The "Pattern Effect": Conceptual Frameworks

US CLIVAR Pattern Effect Workshop
5/10/2022

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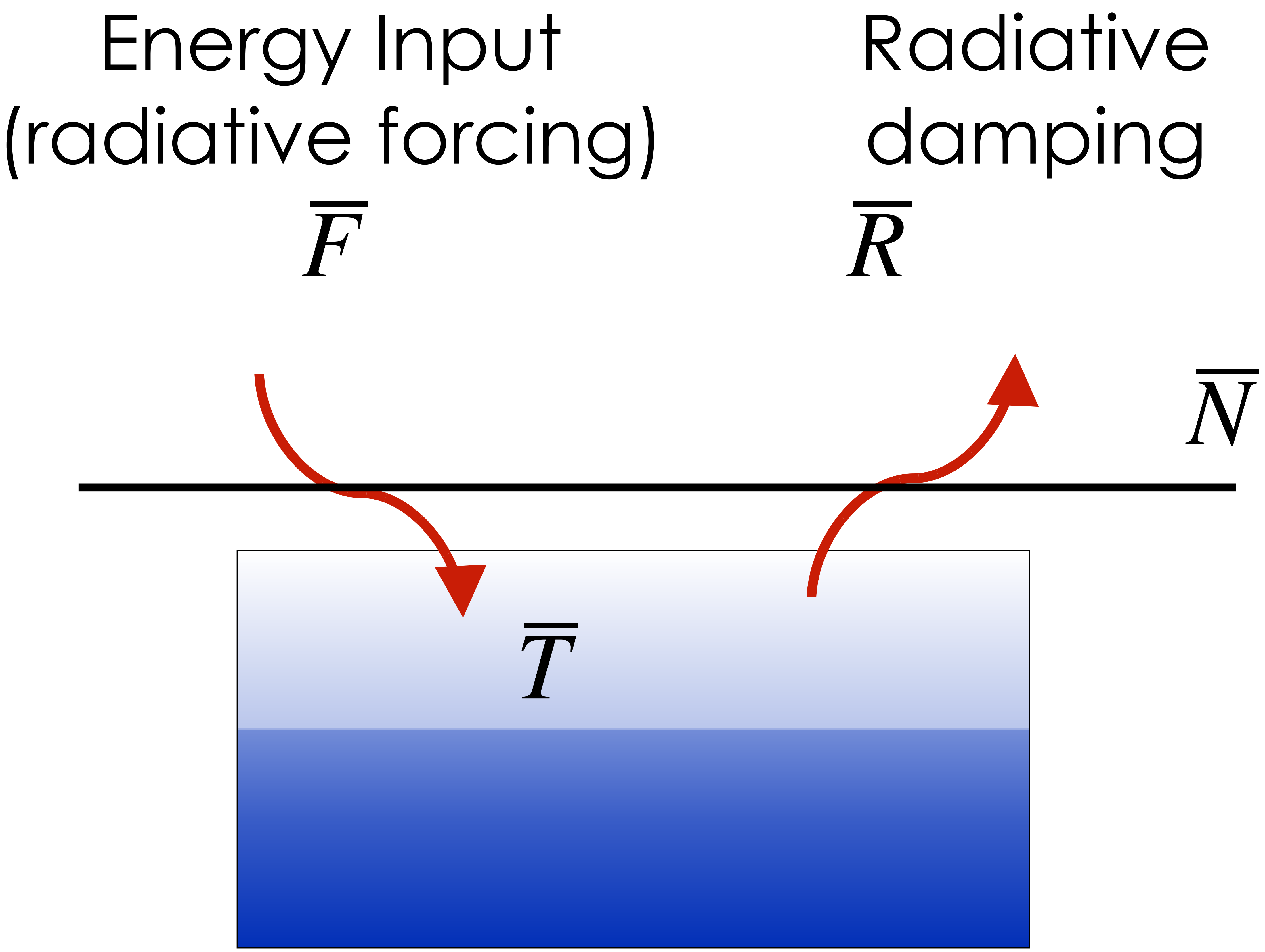
Roadmap

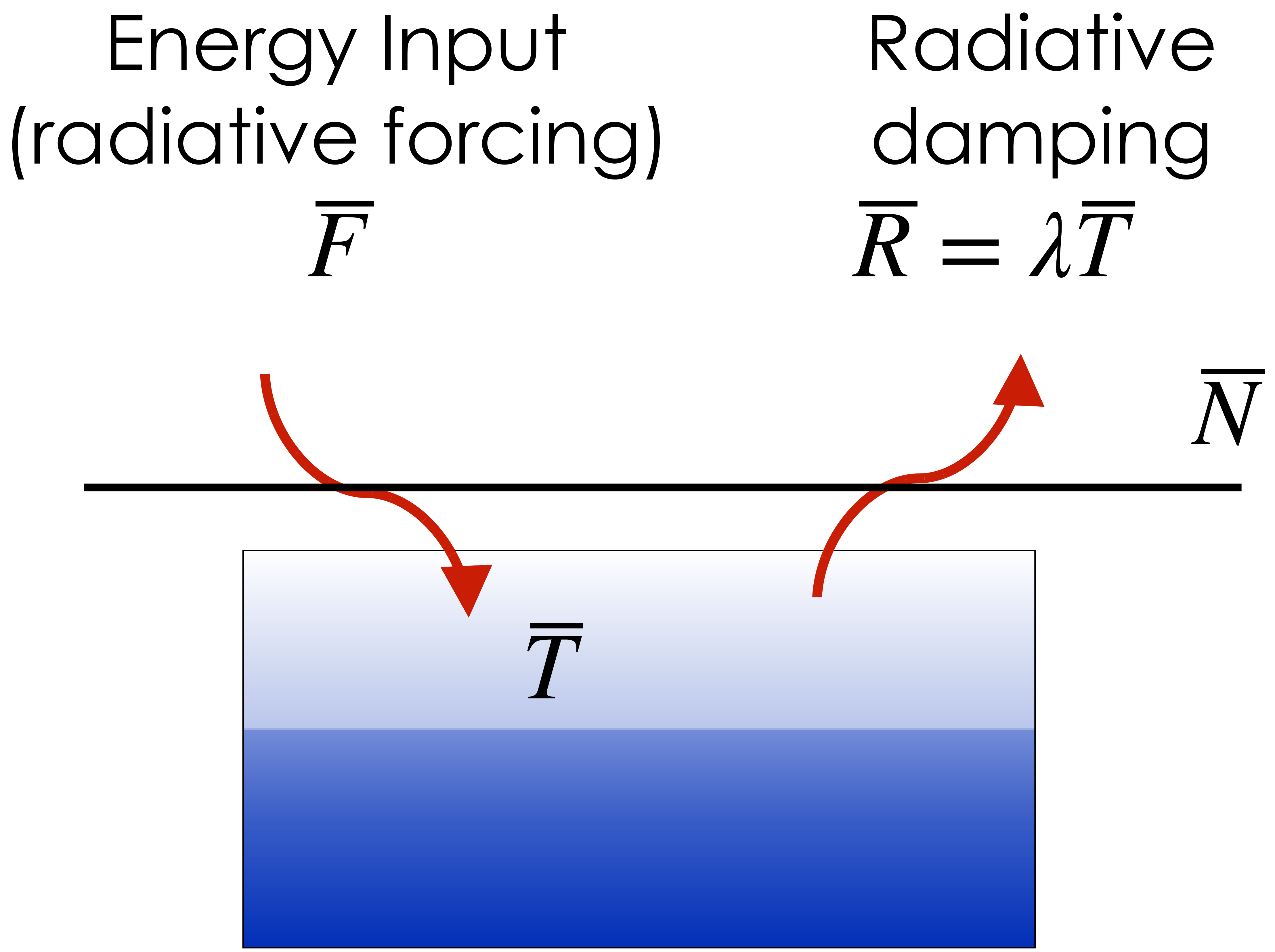
- **Global feedback framework and it’s failure**
- A refined view of the radiative response
- Open Questions
  - Radiative response
  - Forcing and heat uptake
  - Patterns

Energy Budget



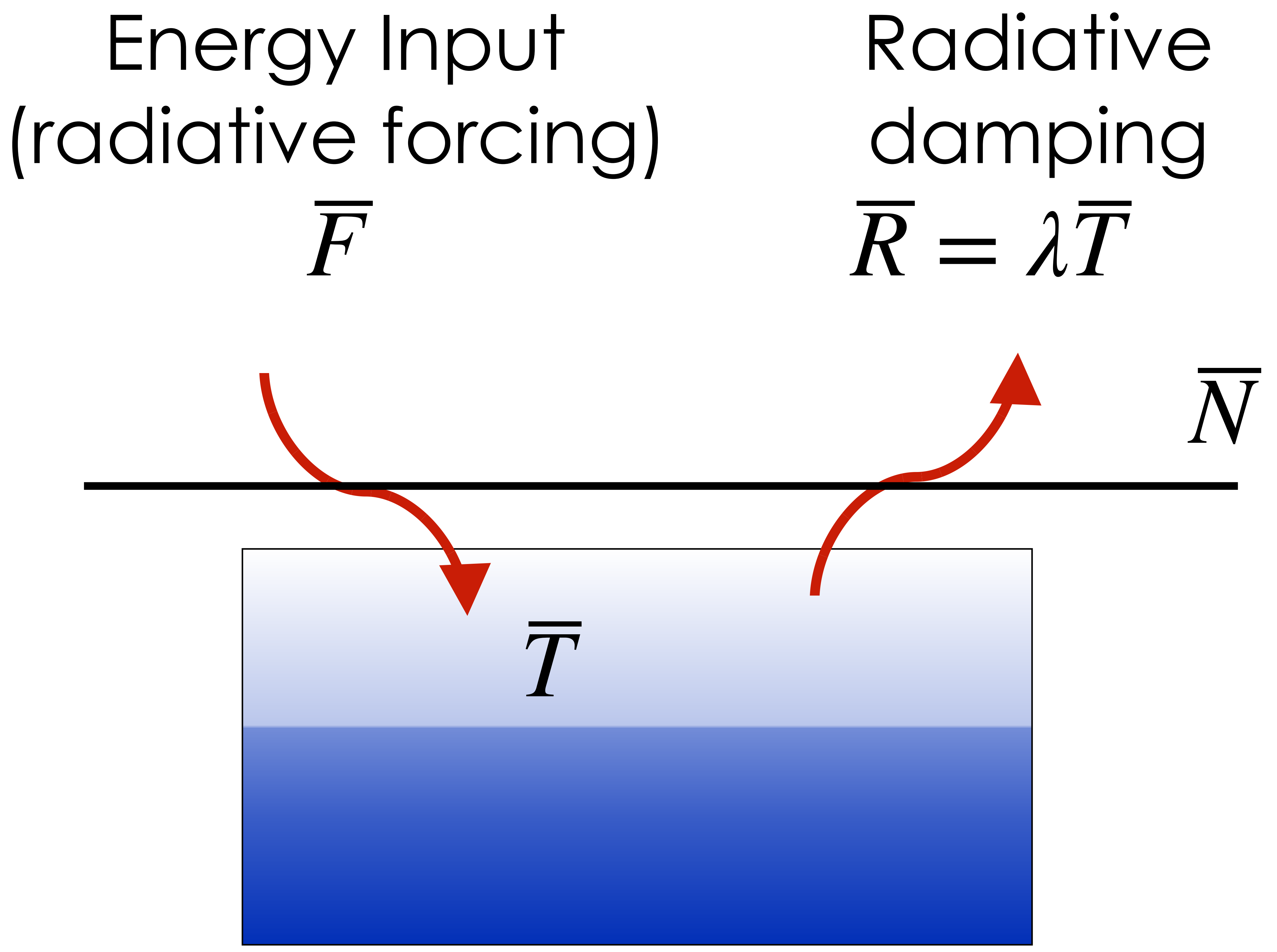
$$\overline{N} = \overline{F} + \overline{R}$$

Radiative feedback λ



$$\boxed{\overline{N} = \overline{F} + \lambda \overline{T}}$$

If you know λ you know ECS



$$\overline{N} = \overline{F} + \lambda \overline{T}$$

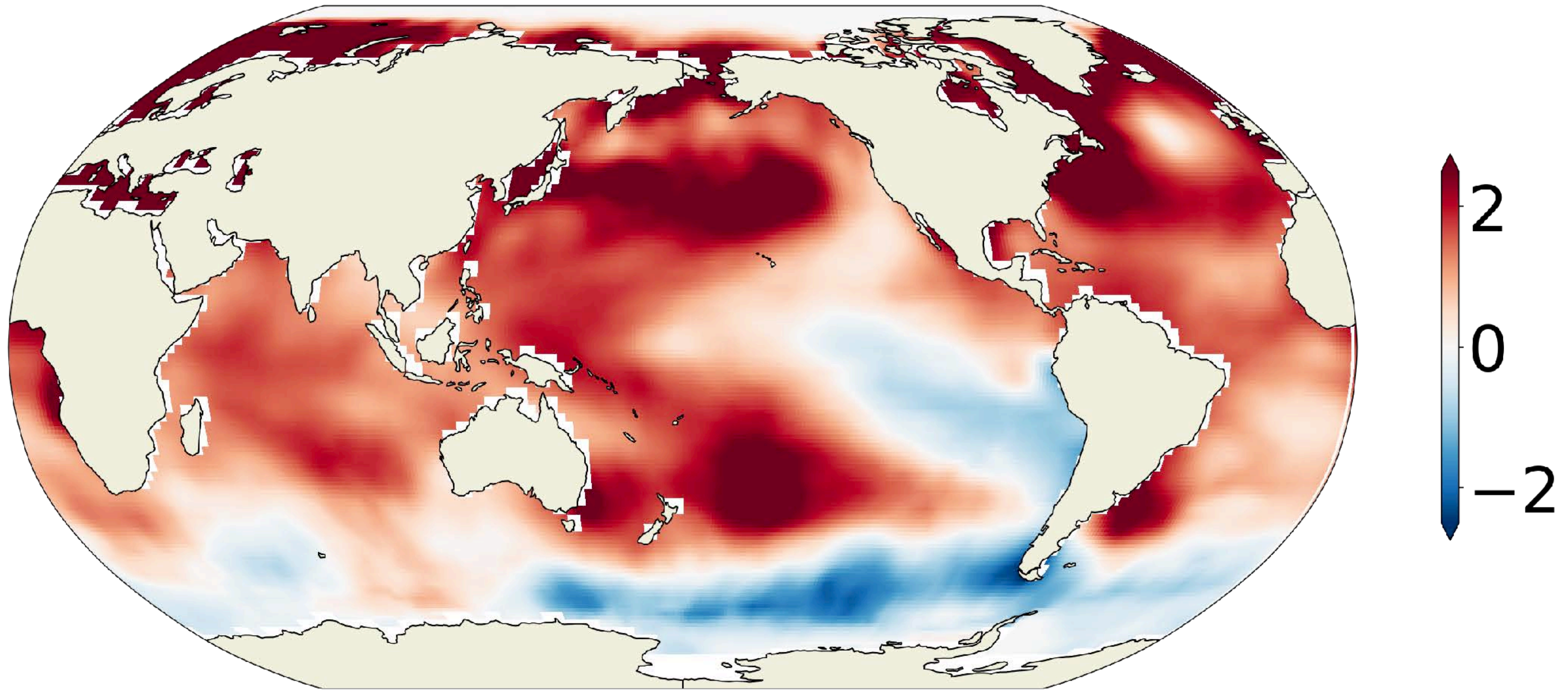
Equilibrium: $\overline{N} = 0$

$$\overline{T}_{eq} = \frac{\overline{F}}{\lambda}$$

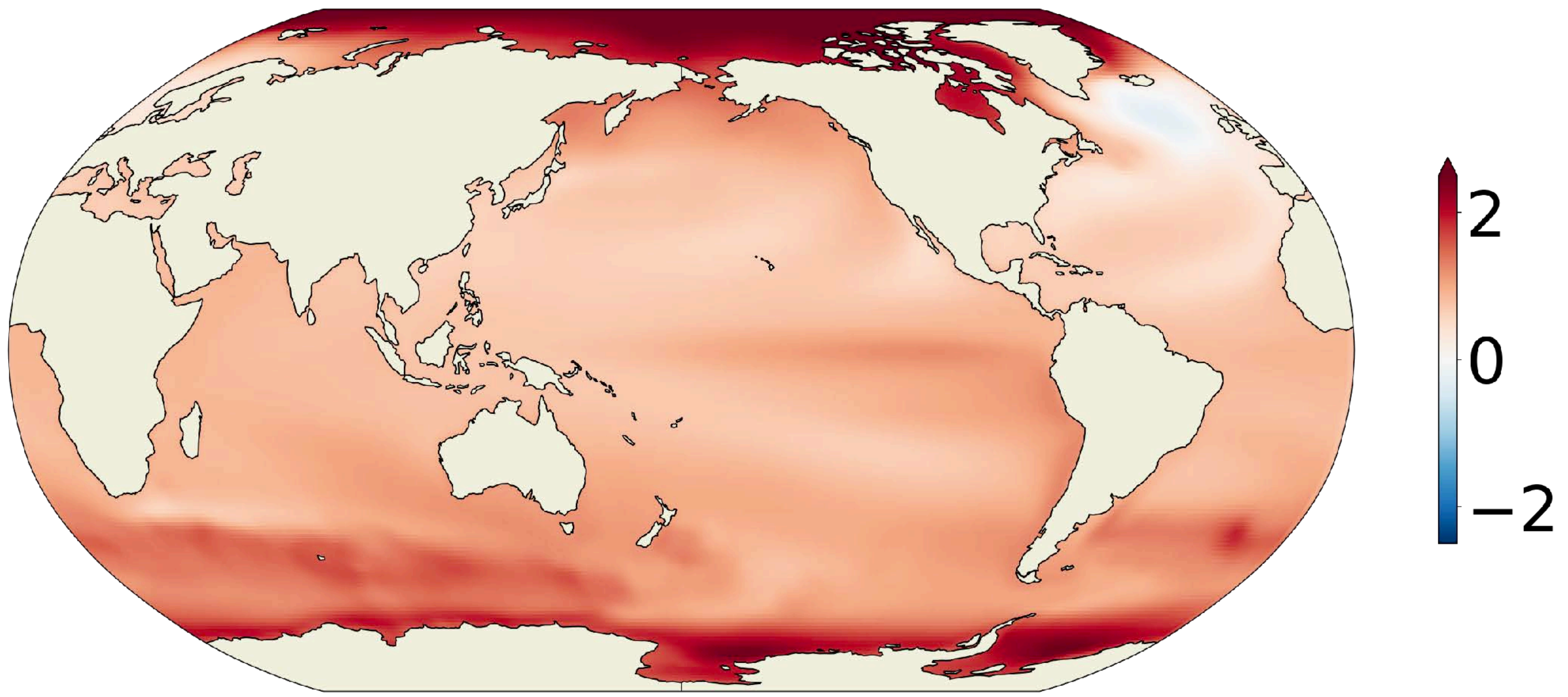
Gregory et al 2002, Otto et al 2013, Forster 2016

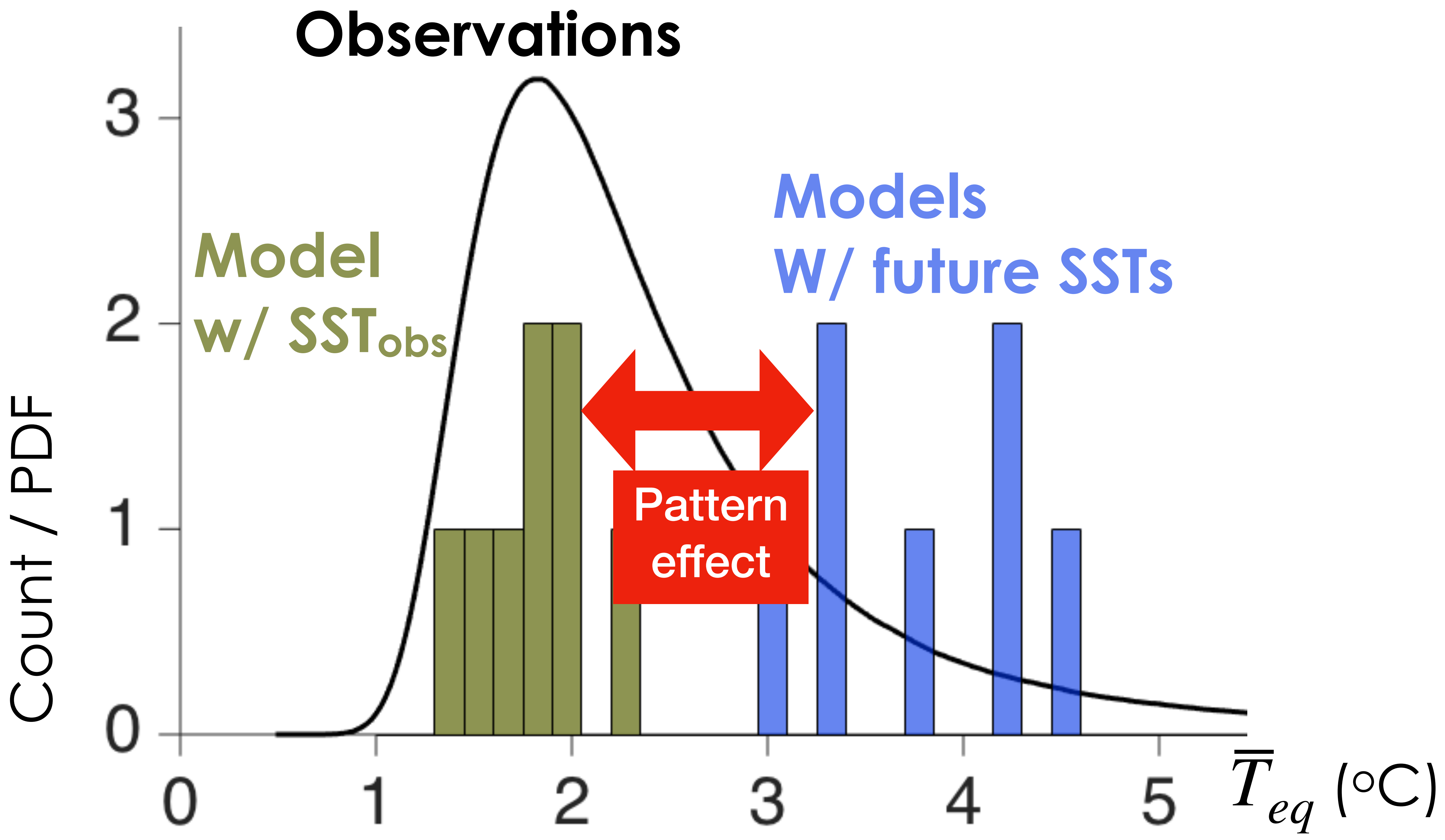
Estimates of ECS

NOAA ERSST 1979-2020



abrupt4xCO2



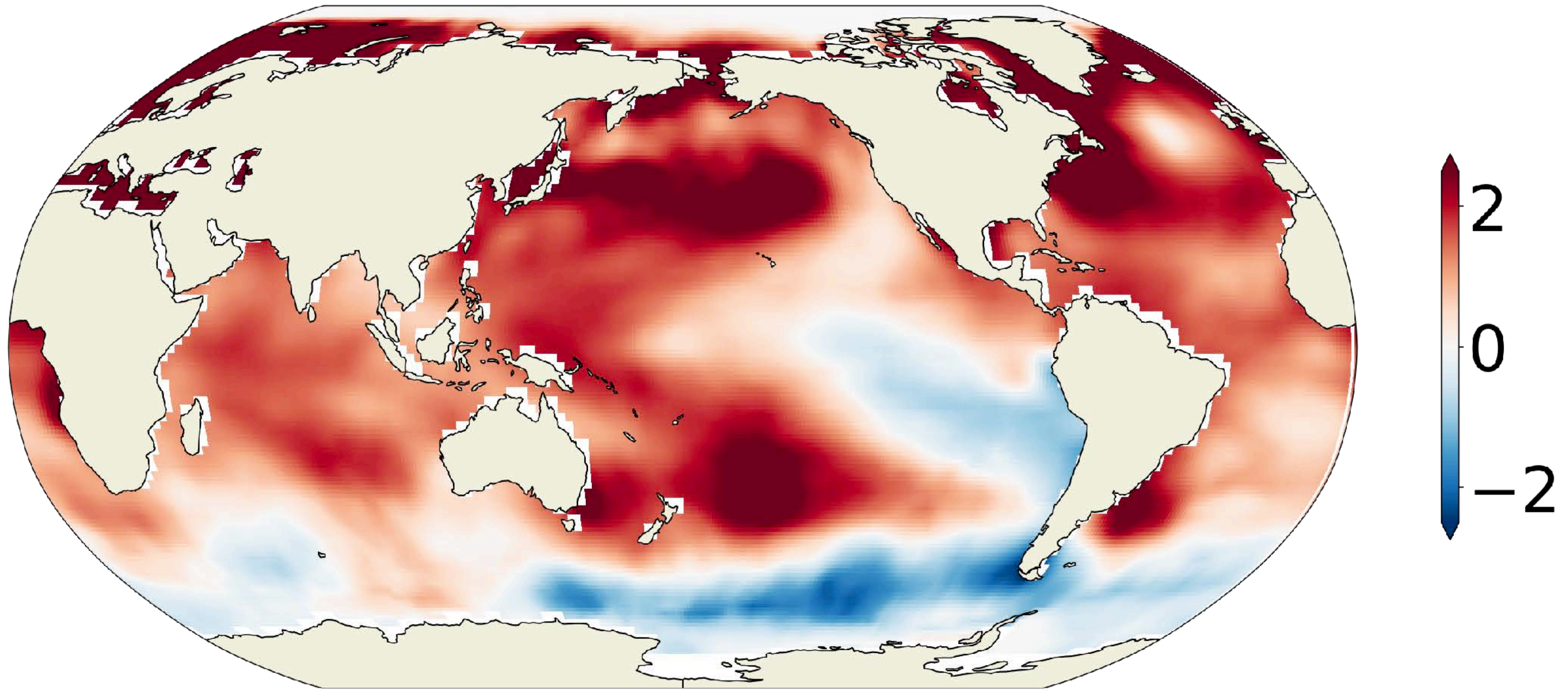


$$\overline{T}_{eq} = \frac{\overline{F}}{\lambda}$$

Murphy et al 1996, Senior and Mitchell 2000, Winton et al 2010, Sherwood et al 2020, Andrews et al 2018 , etc, etc, etc

Turns out radiative response is complicated

NOAA ERSST 1979-2020



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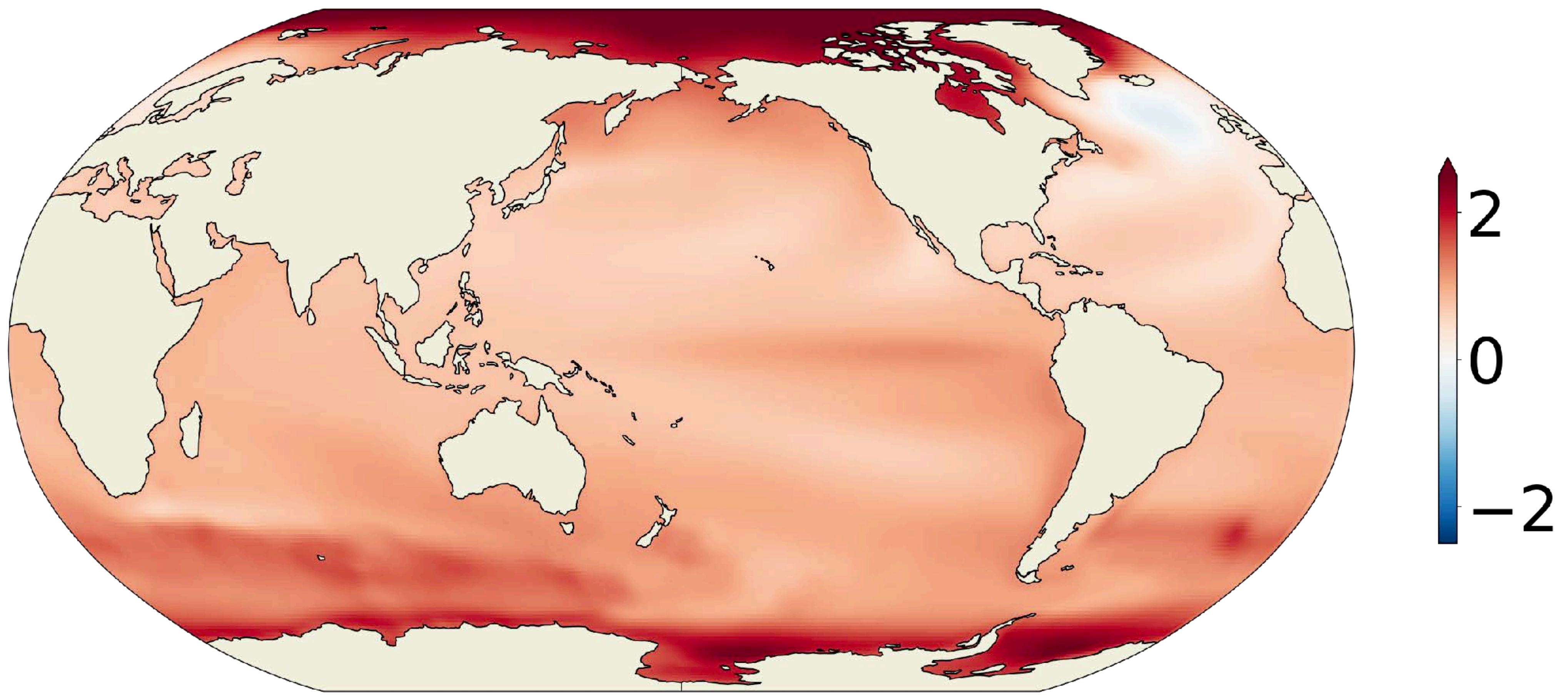
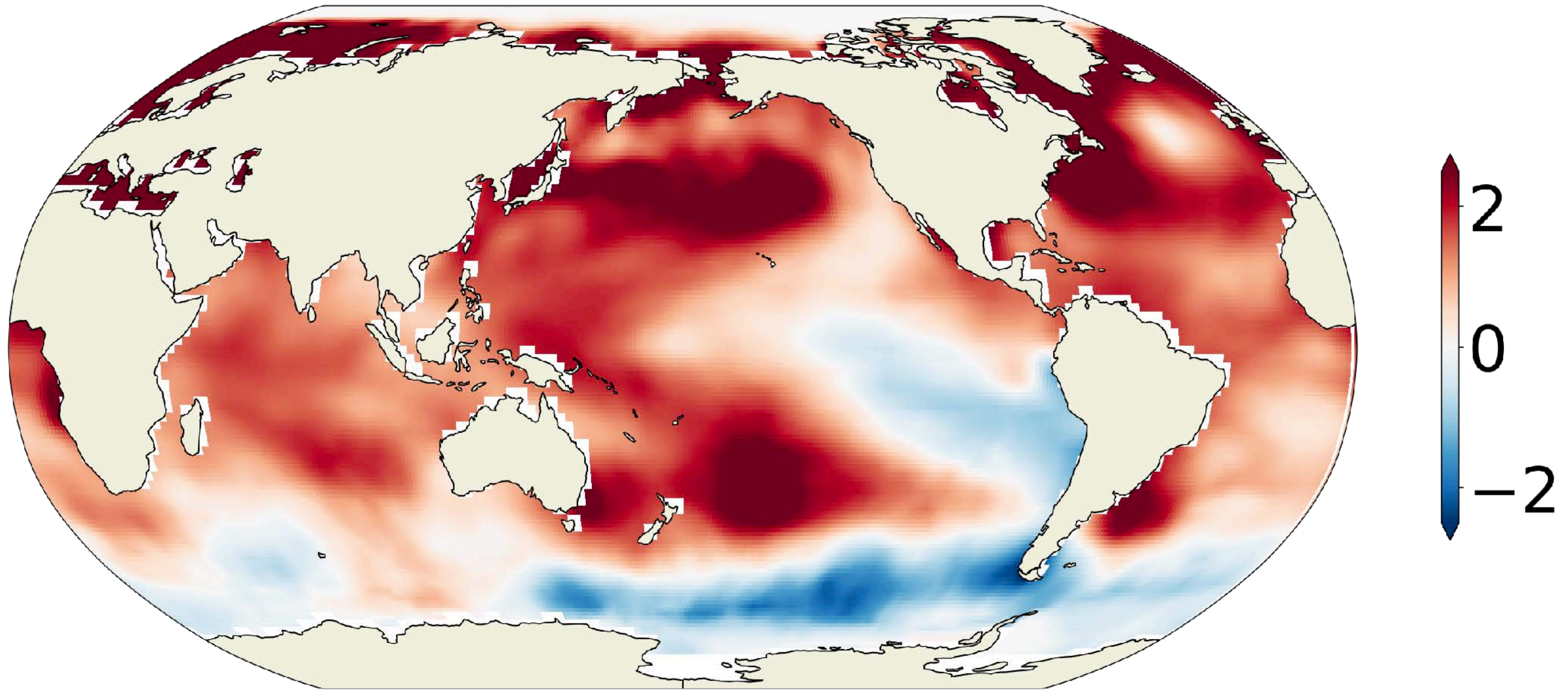


$$\boxed{\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)}$$

Murphy et al 1996, Senior and Mitchell 2000, Winton et al 2010, Sherwood et al 2020, Andrews et al 2018 , etc, etc, etc

The big questions:

NOAA ERSST 1979-2020



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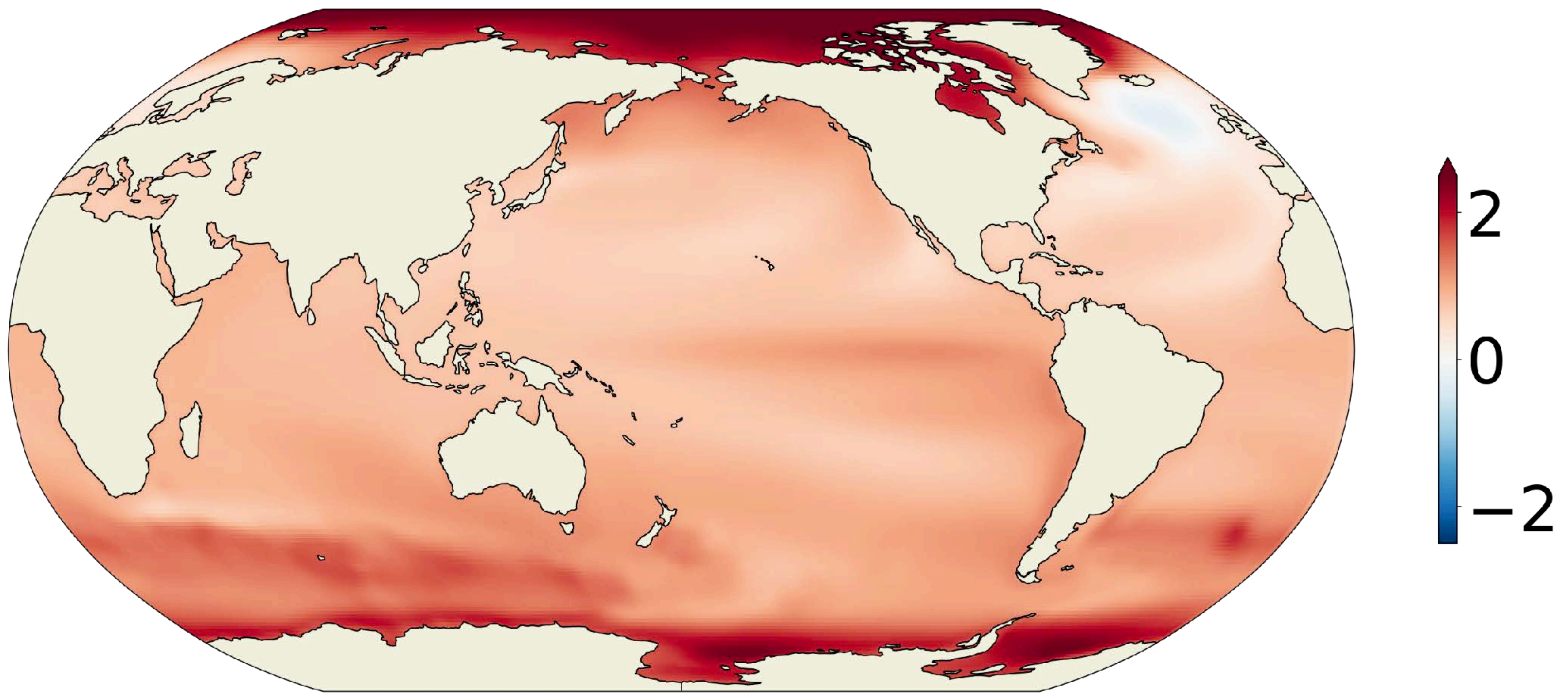

$$\boxed{\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)}$$

- $\overline{R}\left(T(x)\right)$
- $N, F, T(x)$

Roadmap

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  - Radiative response
  - Forcing and heat uptake
  - Patterns

General energy budget equation

$$\boxed{\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)}$$

Feedbacks are just Taylor series in disguise

$$\boxed{\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)}$$

Global temperature expansion

$$\overline{R} \approx \overset{\lambda}{\boxed{\frac{\partial \overline{R}}{\partial \overline{T}}}}\,\overline{T}$$

Soden and Held 2008, Roe 2008

Feedbacks are just Taylor series in disguise

$$\boxed{\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)}$$

Global temperature expansion

$$\overline{R} \approx \overbrace{\boxed{\frac{\partial \overline{R}}{\partial \overline{T}}}}^{\lambda}\,\overline{T}$$

Regional temperatures expansion (WRONG)

$$\overline{R} \approx \sum_x \frac{\partial R(x)}{\partial T(x)} T(x)$$

Armour 2013, Rose et al 2014, Budyko 1969, Sellers 1969

Nonlocal effects matter

$$\boxed{\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)}$$

Global temperature expansion

$$\overline{R} \approx \overbrace{\boxed{\frac{\partial \overline{R}}{\partial \overline{T}}}}^{\lambda}\,\overline{T}$$

Regional temperatures expansion (Correct)

$$\overline{R} \approx \sum_{x,y} \frac{\partial R(y)}{\partial T(x)} T(x)$$

Zhou et al 2017, Dong et al 2019

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Global temperature expansion

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Global temperature expansion

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Regional temperatures expansion (Correct)

$$\overline{R} \approx \sum_x \frac{\partial \overline{R}}{\partial T(x)} \frac{T(x)}{\overline{T}} \overline{T}$$

Radiative response. pattern

Nonlocal effects matter

$$\boxed{\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)}$$

Global temperature expansion

$$\overline{R} \approx \underbrace{\boxed{\frac{\partial \overline{R}}{\partial \overline{T}}}}_{}\overline{T} \qquad \left(\lambda = \frac{\partial \overline{R}}{\partial \overline{T}}\right)$$

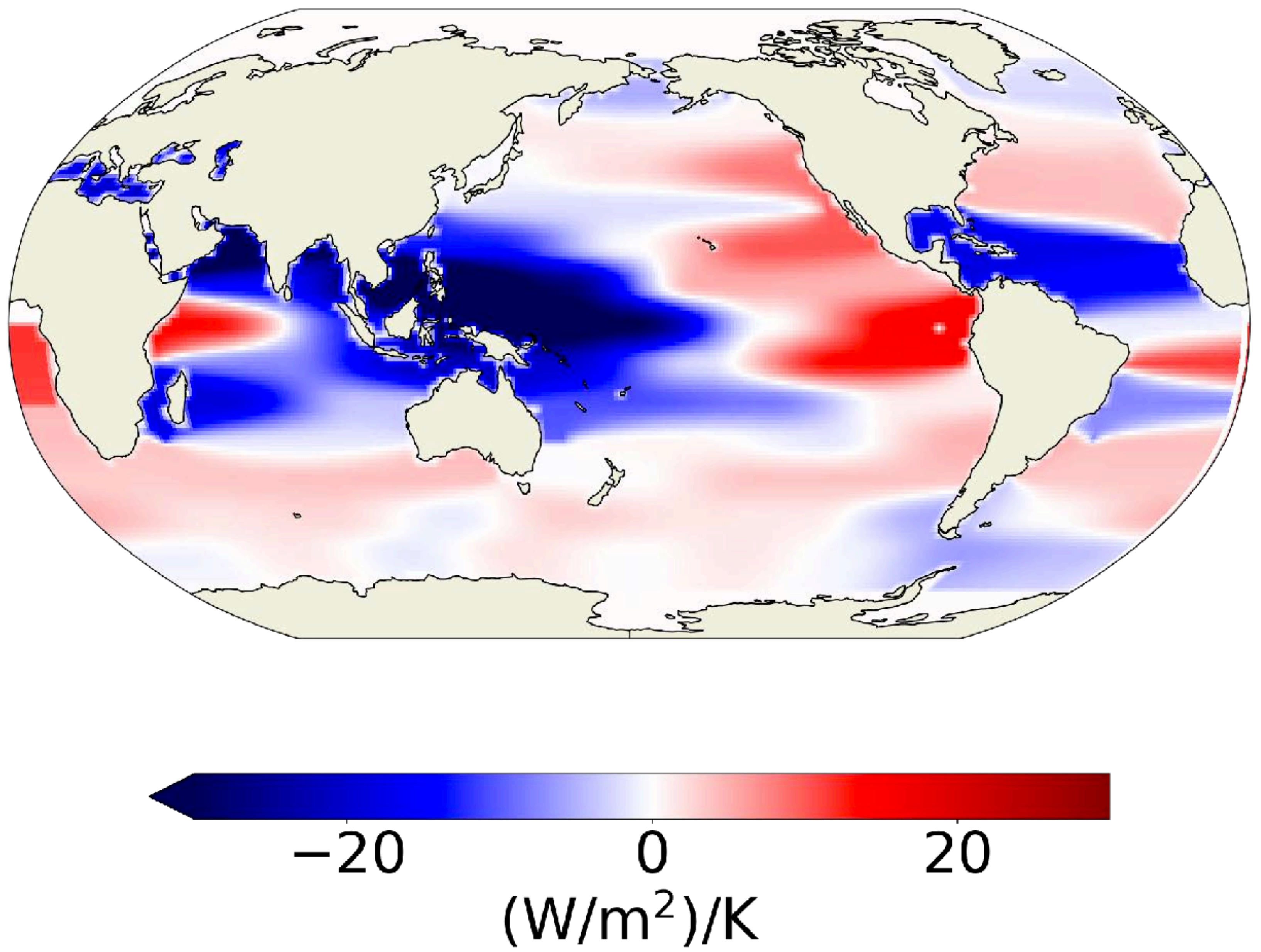
Regional temperatures expansion (Correct)

$$\overline{R} \approx \overset{\lambda}{\boxed{\sum_x \frac{\partial \overline{R}}{\partial T(x)} \frac{T(x)}{\overline{T}}}}\,\overline{T}$$

Radiative response. pattern

Green's Function

$$\frac{\partial \overline{R}}{\partial T(x)}$$



Zhou et al 2017, Dong et al 2019

Regional temperatures expansion (Correct)

$$\overline{R} \approx \boxed{\sum_x \frac{\partial \overline{R}}{\partial T(x)} \frac{T(x)}{\overline{T}}}\,\overline{T}$$

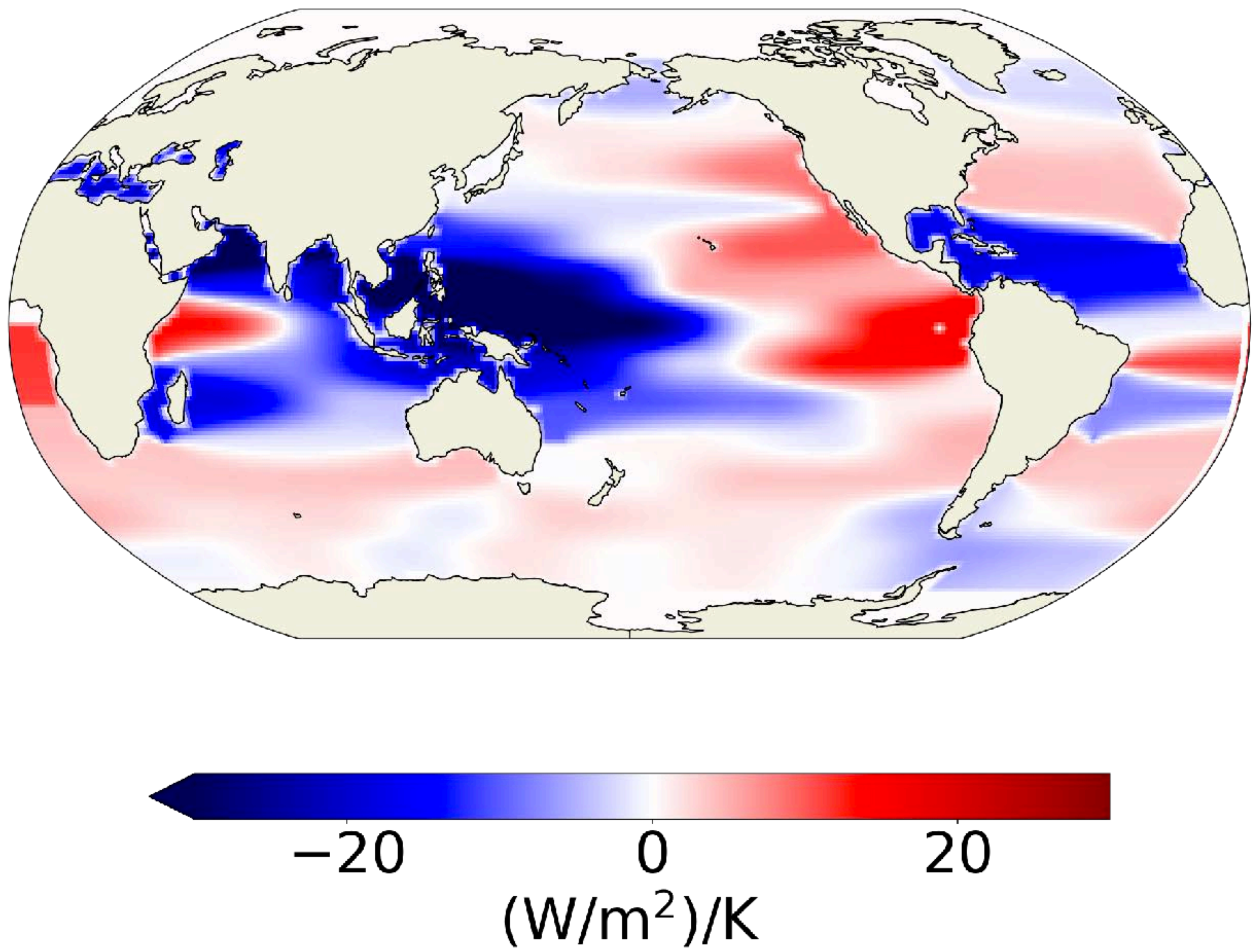
λ

Radiative response.

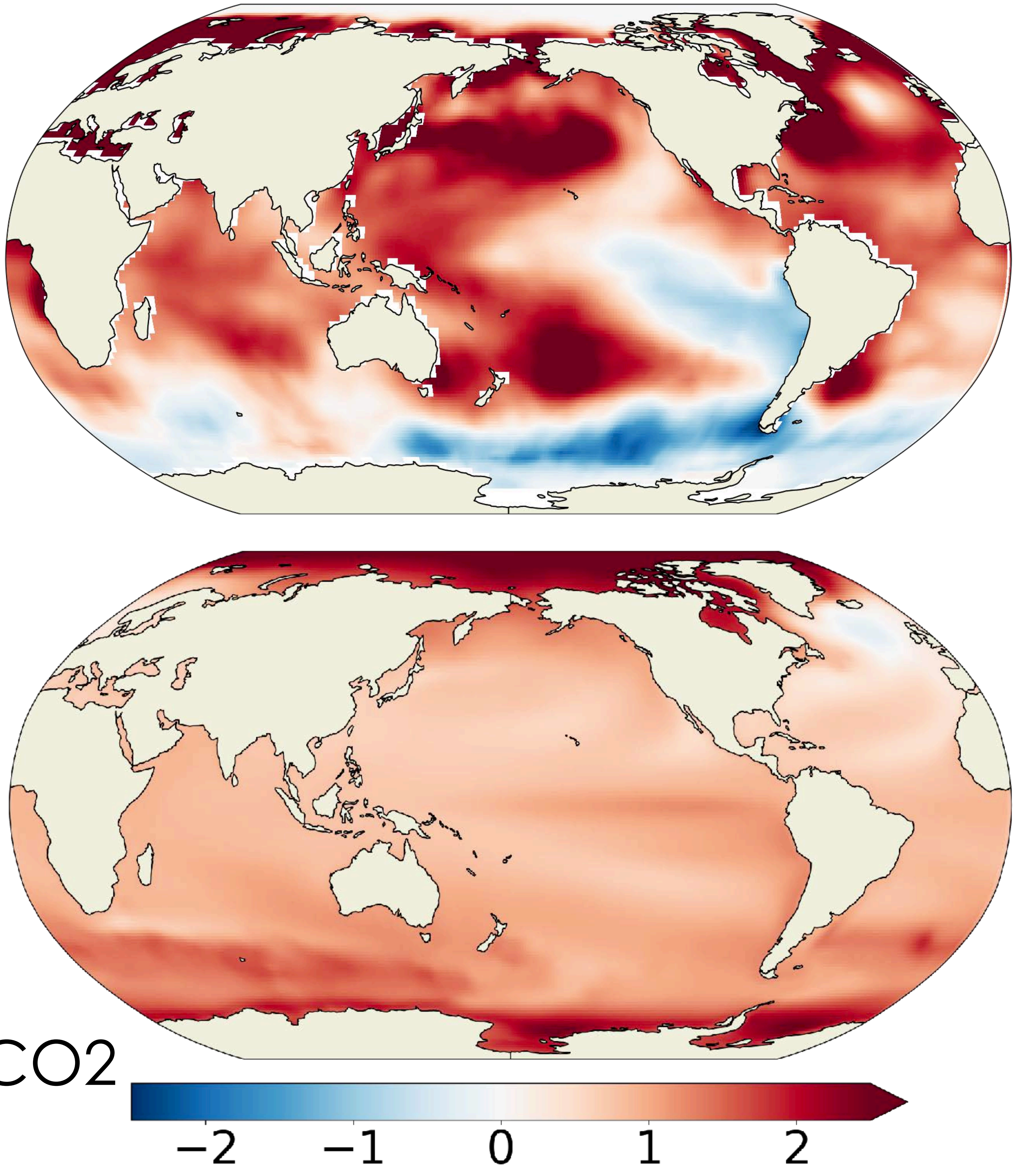
pattern

Pattern effect summary

$$\lambda = \sum \frac{\partial \overline{R}}{\partial T(x)} \times \frac{\Delta T(x)}{\Delta \overline{T}}$$



historical



abrupt-4xCO2

Pattern effect:

Long-term warming pattern
Will actuate more
Positive feedbacks

$$\lambda_{hist} < \lambda_{eq} < 0$$

Frameworks:

Earth's Energy Budget

$$\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)$$

$$\overline{R} \approx \sum_x \overbrace{\boxed{\frac{\partial \overline{R}}{\partial T(x)} \frac{T(x)}{\overline{T}}}}^{\lambda} \overline{T}$$

Frameworks:

Earth's Energy Budget

$$\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)$$

$$\overline{R} \approx \sum_x \boxed{\frac{\partial \overline{R}}{\partial T(x)} \frac{T(x)}{\overline{T}}}^{\,\lambda}\,\overline{T}$$

Time dependent feedbacks

$$N = F + \lambda(t)T(t)$$

Murphy 1995, Senior and Mitchell 2000

Stability

$$N = F + \lambda T + \beta S$$

Ceppi and Gregory 2020

Heat uptake efficacy

$$\varepsilon N = F + \lambda T$$

Winton et al 2010

Warm Pool

$$N = F + \alpha T + \gamma T^{\#}$$

Fueglistaler 2019, Dong et al 2019

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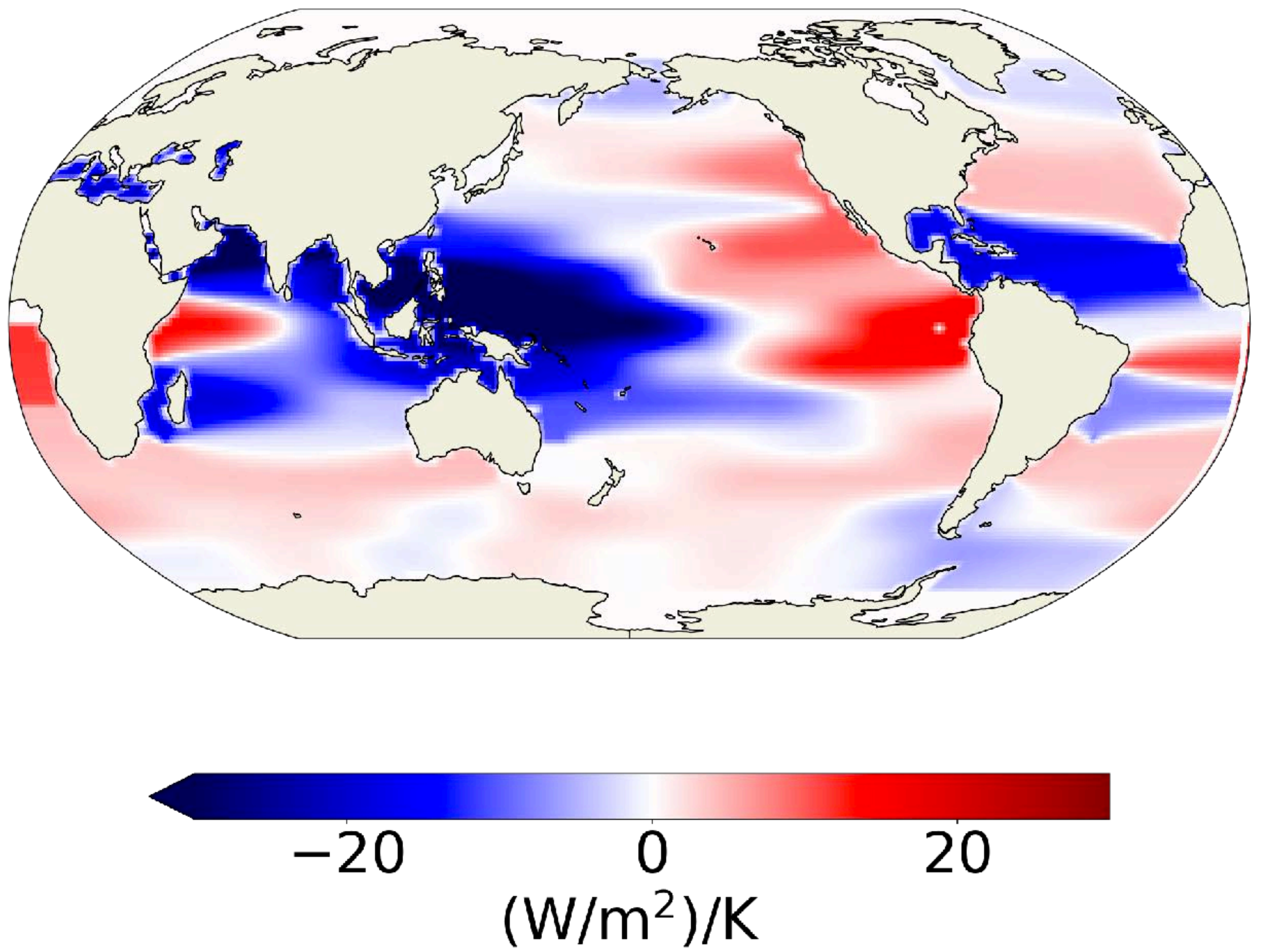
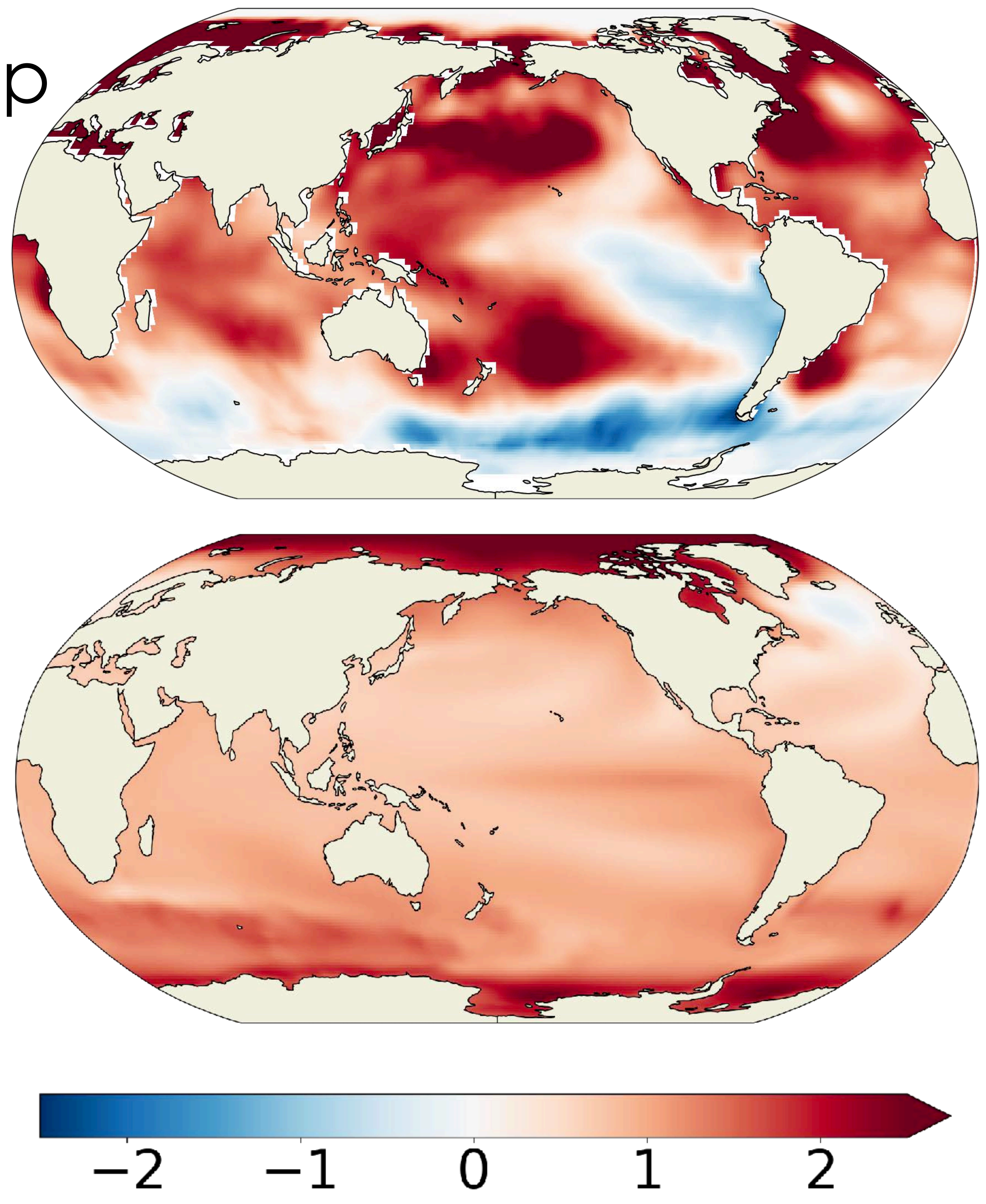
Time dependent feedback

$$\lambda = \sum \frac{\partial \bar{R}}{\partial T(x)} \times \frac{T(x)}{\bar{T}}$$



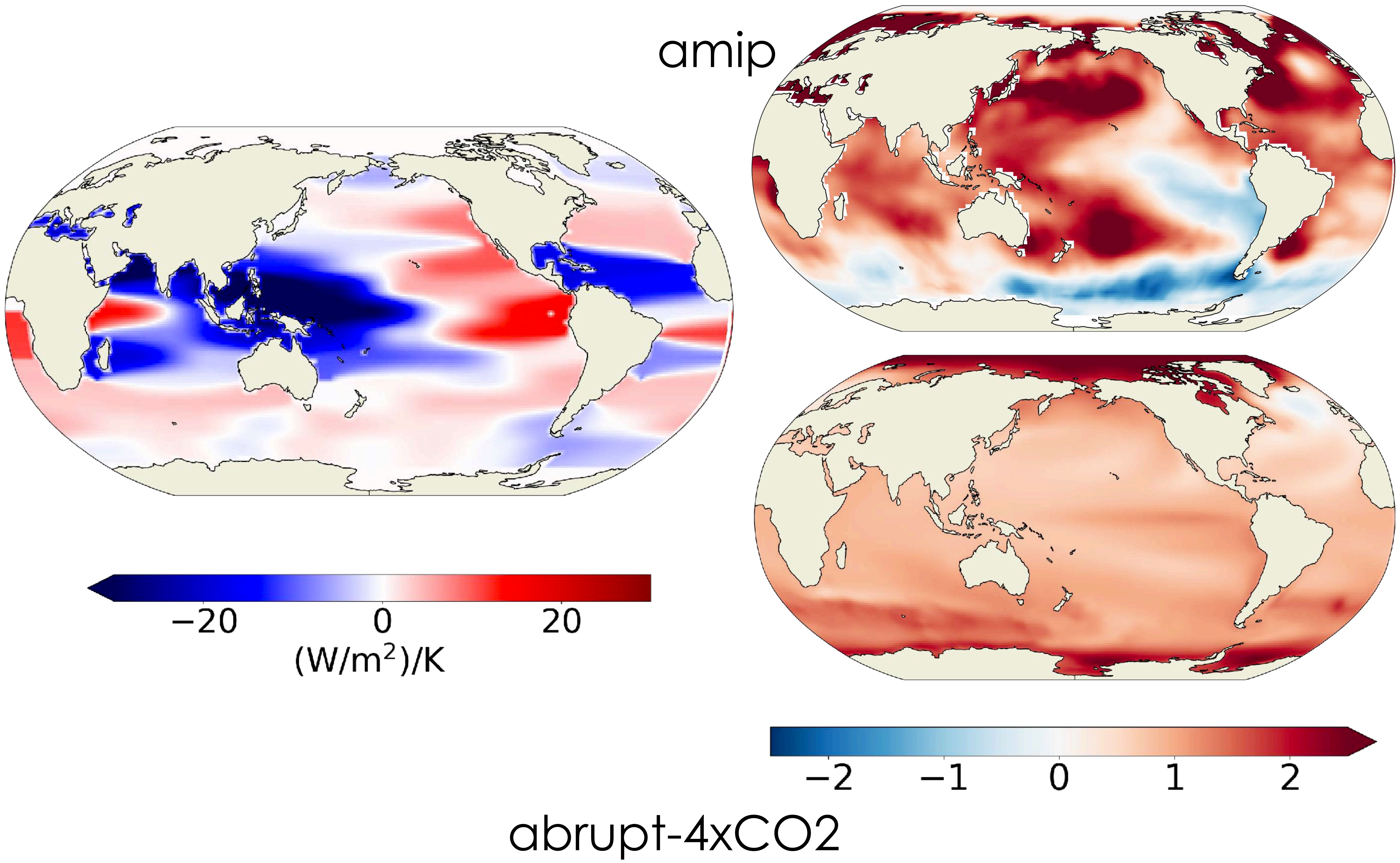
amip



abrupt-4xCO2

Time dependent feedback

$$\lambda(t) = \sum \frac{\partial \overline{R}}{\partial T(x)} \times \frac{T(x,t)}{\overline{T}}$$



Time dependent feedback

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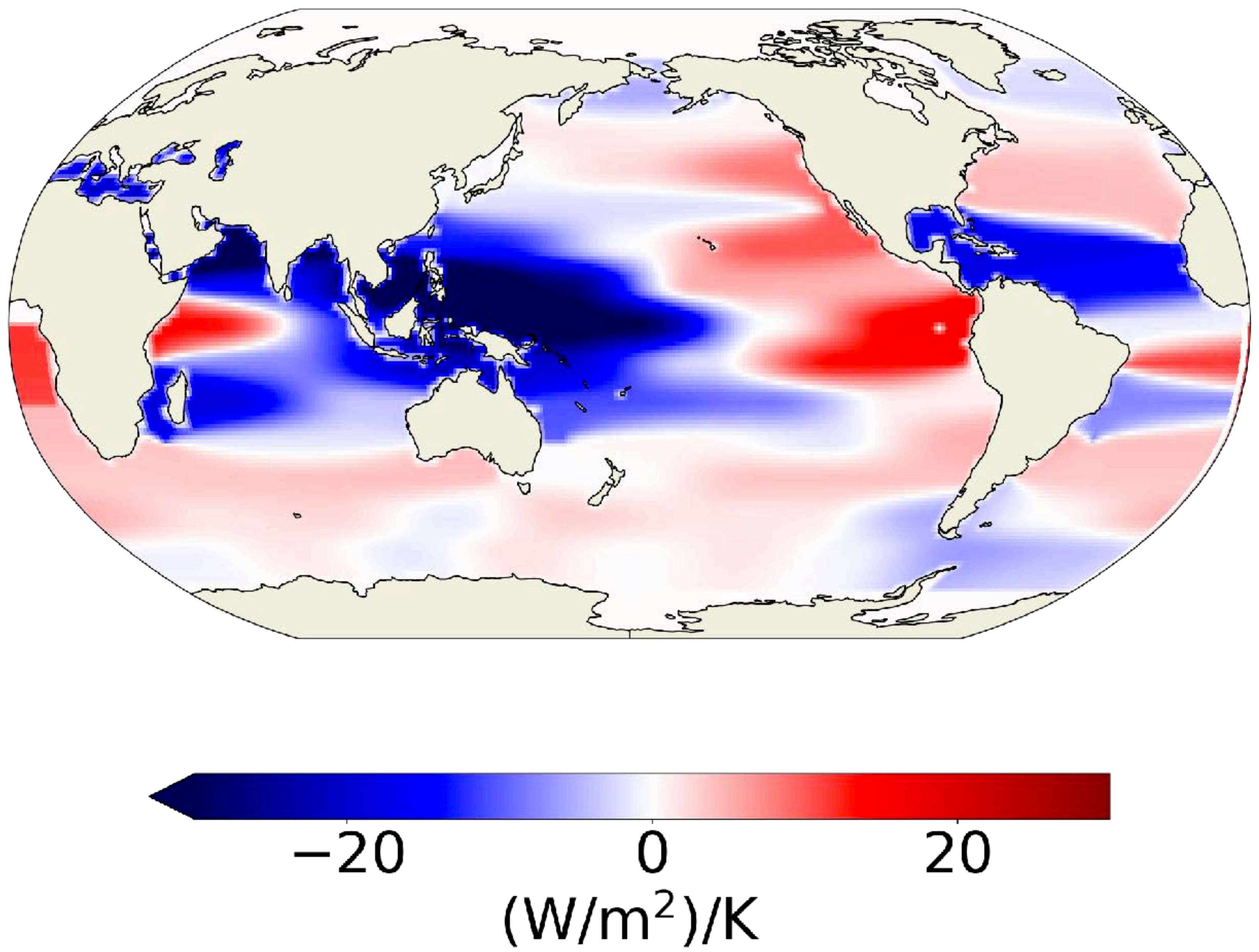

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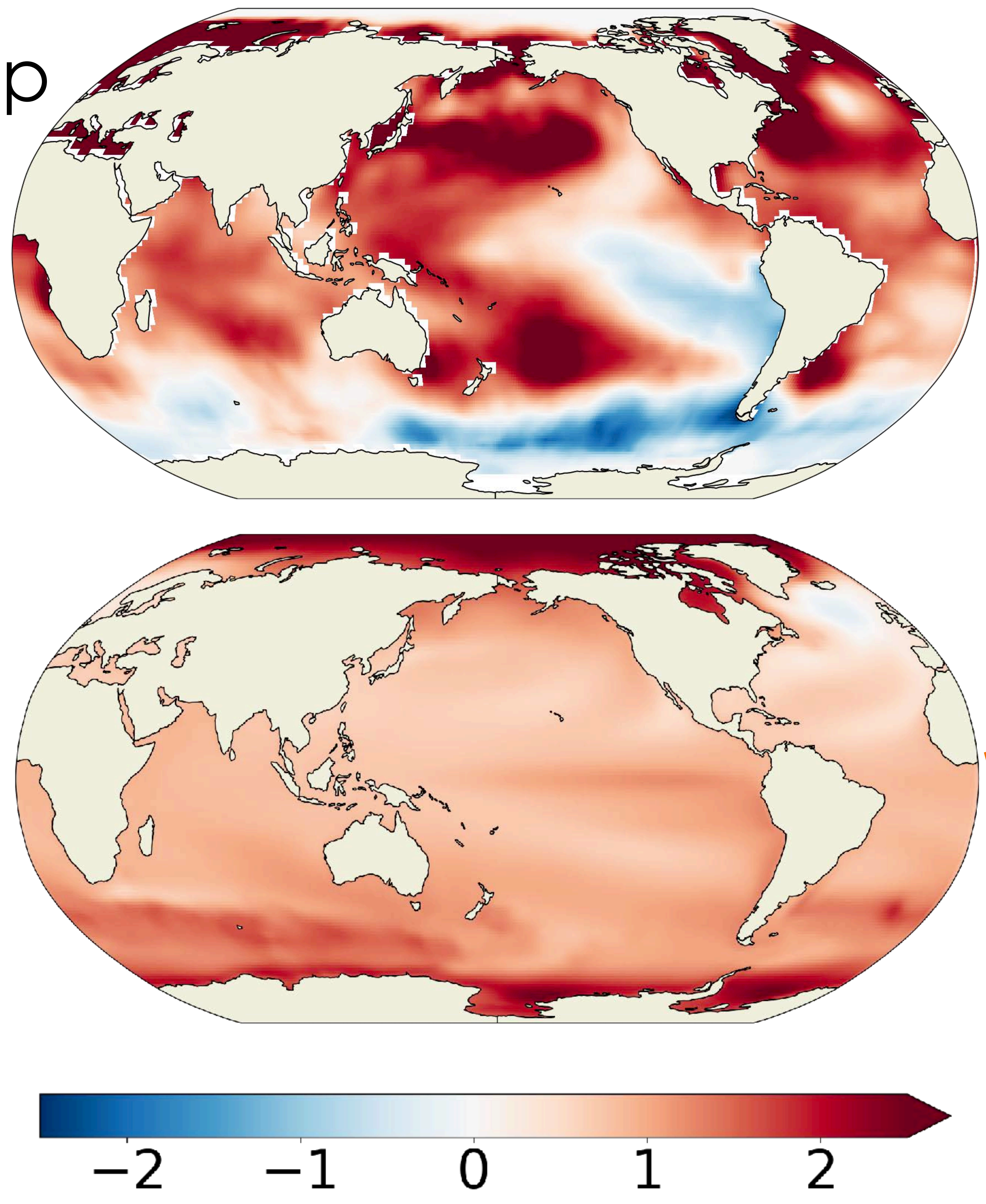
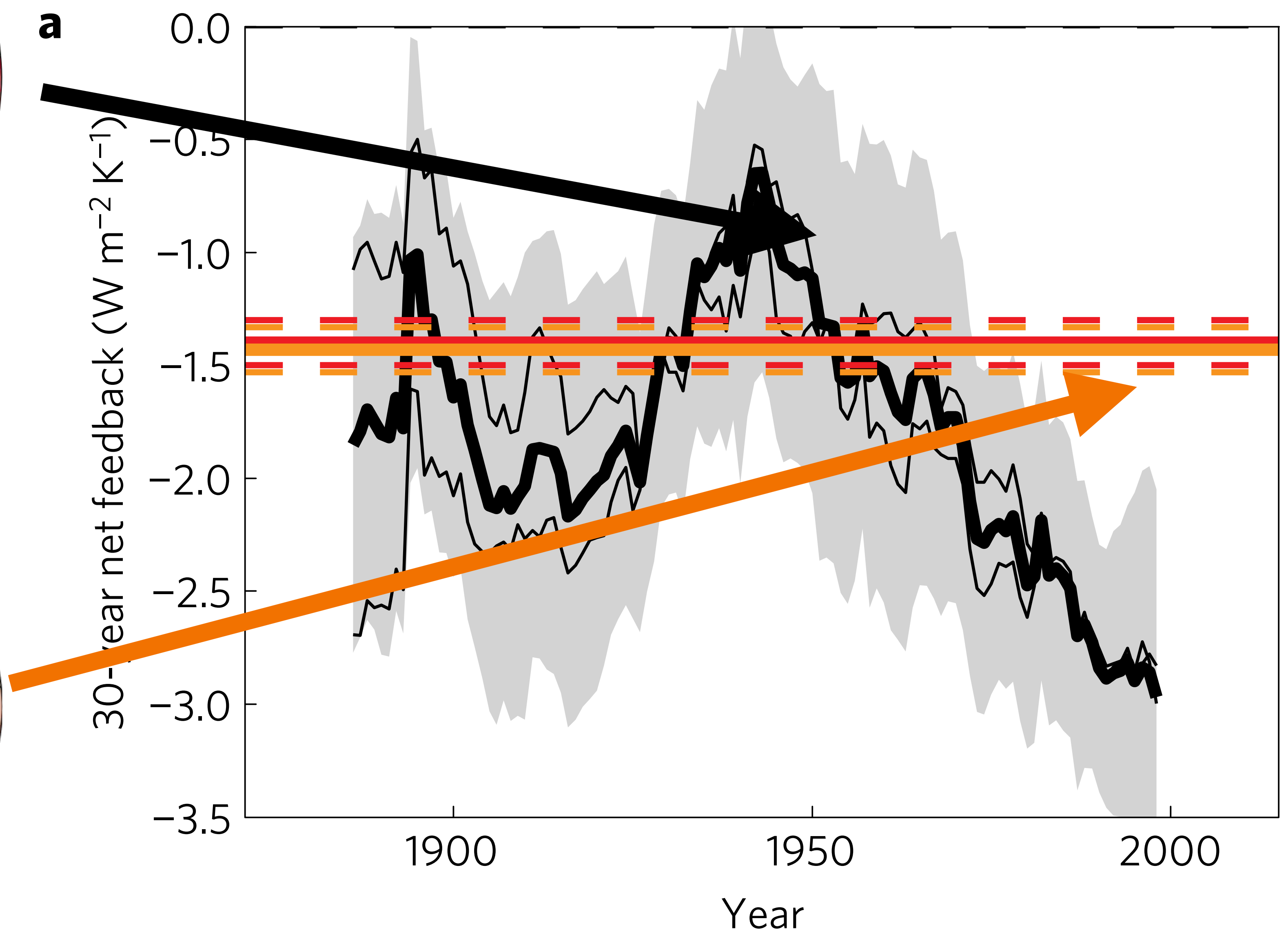


abrupt-4xCO2



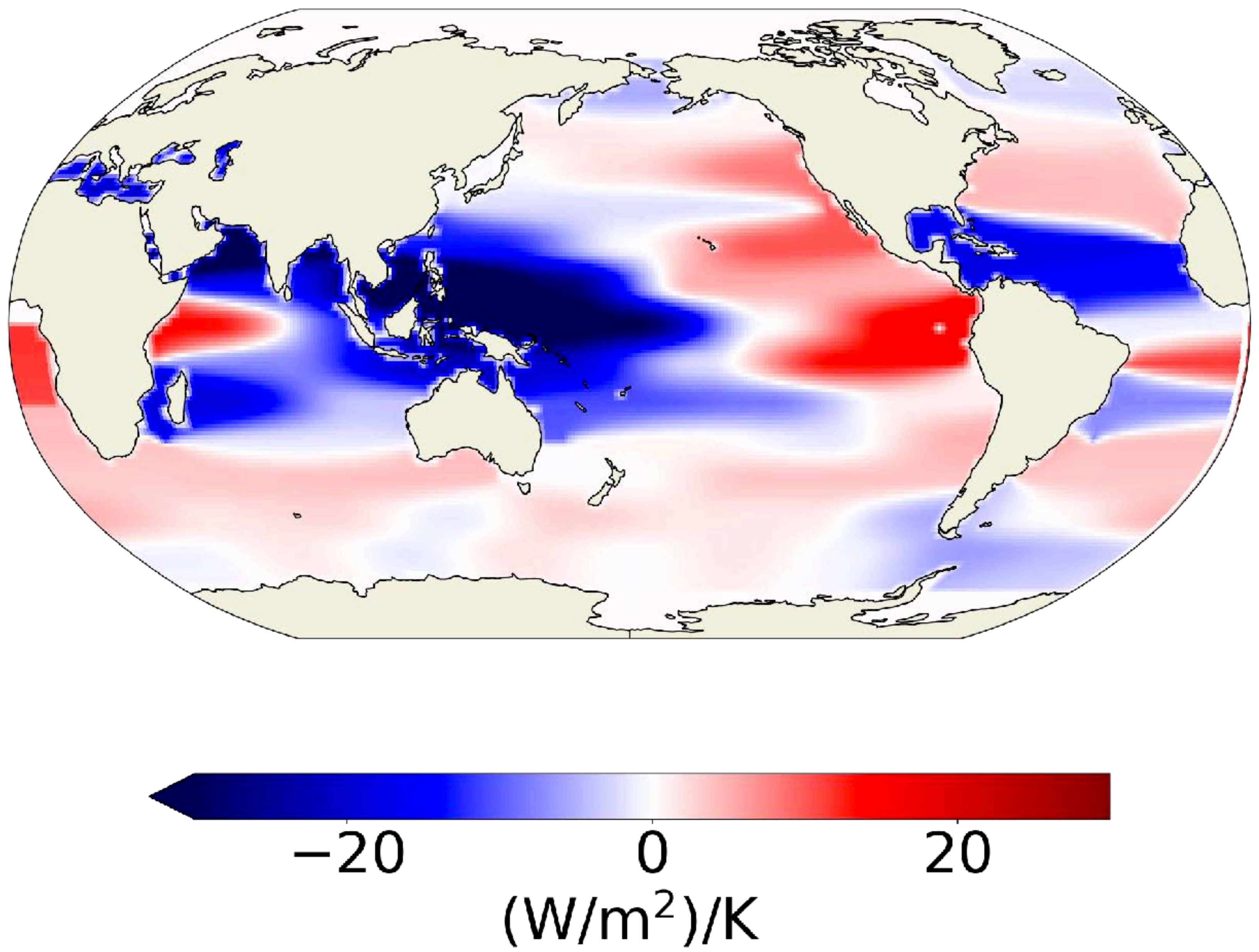
Zhou et al 2016

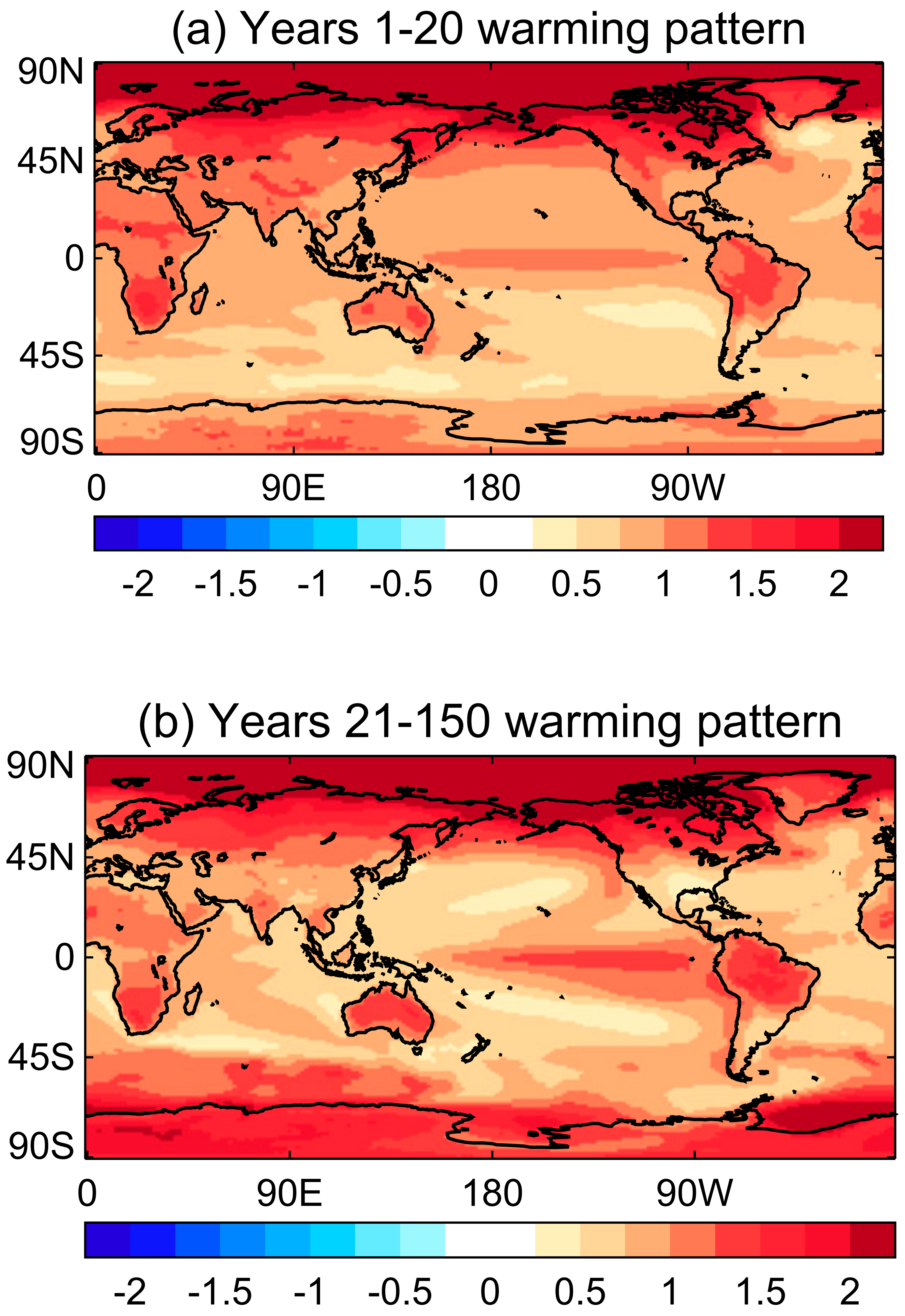
Time dependent feedback

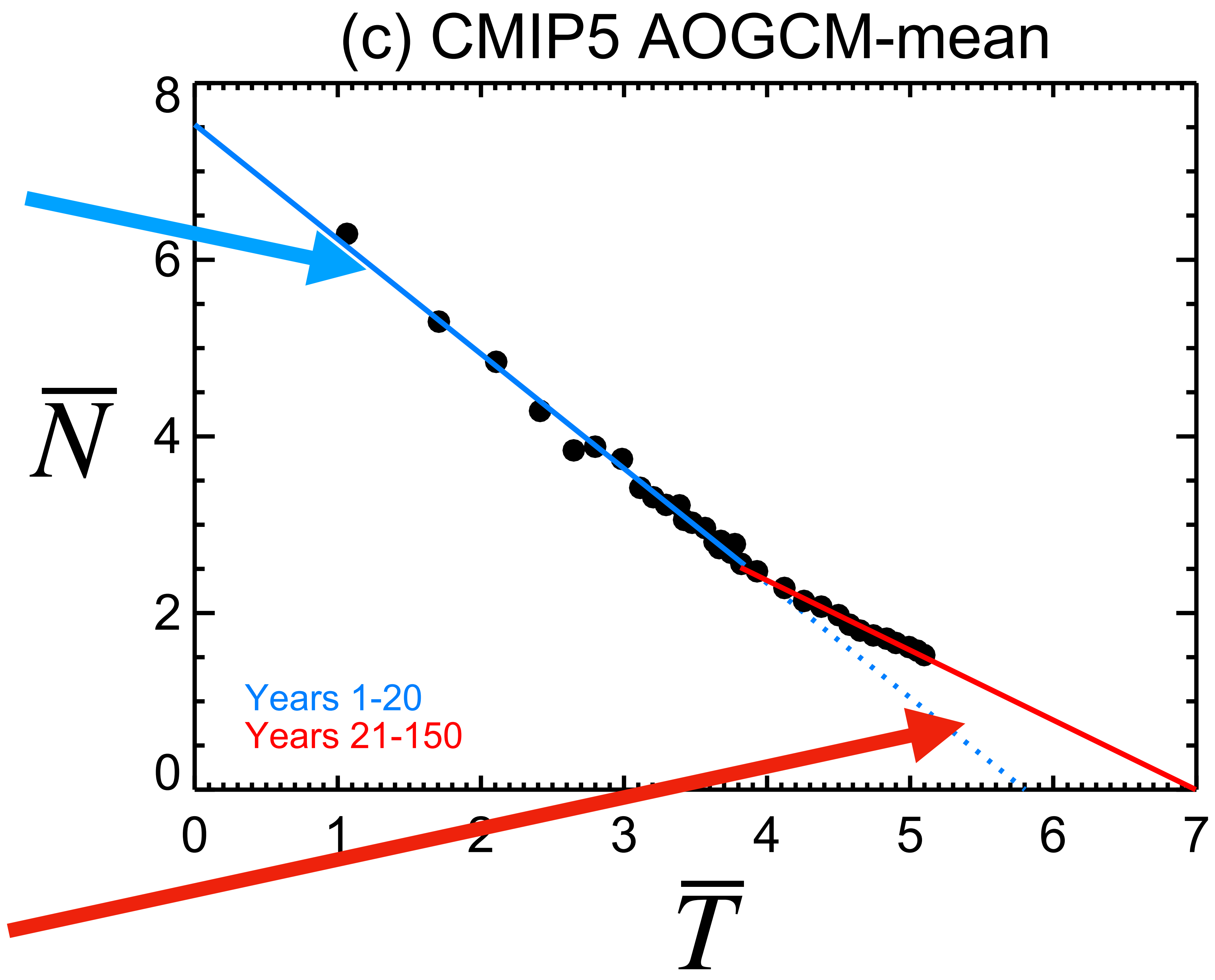
$$\lambda(t) = \sum \frac{\partial \overline{R}}{\partial T(x)} \times \frac{T(x,t)}{\overline{T}}$$

$\lambda(t)$

$$\overline{N} = \overline{F} - \boxed{\sum_x \frac{\partial \overline{R}}{\partial T(x)} \frac{T(x,t)}{\overline{T}}} \overline{T}$$



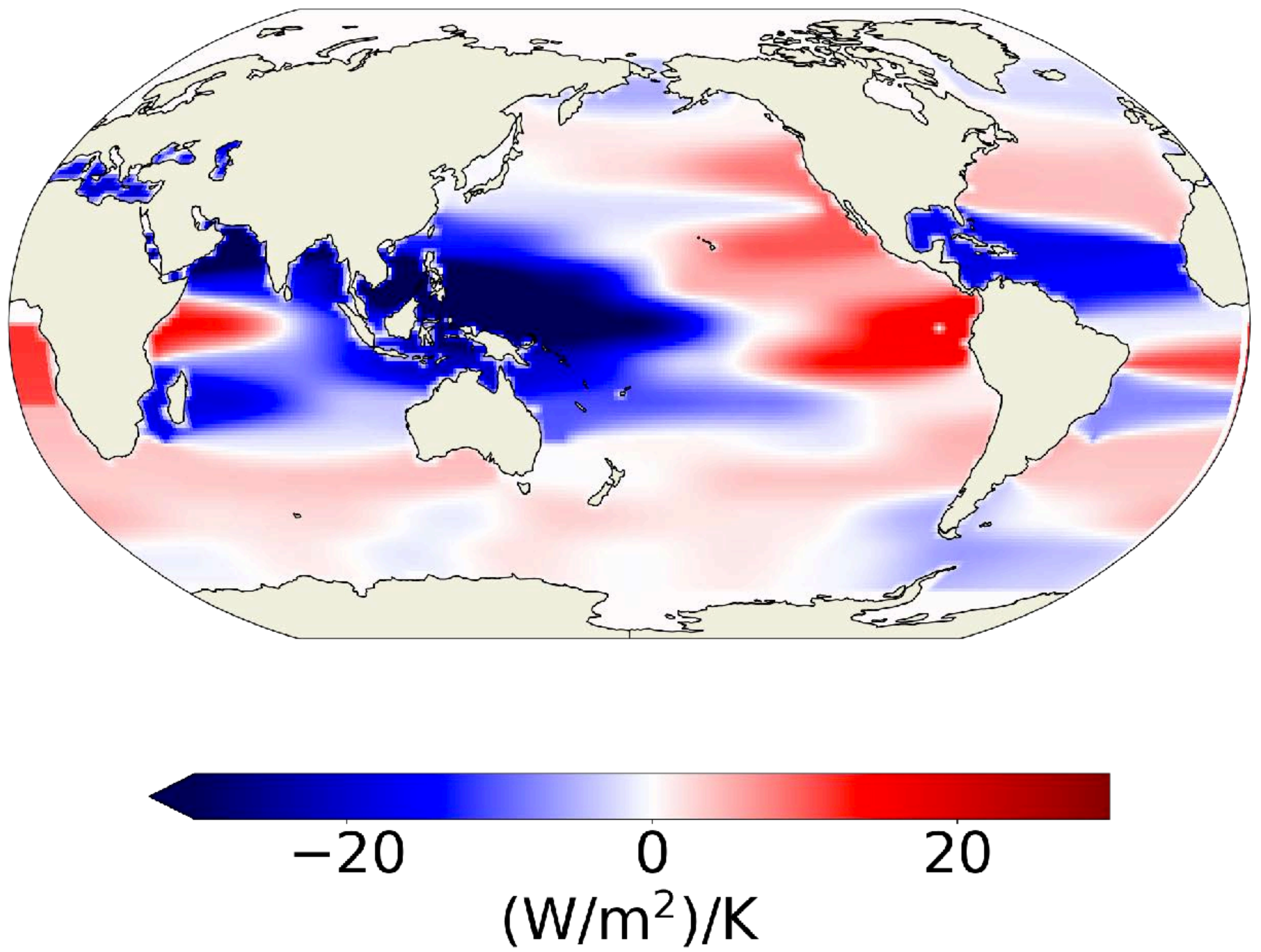


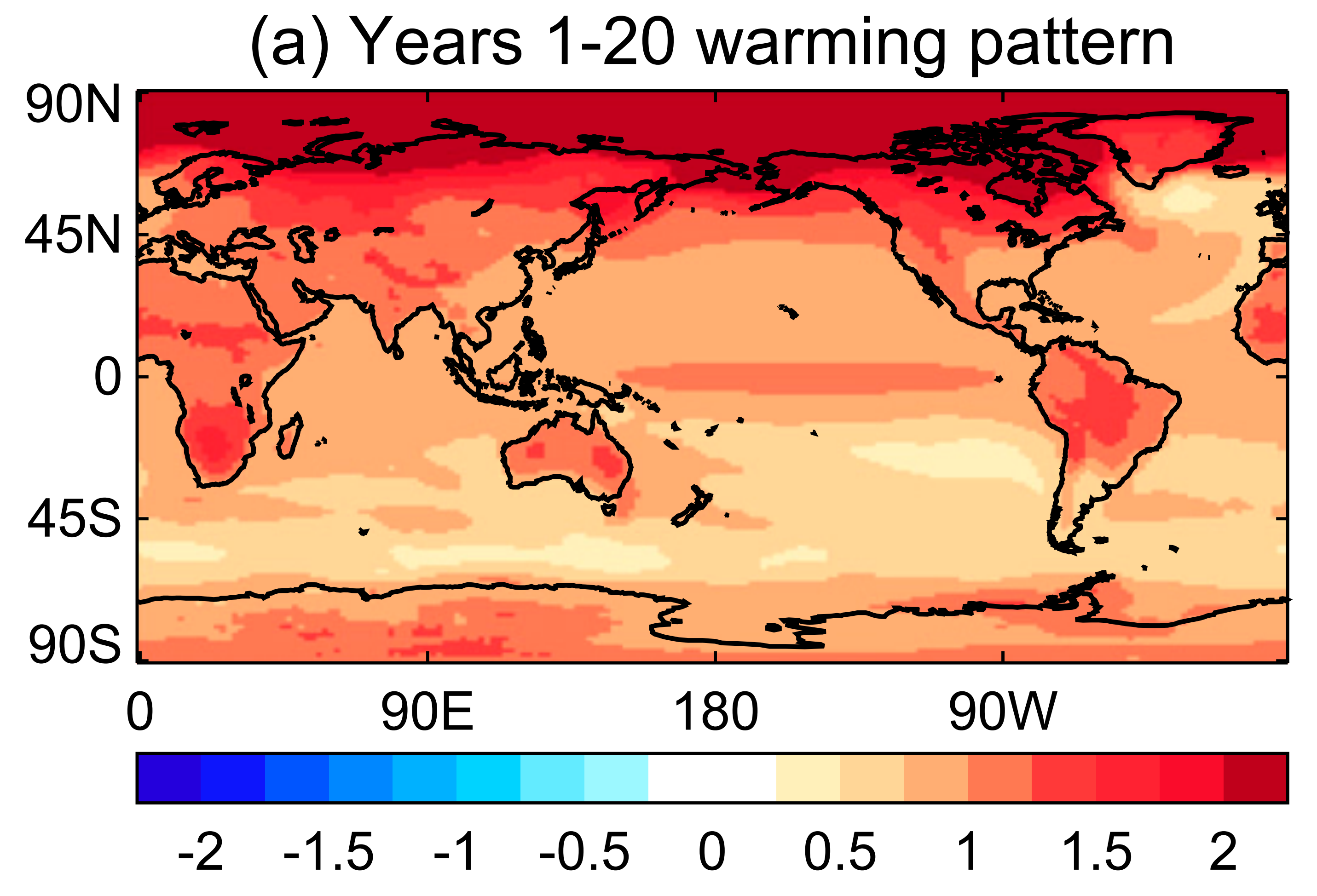


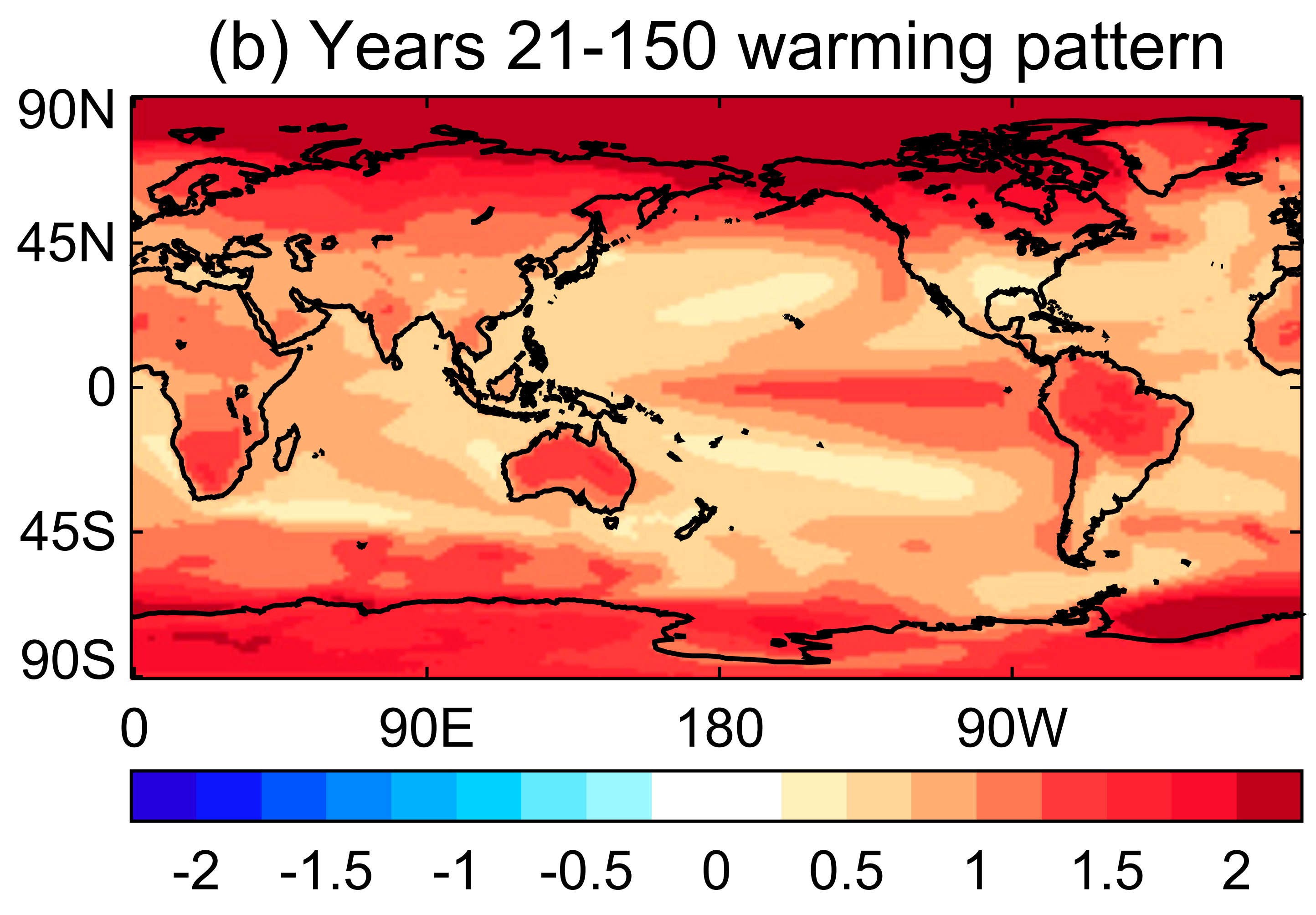
Andrews et al 2015

Warning: do not confuse these two:

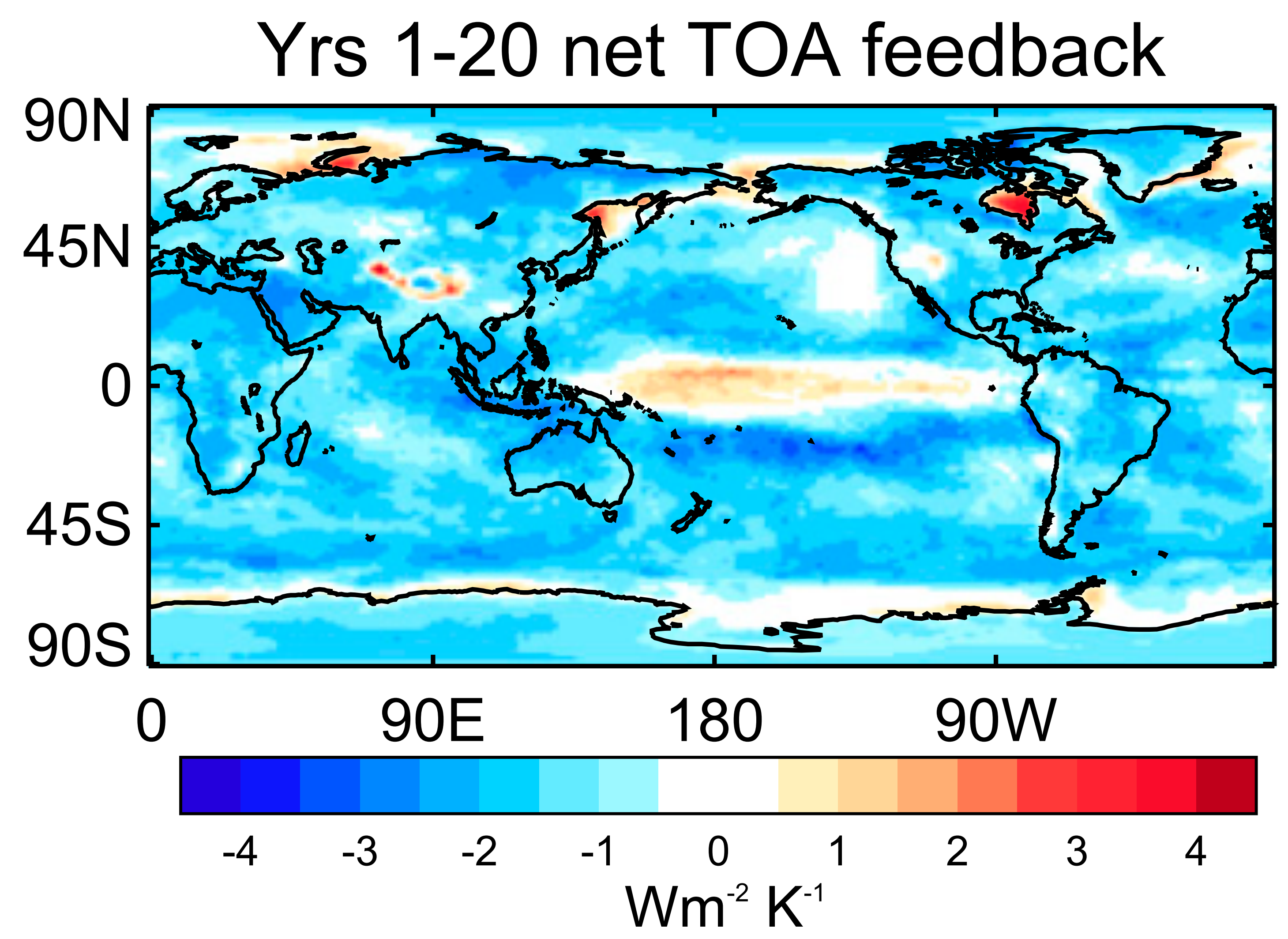
$$\lambda(t) = \sum \frac{\partial \overline{R}}{\partial T(x)} \times \frac{T(x,t)}{\overline{T}}$$

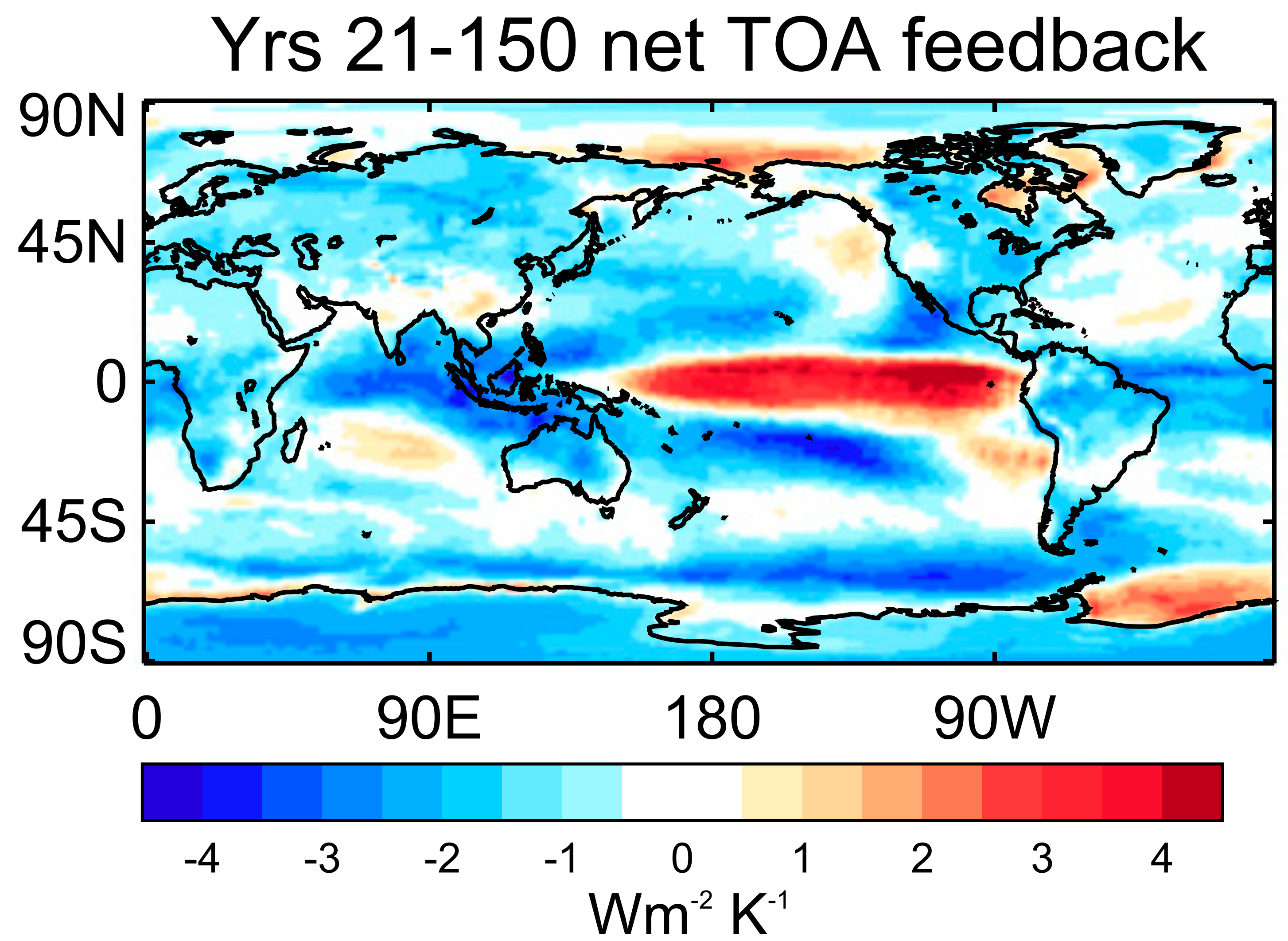






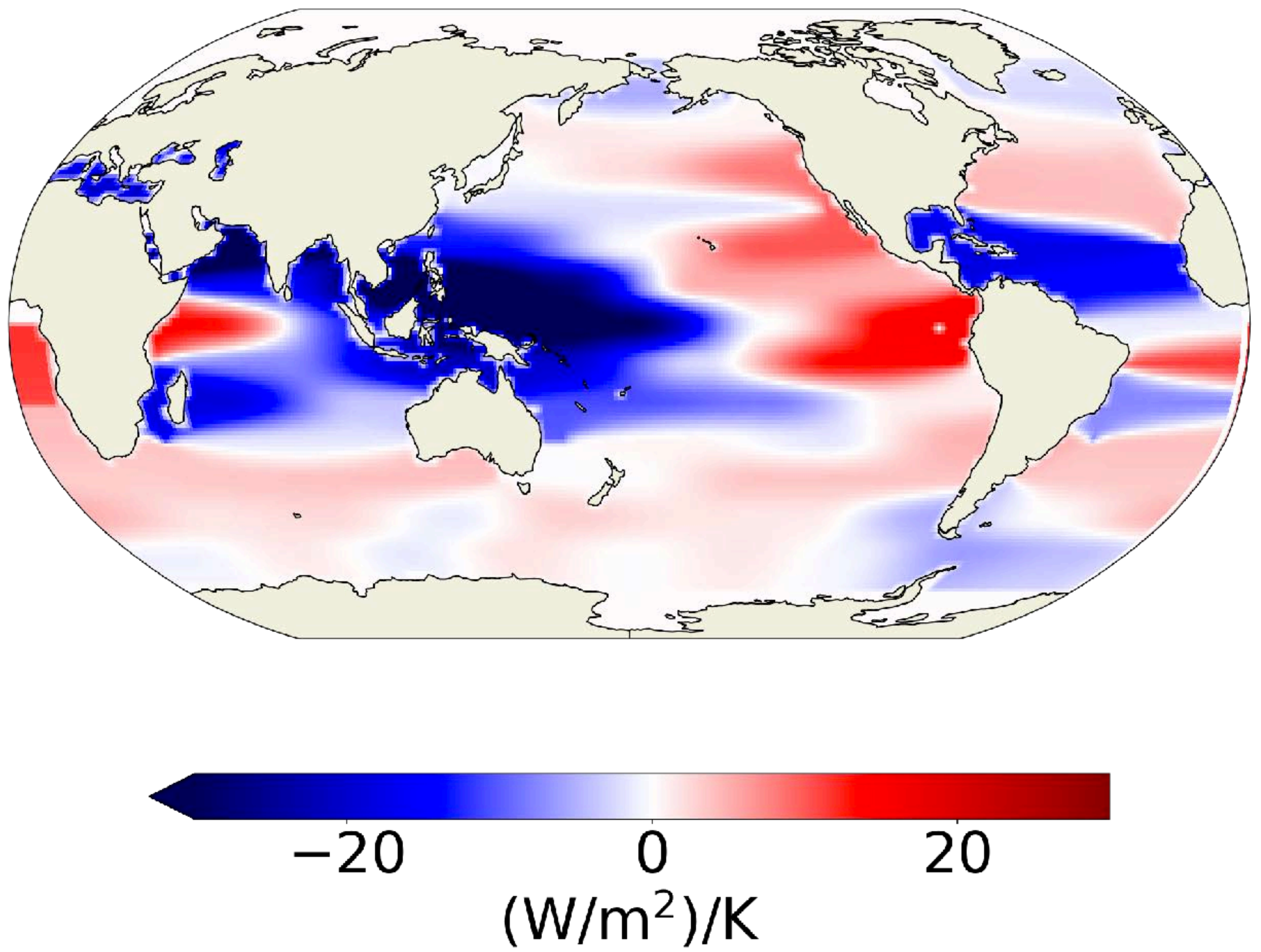
$$\lambda(t) = \frac{\partial R(y,t)}{\partial \overline{T}}$$





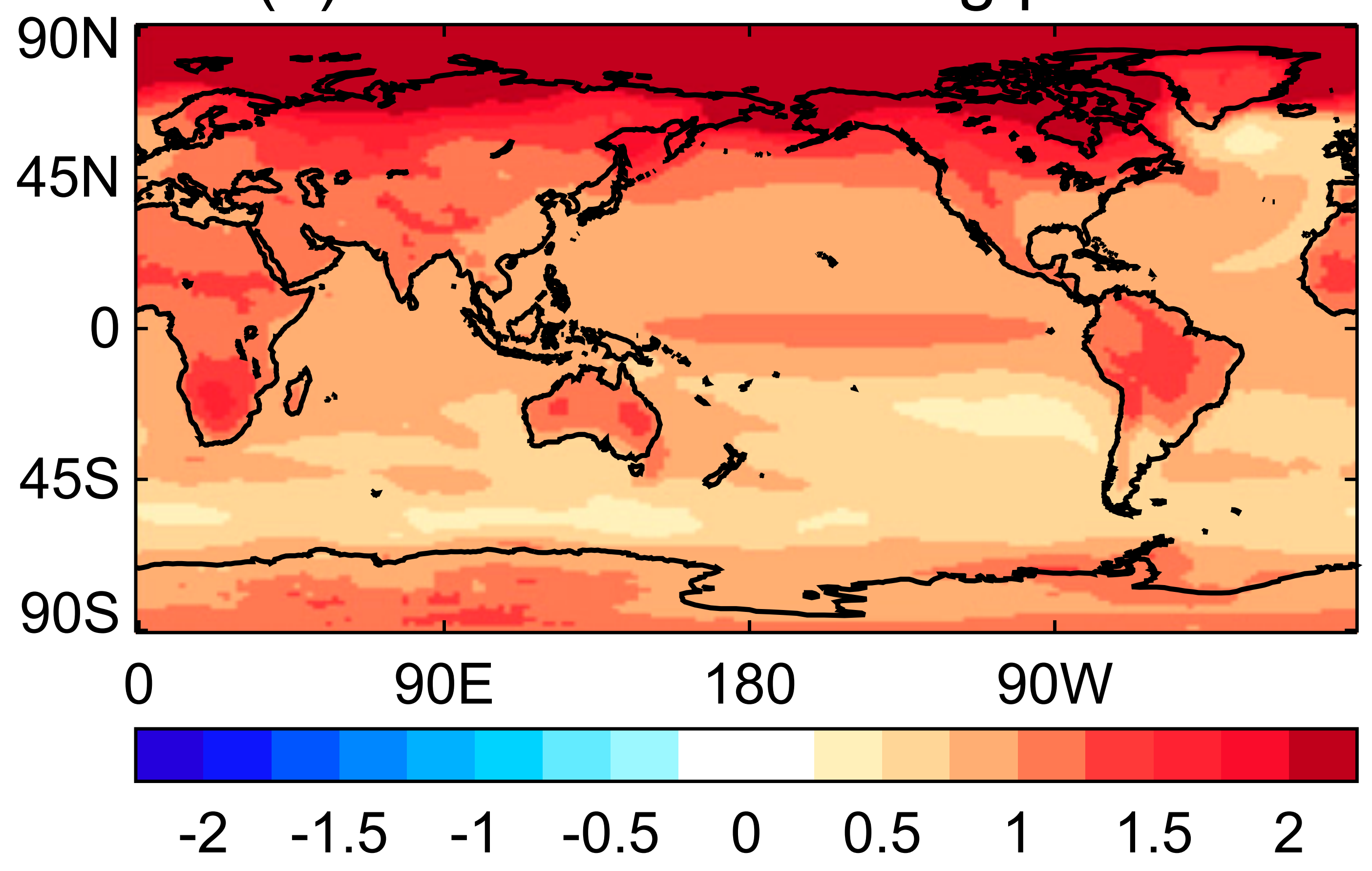
Warning: do not confuse these two:

$$\frac{\partial \bar{R}}{\partial T(x)} = \sum_y \frac{\partial R(y)}{\partial T(x)}$$

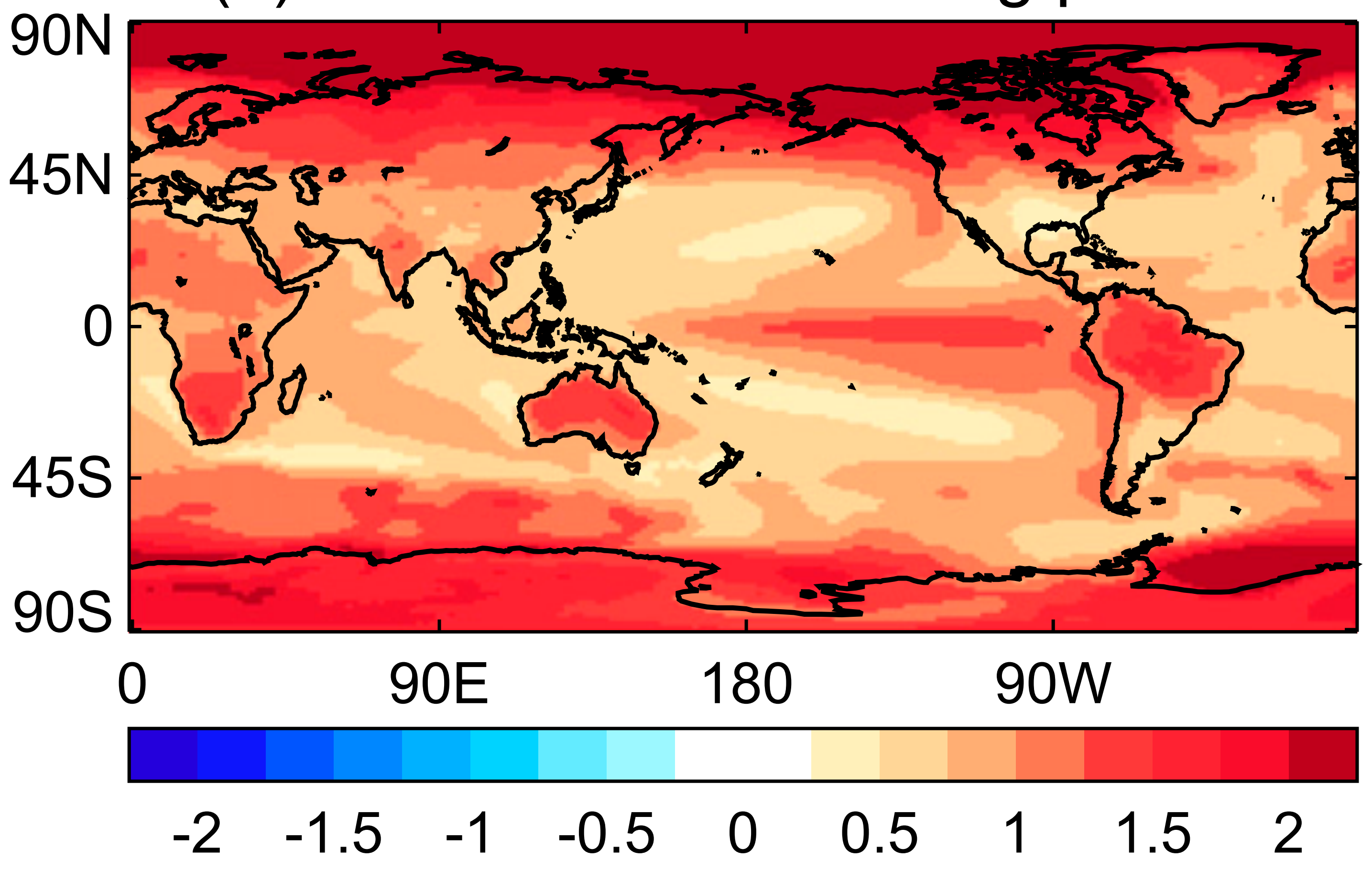


$$\frac{T(x,t)}{\bar{T}}$$

(a) Years 1-20 warming pattern

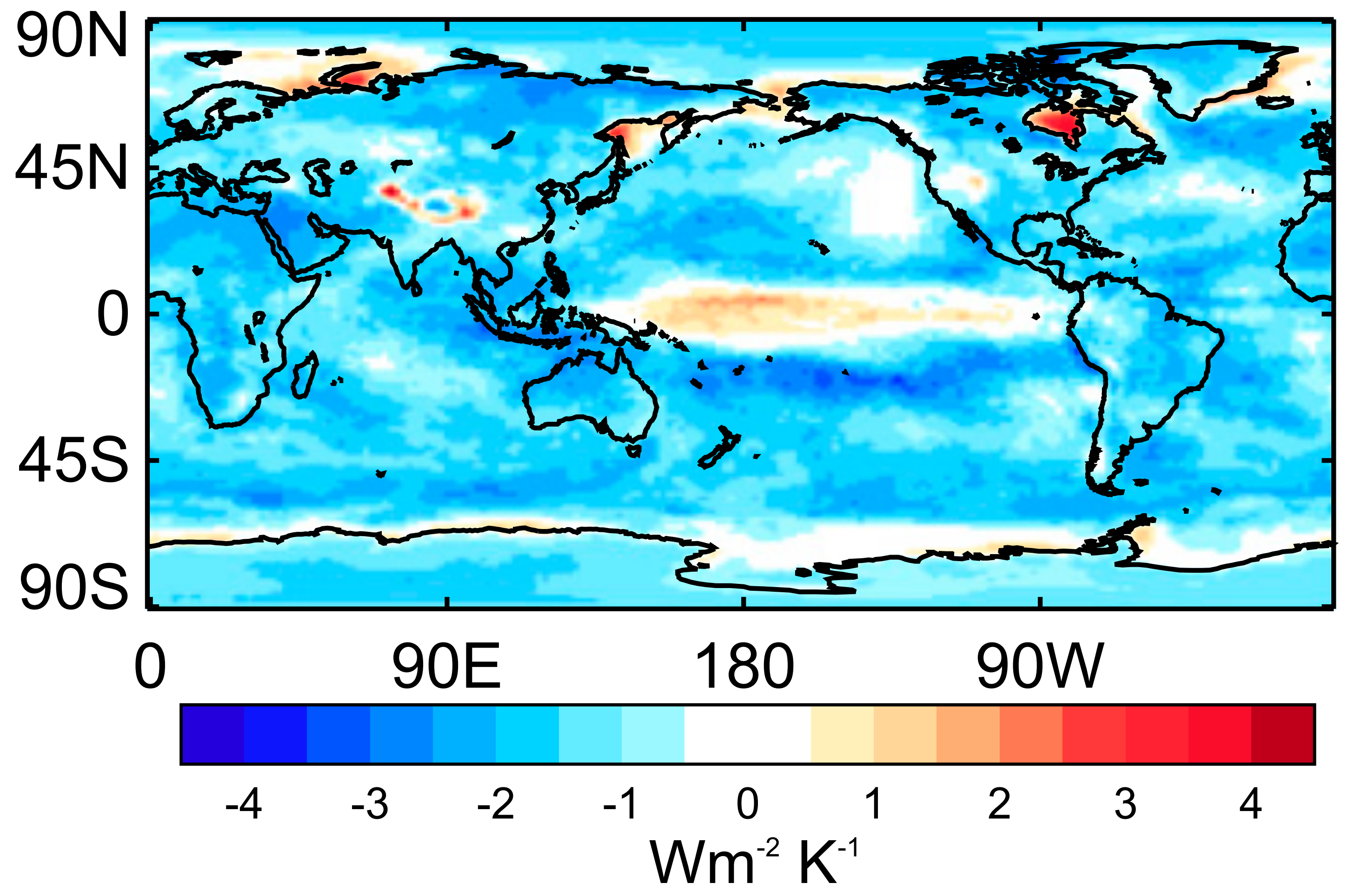


(b) Years 21-150 warming pattern

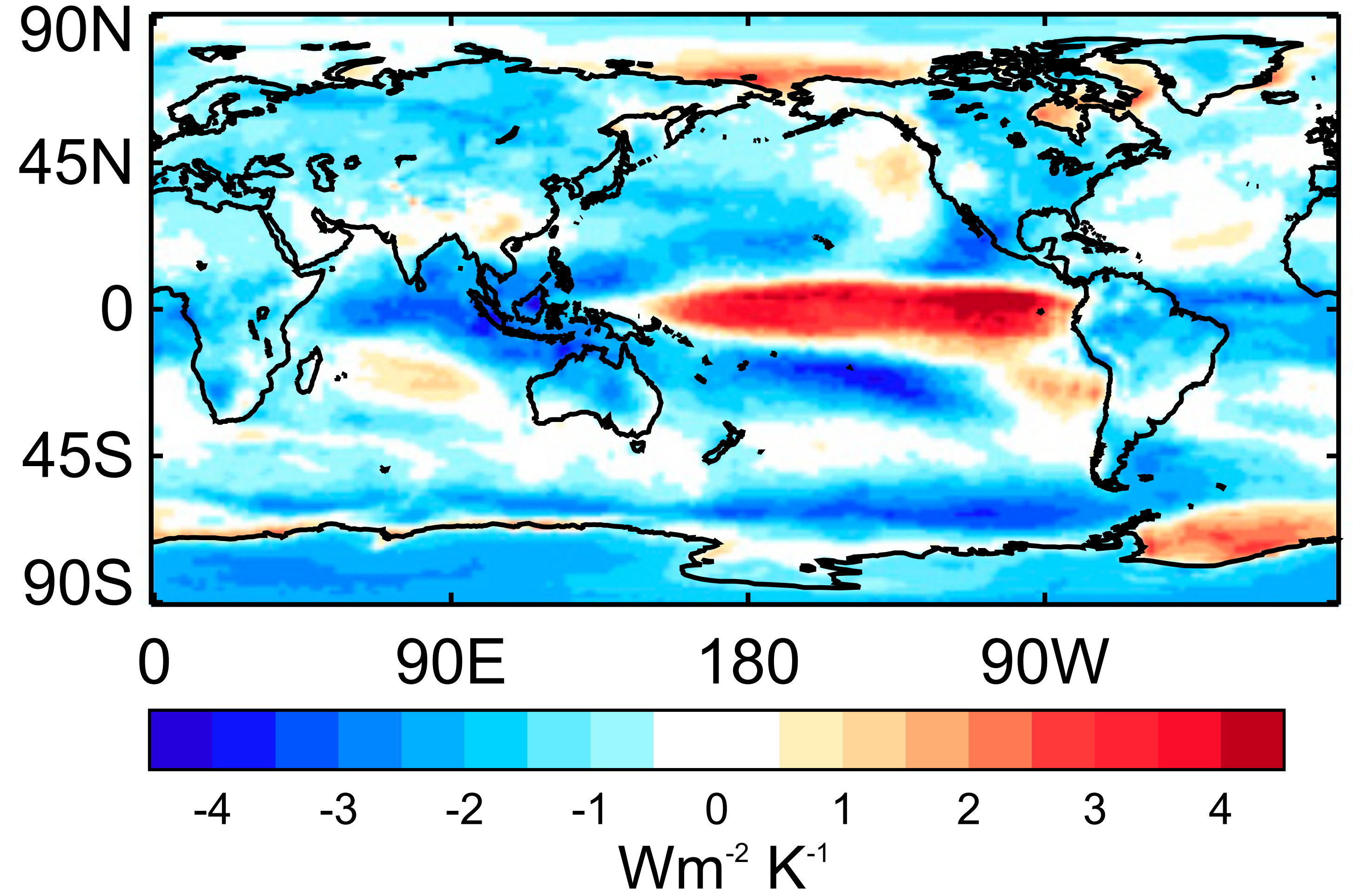


$$\frac{\partial R(y,t)}{\partial \bar{T}} = \sum_x \frac{\partial R(y)}{\partial T(x)} \frac{T(x,t)}{\bar{T}}$$

Yrs 1-20 net TOA feedback



Yrs 21-150 net TOA feedback



Frameworks:

Earth's Energy Budget

$$\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)$$

$$\overline{R} \approx \sum_x \overset{\lambda}{\boxed{\frac{\partial \overline{R}}{\partial T(x)} \frac{T(x)}{\overline{T}}}} \overline{T}$$

Time dependent feedbacks

$$N = F + \lambda(t)T(t)$$

Murlpy 1995, Senior and Mitchell 2000

Stability

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Ceppi and Gregory 2020

Heat uptake efficacy

$$\varepsilon N = F + \lambda T$$

Winton 2010

Warm Pool

$$N = F + \lambda T + \gamma T^{\#}$$

Fueglistaler 2019

Forcing efficacy

Equilibrium

$$0 = \overline{F} + \lambda T$$

CO_2

$$0 = \overline{F}_{CO_2} + \lambda_{CO_2} T$$

Ocean Heat Uptake

$$0 = -N + \lambda_{OHU} T$$

Hansen 1995, Winton et al 2010

Forcing efficacy

Equilibrium

$$0 = \overline{F} + \lambda T$$

CO_2

$$0 = \overline{F}_{CO_2} + \lambda_{CO_2} T$$

Ocean Heat Uptake

$$0 = -\varepsilon_N N + \lambda_{CO_2} T$$

Hansen 1995, Winton et al 2010

Forcing efficacy

Energy Budget

$$\varepsilon_N N = \overline{F} + \lambda T$$

CO_2

$$0 = \overline{F}_{CO_2} + \lambda_{CO_2} T$$

Ocean Heat Uptake

$$0 = -\varepsilon_N N + \lambda_{CO_2} T$$

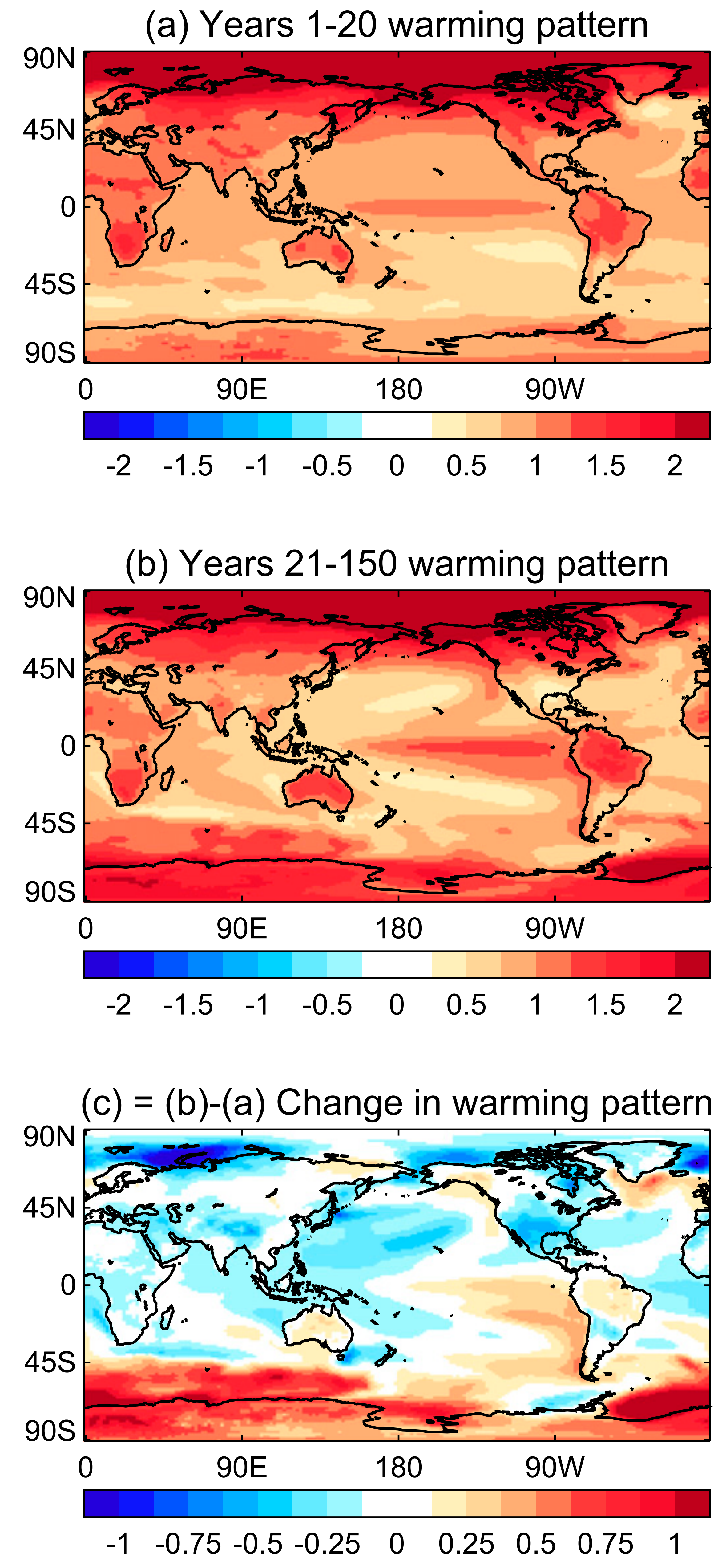
Winton et al 2010, Held et al 2010

Forcing efficacy

$$\varepsilon_N = \frac{\lambda_{CO_2}}{\lambda_N} =$$

Forcing efficacy

$$\varepsilon_N = \frac{\lambda_{CO_2}}{\lambda_N} = \frac{\sum_x \frac{\partial \bar{R}}{\partial T(x)} \frac{T_{CO_2}(x)}{\bar{T}_{CO_2}}}{\sum_x \frac{\partial \bar{R}}{\partial T(x)} \frac{T_N(x)}{\bar{T}_N}}$$



Rose et al 2014

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$$\overline{N} = \overline{F} + \overline{R}\left(T(x)\right)$$

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Fueglistaler 2019

Stability

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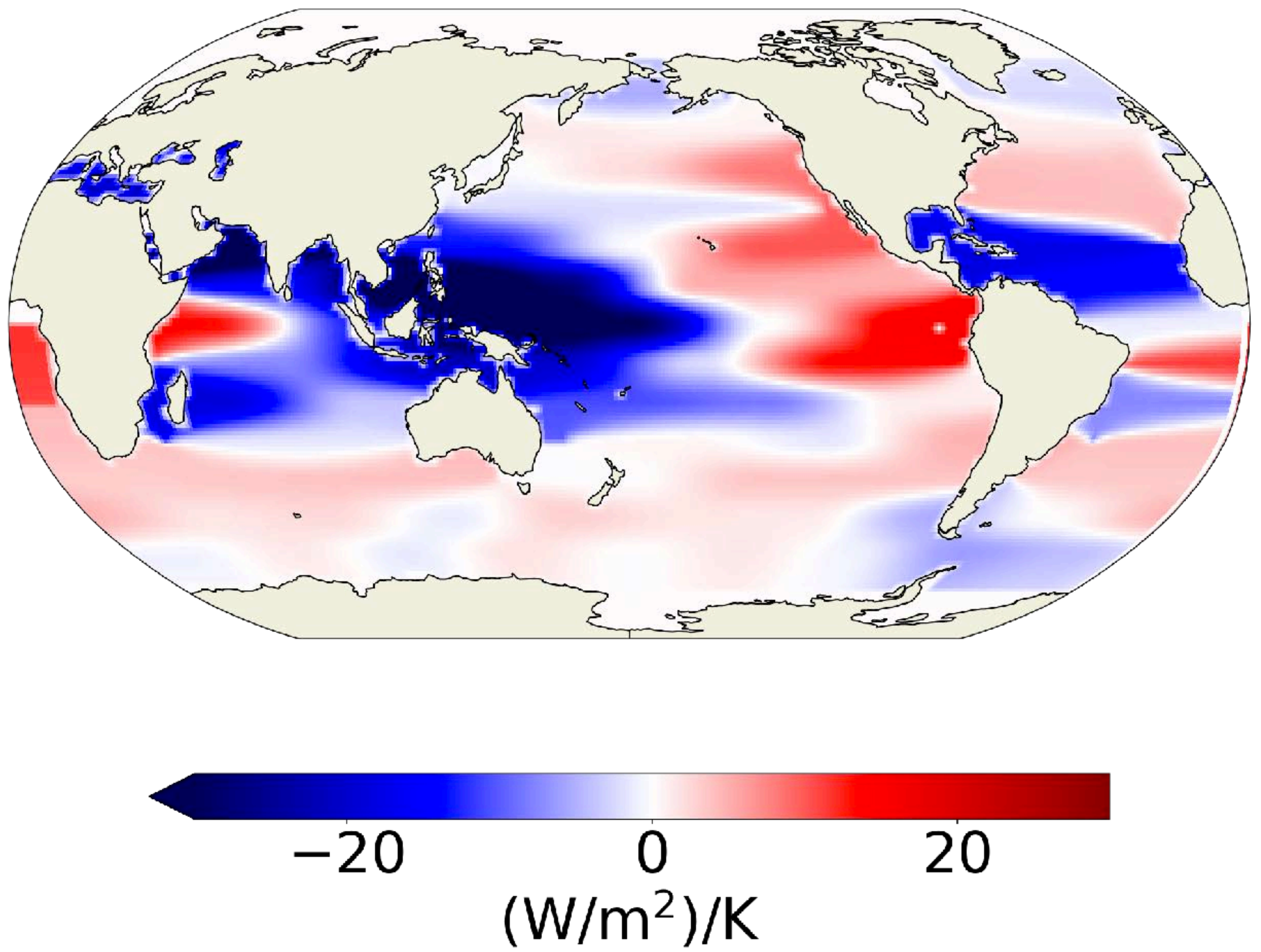
Ceppi and Gregory 2020

Radiative response dominated by warm pool

$$\frac{\partial \overline{R}}{\partial T(x)}$$

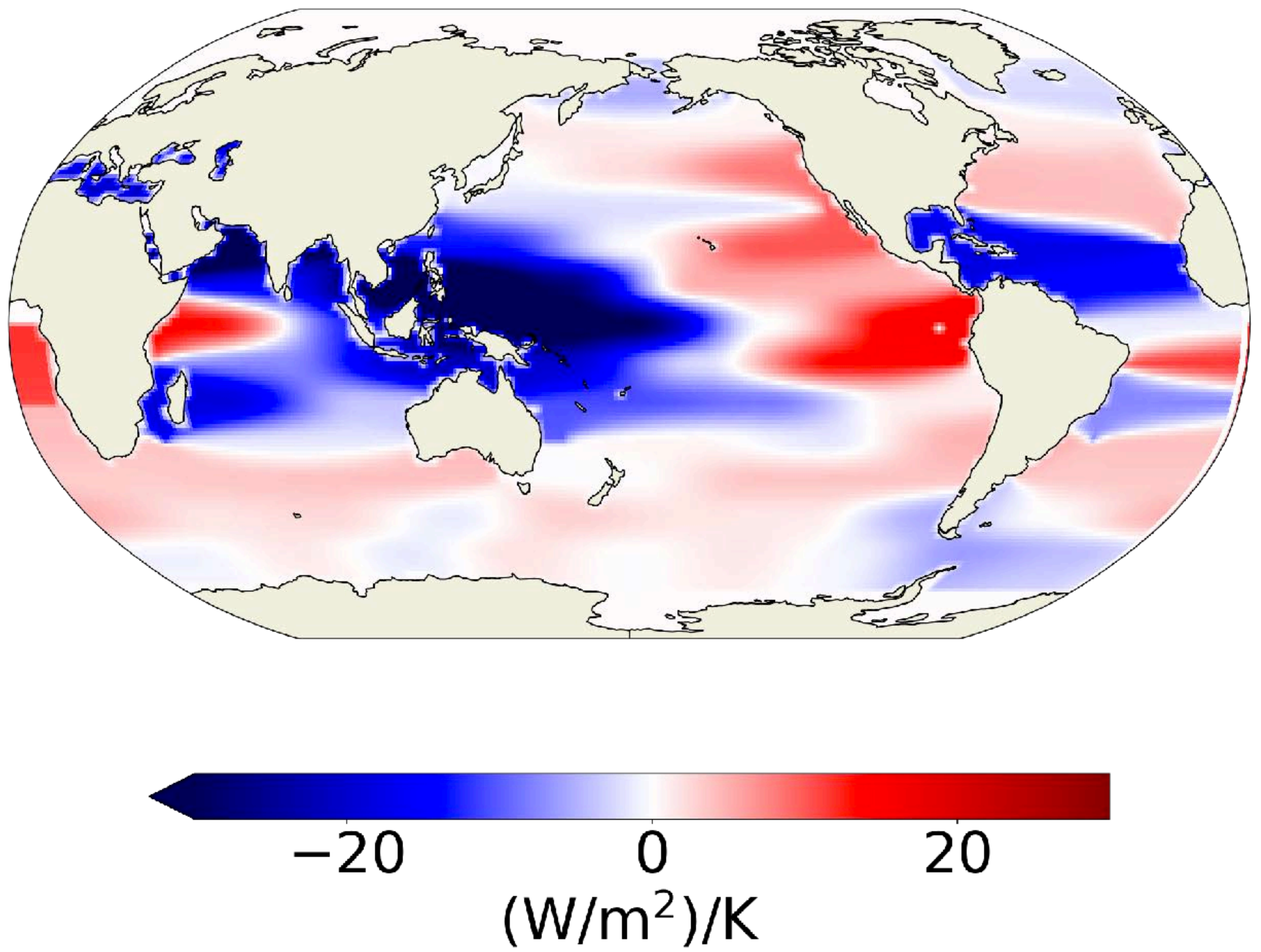


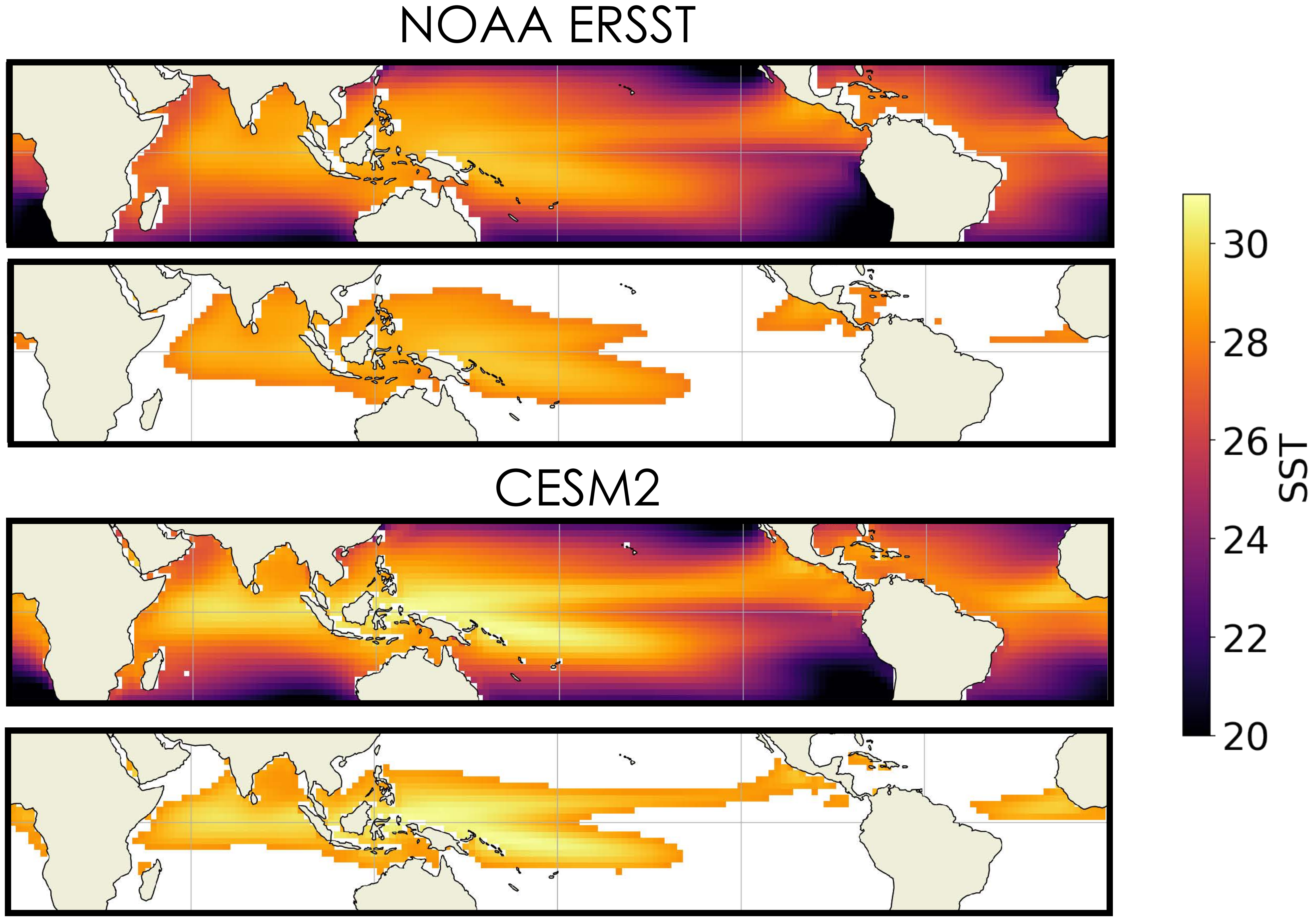
$$N = F + \alpha T + \gamma T^{\#}$$

Fueglistaler 2019, Dong et al 2019

Warm pool location varies between models and in time

$$\frac{\partial \overline{R}}{\partial T(x)}$$

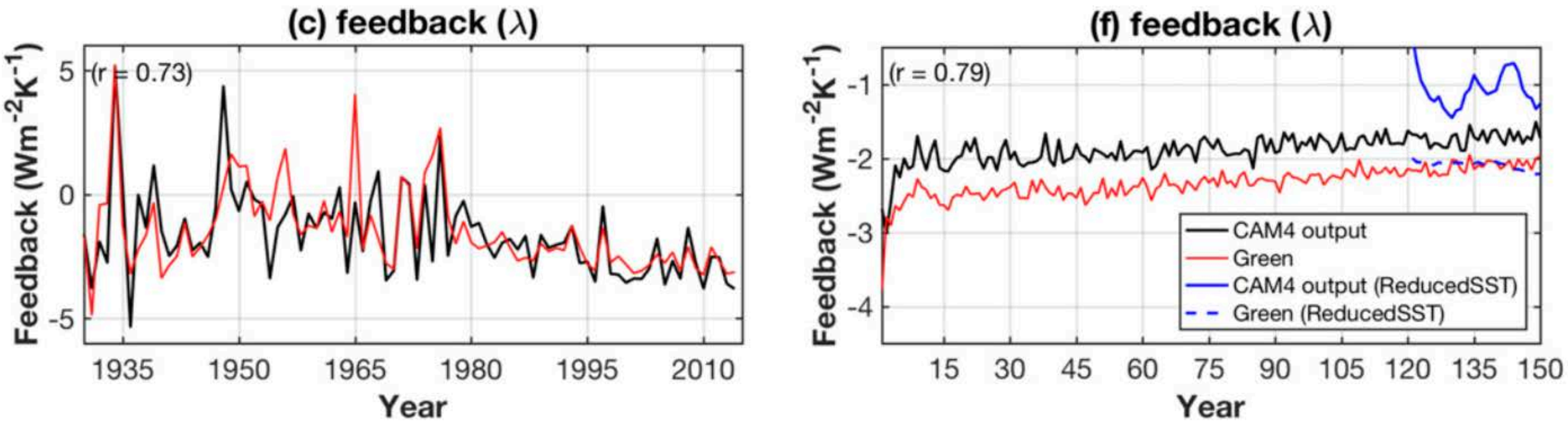




Roadmap

- Global feedback framework and it’s failure
- A refined view of the radiative response
- **Open Questions**
    - Radiative response
    - Forcing and heat uptake
    - Patterns

Open questions: Green's Function is **not quantitative**



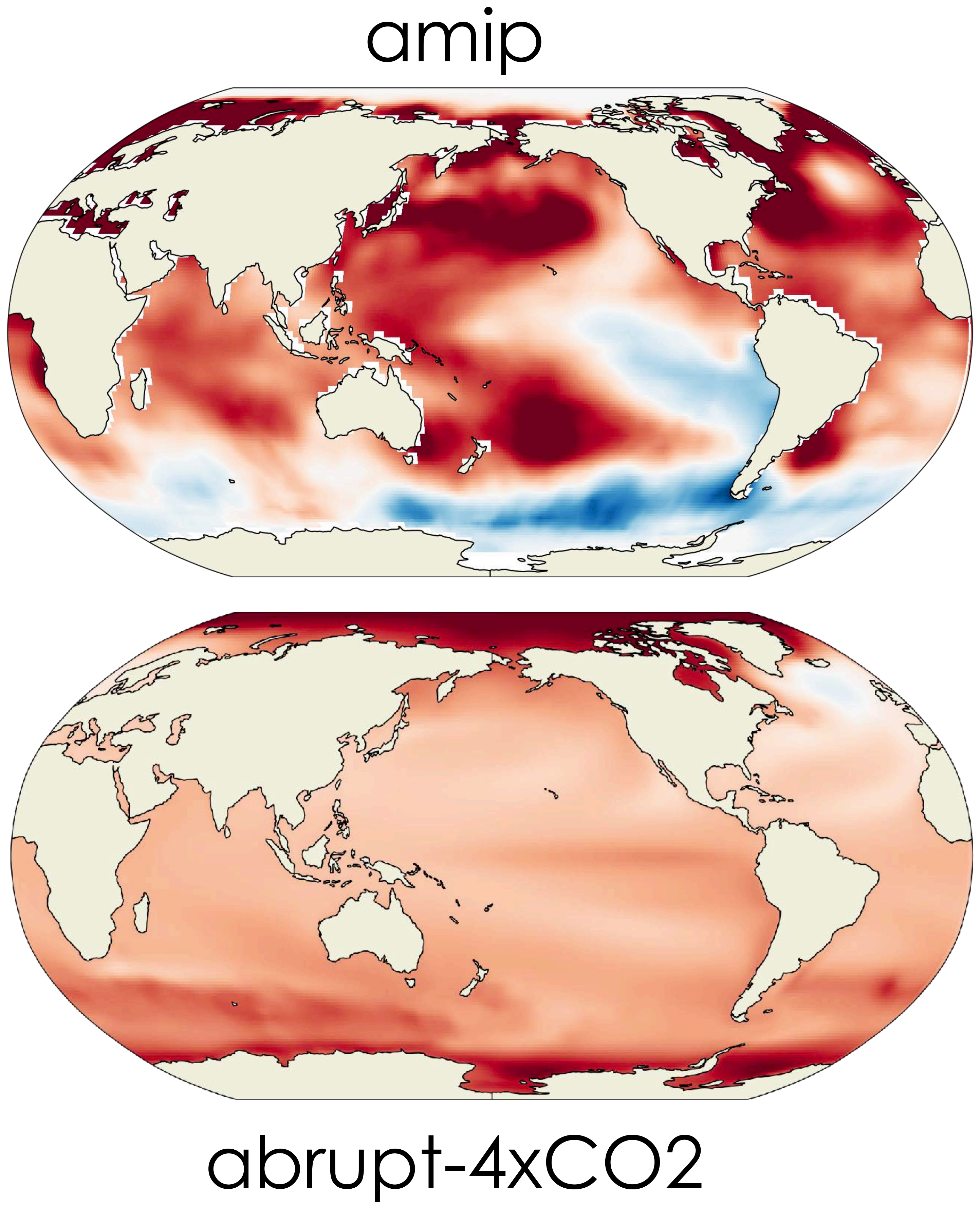
Nonlinearity? $T(x)^2, T(x) \cdot T(y)$?

Non-geographical framework?

Observational constrained? (~150 DOFs)

Open questions: Warming Patterns

$$N(t) = \overline{F} + \overline{R}\left(\boxed{T(x,t)}\right)$$



Open questions: Warming Patterns

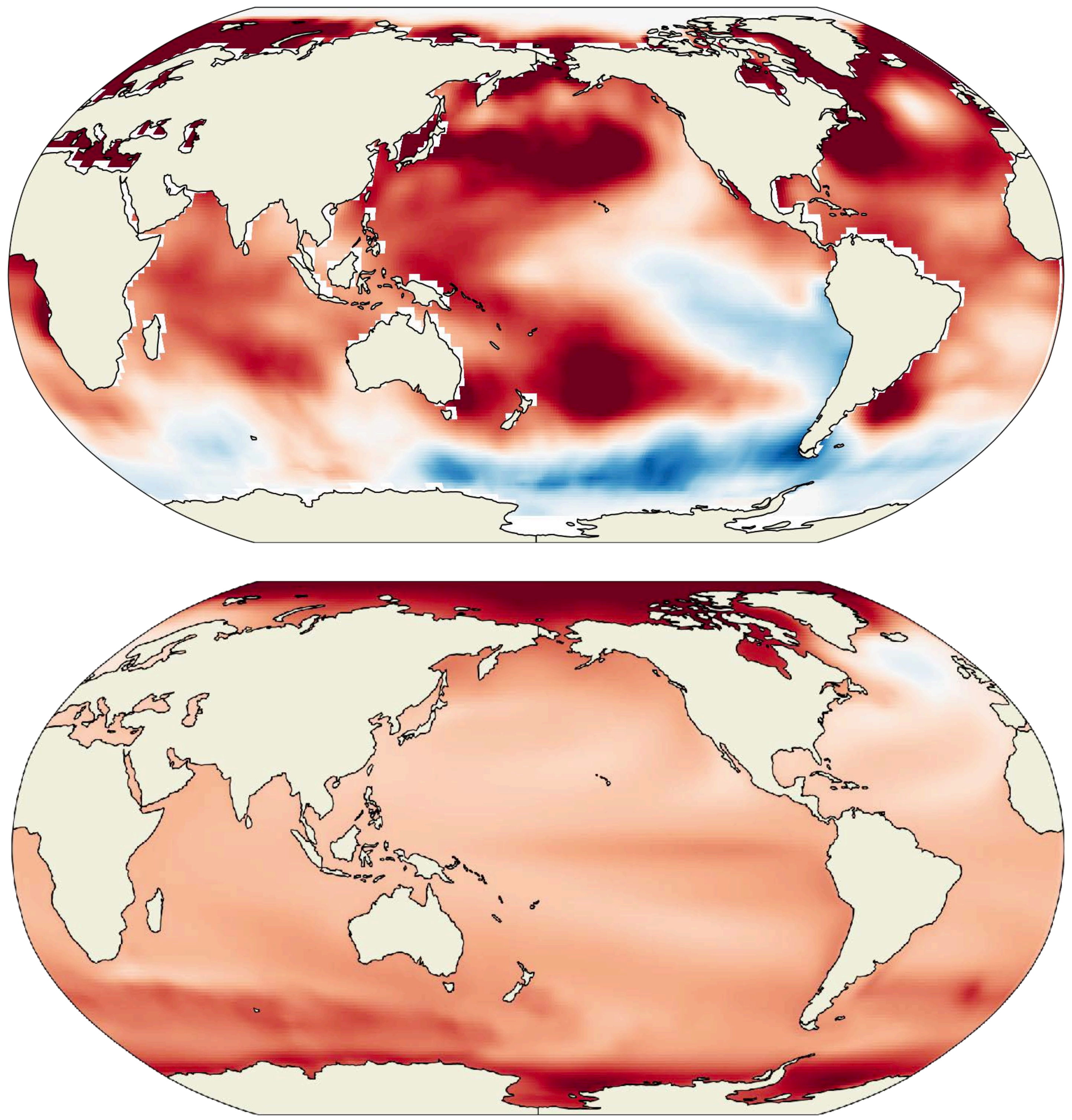
$$N(t) = \overline{F} + \overline{R}\left(\boxed{T(x,t)}\right)$$

$\psi(x)$:

Internal Variability:
ENSO?
PDO?
IPO?
AMO?

Forced Response?
CO2 - fast/slow mode?
Aerosols
Volcanoes
Meltwater

amip



abrupt-4xCO2

$$T(x,t) = \sum \psi(x)\phi(t)?$$

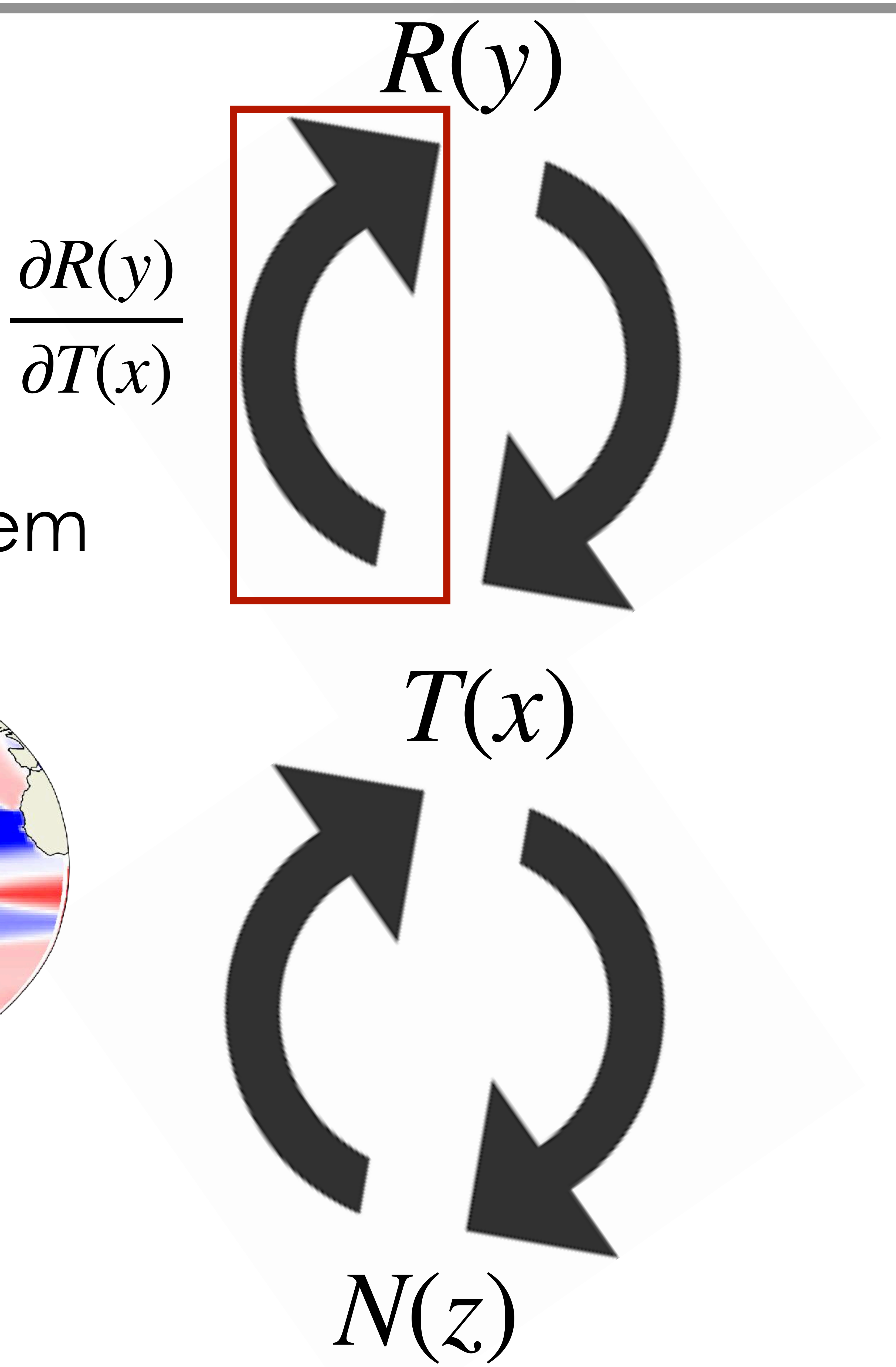
Open questions: Coupled problem

$R(y)$

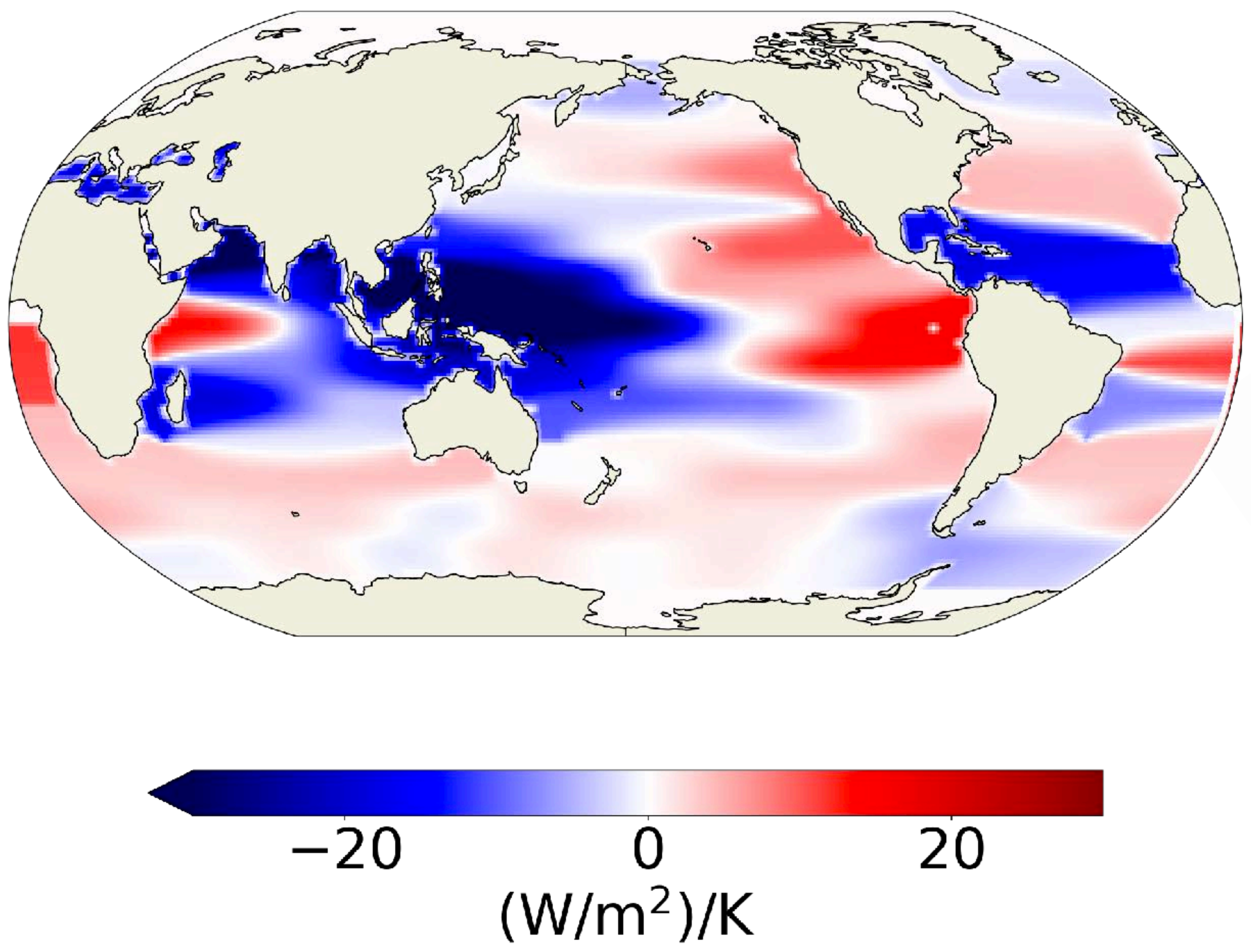
$T(x)$

$N(z)$

Open questions: Coupled problem



The AMIP/CFMIP problem



Open questions: Climate Dynamics

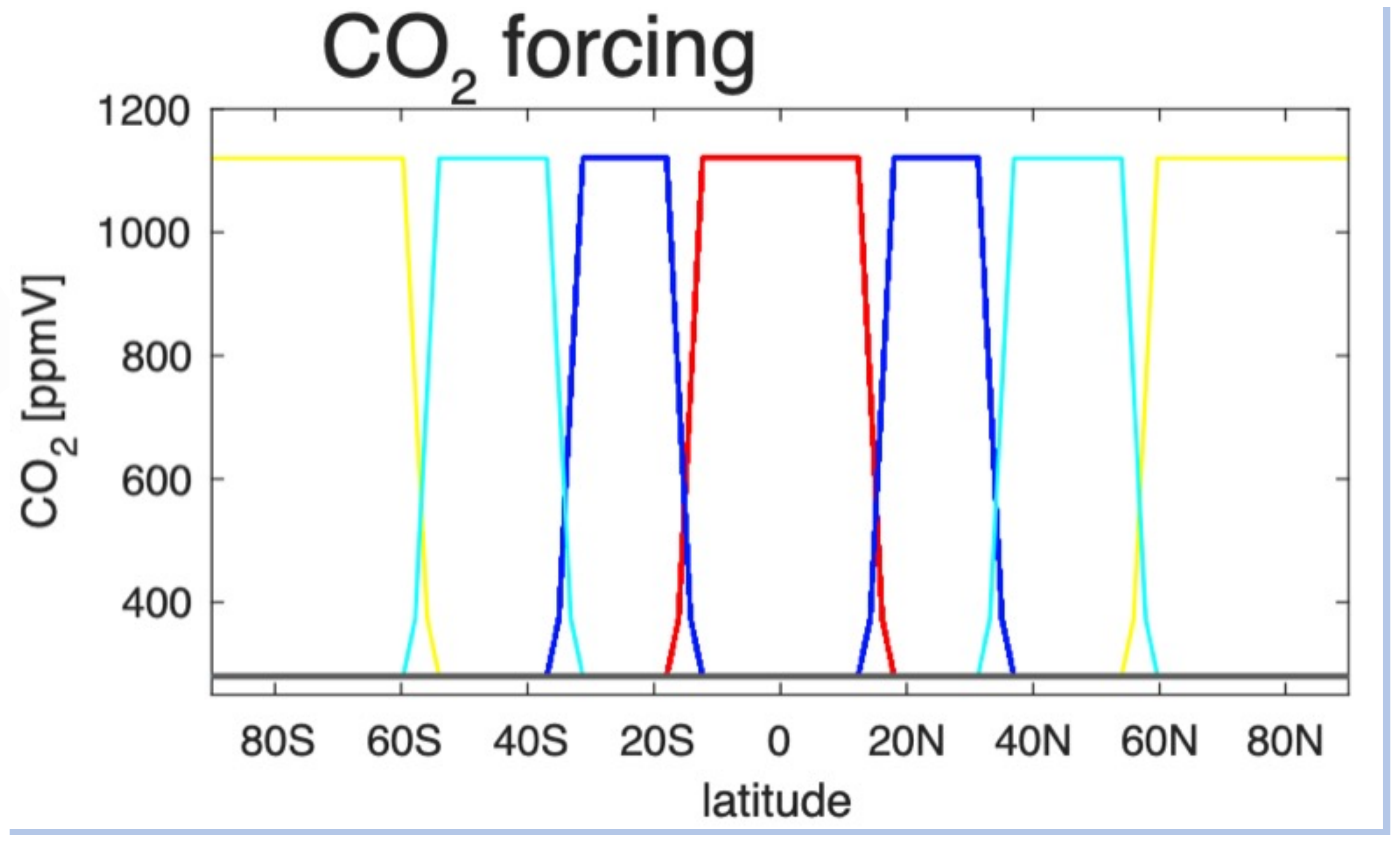
$$R(y)$$

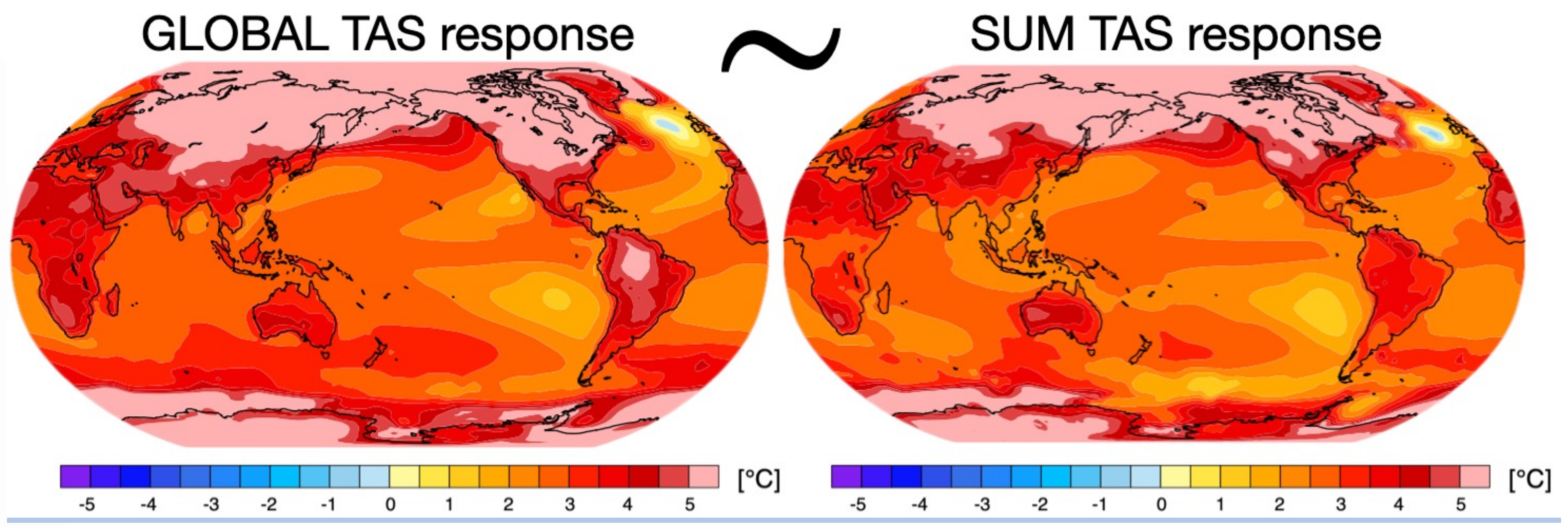
$$\frac{\partial R(y)}{\partial T(x)}$$

$$T(x)$$

$$N(z)$$

$$T(x) = \frac{\partial T(x)}{\partial F(y)} F(y)$$





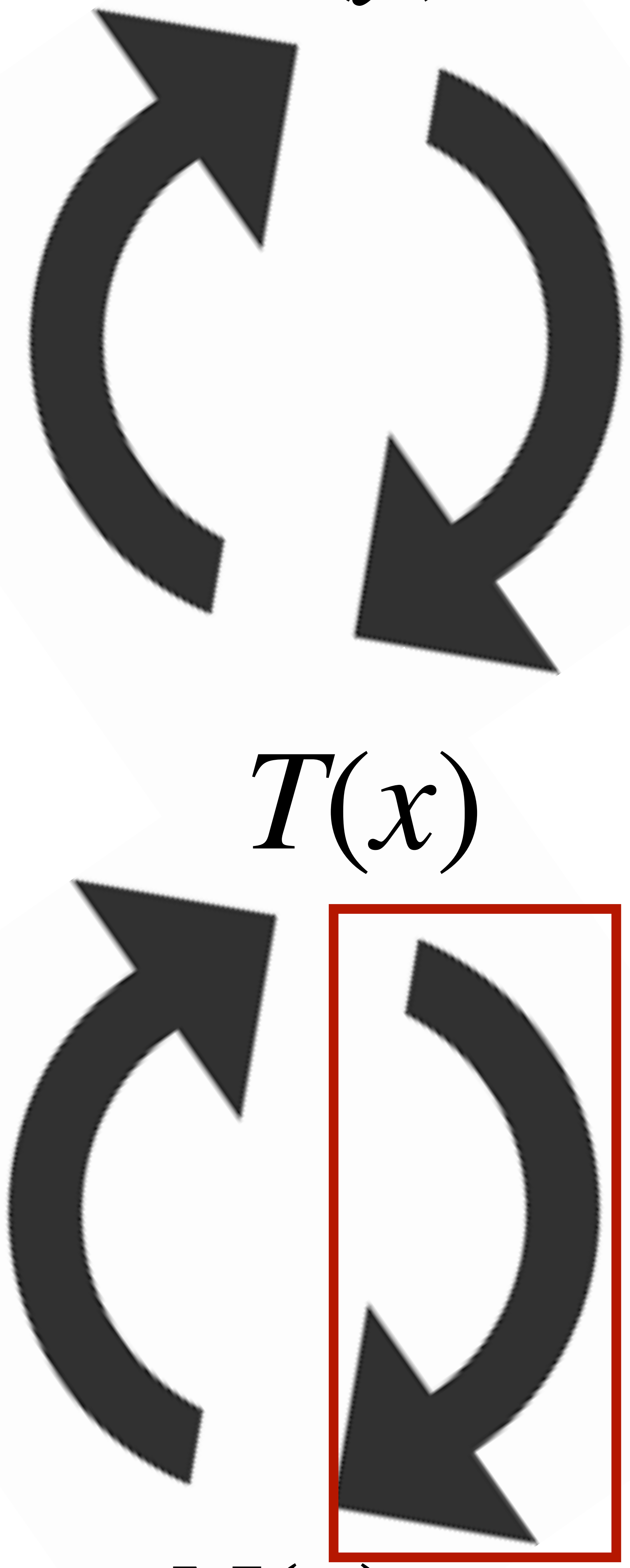
Stuecker et al 2020

Open questions: Climate Dynamics

$$R(y)$$

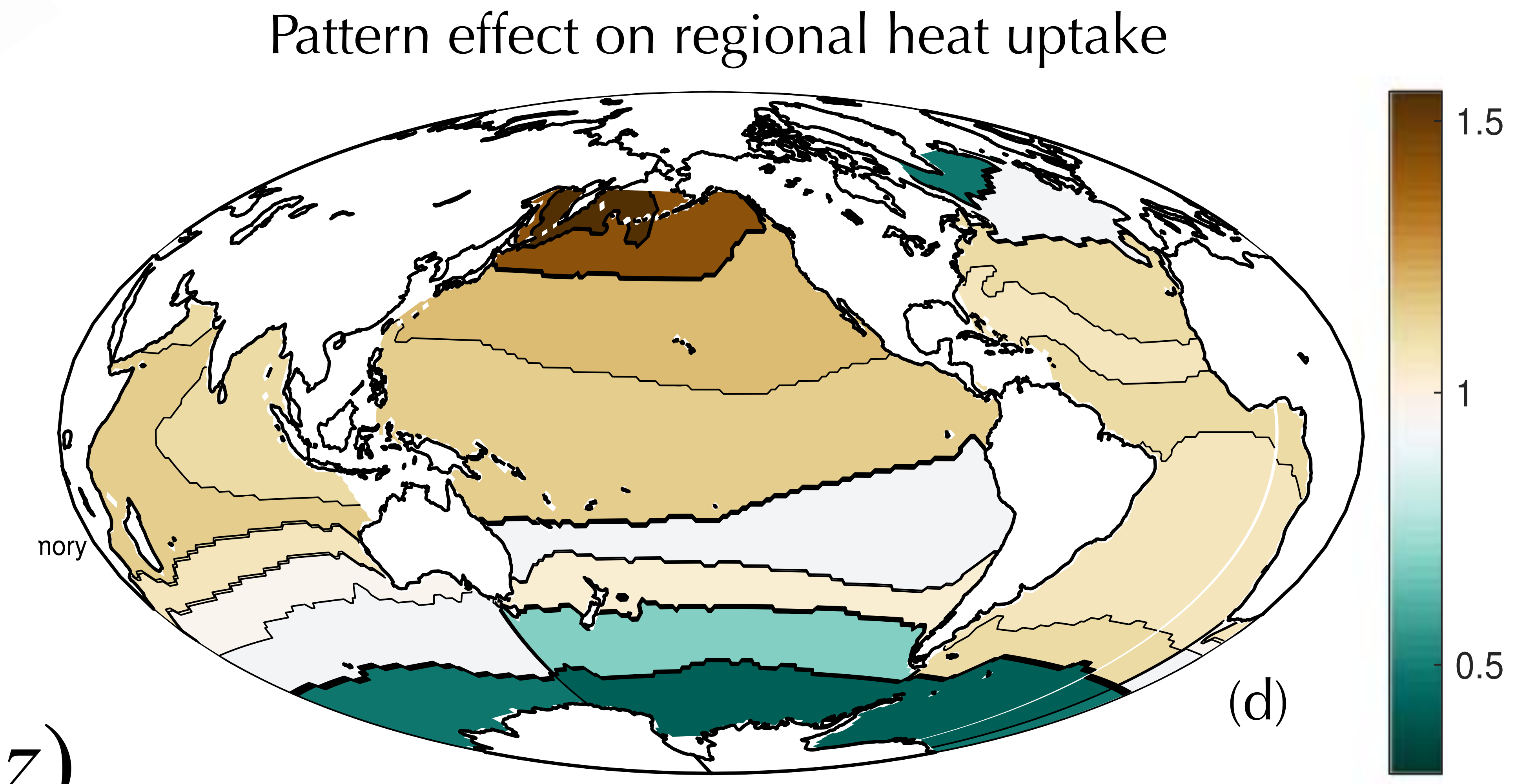
$$\frac{\partial R(y)}{\partial T(x)} \qquad \frac{\partial T(x)}{\partial R(y)}$$

$$T(x)$$



$$\frac{\partial N(z)}{\partial T(x)}$$

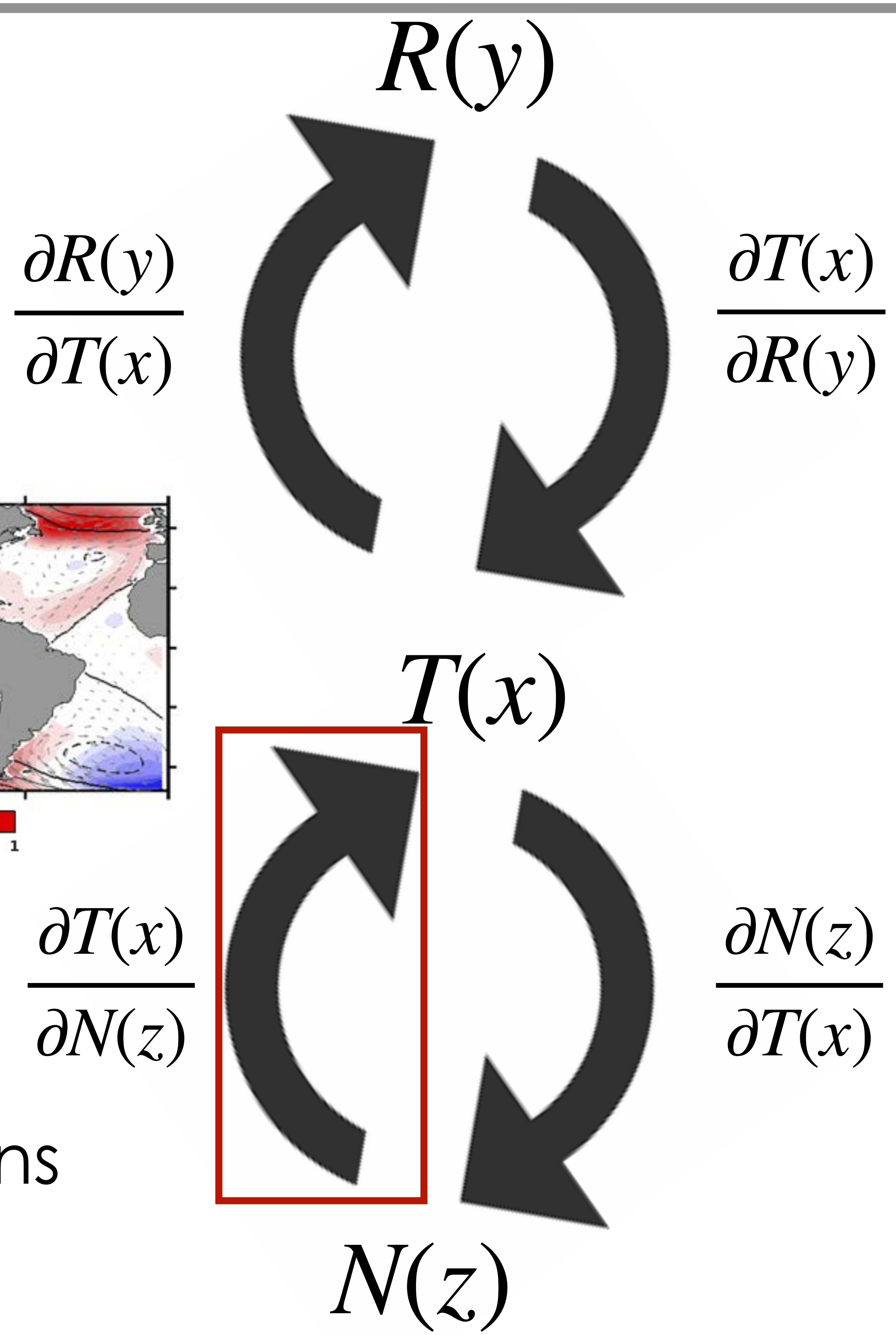
$$N(z)$$

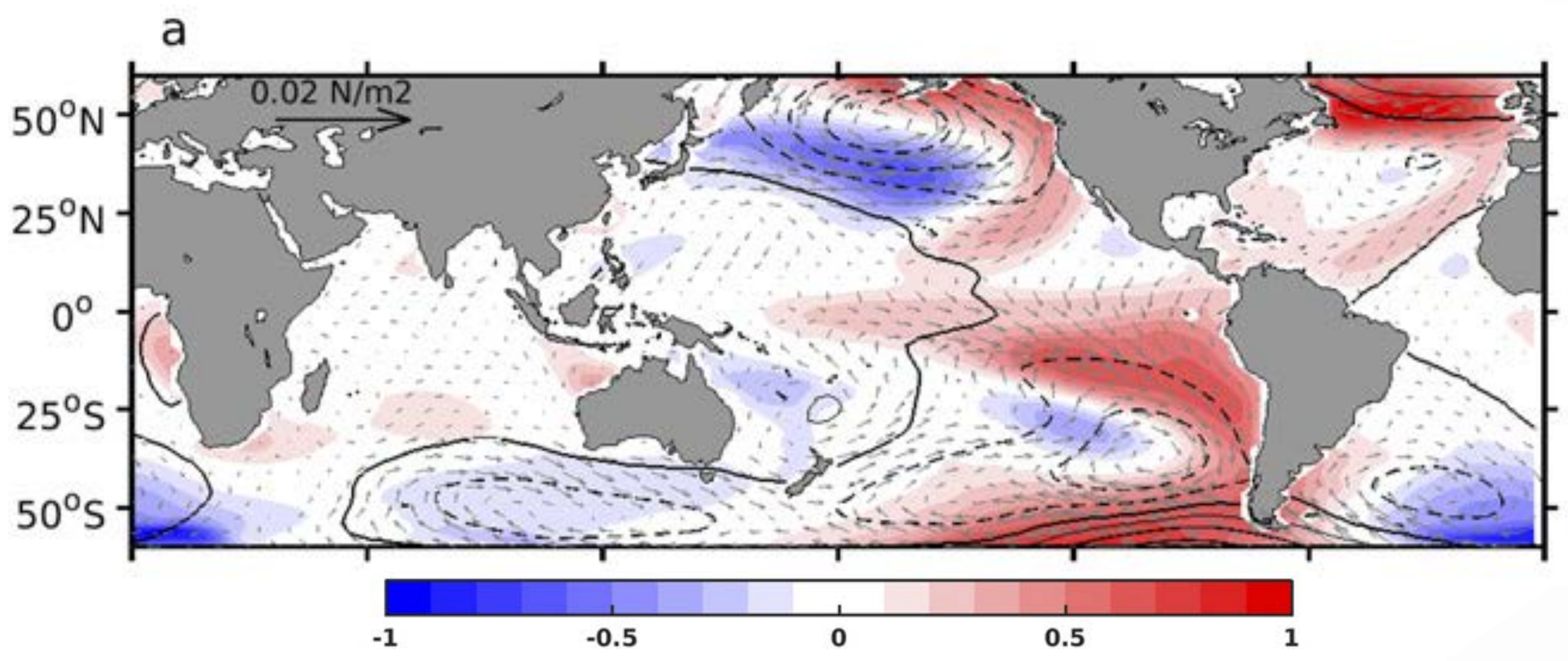


OHU green's functions

Newsom et al 2020

Open questions: Climate Dynamics

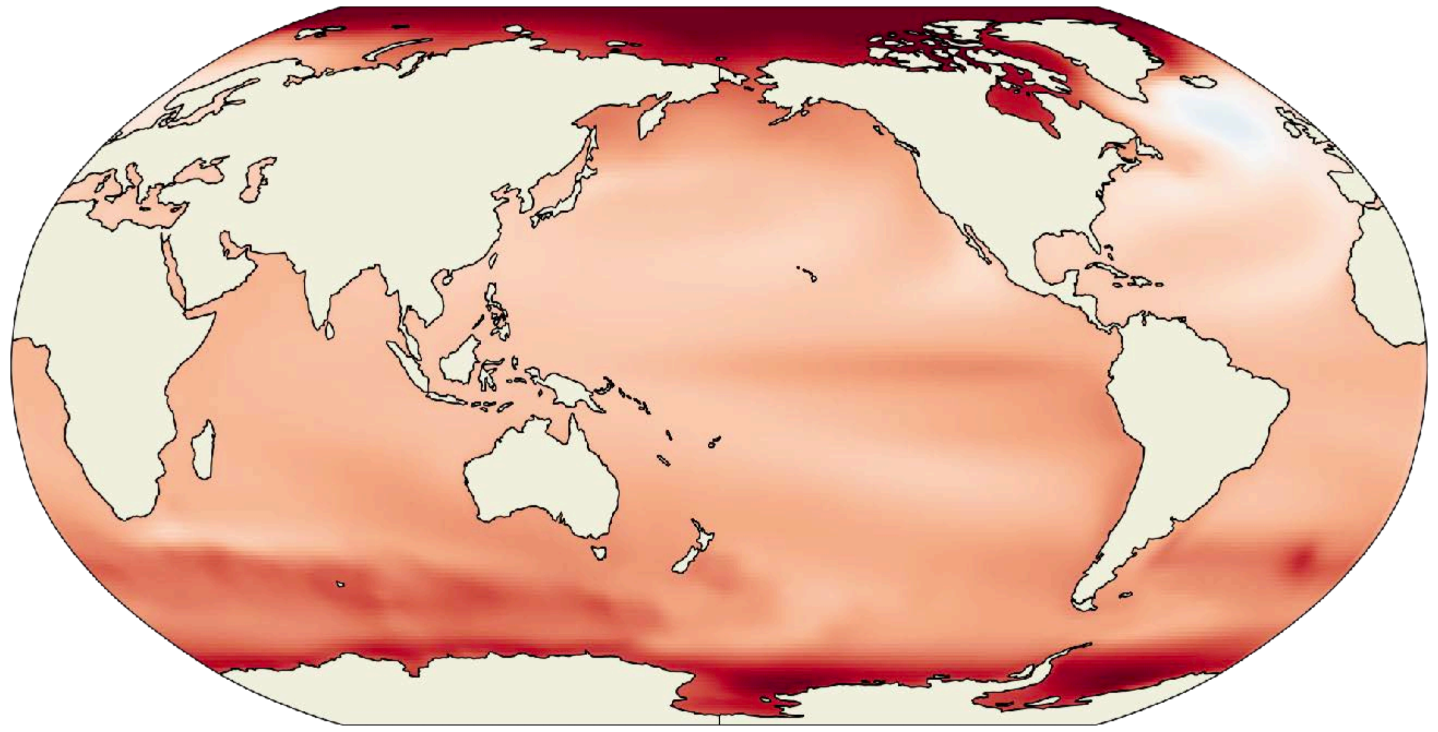




Q-flux green's functions

Liu et al 2018

Open questions: Near-term warming



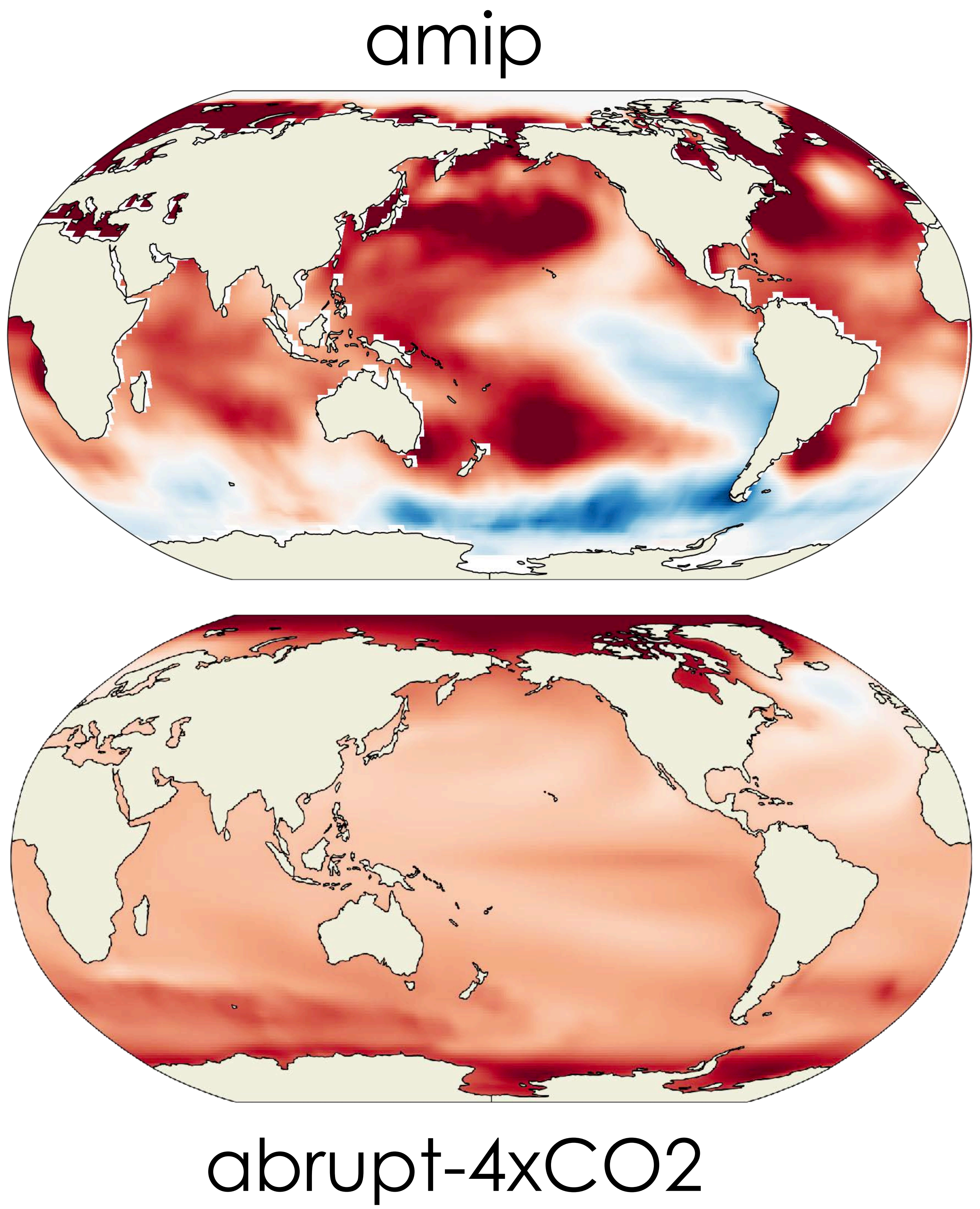
abrupt-4xCO2

ECS: $$T = \frac{\overline{F}}{\lambda}$$

$$\lambda = \frac{\partial R}{\partial T}$$

Gregory and Mitchell 1997, Held et al 2010

Open questions: Near-term warming



TCR: $$T = \frac{\overline{F}}{\lambda + \kappa}$$

$$\kappa = \frac{\partial N}{\partial T}$$

ECS: $$T = \frac{\overline{F}}{\lambda}$$

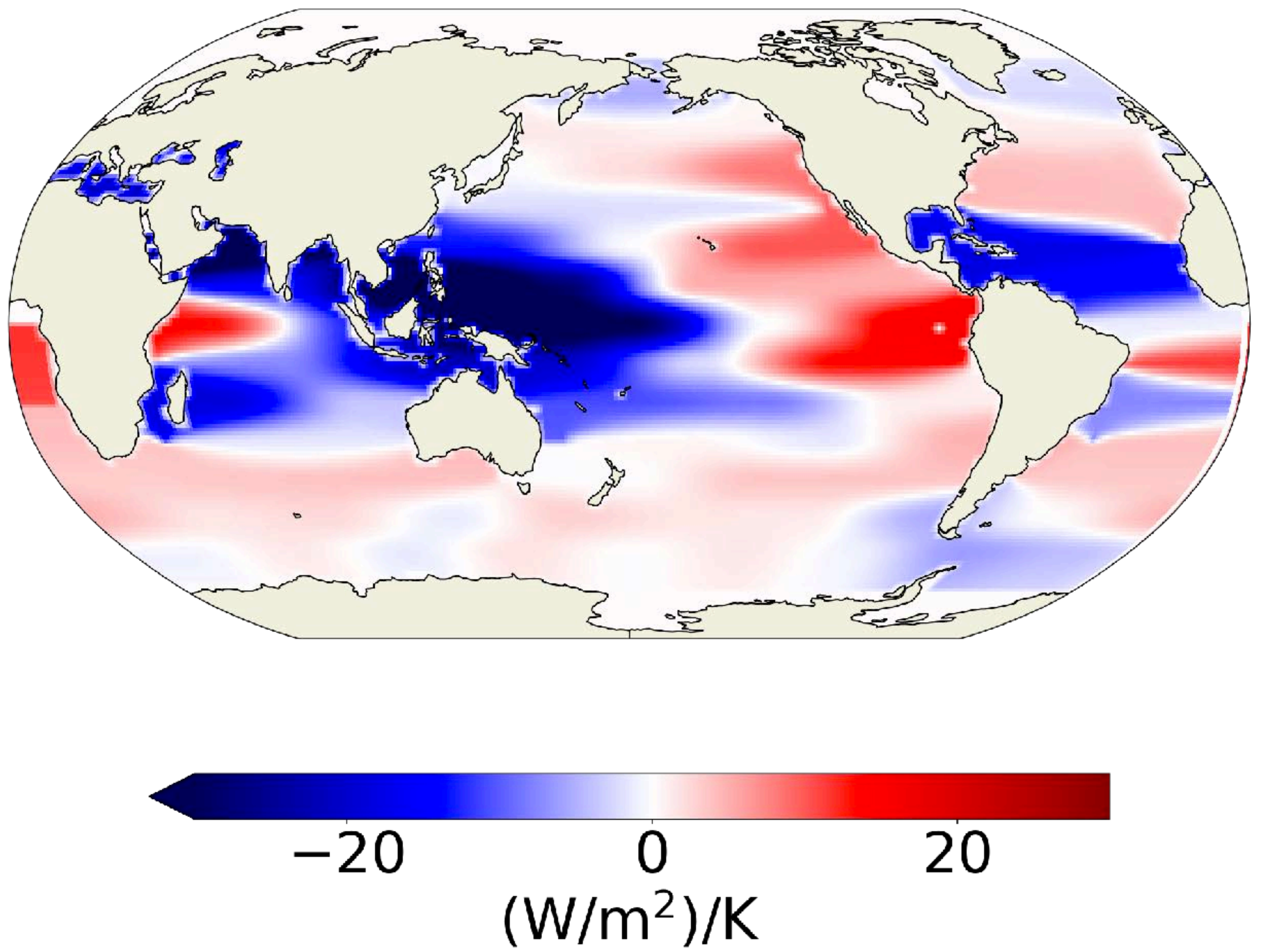
$$\lambda = \frac{\partial R}{\partial T}$$

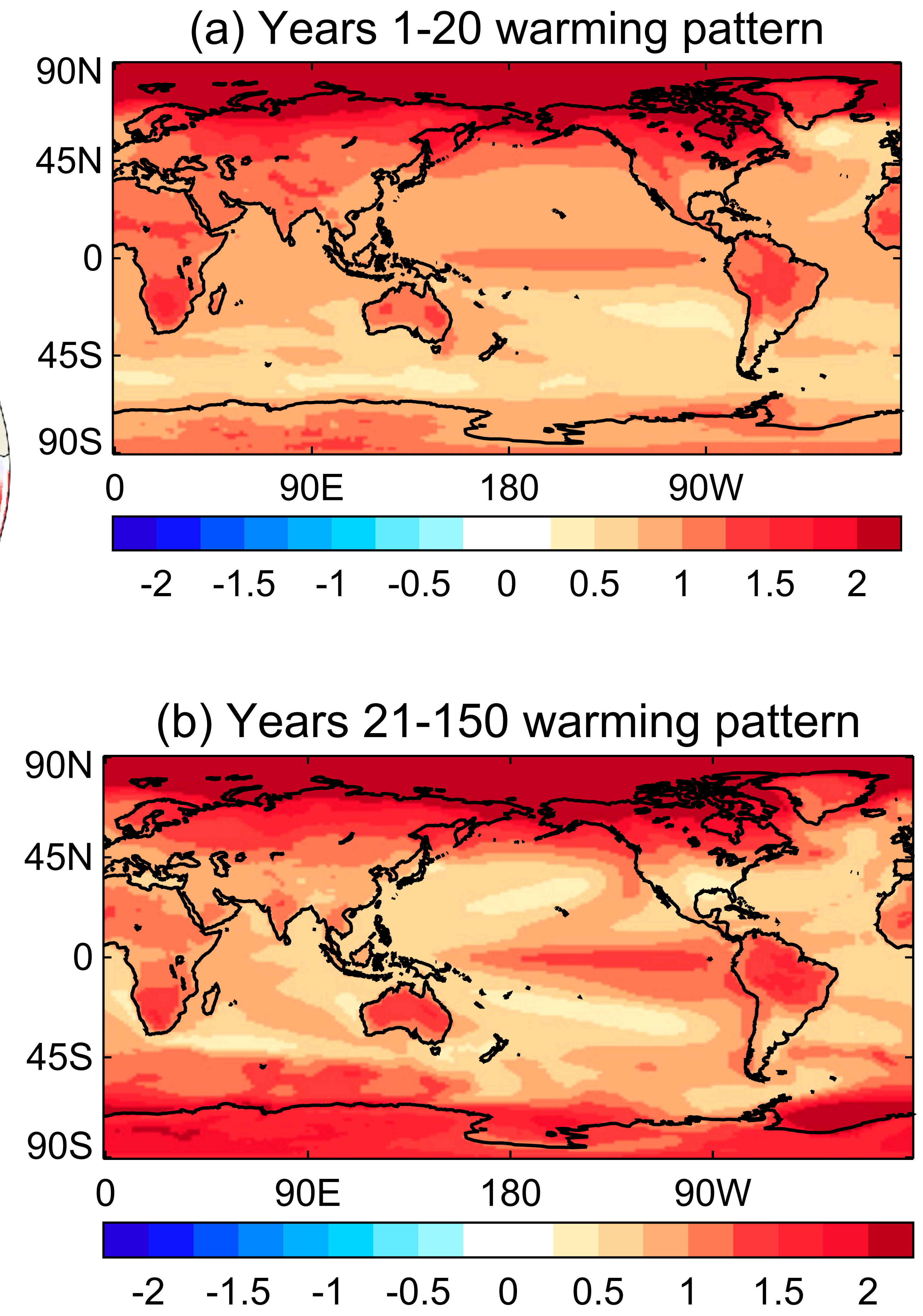
Gregory and Mitchell 1997, Held et al 2010

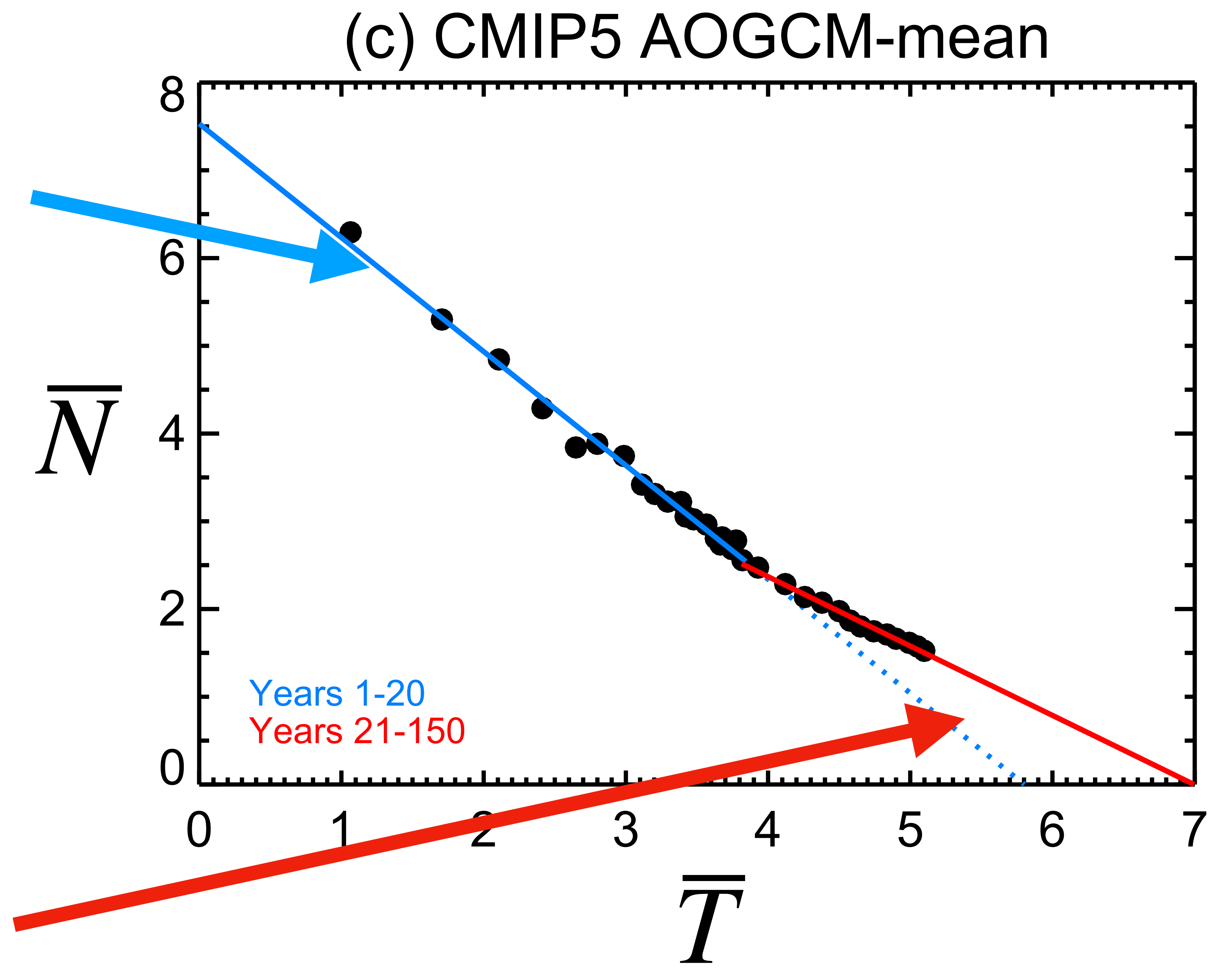
Summary slide Option 1

$$\lambda(t) = \sum \frac{\partial \overline{R}}{\partial T(x)} \times \frac{T(x,t)}{\overline{T}}$$

$$\overline{N} = \overline{F} - \overbrace{\boxed{\sum_x \frac{\partial \overline{R}}{\partial T(x)} \frac{T(x,t)}{\overline{T}}}}^{\lambda(t)} \overline{T}$$



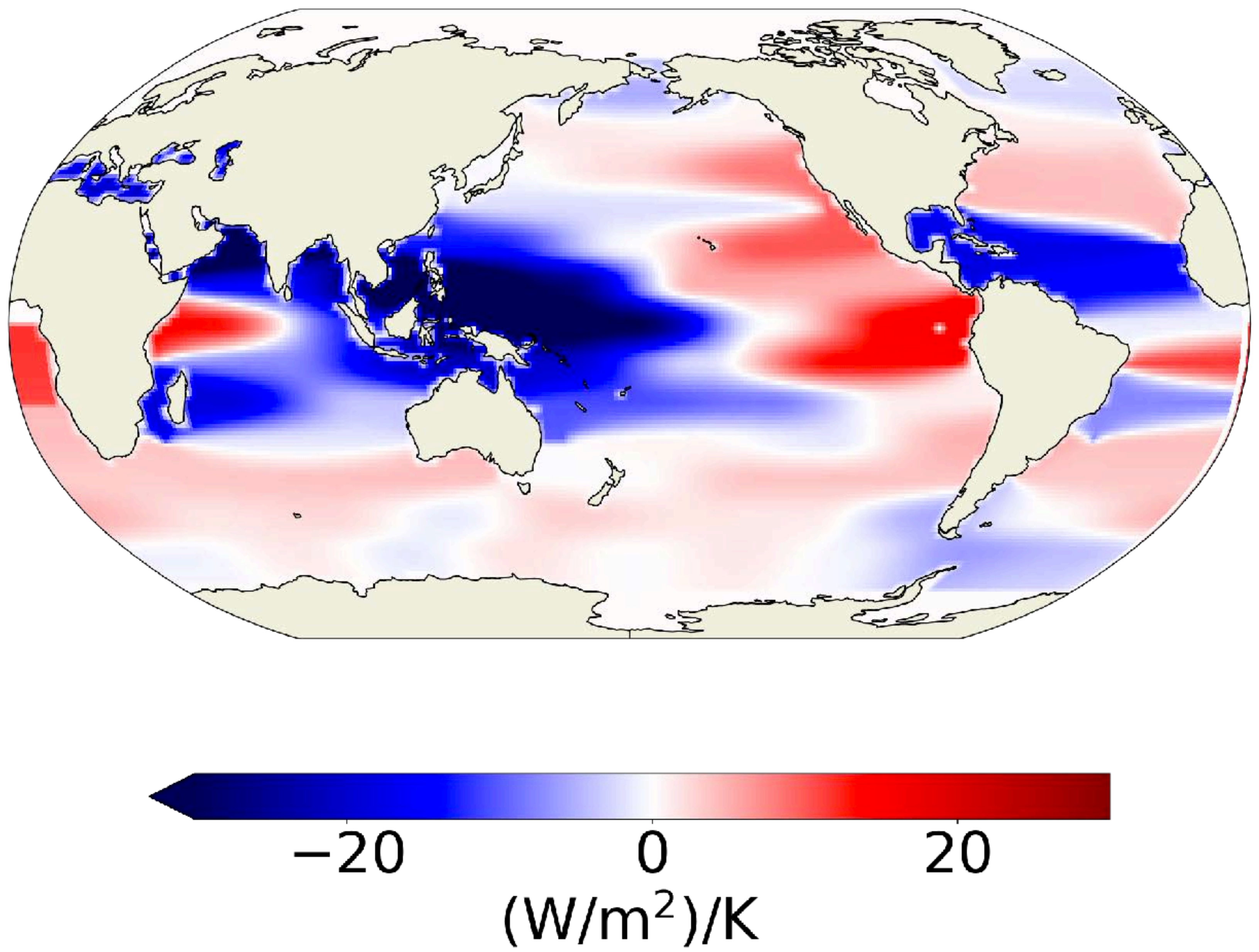




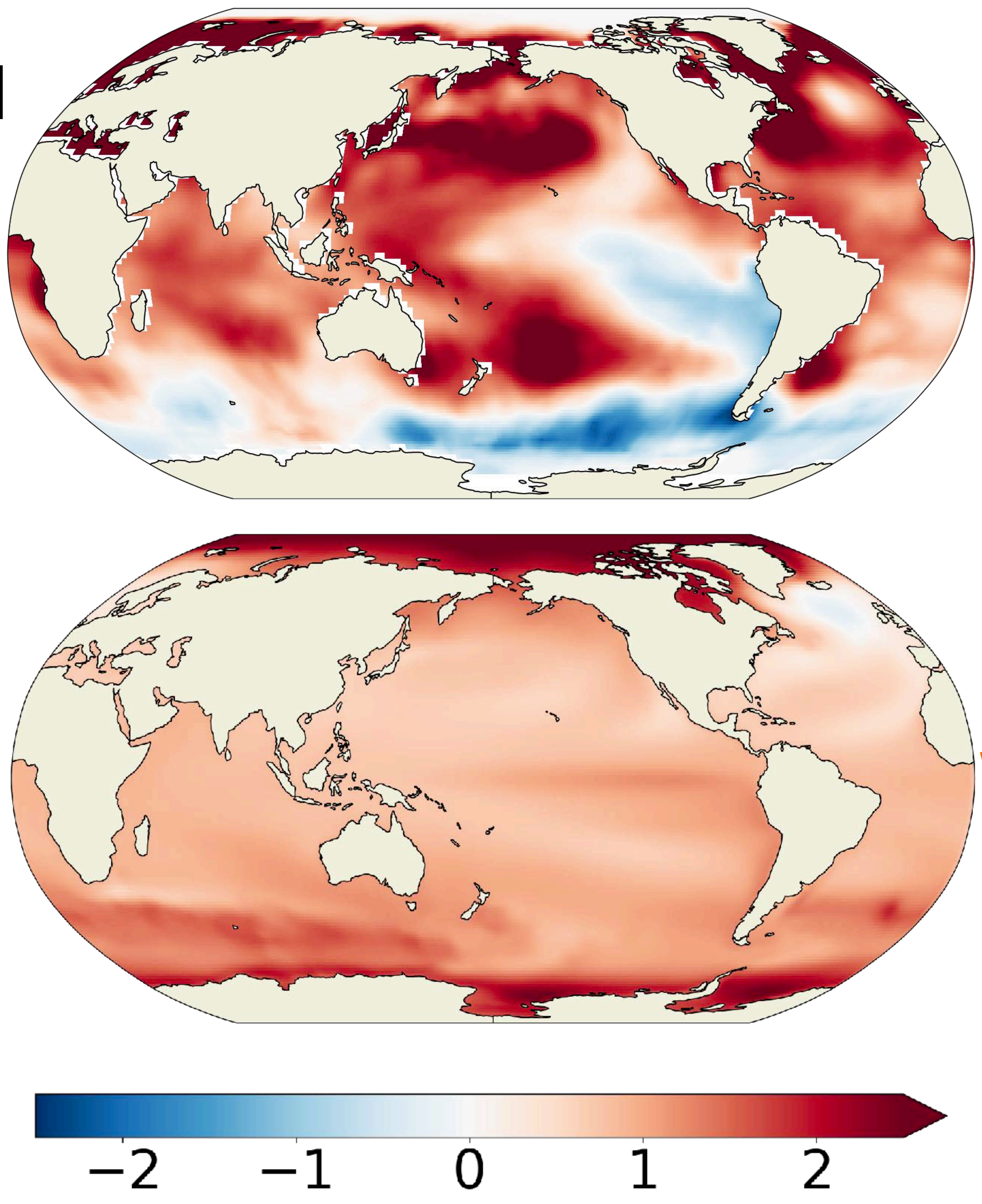
Andrews et al 2015

Summary slide Option 2

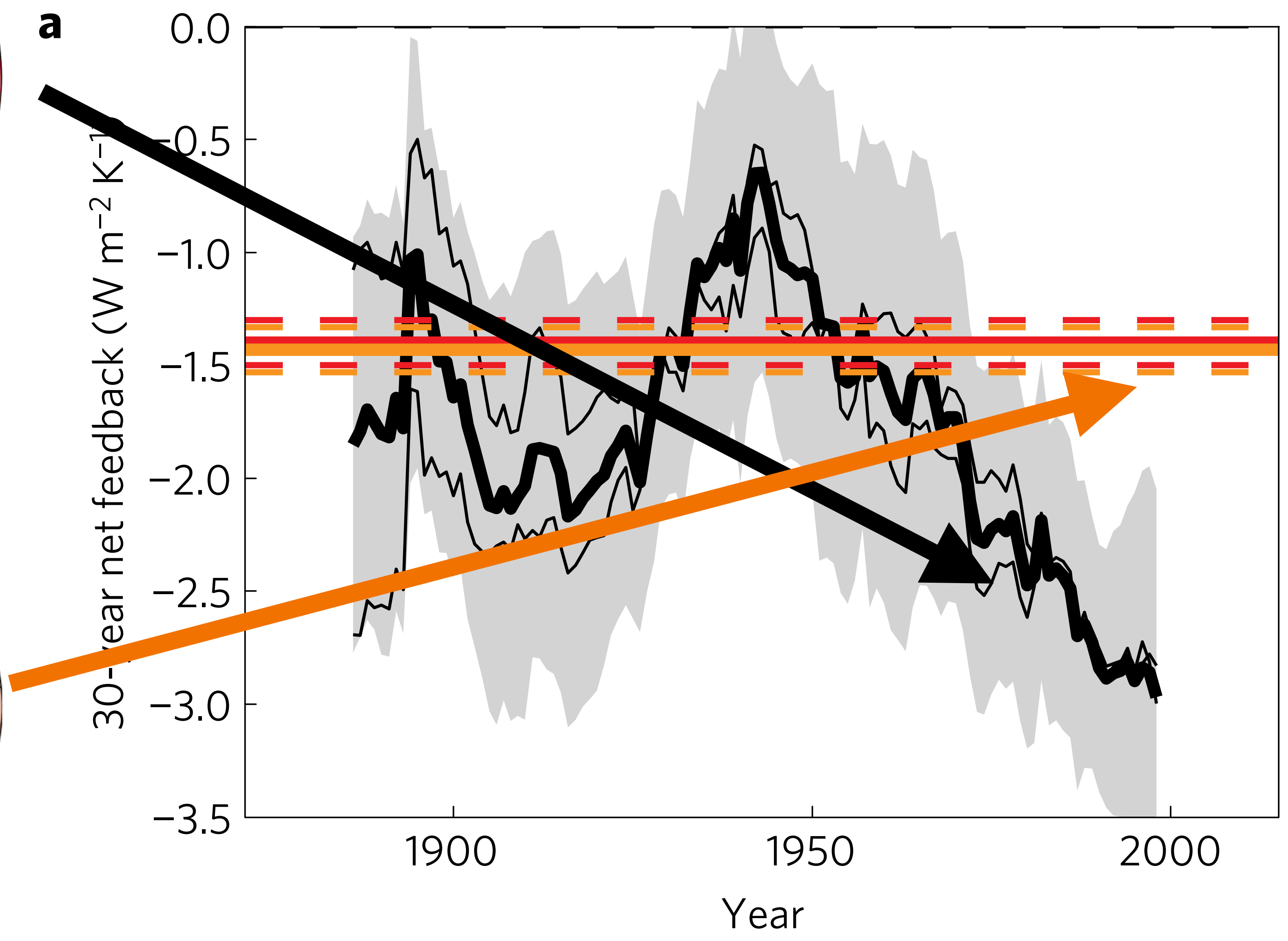
$$\lambda(t) = \sum \frac{\partial \bar{R}}{\partial T(x)} \times \frac{T(x,t)}{\bar{T}}$$



historical



abrupt-4xCO2



Zhou et al 2016

Supplementary Slides

Feedbacks are just Taylor Series in disguise

Global-temperature

$$\Delta\overline{R} \approx \underbrace{\boxed{\frac{\partial\overline{R}}{\partial\overline{T}}}}_{}\Delta\overline{T}$$

λ

Roe et al 2008

Regional Temperatures

$$\Delta\overline{R} \approx \boxed{\sum_x \frac{\partial\overline{R}}{\partial T(x)}\frac{\Delta T(x)}{\Delta\overline{T}}}\Delta\overline{T}$$

λ

Radiative Response

Warming pattern

Armour et al 2013
Proistosescu & Huybers 2017

Anatomy of a low cloud feedback

$$\Delta \overline{R} \approx \sum_{x,y} \frac{\partial R(y)}{\partial M(y)} \frac{\partial M(y)}{\partial T(x)} \frac{\Delta T(x)}{\Delta \overline{T}} \Delta \overline{T}$$

Cloud Radiative Effect

Meteorology

Warming pattern

Klein et al 2017
Scott et al 2020
Myers et al 2022

Anatomy of a low cloud feedback

$$\Delta\overline{R} \approx \sum_{x,y} \frac{\partial R(y)}{\partial C(\tau,p,y)} \frac{\partial C(\tau,p,y)}{\partial M(y)} \frac{\partial M(y)}{\partial T(x)} \frac{\Delta T(x)}{\Delta\overline{T}} \Delta\overline{T}$$

Cloud Radiative Effect

Cloud fraction

Meteorology

Warming pattern

Klein et al 2017
Scott et al 2020
Myers et al 2022

Anatomy of a low cloud feedback

$$\Delta\overline{R} \approx \sum_{x,y} \frac{\partial R(y)}{\partial C(\tau,p,y)} \frac{\partial C(\tau,p,y)}{\partial M(y)} \frac{\partial M(y)}{\partial T(x)} \frac{\Delta T(x)}{\Delta\overline{T}} \Delta\overline{T}$$

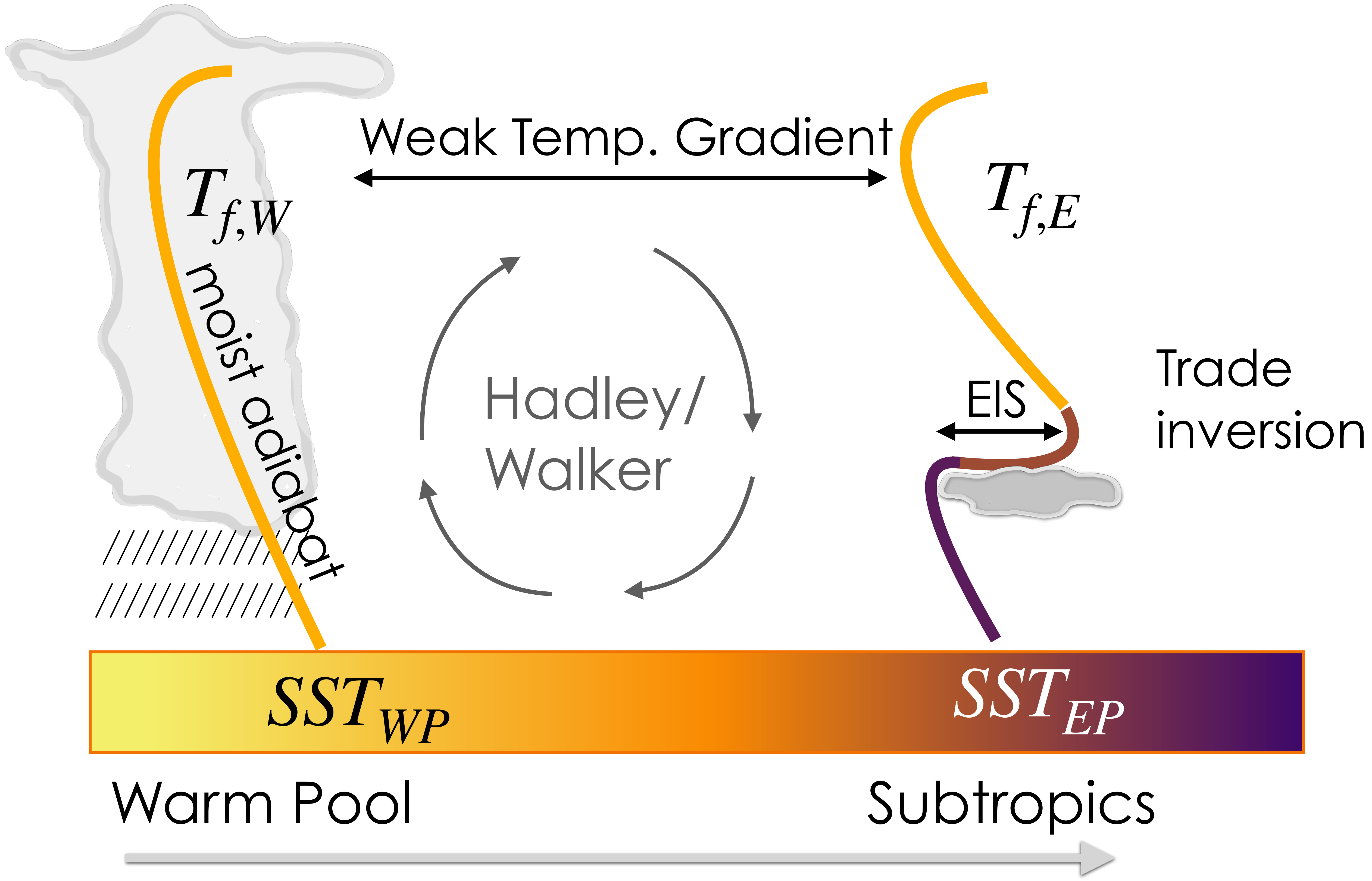
Radiative Transfer

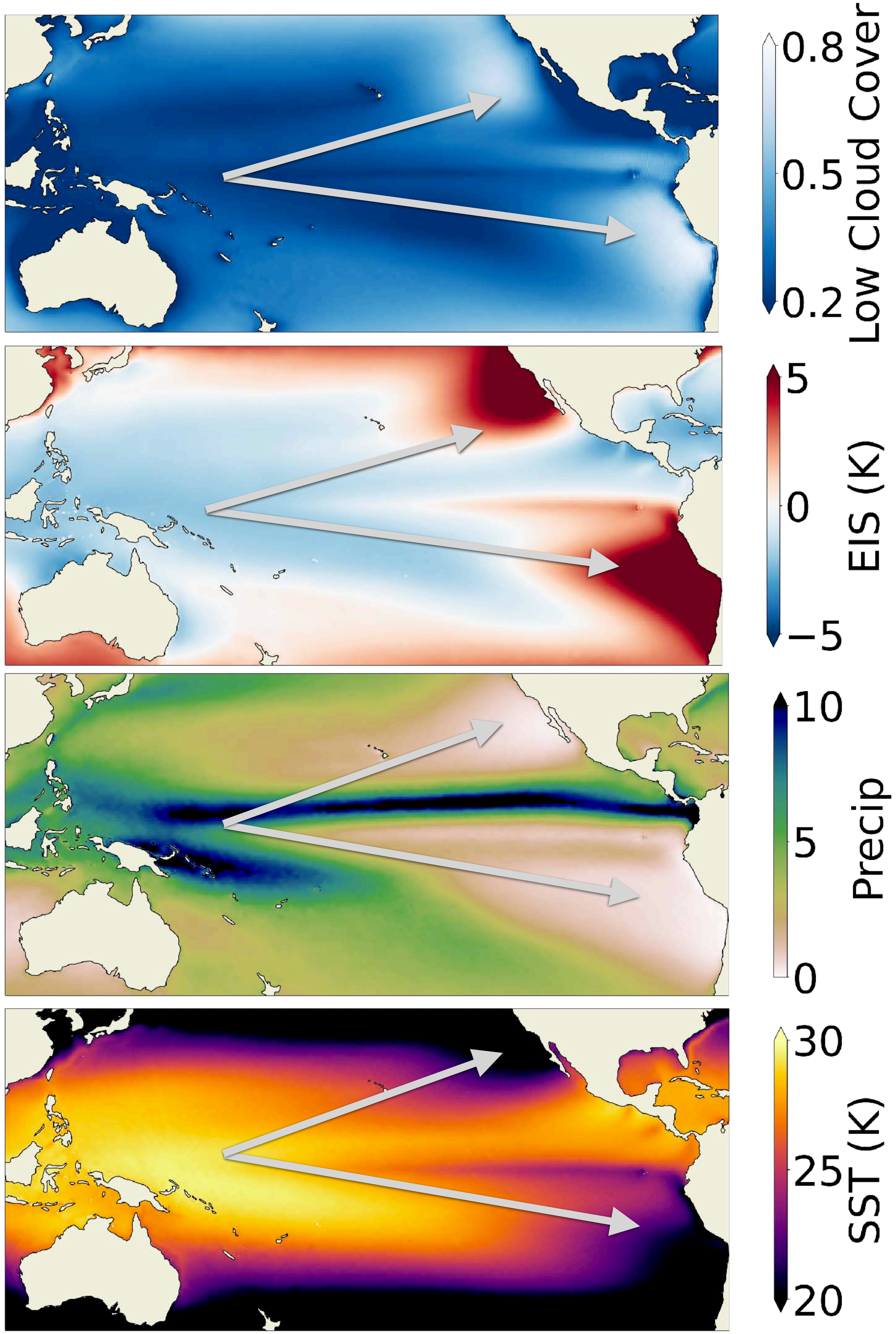
Cloud physics

Atmospheric Circulatlon

Coupled Dynamics

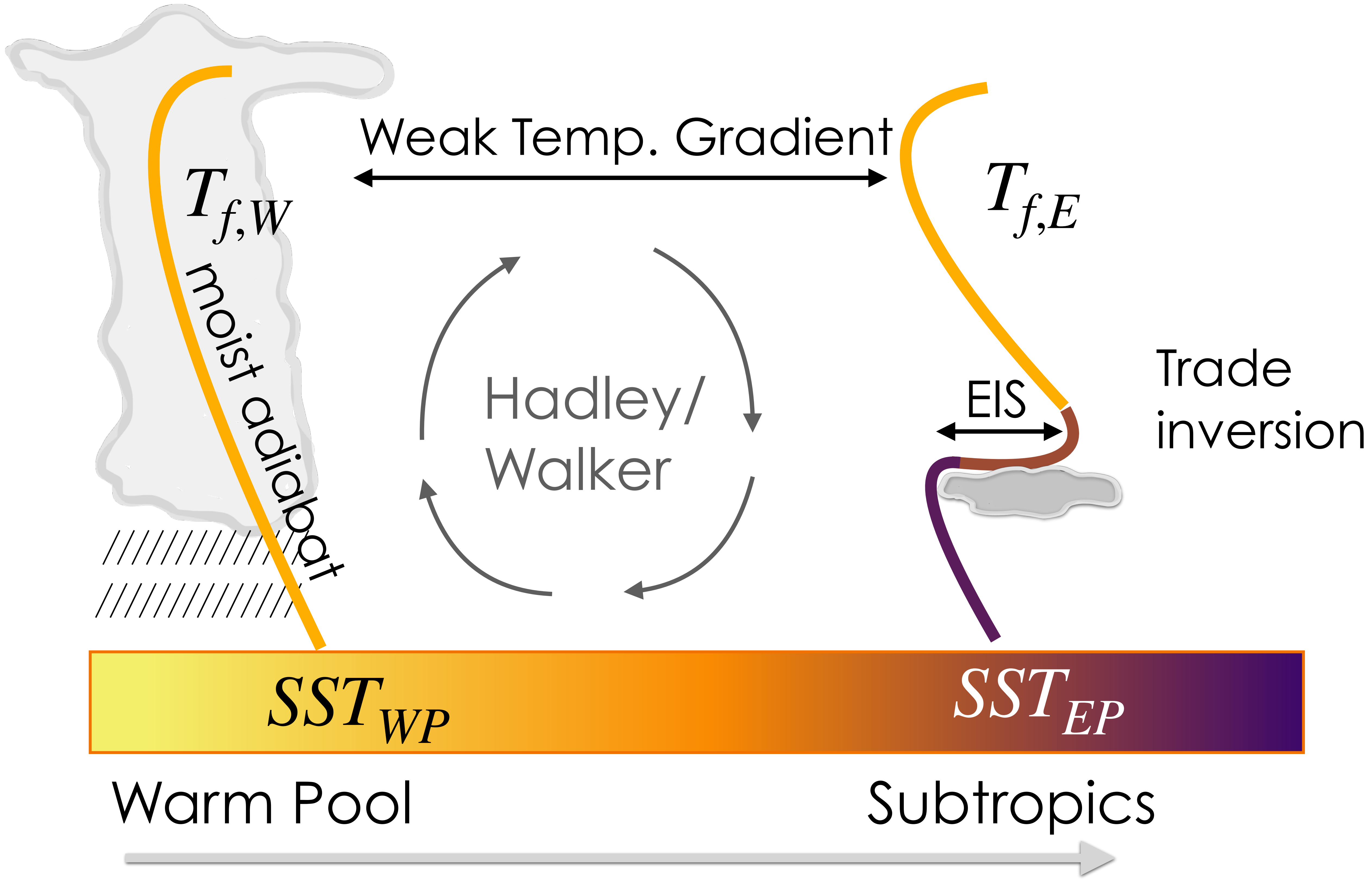
Tropical Climate Dynamics

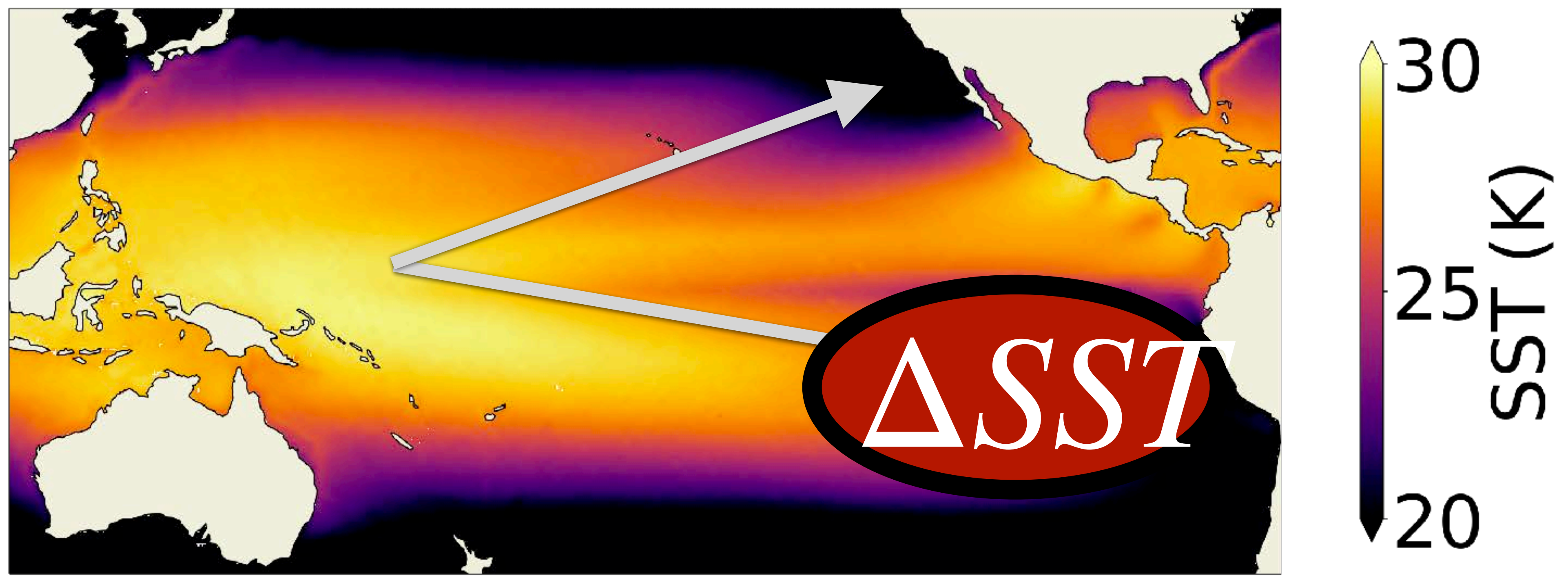




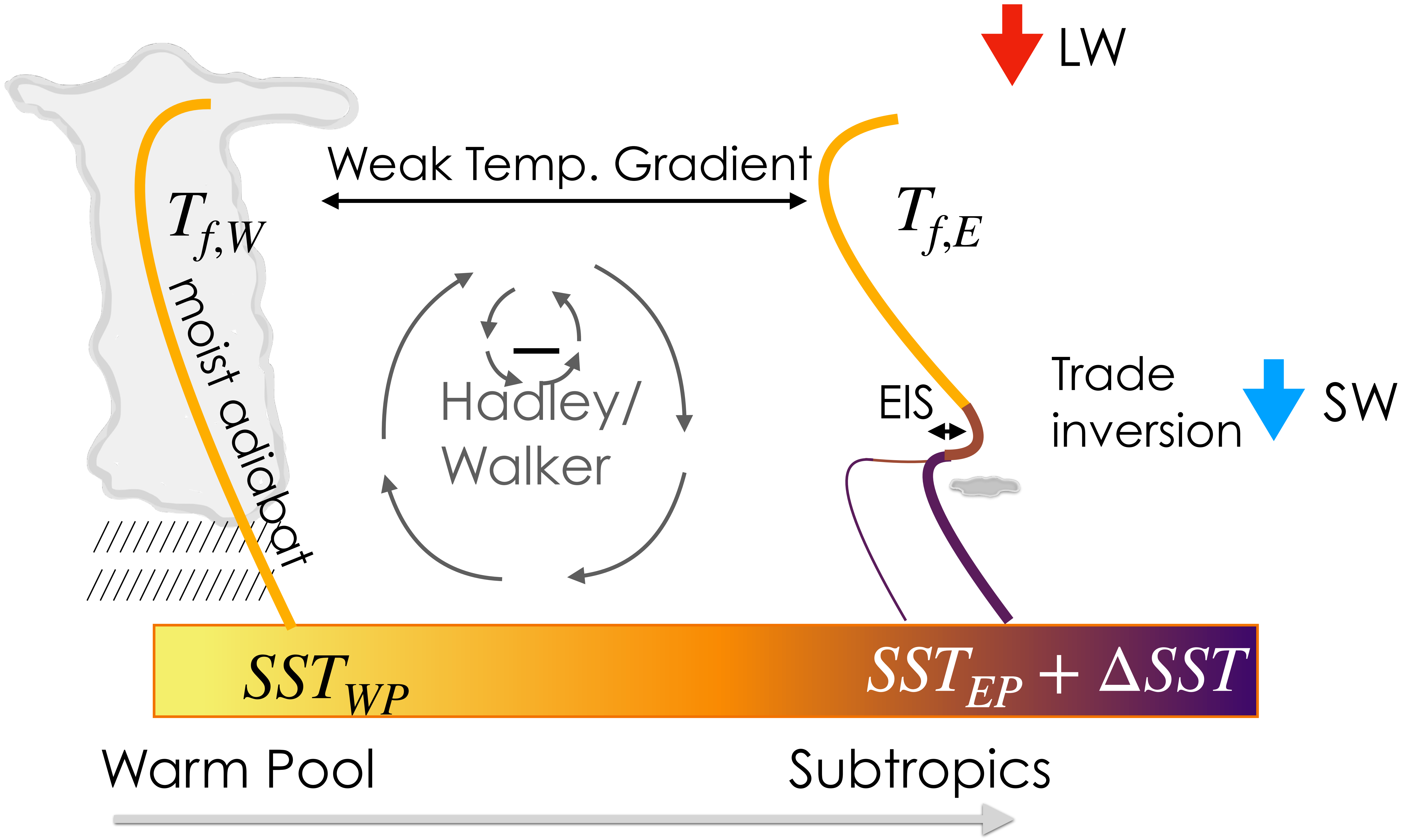
Wood & Bretherton 2006
Klein & Hartmann 1993
Arakawa 1975
Stevens 2005

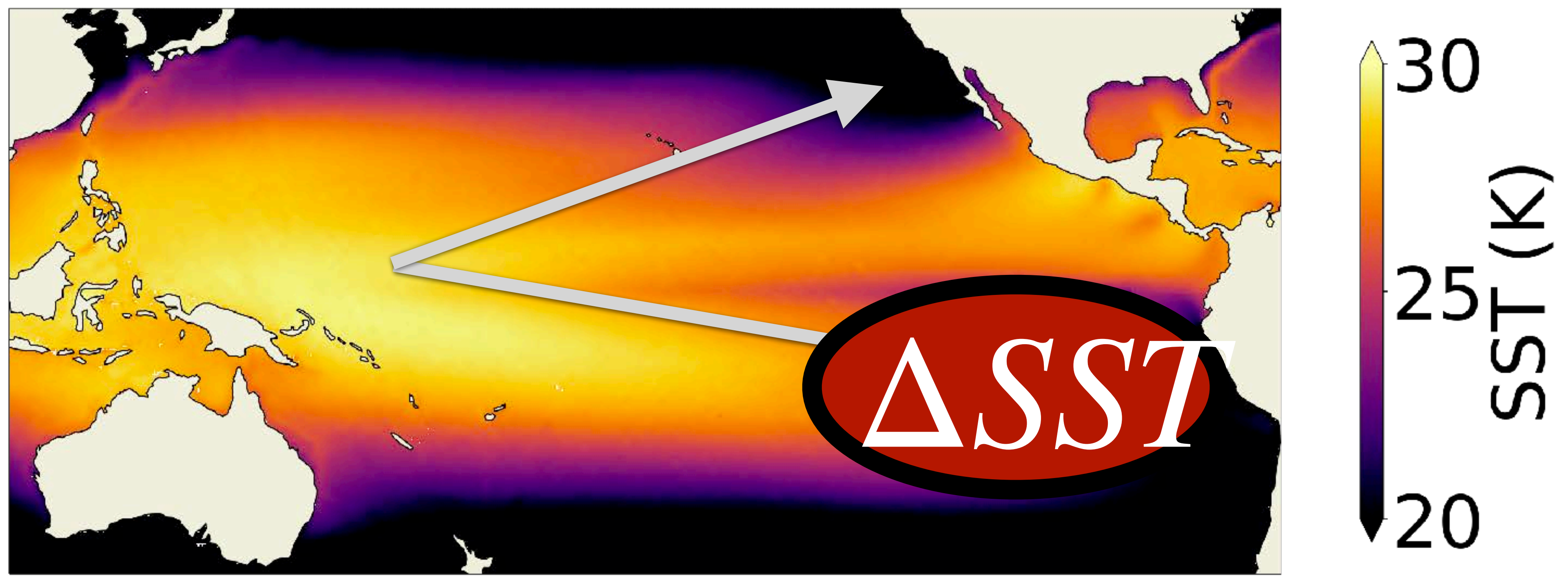
Response to East Pacific warming



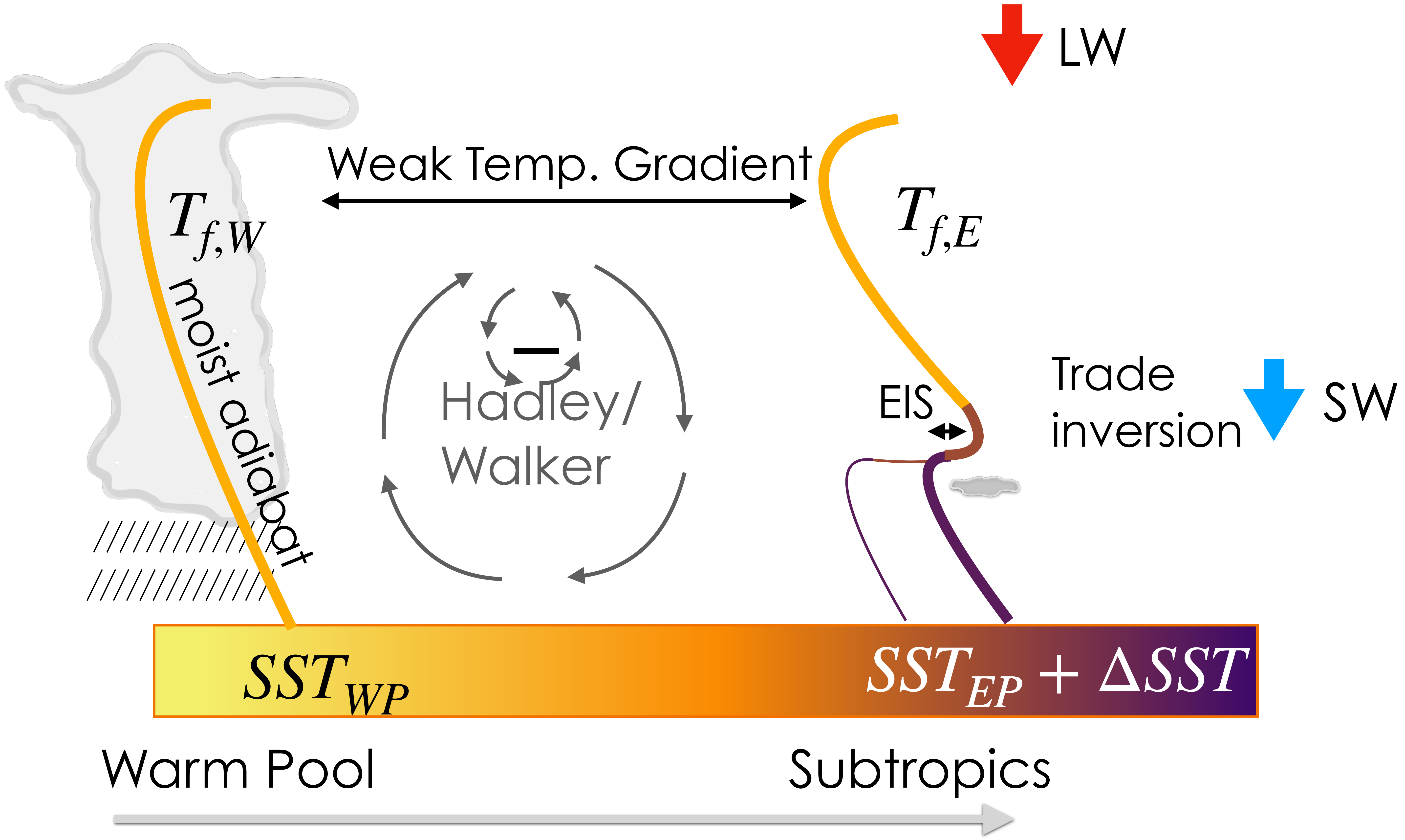


Response to East Pacific warming





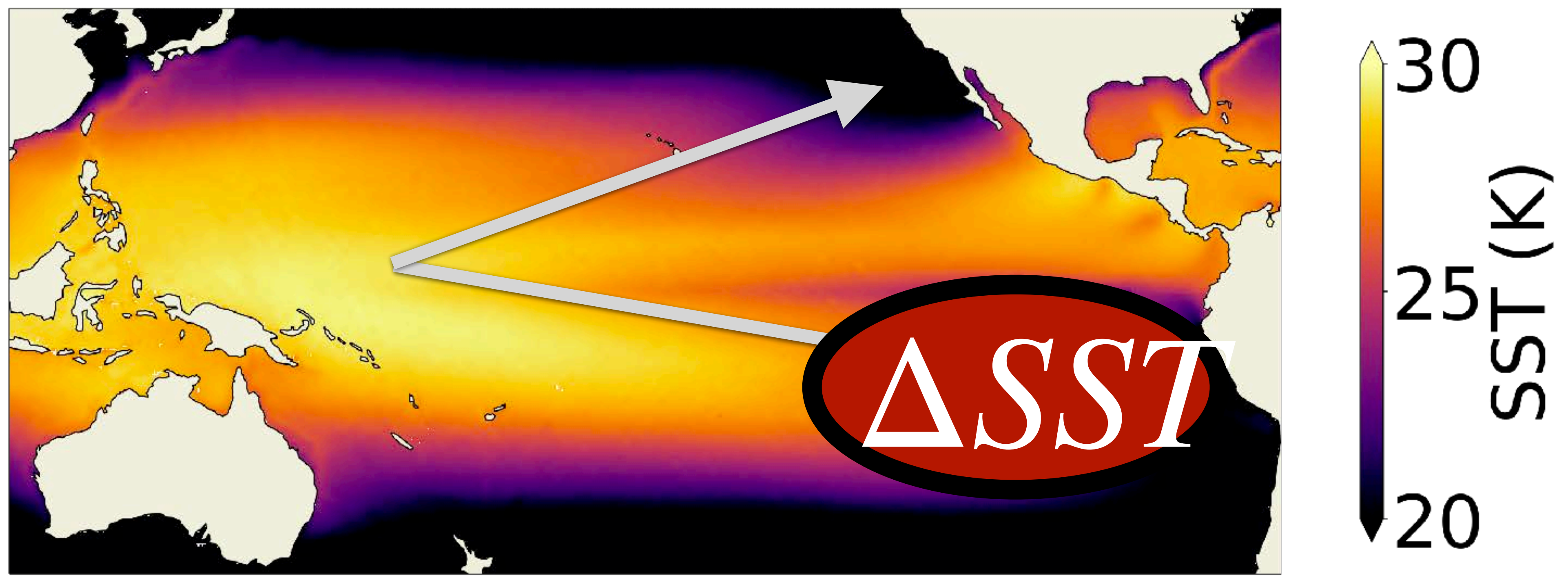
Response to East Pacific warming



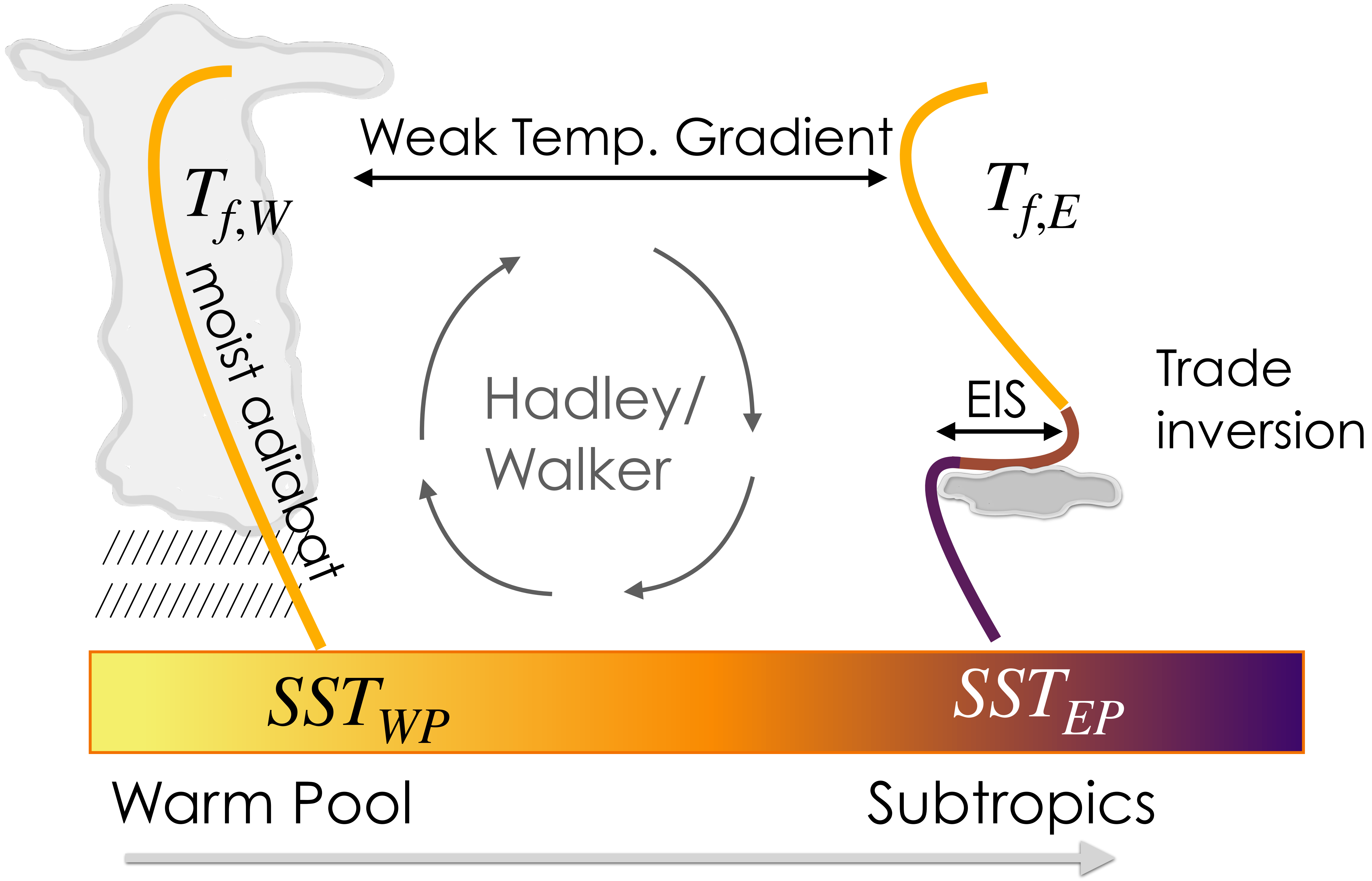
Warming the cool tropical SSTs

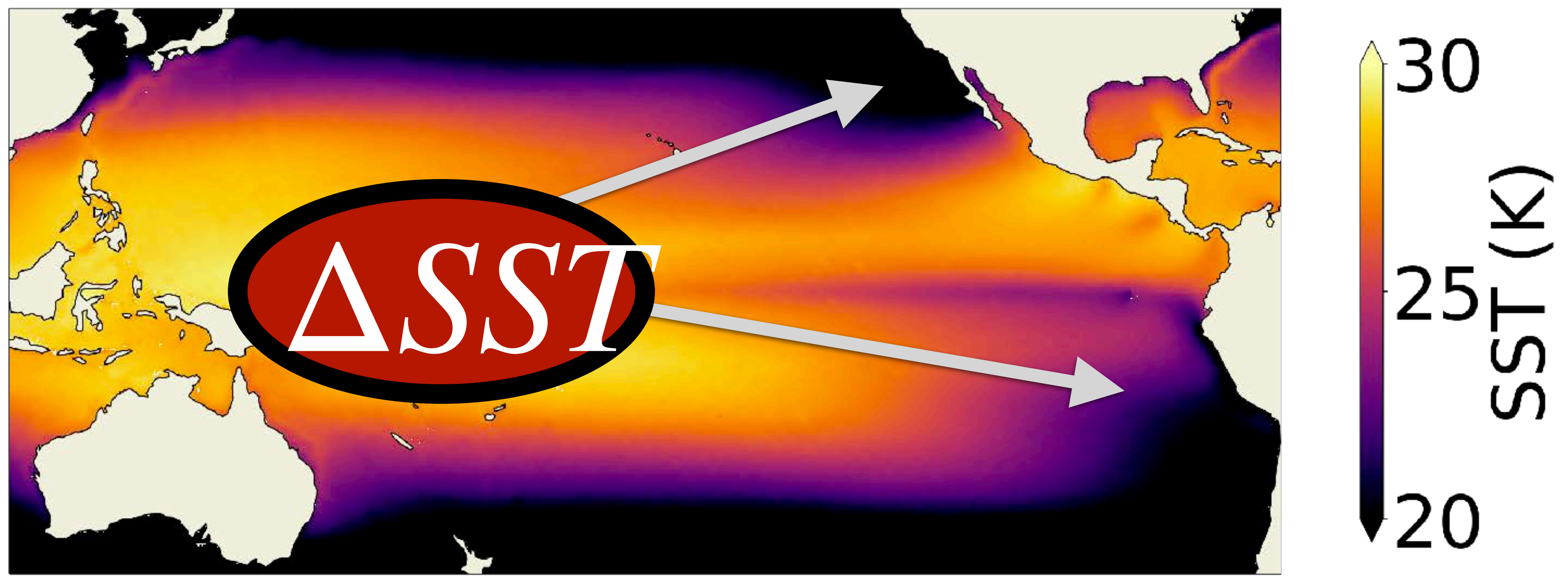
$\Rightarrow$

Positive (downward) radiative response



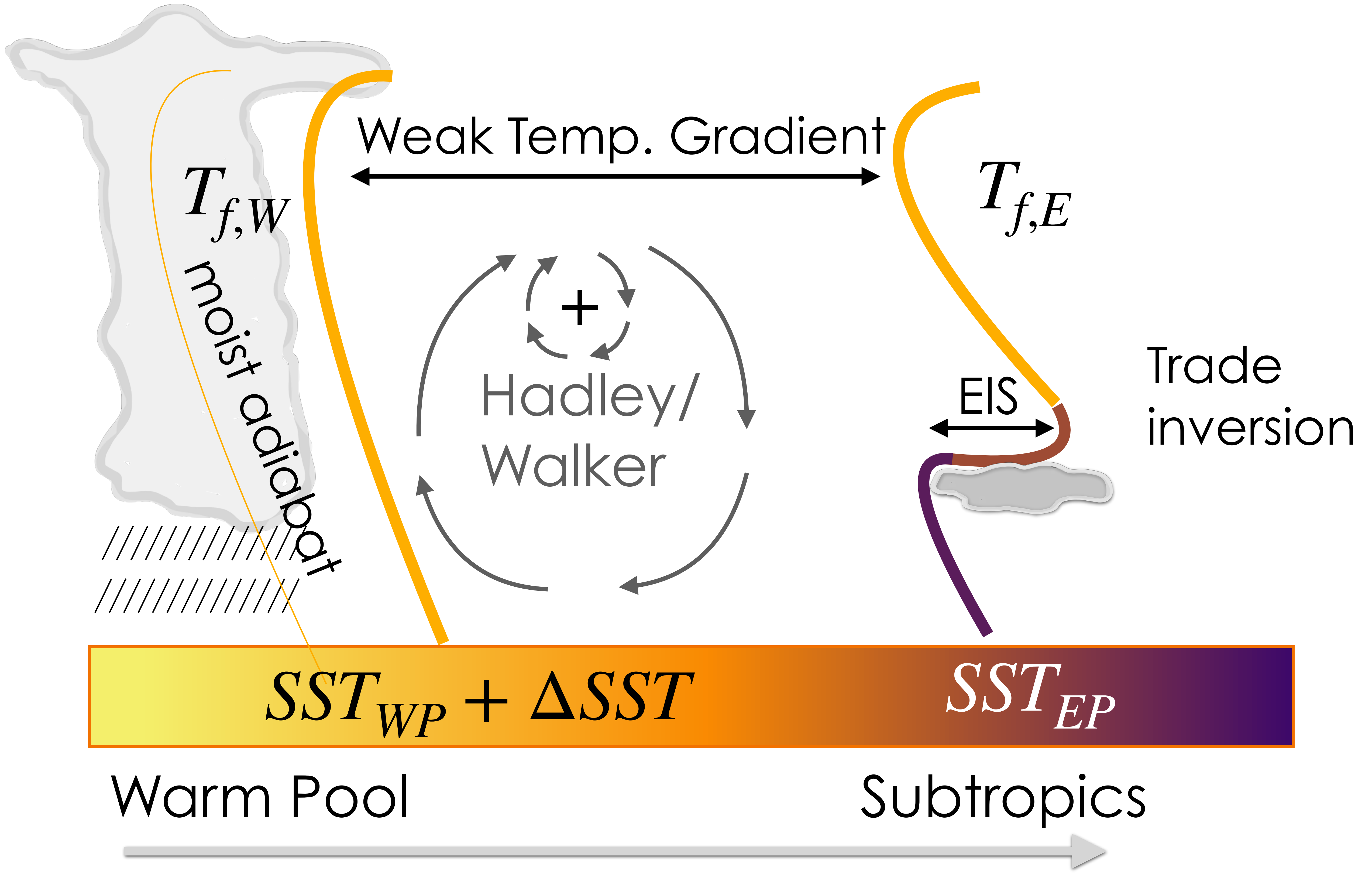
Response to Warm Pool warming

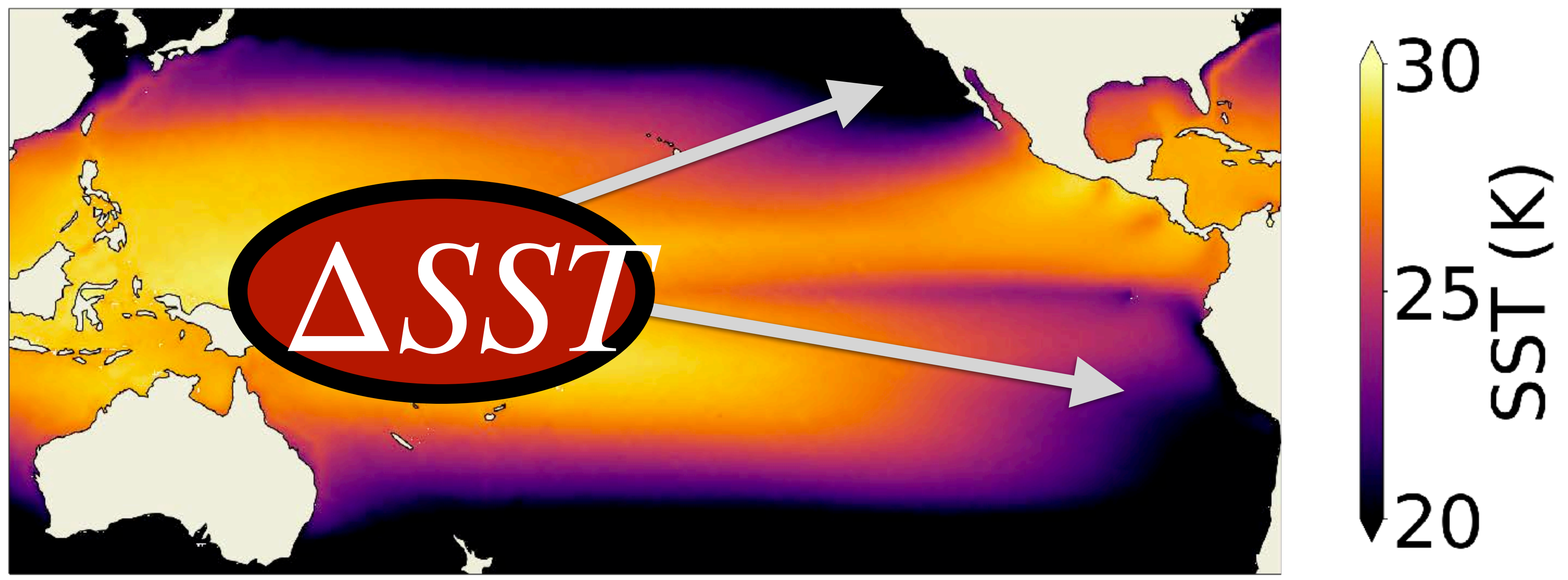




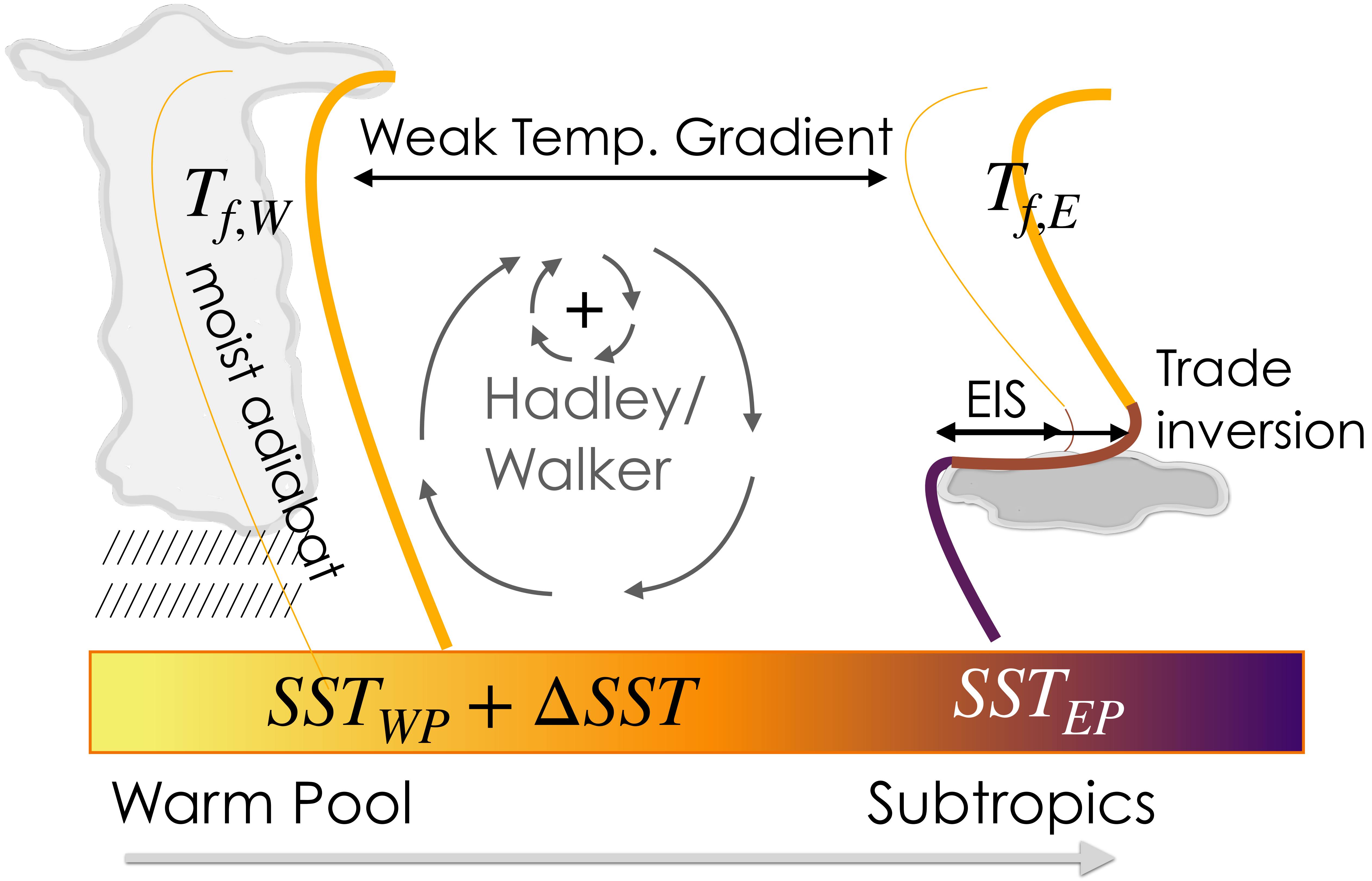
Zhou et al 2017
Dong et al 2019

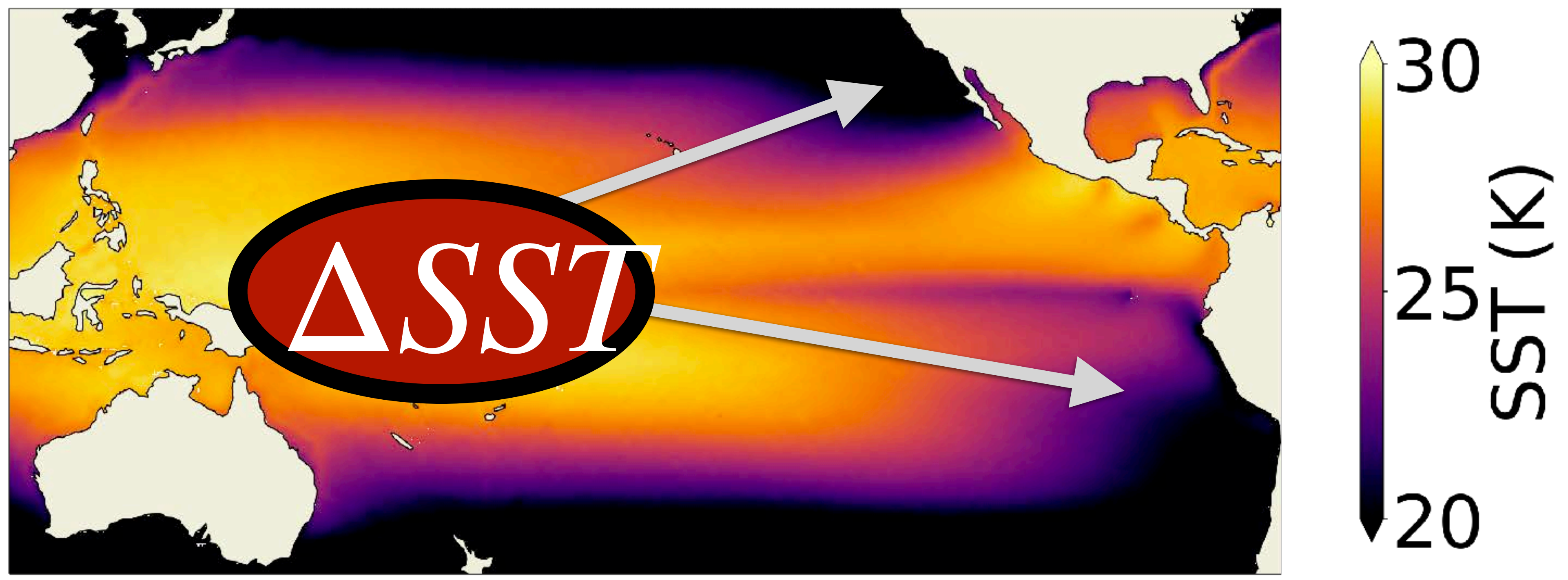
Response to Warm Pool warming



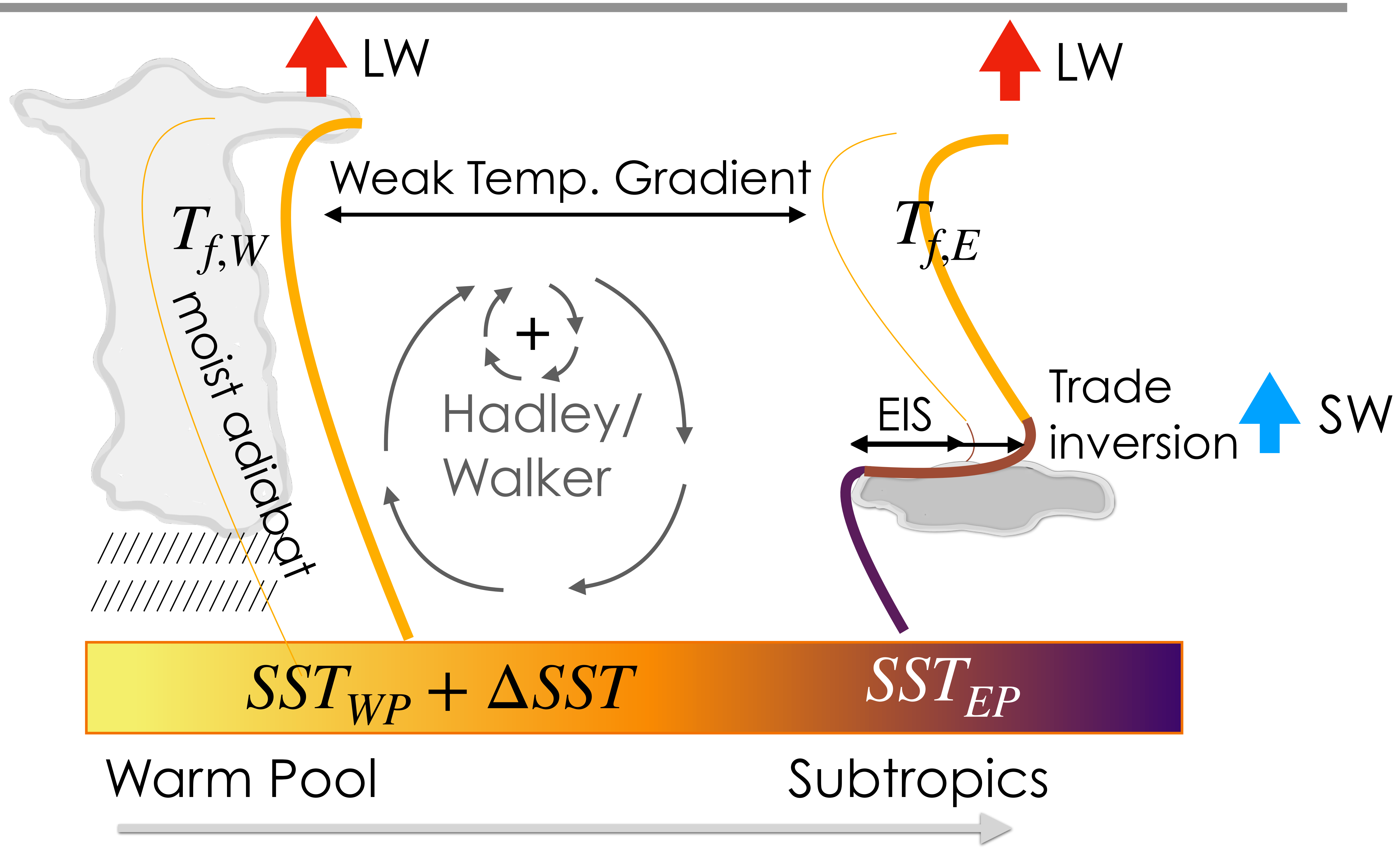


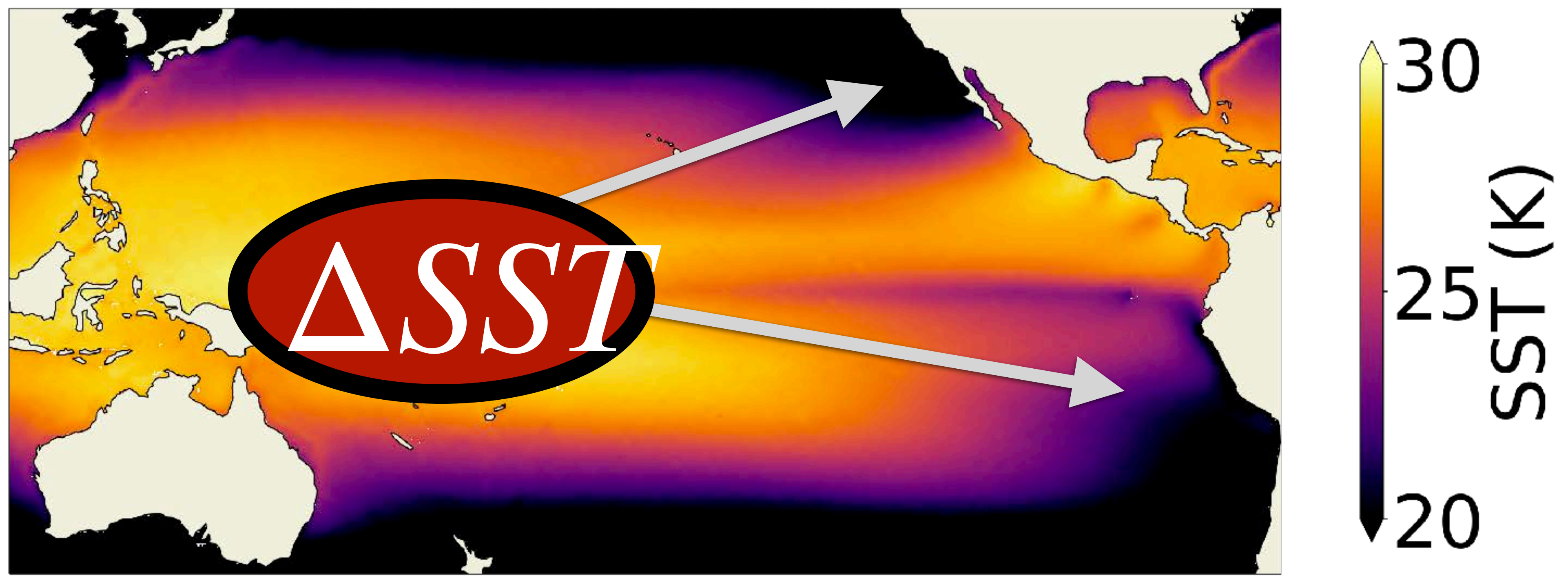
Response to Warm Pool warming



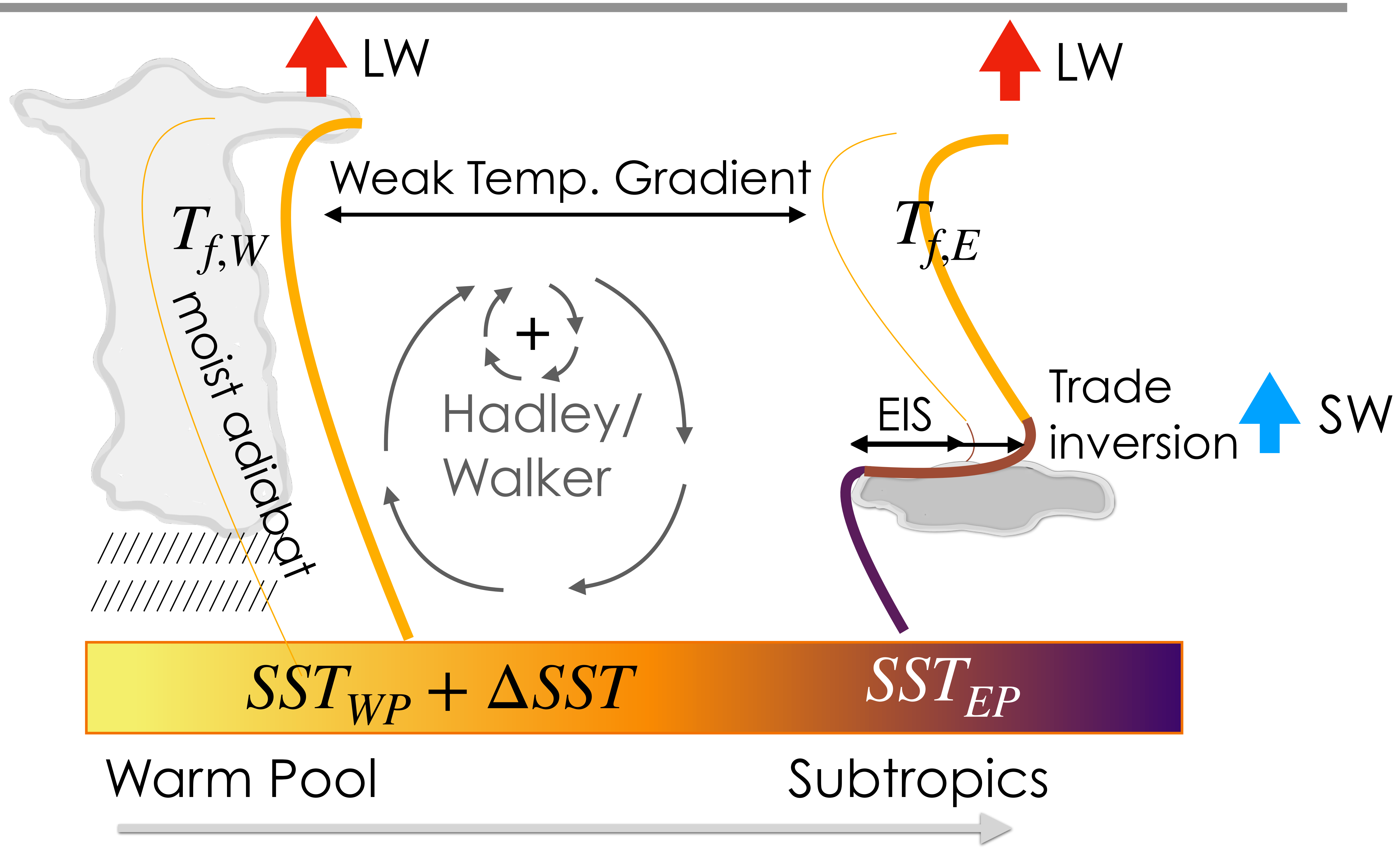


Response to Warm Pool warming





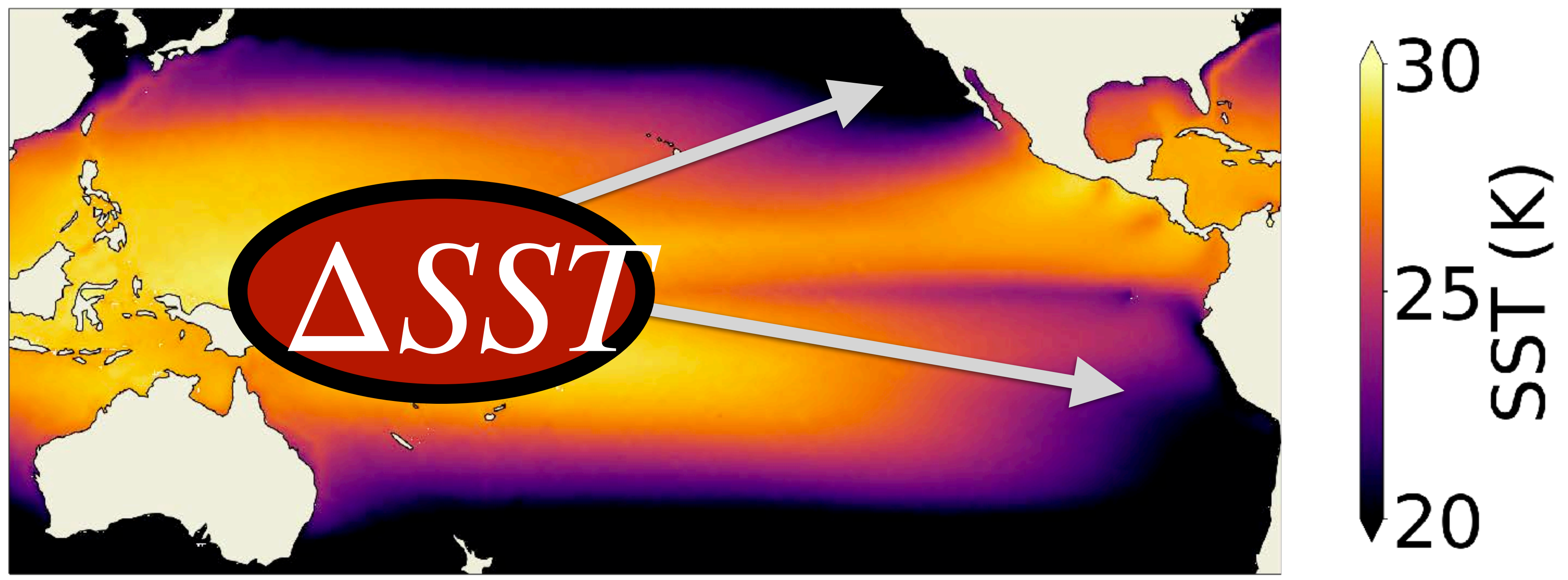
Response to Warm Pool warming



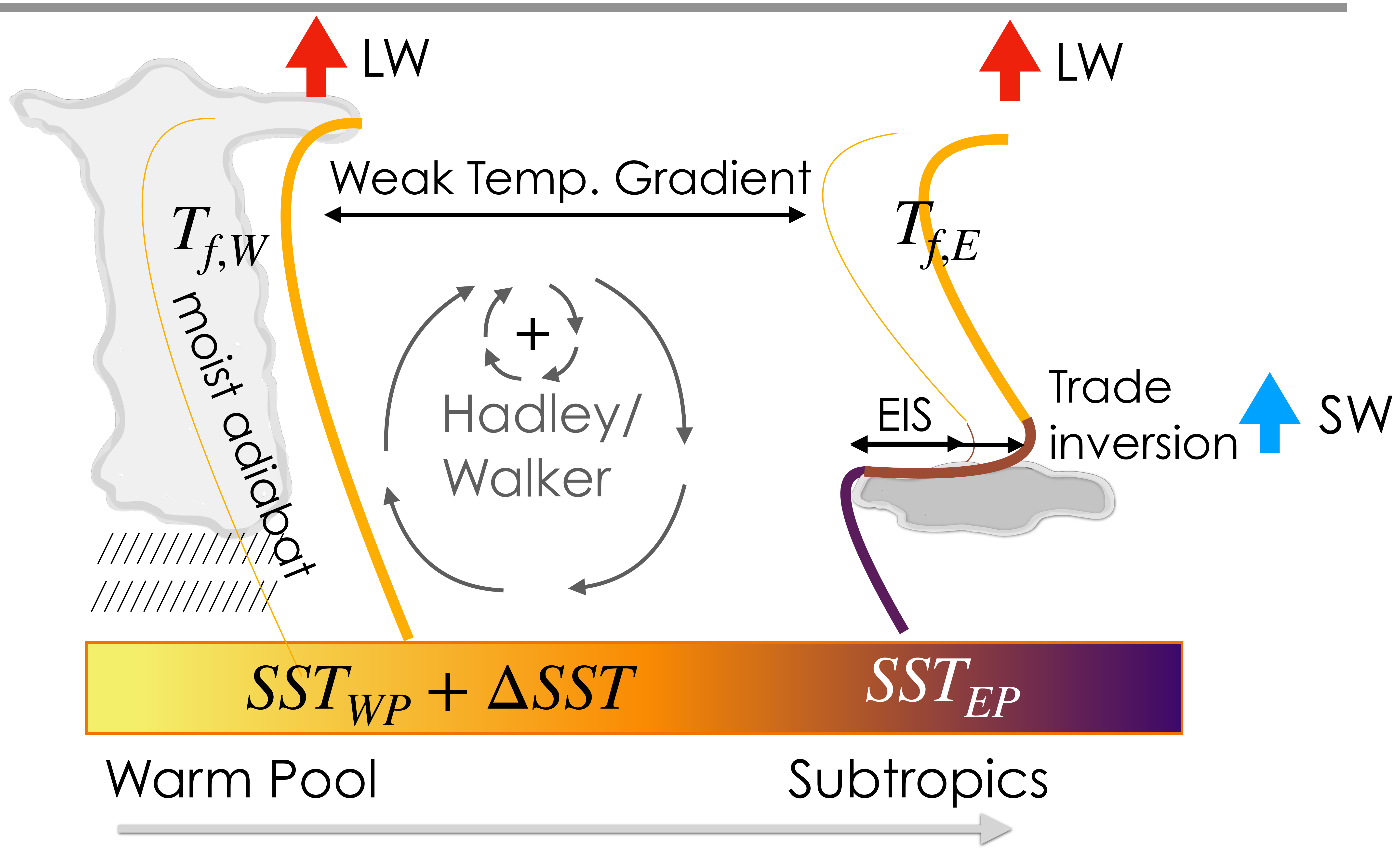
Warming the warmest SSTs

⇒

Negative (outgoing) radiative response



Response to Warm Pool warming



$$\Delta\overline{R} \approx \sum_{x,y} \frac{\partial R(y)}{\partial C(\tau,p,y)} \frac{\partial C(\tau,p,y)}{\partial M(y)} \frac{\partial M(y)}{\partial T(x)} \frac{\Delta T(x)}{\Delta\overline{T}} \Delta\overline{T}$$

Radiative Transfer

Cloud physics

Atmospheric Circulation

Coupled Dynamics