Ocean – Atmosphere Interaction

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Ocean-Atmosphere Interaction

1. Tropical-Extratropical, Interhemispheric Climate Interaction : Atmospheric Bridge and Oceanic Tunnel
2. Dynamics of Decadal Climate Variability and Tropical Decadal Variability
3. Ocean-Atmosphere Interaction: A Global Scale, Coupled Climate Dynamics and Bjerknes Compensation
4. **Timescale and Reversibility of Climate Change**

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Can We Return to Normal?

If not, why?

If so, how long?

- Linear system – Reversible
- Complex system – Irreversible
- Atmosphere and Ocean – Different timescales

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Concept

- Climate Sensitivity
- Climate Response Pattern
- Climate Response Timescale

Timescale for Climate Change

- Relaxation or Recovery timescale
  - Response to a pulse forcing

- Transient and Equilibrium Response timescale
  - Response to a persistent forcing

Definition of Timescale

- Transient Response Timescale
  - *e*-folding time: time for 1/*e* of final response
- Equilibrium Response Timescale
  - (1-1/e) of final response
- Do we know "Final response"?

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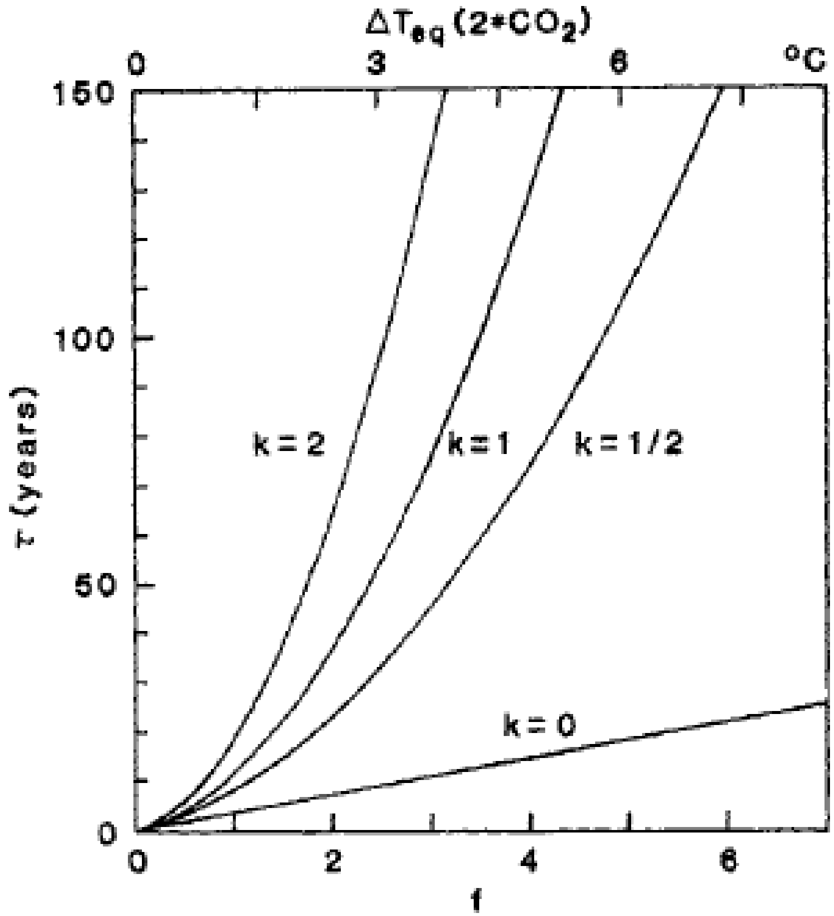
What Determine Timescale?

- Climate sensitivity
- Ocean mixing
- Form of external forcing
- etc.....

Climate Sensitivity and Feedback on the Timescale



- 1-d model box diffusion model

$$\tau \simeq k f^2 \left(\frac{\tau_b}{d_0}\right)^2 \propto f^2 \text{ (large } k\text{)}$$

- Climate sensitivity
- Feedbacks *f* delay
- Mixing *k*

Hansen et al. (1985)

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Climate Sensitivity and Feedback on the Timescale

- Diffusion-upwelling model (Dickinson and Schaudt, 1998)

$$\partial T/\partial t + w\,\partial T/\partial z - k\,\partial^2 T/\partial z^2 = 0,$$

$$F(t, T) = kc\,\partial T/\partial z \quad \text{at} \quad z = 0,$$

$$T(z) = (T_{\text{surf}} - T_{\text{bot}})\exp(\gamma z) + T_{\text{bot}}, \quad \gamma = w/k,$$

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Climate Sensitivity and Feedback on the Timescale

- Fast timescale: damping

$$\tau_c = C/a = cD/a = ck/(wa) = \frac{71}{\lambda}\,\mathrm{yr}.$$

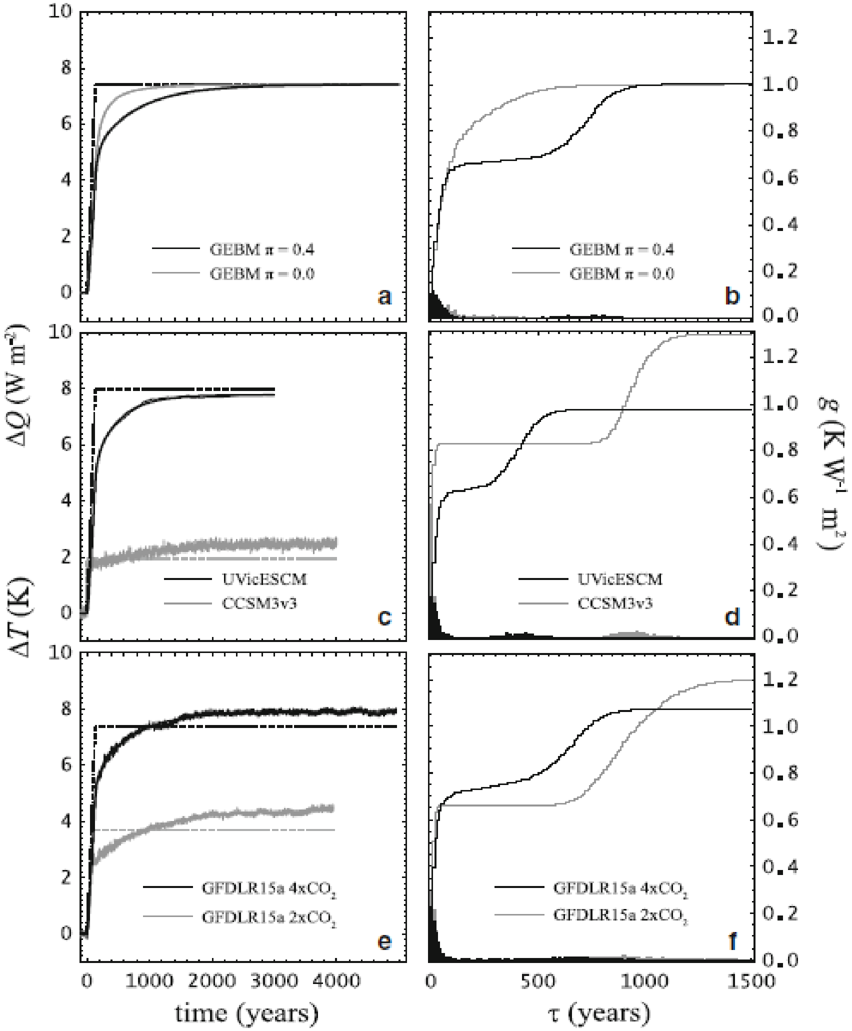
  - λ: non-dimensional sensitivity parameter
  - λ =1 for a “sensitive climate” 4 °C for 2CO2
  - λ =2 for a “insensitive climate” 2 °C for 2CO2

- Slow timescale: upwelling

$$\tau_u = k/w^2.$$

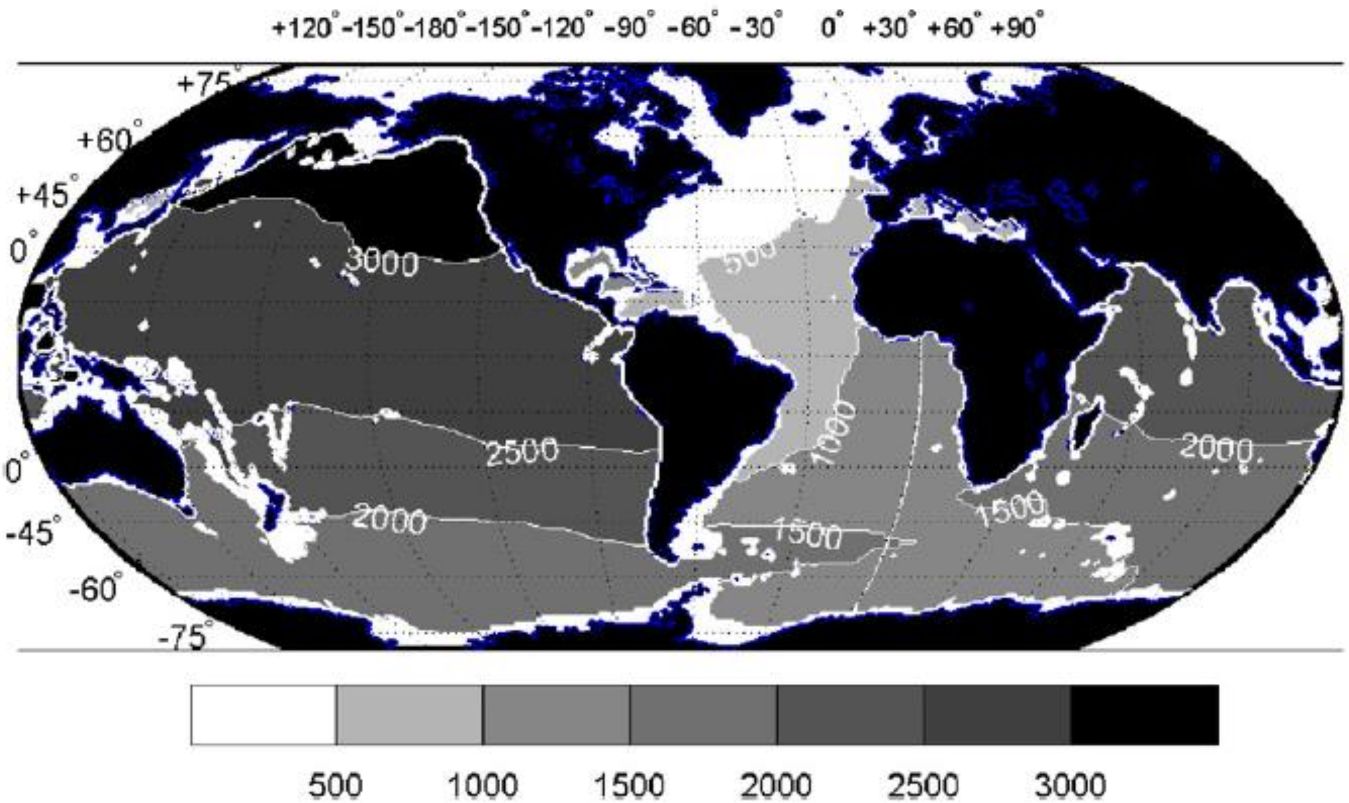
  - 197 yrs for w=4m/yr and k=1 cm^2/s

Timescale in GEBM



- 1-D GEBM (Jarvis and Li, 2010)
- GEBM & Coupled Models
- 20 yrs for upper ocean
- 700 yrs for deep ocean

Timescale in OGCM



- Tracer equilibrium timescale (Wuncsh and Heimbach, 2008)
- t_{90} at 1975 m for source in global surface

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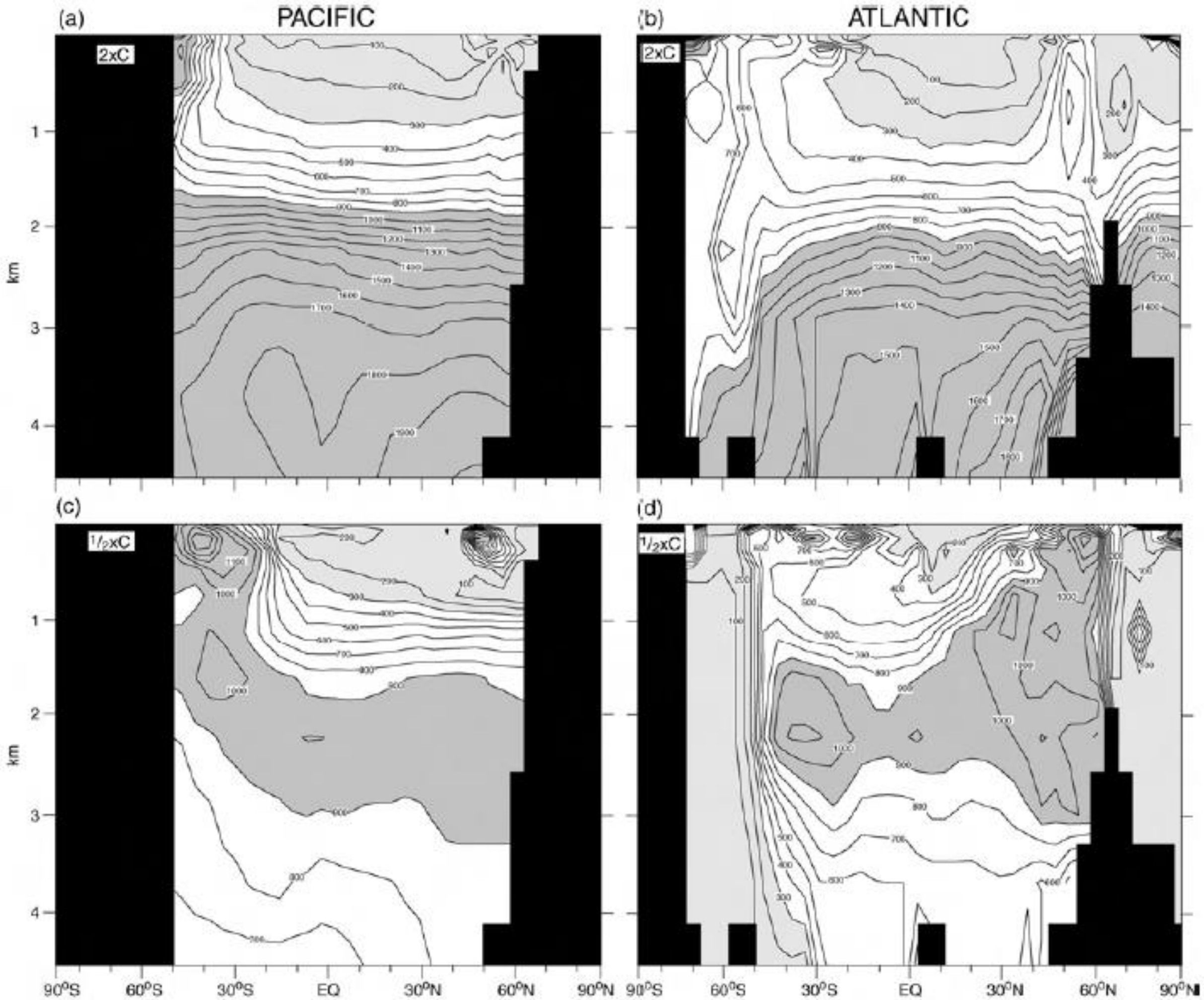
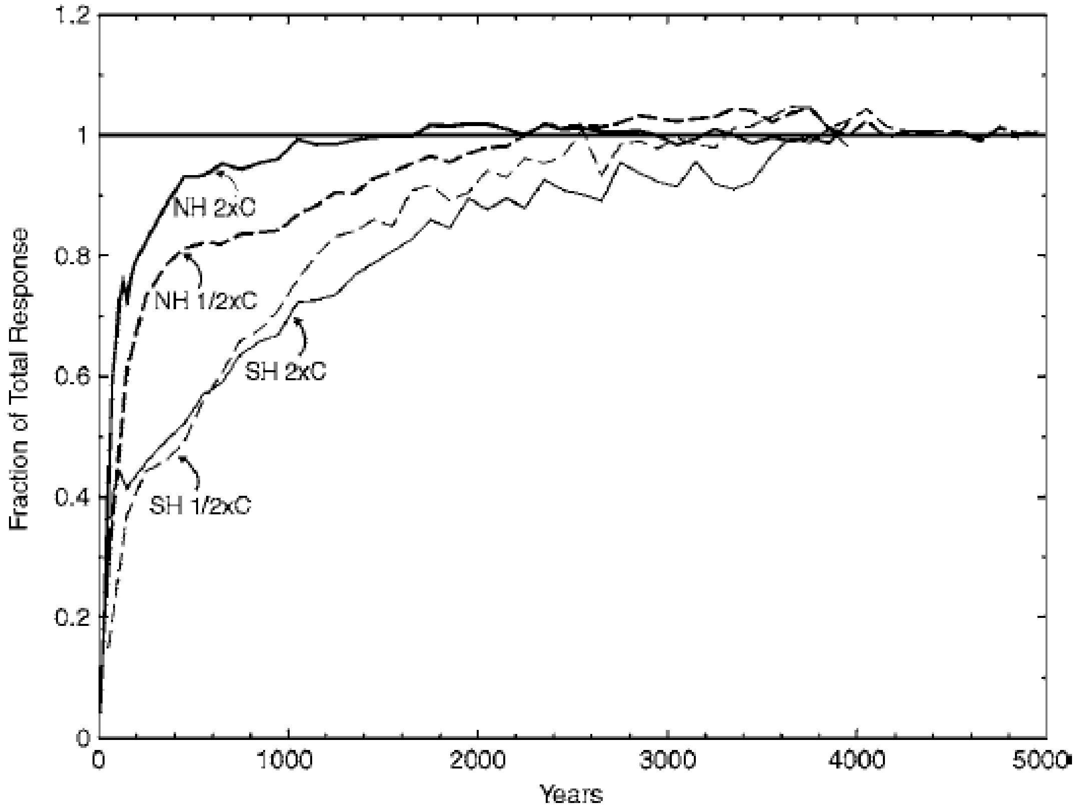
Timescale in AOGCM



Different in different basin, forcing size and sign (Stouffer, 2004)

Timescale in AOGCM

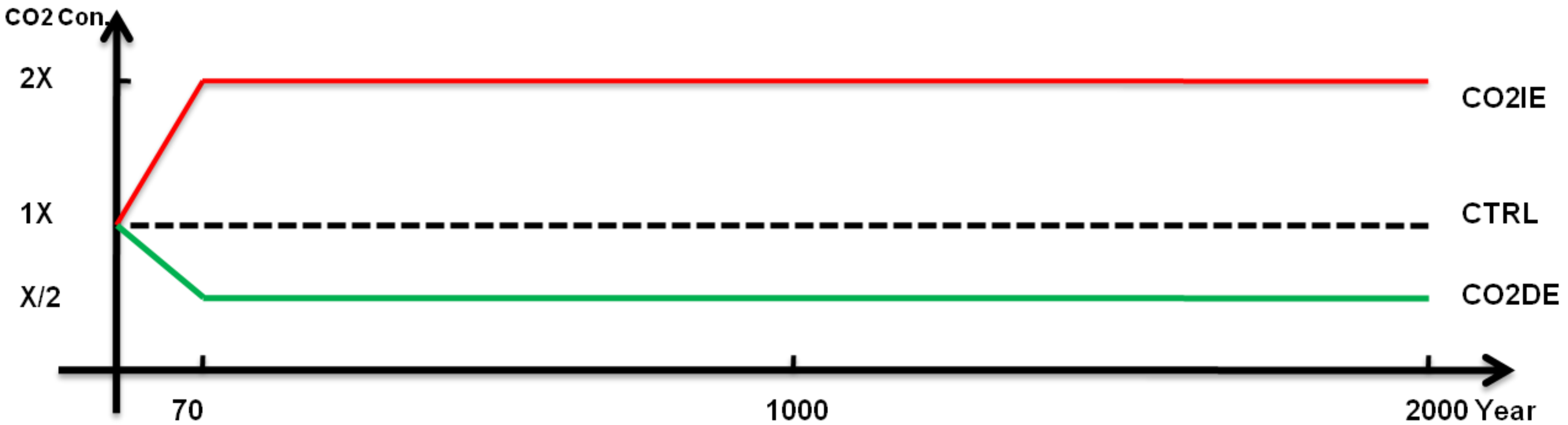


Fraction of the total response, interhemispheric difference

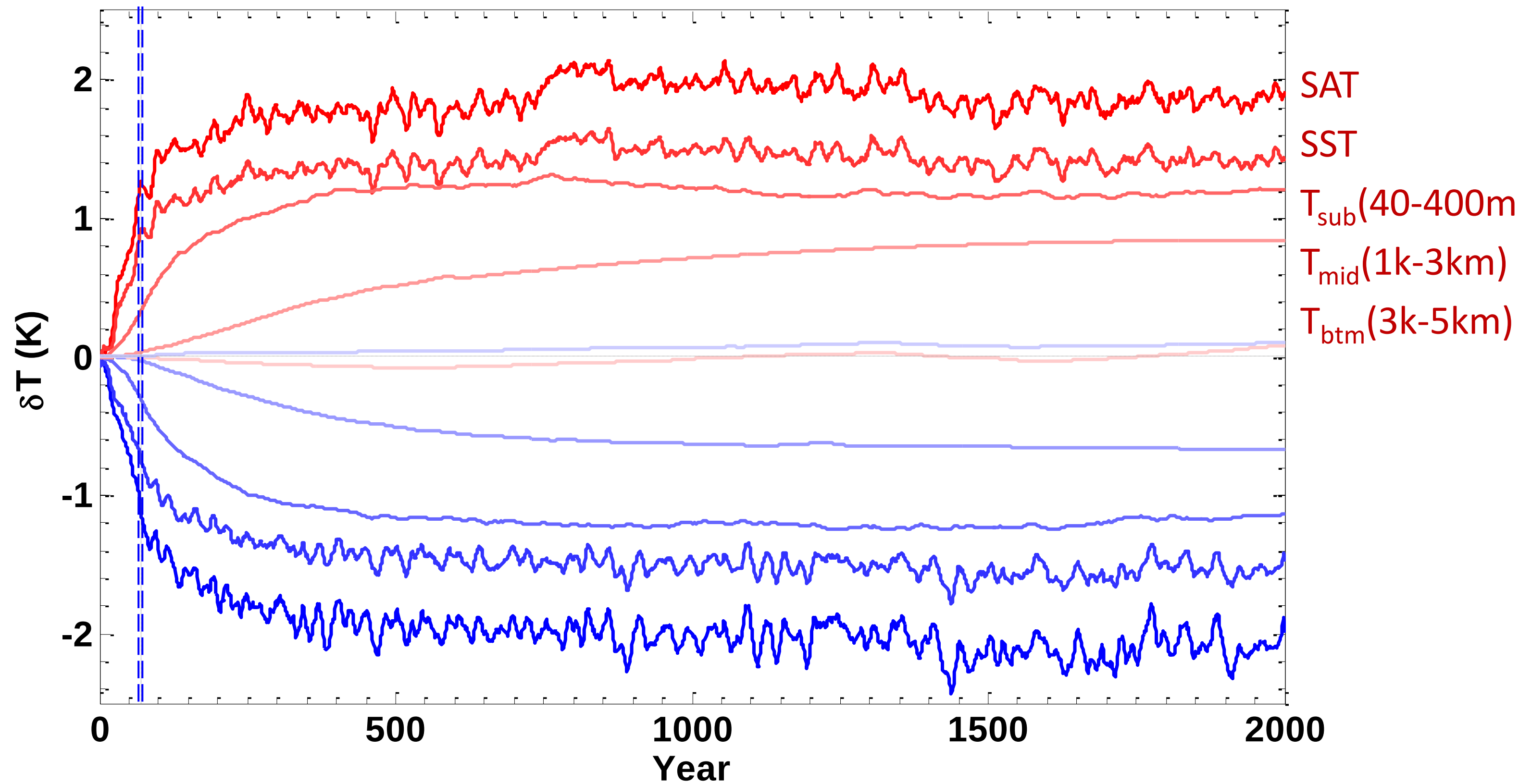
(Stouffer, 2004)

Model and Experiments

- Fast Ocean-Atmosphere Model (FOAM)
  - Atmos. – R15, NCAR-CCM3
  - Ocean – 1.4°×2.8°×32-level, GFDL-MOM2
  - Control Run: 2000 years



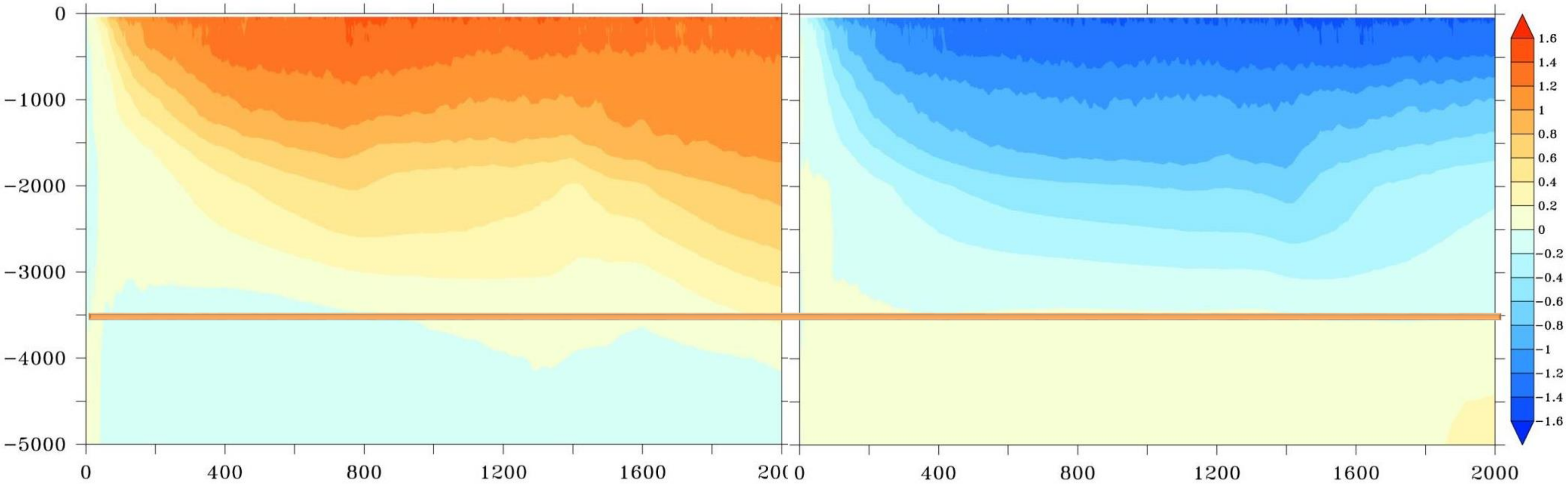
General Responses



Sensitivity:

- SAT and SST: 0.8-1.2°C at 70, 1.4-2.0°C at final
- Tsub: 0.4°C, 1.2°C; Tmid: < 0.1°C, 0.9°C

Evolution of Ocean Temperature



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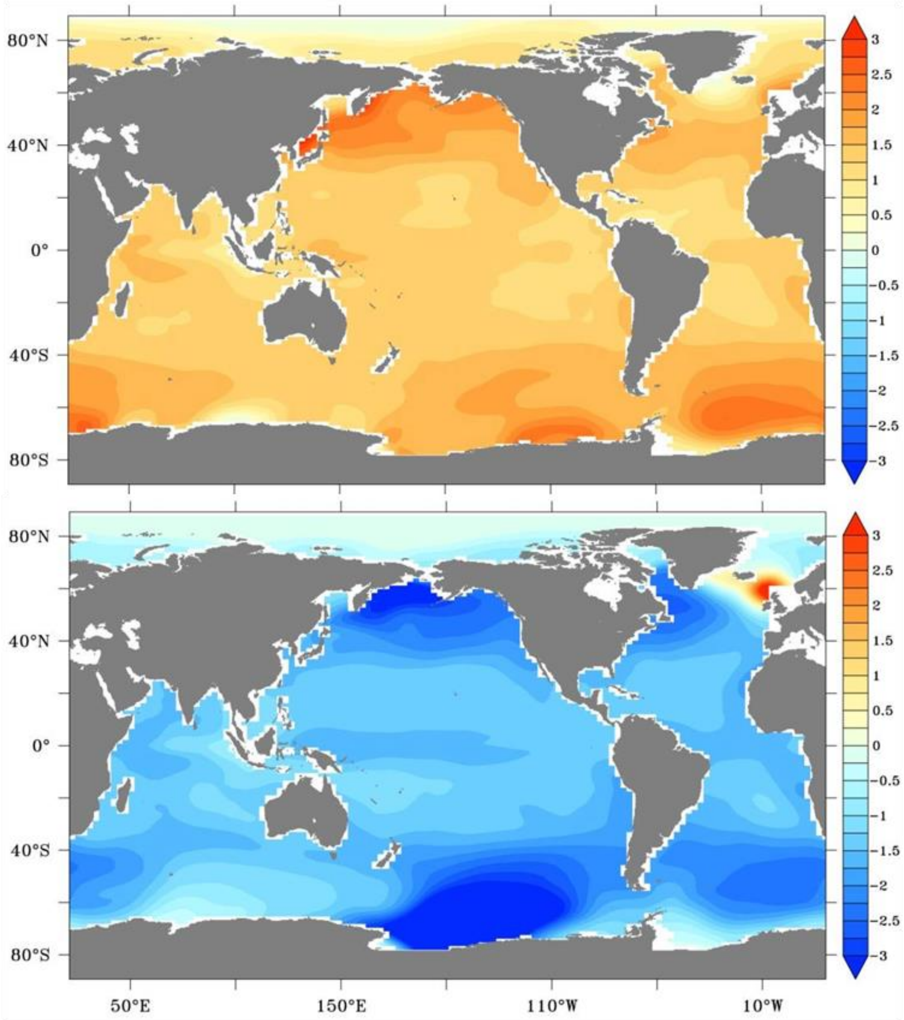
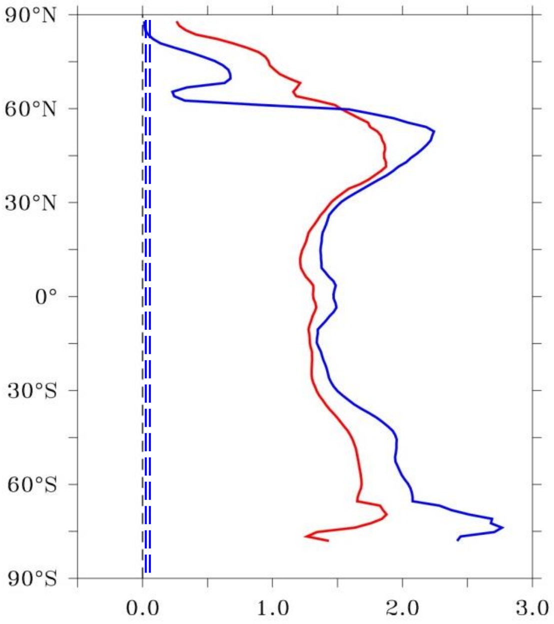
Final SST



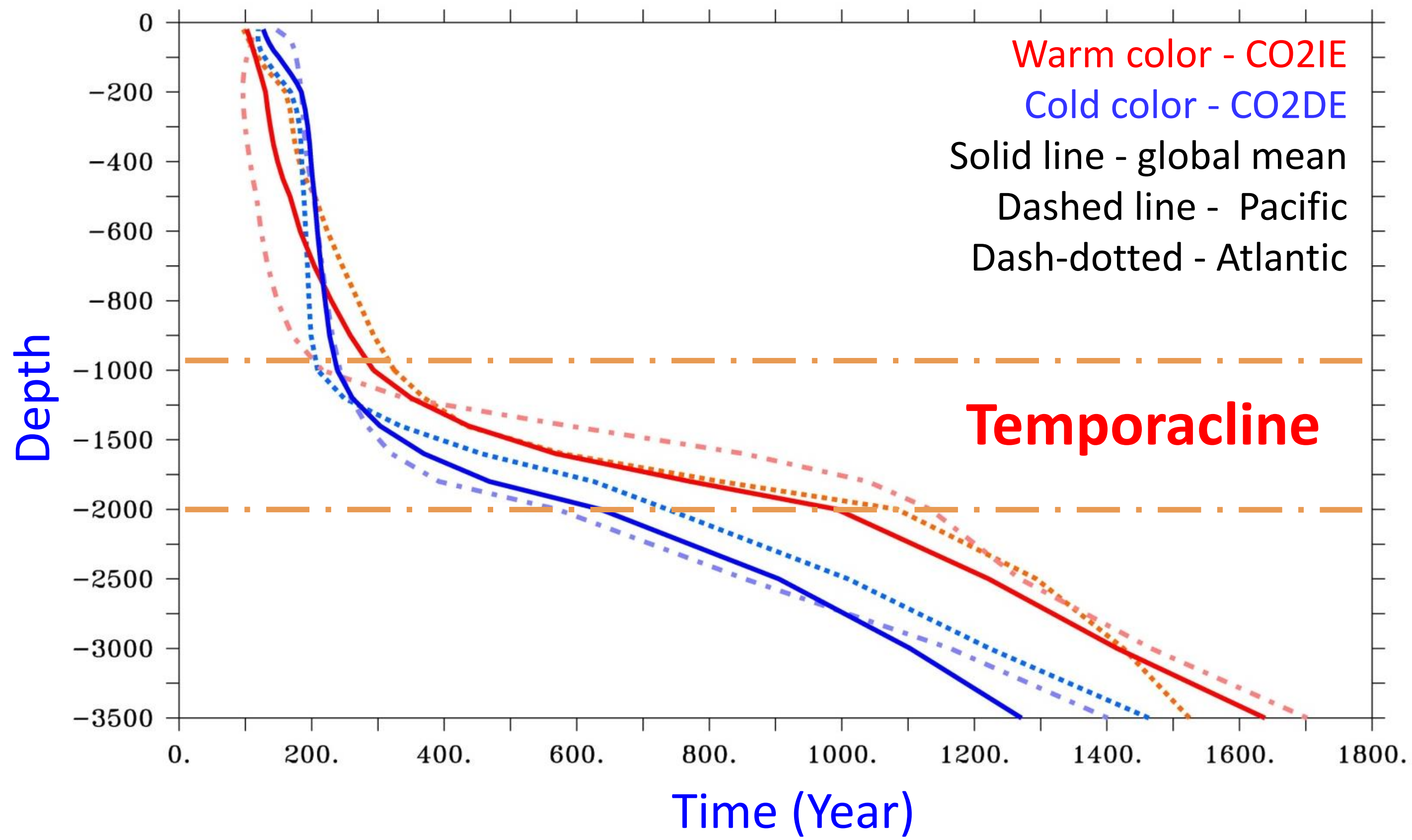


- Symmetric in low latitudes
- Big different in high latitudes

Defining the Timescale of Climate Response

- Assuming that the climate system has reached equilibrium monotonously, and using anomalies of the last 100 years as the final changes, we define the year when reaching their 70% as the response timescale (Stouffer, 2004).

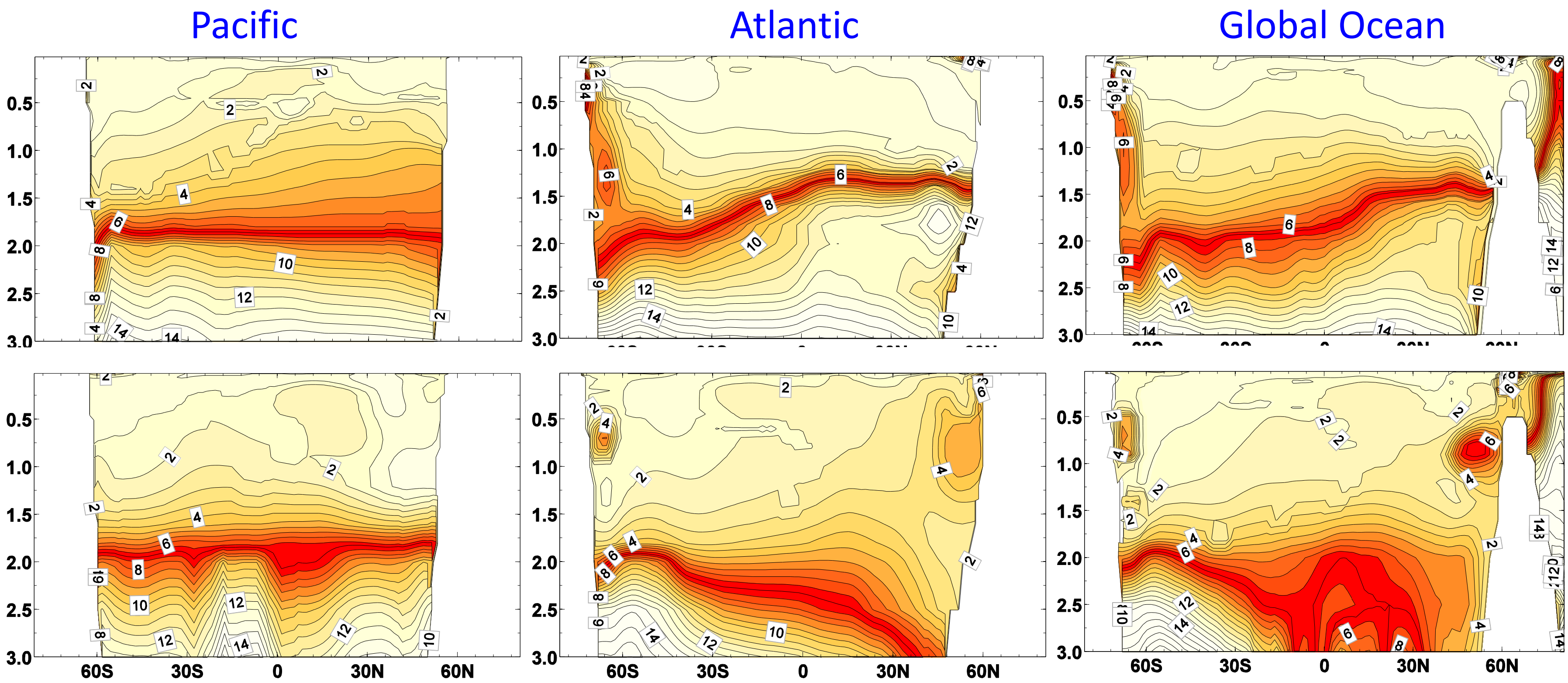
Time Profile with Depth



Time Profile – "Temporacline" ⇔ "Density-profile or Pycnocline or Thermocline

200 yrs for upper 1km; 300-1000 yrs for 1-2km; > 1000-2000 yrs for deep ocean

Timescale for Global Oceans

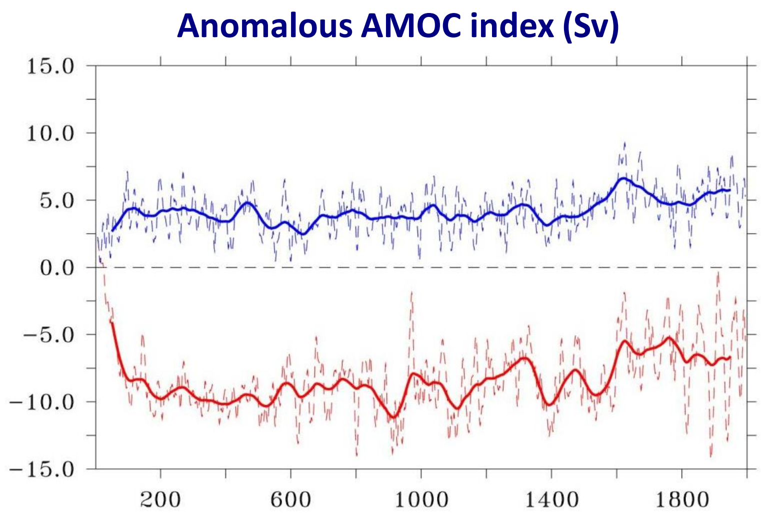


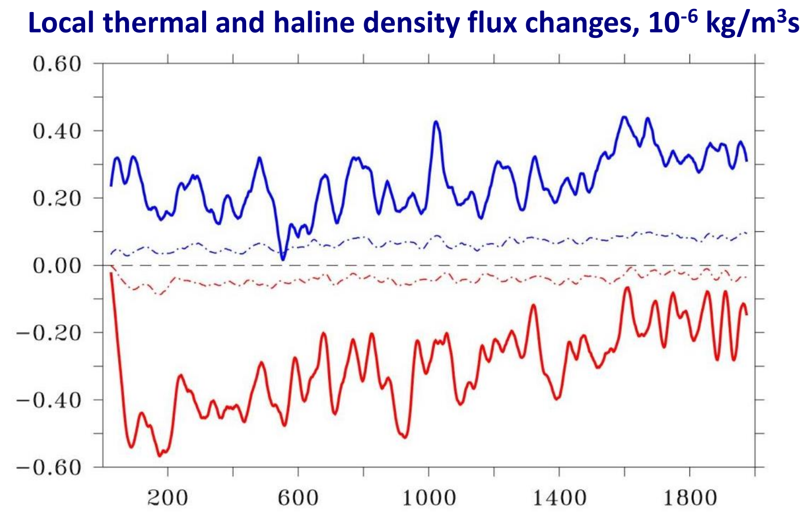
- 200 yrs above1000m;   > 1000 yrs below 2000m
- Time abrupt change zone: 1500-2000m
- Different timescale for warming and cooling forcings

Summary and Mechanism

- General timescale
- **Temporacline** – Upper ocean and deep ocean
  - Upper ocean – MLD and thermocline circulation
  - Lower ocean – Deep water formation and AMOC
- Different timescale in warming and cooling world
  - Different Responses in AMOC

Lower Ocean: AMOC Changes





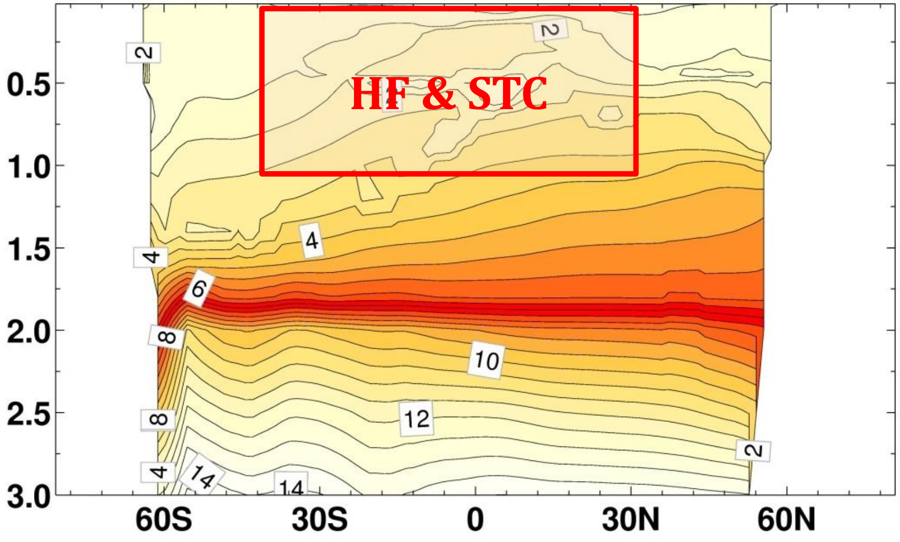
Warming : AMOC ⇓→ Longer time;   Cooling : AMOC ⇑ → Shorter time

AMOC changes mainly determined by local heat flux change in North Atlantic sub-polar region

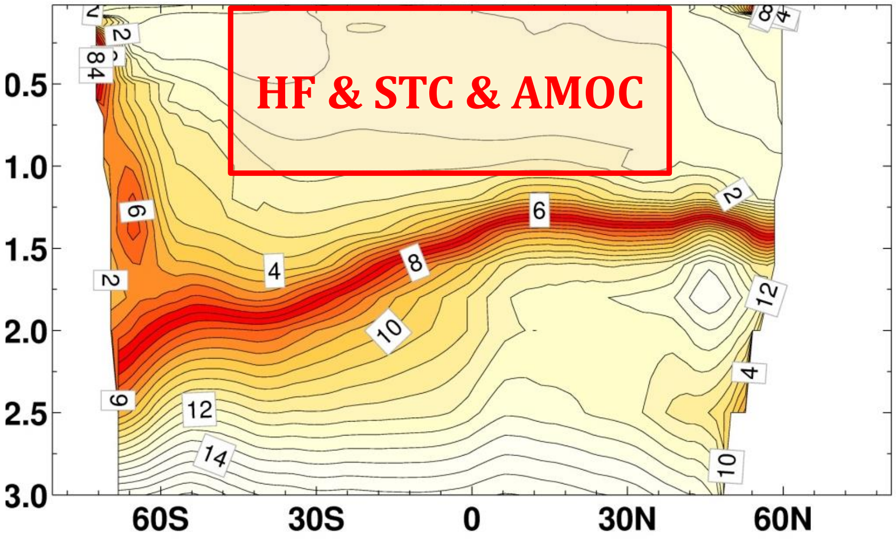
Asymmetric changes in AMOC in warming and cooling world: Nonlinearity , local feedback and remote feedback

Upper Ocean: Surface Heat Flux, STC and AMOC

Pacific Warming



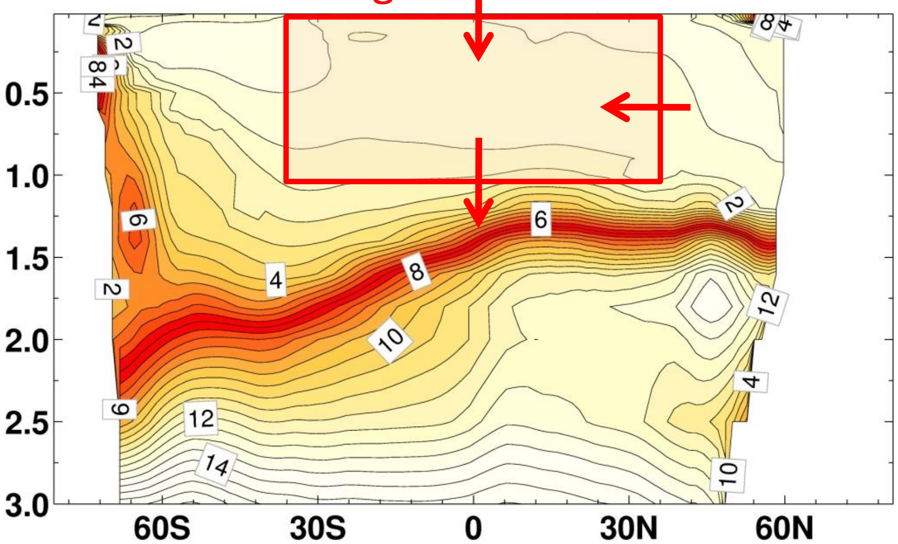
Atlantic Warming



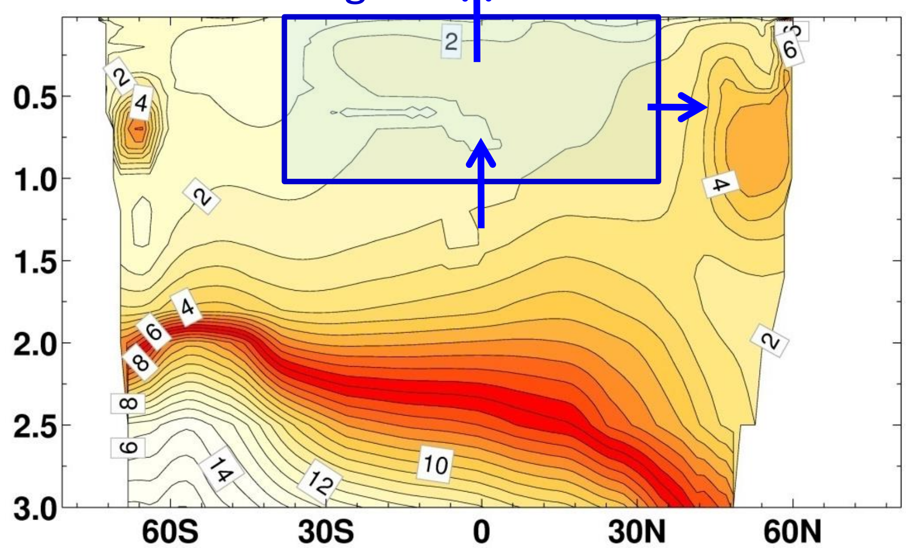
AMOC ⇓ → Upwelling and northward HT ⇓ → Warming enhanced

Upper Ocean: Surface Heat Flux and AMOC

Atlantic Warming



Atlantic Cooling



Warming: HF stabilize upper ocean, AMOC ⇓ → weaken vertical exchange

Cooling : HF destabilize upper ocean, AMOC ⇑ → strengthen vertical exchange

Discussions

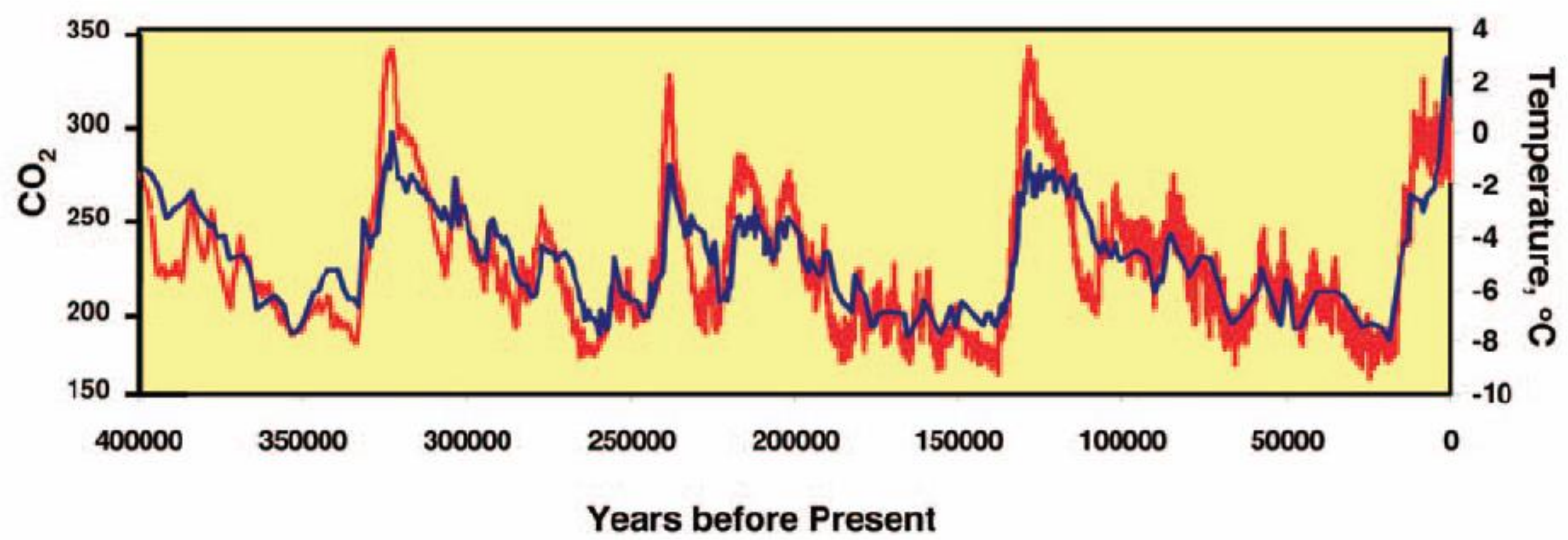
- The deep ocean is far from equilibrium.
- Lacking of AABW: affect the deep ocean greatly.
- Abrupt changes could happen in some regions.

Reversibility of the Climate Change

- To what extend the climate is reversible?
- Threshold for climate reversibility?
- Reversible aspects – how long?
- Irreversible aspects – timescale and impact

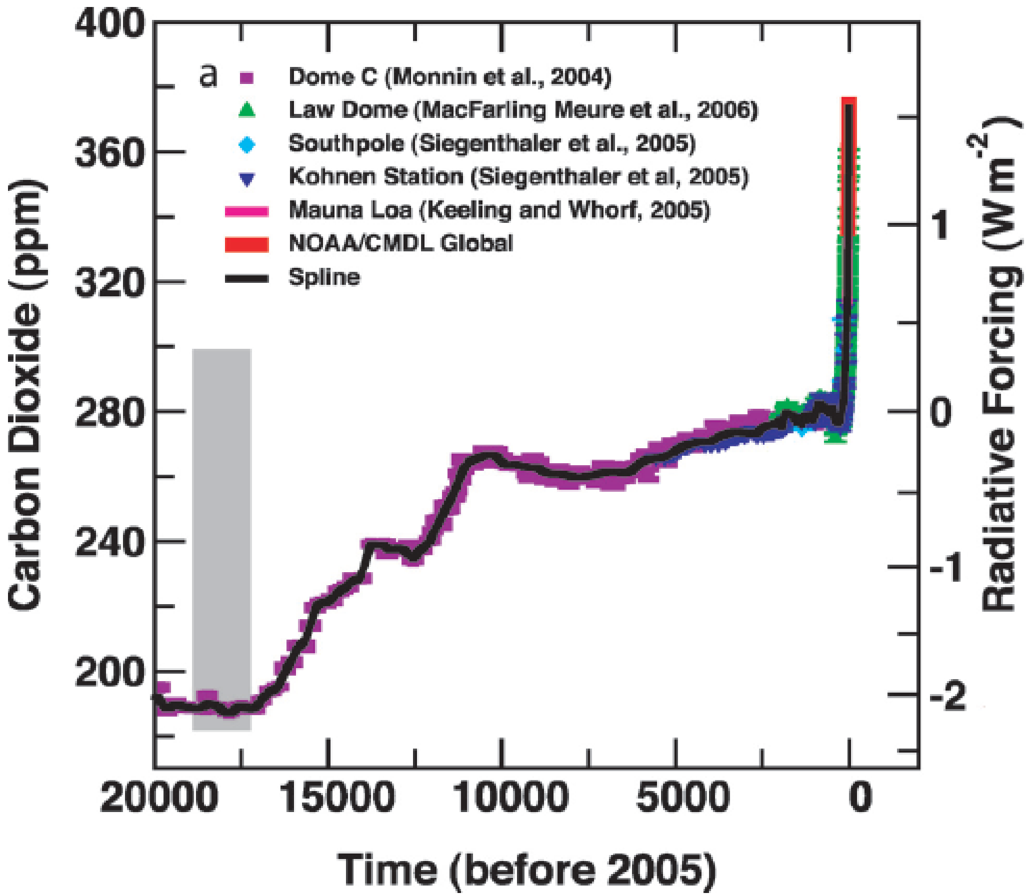
Solomon et al., 2009: Irreversible climate change due to CO2 emissions, PNAS, 1704-1709.

Periodic Change in Past Climate



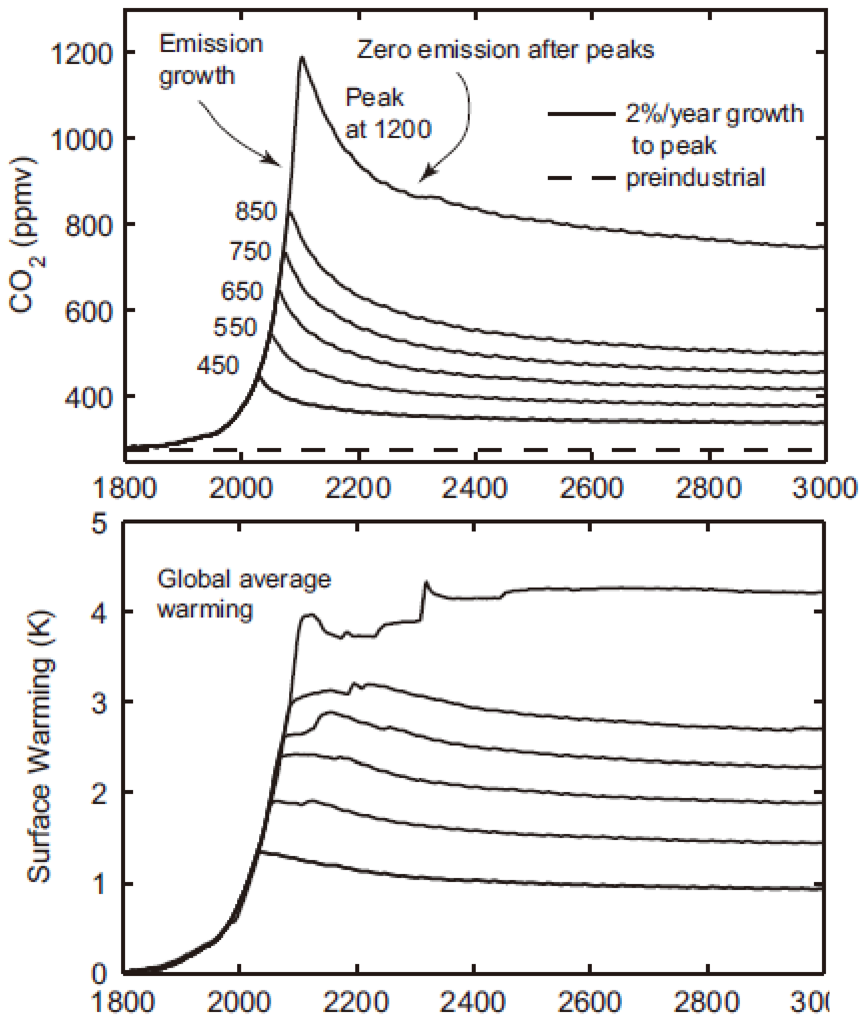
Paleoclimate data: Ice core from Vostok, Antarctica. Petit et al. (1999, Nature)

CO2 Change Since LGM



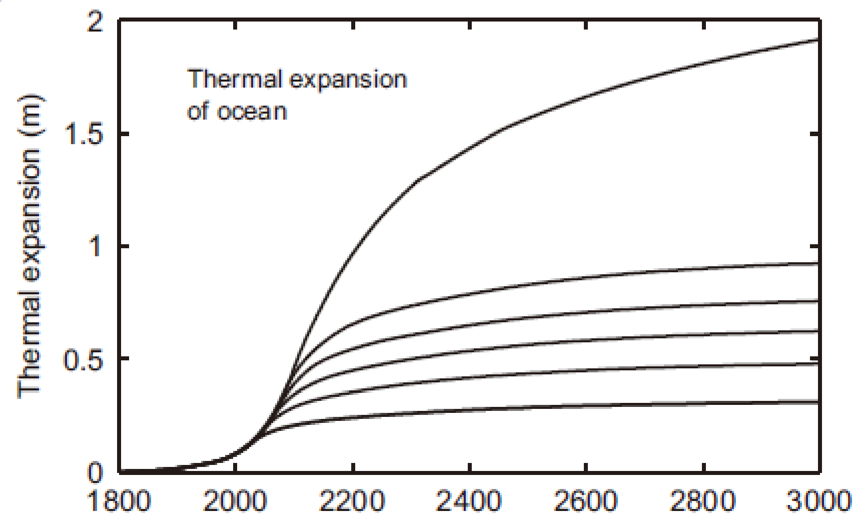
IPCC, AR4, 2007

Irreversible Climate Change ?

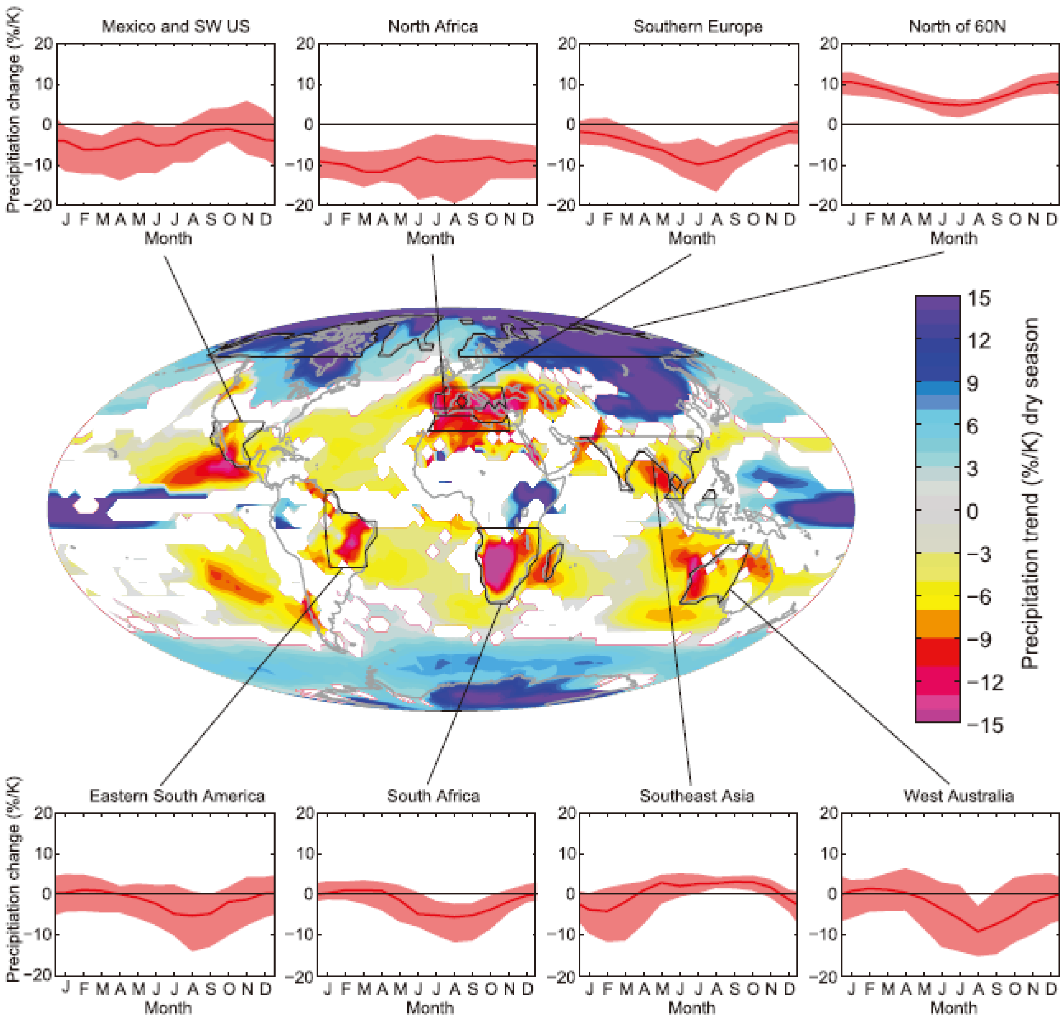


- irreversibility – climate change does not recover for 1000 years after emission stop
- Bern 2.5CC EMIC

(Solomon et al., 2009)



Irreversible Climate Change: Precipitation Change



(Solomon et al., 2009)

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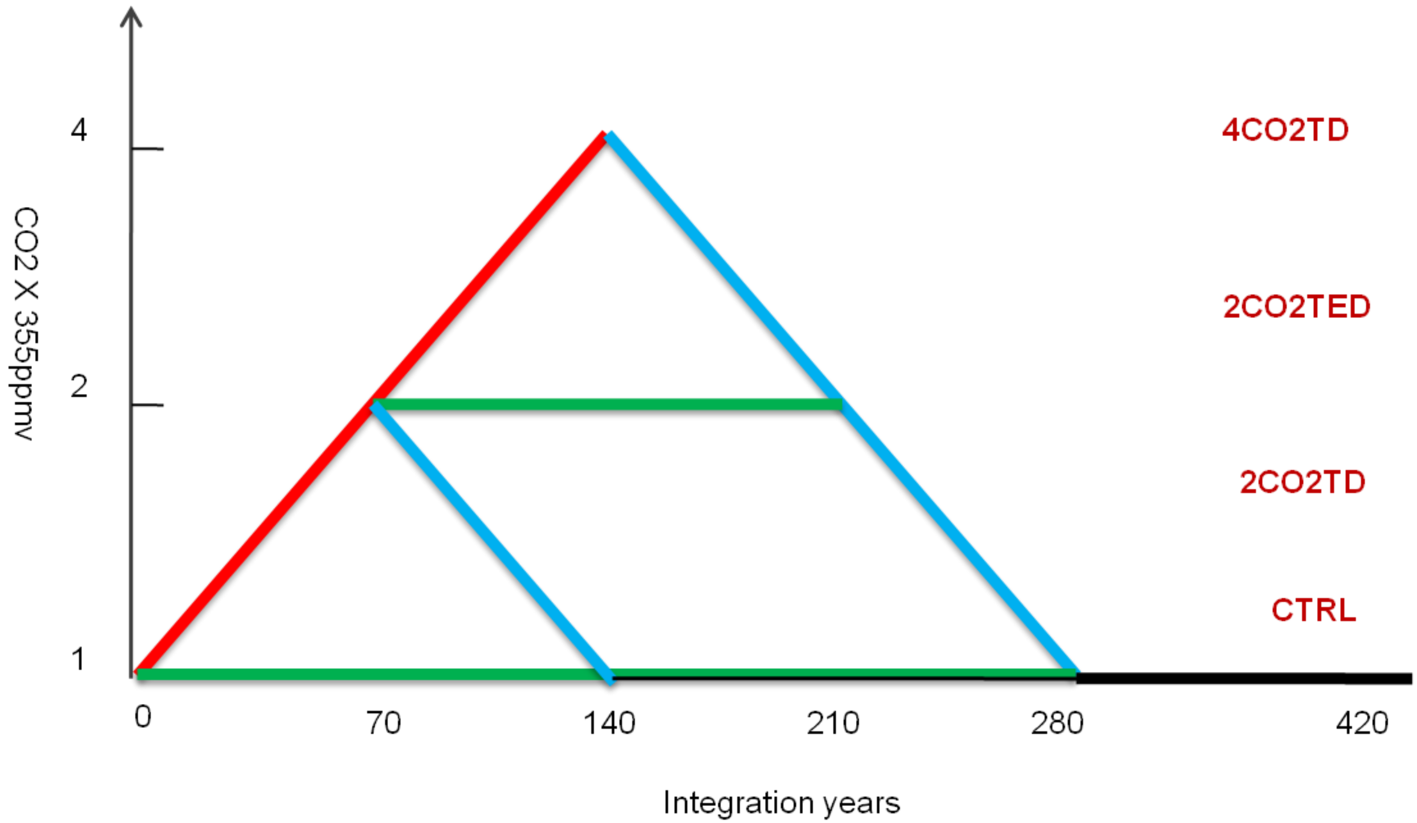
Questions

- Regarding the dramatic increase of CO2 now, can our climate system recover in the future if CO2 recovers?
  - Paleoclimate data during past 500k: CO_2 200~300 ppmv
  - Past 150 years: CO_2 nearly doubled.

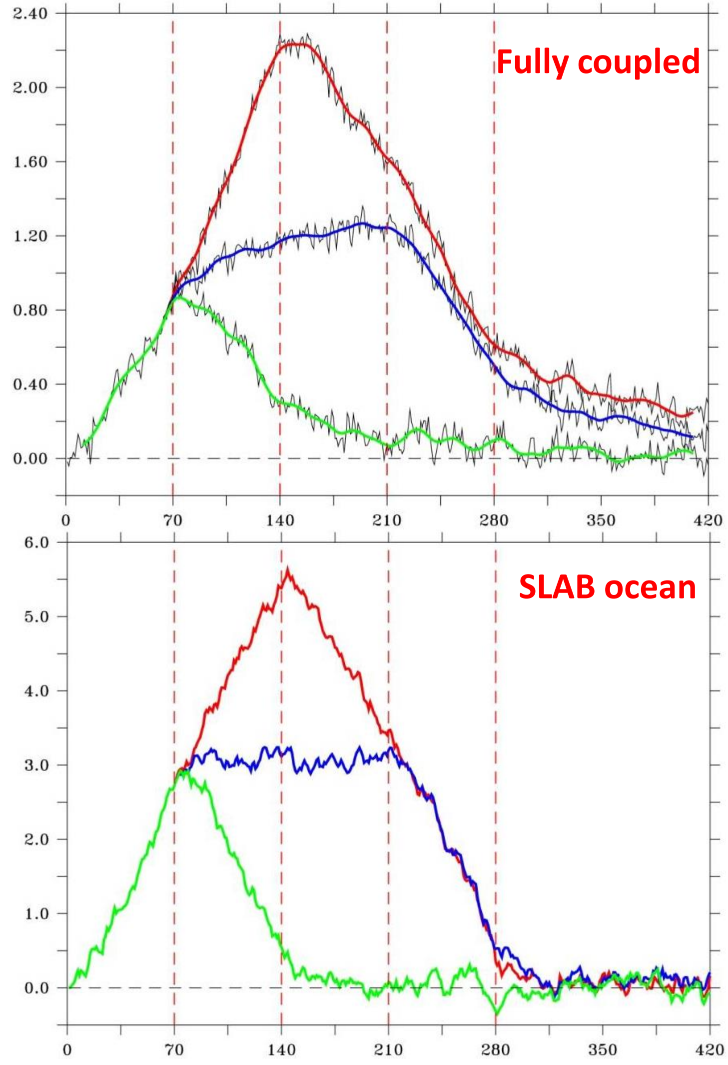
- If the climate system can recover, how many extra years it will take after CO2 recovery?
  - Ocean delay the recovery process.

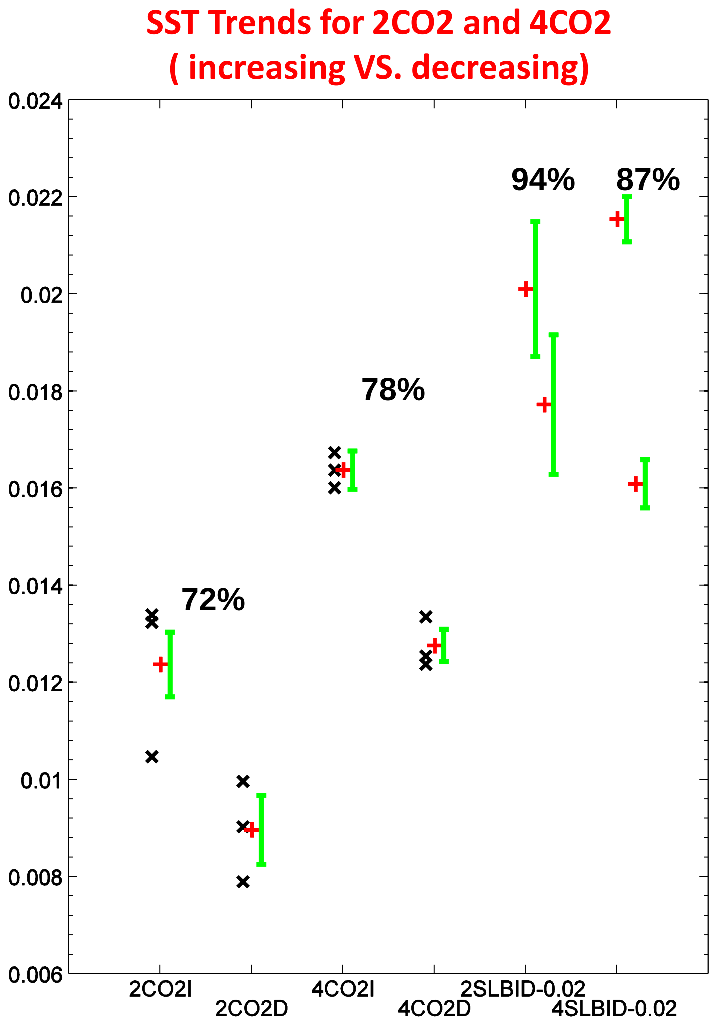
Experiments



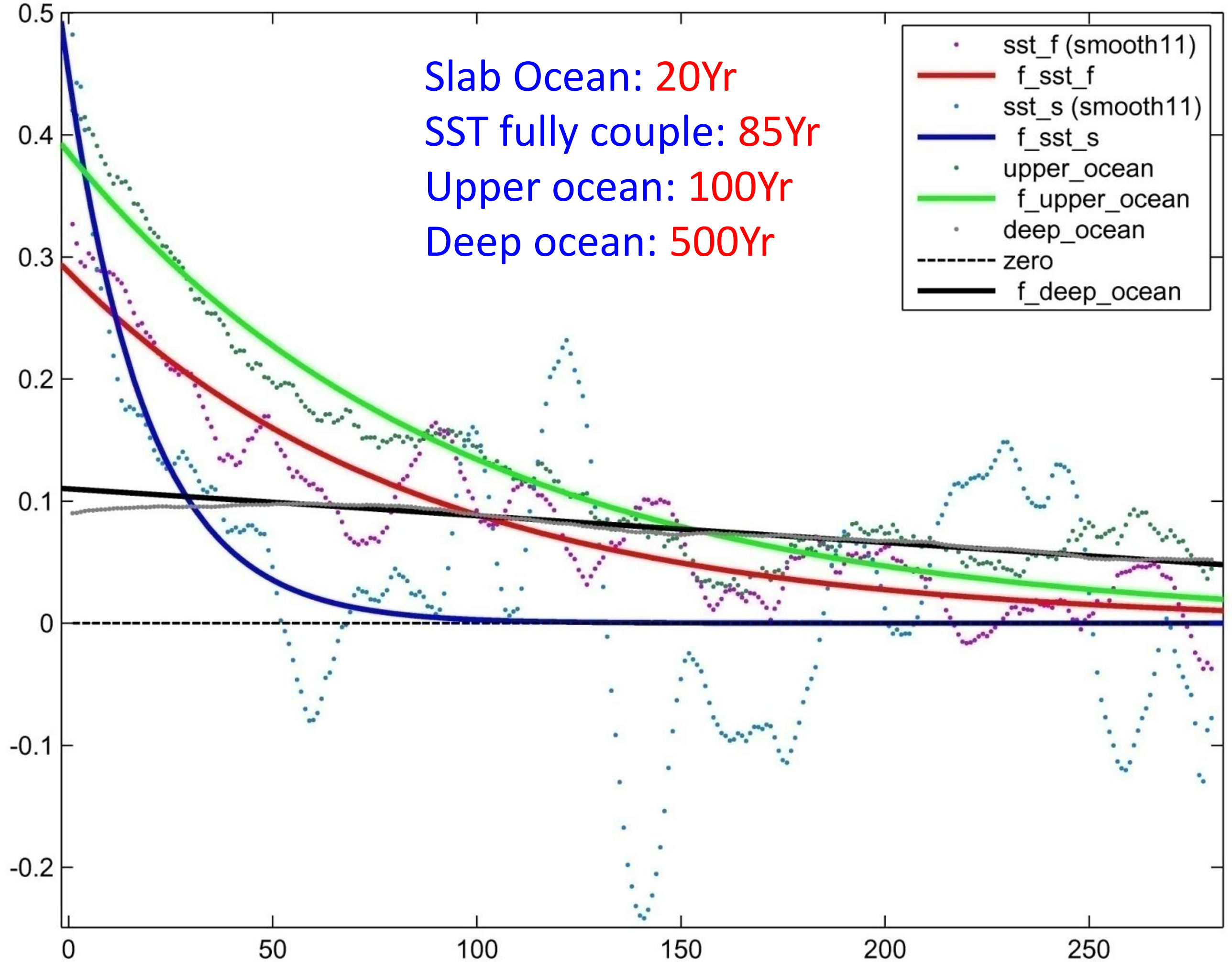
- All experiments run for 420 years
  - Each has 3 ensembles

General Evolution in Global SST

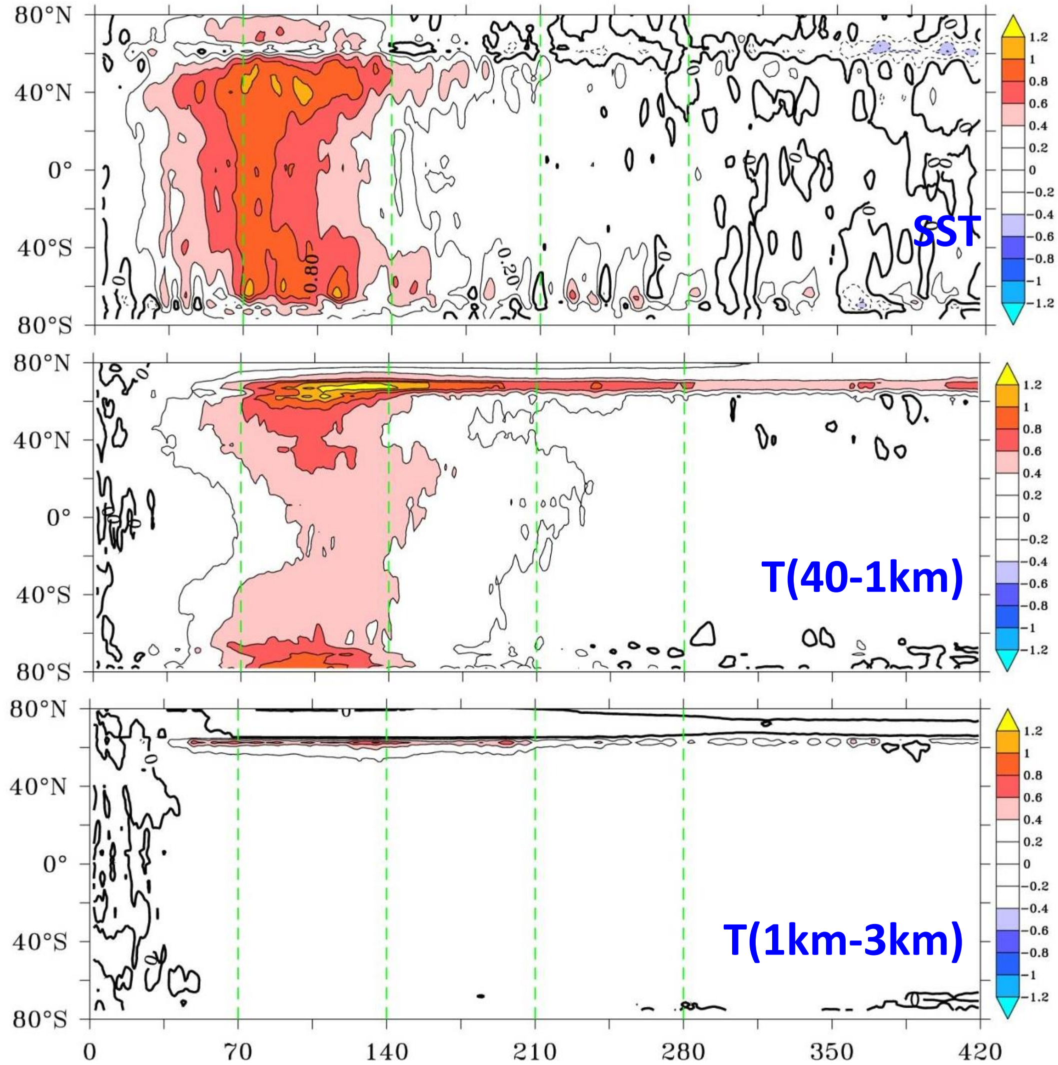




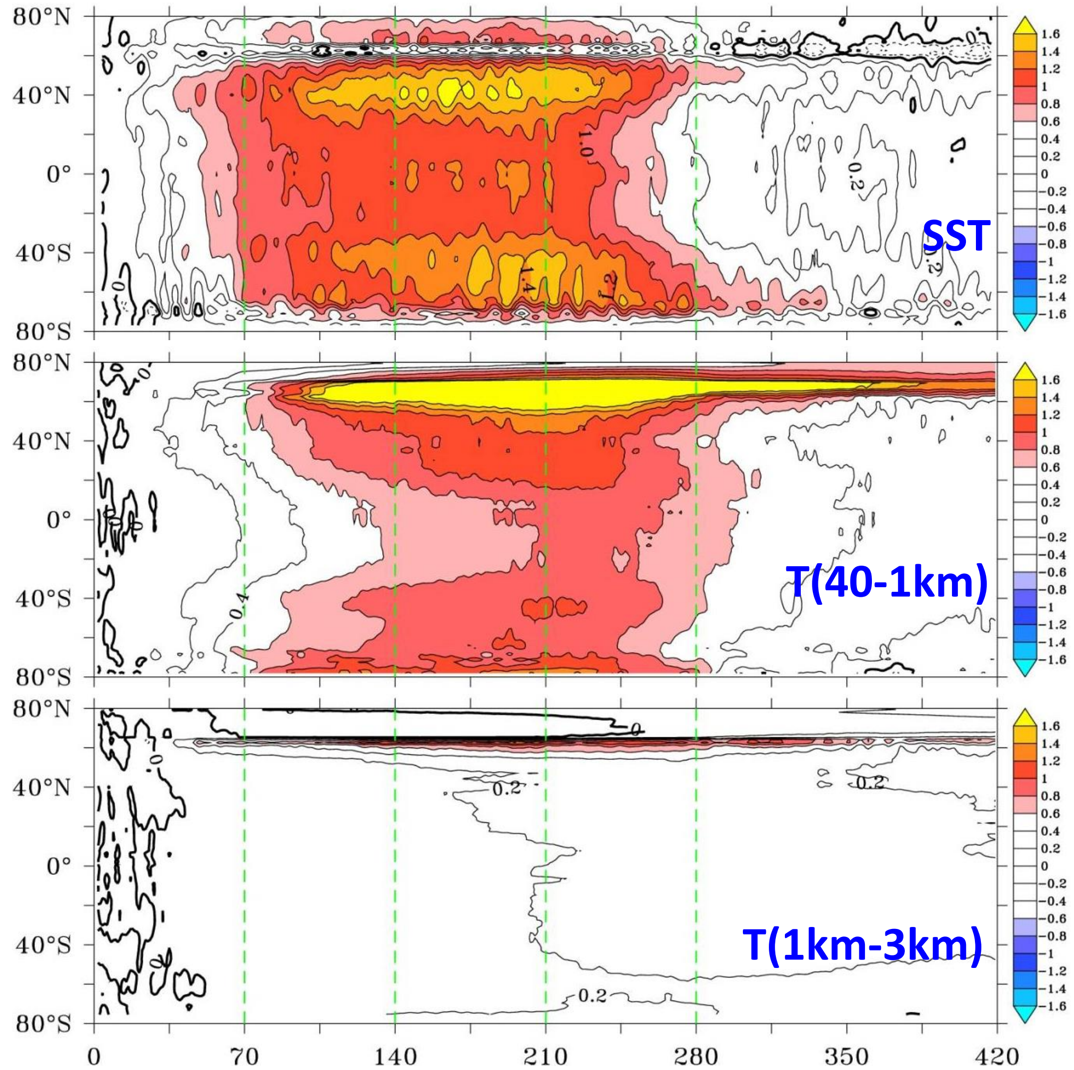
Recovery Time



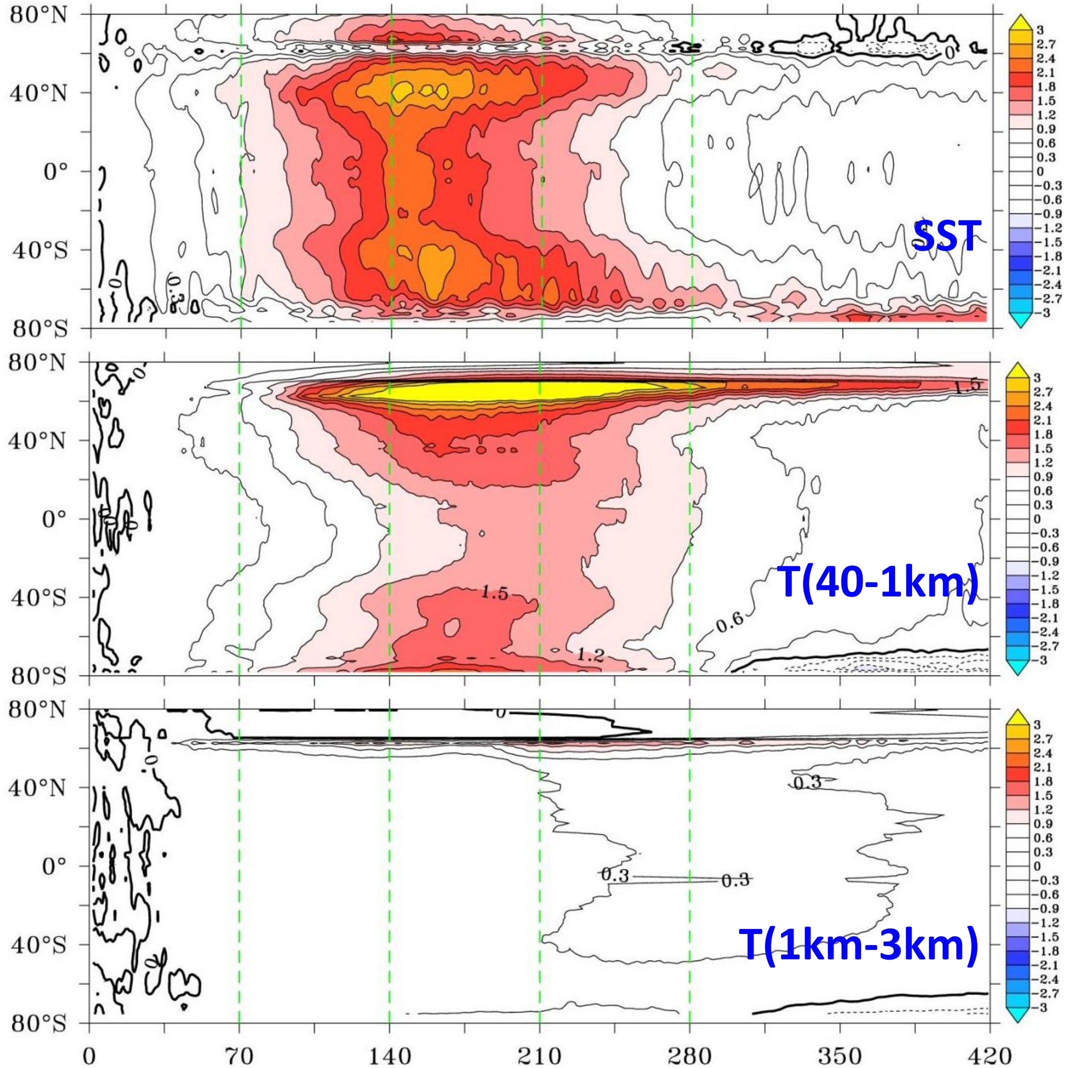
Evolution in Ocean Temperature in 2CO2TD



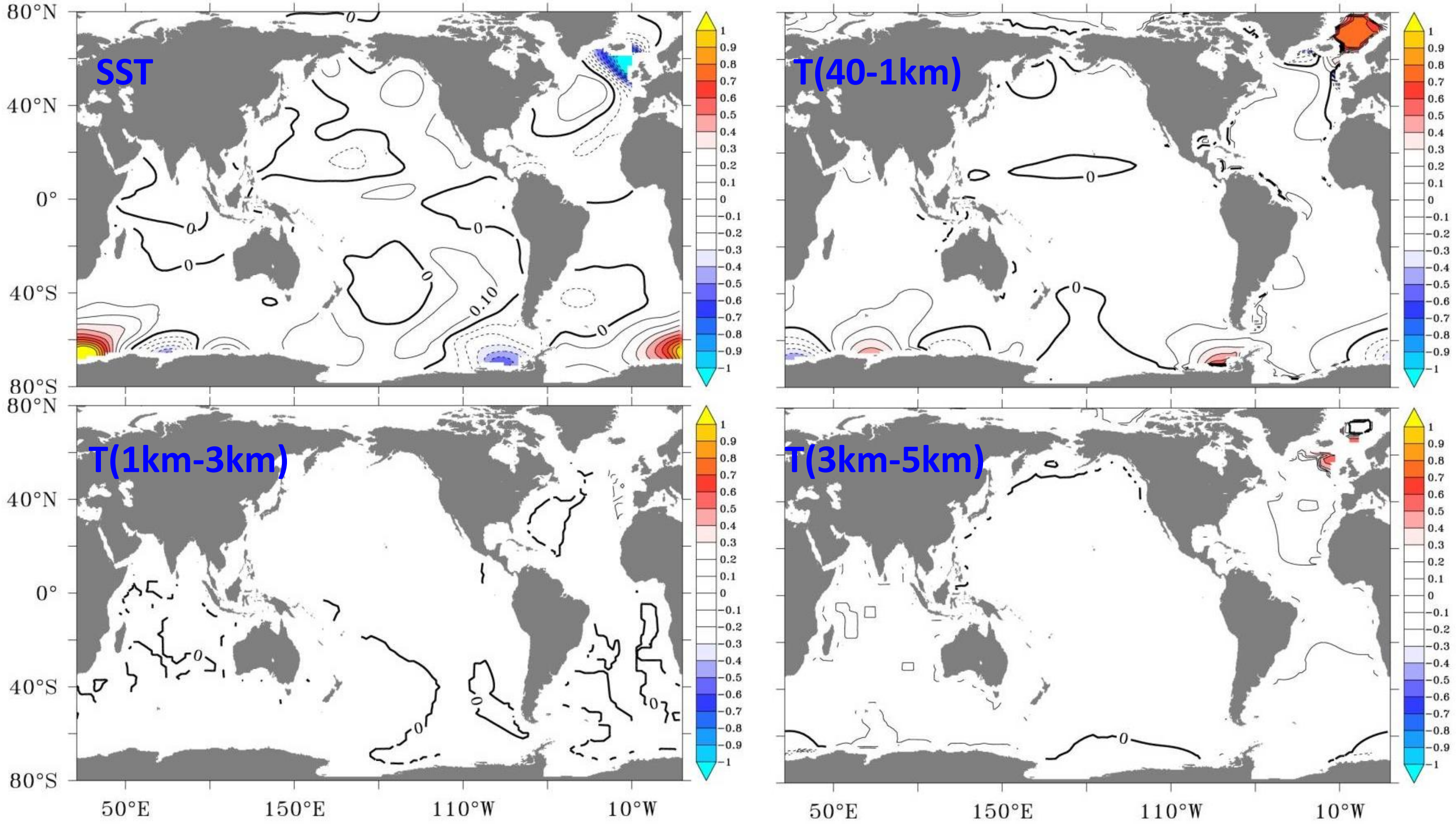
Evolution in Ocean Temperature in 2CO2TED



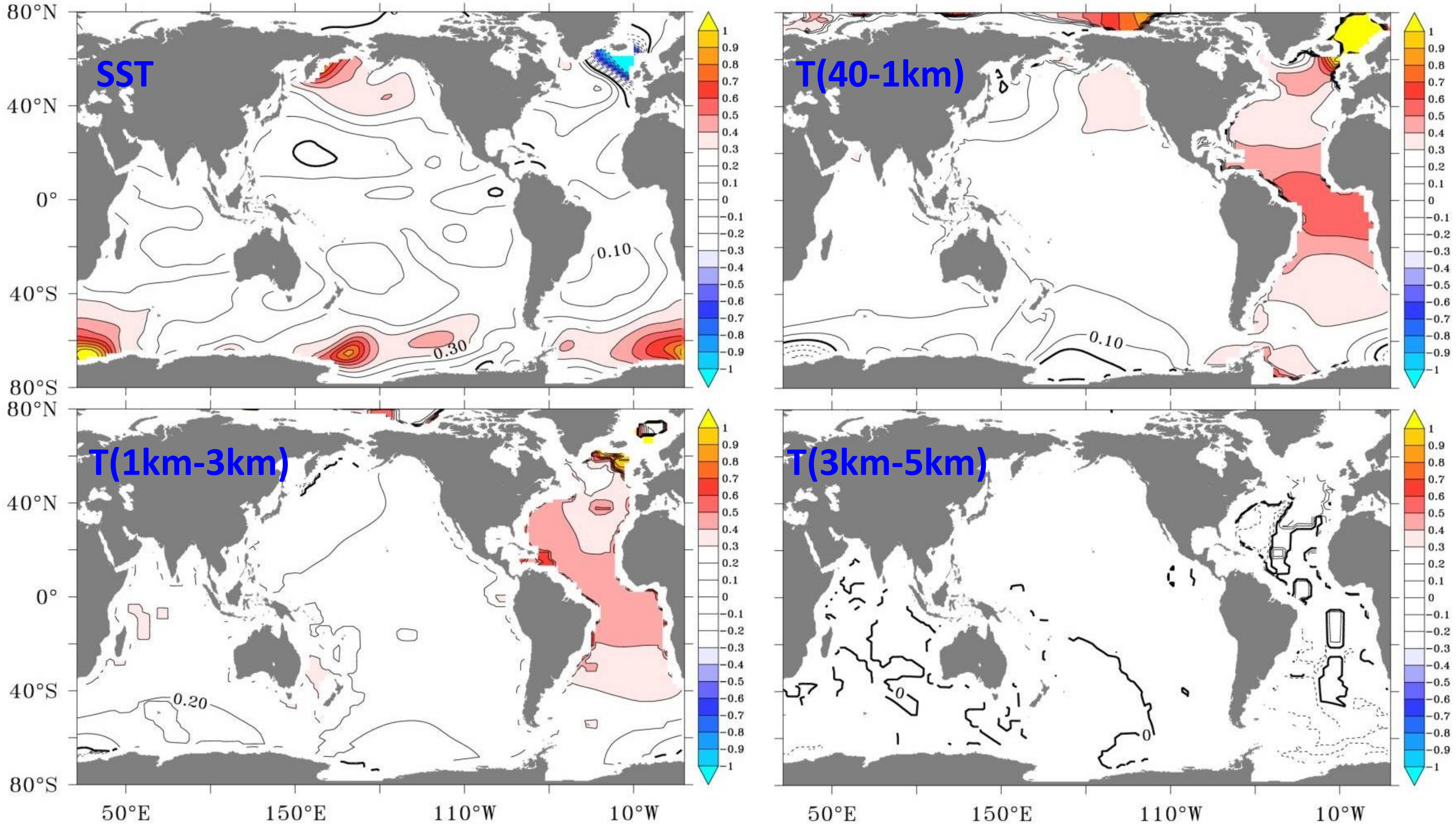
Evolution in Ocean Temperature in 4CO2TD



Residuals in 2CO2TD



Residuals in 2CO2TED



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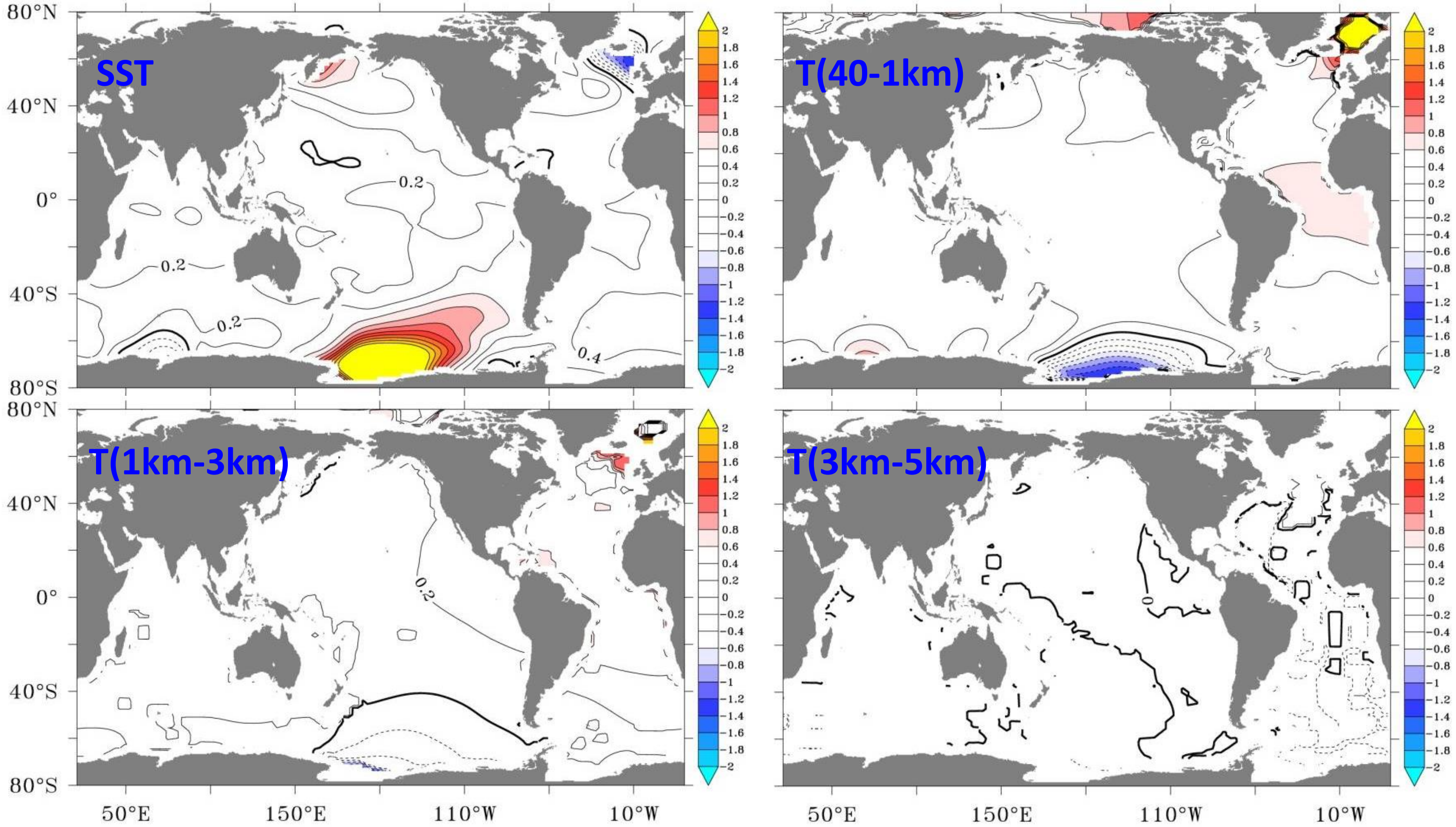
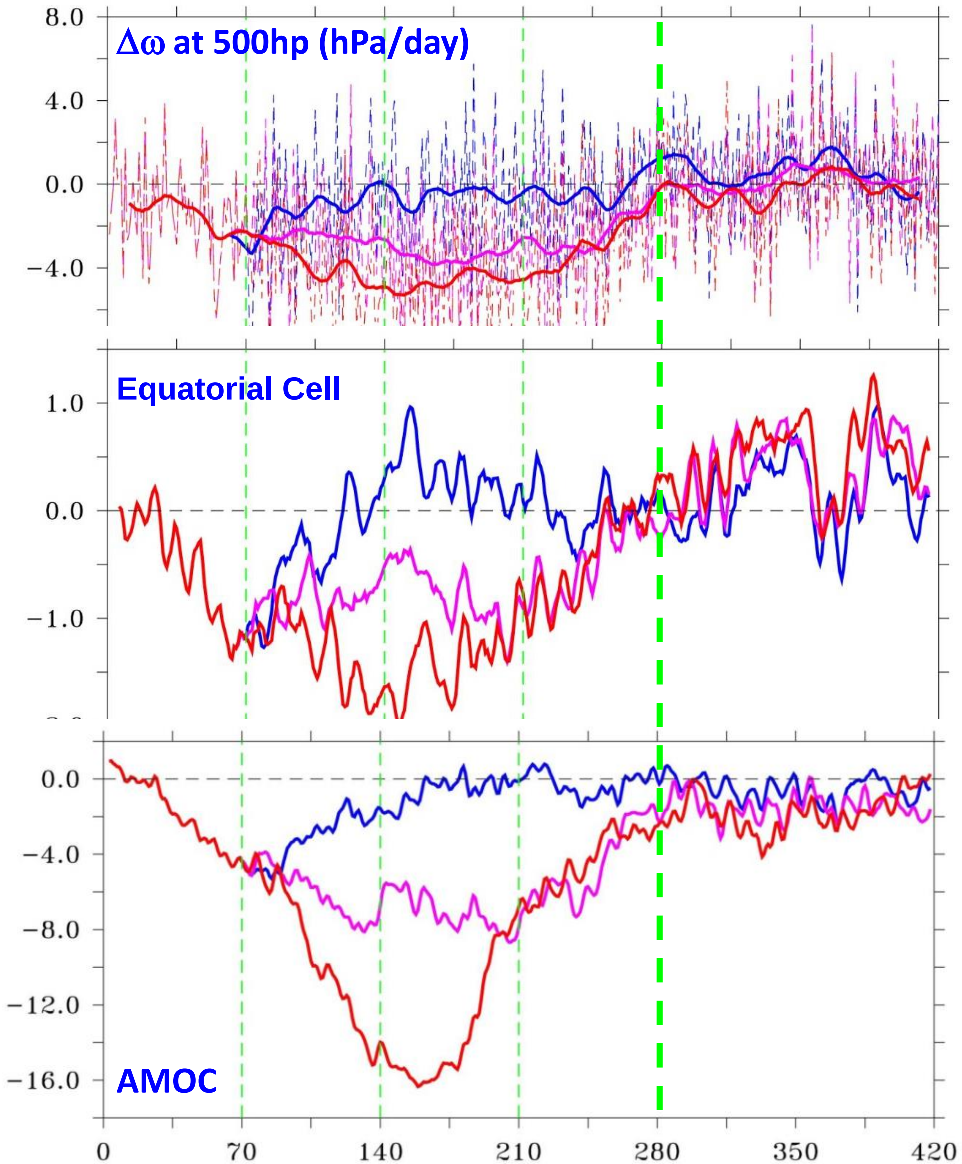
Residuals in 4CO2TD



Walker Circulation and STC and AMOC



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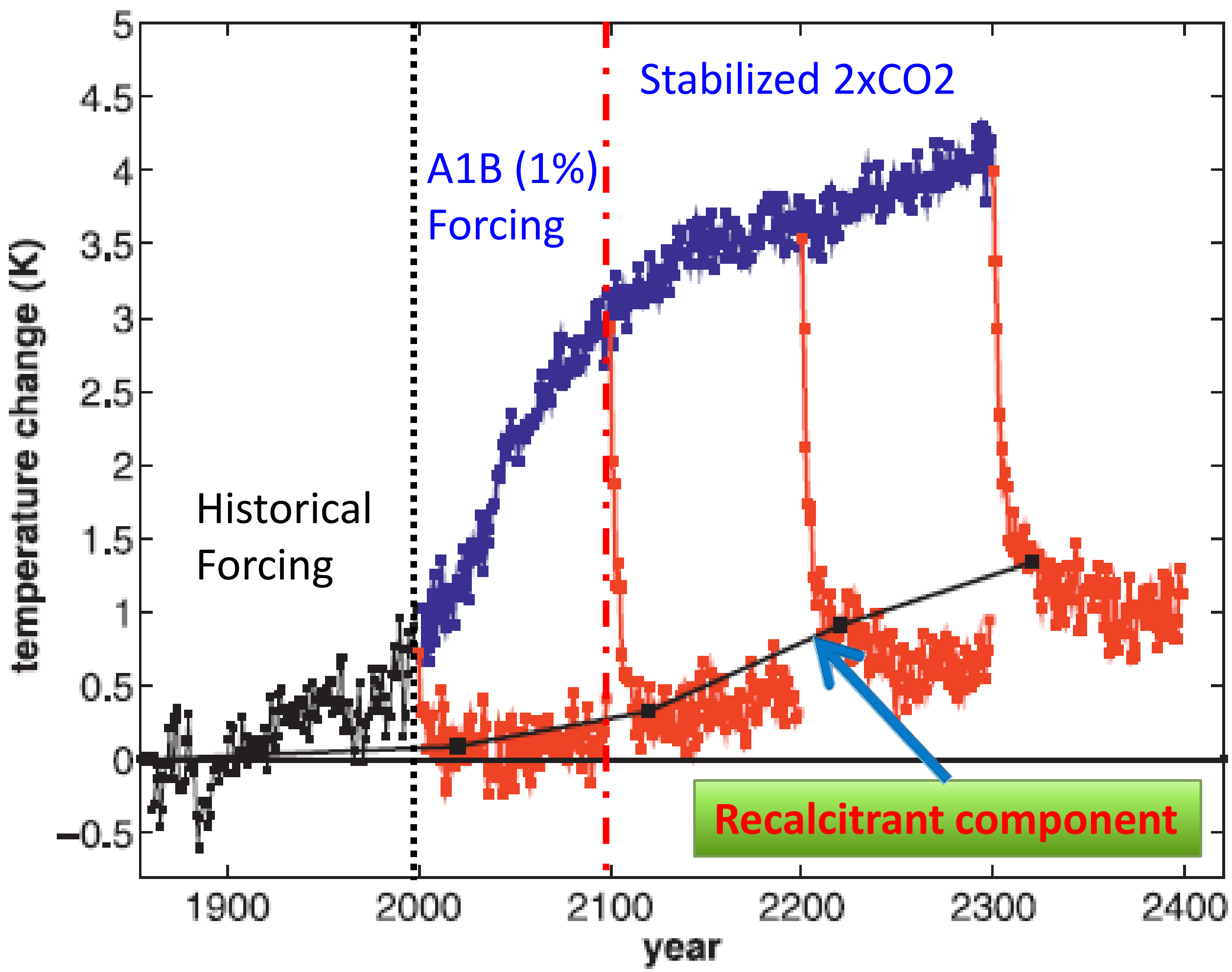
Conclusion and Implication

- Ocean delays the recovery and changes the reversibility of the climate system;
- Time scale: 20 Ys for surface ocean; >100 Ys for upper ocean; > 500 Ys for deep ocean;
- Earlier action for better recover

Sensitivity of SAT to the Slow Ocean



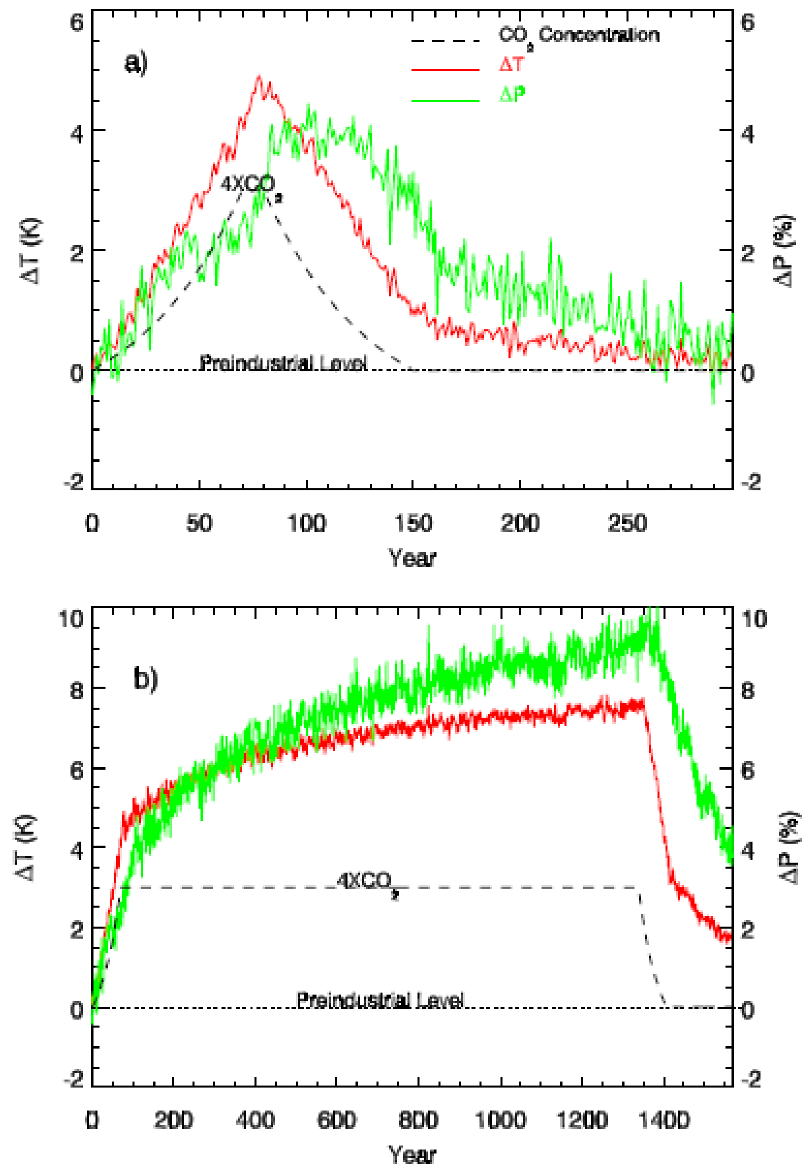
- Held et al., 2010: Probing the Fast and Slow Components of Global Warming by Returning Abruptly to Preindustrial Forcing. J. Climate, 2418-2427.

Time Evolution of SAT and Precipitation

- Wu et al., 2010: Temporary acceleration of the hydrological cycle in response to a CO2 rampdown. GRL, 37, L12705.

Hydrological sensitivity

- 1%/K during transient warming
- 1.6%/K during stabilization period



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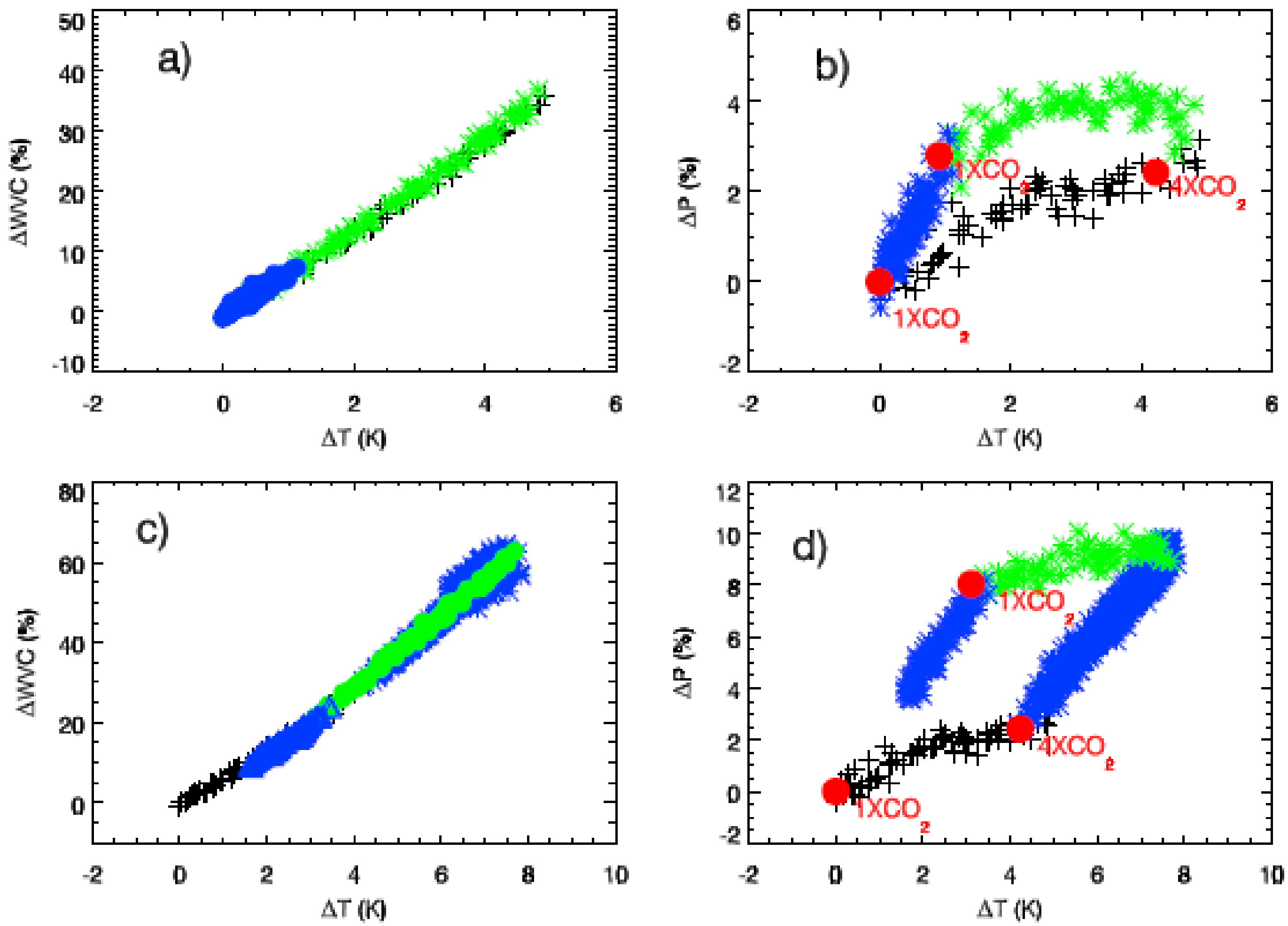
Nonlinearity and Hysteresis

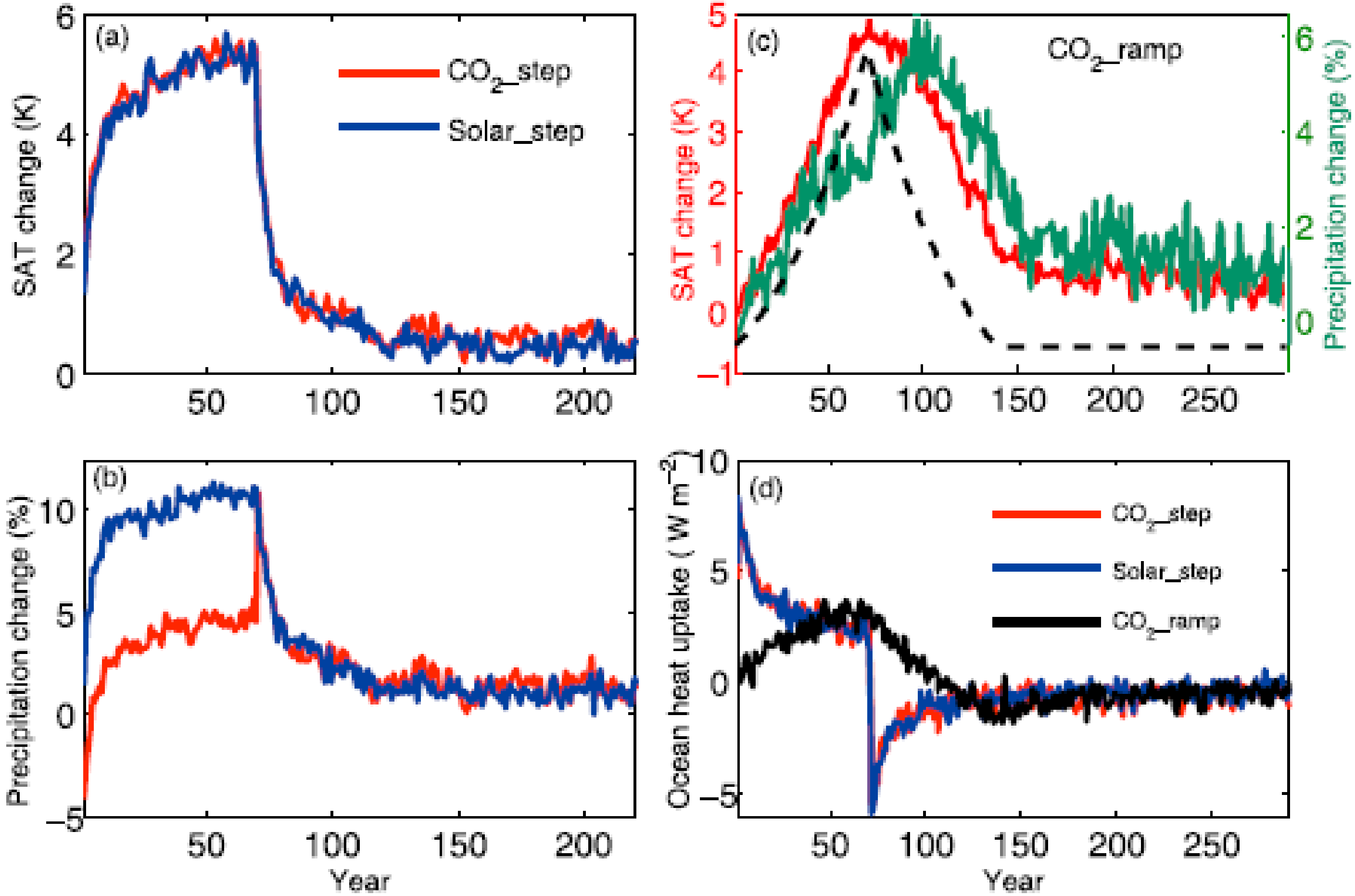


Water Vapour Content (WVC): Linear

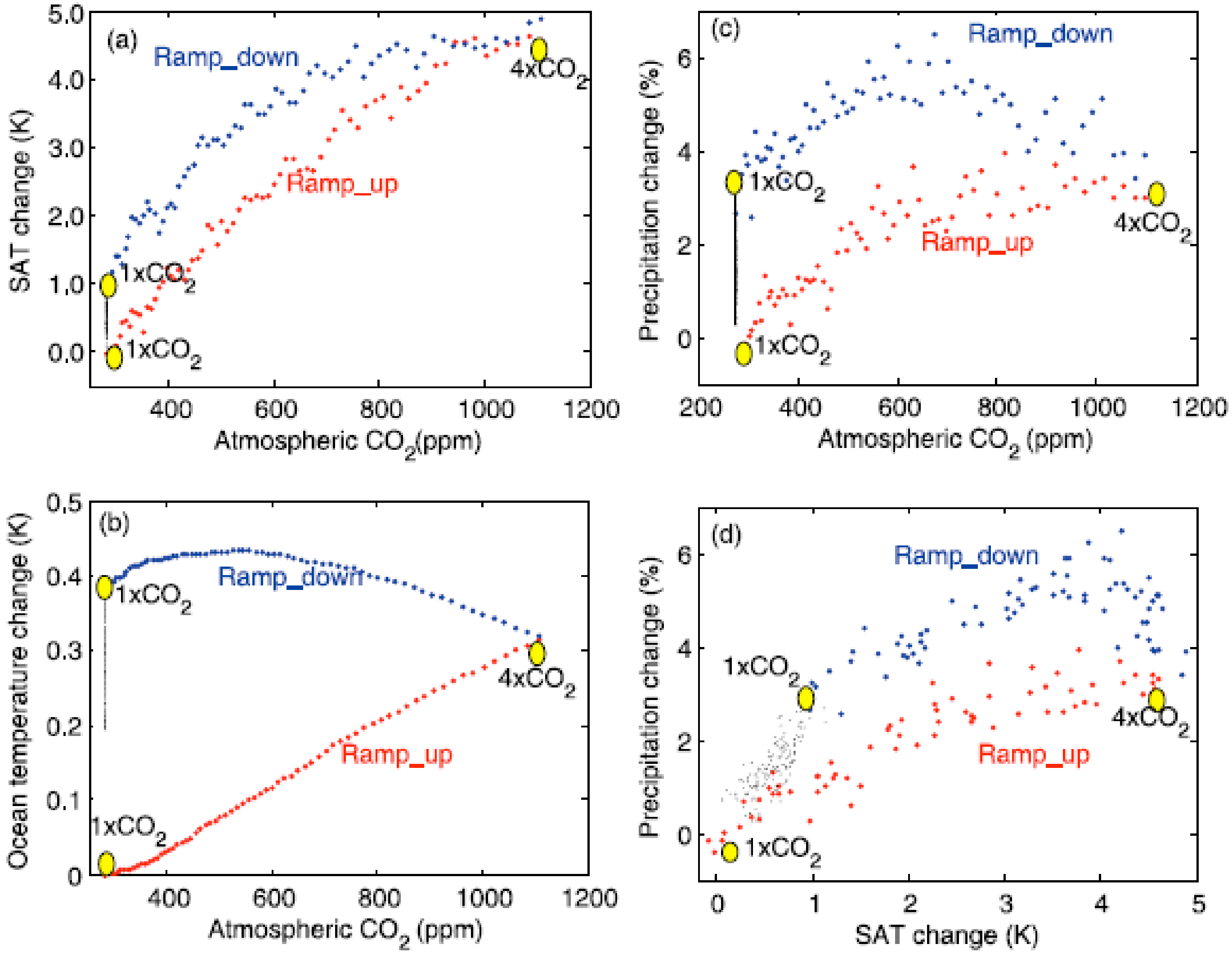
Hydrological Cycle (HC): Hysteresis

(Wu et al., 2010)

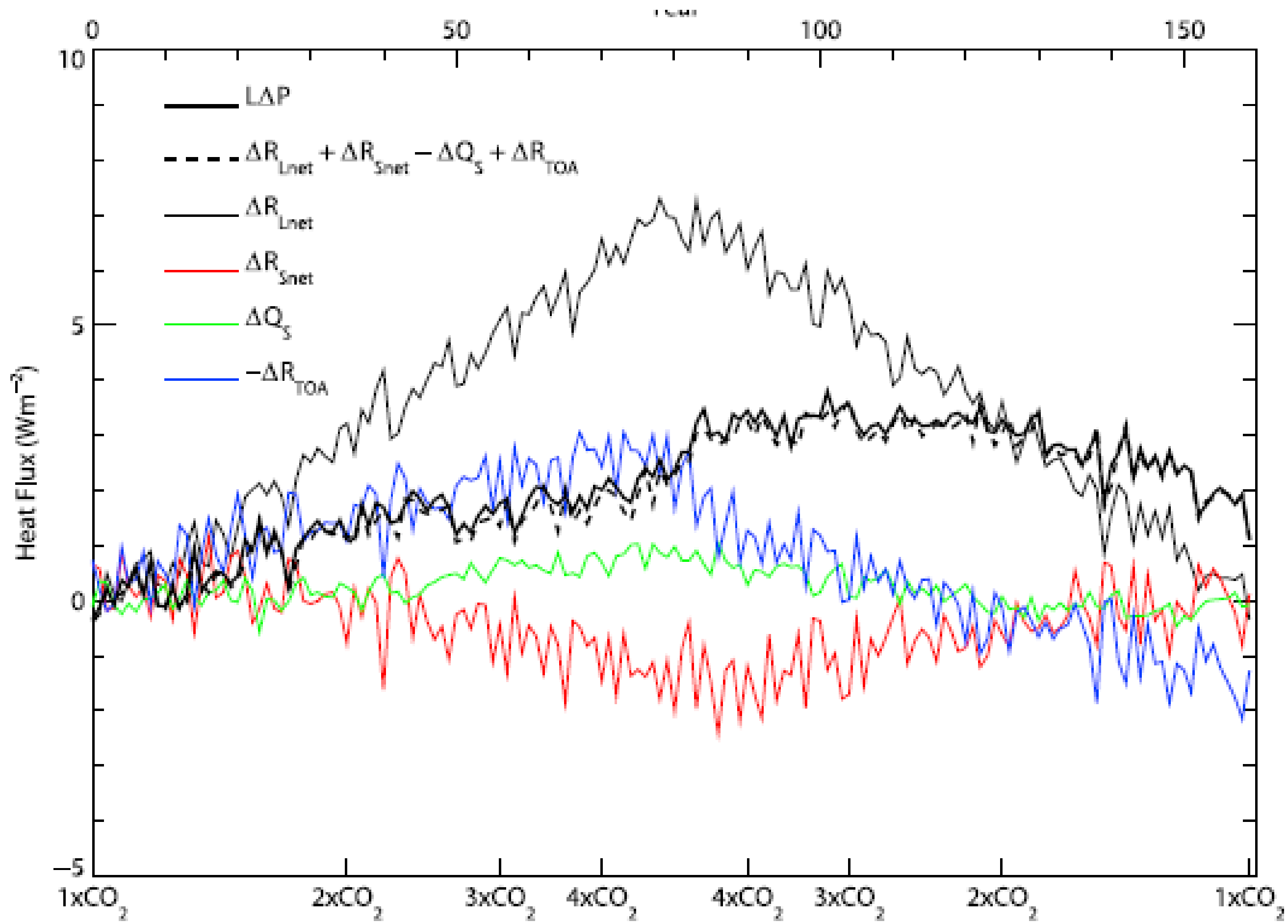
Precipitation in Response to Radiative Forcing



Hysteresis

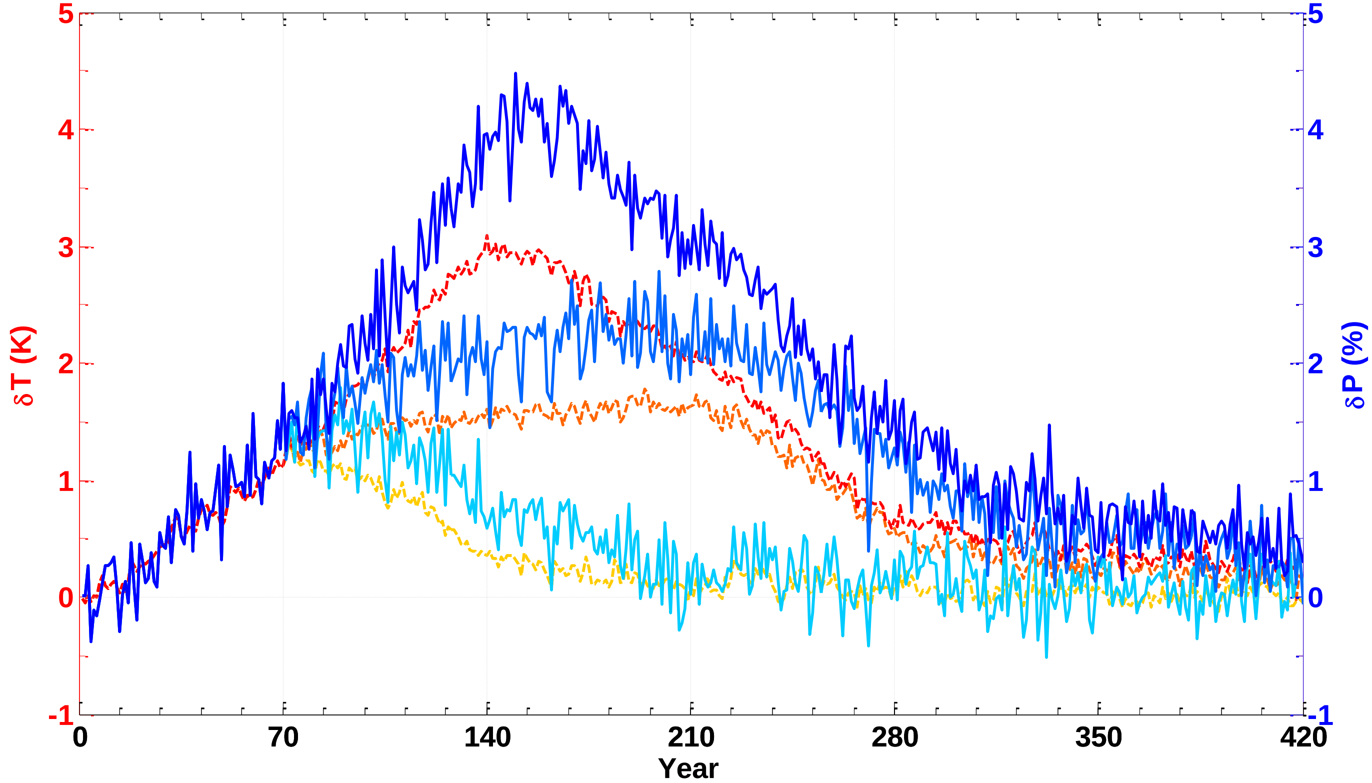

(a)
Ramp_down
Ramp_up
1xCO2
1xCO2
4xCO2
SAT change (K)
Atmospheric CO2(ppm)
(c)
Ramp_down
Ramp_up
1xCO2
1xCO2
4xCO2
Precipitation change (%)
Atmospheric CO2 (ppm)
(b)
Ramp_down
Ramp_up
1xCO2
1xCO2
4xCO2
Ocean temperature change (K)
Atmospheric CO2 (ppm)
(d)
Ramp_down
Ramp_up
1xCO2
1xCO2
4xCO2
Precipitation change (%)
SAT change (K)

Hysteresis in Surface Energy Budget



Hydrological cycle hysteresis mainly due to ocean heat uptake

Time Evolution of SAT and Precipitation



Hydrological sensitivity: 1.3-1.5%/K

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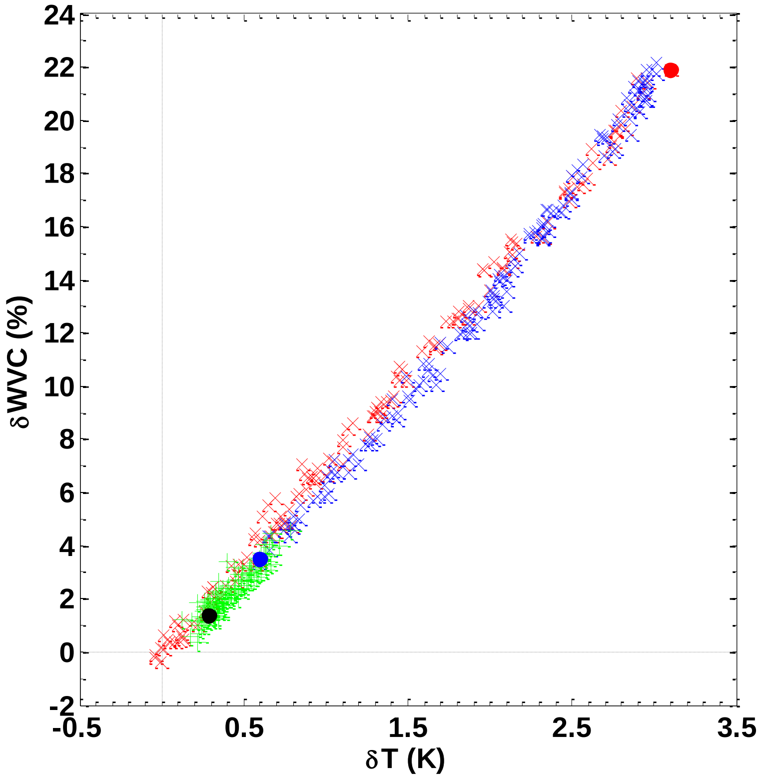
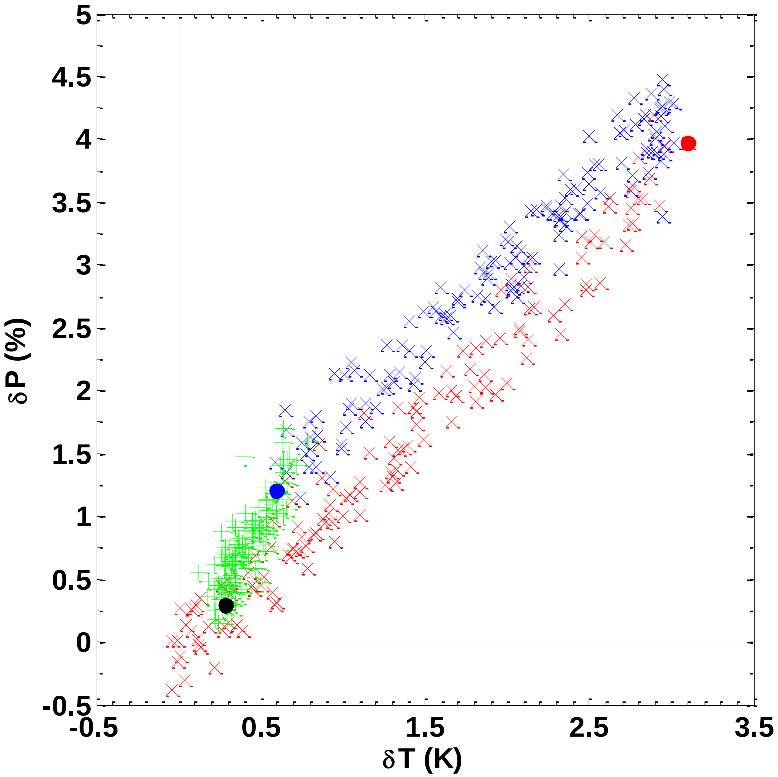
Nonlinearity and Hysteresis

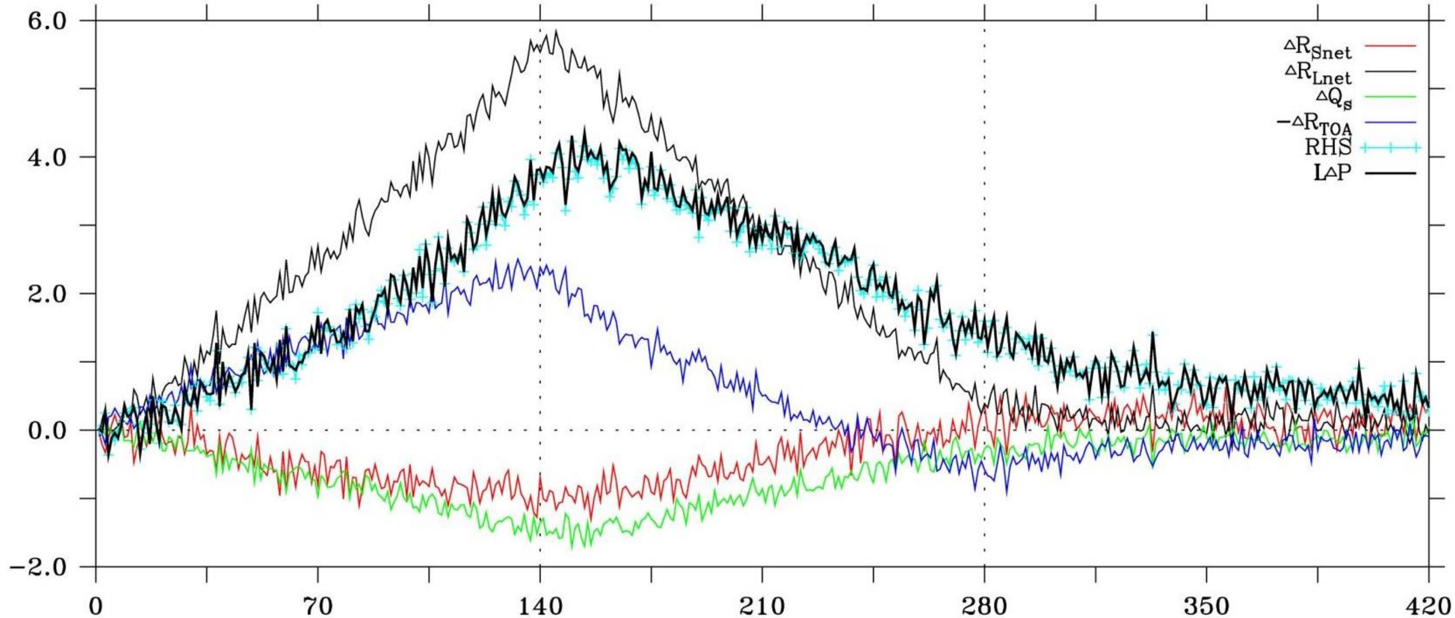




WVC vs. △SAT: Linear

HC: △P vs. △SAT: Hysteresis

Surface Energy Budget



$$L\Delta P = \Delta R_{Lnet} + \Delta R_{Snet} - \Delta Q_s + \Delta R_{TOA}$$

Summary

- Timescale for equilibrium response
  - 100s-1000s years
  - Sensitive to the sign of external forcing
- Timescale for climate recovery
  - Earlier action for better recover
- Reversibility of climate change
  - Very long time, hysteresis, unpredictable and irreversible

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