Mitigating Global Warming: What Climate Feedback, Vertical Mixing and Ocean Circulation Can Do?

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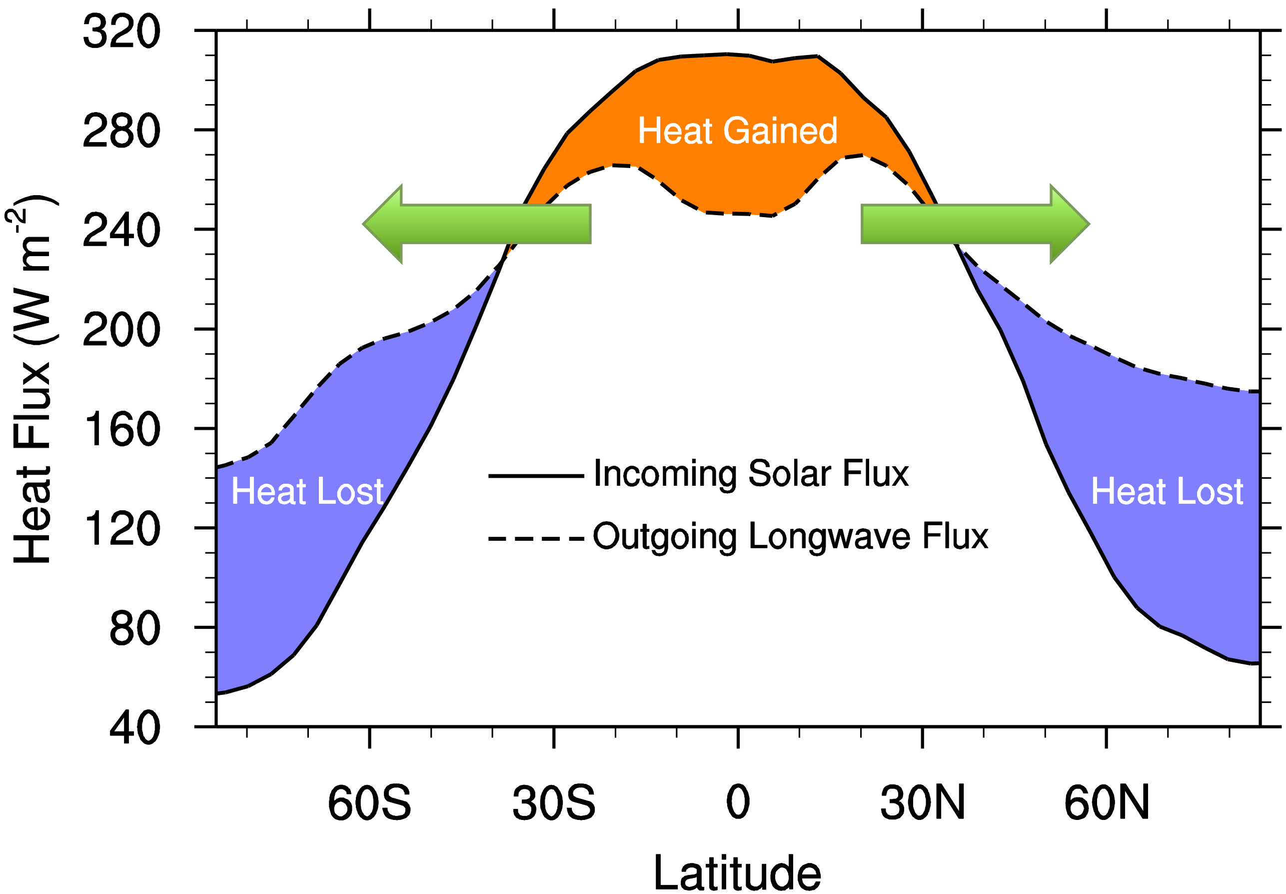
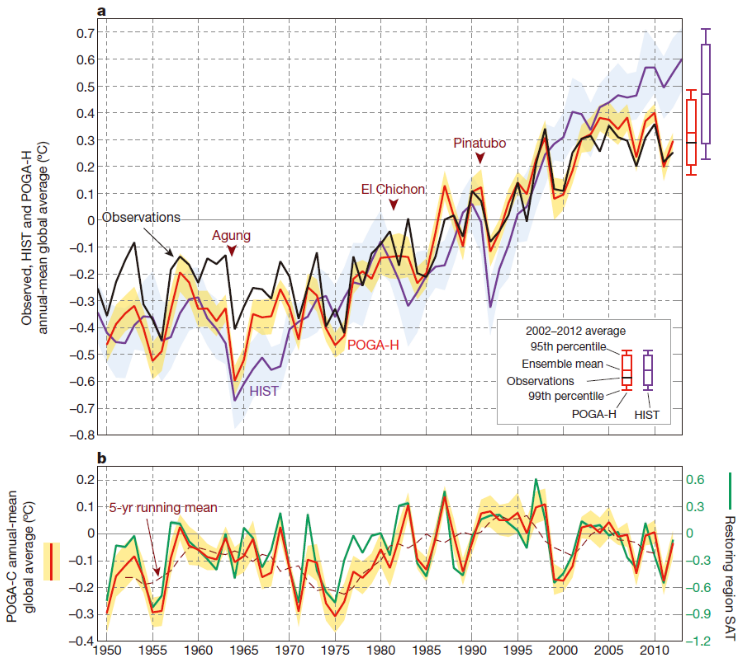
Heat Budget at the TOA

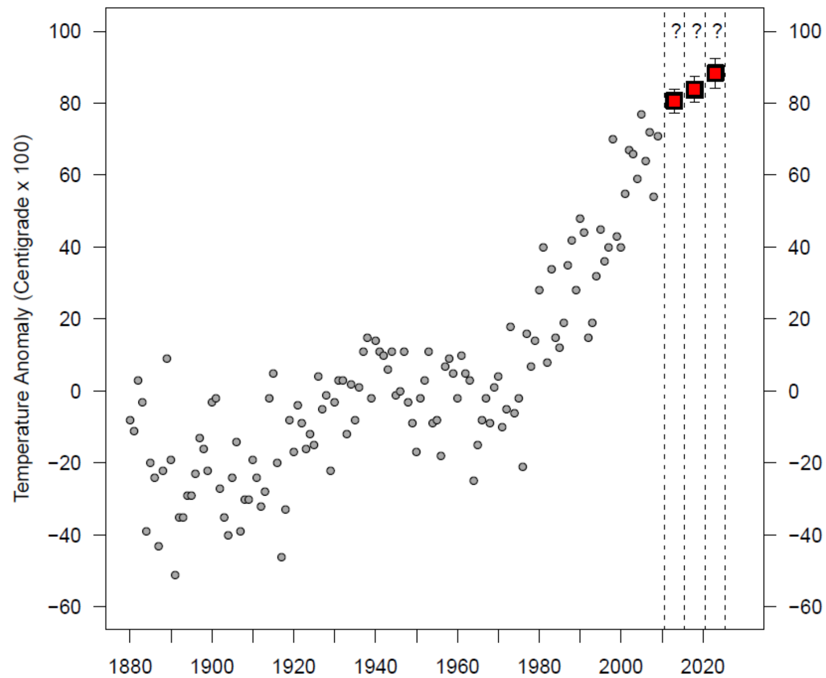


问题：到底有没有Hiatus？主流观点Yes（？）



Kosaka and Xie (2013) 模拟出了Hiatus，辐射强迫外+观测的赤道中东太平洋的降温。并认为Hiatus由自然变率（PDO负位相）造成。

问题：到底有没有Hiatus？主流观点Yes（？）



Lewandowsky (2016) 指出Hiatus的不确定。数据来自GISSTEMP（Hansen et al.，2010）和NASA Goddard Institute for Space Studies.

机制：年代际与长期趋势叠加，低纬降温是主因（？）

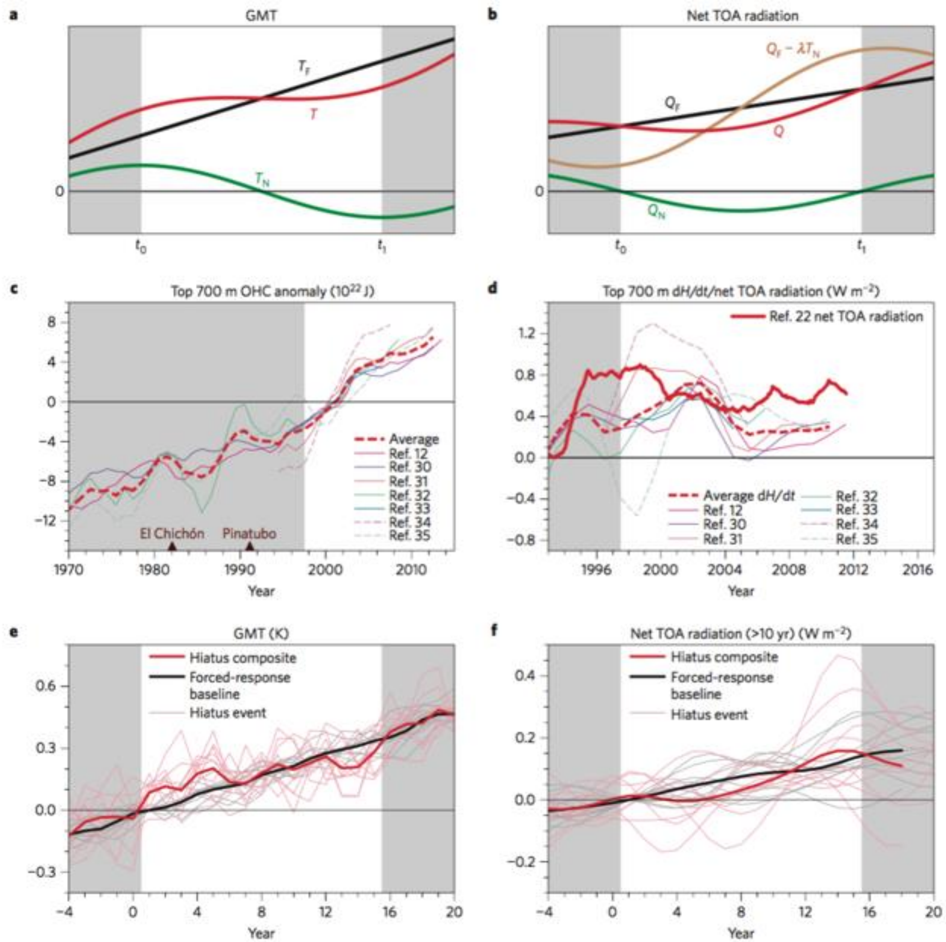


Figure 4 | GMT, TOA radiation and OHC during hiatus. a,b, Schematics of GMT (**a**) and TOA radiation (**b**). See main text for definitions. **c,d**, Observational estimates of OHC anomaly (**c**) and its tendency with reconstructed TOA radiation (**d**). **e,f**, GMT (**e**) and TOA radiation (**f**, ten-year low-pass filtered) for 'hiatus' events in a global-warming simulation. Thin pale and thick red curves represent individual hiatus events (years 1–15) and their average, respectively. Each thin pale black curve is the ten-member ensemble average for one of ten hiatus events, approximating the forced-response baseline. The thick black line is the average of the thin black lines. Ensemble means are adjusted to zero at year 1. TOA radiation deviation of hiatus events from the baseline is −0.0115 ± 0.0353 W m^{-2}.

Xie et.al（2016）从全球能量平衡的角度研究了气候反馈率对hiatus的作用，ΔT=强迫温差+自然变率。图中考虑T_N在多年际尺度上的变化，可以假设T_N呈以2（$t_1 - t_0$）为周期的三角函数分布，叠加在持续增大的T_F之上，如果在$t_0 < t < t_1$时间段内，恰巧T_N处于下降的阶段，那么两者叠加可能会造成hiatus。

机制：年代际与长期趋势叠加，低纬降温是主因（？）

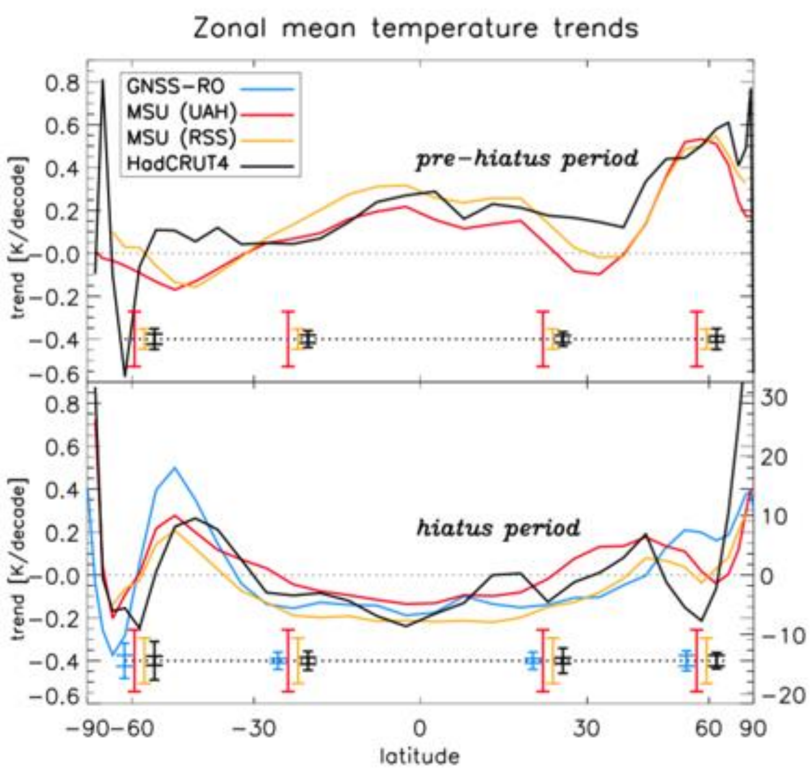
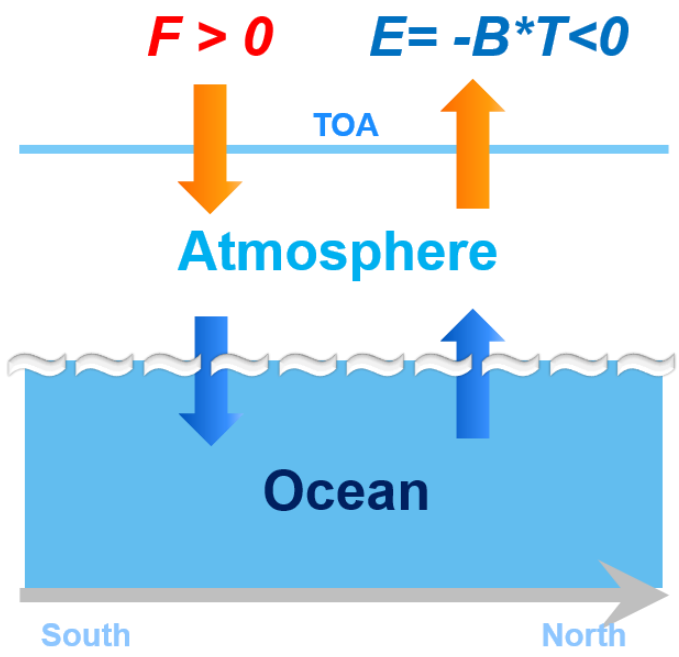


Figure 3. Surface and tropospheric temperature trends in 5° latitude bands for (top panel) the prehiatus period 1985–1997 and (bottom panel) the hiatus period 2002–2013. Error bars (for clarity shown displaced from the observed data) indicate the ±1σ observational uncertainties for the decadal trends. For RO and surface data, estimates of the combined observational and structural uncertainties are indicated by extended error bars. The abscissa has been scaled to reflect the decreasing area per latitude bin toward higher latitudes.

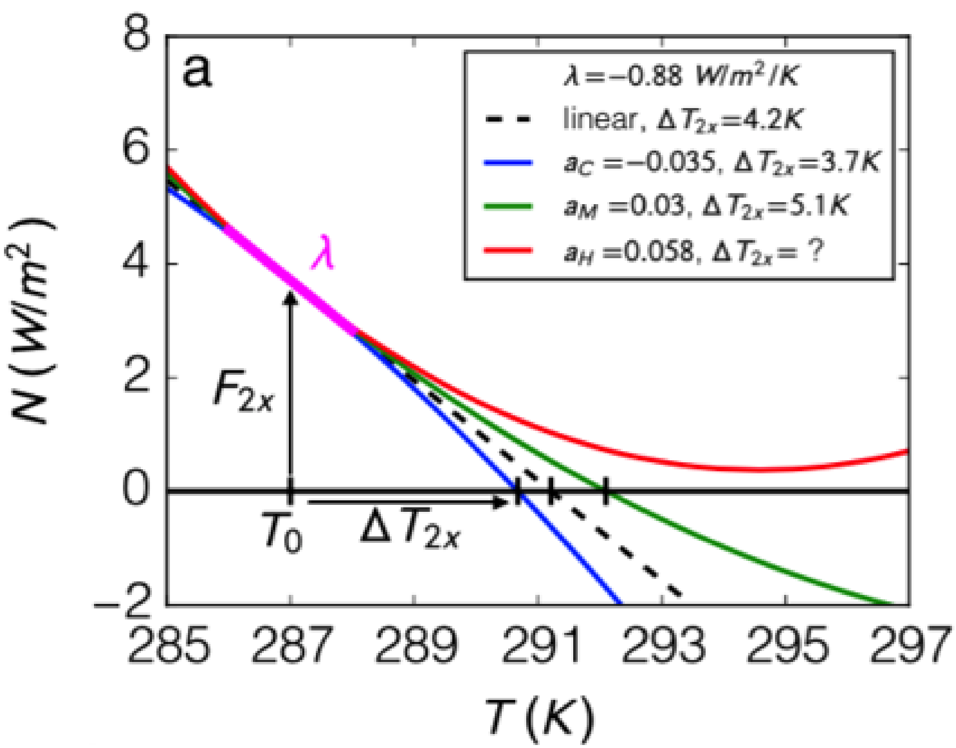
Gleisner et al. (2014) 发现pre-hiatus时期，三个序列都呈现出除了南半球热带外存在温度负异常以外，其他地区都为正异常或零异常；hiatus时期全球分布基本一致，热带为负异常，70° N以北为正异常，南半球中高纬正异常，极地负异常。观测说明低纬的降温是hiatus的主因。

假说：气候反馈和海洋吸热的变化→Hiatus (?)



Solomon et al. (2010); Kaufmann et al. (2011)

Runaway和气候反馈



气候反馈随温度增加而加强时（红线）温度变化就会失控

（Block-Johnson et al., 2015）

Runaway和气候反馈

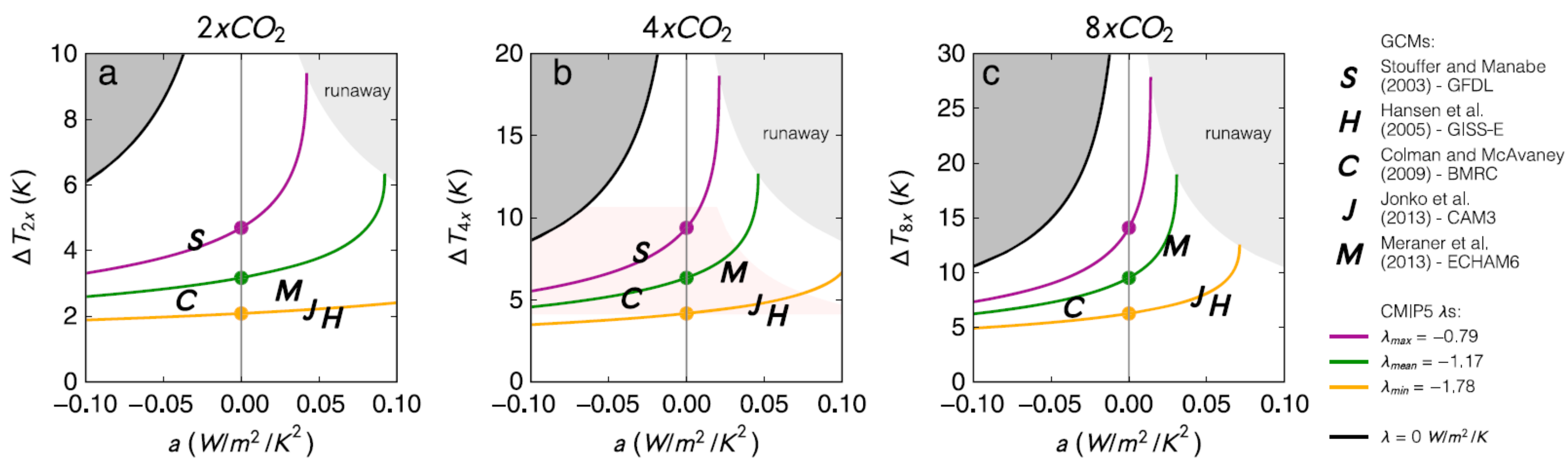
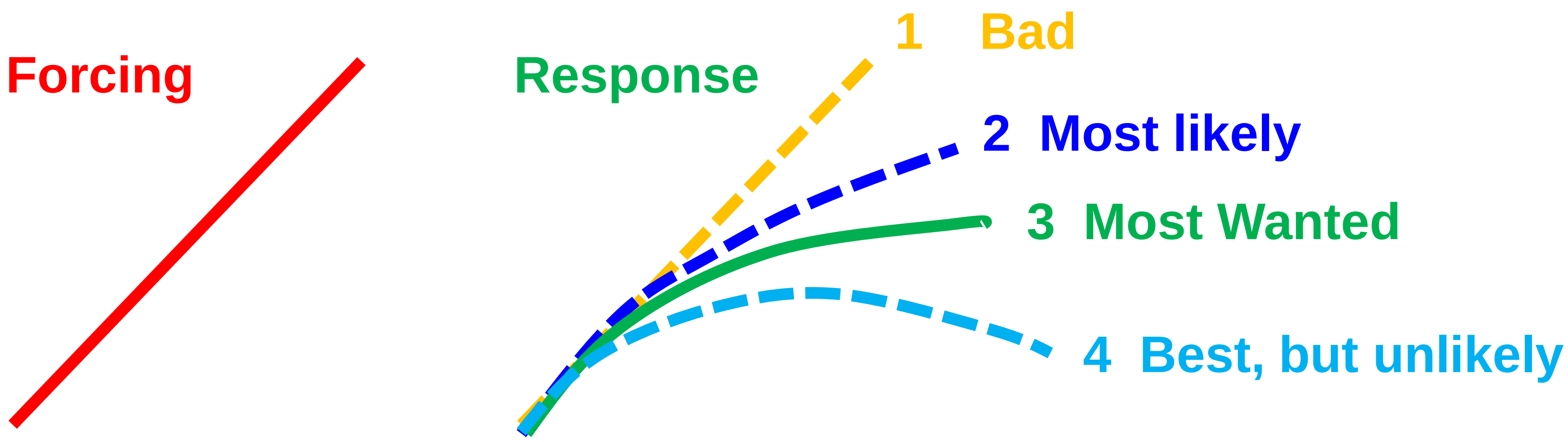


Figure 2. The feedback temperature dependence a versus (a) ΔT_{2x}, (b) ΔT_{4x}, and (c) ΔT_{8x} (the equilibrium warming from one, two, and three doublings of CO_2, respectively). Letters represent GCMs and are centered on pairs of a (quadratic estimate, see supporting information, Section S3) and ΔT_{nx} (reported values). Colored lines show how quadratic estimates of ΔT_{nx} (using equation (1)) vary with a for fixed values of λ, assuming forcings of $F_{nx} = log_2(n)3.71$ W/m^2. Colored circles where these lines intersect the center vertical give linear estimates of ΔT_{nx}. Some lines intersect the shaded regions in the upper right corner of each panel. For values of a greater than these intersections, the quadratic model experiences runaway warming. If we assume that the preindustrial climate was stable, then $\lambda \le 0$, and the dark region in the upper left-hand corner of each panel is inaccessible under the quadratic model. CMIP5 models must lie in the pink region in Figure 2b to avoid quadratic runaway under RCP8.5. Note that the y axis increases proportionally in each panel [*Colman and McAvaney*, 2009; *Hansen et al.*, 2005; *Jonko et al.*, 2013; *Meraner et al.*, 2013; *Stouffer and Manabe*, 2003].

$$(-0.06 \le a \le 0.06\ \mathrm{W/m^2/K^2}$$ [*Roe and Armour*, 2011]).

Why not?

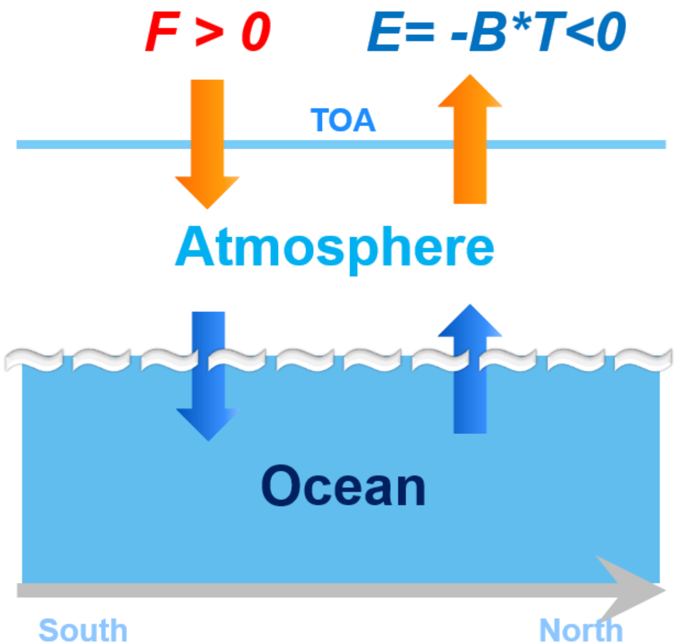
气候反馈的负反馈增强（正反馈减弱）➔ Hiatus？



气候反馈随温度增加而减弱时，温度上升趋势会减缓，如何减缓？

（Yang et al., 2017）

1-Box Energy Balance Model (EBM)

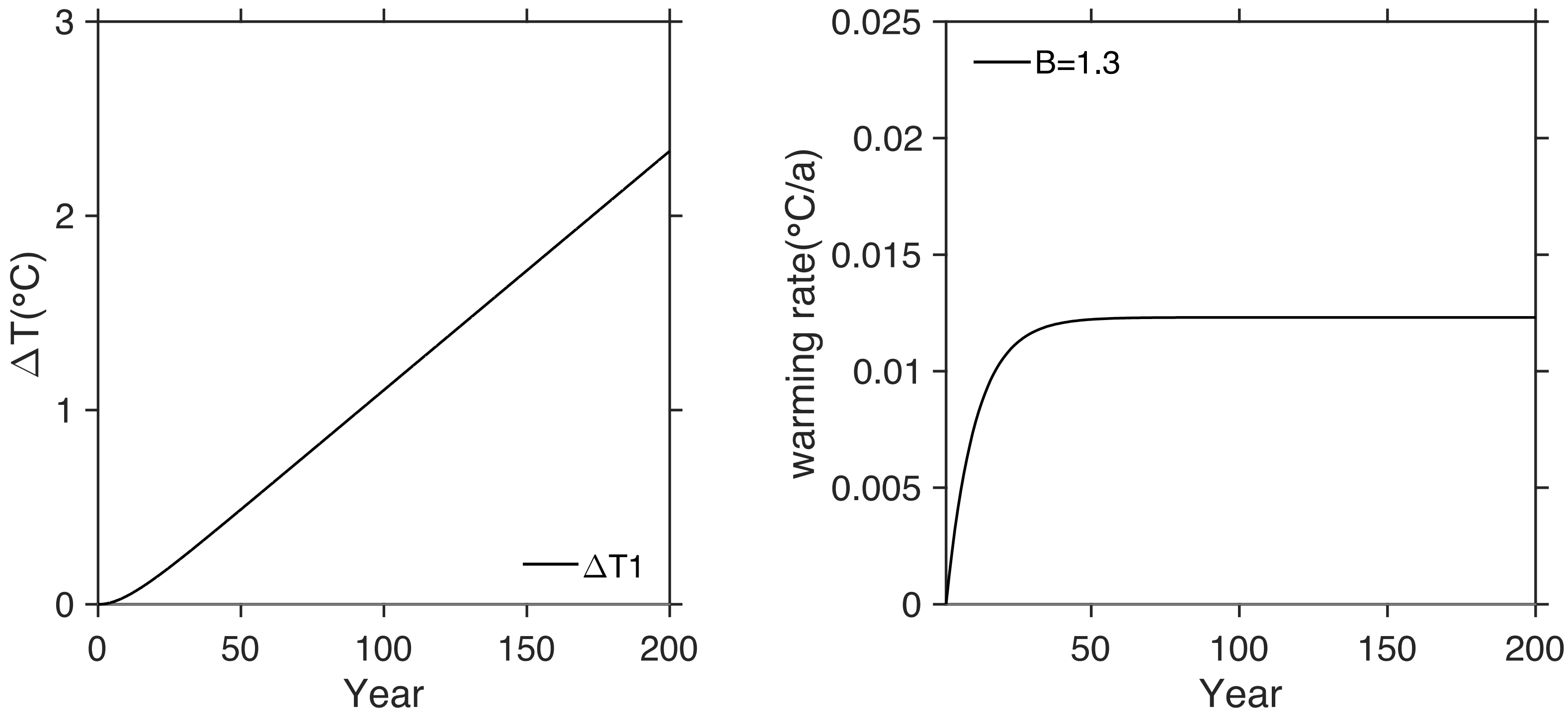


$$\frac{dT}{dt} = F - BT$$

If *F*=const., *T* determined by climate feedback *B*

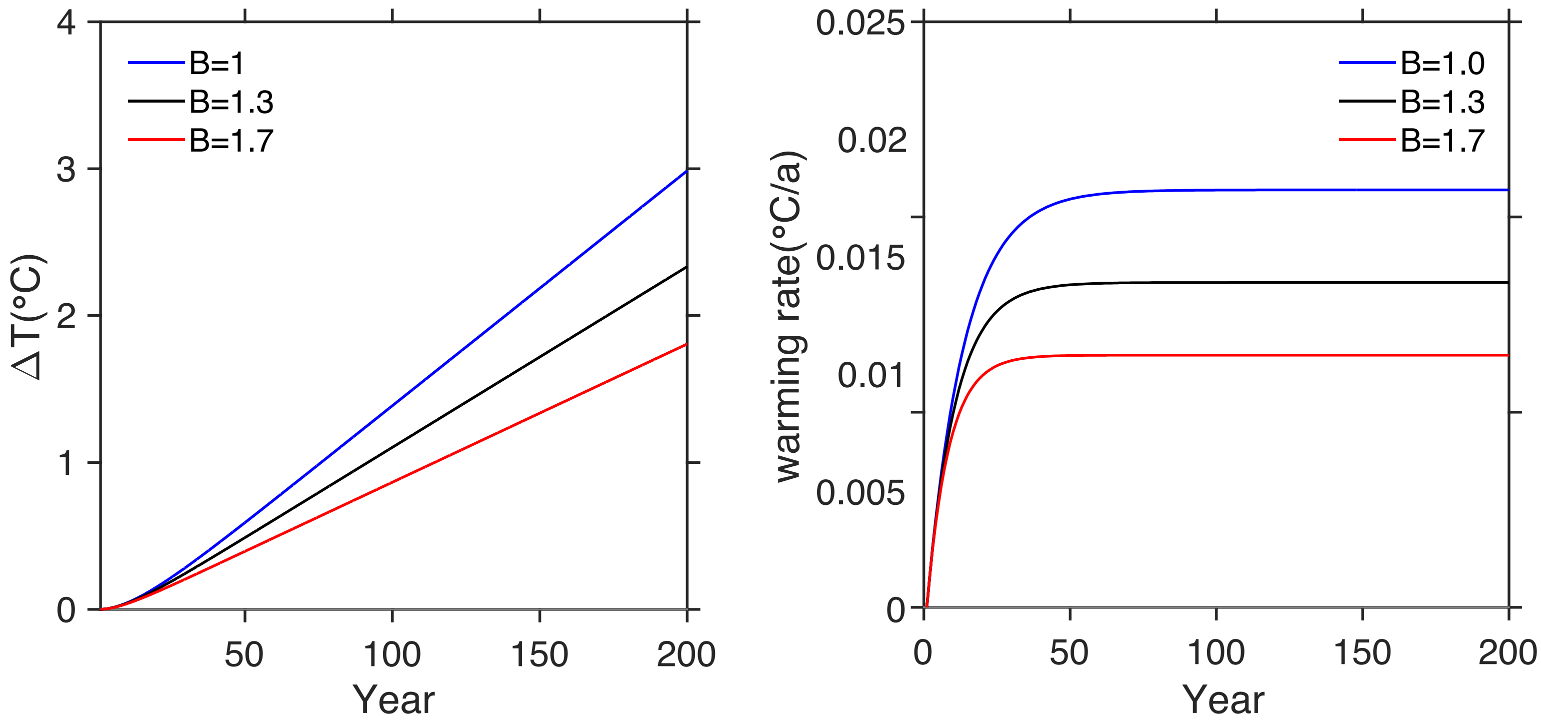
1-Box EBM Forced By Linear Forcing

$$\frac{d\Delta T}{dt} = \Delta F(t) - B\Delta T$$



Role of Climate Feedback

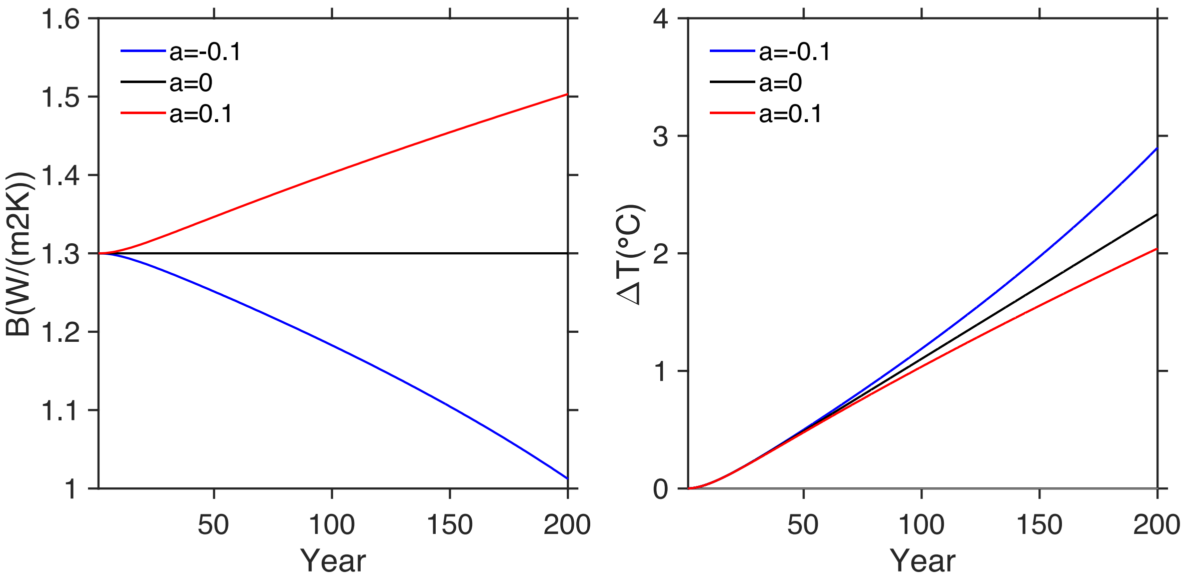
$B\uparrow \Rightarrow T\downarrow$



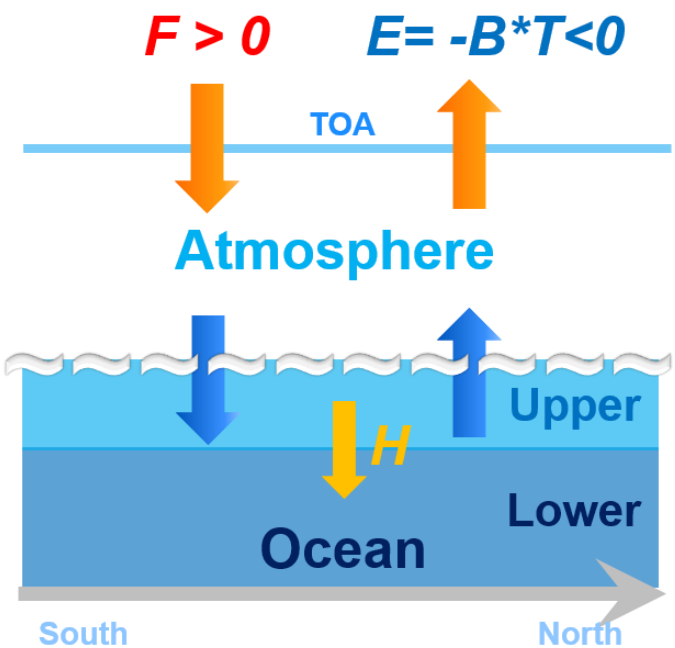
Climate Feedback: Temperature Dependence

$$\frac{d\Delta T}{dt} = \Delta F(t) - (B + \alpha\Delta T)\Delta T$$

$$\alpha \text{ in } Wm^{-2}K^{-2} \begin{cases} > 0, negative\ FB\ enhamced \\ = 0, FB\ unchanged \\ < 0, positive\ FB\ enhanced \end{cases}$$



2-Box Energy Balance Model



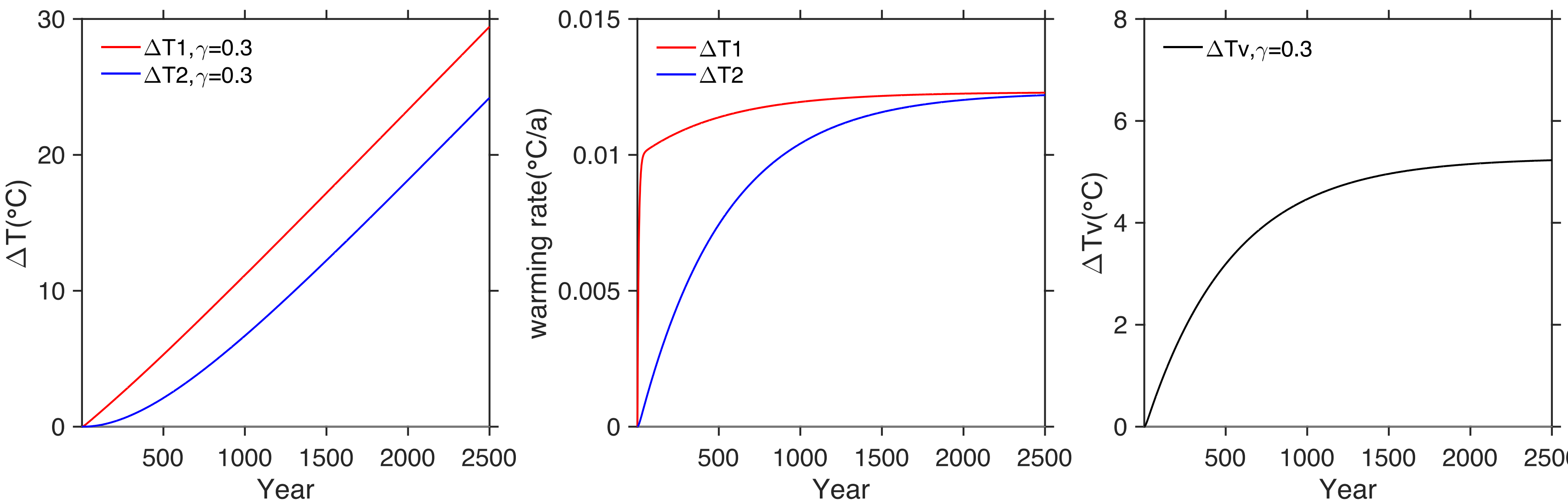
$$D_1 \frac{dT_1}{dt} = F - BT_1 - \gamma(T_1 - T_2)$$

$$D_2 \frac{dT_2}{dt} = \gamma(T_1 - T_2)$$

$$T_v = T_1 - T_2$$

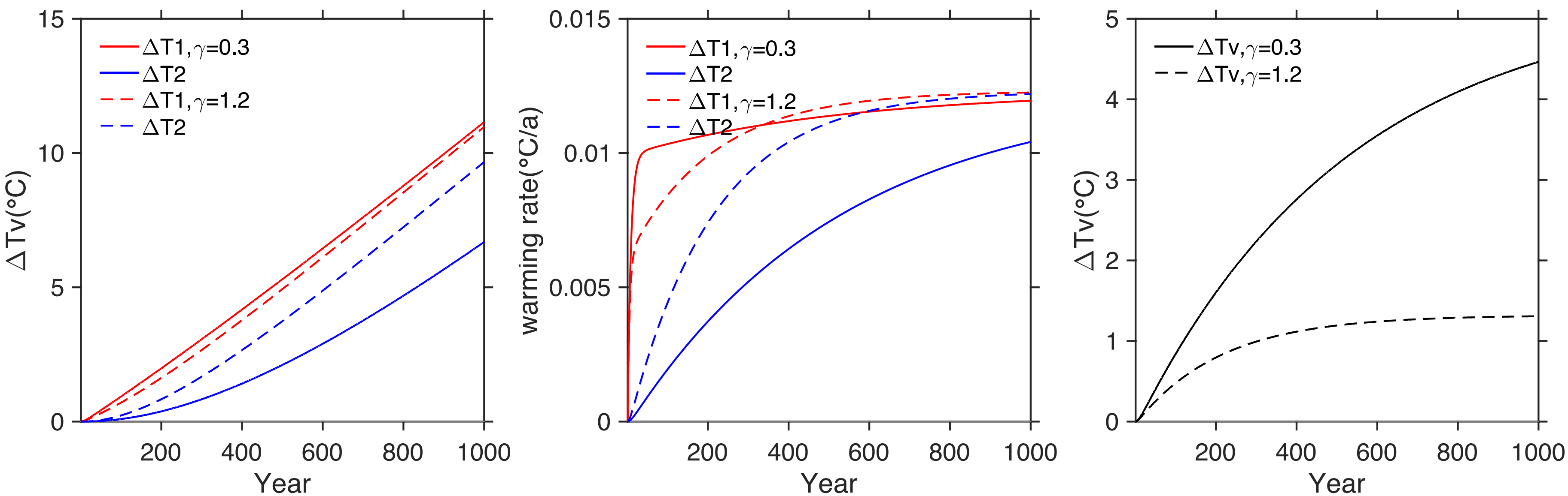
2-Box EBM Forced By Linear Forcing

$$D_1 \frac{d\Delta T_1}{dt} = \Delta F(t) - B\Delta T_1 - \gamma \Delta T_v; \qquad D_2 \frac{d\Delta T_2}{dt} = \gamma \Delta T_v$$



Role of Vertical Mixing

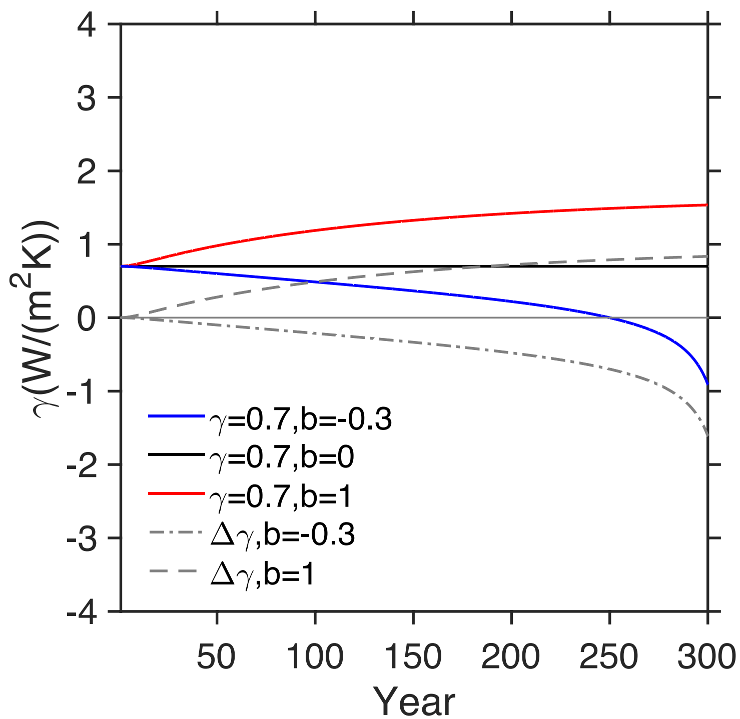
$\gamma\uparrow \Rightarrow T_v\downarrow$

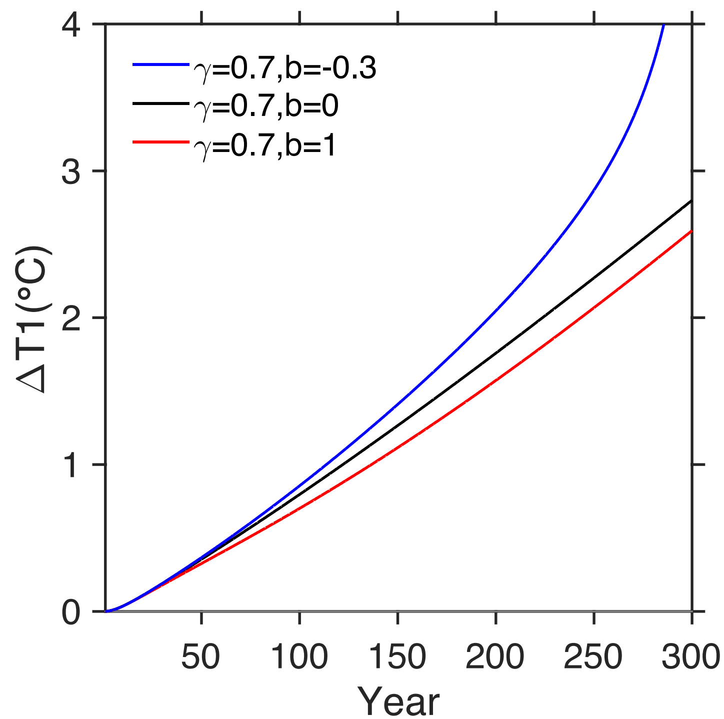


Vertical Mixing: Temperature Dependence

$$D_1 \frac{d\Delta T_1}{dt} = \Delta F(t) - B\Delta T_1 - (\gamma + \beta\Delta T_v)\Delta T_v; \qquad D_2 \frac{d\Delta T_2}{dt} = (\gamma + \beta\Delta T_v)\Delta T_v$$

$$\boldsymbol{\beta} \textbf{ in } \mathrm{W}m^{-2}K^{-2} \begin{cases} > 0, downward\ VM\ enhamced \\ = 0, VM\ unchanged \\ < 0, downward\ VM\ weakened \end{cases}$$

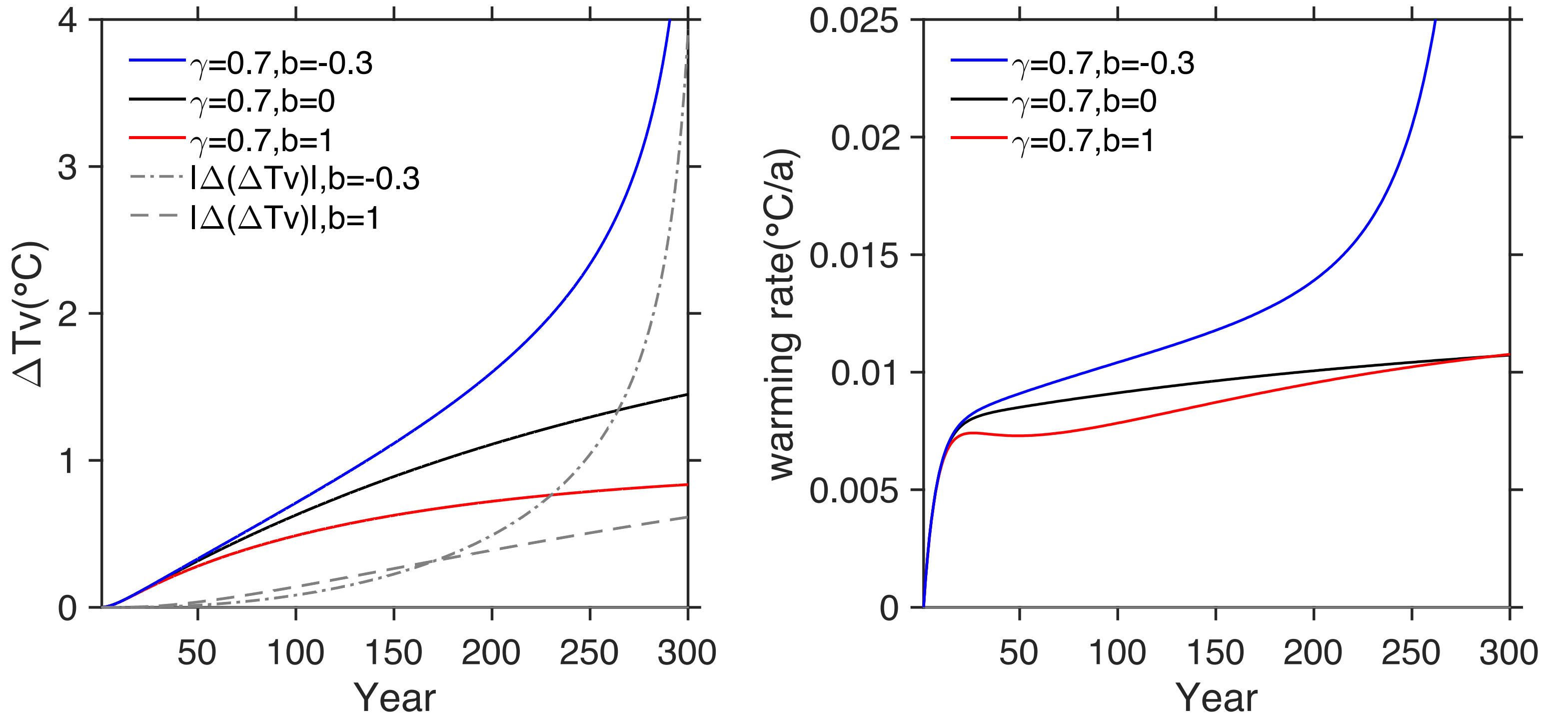




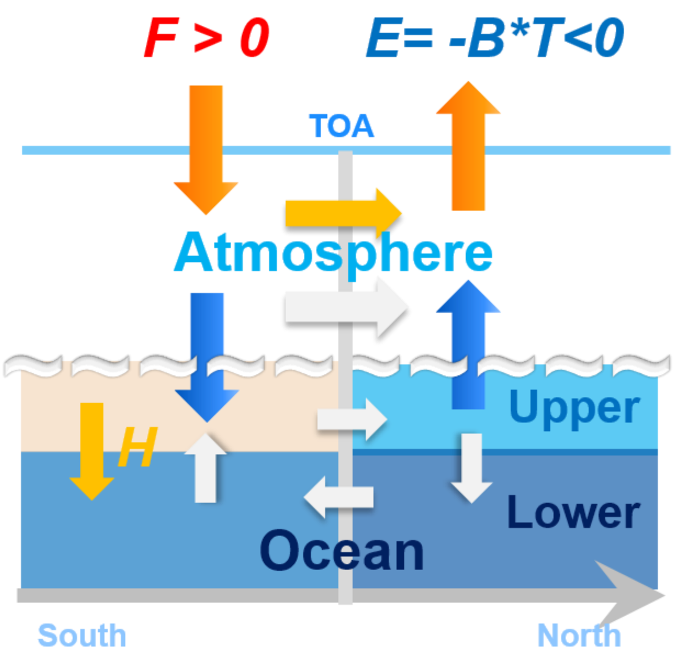
Vertical Mixing: Temperature Dependence

$$D_1\frac{d\Delta T_1}{dt} = \Delta F(t) - B\Delta T_1 - (\gamma + \beta\Delta T_v)\Delta T_v; \qquad D_2\frac{d\Delta T_2}{dt} = (\gamma + \beta\Delta T_v)\Delta T_v$$

$$\boldsymbol{\beta}\ \textbf{in}\ Wm^{-2}K^{-2}\begin{cases} > 0, downward\ VM\ enhamced \\ = 0, VM\ unchanged \\ < 0, downward\ VM\ weakened \end{cases}$$



4-Box Energy Balance Model



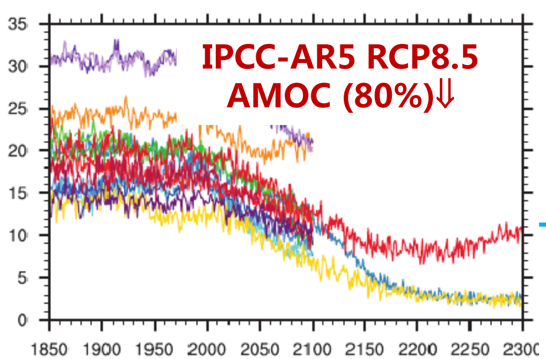
- *Meridional Heat Transport*
- *Meridional Freshwater Transport*
- *Hadley Circulation*
- *Eddy Storm Track*
- *Thermohaline Circulation*
- *Vertical Mixing*

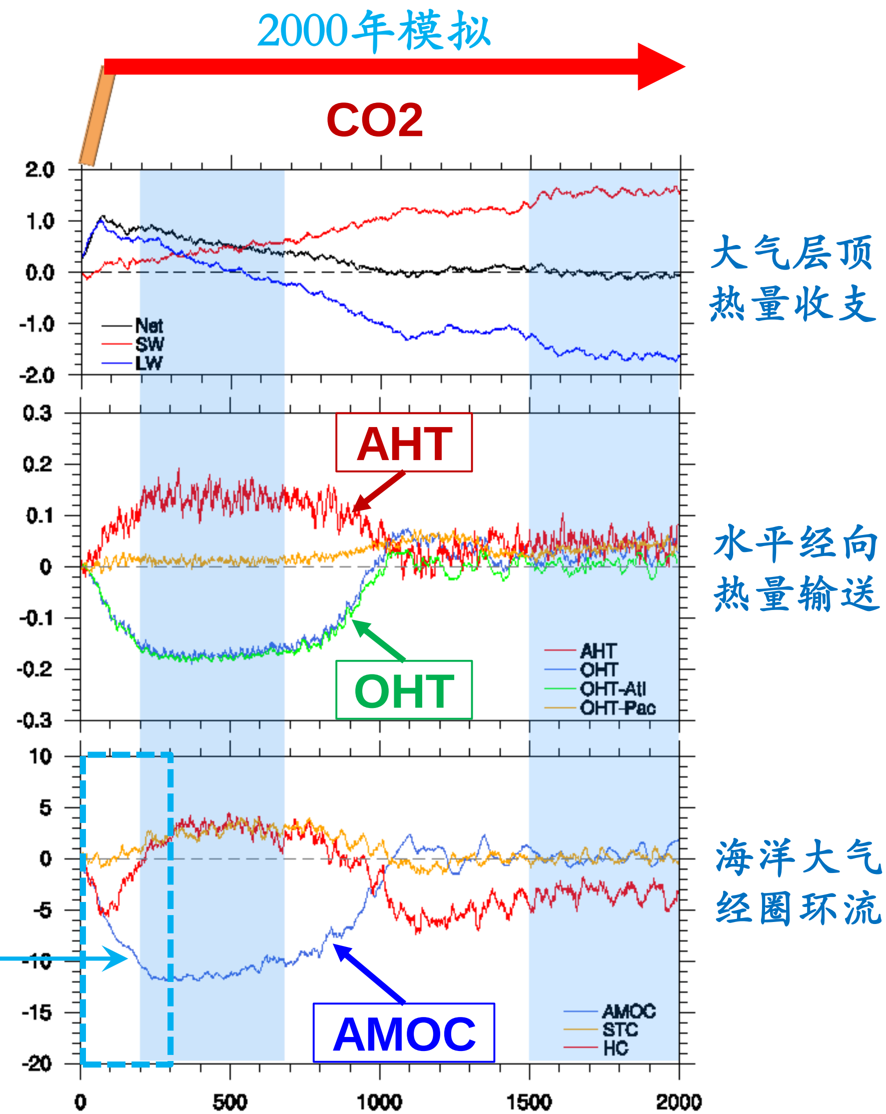
Yang et al. 2015, 2016, 2017

Working……

Heat Budget and Ocean Circulation in CESM-CO2

- 单平衡态：大气层顶热量收支
- 双稳定态：热量输送与海洋环流
- 热量输送和海洋环流气候态可以恢复！

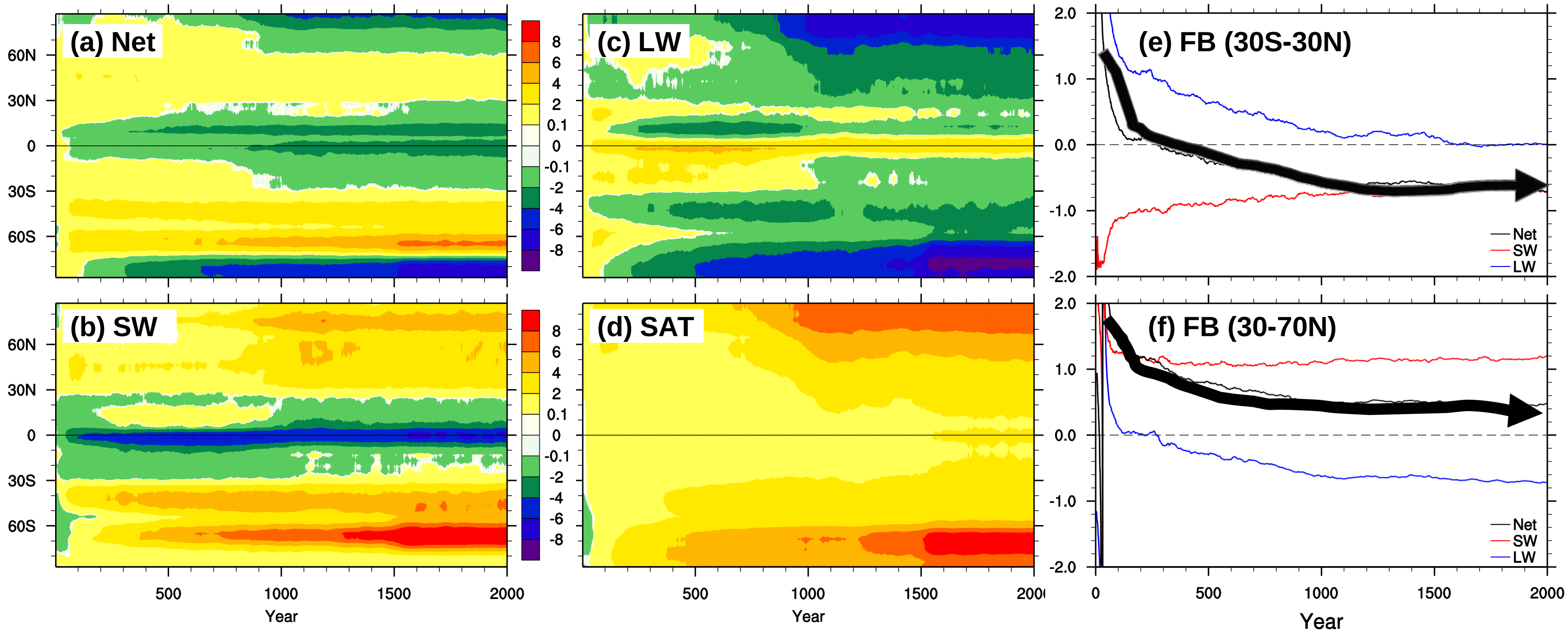




Yang et al. (2017)

Radiation Flux and Climate Feedback in CESM-CO2

Enhanced Negative Climate Feedback !



Yang et al. (2017)

Summary and Discussion

- Hiatus under linear heating
  - Possible
- New mechanisms
  - Enhancing **negative** climate feedback
  - Enhancing downward heat mixing (?) (Short)
  - Ocean circulation (? to be investigated)
- How to realize in real world?
  - Understanding climate feedback first!

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Thanks

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