上海交通大学 SHANGHAI JIAO TONG UNIVERSITY

上海交通大学海洋学院

气候学与全球变化
Climate and Global Change

2022.05.13

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

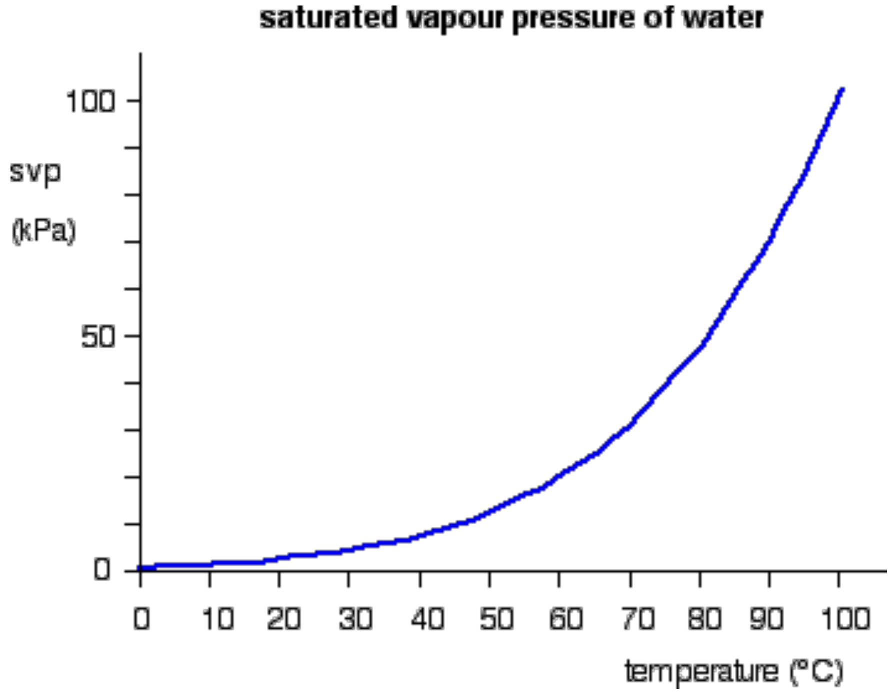
回顾

1. 辐射强迫 ->气候系统->气候响应
2. 气候敏感性： $\lambda = dT/dQ$
3. 反馈机制：

- 普朗克反馈： $\lambda_{BB} = 0.26\, K(Wm^{-2})^{-1}$

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

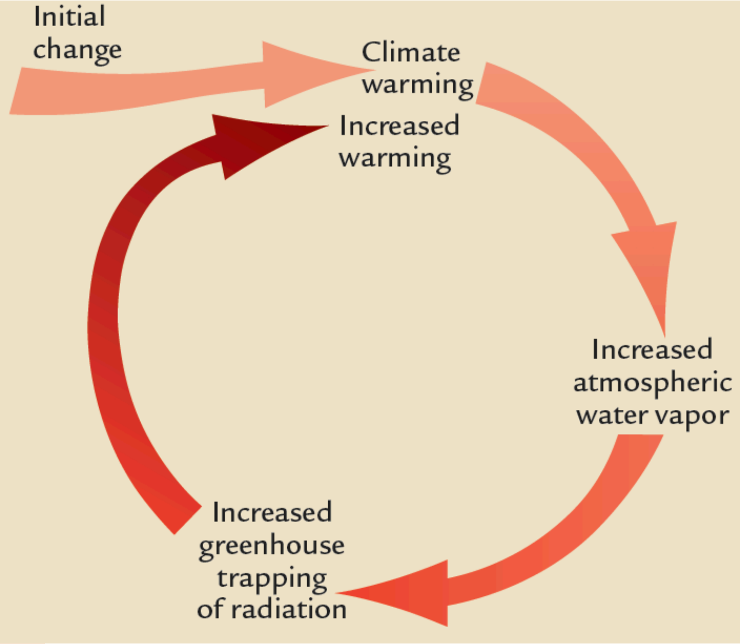
$+\Delta Q$

-> $T\uparrow$

-> Water Vapor ↑

-> Greenhouse effect ↑

->$+\Delta Q_{\text{feedback}}$



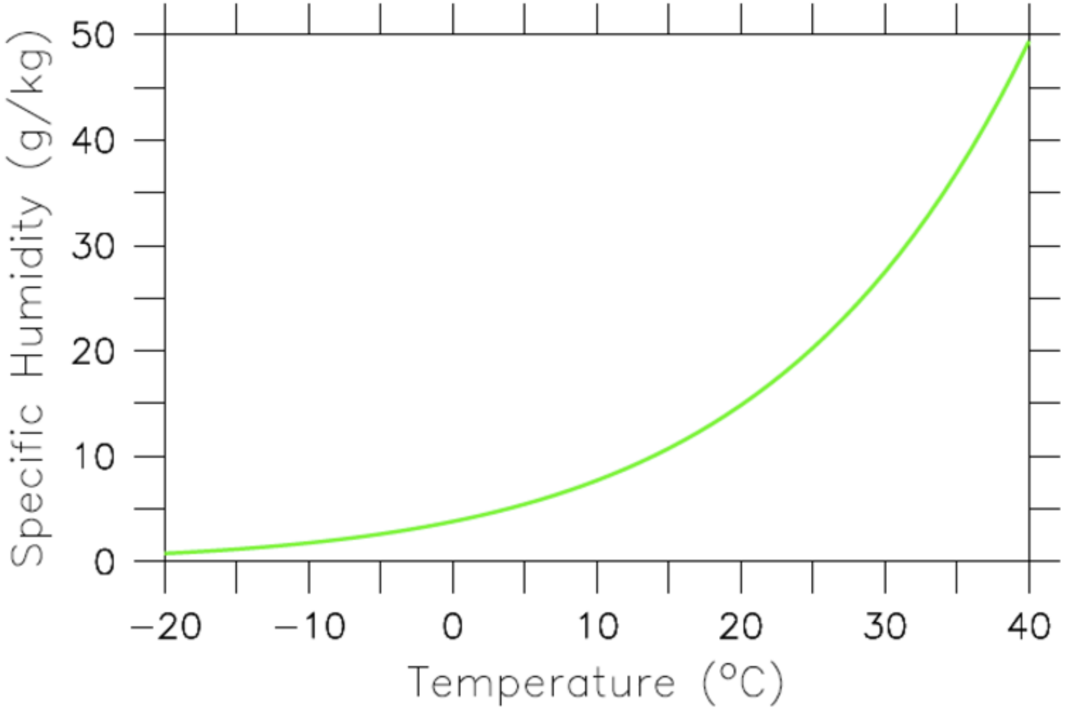
10.2 辐射反馈过程 (Basic Radiative Feedback Processes)

b. 水汽反馈 (Water Vapor Feedback)

Clausius–Clapeyron relationship：

$$\frac{de_s}{dT} = \frac{L}{T(\alpha_v - \alpha_l)}$$

e_s:饱和水汽压; L:潜热; T:温度;
α_v:气态比容; α_l:液态比容



饱和比湿 q^*的变化(结合状态方程)：

$$\frac{dq^*}{q^*} = \frac{de_s}{e_s} = \left(\frac{L}{R_v T}\right)\frac{dT}{T}$$

$$\frac{L}{R_v T} \sim 20$$

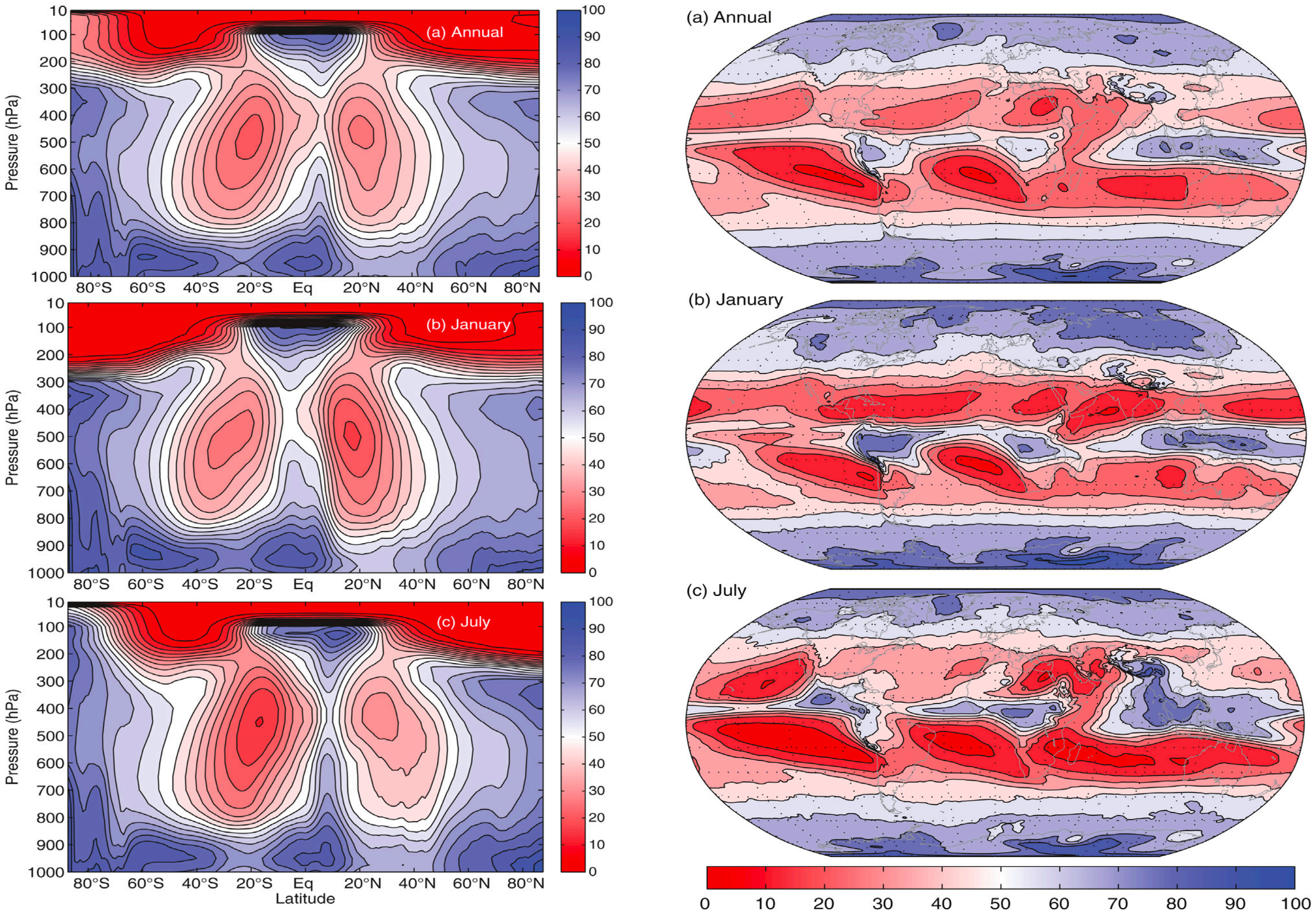
$\Delta T + 1K \rightarrow q^*$增加 ~ 7%

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

b. 水汽反馈 (Water Vapor Feedback)

relative humidity $(\frac{q}{q^*})$ ：

approximately constant when climate warms or cools.



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

b. 水汽反馈 (Water Vapor Feedback)

Fixed relative humidity (FRH):

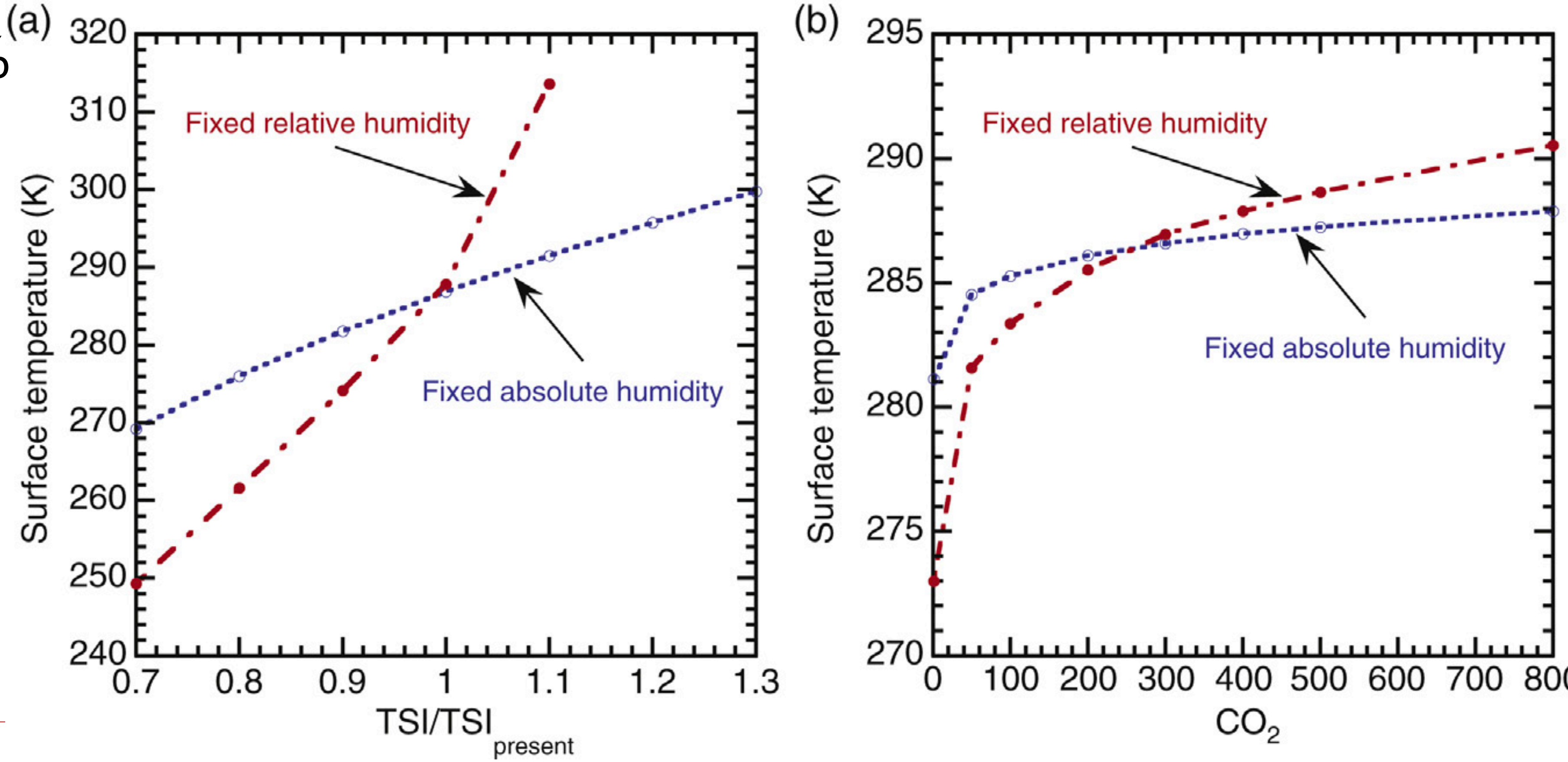
$\Delta T + 1K$

$\rightarrow q^*$增加 ~ 7%

$\rightarrow q$增加

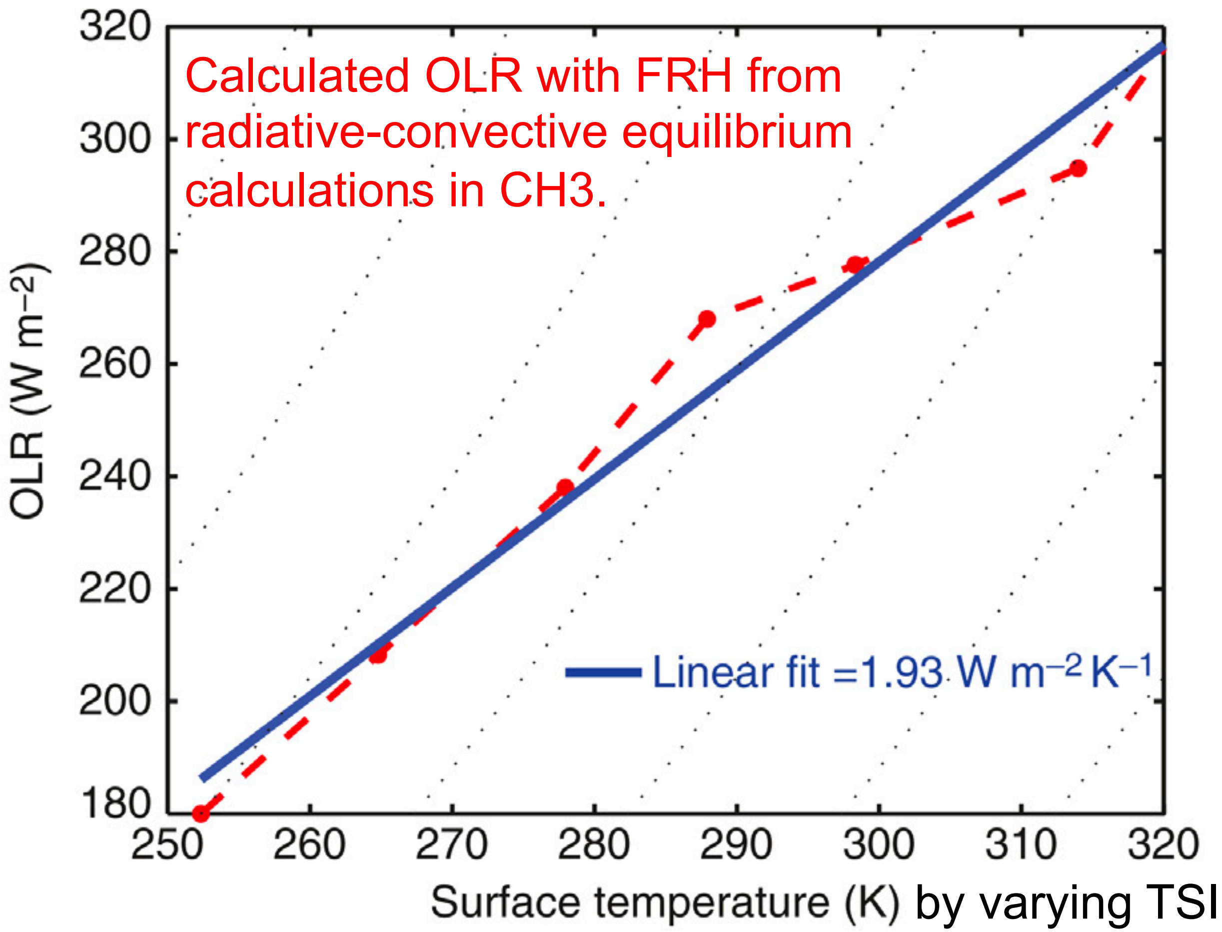
→温室效应增强

强烈的水汽正反馈



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

b. 水汽反馈 (Water Vapor Feedback)



$$\Rightarrow \lambda_{FRH} = (1.93)^{-1} \approx 0.5K(Wm^{-2})^{-1}$$

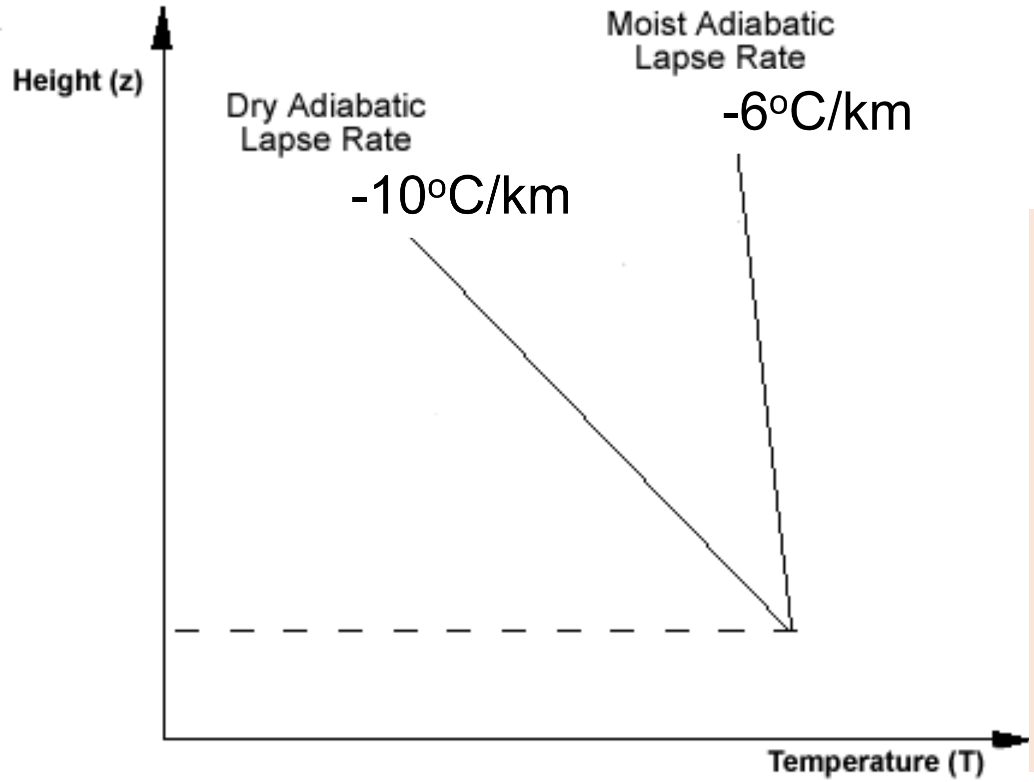
$$\lambda_{BB} = 0.26\,K(Wm^{-2})^{-1}$$

FRH ≈ 2BB

$\Rightarrow$2xCO_2 ~ 2^oC

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

c. 温度递减率反馈 (Lapse-Rate Feedback)



正反馈还是负反馈？

负反馈

OLR主要取决于高层大气的温度

$+\Delta Q$

->LR↓, heat to higher levels ↑

-> Te ↑

-> F_{out} ↑

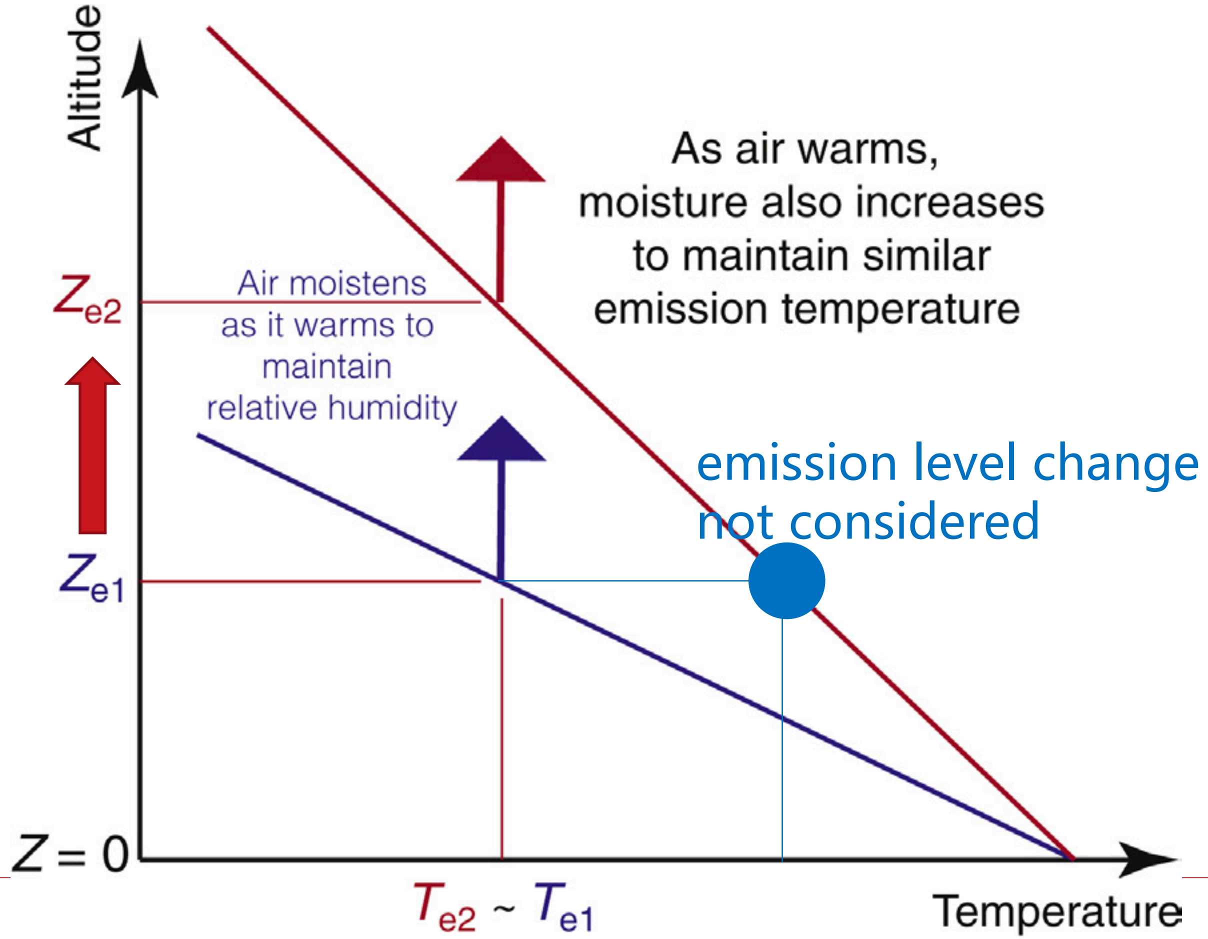
-> $-\Delta Q_{\mathrm{feedback}}$

假设其他条件不变：emission level fixed

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

c. 温度递减率反馈 (Lapse-Rate Feedback)

Relative humidity feedback offsets the effect of lapse-rate feedback



$$e_s(T), RH\ fixed\ \rightarrow q(T)$$

LR↓
-> T ↑, 更多水汽
->emission level升高
-> Te ~不变

Lapse-rated feedback muted by water vapor feedback

10.3 冰雪反照率反馈 (Ice-albedo Feedback)

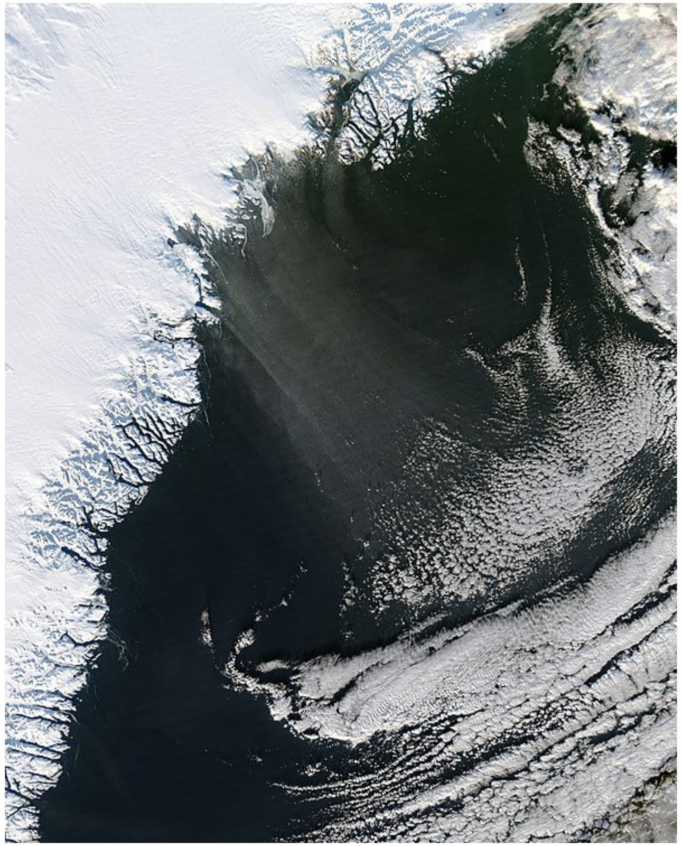
正反馈还是负反馈？

正反馈

TABLE 2-1 Average Albedo Range of Earth's Surfaces

Surface	Albedo range (percent)
Fresh snow or ice	60–90%
Old, melting snow	40–70
Clouds	40–90
Desert sand	30–50
Soil	5–30
Tundra	15–35
Grasslands	18–25
Forest	5–20
Water	5–10

Adapted from W. D. Sellers, Physical Climatology *(Chicago: University of Chicago Press, 1965), and from R. G. Barry and R. J. Chorley,* Atmosphere, Weather, and Climate, *4th ed. (New York: Methuen, 1982).*



Striking contrast between ice-covered and ice-free surfaces

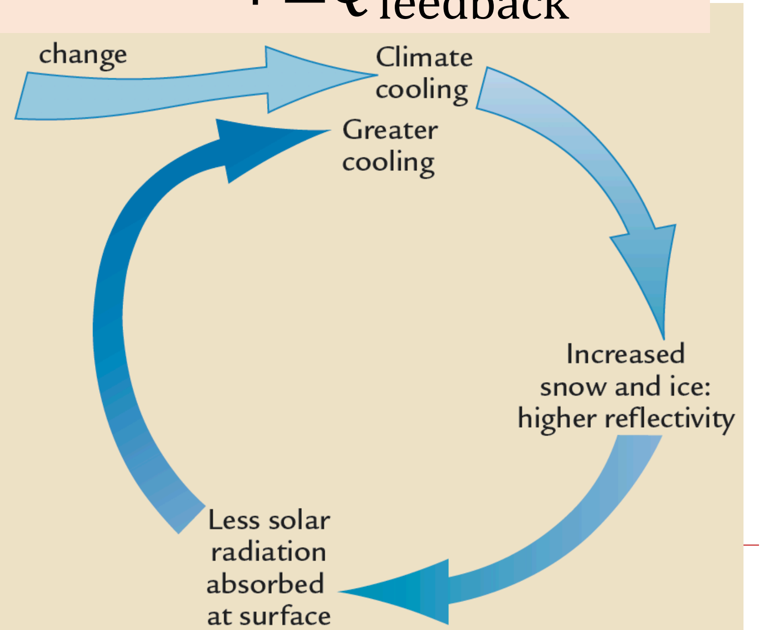
$+\Delta Q$

-> $T\uparrow$

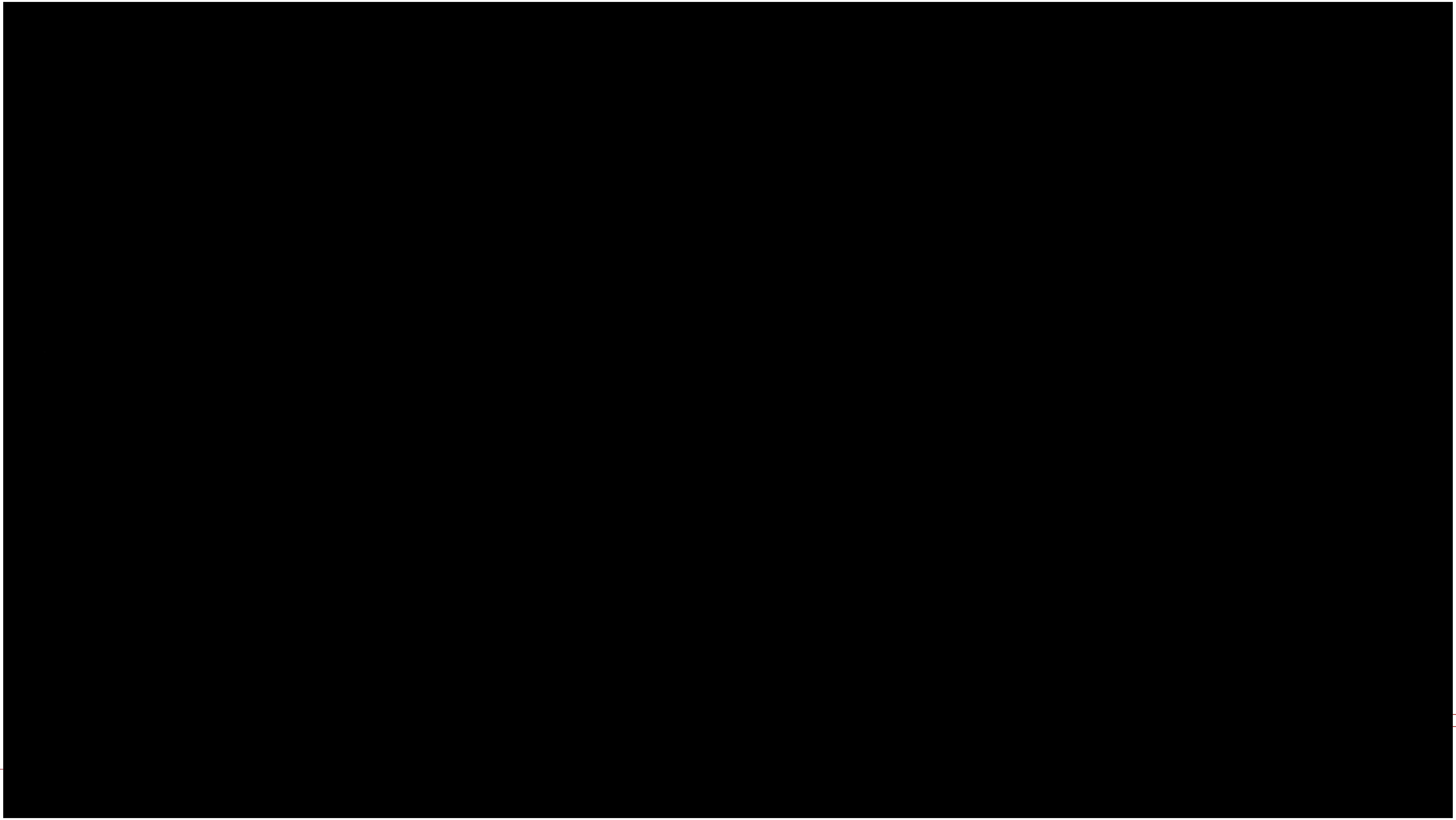
->snow and ice melt

-> $\alpha\downarrow$

-> $+\Delta Q_{\text{feedback}}$

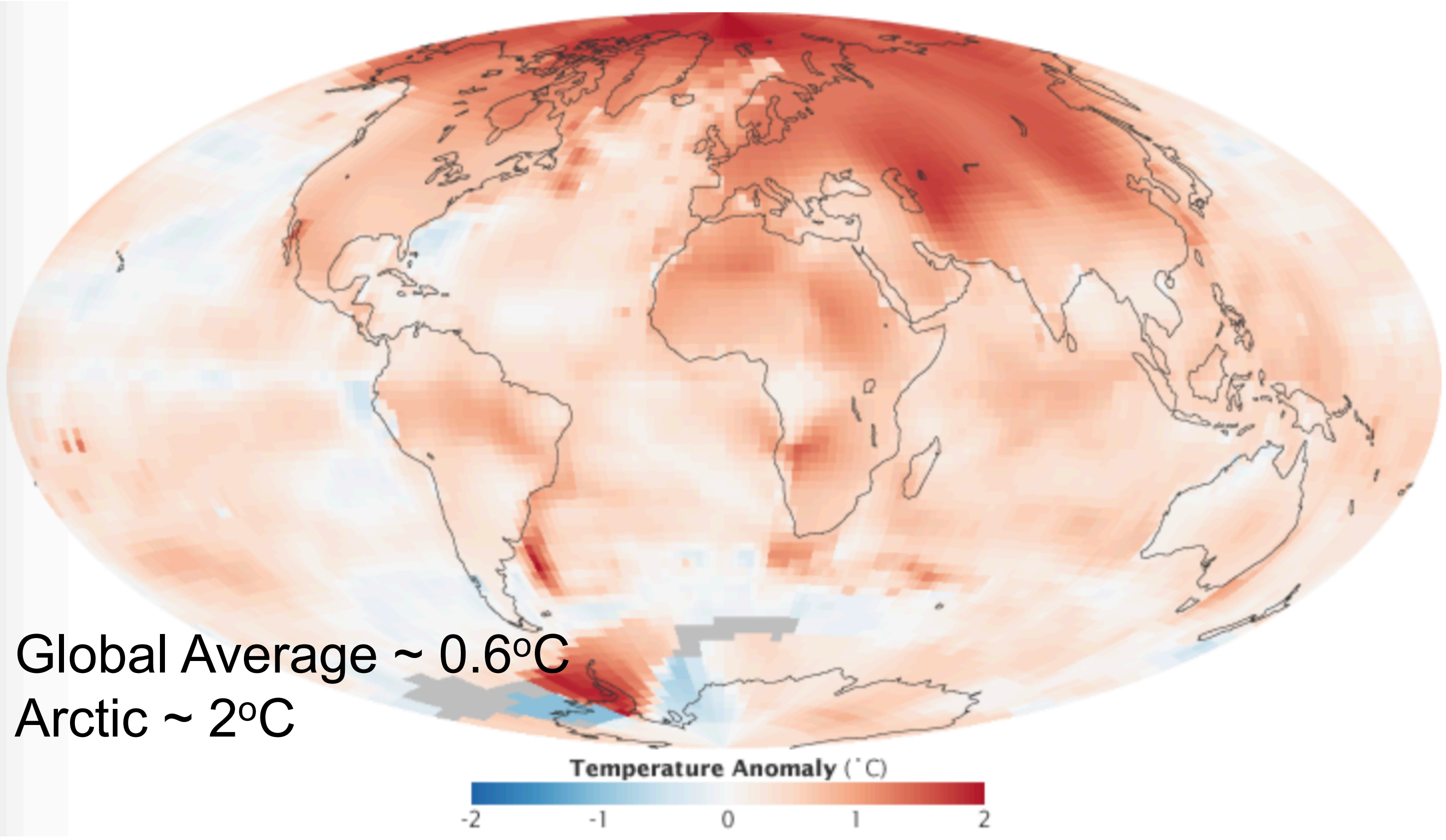


Disappearing Arctic sea ice

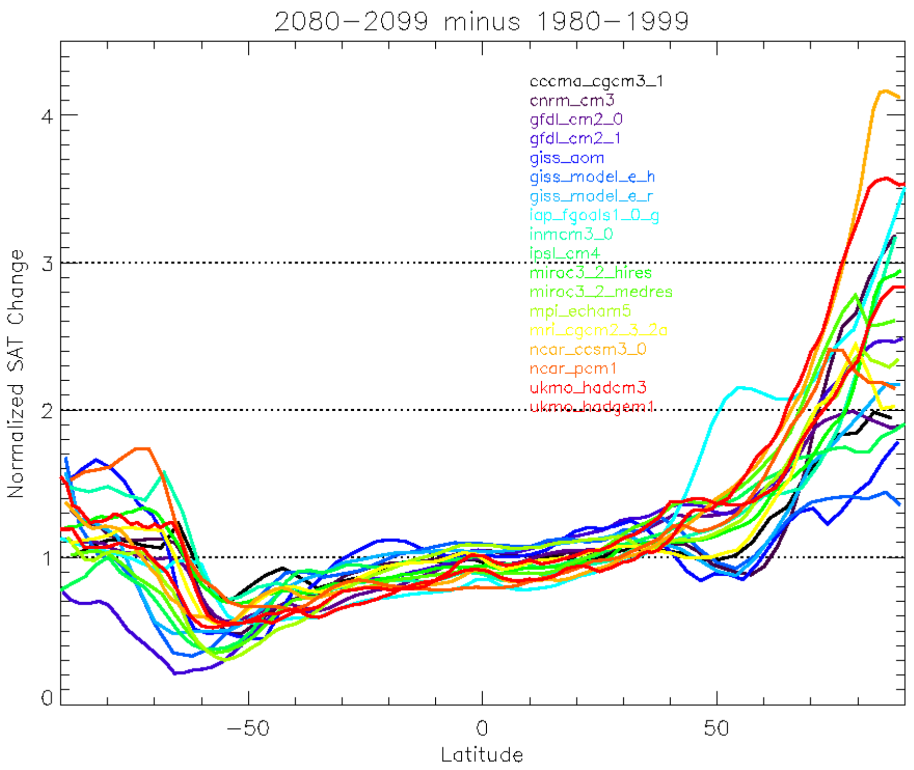


10.3 冰雪反照率反馈 (Ice-albedo Feedback)

Polar Amplification　　Manabe and Stouffer (1980)



January 1, 2000.1.1 - 2009.12.31

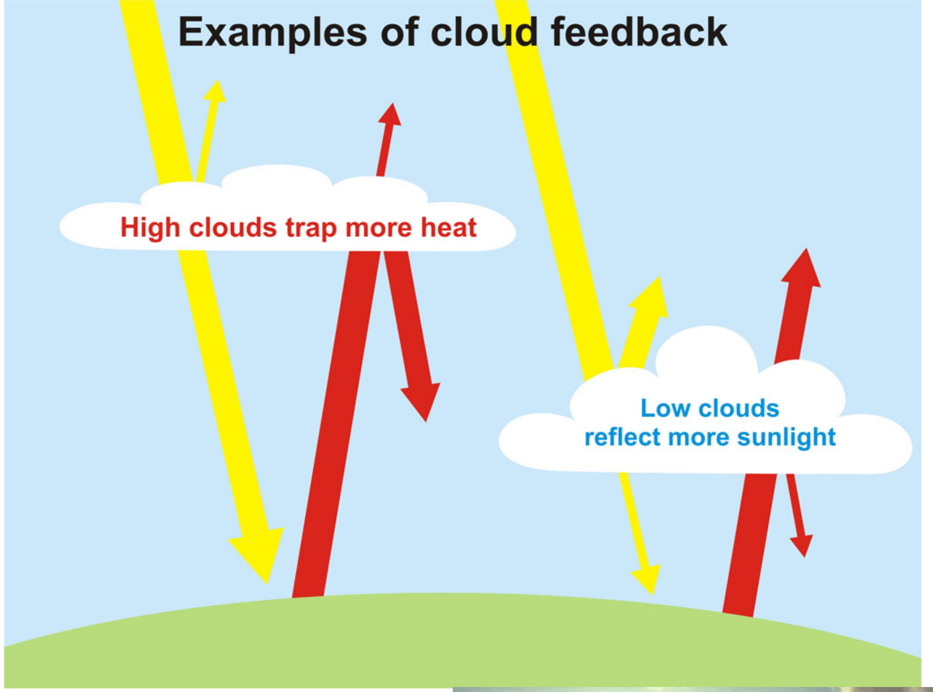


IPCC AR4

10.4 云反馈

TABLE 3.2 Cloud Radiative Effect on the Top-of-Atmosphere Global Energy Balance as Estimated from Satellite Measurements

	Average	Cloud free	Cloud effect
OLR	240	266	+26
Absorbed solar radiation	240	288	−47
Net radiation	+0.56	+22	−21
Albedo	29%	15%	+14%



- 云同时影响短波辐射和长波辐射；
- 云增加反照率->降温(负反馈)；减少OLR->增温(正反馈);
- 云对气候的净影响取决于云的类型和它们的光学特性;
- 通常来说, 高云->正反馈；低云->负反馈。

highly uncertain!

High cirrus clouds
Positive feedback

Low cumulus clouds
Negative feedback

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019RG000678

10.5 其他反馈

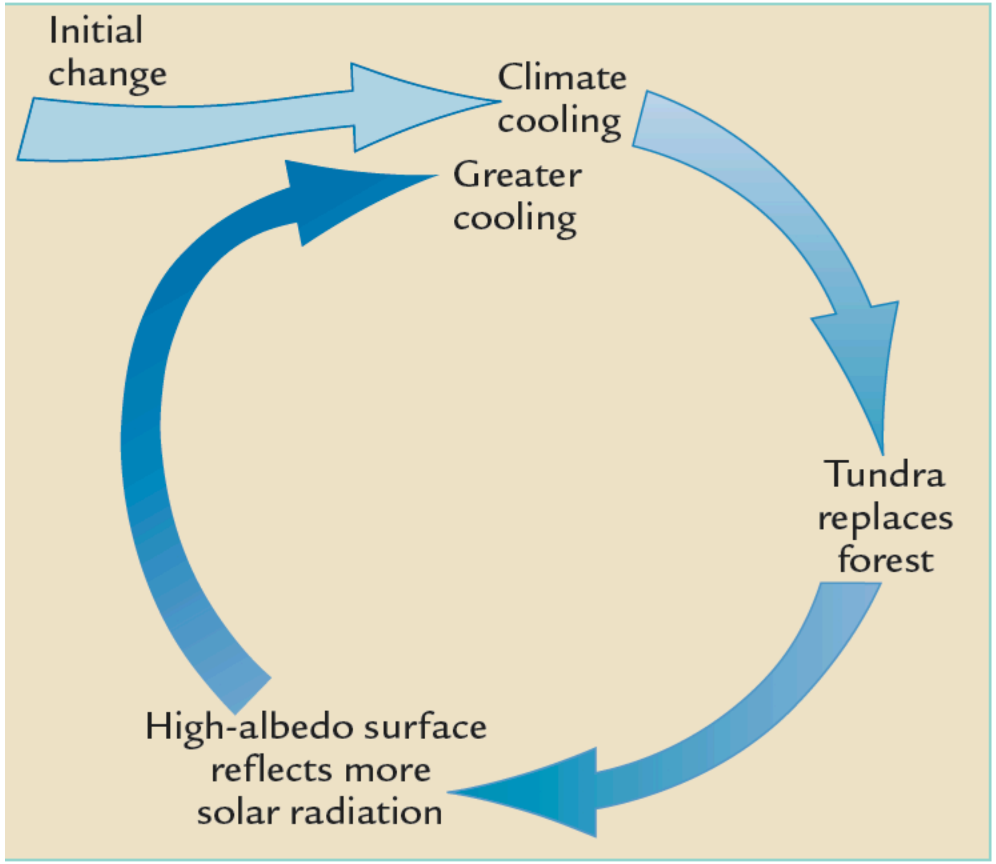
植被反馈 (Vegetation Feedbacks)

北极的植被类型：

苔原

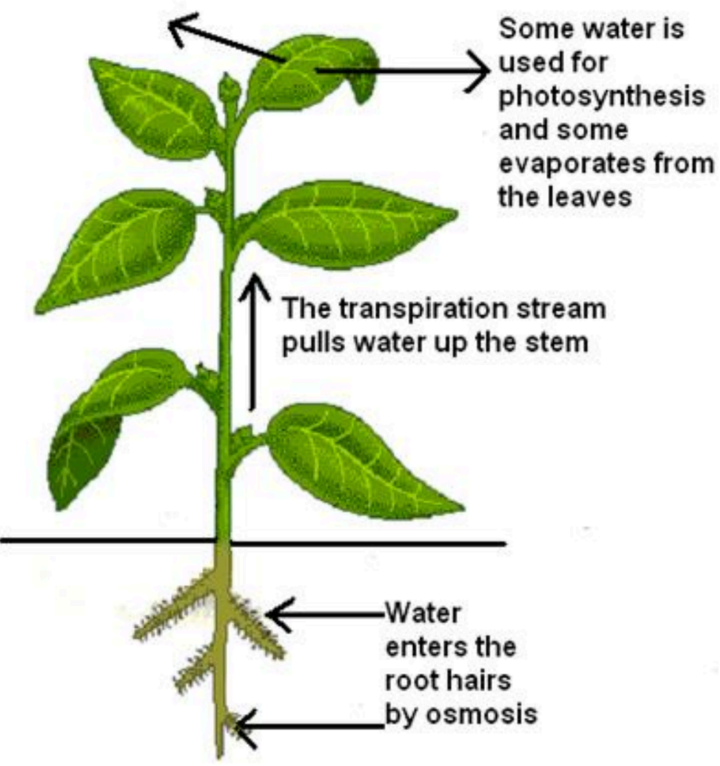
云杉

Vegetation-albedo feedback

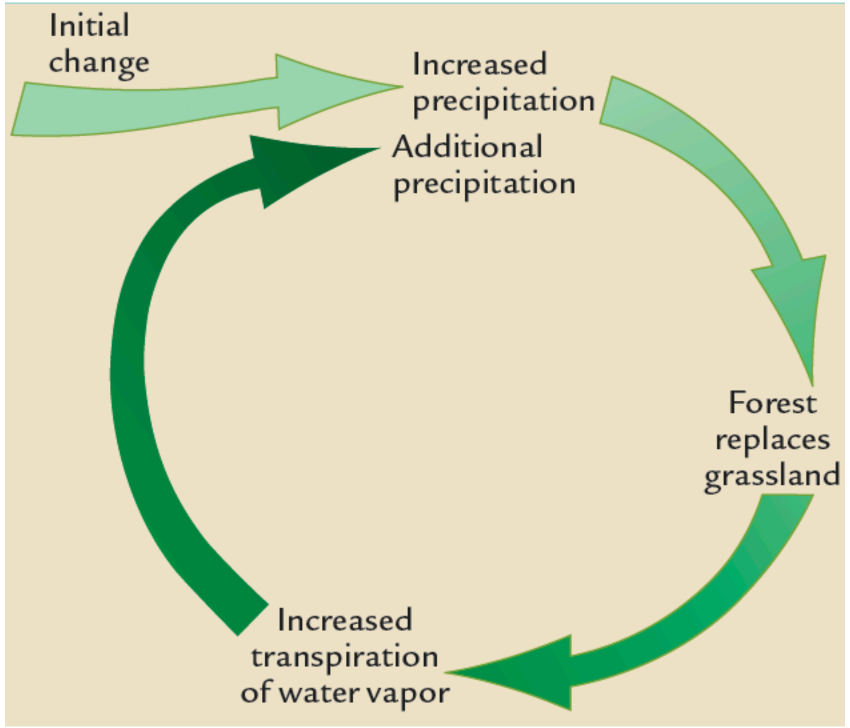


10.5 其他反馈

植被反馈 (Vegetation Feedbacks)

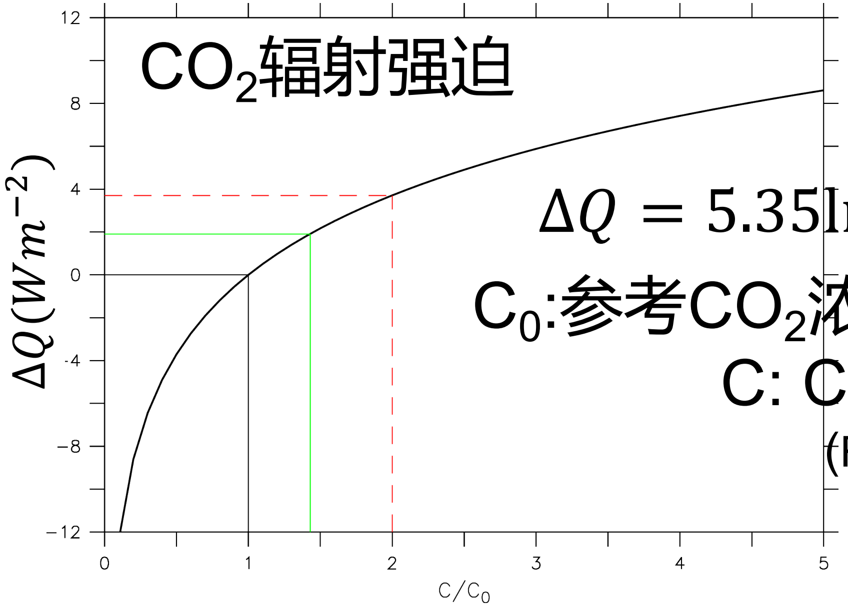


Vegetation-precipitation feedback



10.5 气候敏感性的估计

2xCO_2　　气候敏感性: $\lambda = \dfrac{dT}{dQ}$，或ΔT_{2xCO2}



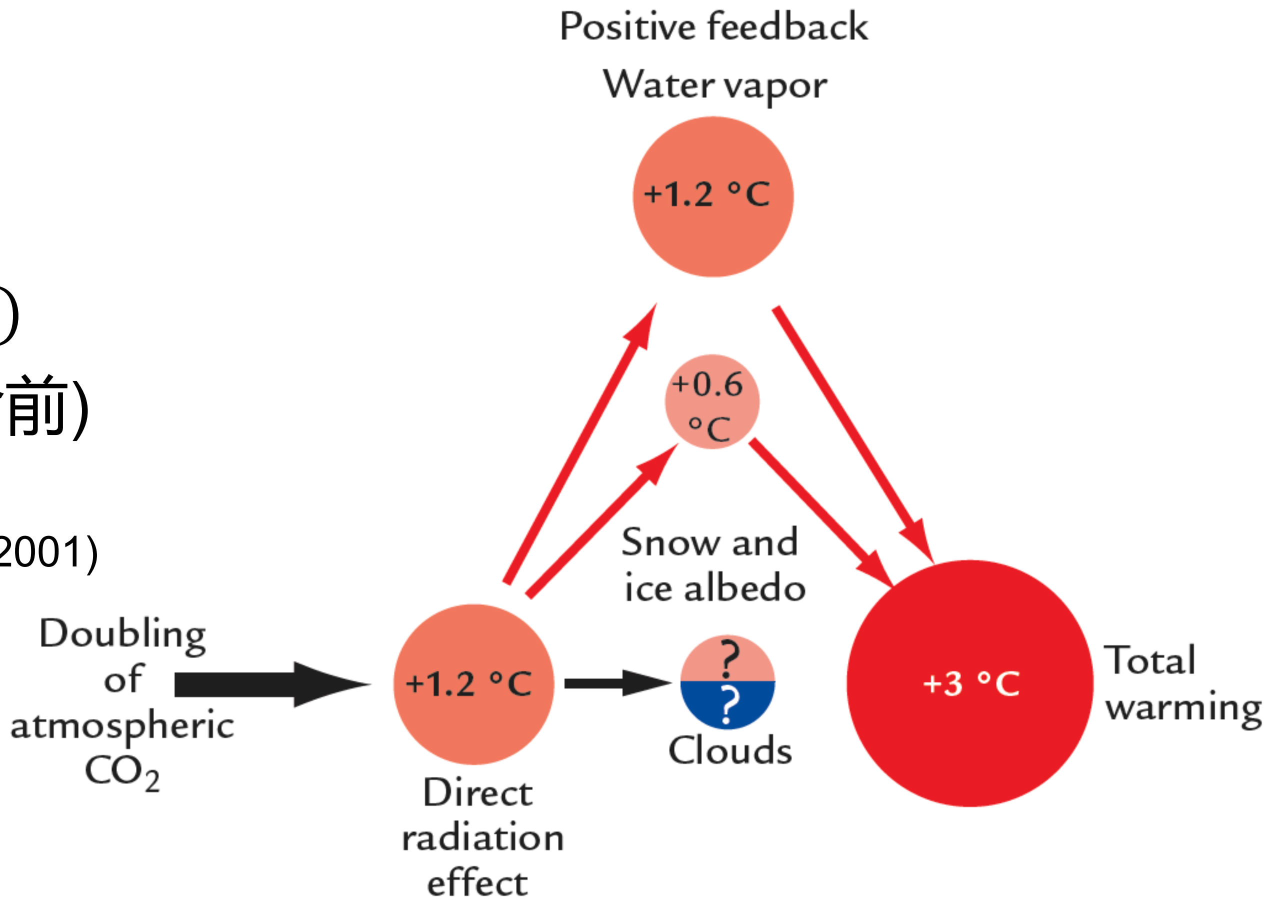
$$\Delta Q = 5.35\ln\left(\frac{C}{C_0}\right)\ (Wm^{-2})$$

C_0:参考CO_2浓度 (工业革命前)

C: CO_2浓度

(Ramaswamy et al., 2001)

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



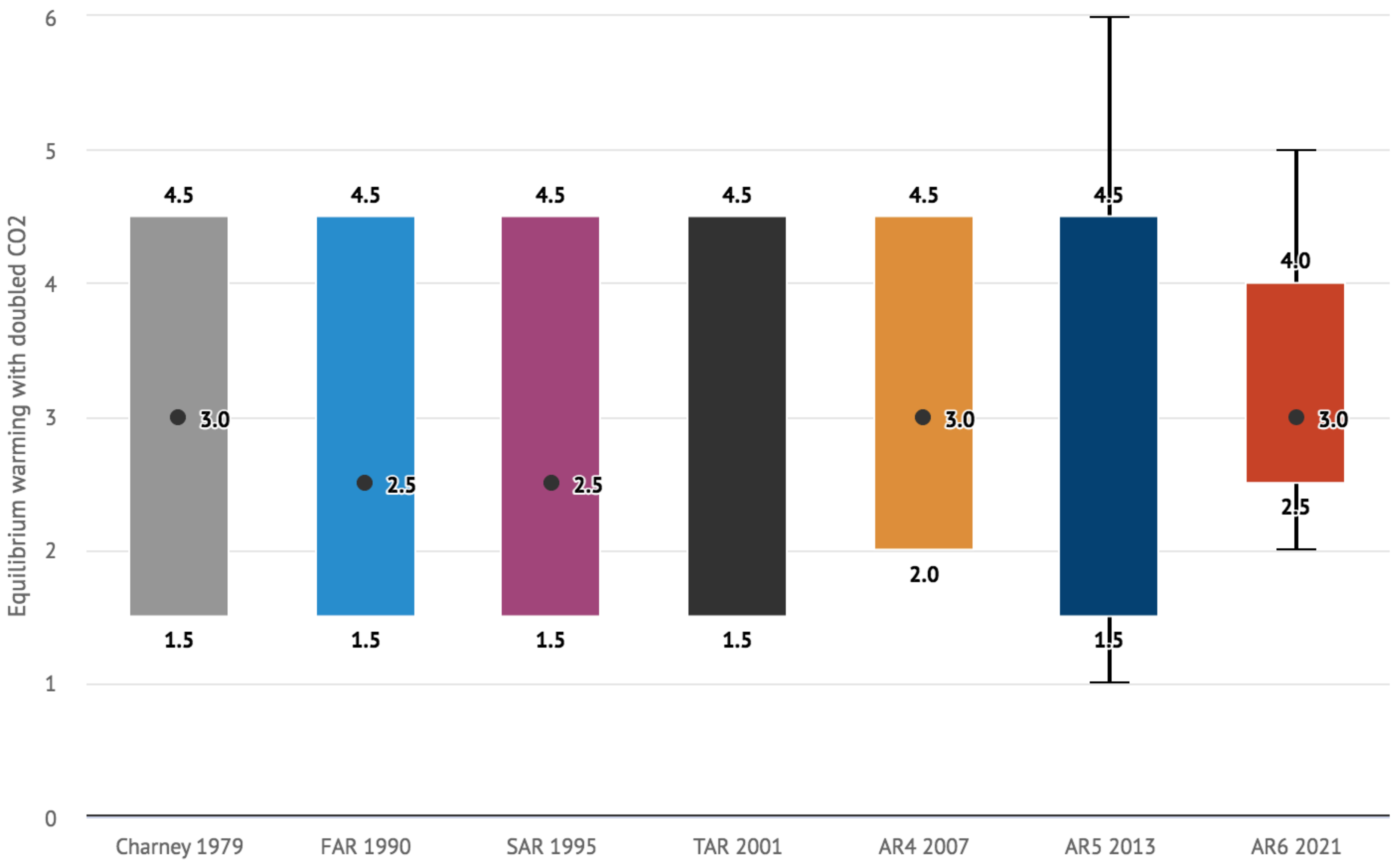
10.5 气候敏感性的估计

$2xCO_2$

ΔT_{2xCO2} from IPCC AR6: 3K,

likely range: 2.5-4.0

very likely range: 2-5k



10.5 气候敏感性的估计

如何估计？

1. **古气候**

+：真实发发生，包含所有的反馈 ；
-： 精确重建气候强迫以及全球温度变化存在困难；

2. **根据物理原理计算（利用数值模式）**

+：物理过程, 定量衡量不同反馈的重要性；
-： 模式“误差” ；

10.5 气候敏感性的估计

如何估计？

1. **古气候**

- LGM (纪录相对丰富)：

CO_2 190ppm

CH_4 350ppm

$\approx$ 45% lower CO_2

LGM mean surface temperature

-> ΔT_{2xCO2}

Article

Glacial cooling and climate sensitivity revisited

https://doi.org/10.1038/s41586-020-2617-x

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Check for updates

Jessica E. Tierney[1]✉, Jiang Zhu[2,3], Jonathan King[1], Steven B. Malevich[1], Gregory J. Hakim[4] & Christopher J. Poulsen[3]

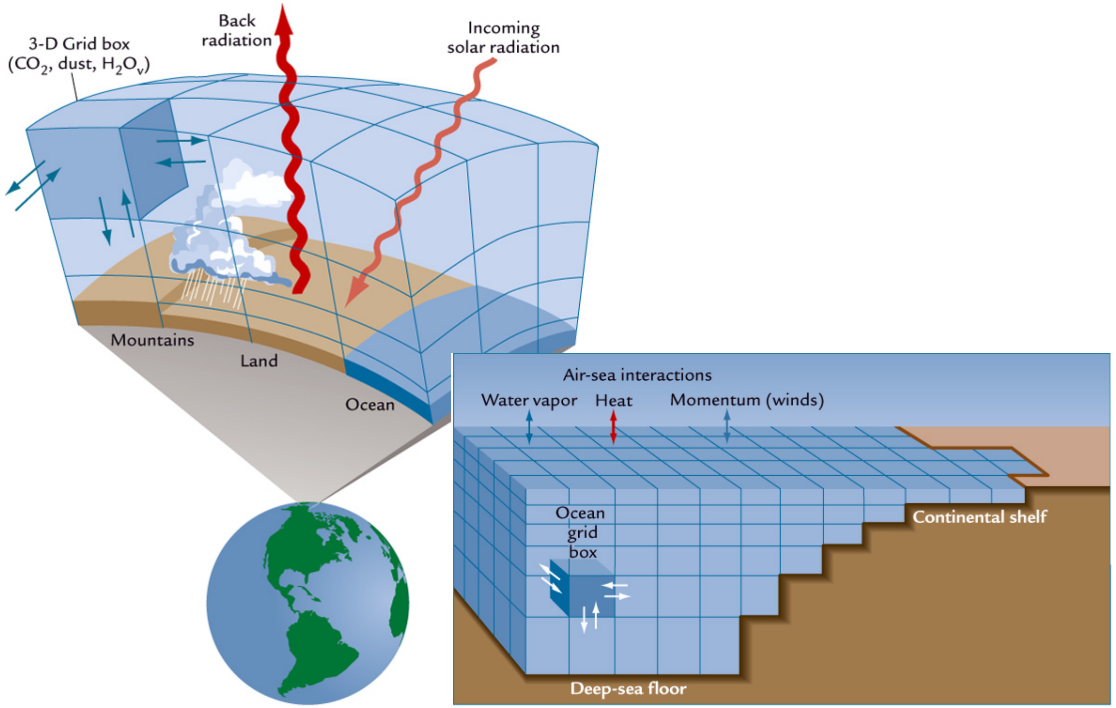
The Last Glacial Maximum (LGM), one of the best studied palaeoclimatic intervals, offers an excellent opportunity to investigate how the climate system responds to changes in greenhouse gases and the cryosphere. Previous work has sought to constrain the magnitude and pattern of glacial cooling from palaeothermometers[1,2], but the uneven distribution of the proxies, as well as their uncertainties, has challenged the construction of a full-field view of the LGM climate state. Here we combine a large collection of geochemical proxies for sea surface temperature with an isotope-enabled climate model ensemble to produce a field reconstruction of LGM temperatures using data assimilation. The reconstruction is validated with withheld proxies as well as independent ice core and speleothem $\delta^{18}O$ measurements. Our assimilated product provides a constraint on global mean LGM cooling of −6.1 degrees Celsius (95 per cent confidence interval: −6.5 to −5.7 degrees Celsius). Given assumptions concerning the radiative forcing of greenhouse gases, ice sheets and mineral dust aerosols, this cooling translates to an equilibrium climate sensitivity of 3.4 degrees Celsius (2.4–4.5 degrees Celsius), a value that is higher than previous LGM-based estimates but consistent with the traditional consensus range of 2–4.5 degrees Celsius[3,4].

Tierney et al., 2020, Nature

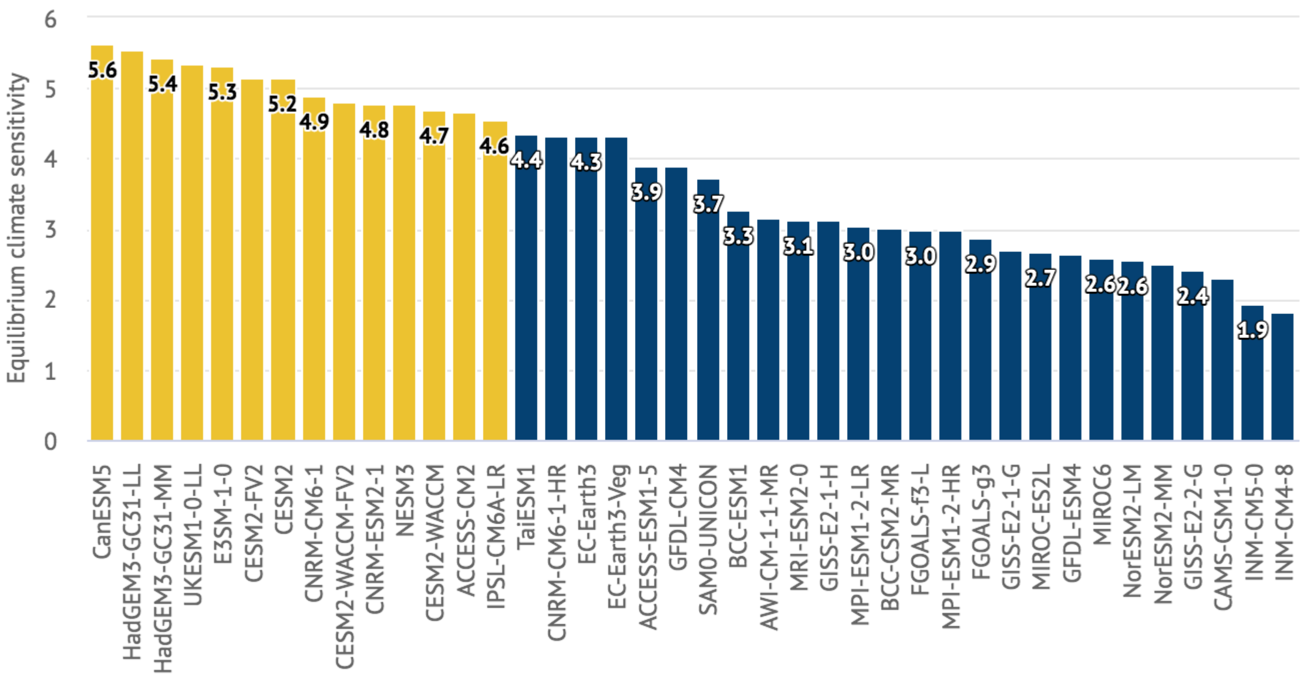
10.5 气候敏感性的估计

如何估计？

2. 气候模式



Coupled Model Intercomparison Project (CMIP)

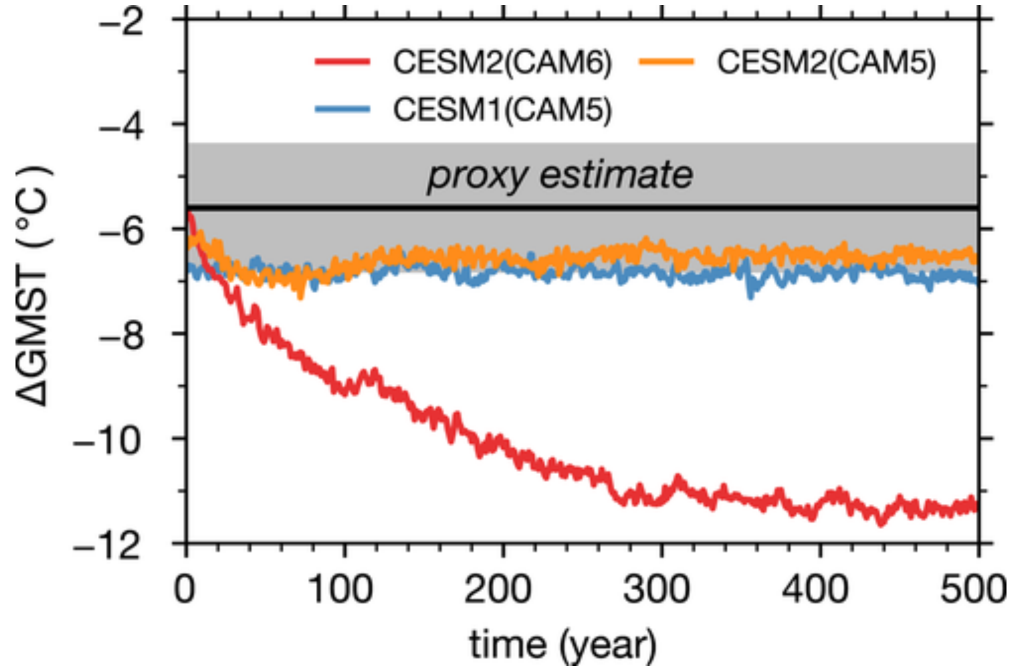


10.5 气候敏感性的估计

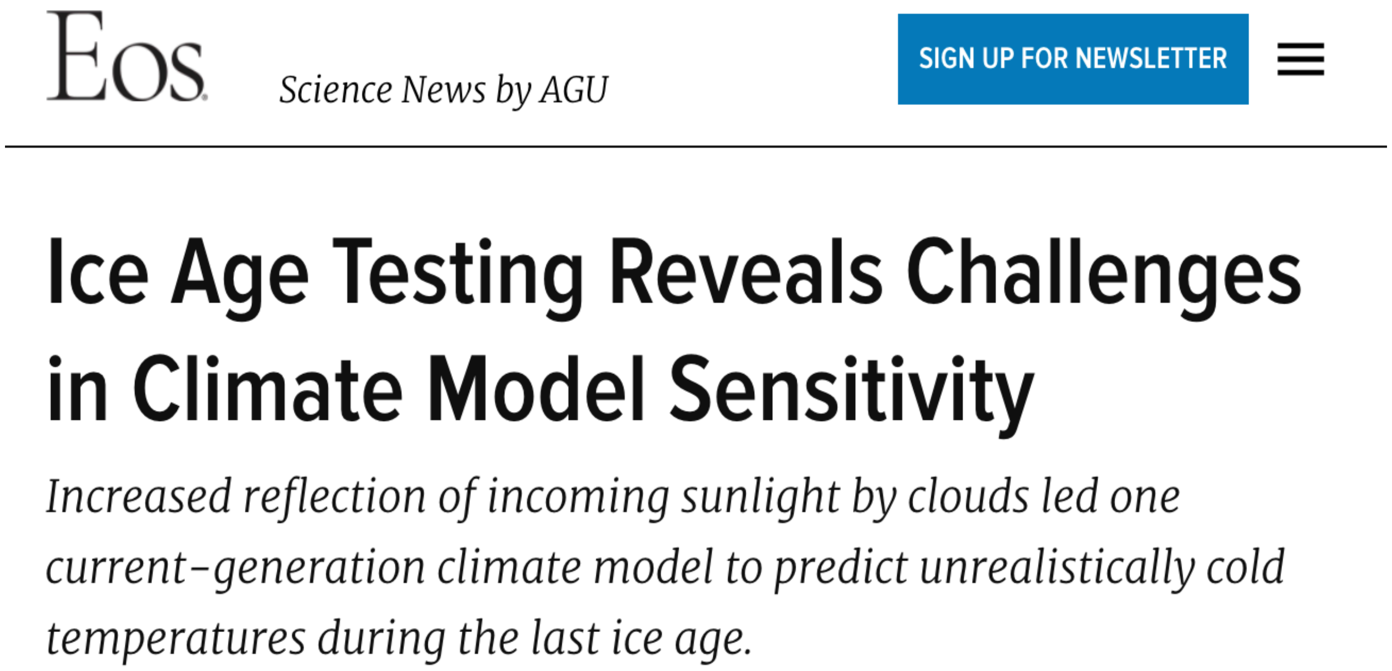
如何估计？

2. 气候模式

云反馈的不确定性



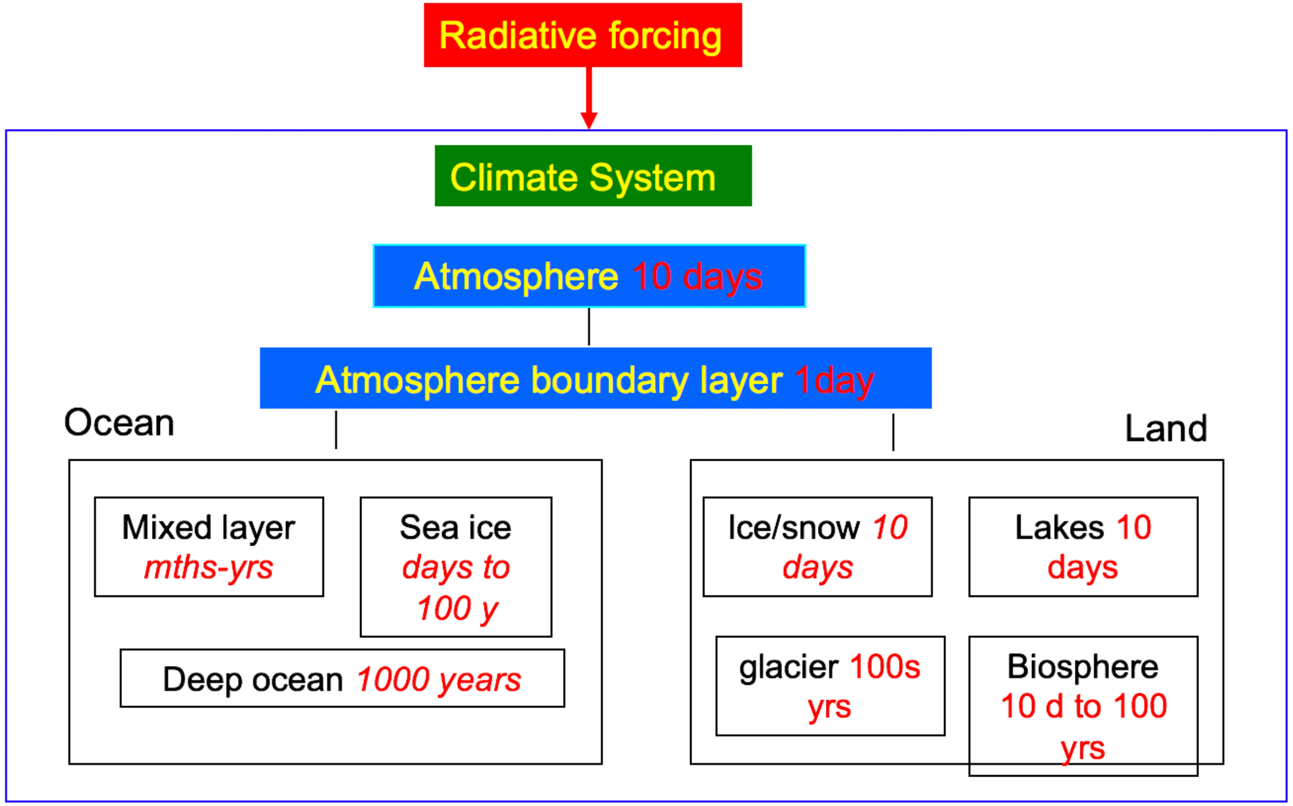
Zhu et al., 2021, GRL



https://eos.org/research-spotlights/ice-age-testing-reveals-challenges-in-climate-model-sensitivity

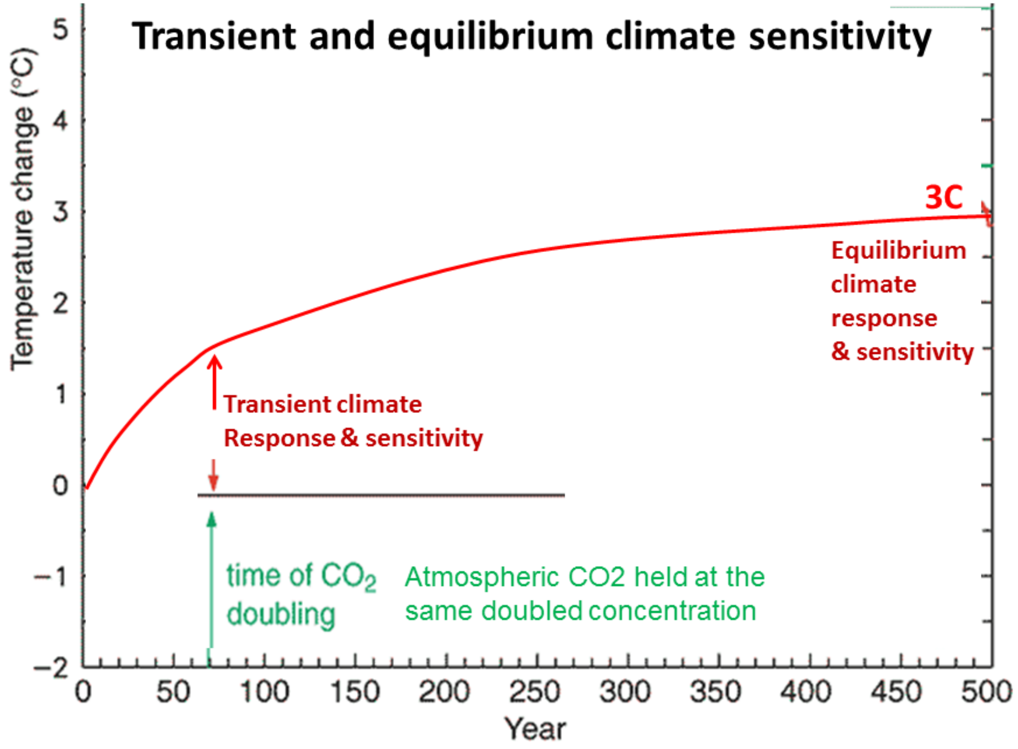
10.5 气候敏感性的估计

Equilibrium Climate Sensitivity (ECS)
Transient Climate Response (TCS)



10.5 气候敏感性的估计

Equilibrium Climate Sensitivity (ECS)
Transient Climate Response (TCR)



1%/yr increase of CO2, ~70yrs 2XCO2

Model	Transient Climate Response	Equilibrium Climate Sensitivity
CM2.1	1.5 K (Randall et al 2007)	3.4 K (Stouffer et al 2006)
ESM2M	1.3 K (Flato et al 2013)	3.3 K (Paynter et al 2018)
ESM2G	1.1 K (Flato et al 2013)	3.3 K (Krasting et al 2018)
CM3	2.0 K (Flato et al 2013)	4.8 K (Paynter et al 2018)
CM4	2.1 K (Winton et al submitted)	5.0 K (Winton et al submitted)
ESM4	1.6 K (Dunne et al in prep)	3.2 K (Dunne et al in prep)

总结

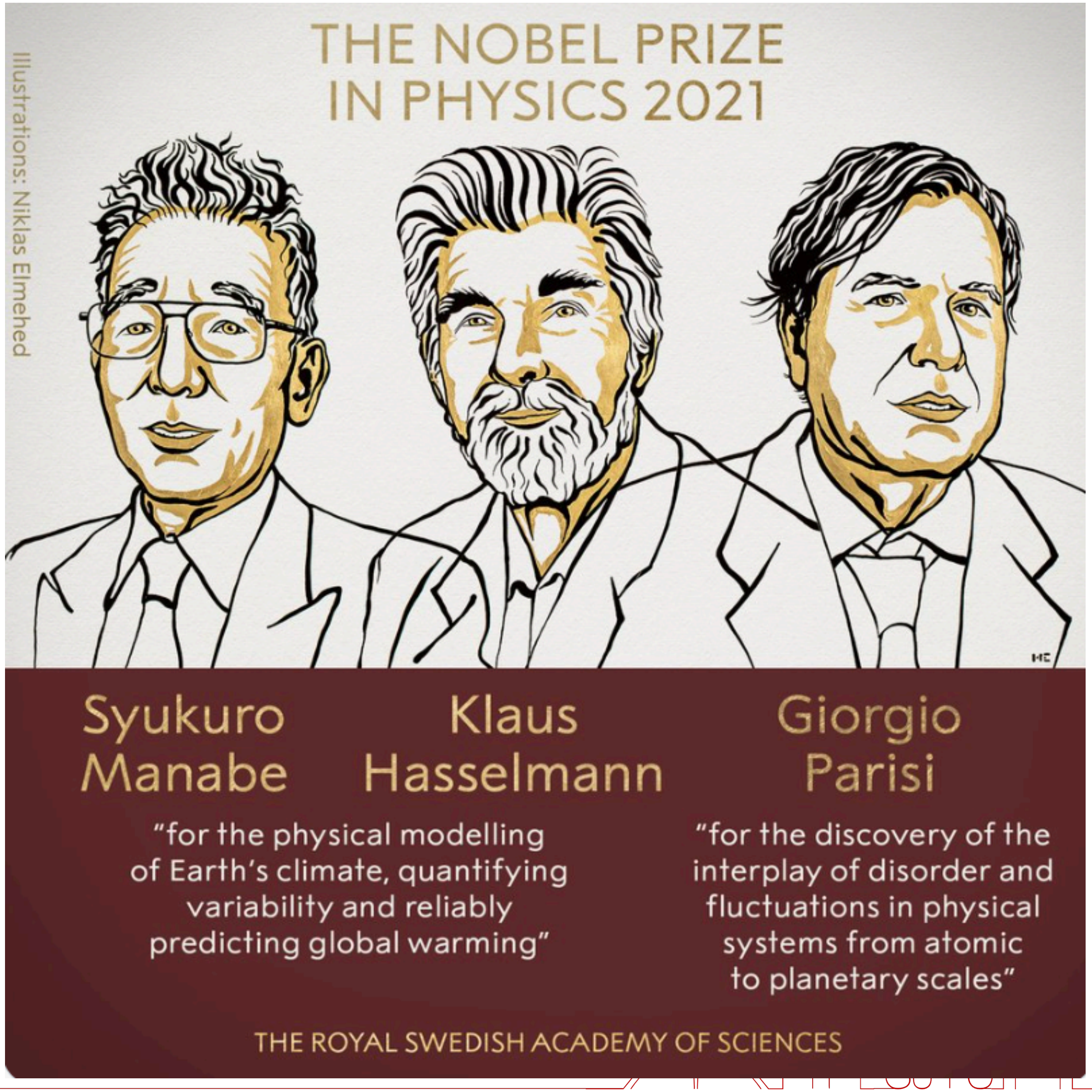
- 气候系统和气候强迫；
- 气候系统的反馈机制：

Planck (-)(利用能量平衡模型进行估计), water vapor (+), lapse rate (-), ice albedo (+), cloud (?)

- 什么是气候敏感性；气候敏感性的估计方法，各自的优缺点？

Syukuro Manabe:
利用气候模式再现气候系统中各个过程的相互作用，为预测温室气体排放对气候的影响奠定基础。

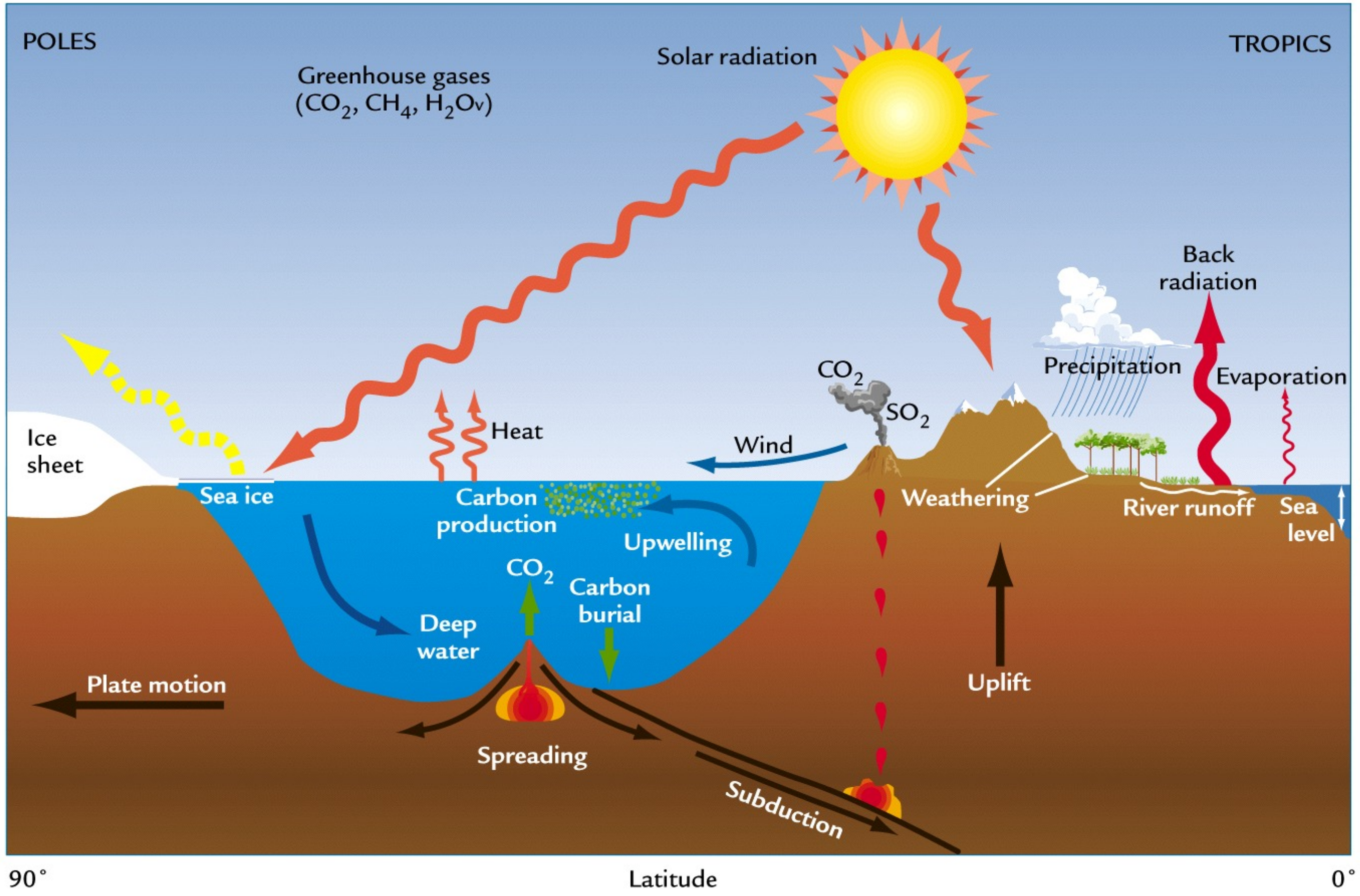
Klaus Hasselmann：
揭示了如何在高频的混沌天气过程中预测气候系统的变化， 奠定了气候变化的检测和归因工作的基础。



- Why we need a Climate Model?
- What models are available?
- Why simple models?
- How to evaluate models?
- Challenges in Numerical Climate Model
- Applications in Climate Science

Why we need a Climate Model?

Complex Climate System

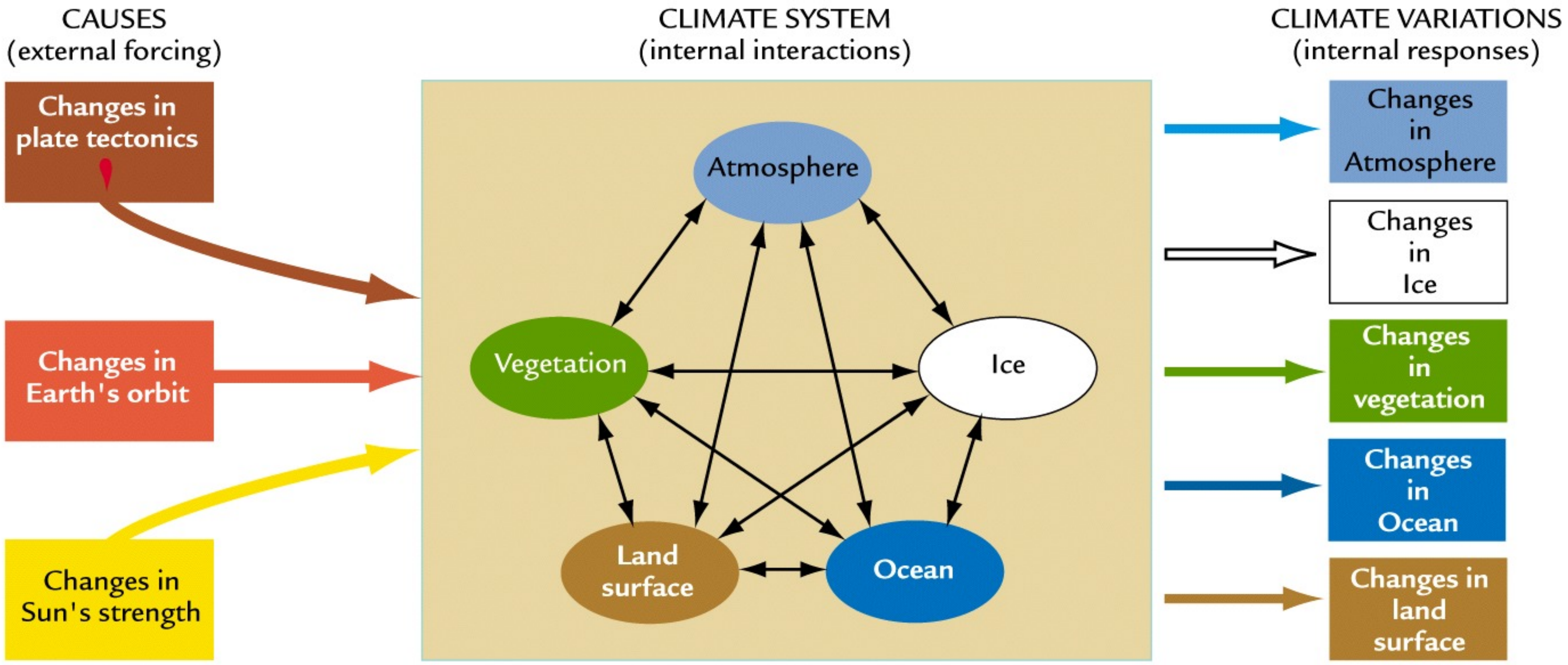


<u>主要组成部分：</u>
大气圈，水圈，冰冻圈，生物圈（植被），岩石圈（土地）

<u>主要过程：</u>
能量循环，水循环，碳循环……

Why we need a Climate Model?

- 帮助理解气候的因果关系



Why we need a Climate Model?

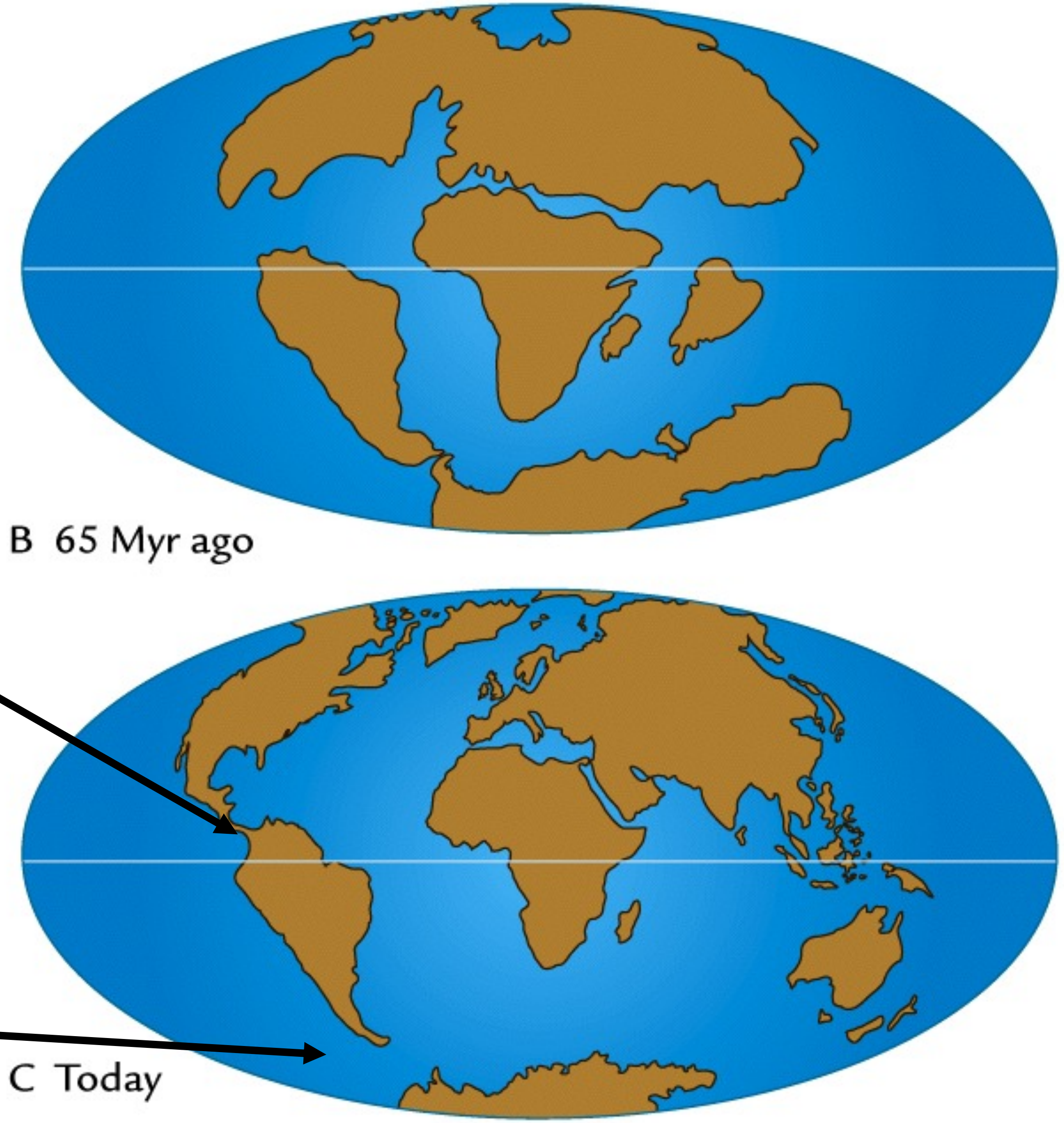
- **检验假说**

5000万年前气候为什么变冷？

Ocean Gateway Hypothesis

巴拿马海峡的关闭的形成（10-4Myr）使温暖/盐度高的海水向北, 阻碍海冰生成,促进蒸发从而促进北极陆地冰川形成。
但是模式模拟发现相反的作用(热量传输)。

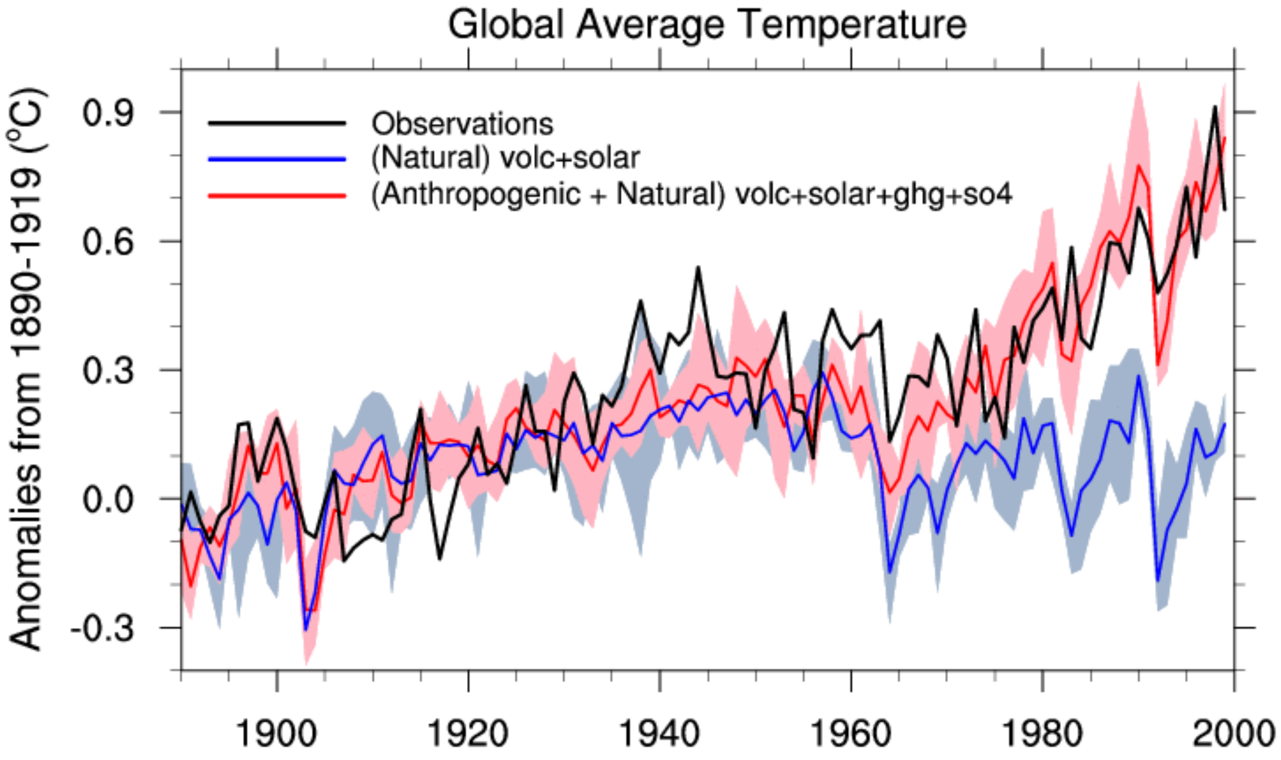
Drake Passage的形成（20Myr）影响向极地的热量输送，导致南极冰川。
但是模式模拟发现此作用效果不明显。



Why we need a Climate Model?

- **定量衡量不同机制**

Global temperature: Anthropogenic or Natural?



Mechanisms in lowering LGM CO_2

Table 3. Mechanism Contributions to Glacial Atmospheric CO_2 Changes

Mechanism	Simulated ΔCO_2 After Carbonate Compensation, ppmv	Proxy Data in Support of the Model Results
	Mechanisms Well Supported by Proxy Data	
Circulation and SST	−43	oceanic $\delta^{13}C$ [*Duplessy et al.*, 1988; *Curry and Oppo*, 2005]
Sea level	12	oceanic $\delta^{18}O$, corals [*Lambeck and Chappell*, 2001; *Waelbroeck et al.*, 2002]
Nutrient utilization in sub-Antactic, Atlantic and Indian oceans	−37	Cd/P, ^{15}N, $\delta^{13}Si$, [*Elderfield and Rickaby*, 2000; *Kohfeld et al.*, 2005]
Land carbon	15	pollen records and oceanic $\delta^{13}C$ [*Bird et al.*, 1994; *Crowley*, 1995; *Joos et al.*, 2004]
Shallow water carbonate sedimentation	−12	carbonate sediments and corals [*Milliman*, 1993; *Milliman and Droxler*, 1996]
Subtotal	−65	
	Less Certain Mechanisms	
10% decrease in weathering	2	
20% decrease in rain ratio	−15	
Nutrients utilization in subantarctic Pacific Ocean	−7	
Total	−85	

Why we need a Climate Model?

- 预测未来