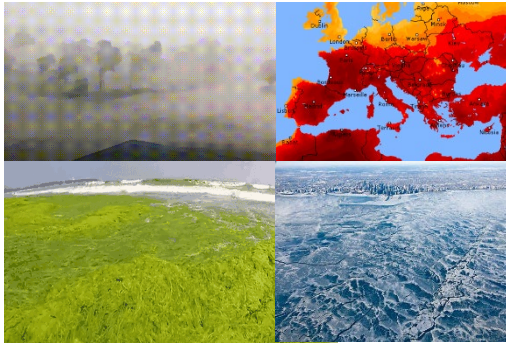
大气科学与海洋科学

现实主义 ⟷ 魔幻现实主义 ⟷ 理想主义



每日/月/年 ⟷ 某日/月/年 ⟷ 有日/月/年

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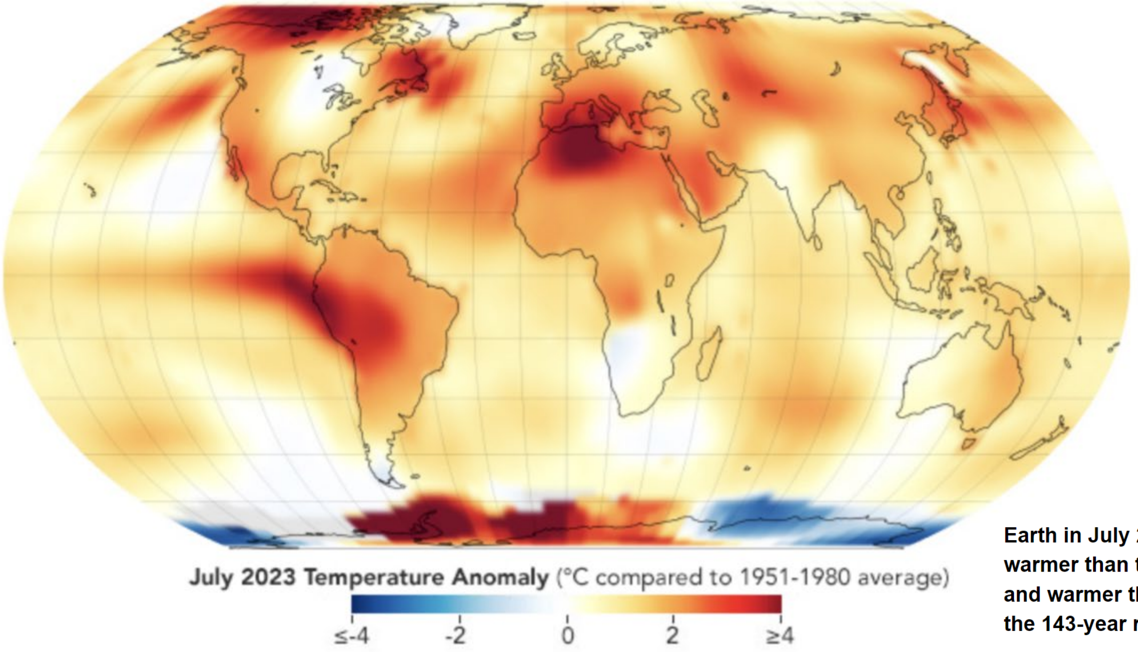
热浪与心浪：高温时代，如何安放我们的气候焦虑？

杨海军
https://corp.fudan.edu.cn

复旦大学大气与海洋科学系/大气科学研究院

2025年11月13日

July 2023 Was the Hottest Month on Record



Earth in July 2023 was 1.18°C (2.12°F) warmer than the average for the month, and warmer than any other month in the 143-year record.

NASA/GSFC/Scientific Visualization Studio
https://www.giss.nasa.gov

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A Rapid Rising Greenhouse Gases

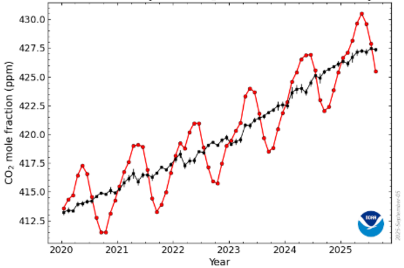
June 2025: 425.83 ppm
June 2024: 423.22 ppm
Last updated: Sep 05, 2025

May 2025: 1933.54 ppb
May 2024: 1925.71 ppb
Last updated: Sep 05, 2025

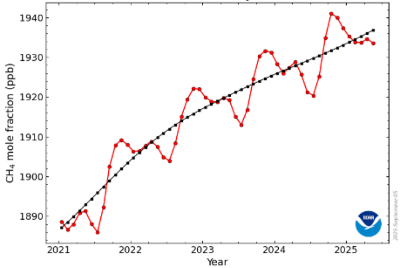
May 2025: 338.66 ppb
May 2024: 337.66 ppb
Last updated: Sep 05, 2025

May 2025: 12.20 ppt
May 2024: 11.77 ppt
Last updated: Sep 05, 2025

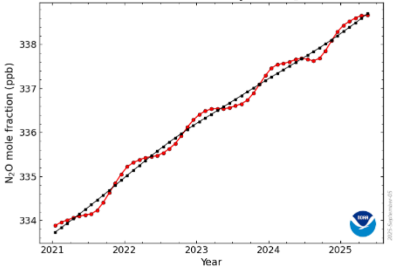
Recent Monthly Mean CO_2 at Mauna Loa Observatory



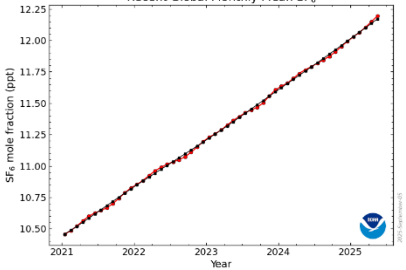
Recent Global Monthly Mean CH_4



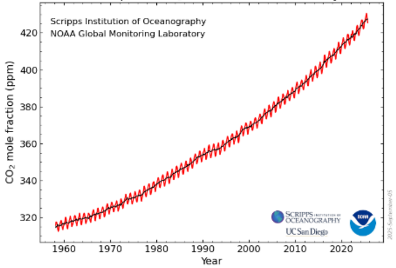
Recent Global Monthly Mean N_2O



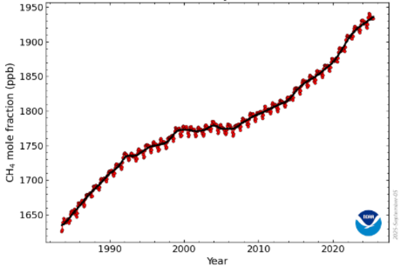
Recent Global Monthly Mean SF_6



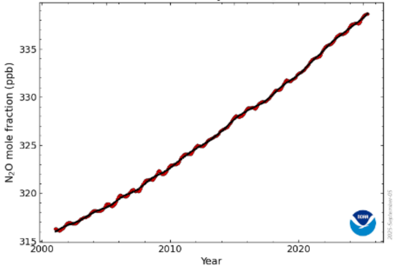
Atmospheric CO_2 at Mauna Loa Observatory



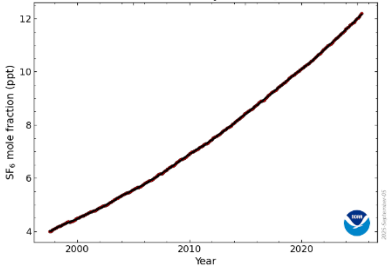
Global Monthly Mean CH_4



Global Monthly Mean N_2O



Global Monthly Mean SF_6



https://www.esrl.noaa.gov/gmd/ccgg/trends/gr.html

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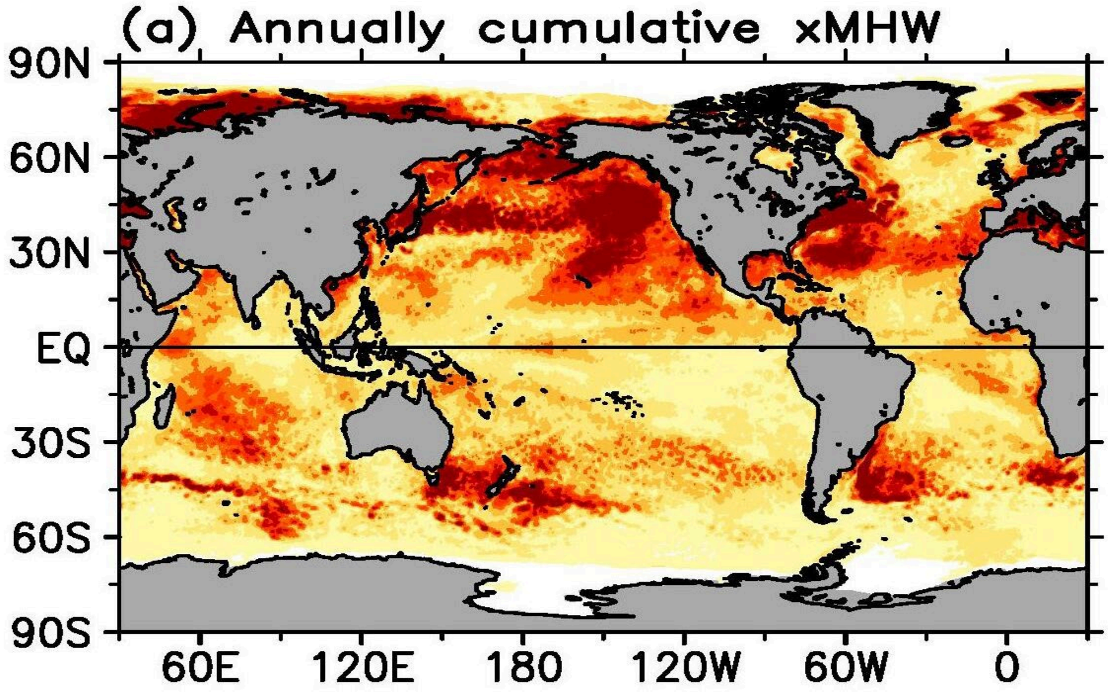
极端海洋热浪发生的海域



Huang et al. (2025)

NOAA Environmental Satellite and Information Service | National Centers for Environmental Information

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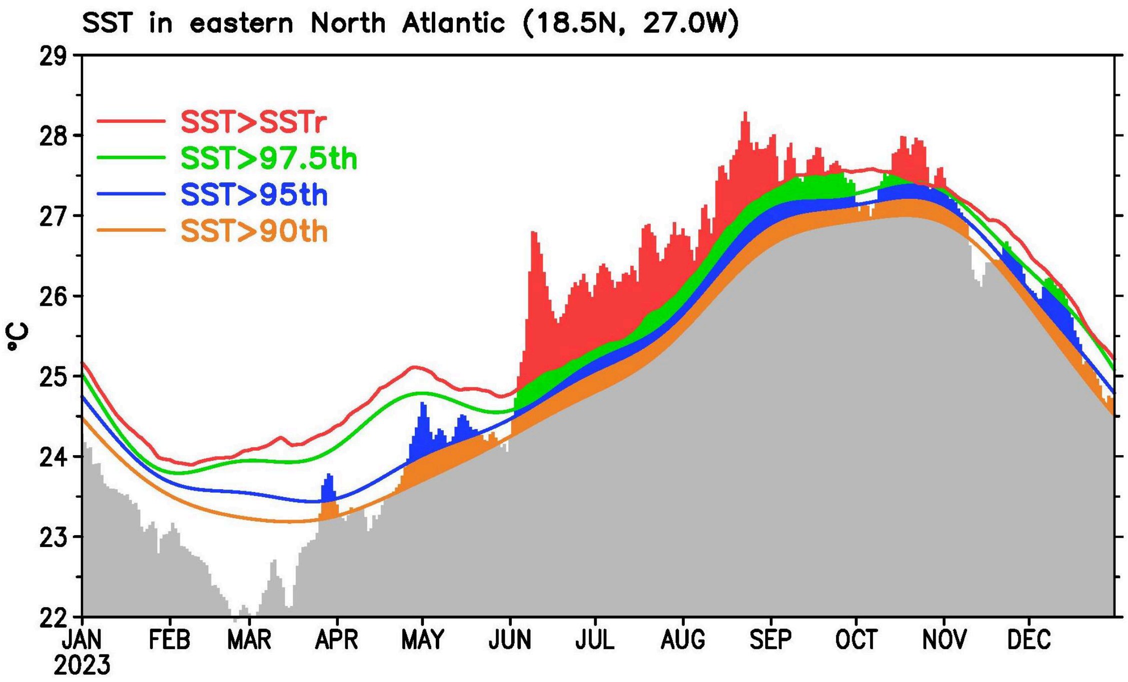
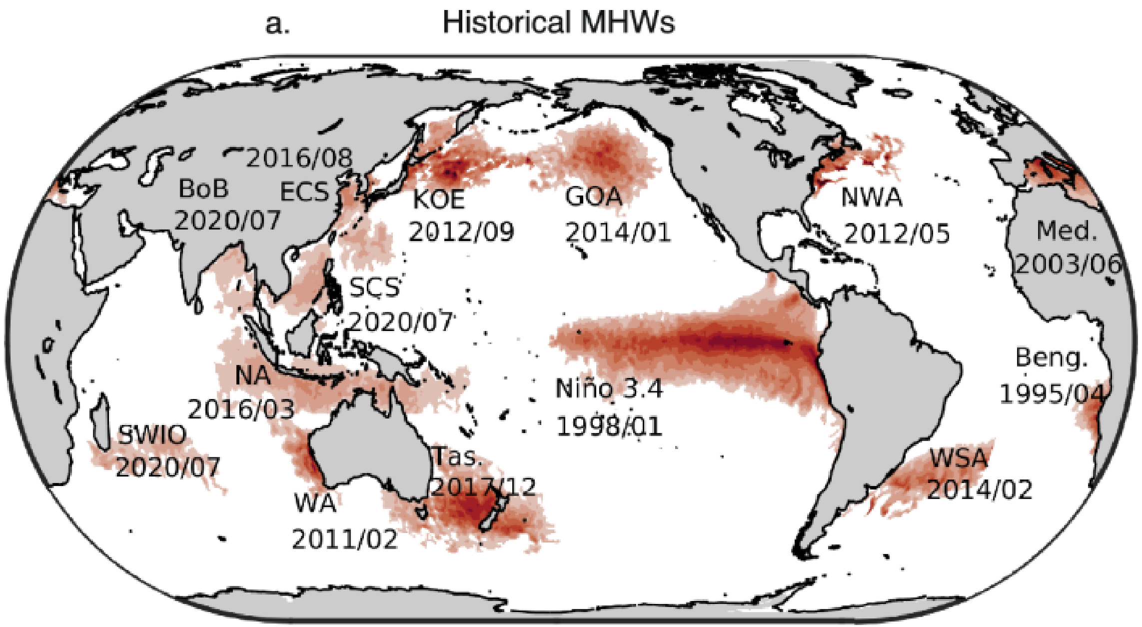
An xMHW (SST>SSTr) in NE. Atlantic (18.5N, 27.0W) in 2023



Huang et al. (2025)

历史上一些极端海洋热浪



Capotondi et al. (2024)

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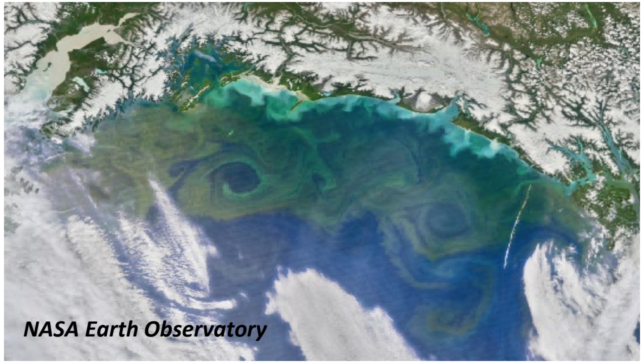
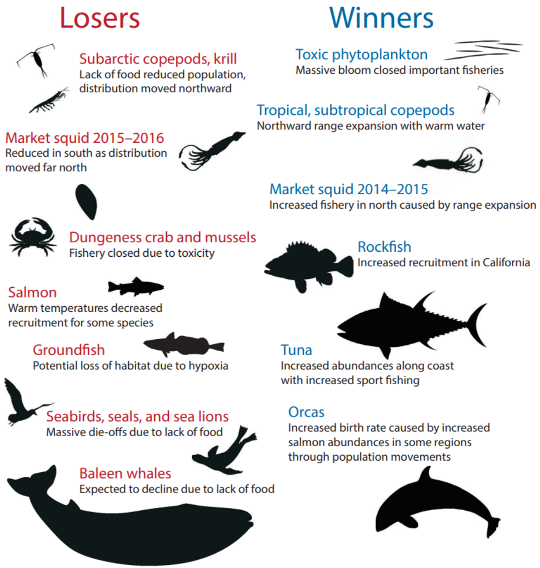
海洋热浪的环境及生态影响



harmful algal blooms
decreased primary productivity



alterations in marine species

Shi et al. (2025)

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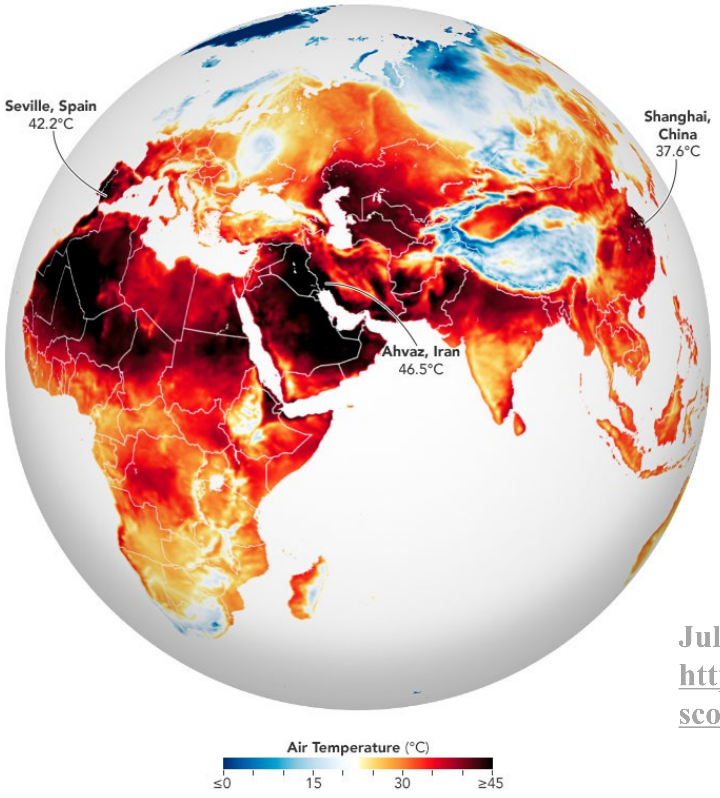
全球各地极端热浪事件同时发生



"China and western North America were both roasting in hotter-than-normal temperatures in late July, at the same time as Europe."

Witze (2022, Nature)

July 13, 2022

https://earthobservatory.nasa.gov/images/150083/heatwaves-and-fires-scorch-europe-africa-and-asia

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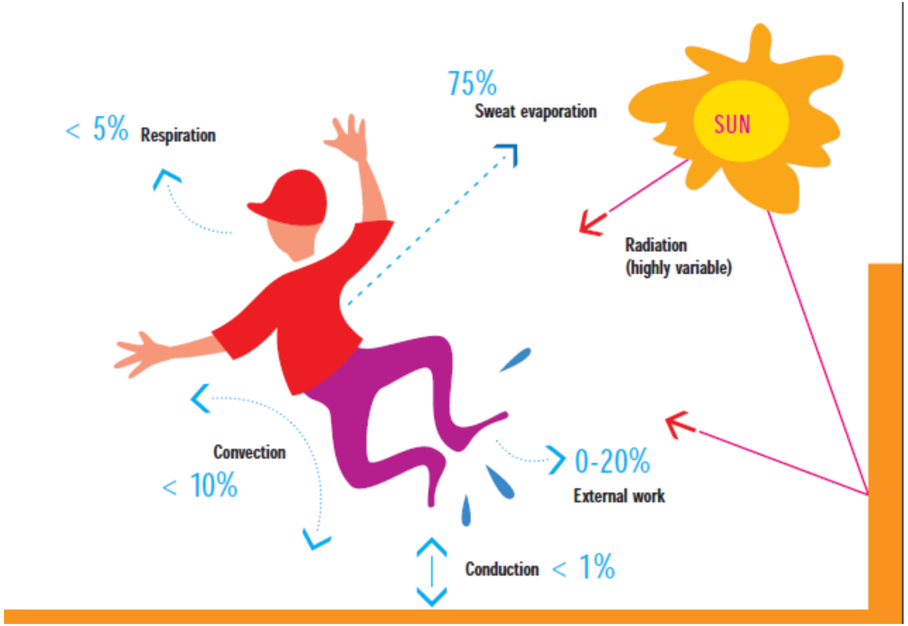
高温高湿对人体带来双重危害

Humid-heat is called "silent killer"



High humidity → Sweat hardly evaporate → Core body temperature increases → Thermal damage

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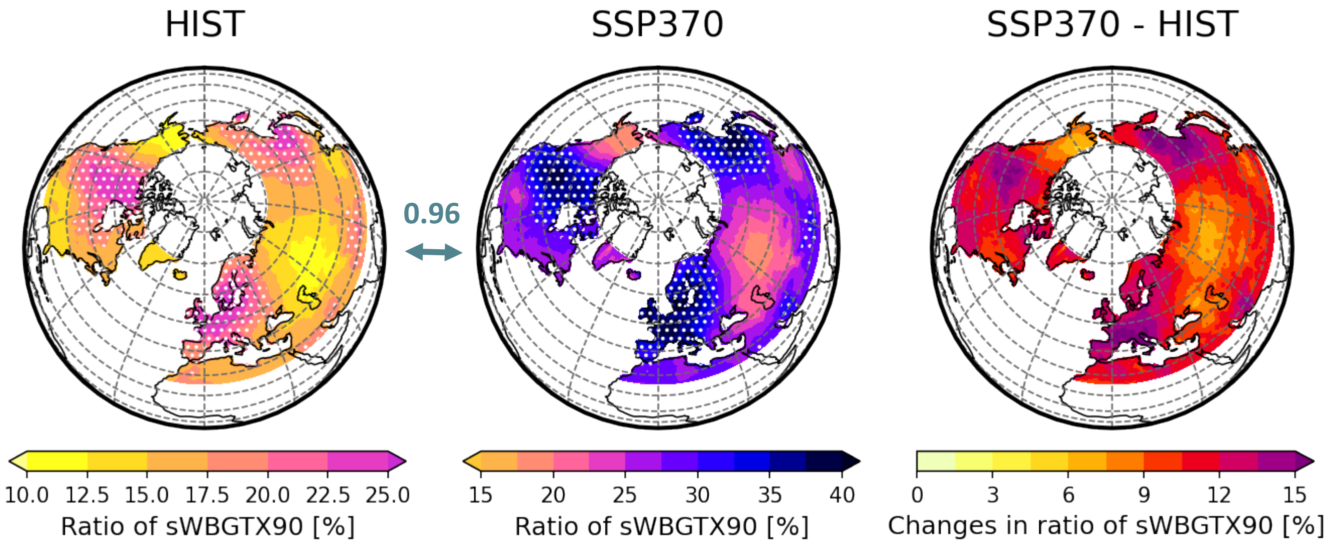
极端湿热浪事件的未来预估



空间型态基本不变

发生频率增加强度加大

Lin, Yuan* et al. (2025, GRL)

我们该怎么办？

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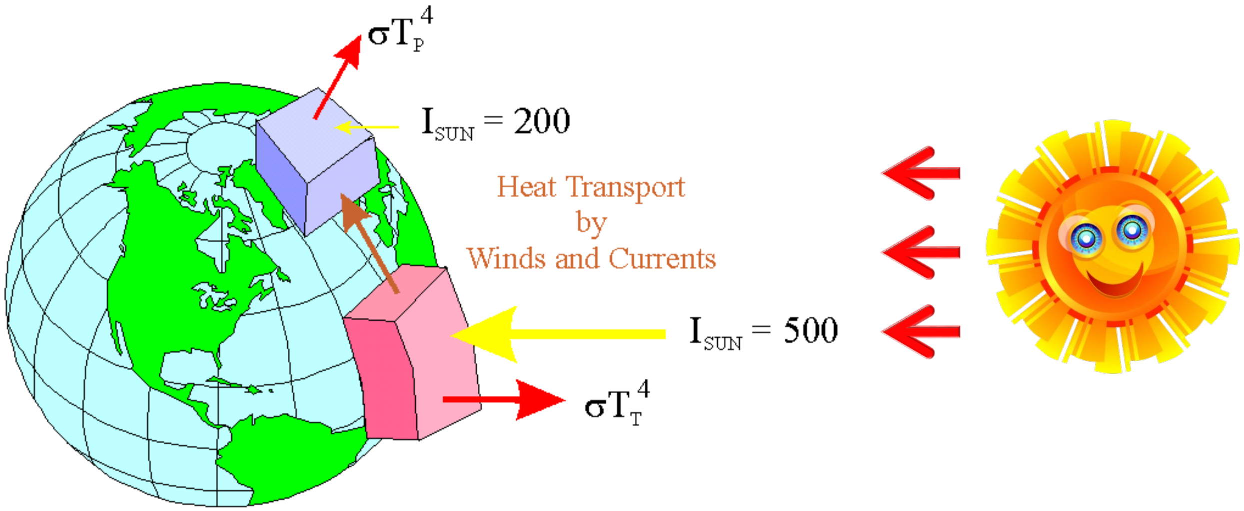
回到根本：理解地球热量平衡



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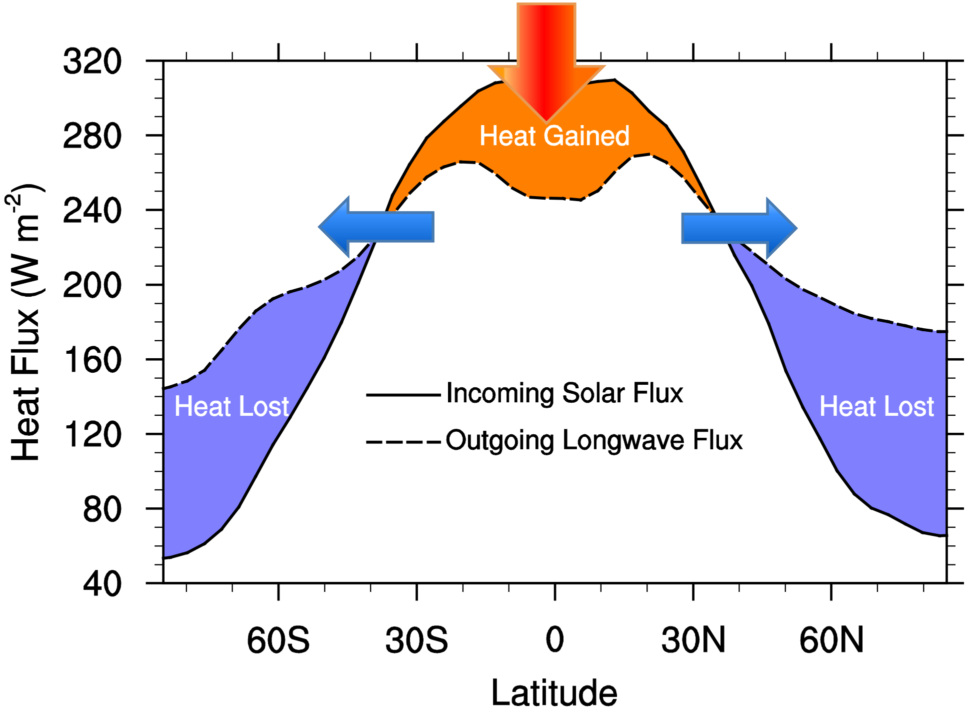
大气层顶的热量收支



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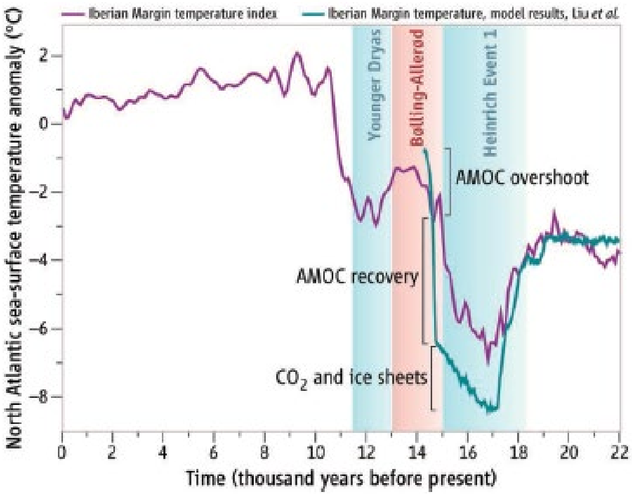
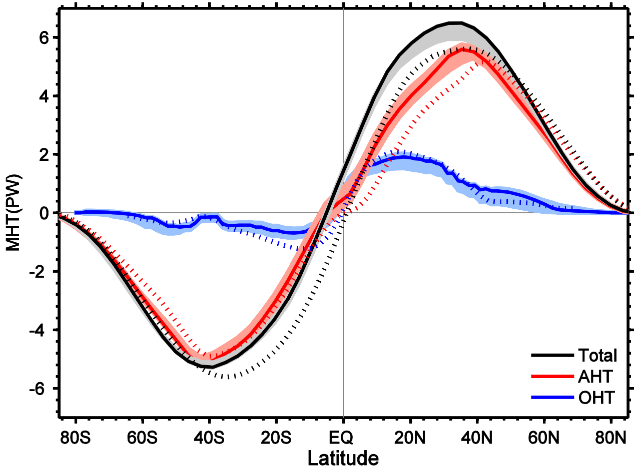
地球气候稳定的能量约束

Earth Climate Stability Mechanism?



Climate Change during Past 22 kyr

Timmermann (2009), Science



MHT from CCSM3 simulation TraCE-21K, From LGM to present

Liu et al. (2009); He (2011)

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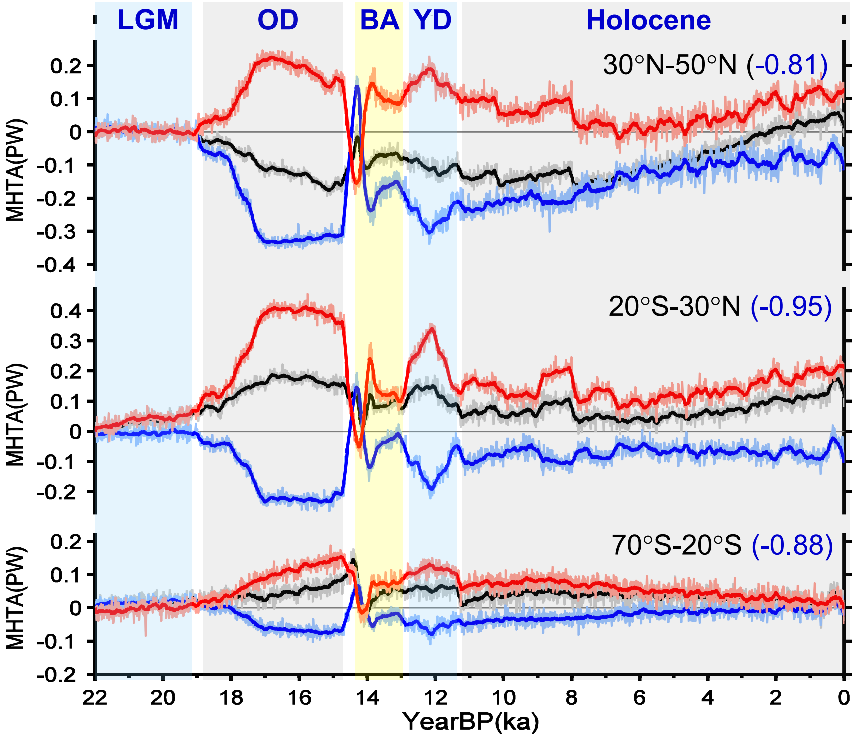
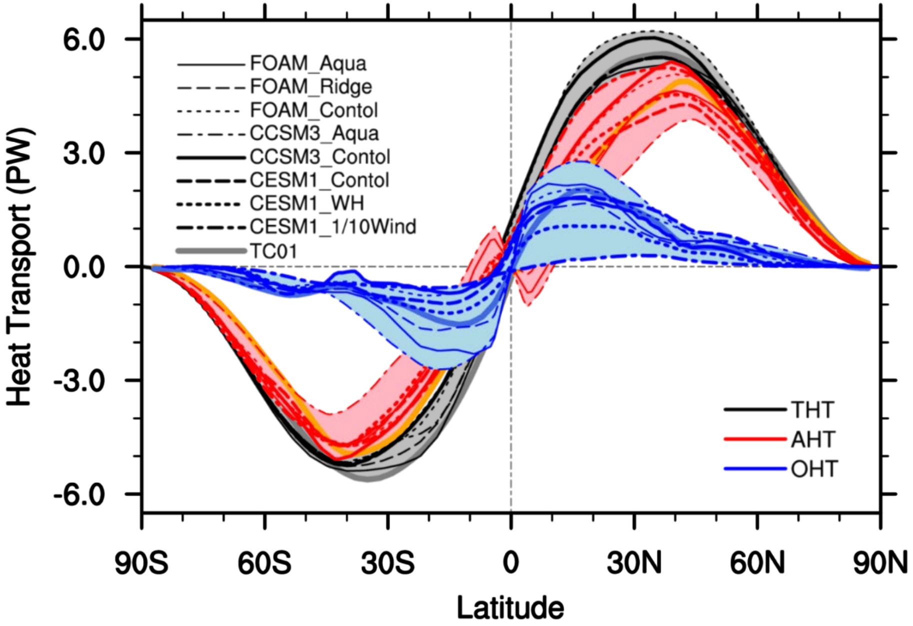
地球气候稳定的能量约束



Yang et al. (2015)

大气海洋能量经向输送互相补偿



Note: TC01 is from Trenberth and Caron (2001)

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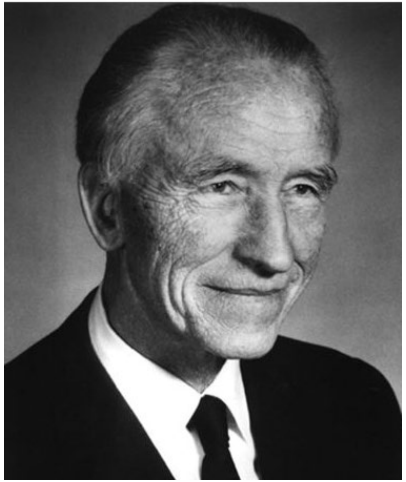
Bjerknes补偿假说

Jacob Aaal Bonnevie Bjerknes
1897-1975



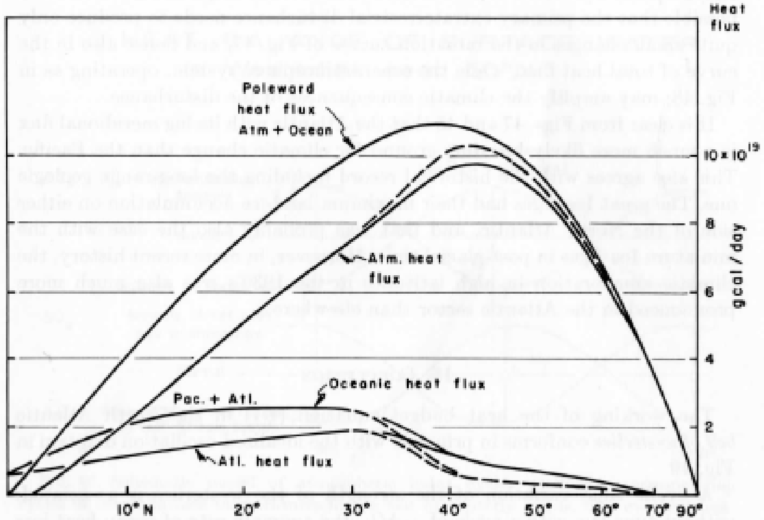
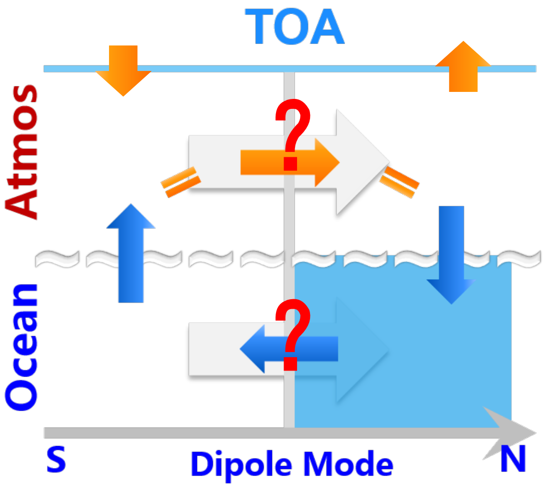


FIG. 48. Solid lines: flux data from Fig. 47 pertaining to present climatic conditions. Dashed lines refer to a sketchy model of the conditions around 1800 A.D. and show qualitative estimate of curtailed Atlantic and total oceanic heat flux as well as increased heat flux by low index atmospheric circulation. The anomalies of heat flux in oceans and atmosphere are assumed to cancel, leaving total heat flux and radiation budget unchanged. Actually, some change in the radiation budget is also likely to have taken place, but it could well have been quite small.

Bjerknes, 1964: Atlantic Air-Sea Interaction, Advances in Geophysics, Vol. 10, P77

Bjerknes补偿假说



$A + B = 0 \rightarrow A = -B$

but $A + B + C = 0$ C: climate feedback

Then $A = -(B+C)$

Energy Conserved

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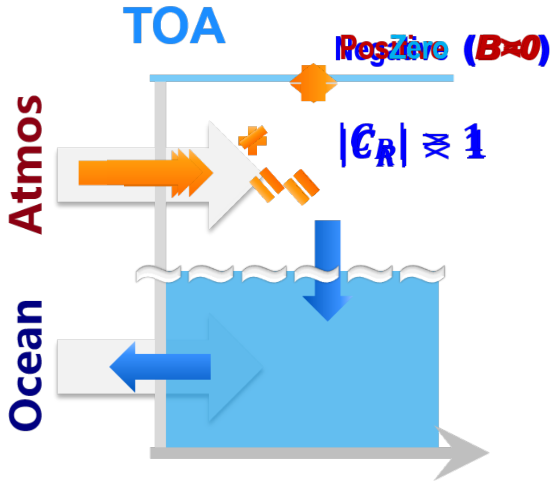
耦合地球气候系统的本征模态



$$C_R \equiv \frac{\Delta F_a}{\Delta F_o} = -\frac{1}{1-B} < 0$$

Local climate feedback $B(y)$

Yang, Zhao and Liu (2016)
Zhao, Yang and Liu (2016)

Climate Feedback + MHT ➔ Earth Energy Balance

耦合地球气候系统的本征模态

能量补偿 ⇔ 体重保持

饮食
(海洋)

运动
(大气)

新陈代谢
(气候反馈)

$$C_R = -\frac{1}{1-B}$$

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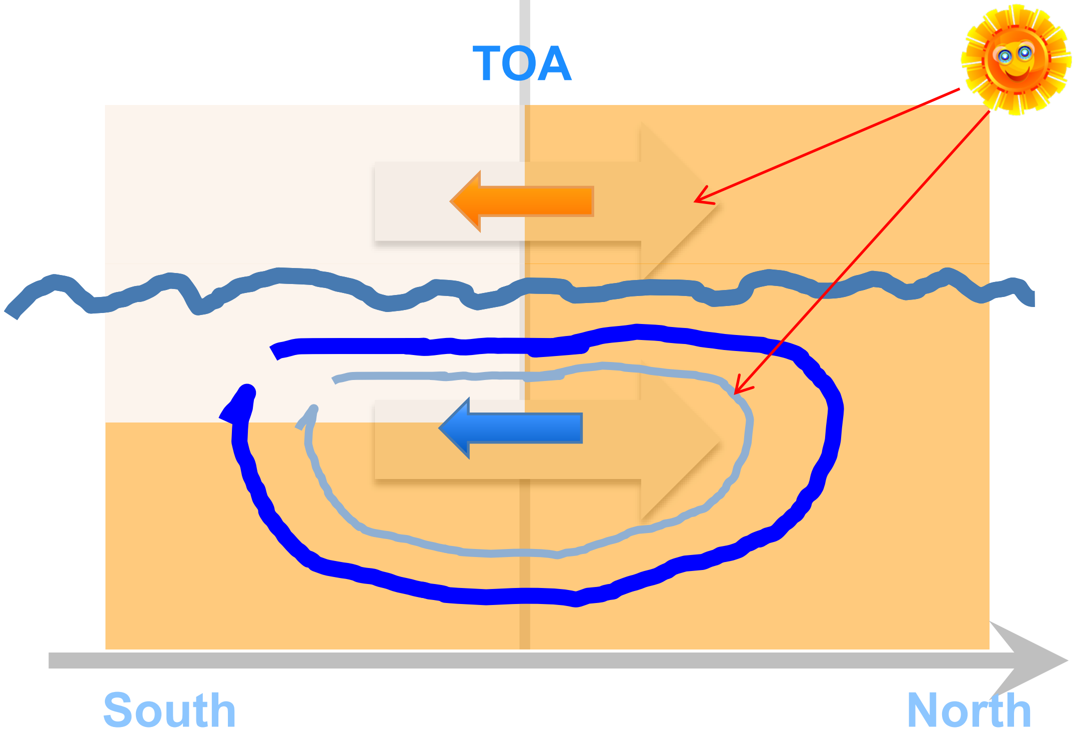
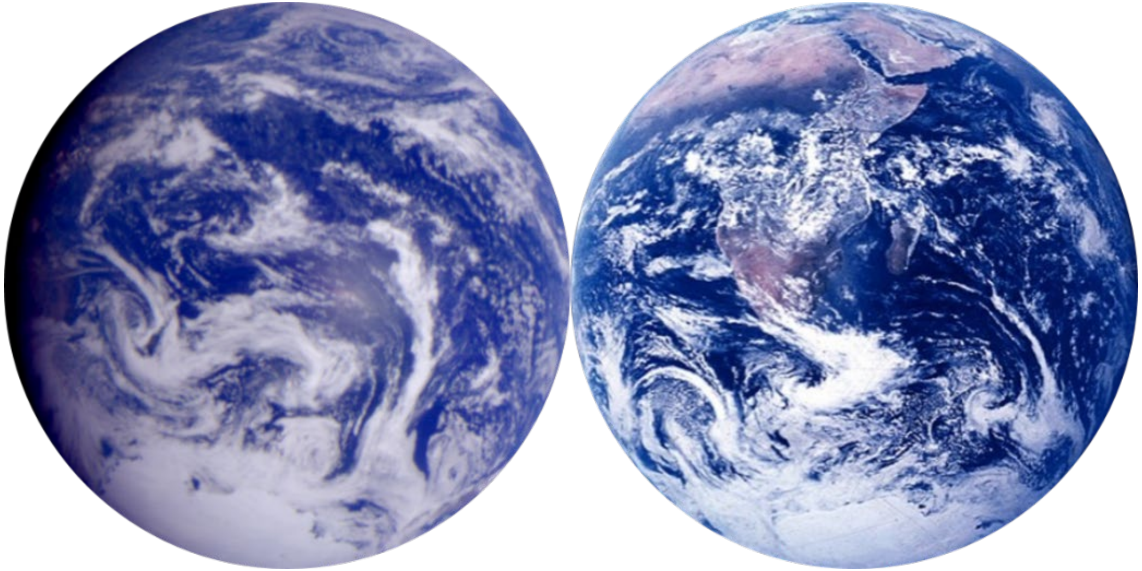
全球变暖打破了能量守恒约束

$$C_h \equiv \Delta H_a/\Delta H_o = \{1/[1+(B_2\text{-}B_1)\ \Delta A/\Delta T_S[B_1B_2+(B_1+B_2)\chi]]\}\ C_R$$



希望在海洋?



Aqua-Planet: 71% covered by ocean

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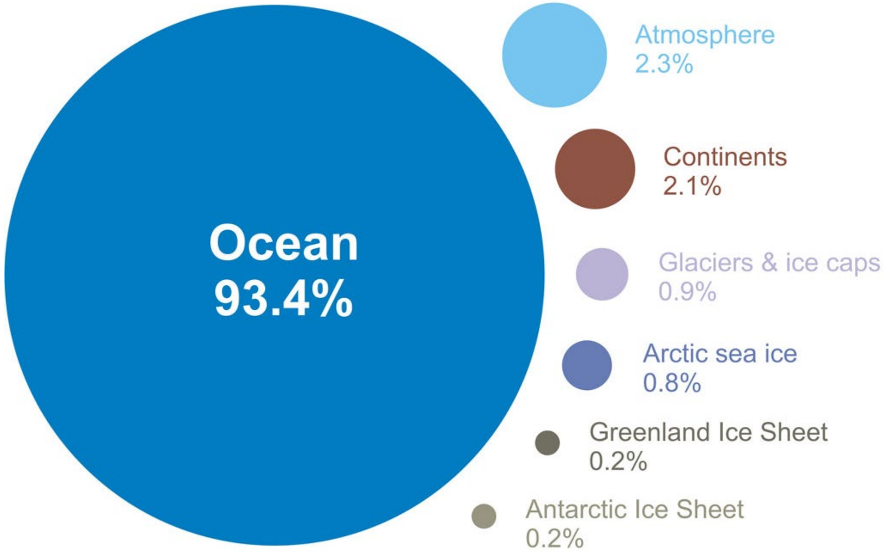
海洋：全球变暖缓冲器

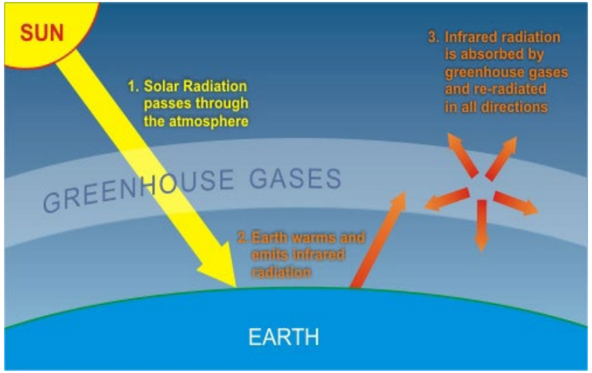


S. Levitus, J. I. Antonov, T. P. Boyer,O. K. Baranova,H. E. Garcia,R. A. Locarnini,A. V. Mishonov,J. R. Reagan,D. Seidov,E. S. Yarosh, and M. M. Zweng | published 17 May 2012

海洋：全球变暖缓冲器

Resulted from

Heating | **Hosing**



Decoding Hosing and Heating Roles in a Warming Climate

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海洋：全球变暖缓冲器

Lapse Rate

Dry Air: $\Gamma_d = g/c_p = 9.8$ °C/km

Wet Air: $\Gamma_w = \ldots\ldots = 6\text{-}7$ °C/km

30%

Latent Heat: Solid —334J/g→ Liquid —2260J/g→ Gas

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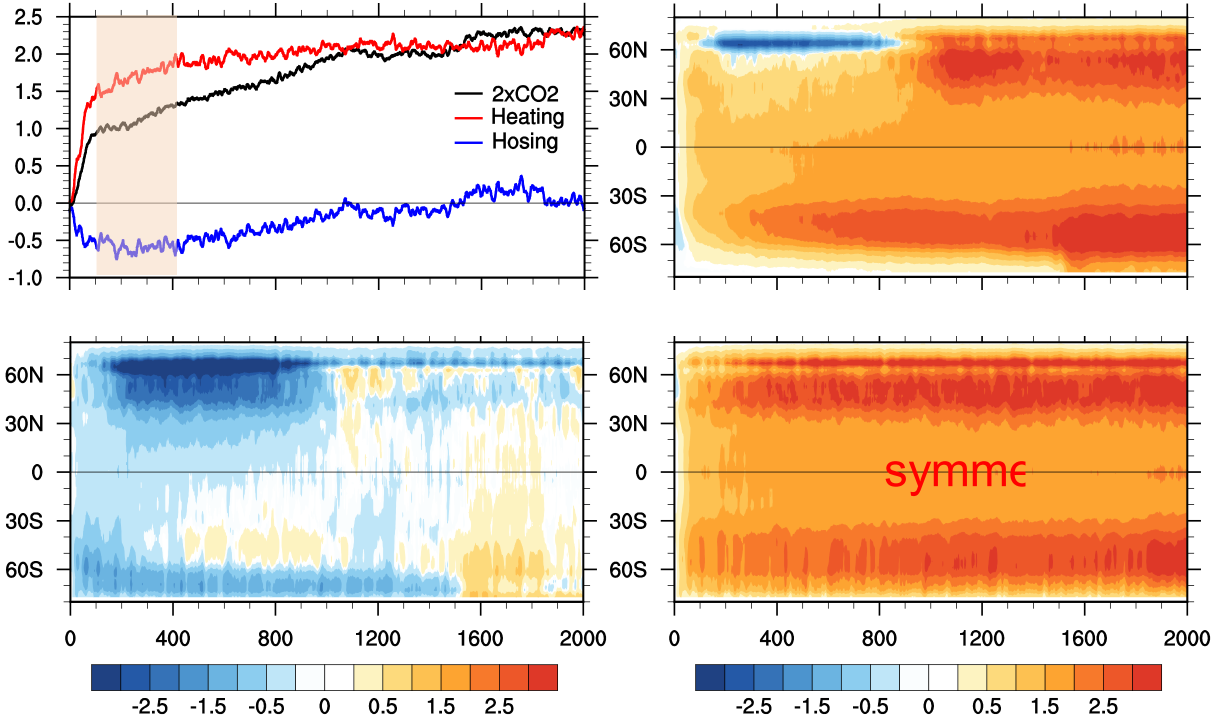
模拟的未来全球气温演变



Wen et al. JC, (2018)

我们该怎么办？

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植树造林？

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植树造林？

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植树造林？

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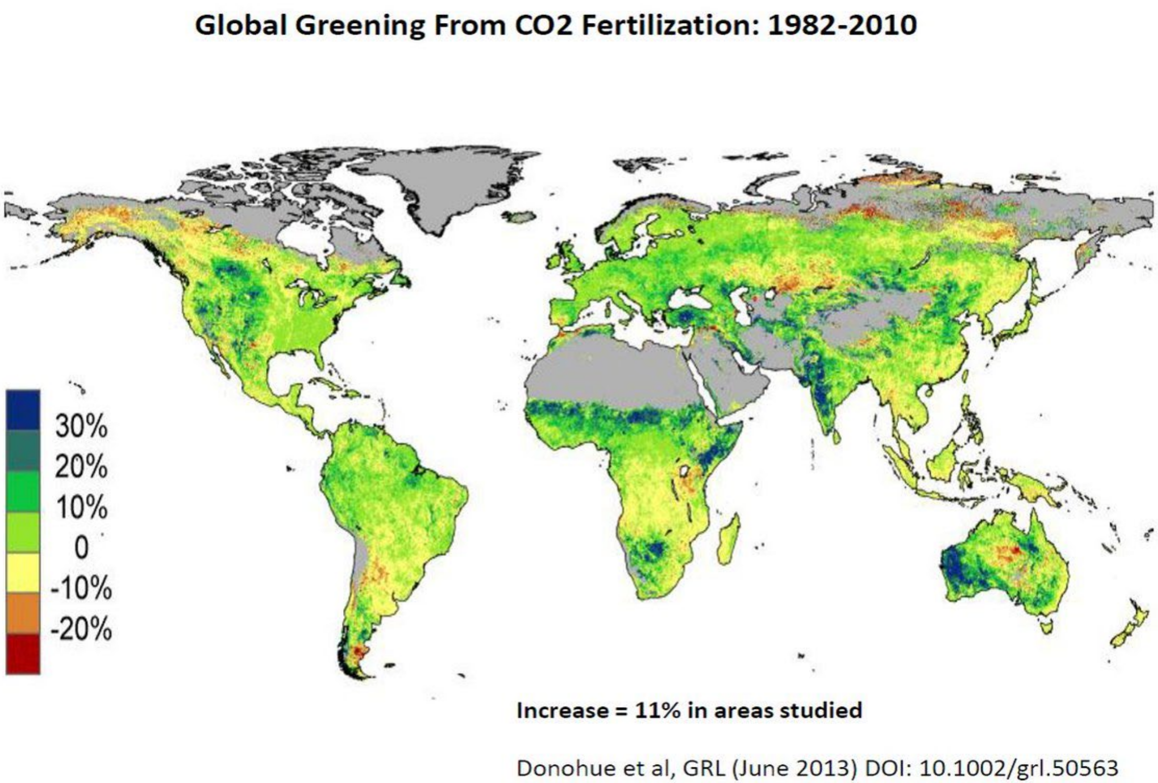
撒哈拉沙漠有变率趋势？



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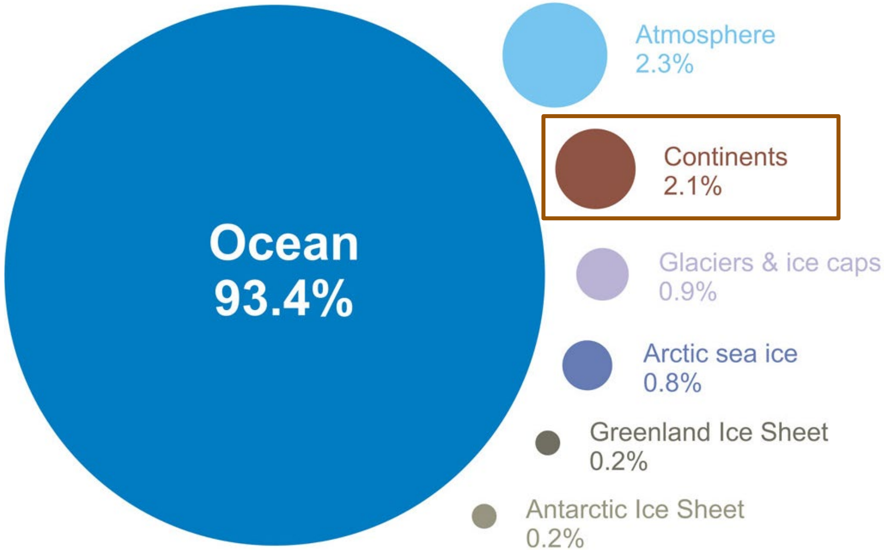
海洋：全球变暖缓冲器



S. Levitus, J. I. Antonov, T. P. Boyer,O. K. Baranova,H. E. Garcia,R. A. Locarnini,A. V. Mishonov,J. R. Reagan,D. Seidov,E. S. Yarosh, and M. M. Zweng | published 17 May 2012

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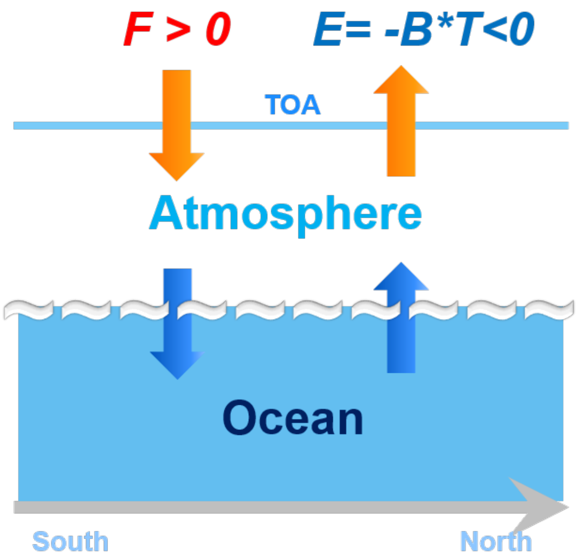
能量平衡模式的启示：地球工程?



$$\frac{dT}{dt} = F - BT$$

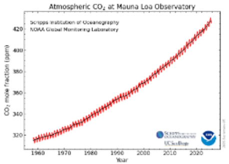
If F=const., T determined

by climate feedback B

Yang et al. CD, (2022)

能量平衡模式的启示：地球工程买时间

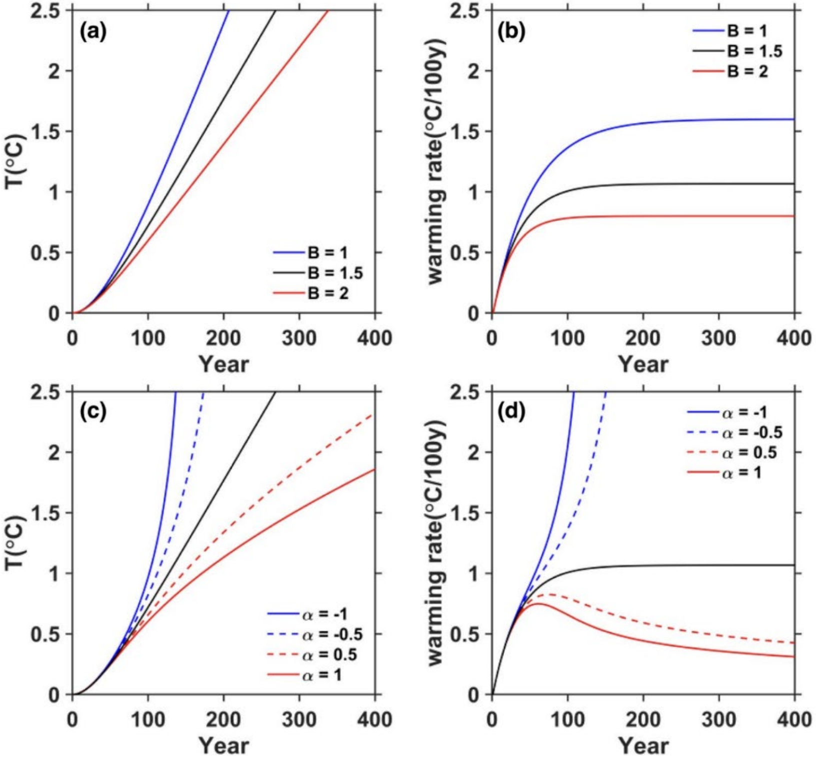
$$F = \varepsilon t; B = const.$$



$$T = \frac{\varepsilon}{B}\left(t - \frac{C}{B}\right) \to \infty, \frac{dT}{dt} = \frac{\varepsilon}{B}, \text{when} t \to \infty.$$

$$F = \varepsilon t; B = B_0 + \alpha T$$

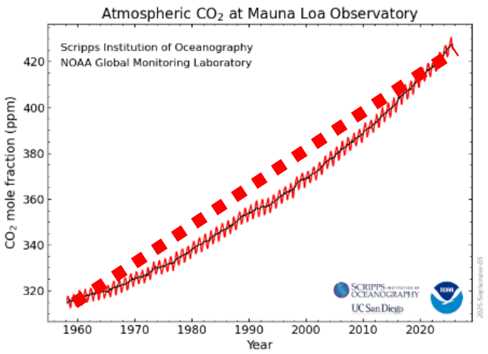
$$\begin{cases} T = -\frac{b}{2a} + \left(\frac{b^2}{4a^2} + \frac{K}{a}t\right)^{\frac{1}{2}} \to \infty \\ \frac{dT}{dt} = Kt - (b + aT)T \to 0 \end{cases}, \text{when } t \to \infty.$$

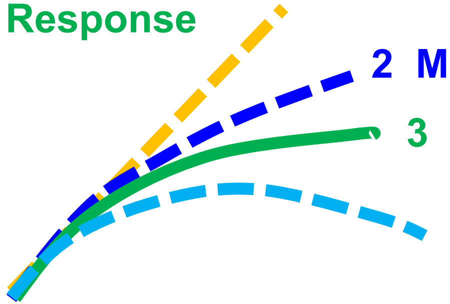


Yang et al. CD, (2022)

未来的几种可能性

Forcing





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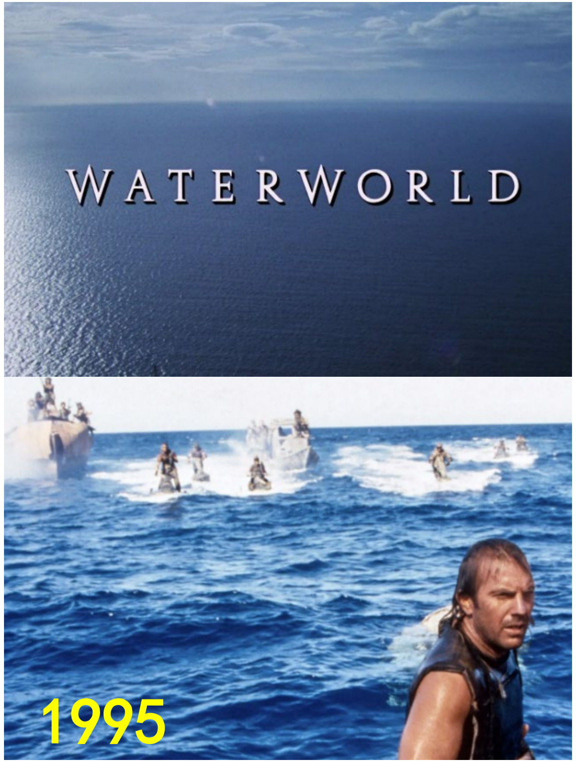
未来命运？



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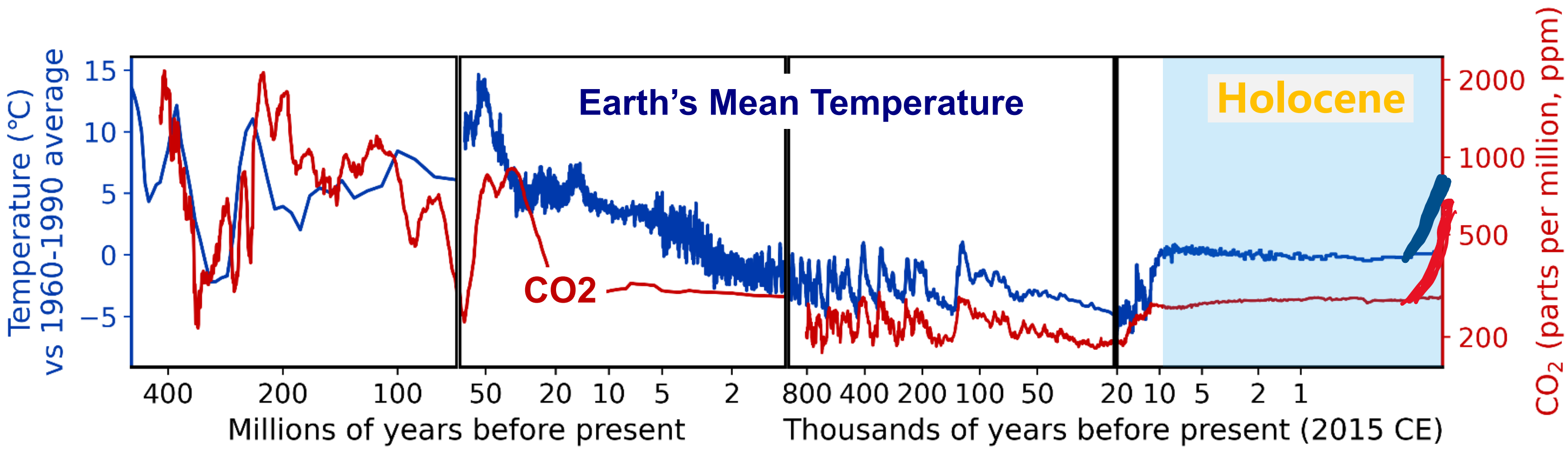
地球气候历史长河



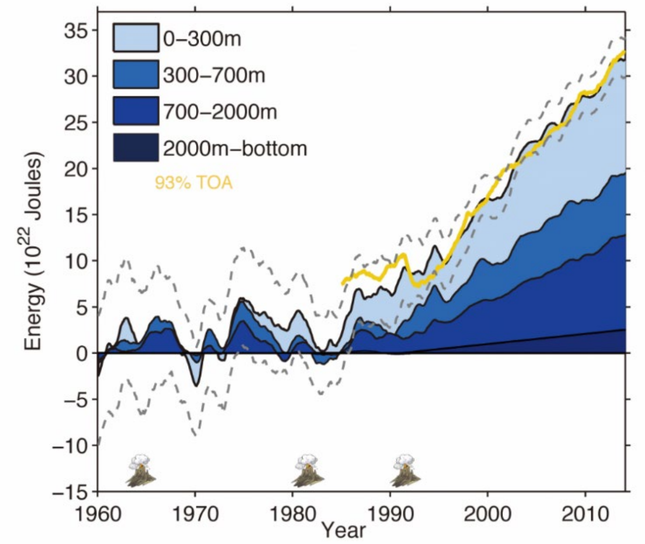
https://earth.org/data_visualization/a-brief-history-of-co2/

适应这个更“温暖”的星球！

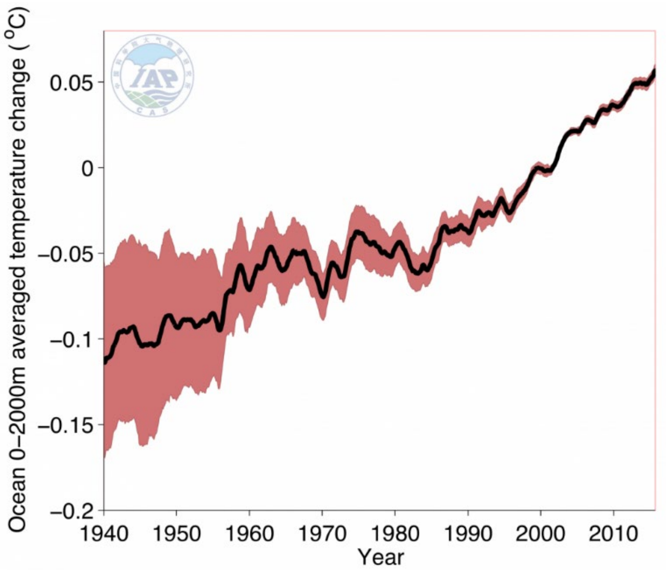
改变自己，创造美好未来！

https://corp.fudan.edu.cn

Ocean Heat Content Change



Ocean energy budget based on IAP ocean temperature analysis. The 93% of the energy imbalance observed from the top of atmosphere is shown in yellow. OHC change below 2000m is from Purkey and Johnson 2010. (contributed by L Cheng)



0-2000m averaged temperature change since 1940/01 to 2016/12 along with uncertainty estimates (95% confidence interval). (contributed by L Cheng)

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