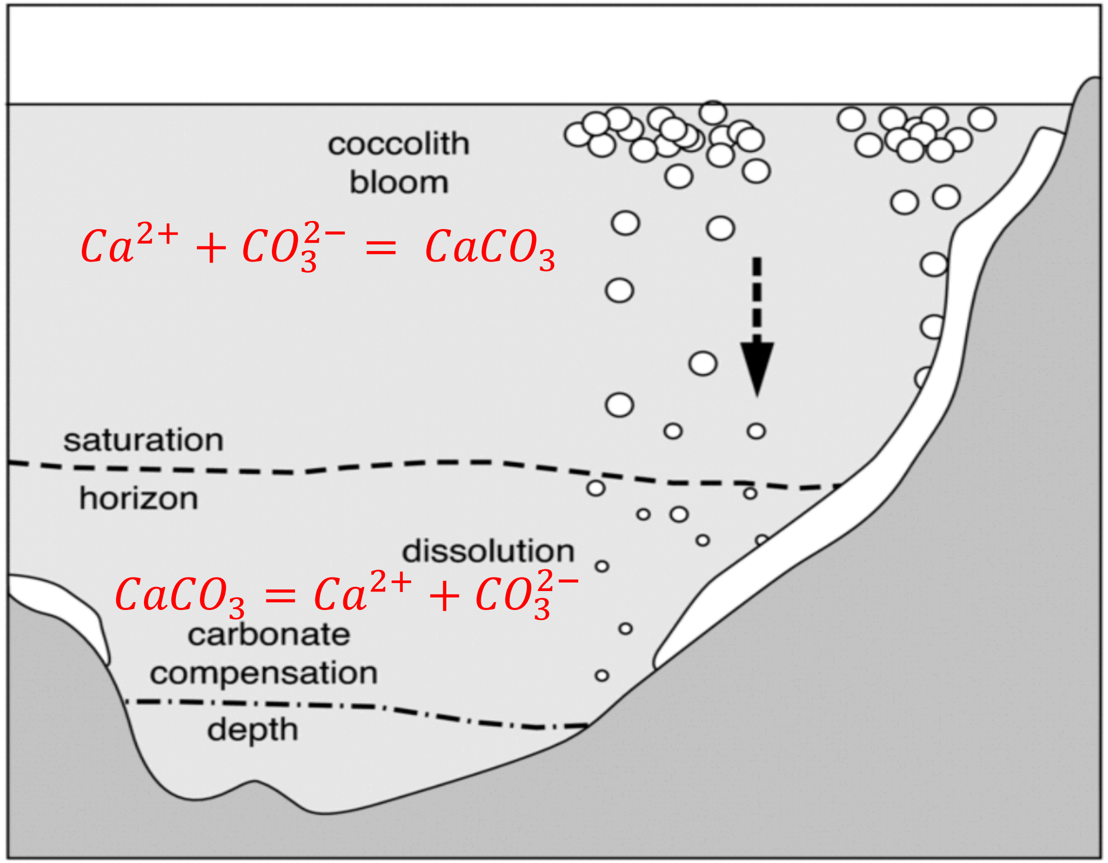
High latitude: elevated DIC comes to surface, outgassing

Low latitude: biological fixation cause a deficit relative to atm CO2, more uptake

=>reduced vertical gradient

Ocean carbon pumps

Carbonate pump



$$pCO_2^{ocn} \approx \frac{K_2}{K_0 K_1} \frac{(2DIC - ALk)^2}{Alk - DIC}$$

Alk (total alkalinity): Alk

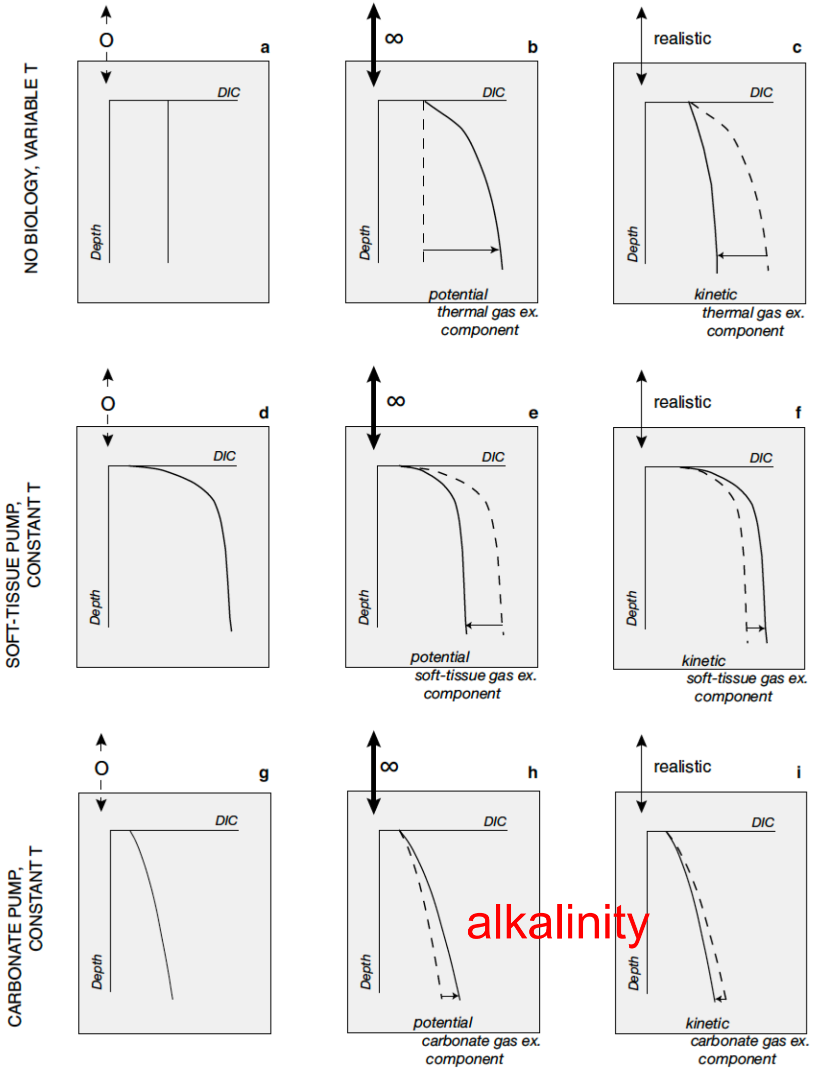
$= [HCO_3^-] + 2[CO_3^{2-}]$ + $[OH^-]$ + $[B(OH)_4^-]$ + minor bases - $[H^+]$

= $[Na^+]+[K^+]+2[Mg^{2+}]+2[Ca^{2+}]-[Cl^-]-2[SO_4^{2-}]-[Br^-]-[NO_3^-]$

Surface: decrease DIC, decreases alkalinity

Ocean carbon pumps

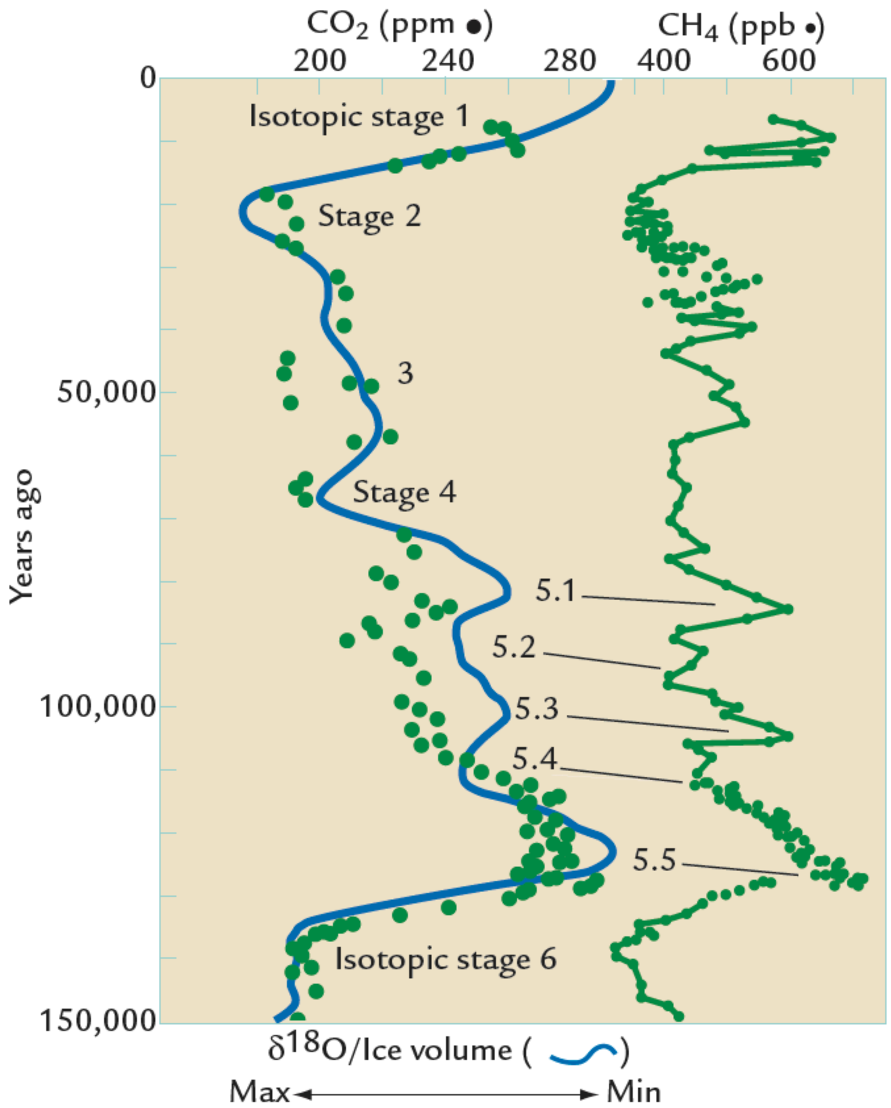
Understanding the different pumps hypothetically



$$pCO_2^{ocn} \approx \frac{K_2}{K_0K_1}\frac{(2DIC - ALk)^2}{Alk - DIC}$$

With gas ex:
High latitude: elevated DIC comes to surface, outgassing
Low latitude: biological fixation cause a deficit relative to atm CO2, more uptake
=>reduced vertical gradient/pump

With gas ex:
High latitude: high Alk deep water comes to surface, more uptake
Low latitude: $CaCO_3$ formation, Alk decrease, $pCO_2^{ocn} > pCO_2^{atm}$, outgassing
=>increased vertical gradient/pump



Deep Ocean Carbon Pumps:

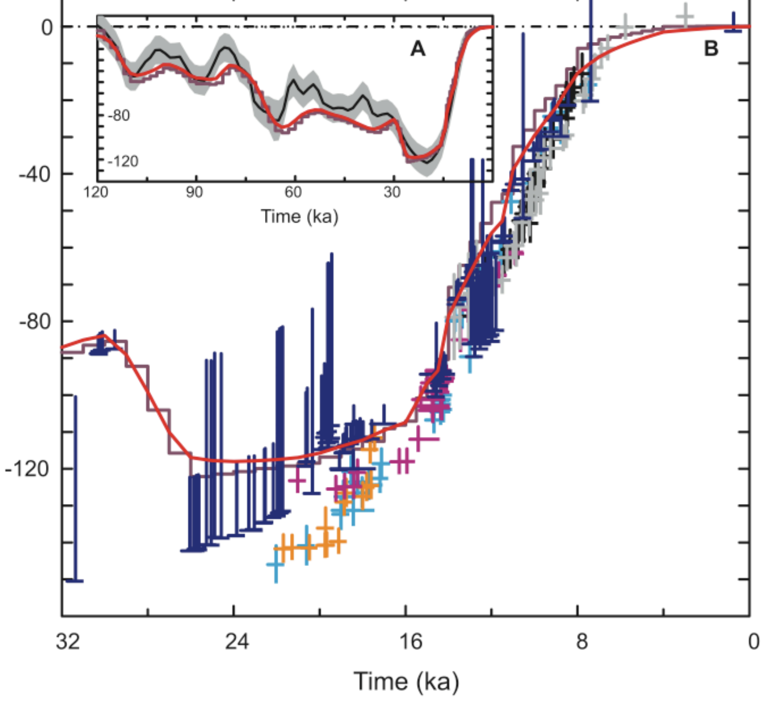
- gas exchange pump (physical pump), including the solubility pump
- soft-tissue pump
- carbonate pump

9.2.3 消冰期气候变化(Deglaciation)

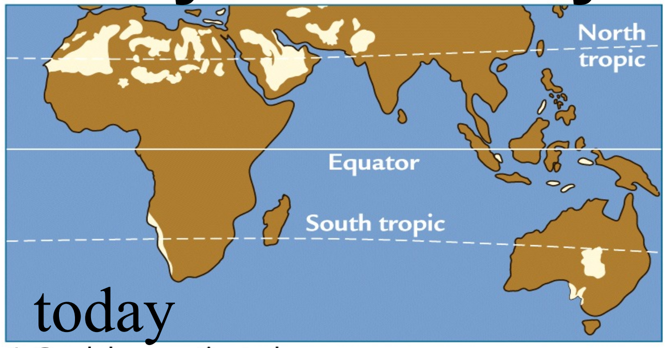
The Last Glacial Maximum (LGM) 末次盛冰期 (~21ka)

Extended ice sheet

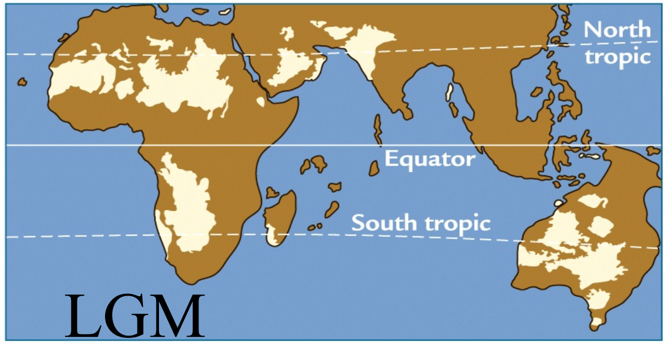
~120m lower sea level



Dry and Windy



A Sand dunes active today

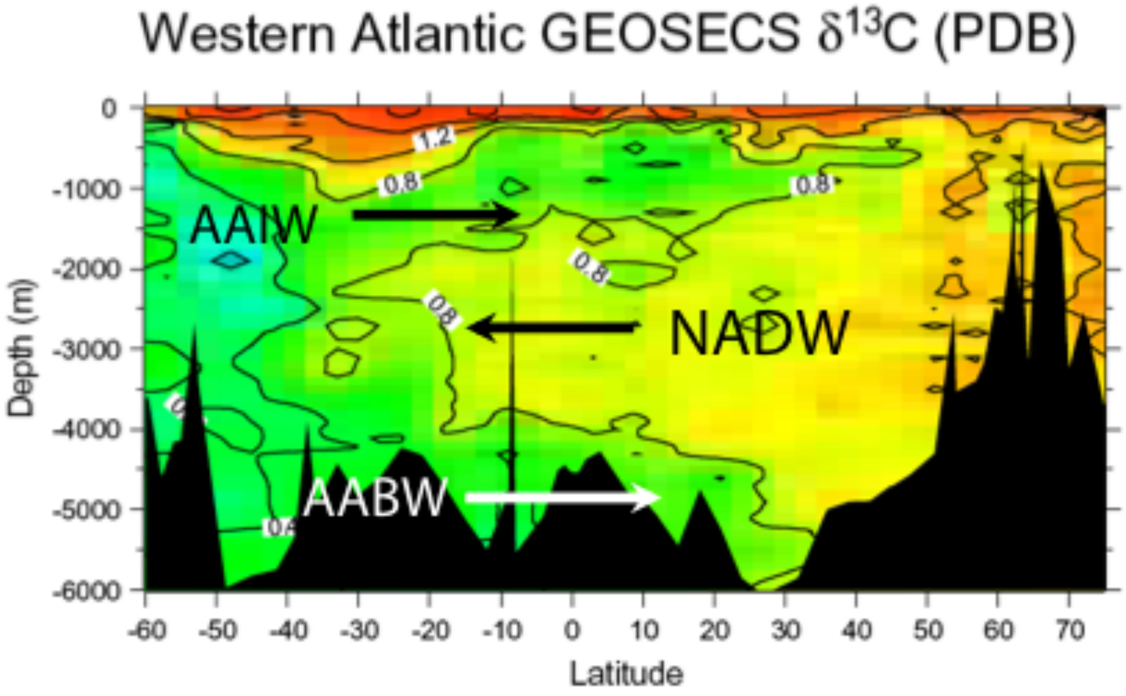


B Sand dunes active at glacial maximum

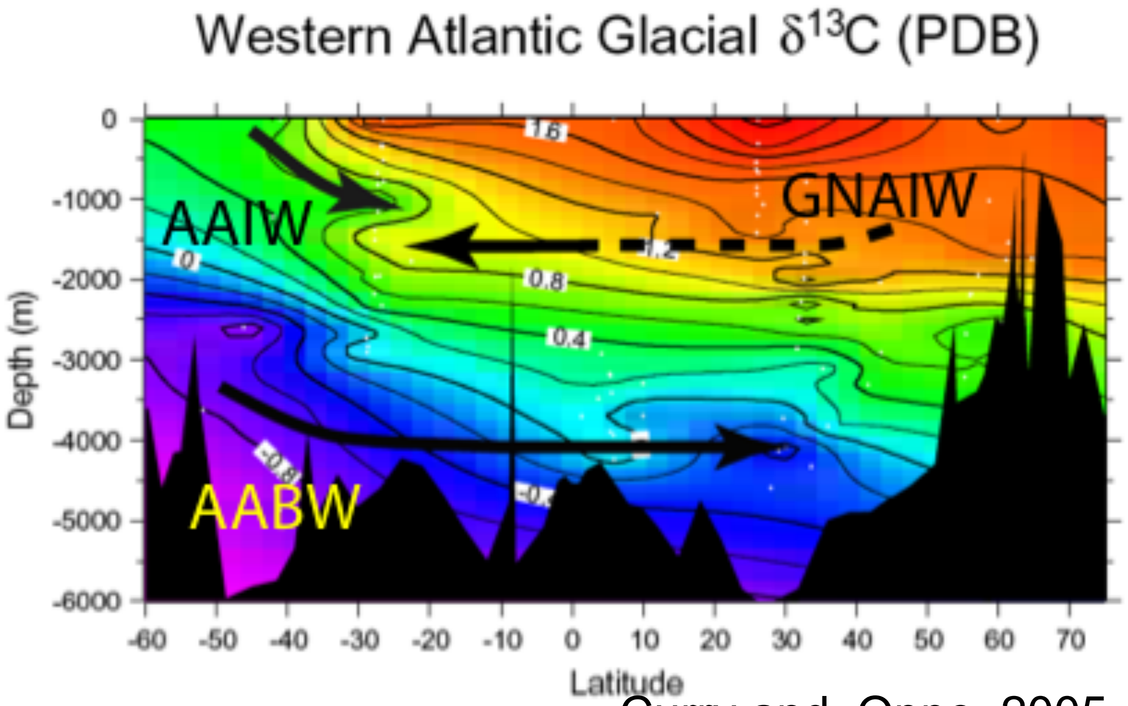
9.2.3 消冰期气候变化(Deglaciation)

The Last Glacial Maximum (LGM) 末次盛冰期 (~21ka)

Shallower LGM AMOC



Glacial North Atlantic Intermediate Water



Curry and Oppo, 2005

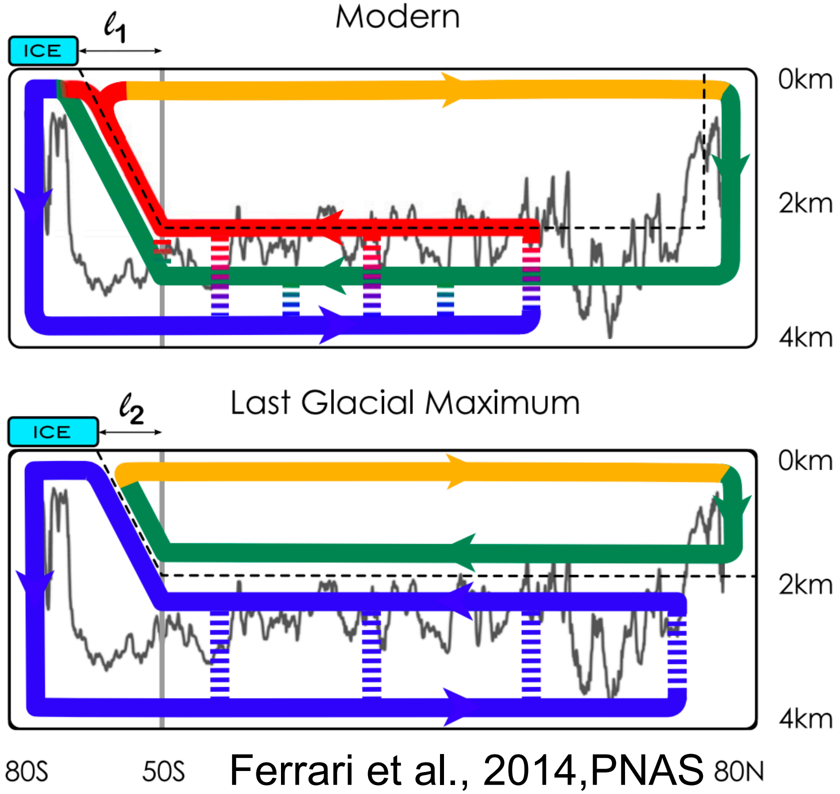
Why AMOC is shallower? Wind or Buoyancy?

9.2.3 消冰期气候变化(Deglaciation)

The Last Glacial Maximum (LGM) 末次盛冰期 (~21ka)

Shallower LGM AMOC

Colder
-> Southern Ocean sea ice expansion
-> brine rejection
-> AABW expansion
-> Shallower AMOC



Ferrari et al., 2014,PNAS

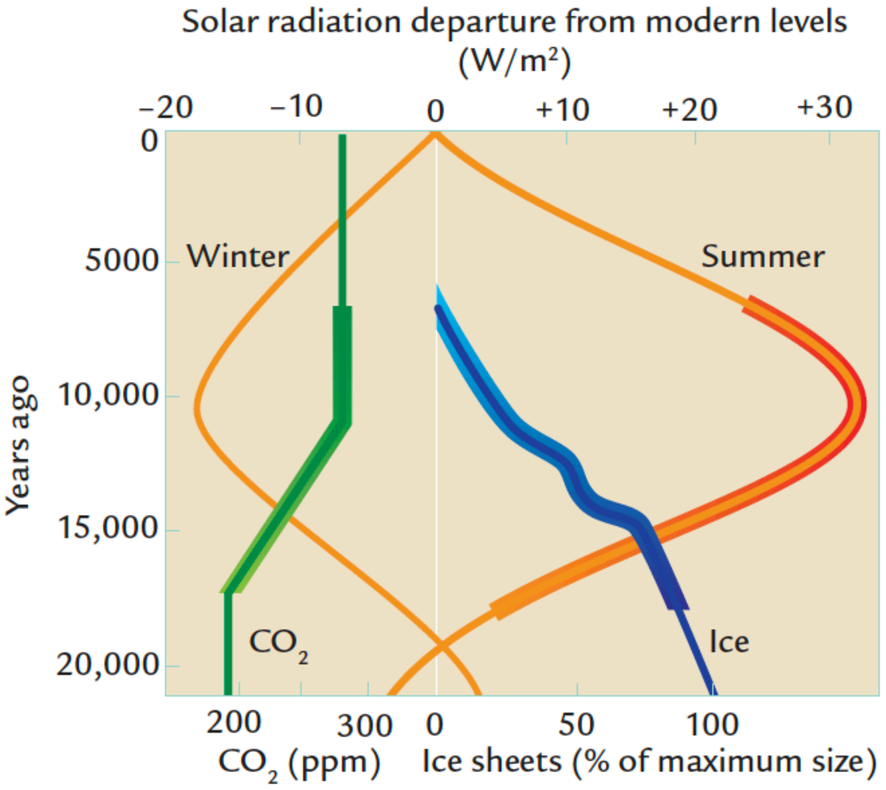
Ferrari, R., Jansen, M. F., Adkins, J. F., Burke, A., Stewart, A. L., & Thompson, A. F. (2014). Antarctic sea ice control on ocean circulation in present and glacial climates. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(24), 8753–8758.
Shin, S. I., Liu, Z., Otto-Bliesner, B. L., Kutzbach, J. E., & Vavrus, S. J. (2003). Southern Ocean sea-ice control of the glacial North Atlantic thermohaline circulation. *Geophysical Research Letters*, *30*(2), 68–71.

9.2.3 消冰期气候变化(Deglaciation)

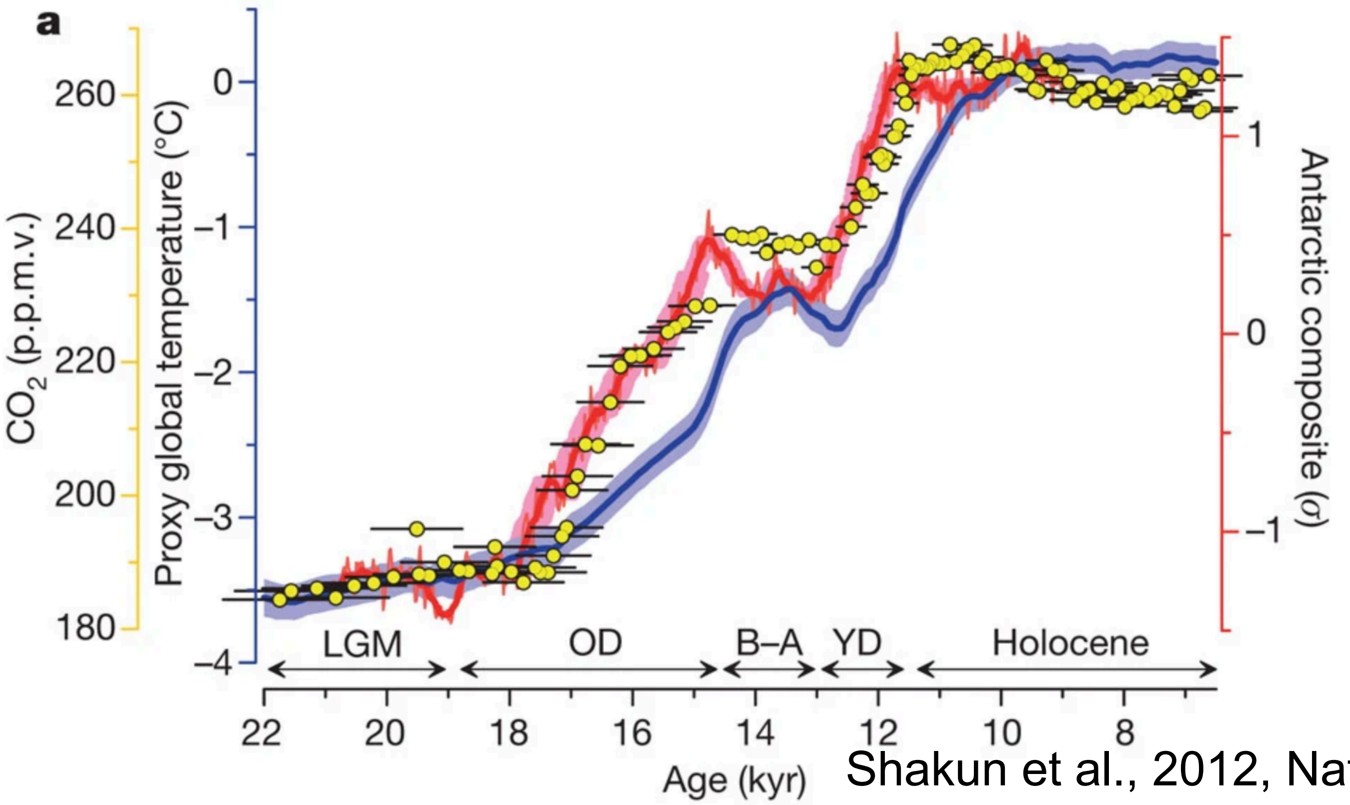
The Last Deglaciation 末次消冰期(~20ka-10ka)

气候强迫：

CO_2, insolation, ice sheet



气候突变



Shakun et al., 2012, Nature

9.2.3 消冰期气候变化(Deglaciation)

The Last Deglaciation 末次消冰期(~20ka-10ka)

Ice sheet retreat

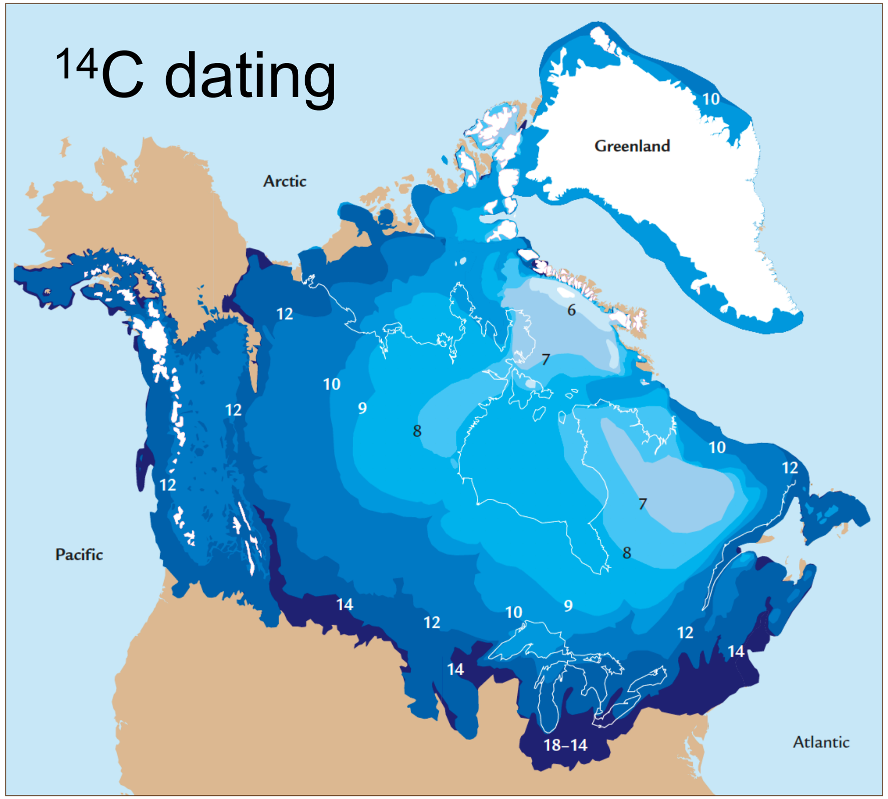


FIGURE 14-2
Retreat of the North American ice sheets

Routes of Meltwater

late melting

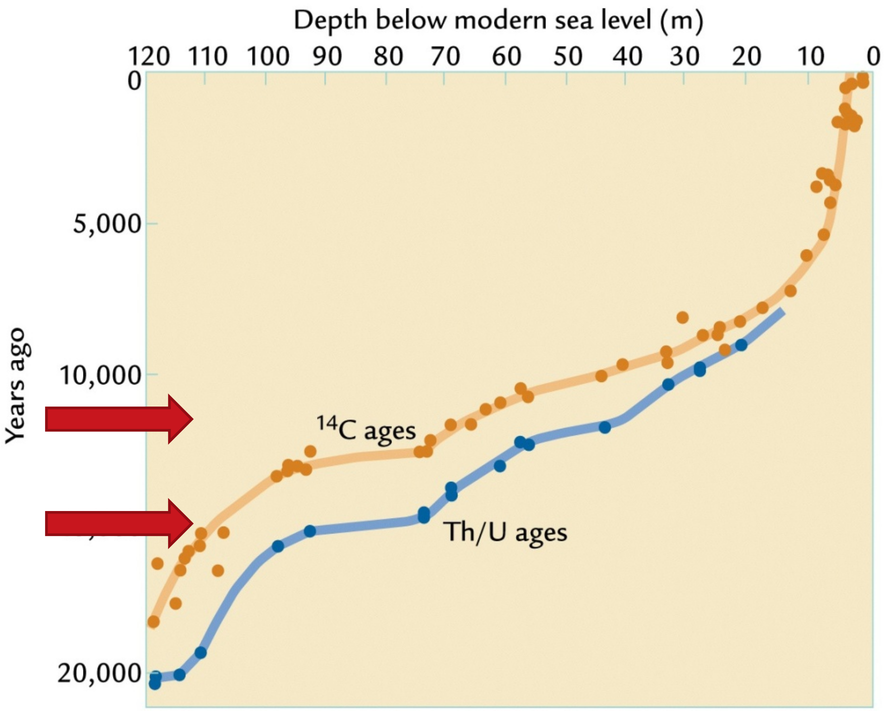
Mid-deglaciation melting

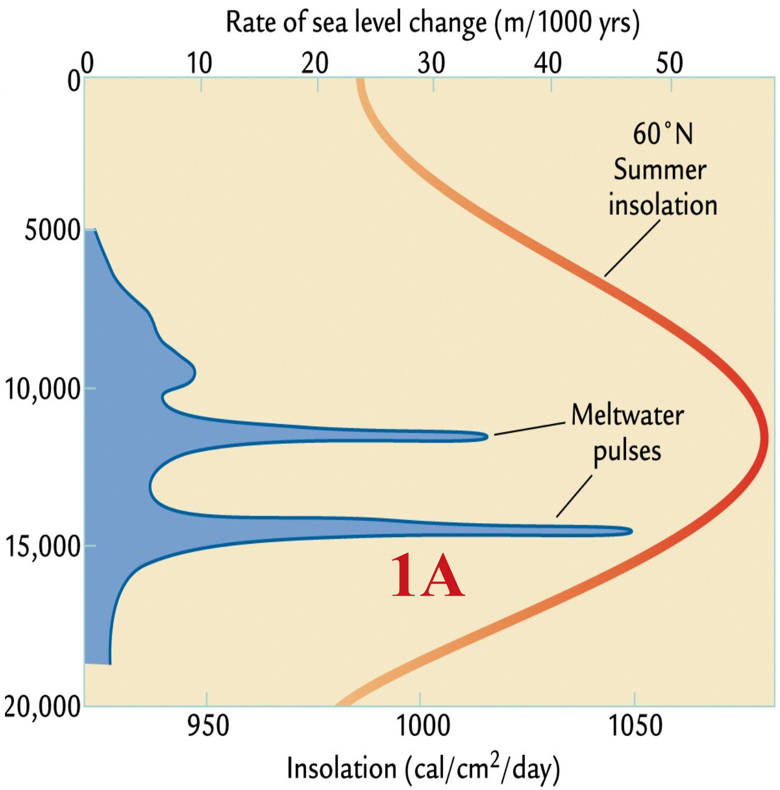
Early melting

9.2.3 消冰期气候变化(Deglaciation)

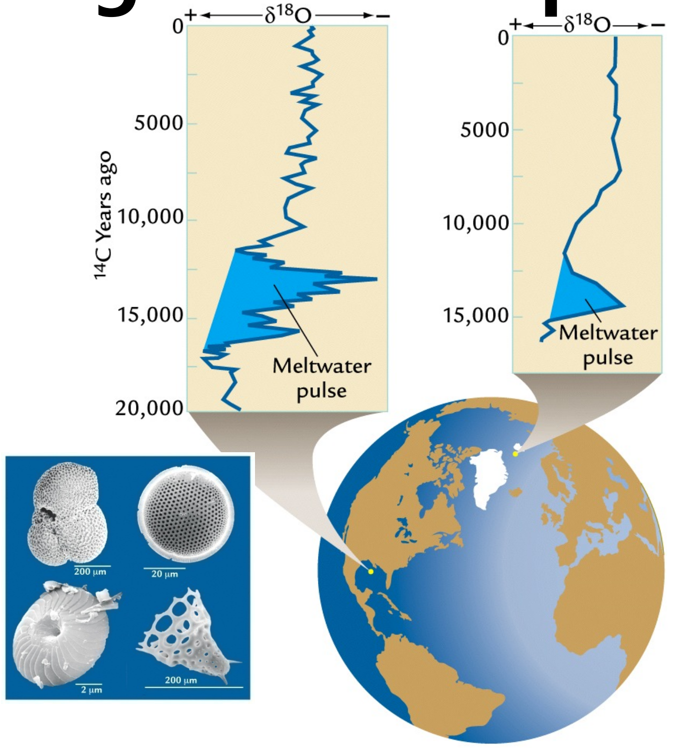
The Last Deglaciation 末次消冰期(~20ka-10ka)

Melting water pulses





- Negative d^{18}O pulse



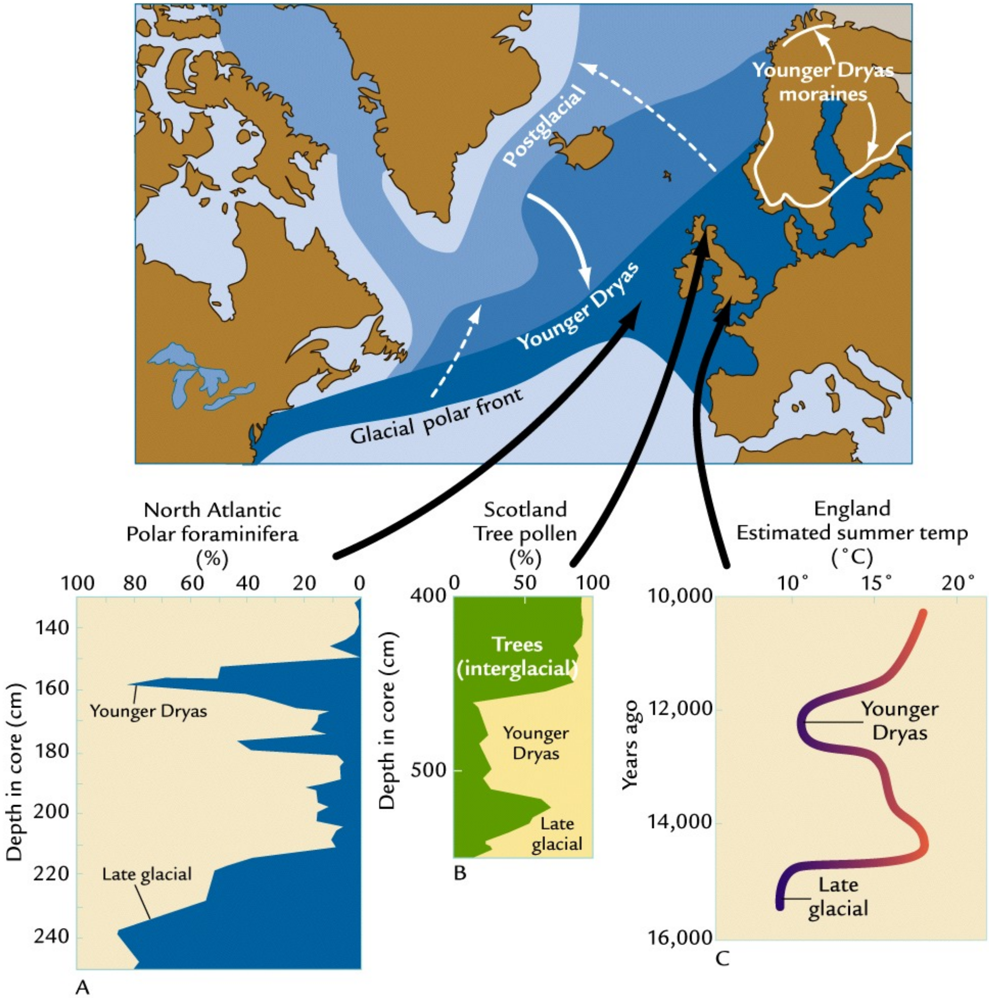
- Ice-rafted debris

9.2.3 消冰期气候变化(Deglaciation)

The Last Deglaciation 末次消冰期(~20ka-10ka)

The Younger Dryas Cooling
新仙女木事件 （ ~13ka ）

- 海洋沉积物中有孔虫指示极地水南移动；
- 苏格兰植被纪录显示北极植物；
- 英国昆虫种群纪录显示降温；



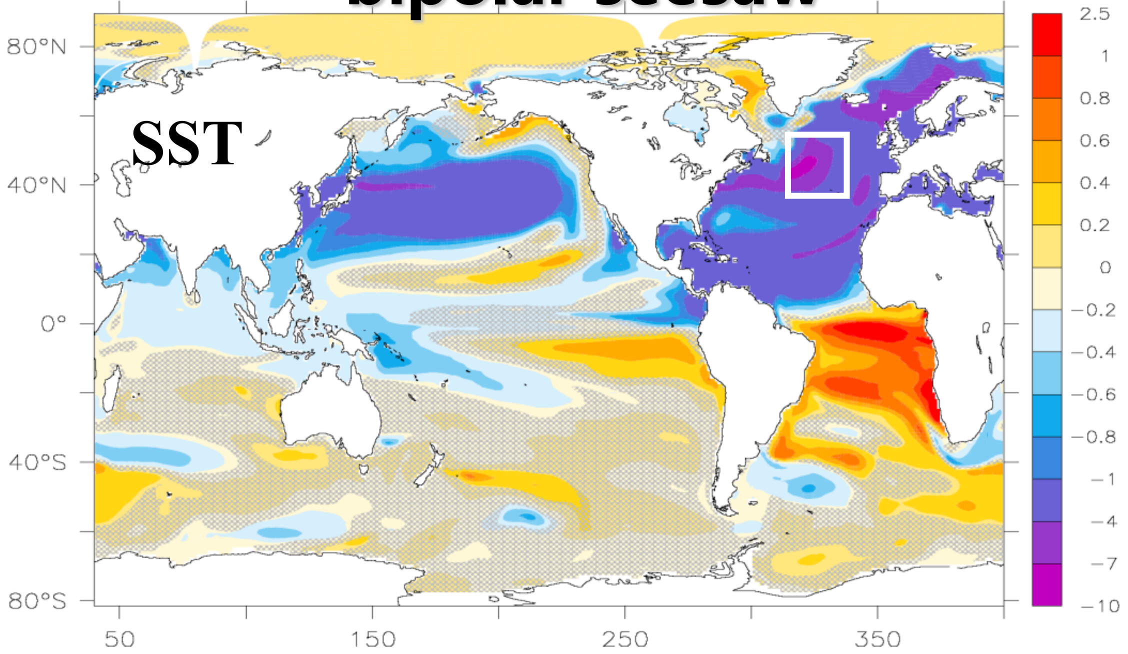
Why melting water cools N. Atlantic?

9.2.3 消冰期气候变化(Deglaciation)

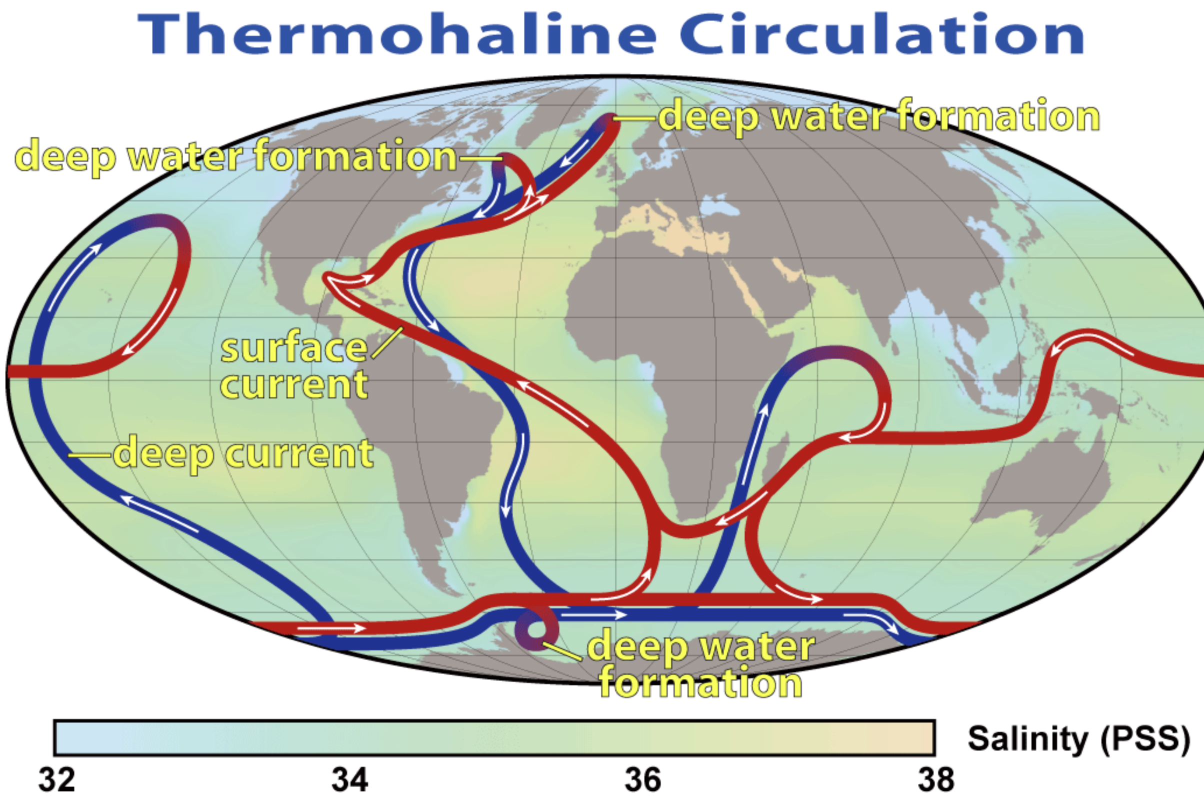
The Last Deglaciation 末次消冰期(~20ka-10ka)

The Younger Dryas Cooling 新仙女木事件（～13ka）

bipolar seesaw

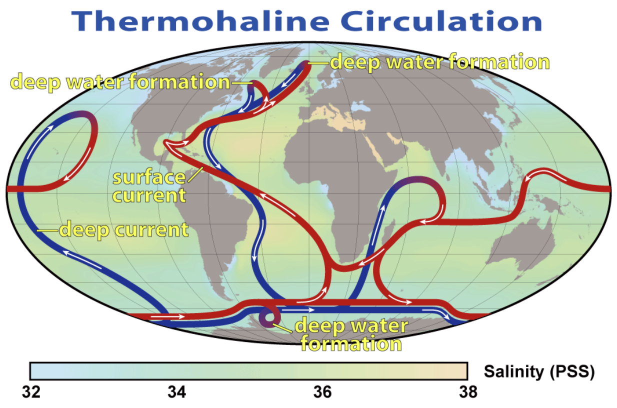


Zhang and Delworth, J. Clim, 2005



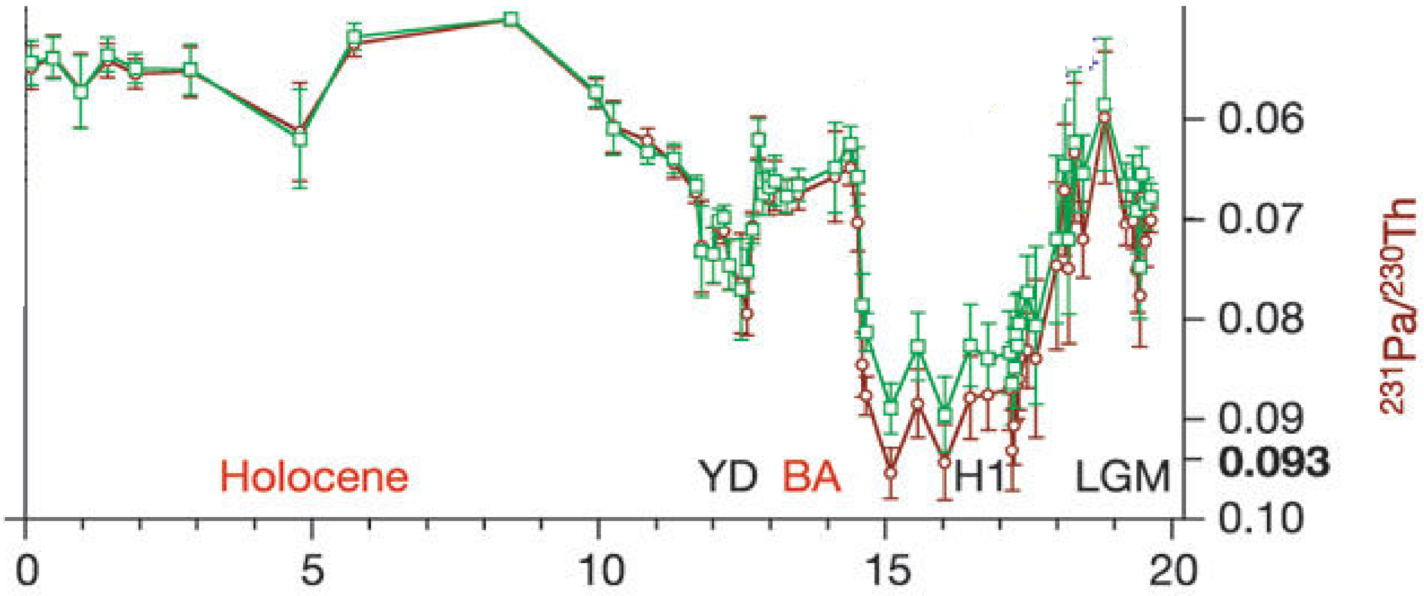
9.2.3 消冰期气候变化(Deglaciation)

The Last Deglaciation 末次消冰期(~20ka-10ka)



北大西洋 ^{231}Pa/230Th 指示 AMOC

AMOC↓,
Southward ^{231}Pa transport ↓
Pa/Th ↑ ,→0.093



McManus et al., 2004,Nature

9.2.3 消冰期气候变化(Deglaciation)

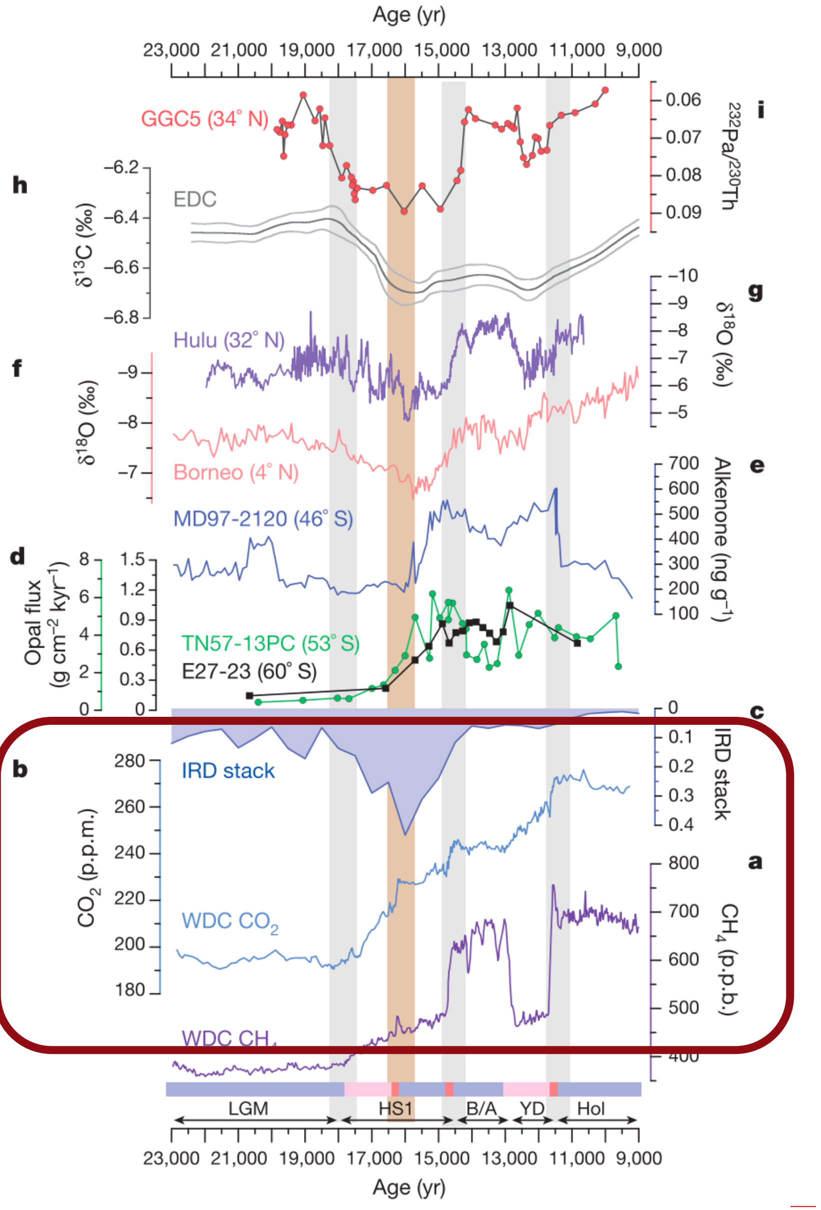
The Last Deglaciation 末次消冰期

CO_2变化：

- <u>缓慢（千年）变化期</u>:18.1ka&13.0ka, ~10ppm/kyr
- <u>迅速（百年）变化期</u>: 10-15ppm in 100-200yr at 16.3ka,14.8ka,11.7ka
- <u>平台期</u>:right after the rapid change lasted for 1000-1500yr

机制？ongoing debate

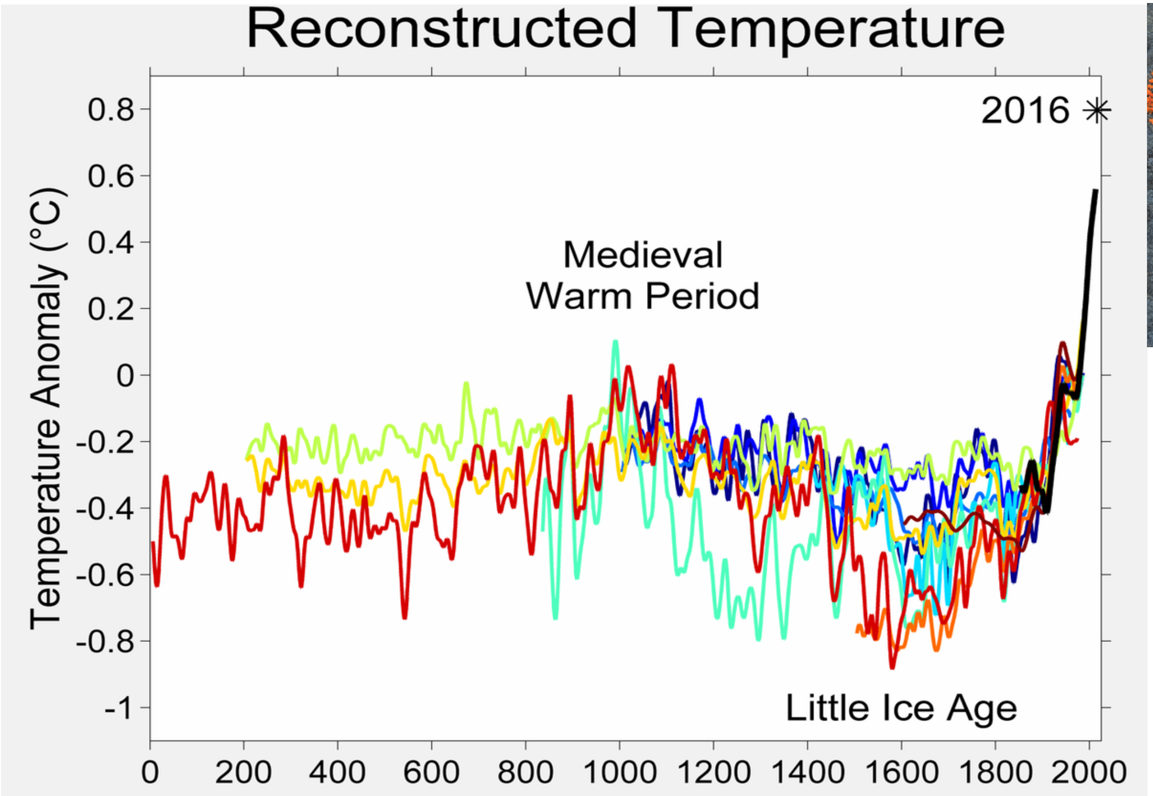
- <u>AMOC</u>: Schmittner et al., 2008, Nature
- <u>SO upwelling</u>: Anderson et al., 2009, Science
- <u>North Pacific</u>: Gray et al., 2018, Nature Geoscience
- <u>Global ocean alkalinity</u>: Sigman et al., 2010, Nature
- <u>AAIW</u>: Yu et al., 2022, Nature Geoscience

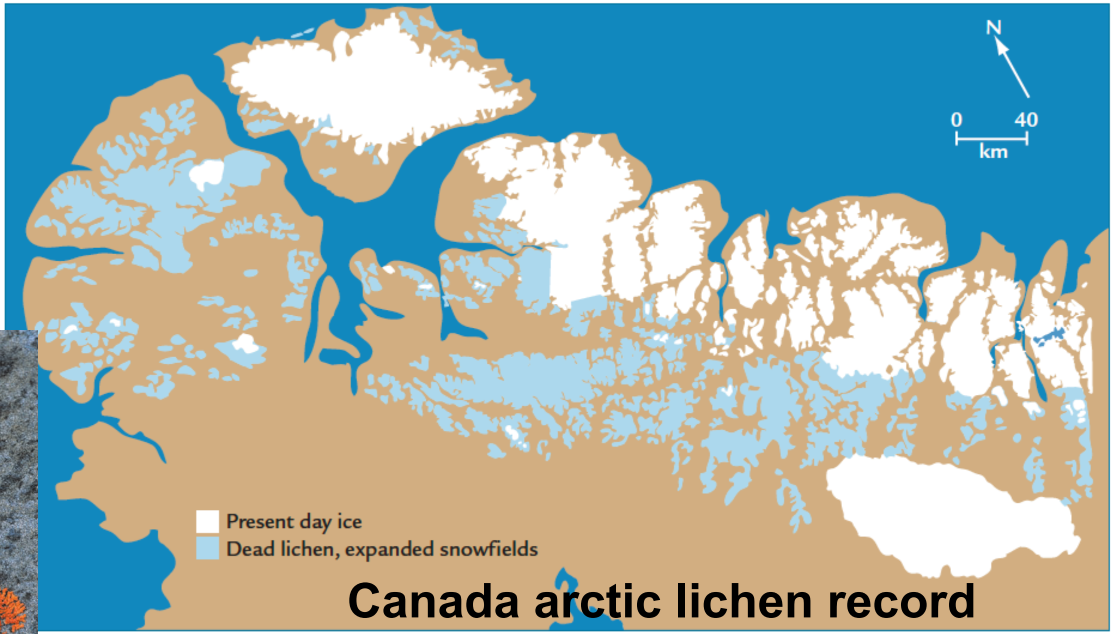


Marcott et al. 2014, Nature

9.2.4 历史时期 (historical scale)

小冰期 (1400-1850)





Is LIA global?

The Little Ice Age and 20th-century deep Pacific cooling

G. Gebbie[1]* and P. Huybers[2]

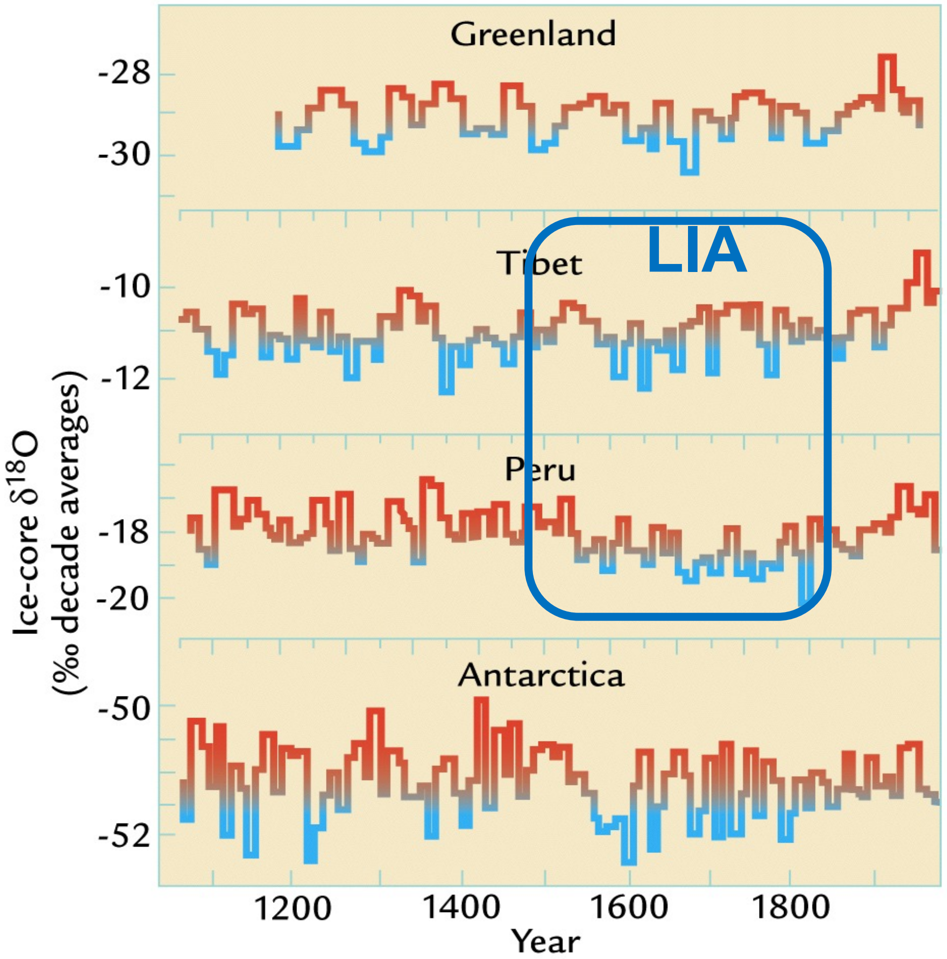
Proxy records show that before the onset of modern anthropogenic warming, globally coherent cooling occurred from the Medieval Warm Period to the Little Ice Age. The long memory of the ocean suggests that these historical surface anomalies are associated with ongoing deep-ocean temperature adjustments. Combining an ocean model with modern and paleoceanographic data leads to a prediction that the deep Pacific is still adjusting to the cooling going into the Little Ice Age, whereas temperature trends in the surface ocean and deep Atlantic reflect modern warming. This prediction is corroborated by temperature changes identified between the HMS Challenger expedition of the 1870s and modern hydrography. The implied heat loss in the deep ocean since 1750 CE offsets one-fourth of the global heat gain in the upper ocean.

Gebbie & Huybers, 2019, Science

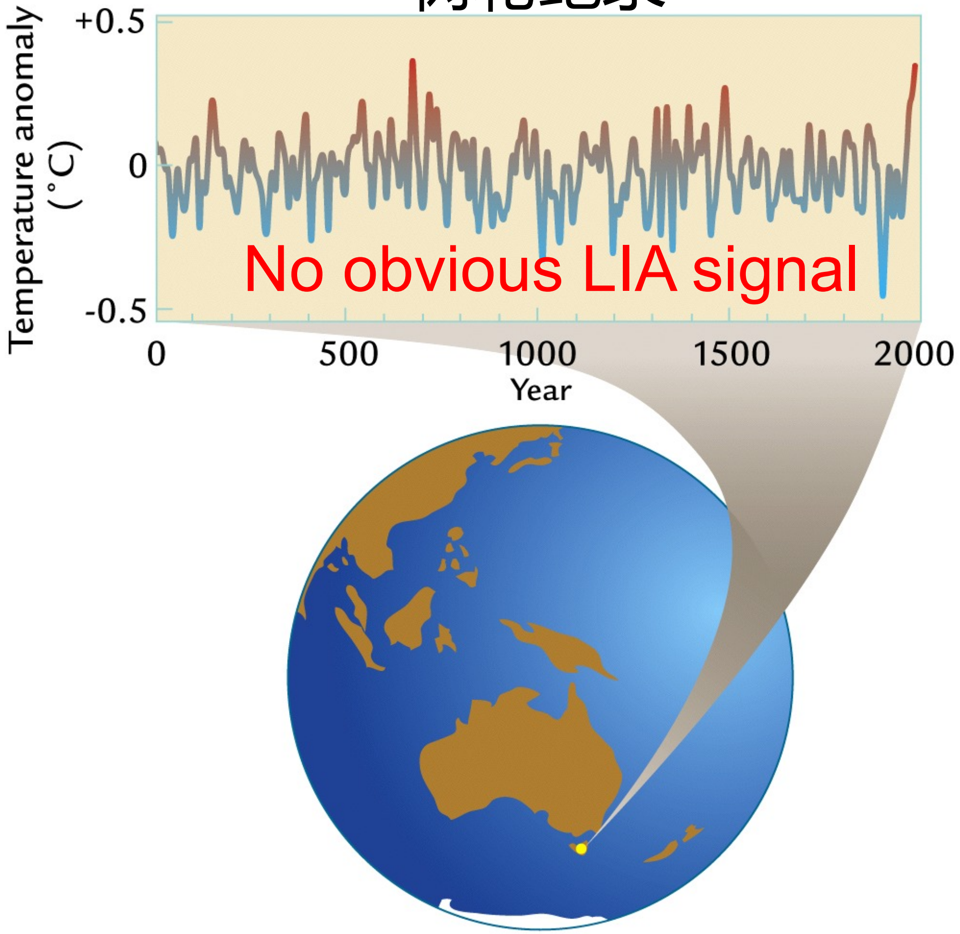
9.2.4 历史时期 (historical scale)

小冰期 (1400-1850) 局部性

冰芯中的$\delta^{18}O$



树轮纪录



9.2 不同时间尺度的气候变化 总结

- CO_2在构造尺度的反馈机制：源和汇；（比如：化学风化作为地球温度调节器，隆升-风化假说, 海底扩张速度）

- 轨道对气候的影响：（比如：季节？岁差与季风？）

- 海洋如何影响大气CO_2： gas exchange pump; soft-tissue pump

- 消冰期的气候：典型气候事件（观测资料如何指示？），冰山的影响

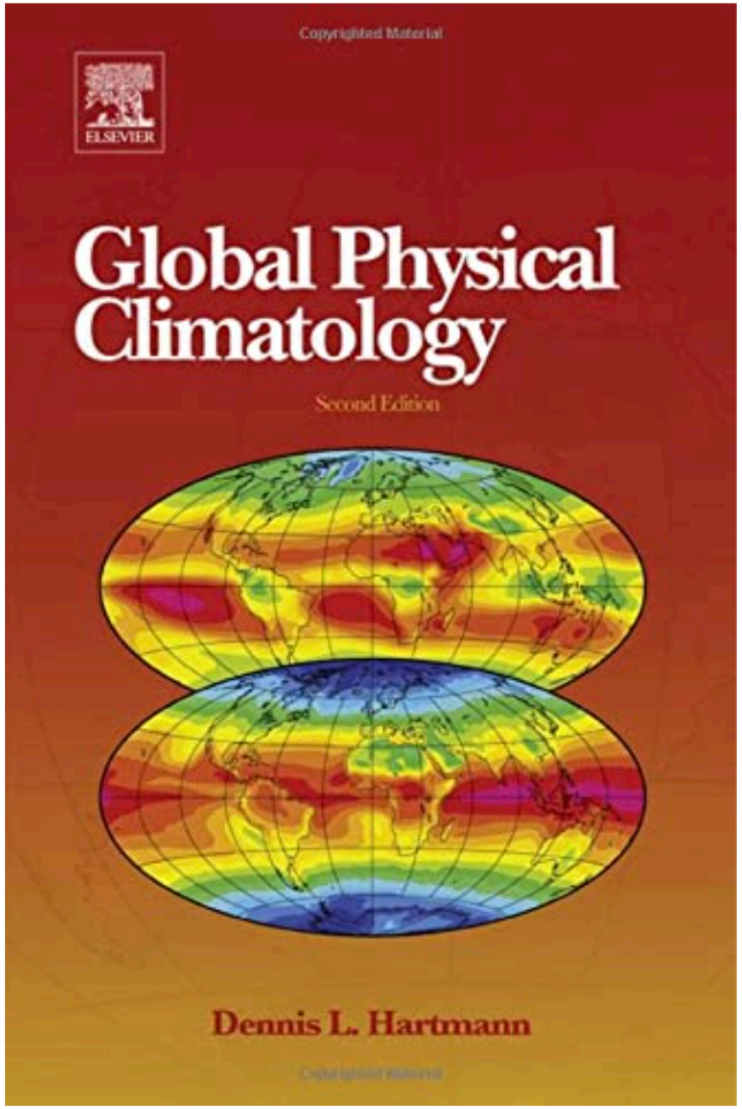
10.1 气候强迫，气候敏感性及反馈机制

10.2 辐射反馈过程 (普朗克反馈, 水汽反馈，温度递减率反馈)

10.3 冰雪反照率反馈

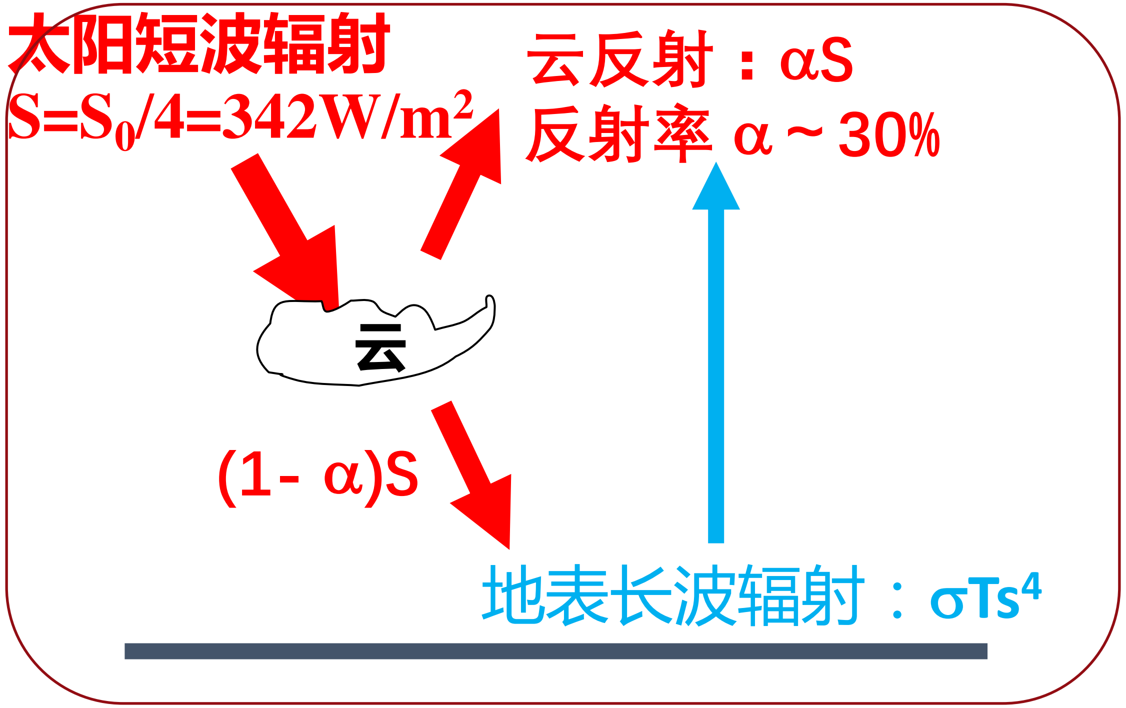
10.4 云反馈

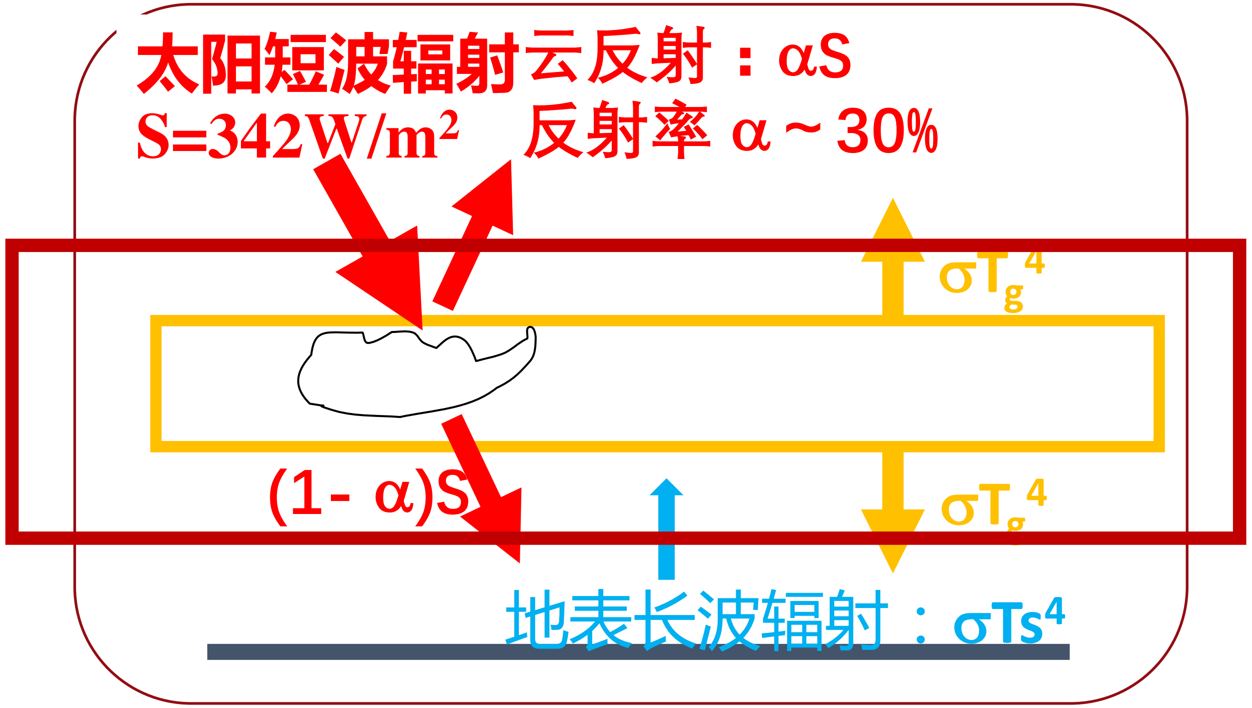
10.5 气候敏感性的估计



10.1气候强迫，气候敏感性及反馈机制

气候强迫 (climate forcing)





$(1-\alpha)\ S = \sigma Ts^4$

Ts = -18°C

地表：$(1-\alpha)\ S + \sigma T_g^4 = \sigma Ts^4$

大气：$2\sigma T_g^4 = \sigma Ts^4$

Ts = 30°C， T_g = -18°C

10.1气候强迫，气候敏感性及反馈机制

气候强迫 (climate forcing)

气候系统

吸收太阳辐射Q

↓

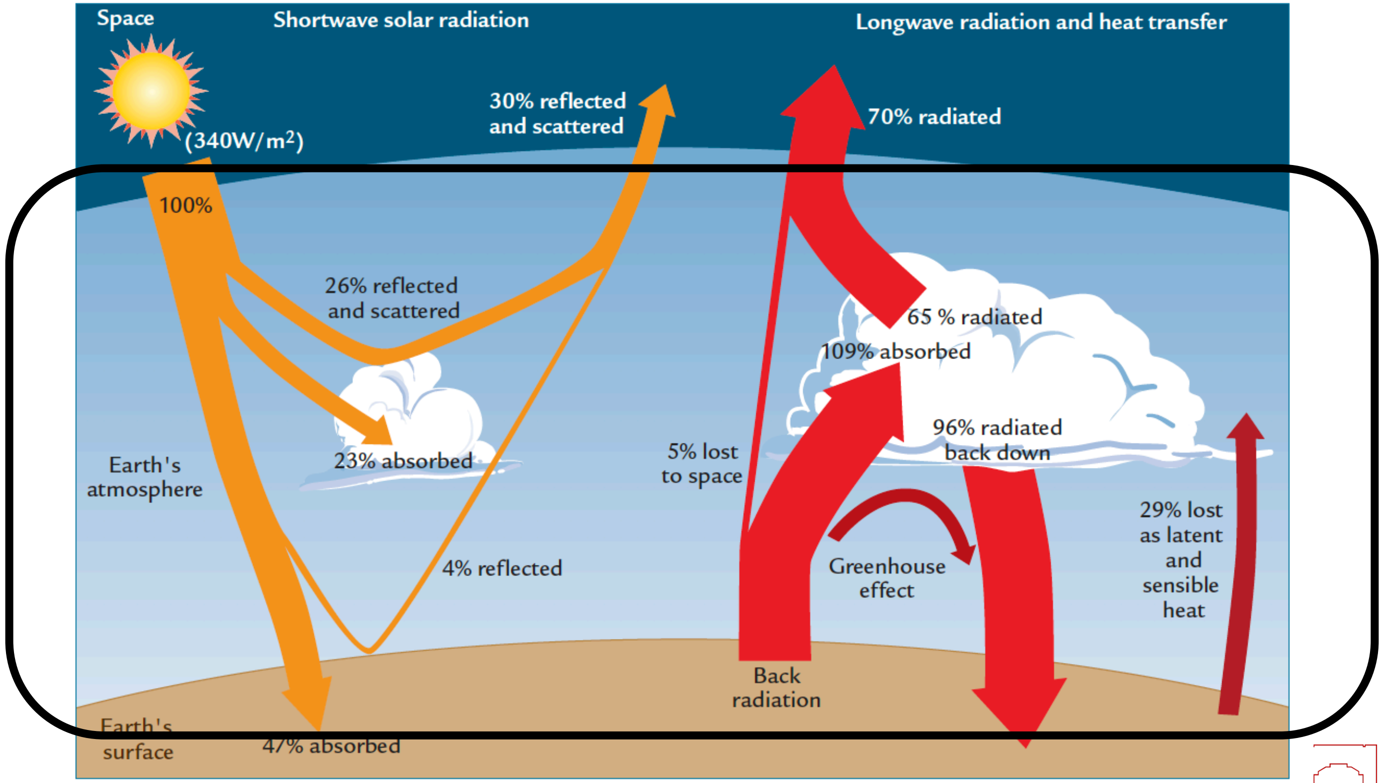
Climate System as a "Black Box"

↓

地表温度 Ts = 15^{o}C

平衡时：Energy In = Energy Out

Earth's radiation budget



10.1气候强迫，气候敏感性及反馈机制

气候强迫 (climate forcing)

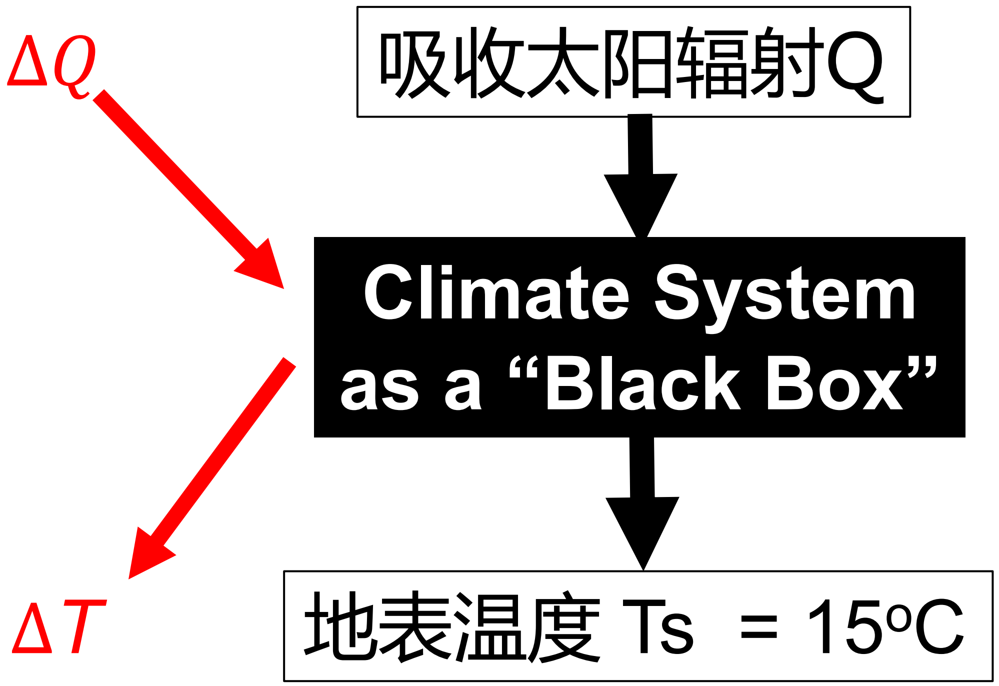
辐射强迫(radiative forcing)定义：

对流层顶净辐射的变化 (ΔQ, W/m^2)

Radiative Forcing : Instantaneous change of the radiative balance at the top of the troposphere due to a change in a process that affect climate.

ΔQ > 0, ΔT >0, 增暖；
ΔQ < 0, ΔT <0, 降温；

哪些因素影响辐射强迫？
温室气体,冰雪反照率,气溶胶,云等等



10.1气候强迫，气候敏感性及反馈机制

气候强迫 (climate forcing)

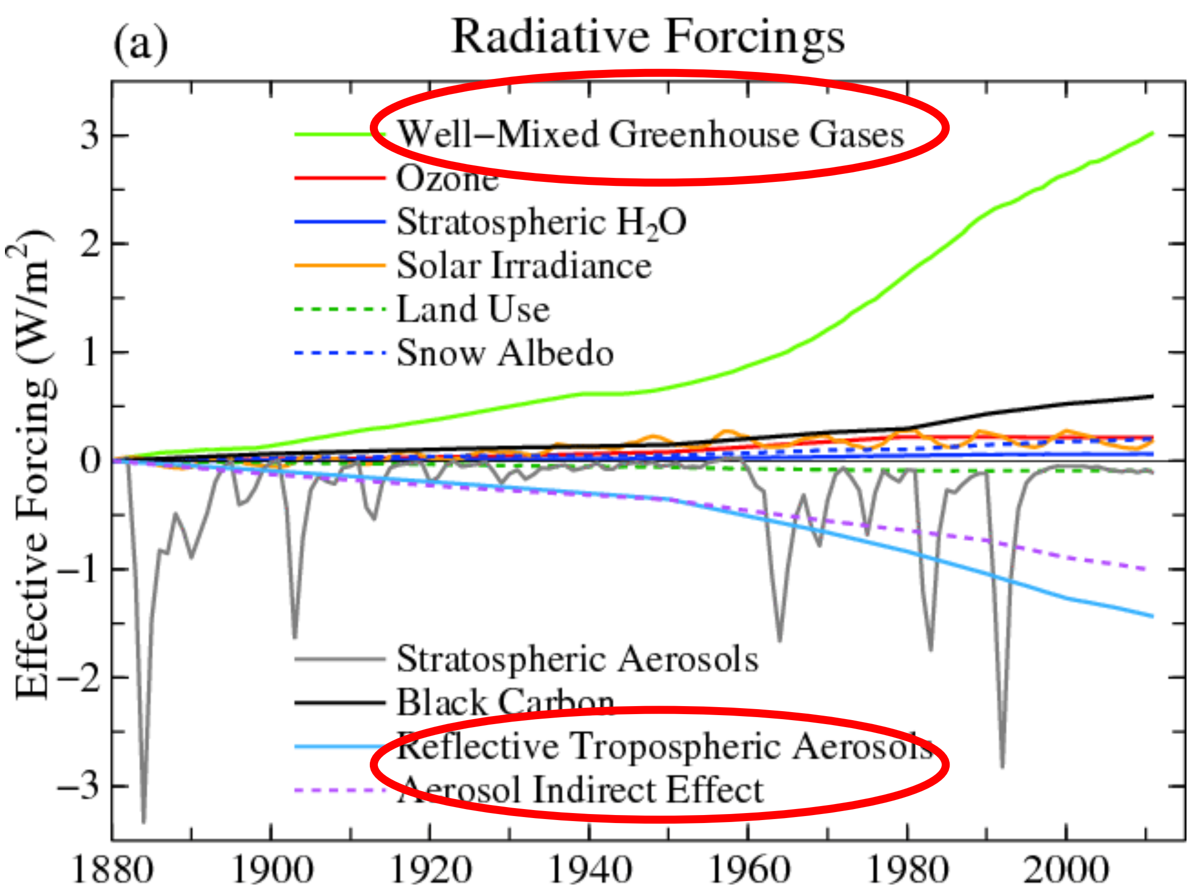
辐射强迫(radiative forcing)定义：

对流层顶净辐射的变化 (ΔQ, W/m^2)

Radiative Forcing : Instantaneous change of the radiative balance at the top of the troposphere due to a change in a process that affect climate.

$\Delta Q > 0, \Delta T > 0$, 增暖；
$\Delta Q < 0, \Delta T < 0$, 降温；

哪些因素影响辐射强迫？
温室气体,冰雪反照率,气溶胶,云等等

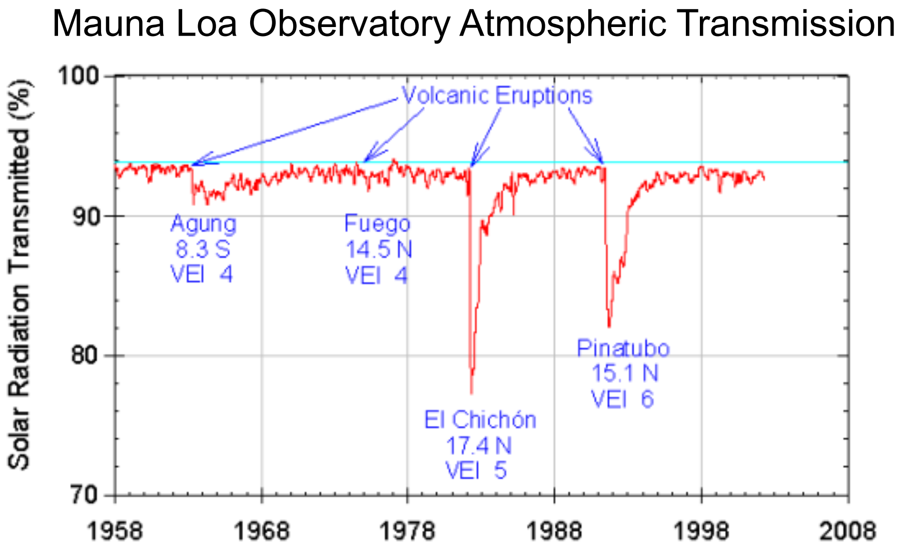


10.1气候强迫，气候敏感性及反馈机制

气溶胶的辐射强迫

气溶胶是大气中来自火山爆发和人类排放的小颗粒，气溶胶增加导致“负”的辐射强迫：

- 直接影响：反射的太阳辐射增加；
- 间接影响：作为云的凝结核，导致更多/更亮的云，增加云的反照率



10.1气候强迫，气候敏感性及反馈机制

气候强迫 (climate forcing)

辐射强迫(radiative forcing)定义：

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哪些因素影响辐射强迫？
温室气体,冰雪反照率,气溶胶,云等等

ΔQ

吸收太阳辐射Q

Climate System as a "Black Box"

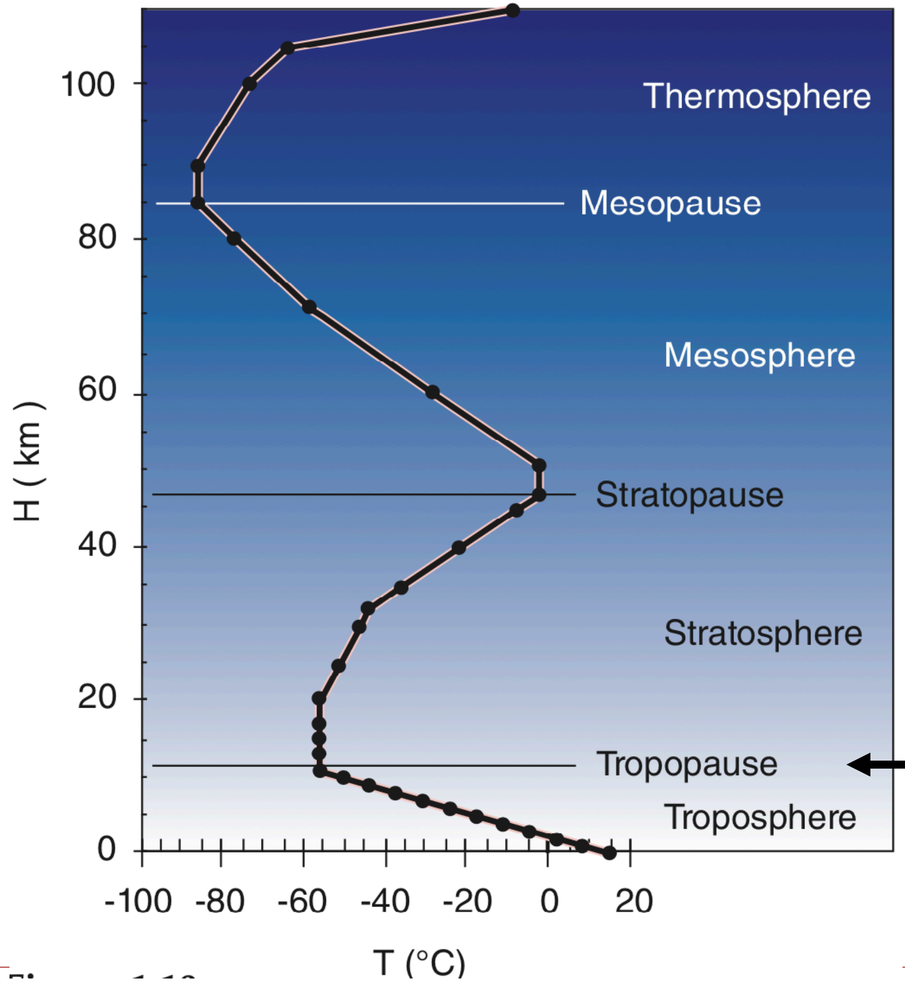
ΔT

地表温度 Ts = 15^{o}C

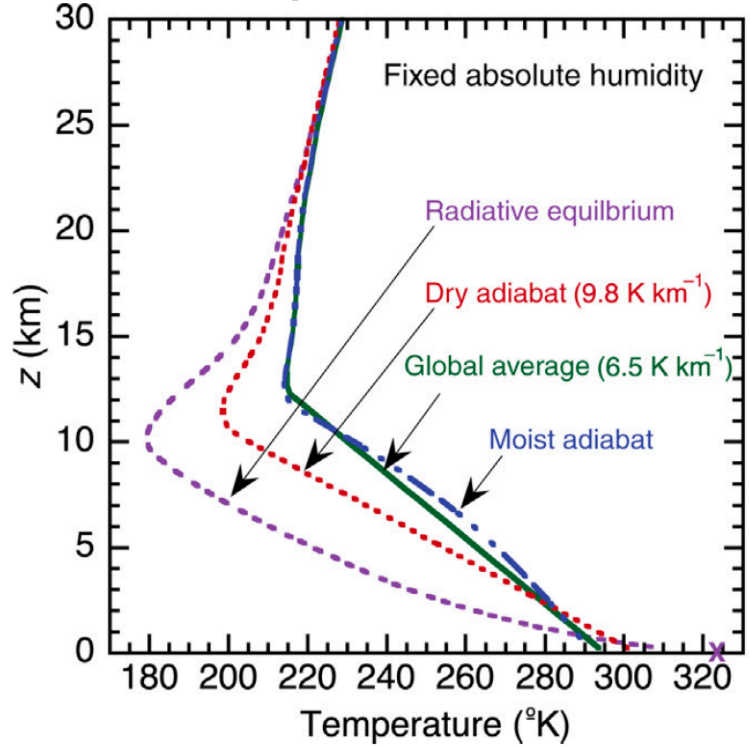
- 辐射强迫是气候变化的驱动力 **(Driver of Climate Change)**
- 用来比较不同因素对气候变化的影响。

10.1气候强迫，气候敏感性及反馈机制

气候强迫 (climate forcing)



Lapse Rate



大气层顶 (Top Of Atmosphere, TOA)
～对流层顶

10.1气候强迫，气候敏感性及反馈机制

气候响应 (climate response)和气候敏感性 (climate sensitivity)

气候敏感性: $\lambda = \frac{dT}{dQ}$

$+1 W/m^2$

ΔQ
气候强迫

吸收太阳辐射Q

Climate System as a "Black Box"

地表温度 Ts = 15^{o}C

ΔT
气候响应

?
λ^{o}C

气候敏感性 (climate sensitivity)

Svante Arrhenius

First estimate of climate sensitivity

To explain the ice age, Arrhenius estimated that halving of CO_2 would decrease temperatures by **4 - 5 °C** (Celsius) and a doubling of CO_2 would cause a temperature rise of **5 - 6 °C** (in 1986). Arrhenius expected CO_2 doubling to take about 3000 years; it is now estimated in most scenarios to take about a century.

10.1气候强迫，气候敏感性及反馈机制

反馈机制 (feedback)

input: 气候强迫ΔQ

Climate System as a “Black Box”

output: 气候响应ΔT

ΔQ_1 …

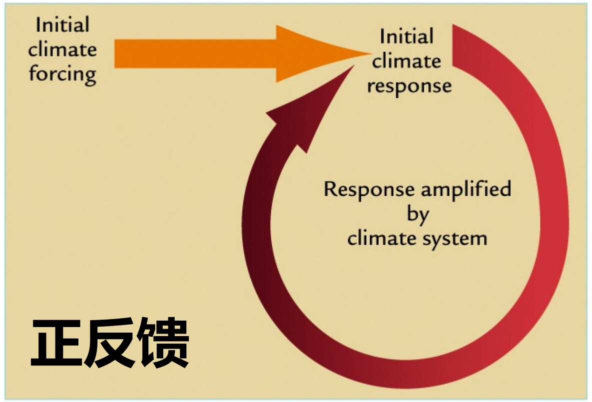
ΔT_1 …

$\Delta \boldsymbol{Q}_{final}$

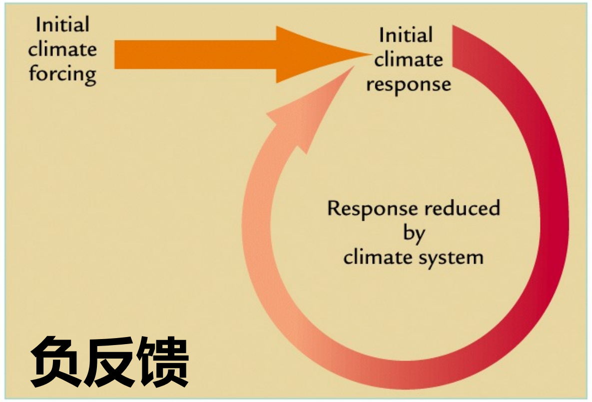
$= \Delta Q + \Delta \boldsymbol{Q}_{\text{feedback}}$

$\Delta \boldsymbol{T}_{final}$

Feedback



A Positive feedback



B Negative feedback

10.1气候强迫，气候敏感性及反馈机制

0维能量平衡模型

大气层顶能量平衡：$R_{TOA} = \frac{S_0}{4}(1-\alpha) - F_{out} = 0$

施加气候强迫ΔQ,气候系统达到新的平衡, $\frac{dR_{TOA}}{dQ} = \frac{\partial R_{TOA}}{\partial Q} + \frac{\partial R_{TOA}}{\partial T_s}\frac{dT_s}{dQ} = 0$

$$\lambda = \frac{dT_s}{dQ} = -\left(\frac{\partial R_{TOA}}{\partial T_s}\right)^{-1} = \left(\frac{S_0}{4}\frac{\partial \alpha}{\partial T_s} + \frac{\partial F_{out}}{\partial T_s}\right)^{-1}$$

在这个简单模型中，气候敏感性由两个基本的反馈过程决定：
反照率对温度的依赖性；向外辐射的能量对温度的依赖性；

10.2 辐射反馈过程 (Basic Radiative Feedback Processes)

a. 普朗克反馈 (Planck Feedback)

正反馈还是负反馈？

负反馈

根据Stefan-Boltzmann law，大气层顶 $F_{out} = \sigma {T_e}^4$

0维能量平衡模型中$\lambda = \left(\frac{S_0}{4}\cancel{\frac{\partial\alpha}{\partial T_s}} + \frac{\partial F_{out}}{\partial T_s}\right)^{-1}$

$+\Delta Q$
-> $T\uparrow$
-> $F_{out}\uparrow$
-> $-\Delta Q_{\mathrm{feedback}}$

如果忽略反照率对温度的依赖性，并且假设$T_e \sim T_s$

$$\Rightarrow \lambda_{BB} = \left(\frac{\partial\left(\sigma {T_e}^4\right)}{\partial T_s}\right)^{-1} = \left(4\sigma {T_e}^3\right)^{-1} = 0.26\, K(Wm^{-2})^{-1}$$

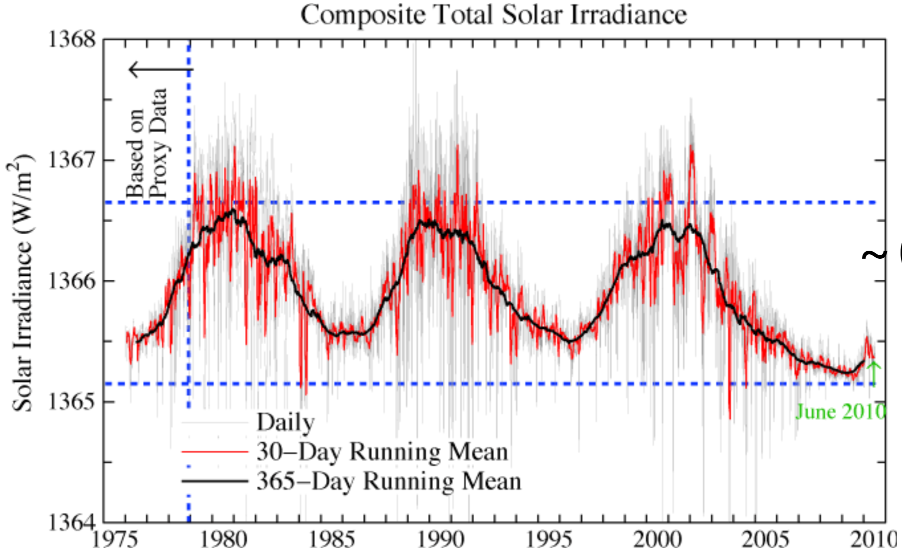
10.2 辐射反馈过程 (Basic Radiative Feedback Processes)

a. 普朗克反馈 (Planck Feedback)

$$\lambda_{BB} = 0.26\ K\left(Wm^{-2}\right)^{-1}$$

$S_0(1360Wm^{-2})$增加多少可以使得全球气温升高1°C(设α=0.3)？

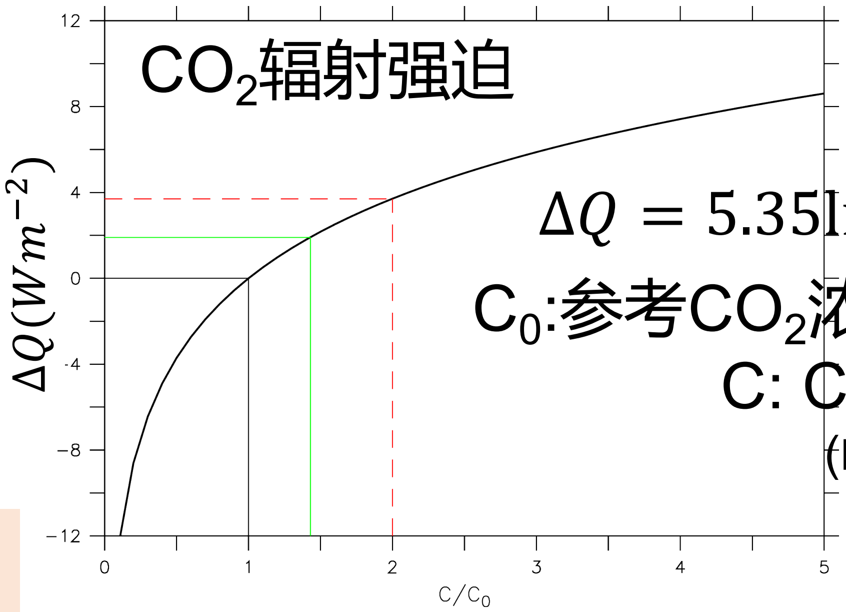
$$\frac{1}{\lambda_{BB}}/(1-\alpha)/(S_0/4) = \frac{4}{0.26*0.7*1360} = 1.6\%$$



~0.07%

≈
效果相当

CO_2增加一倍会造成全球温度升高多少？



$$\Delta Q = 5.35\ln\left(\frac{C}{C_0}\right)\ (Wm^{-2})$$

C_0:参考CO_2浓度 (工业革命前)

C: CO_2浓度

(Ramaswamy et al., 2001)

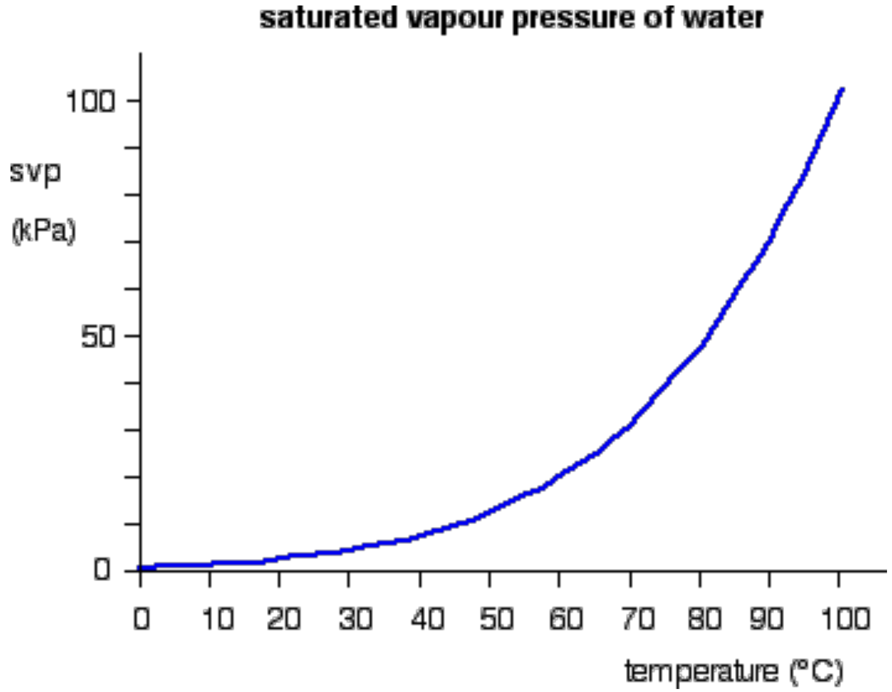
$$\Delta Q = 5.35\ln 2 = 3.7\ (Wm^{-2})$$

$$\Delta T = \lambda_{BB}\Delta Q = 1^{o}C$$

(only Planck feedback considered)

10.2 辐射反馈过程 (Basic Radiative Feedback Processes)

b. 水汽反馈 (Water Vapor Feedback)



正反馈还是负反馈？

正反馈

$+\Delta Q$

-> $T\uparrow$

-> Water Vapor ↑

-> Greenhouse effect ↑

$\to +\Delta Q_{\text{feedback}}$