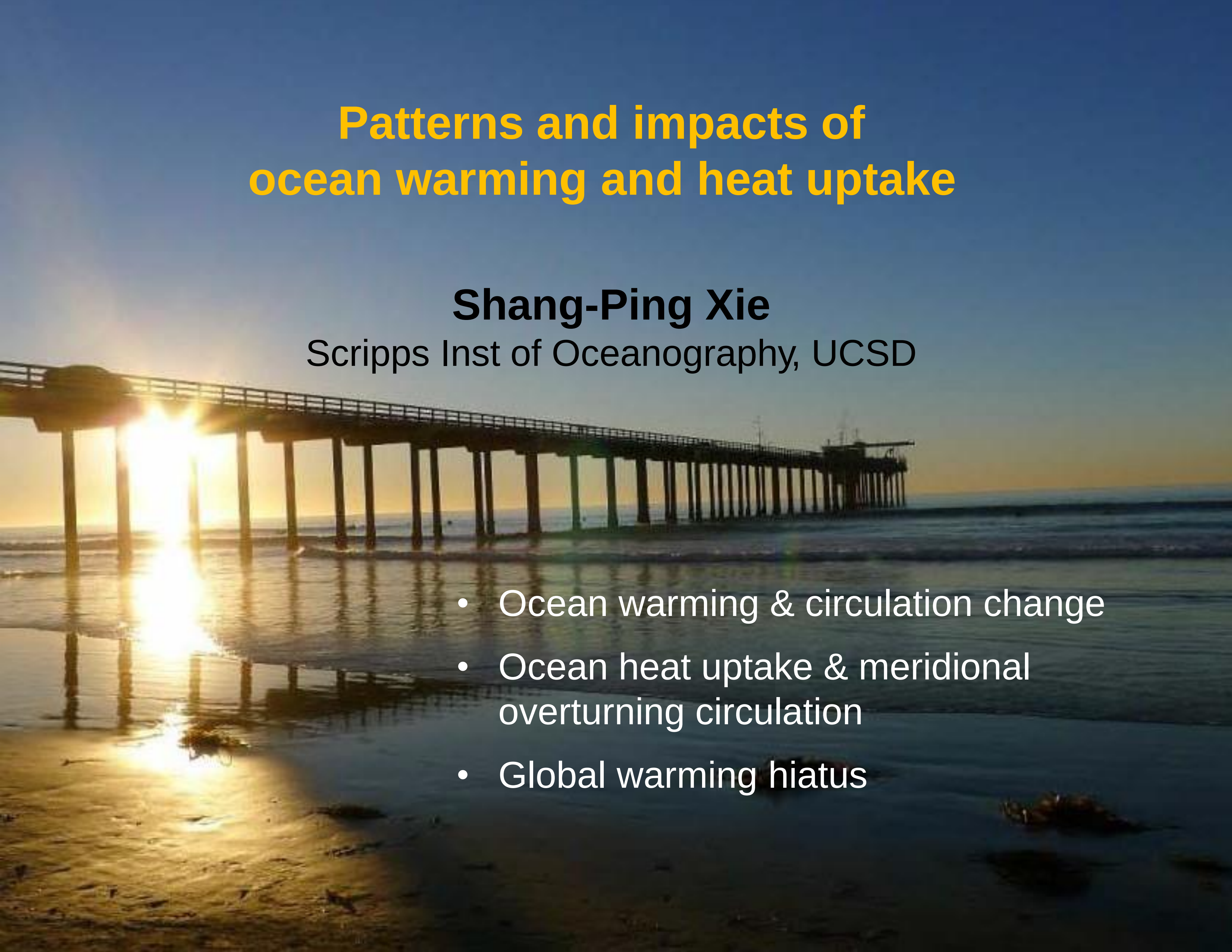


Patterns and impacts of ocean warming and heat uptake

Shang-Ping Xie

Scripps Inst of Oceanography, UCSD

- Ocean warming & circulation change
- Ocean heat uptake & meridional overturning circulation
- Global warming hiatus

Planetary Energy balance

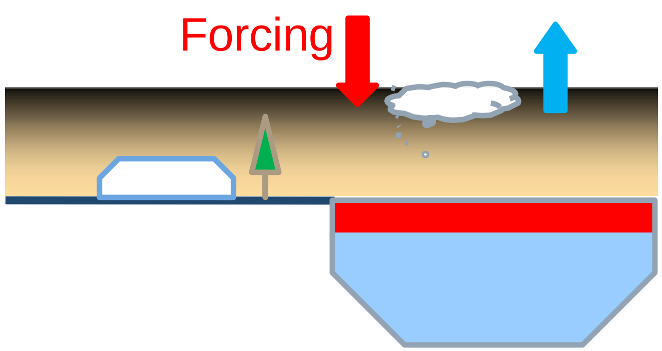
$$H_t = NTO_A = F - \lambda T$$

Ocean heat content change

TOA radiative imbalance

Radiative forcing

Climate feedback

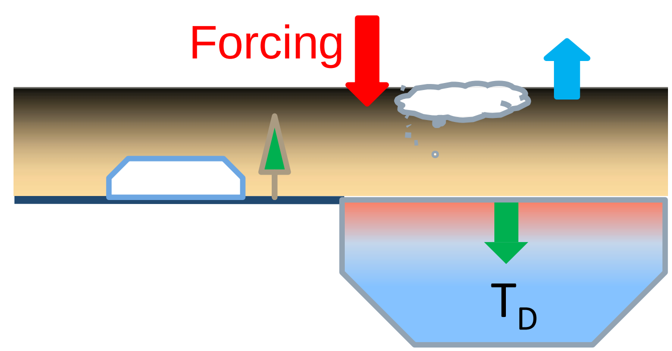


No exchange w/ deep ocean

→ TOA energy flux = 0 in ~10 yrs

→ **Equilibrium response**

Ocean heat uptake slows sfc warming



Exchange w/ deep ocean

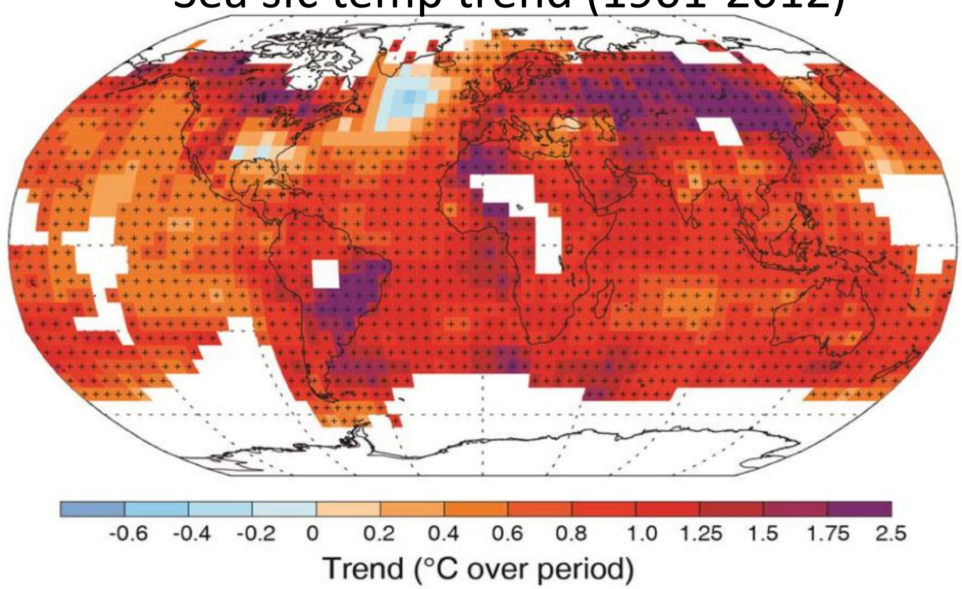
→ Ocean heat uptake = TOA energy flux

→ Smaller **transient response**

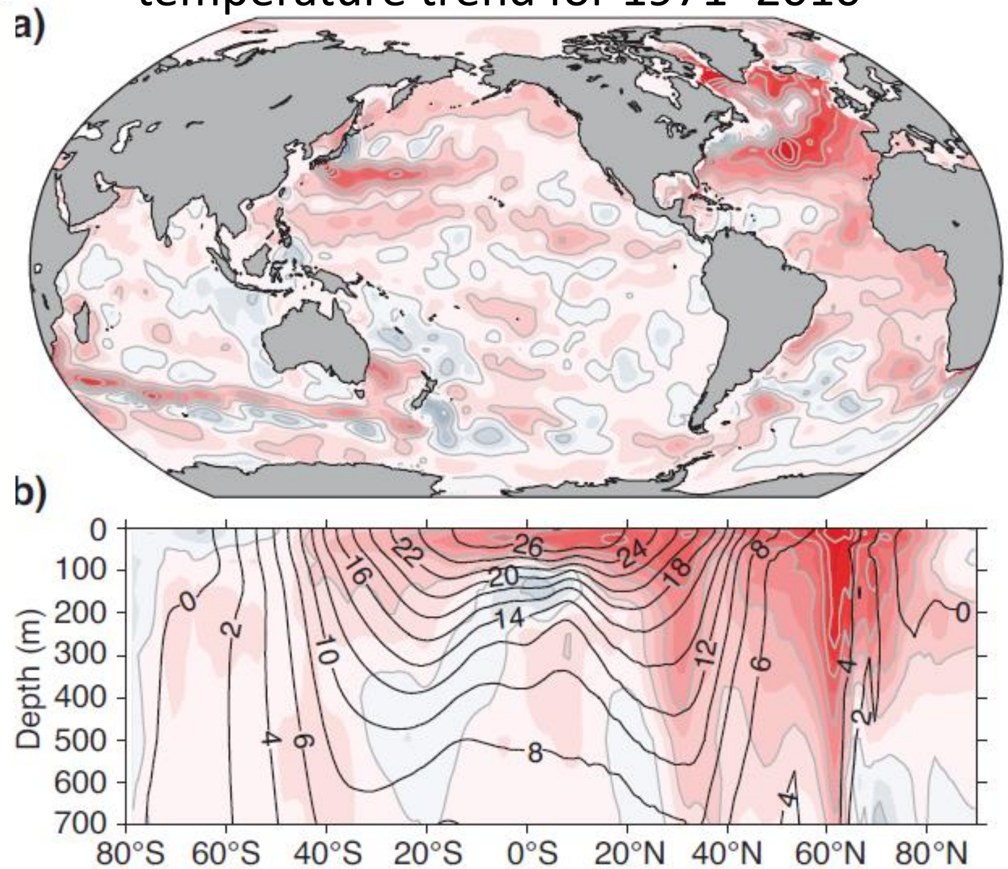
Historical warming

Ocean warming stores energy and slows atmospheric warming by ~50%.

Sea sfc temp trend (1901-2012)



0–700 m depth-averaged temperature trend for 1971–2010



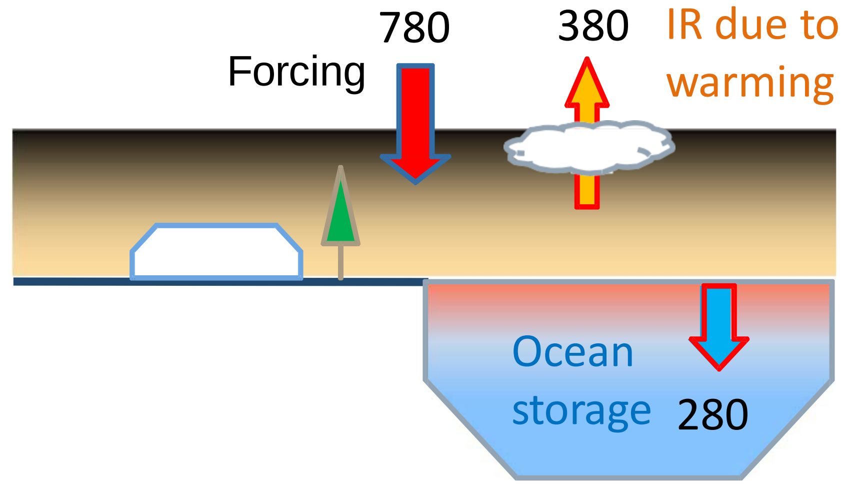
Zonal-mean ocean temp change & mean

Most ocean is stably stratified → warming is most confined above the thermocline.

IPCC AR5 (2013)

Planetary energy balance

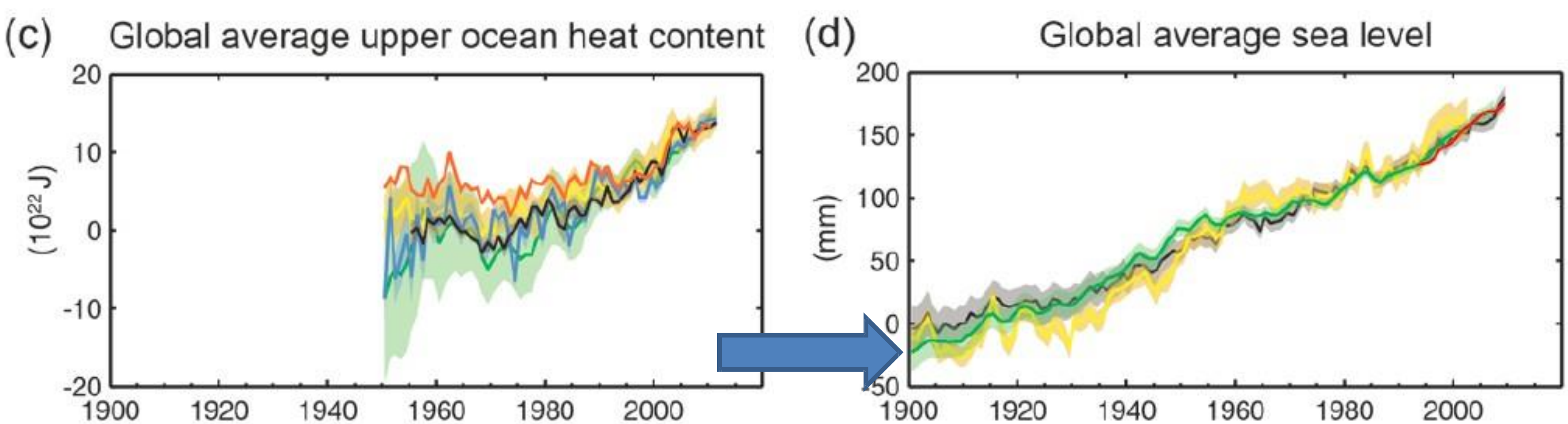
- Ocean stores 93% of Earth's energy gain.
- Anthropogenic radiative forcing is needed to balance increased radiation into space and ocean heat uptake.



Ocean heat uptake

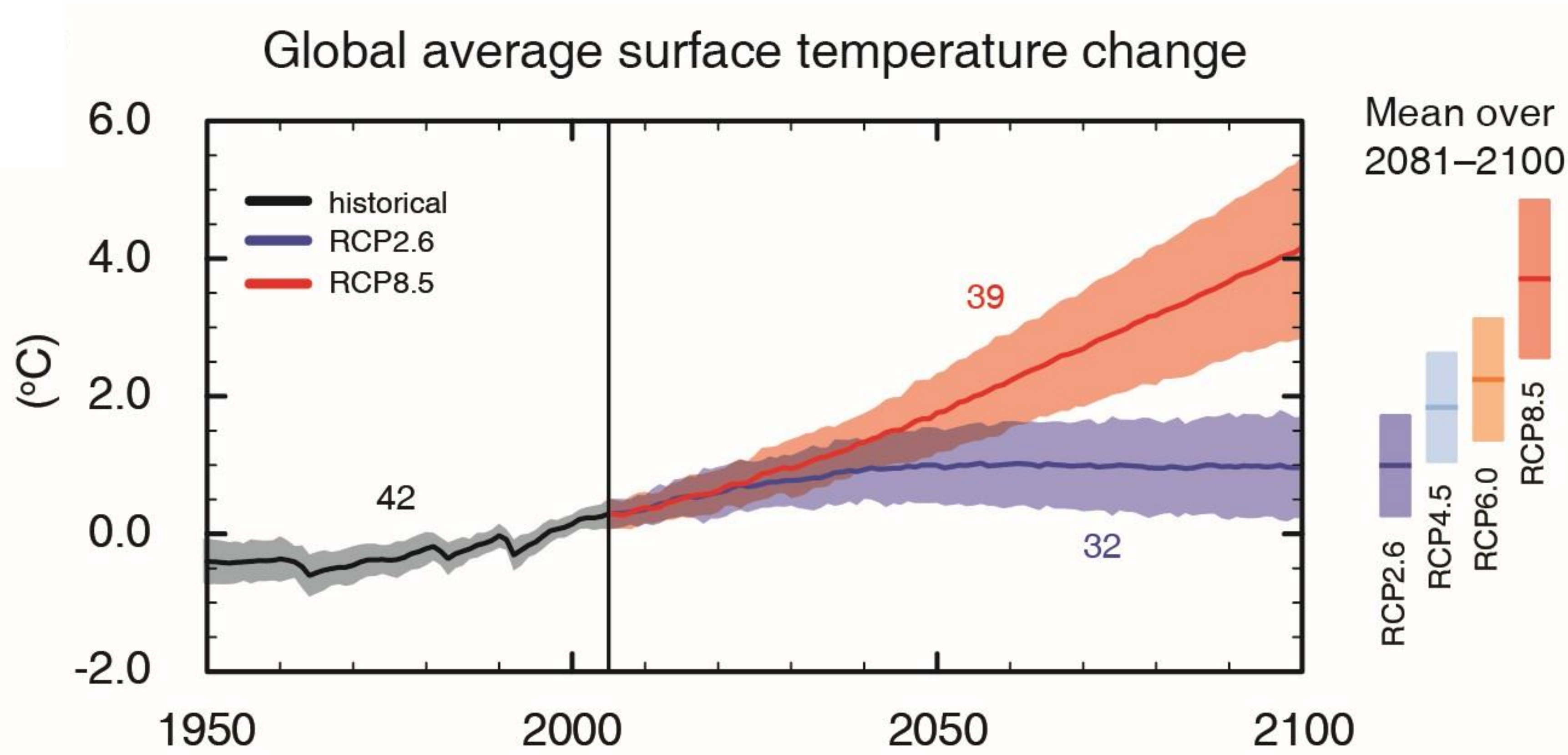
+) increased outgoing IR

= radiative forcing (CO_2 ...)



IPCC AR5 (2013)

Climate Projections



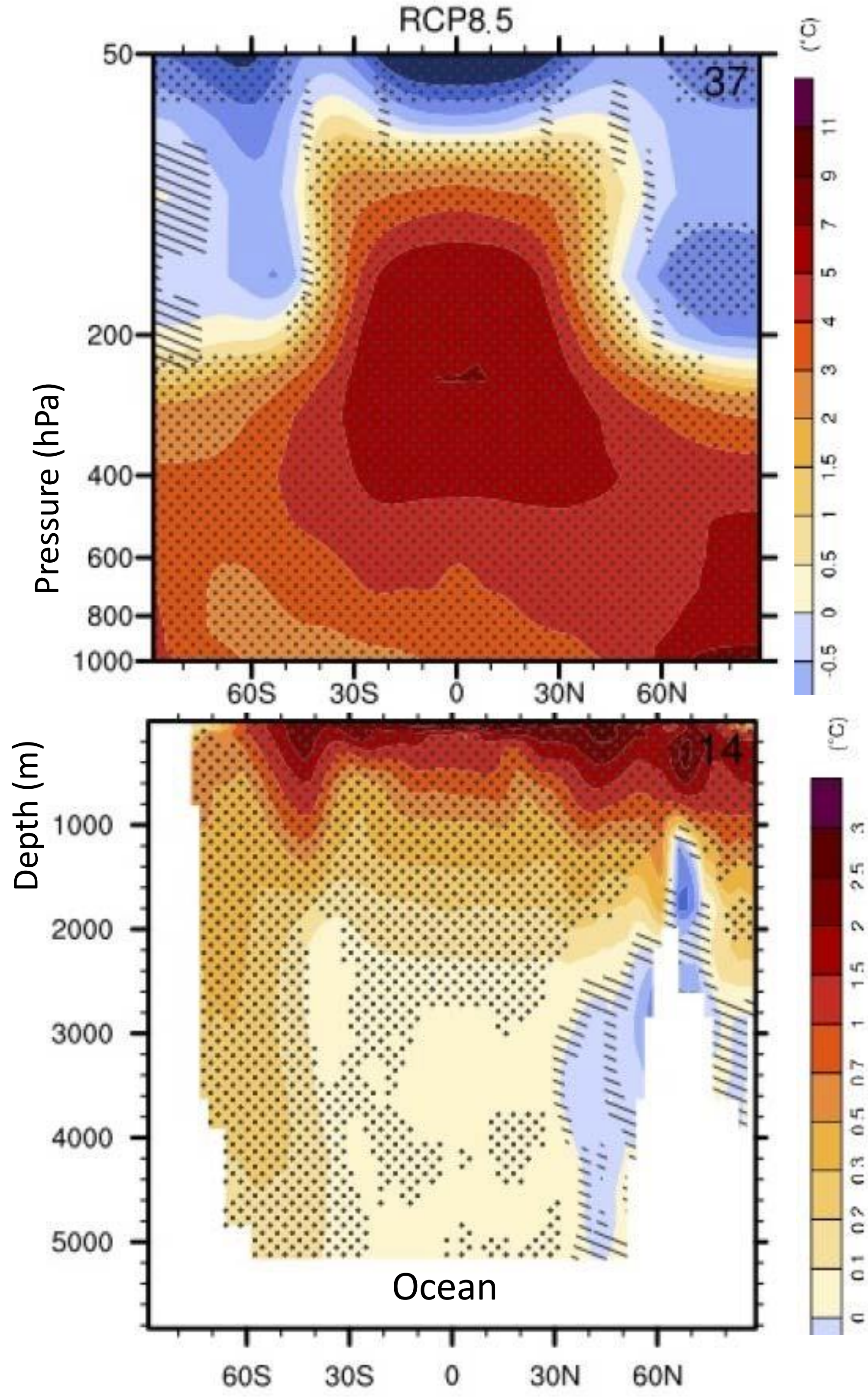
Global surface temperature change for the end of the 21st century is *likely* to exceed 1.5°C relative to 1850.

We are in control of the Earth's thermostat.

IPCC AR5 (2013)

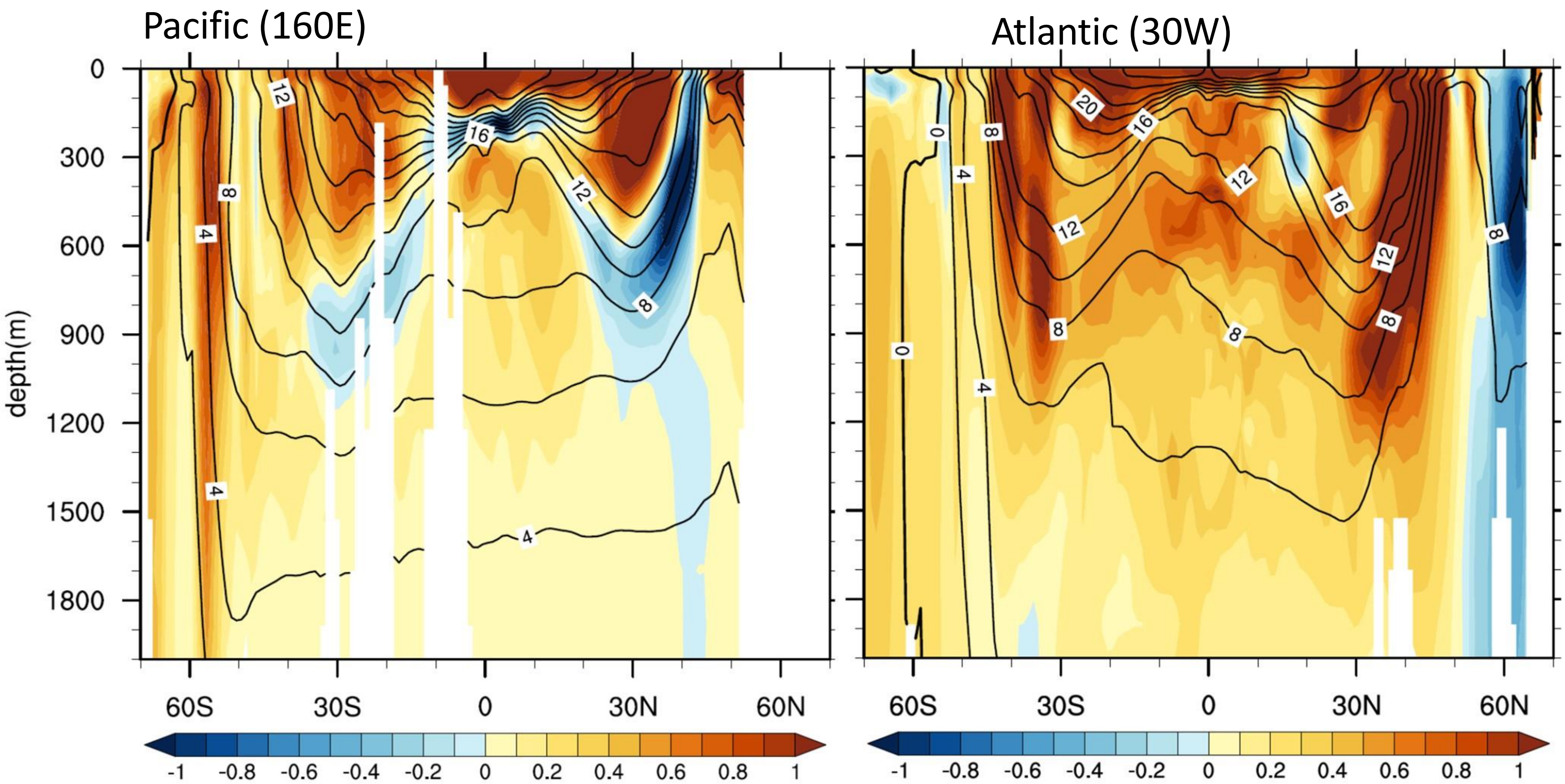
Future projections

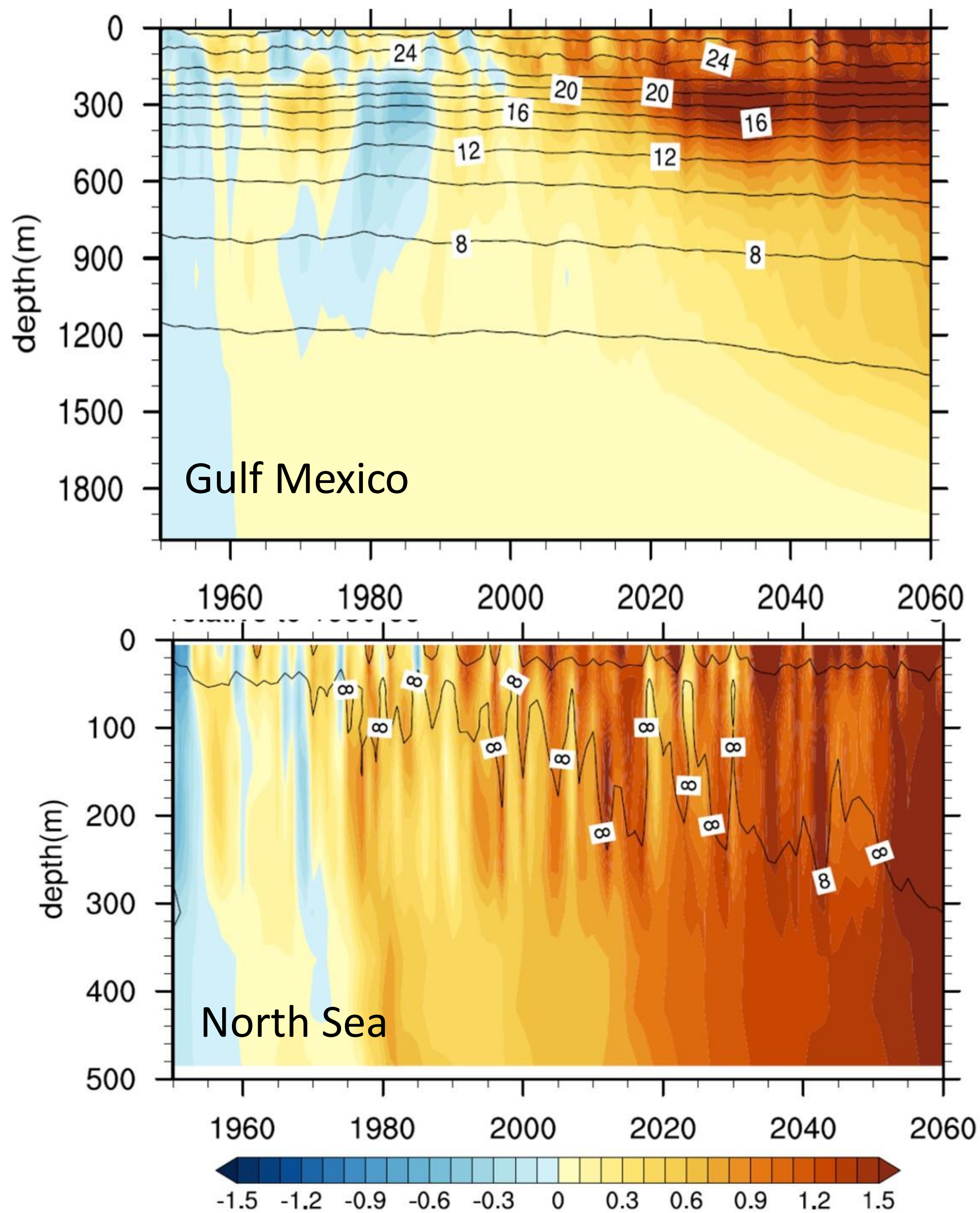
Ann-mean emp change (2081-2100, RCP8.5)



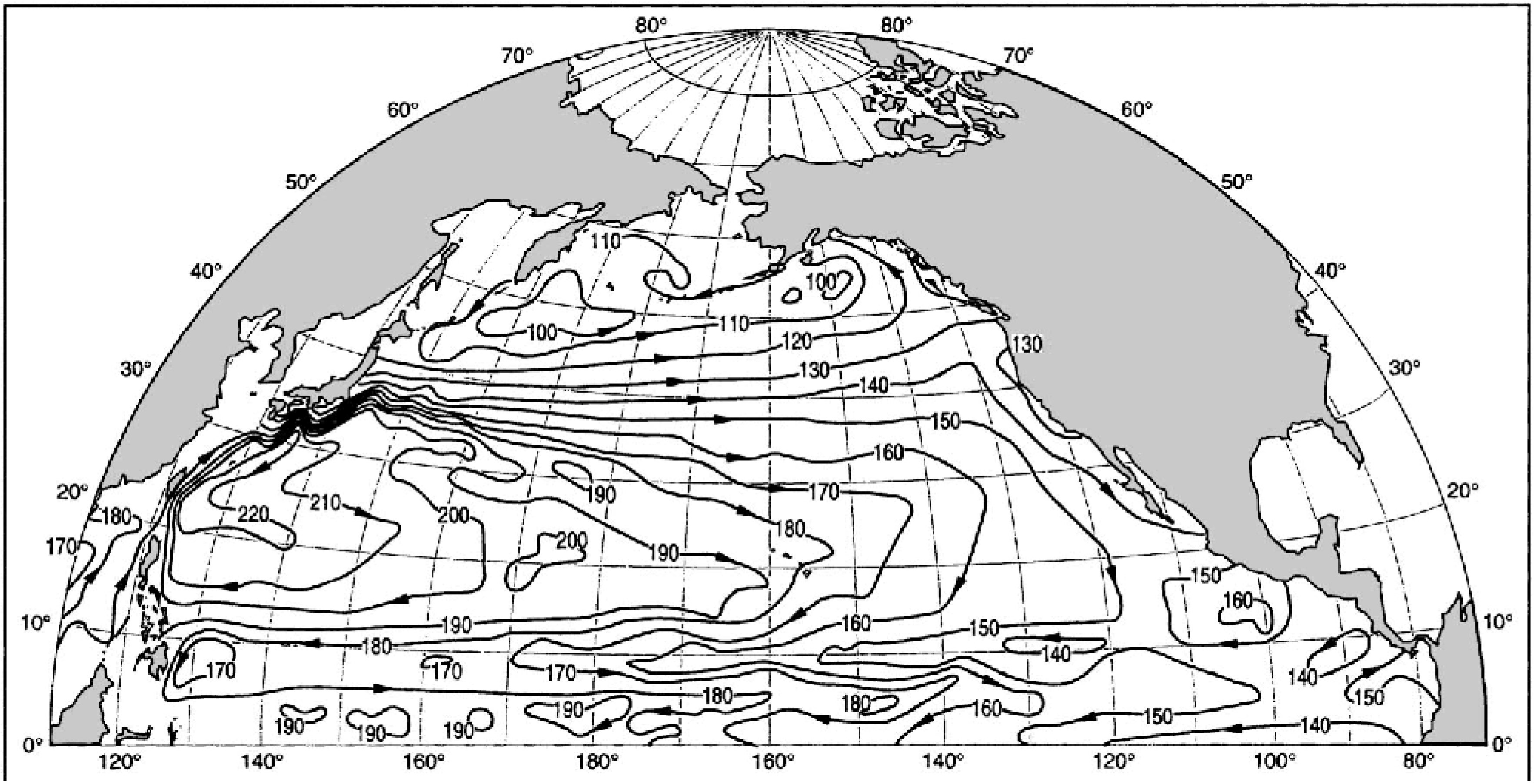
IPCC AR5 (2013)

Temp: mean & change from 1985-2005 to 2040-60

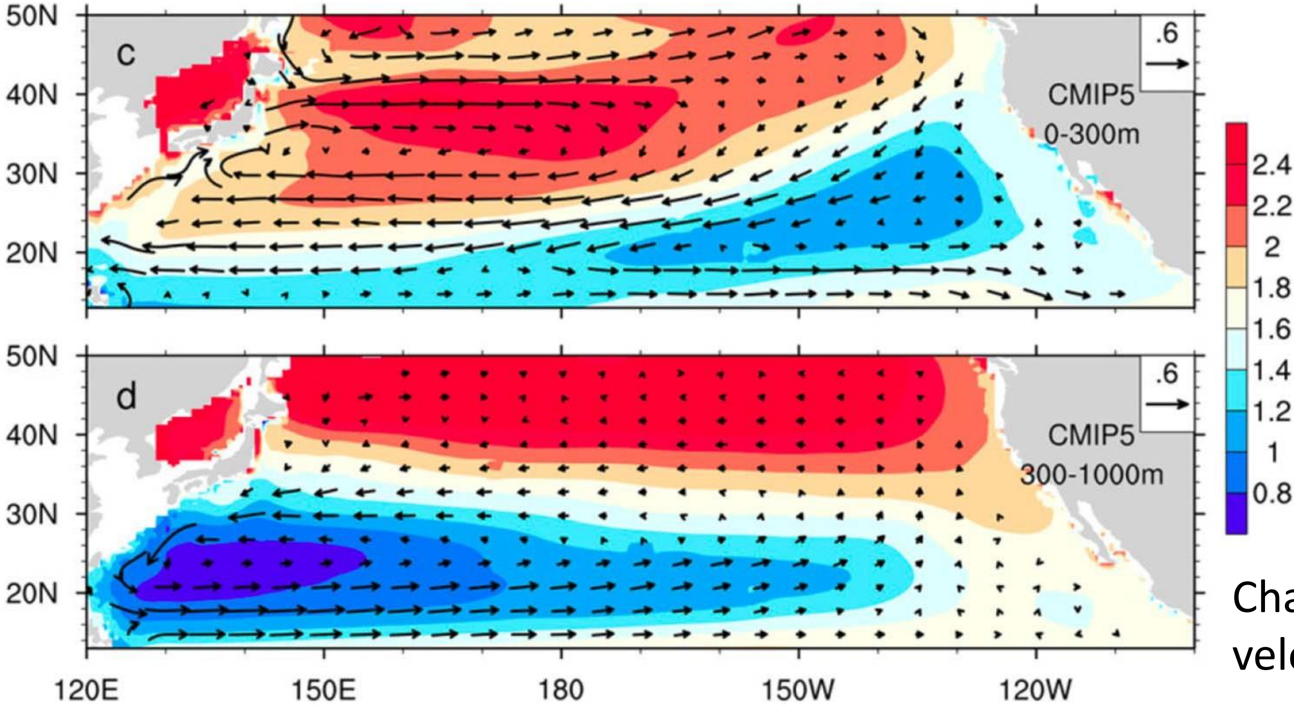




Ocean temp (^{o}C): mean & change from 1905-69



North Pacific surface circulation



Increased temp stratification

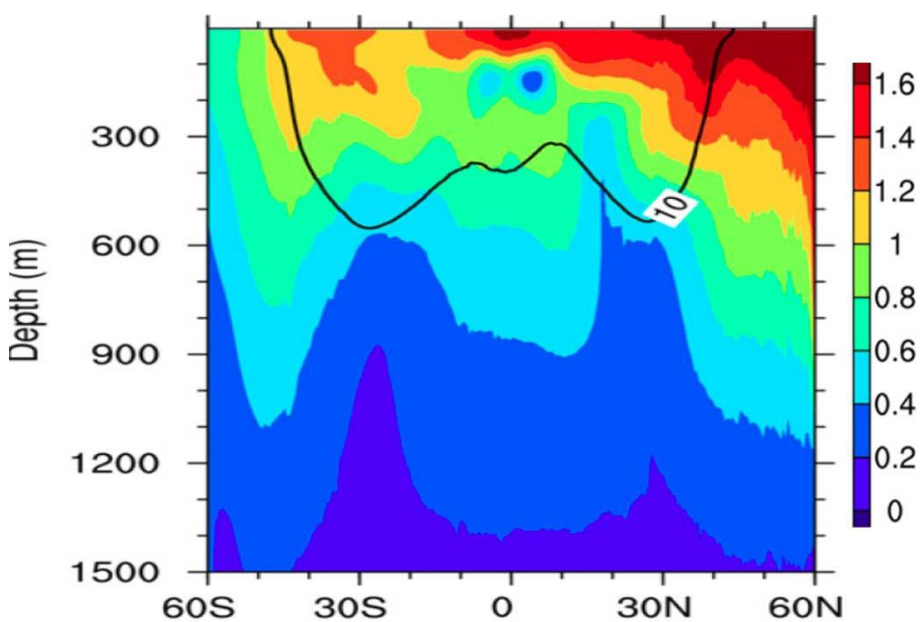
↓

Increased upper circulation

↓

Weakened lower circulation

Changes in current velocity & streamfunction.

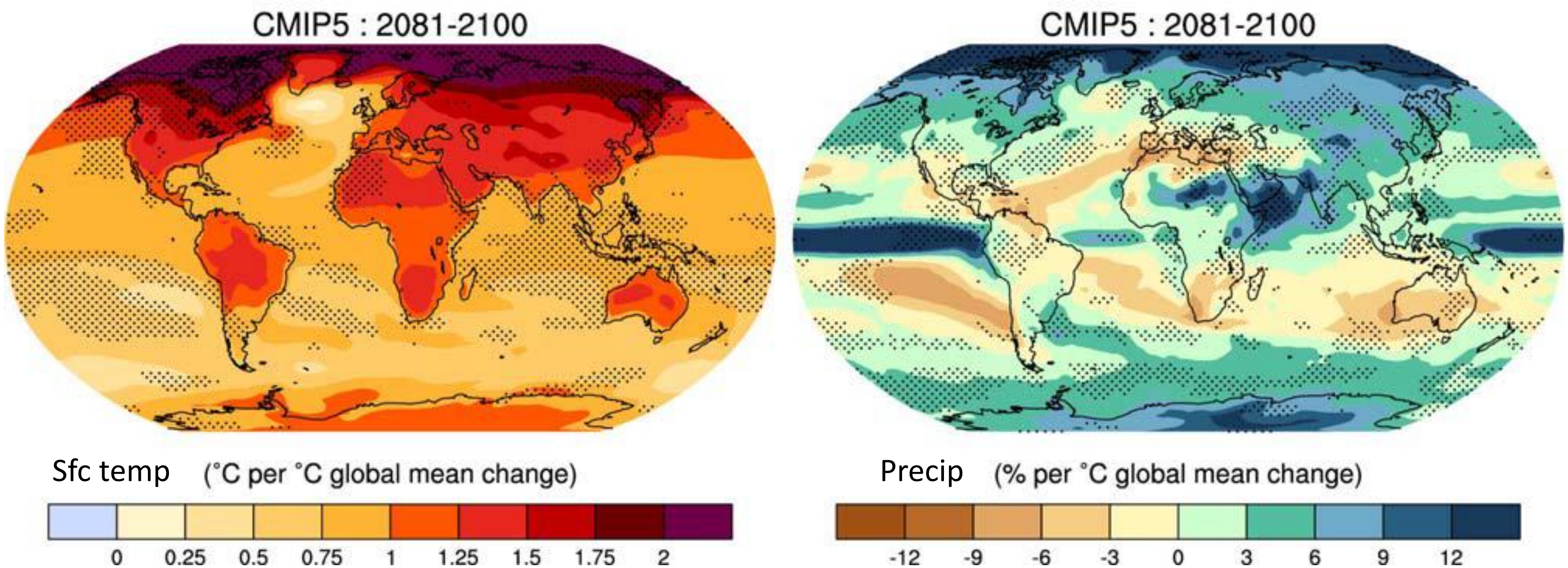


Zonally averaged temperature change (°C; 2076-2100 minus 1976-2000) for the Pacific from the CMIP5 ensemble of RCP4.5.

G. Wang et al. (2015, J Climate)

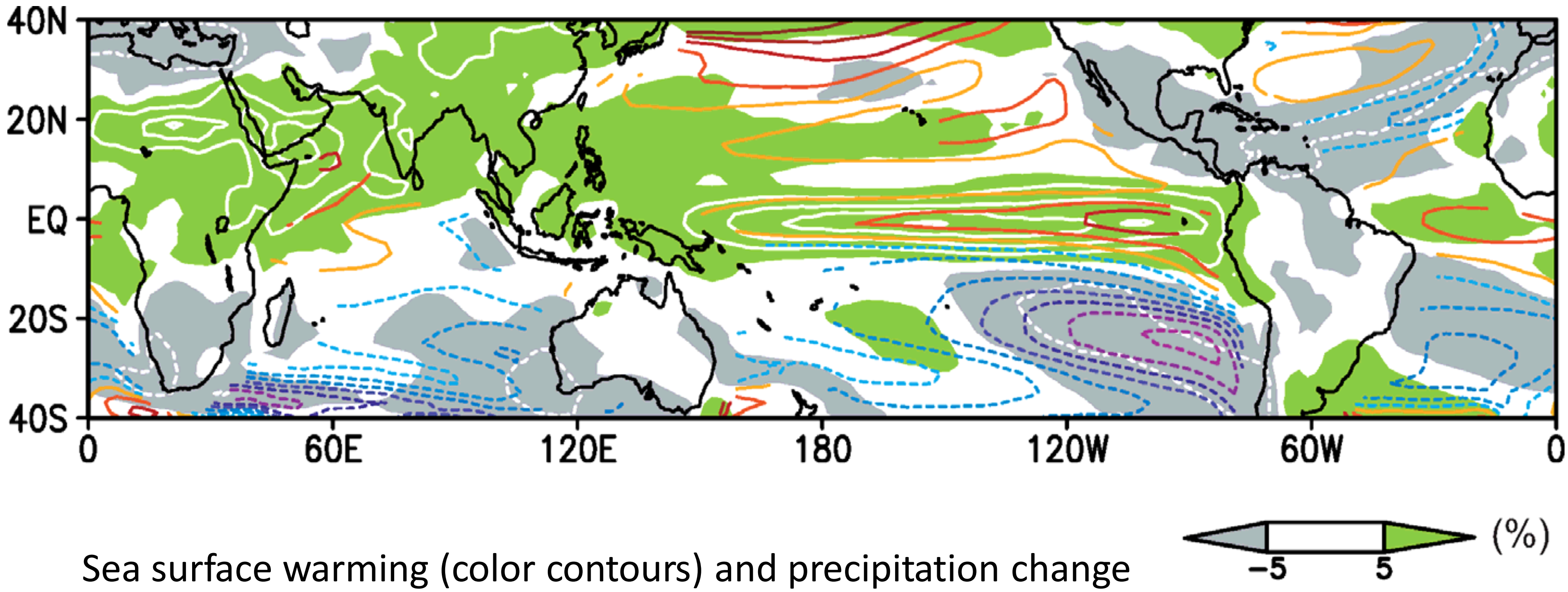
- Temperature rises everywhere.
- Precipitation increases in some regions and decreases in some others (variable in space).

→ What determines regional patterns of precipitation change?



IPCC AR5 (2013)

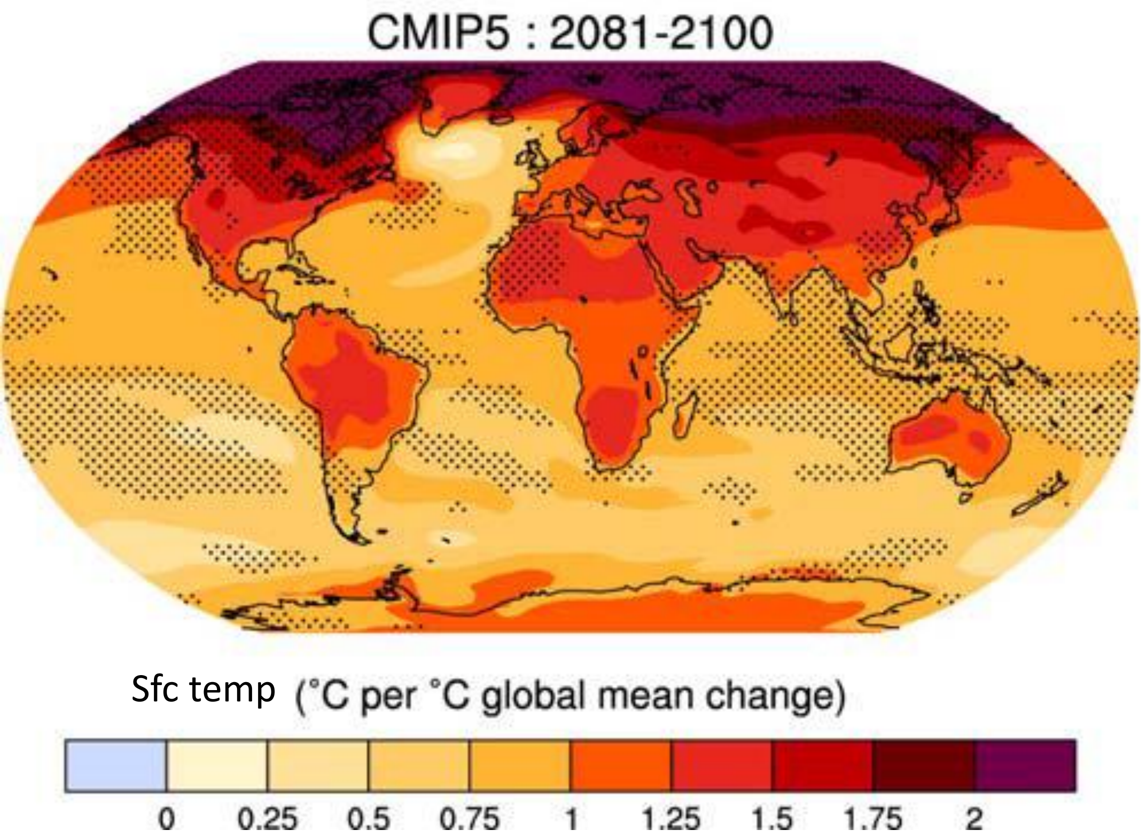
Surface warming effect on tropical rainfall:
Warmer get wetter, r(δT, δP/P)=0.63



Sea surface warming (color contours) and precipitation change (color shading & white contours) over the 21st century (IPCC AR5, 2013)

Summary 1

- Ocean heat uptake and storage is an important component of Earth energy budget.
- Patterns of ocean surface warming affect tropical rainfall, El Nino and storms.
- Rapid ocean warming in and above the thermocline.
- Increased density stratification intensifies the subtropical gyre in the upper layer and slows it down in the lower thermocline.

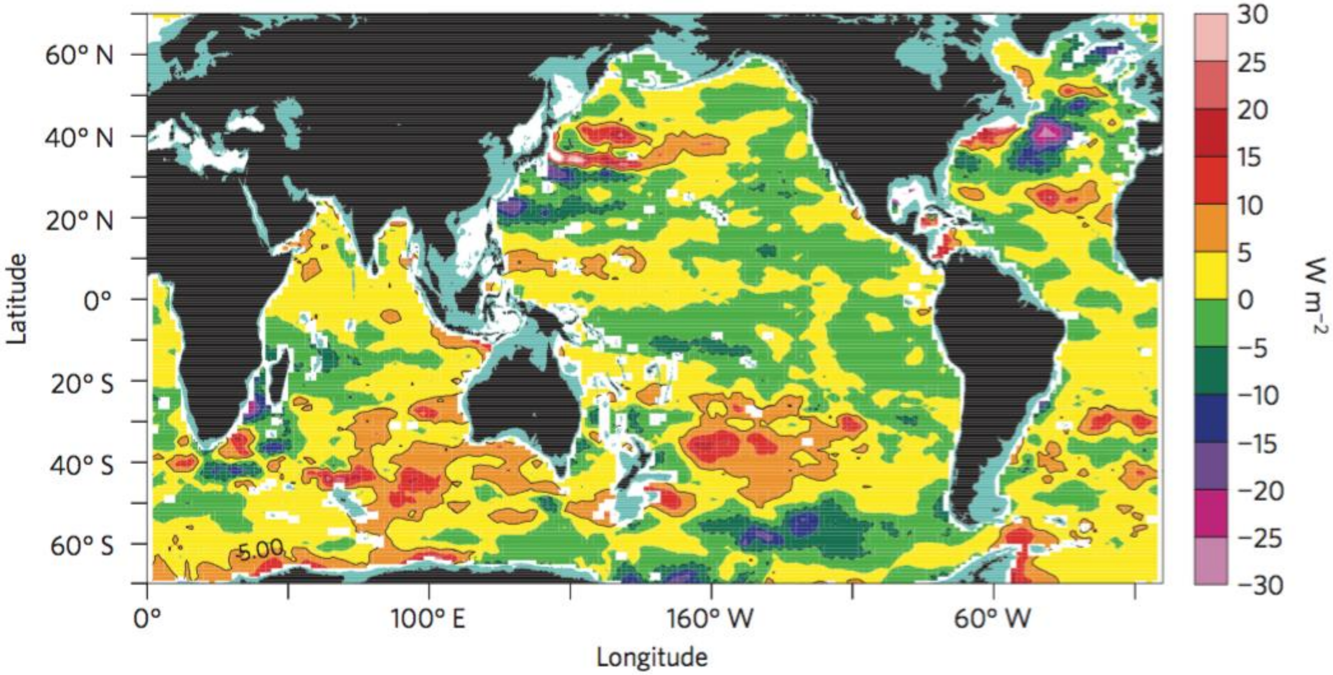


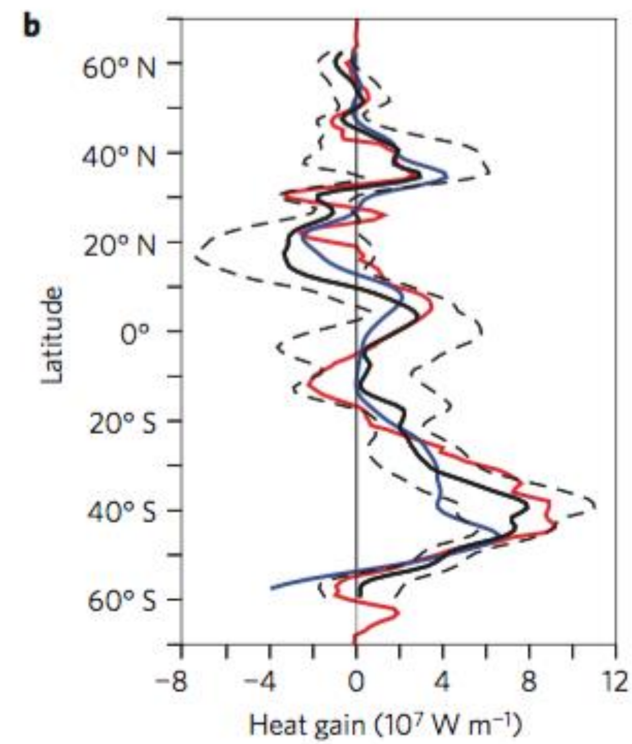
- Amplified warming in Arctic
- Reduced warming in Antarctica

IPCC AR5 (2013)

Uneven ocean heat uptake

Argo Observations





trend in ocean heat content (0-2000m) for 2006 - 13

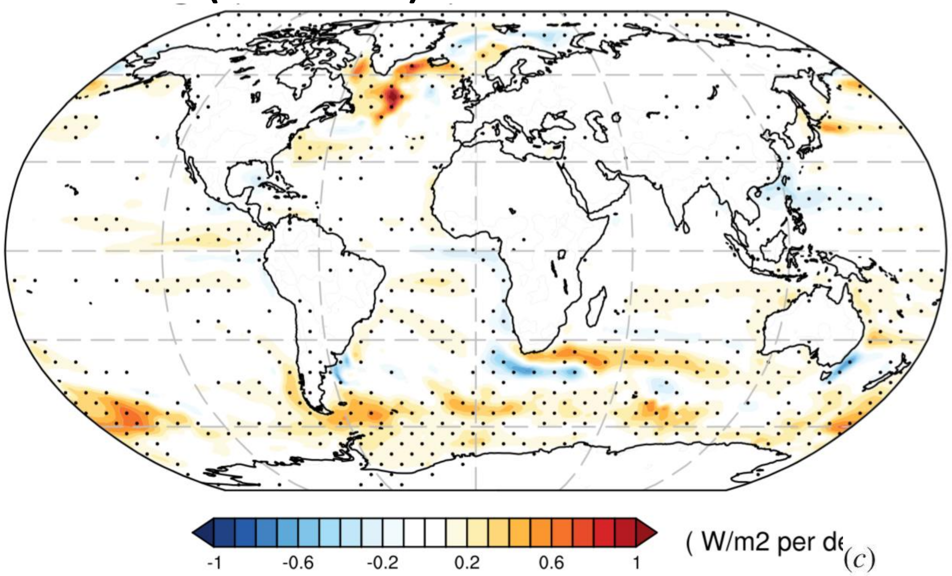
Most of heat gain (67%~98%) occurred in the S.H. extratropical ocean (south of 20˚S)

(Roemmich et al. 2015, Nat Clim Change)

Surface heat flux change

CMIP5 ensemble mean

Historical (1861-2005)



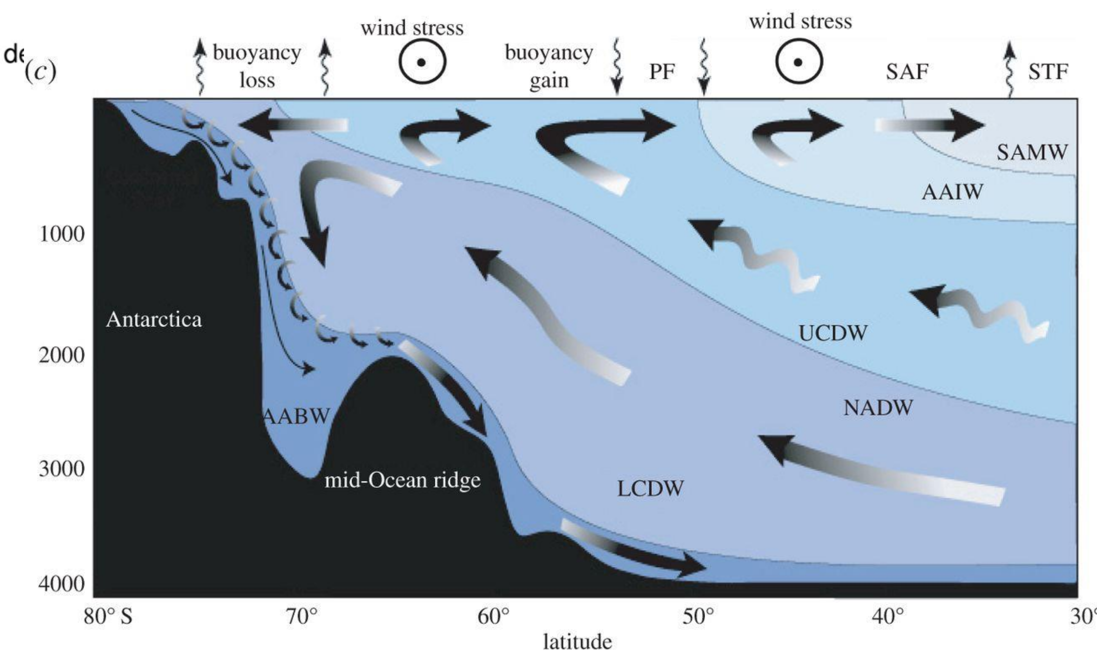
Area-integration over:

NA: 30˚N-70˚N, 80˚W-10˚W
SO: south of 30˚S

Cumulative Heat Uptake over the 20th century:

NA: 6%±39%

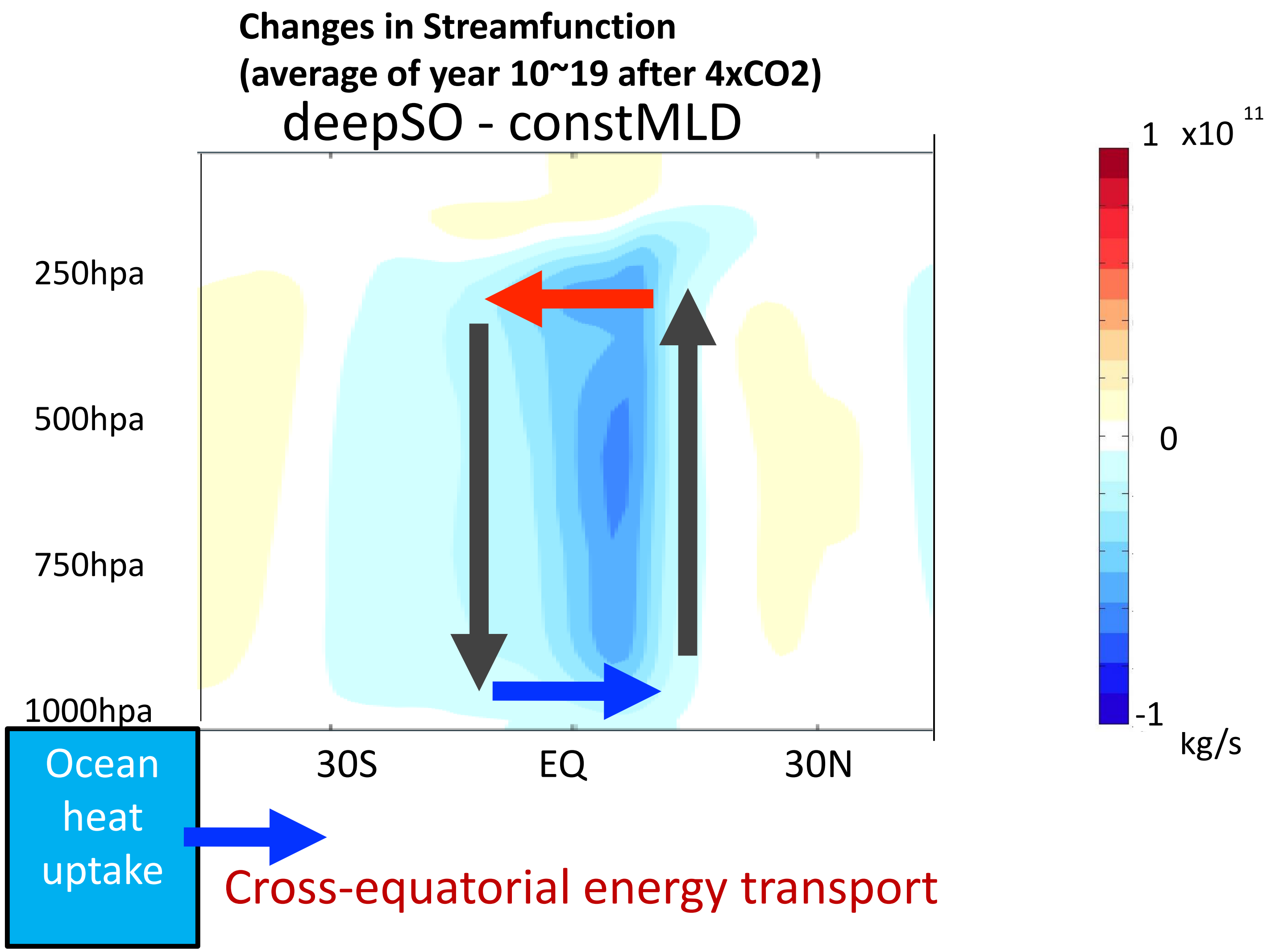
SO: 72%±28%



Southern Ocean Heat Uptake

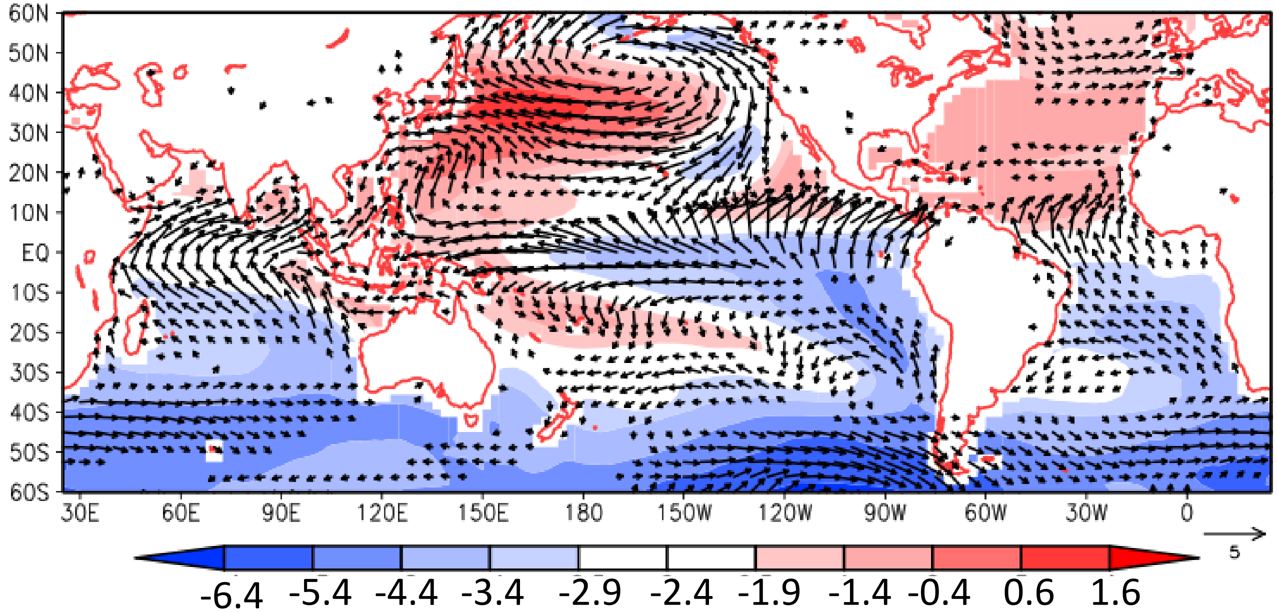
→ Reduced surface warming

(Bryan et al. 1988; Marshall et al. 2014 …)



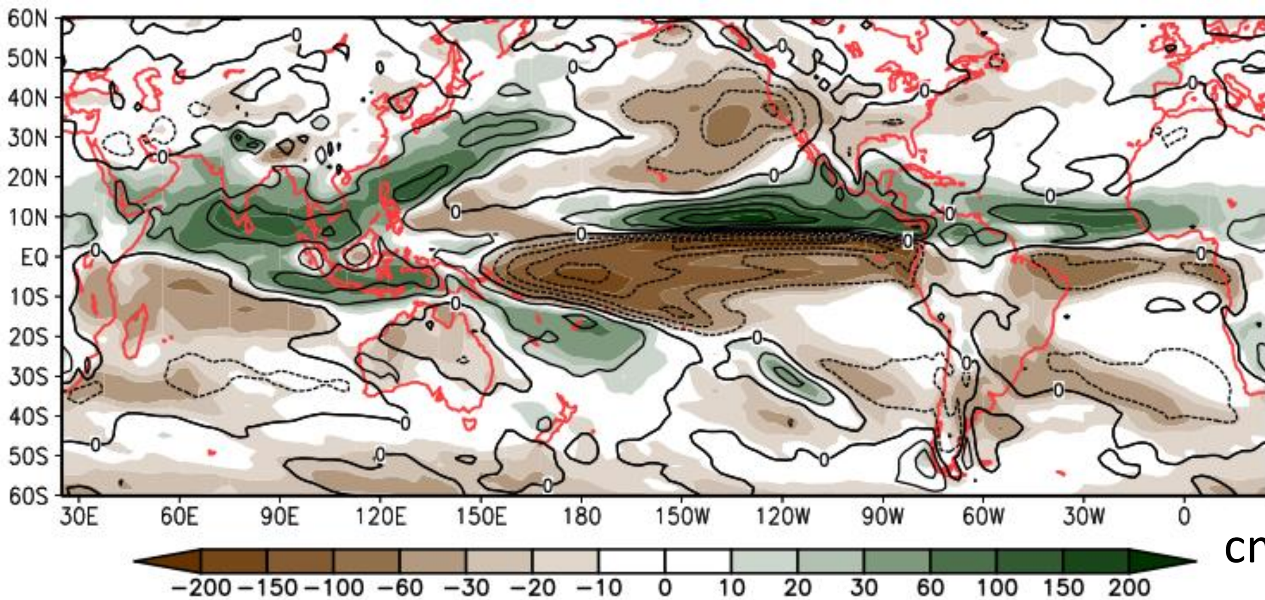
Chiang and Bitz 2005, Kang et al. 2008, 2009; Broccoli et al. 2006, Zhang and Delworth 2005, Frierson and Hwang 2012, Hwang et al. 2013

deepSO – constMLD **Difference (annual mean)**
(year 10~19 after 4xCO2)



SST (shading) & **Sfc Wind** (vectors)

Zonal asymmetry: enhanced c
ooling in SE Pacific



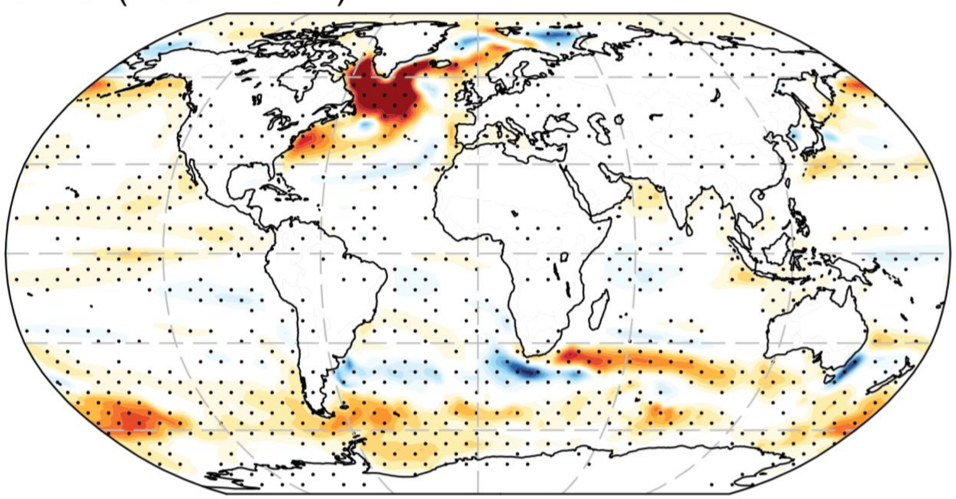
Precipitation

cm/yr

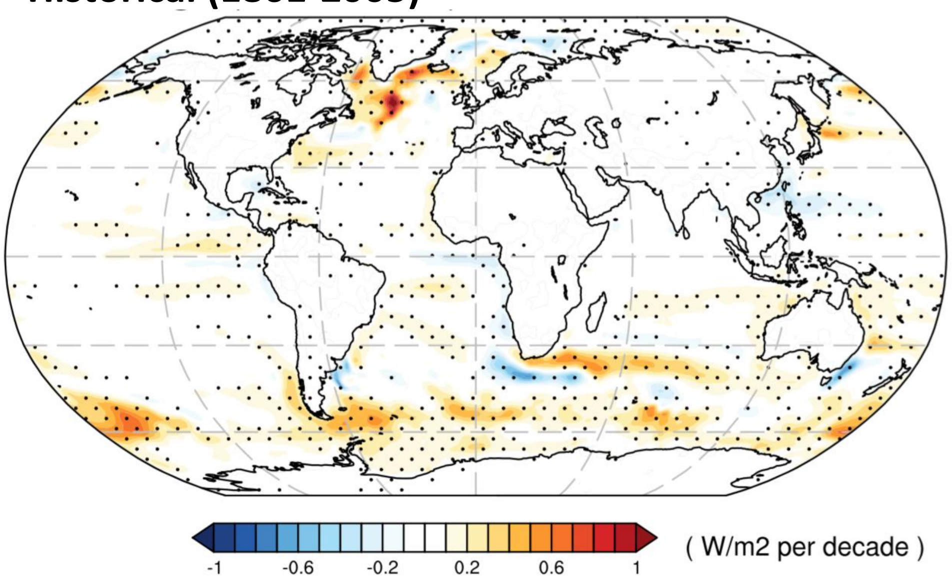
Response of surface heat flux:

CMIP5 ensemble mean

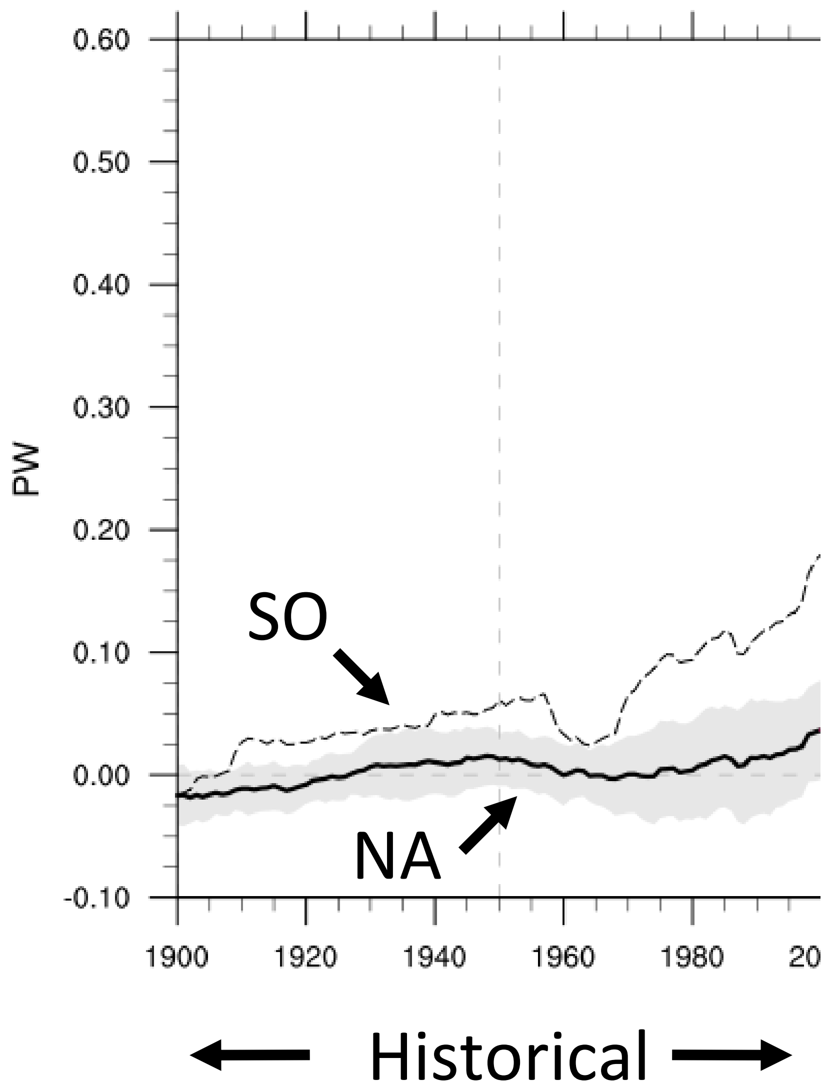
GHG (1861-2005)



Historical (1861-2005)

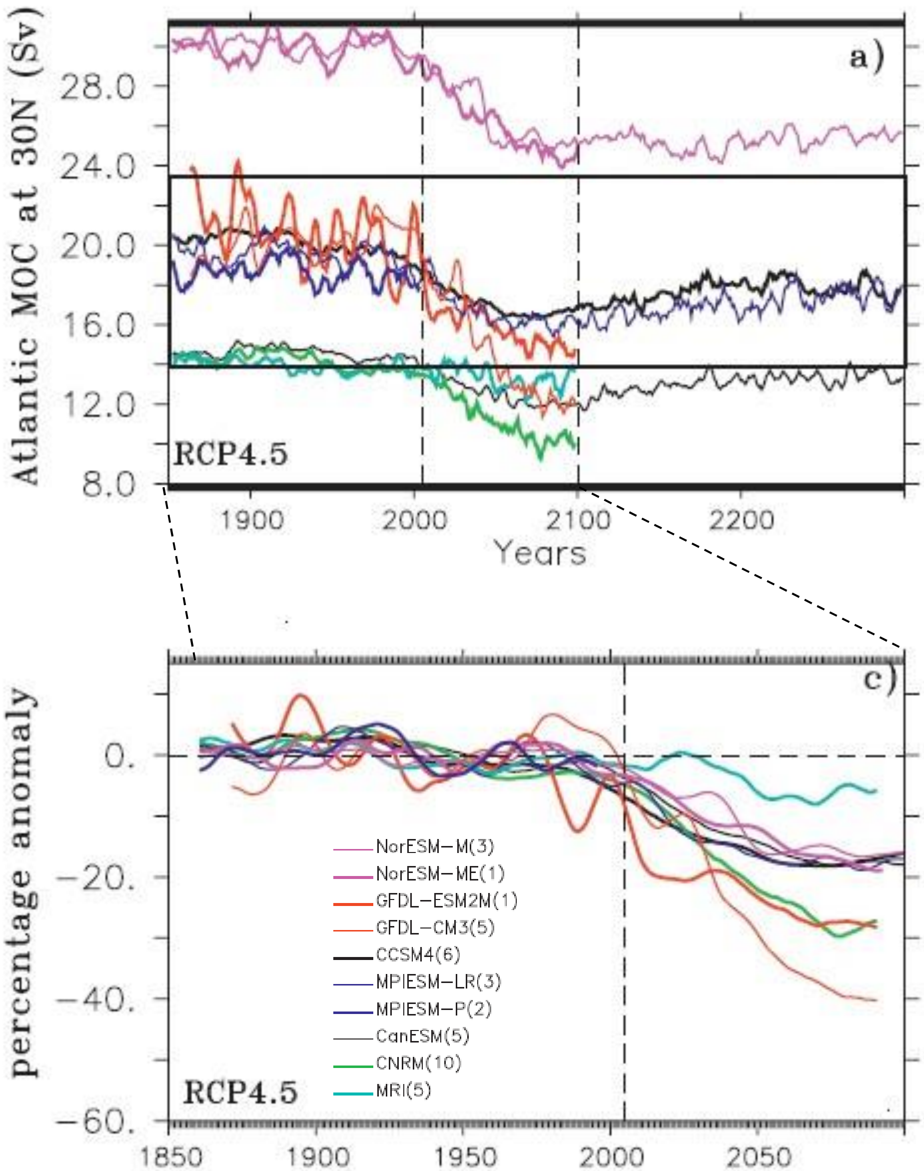


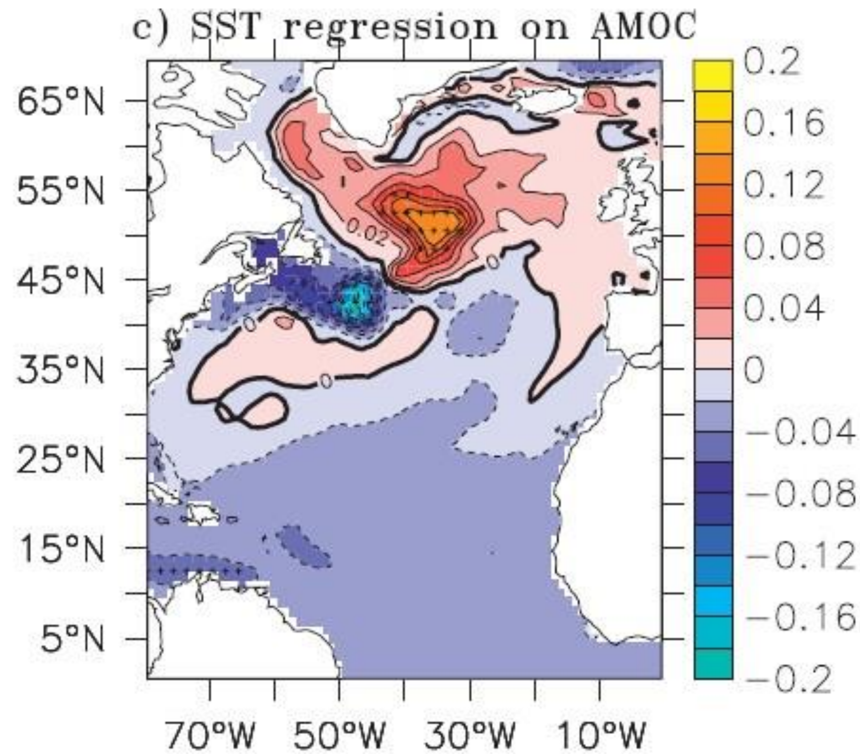
Area-integrated heat flux



Shi, J., S.-P. Xie, and L.D. Tally, 2018: Evolving relative importance of the Southern Ocean and North Atlantic in anthropogenic ocean heat uptake. *J. Climate*, in press.

Atlantic meridional overturning circulation (**AMOC**) **is projected to slow down**

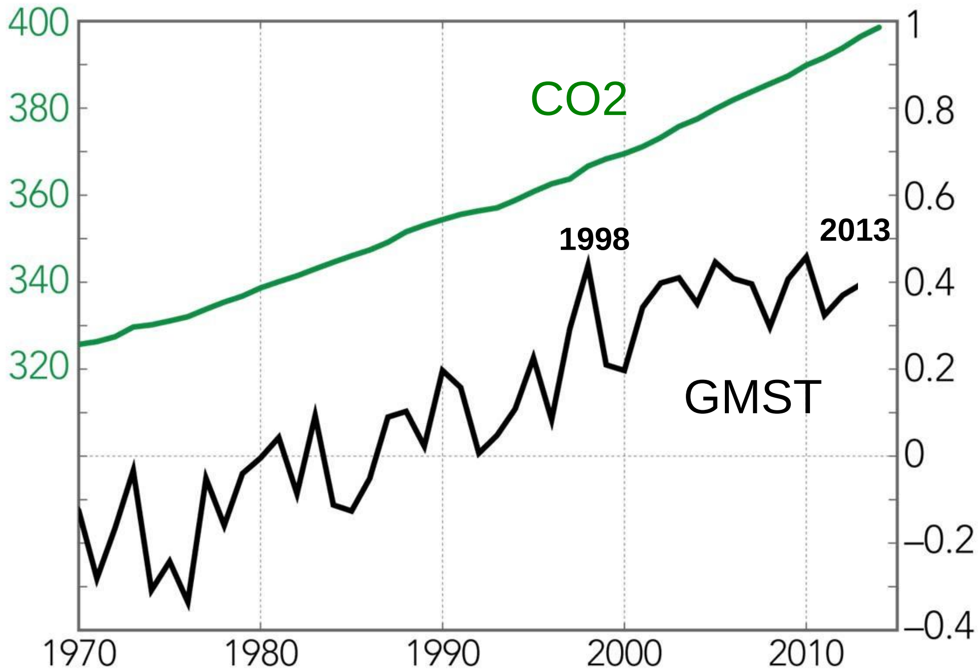




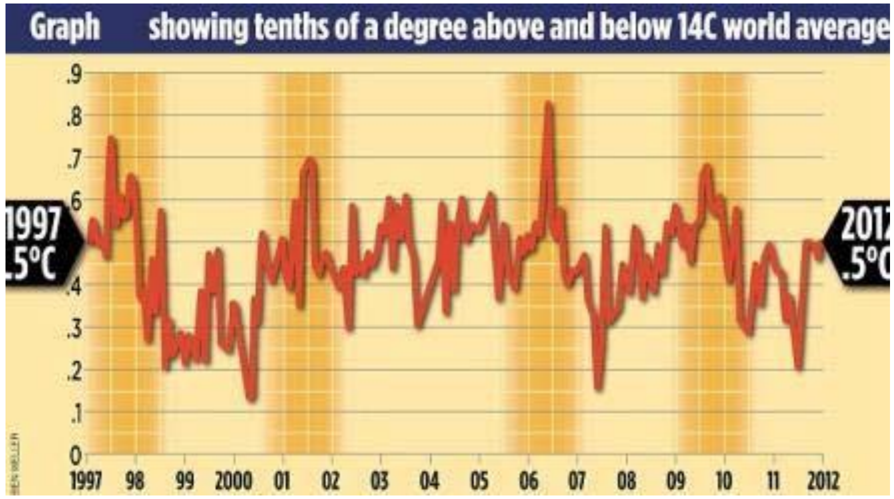
Cheng et al. (2013, J Climate)

Summary 2

- Historically, most ocean heat uptake took place in Southern Ocean
- Localized heat uptake drives cross-equatorial Hadley circulation response and reorganization of tropical monsoon/rainfall.
- With anticipated decline in aerosols, the North Atlantic contribution to heat uptake is expected to increase,
  → slowing down AMOC
  → Inducing further changes in atmospheric circulation/rainfall.



Global warming hiatus



The Mail, UK

The New York Times

July Set Mark as U.S.'s Hottest Month, August 8, 2012

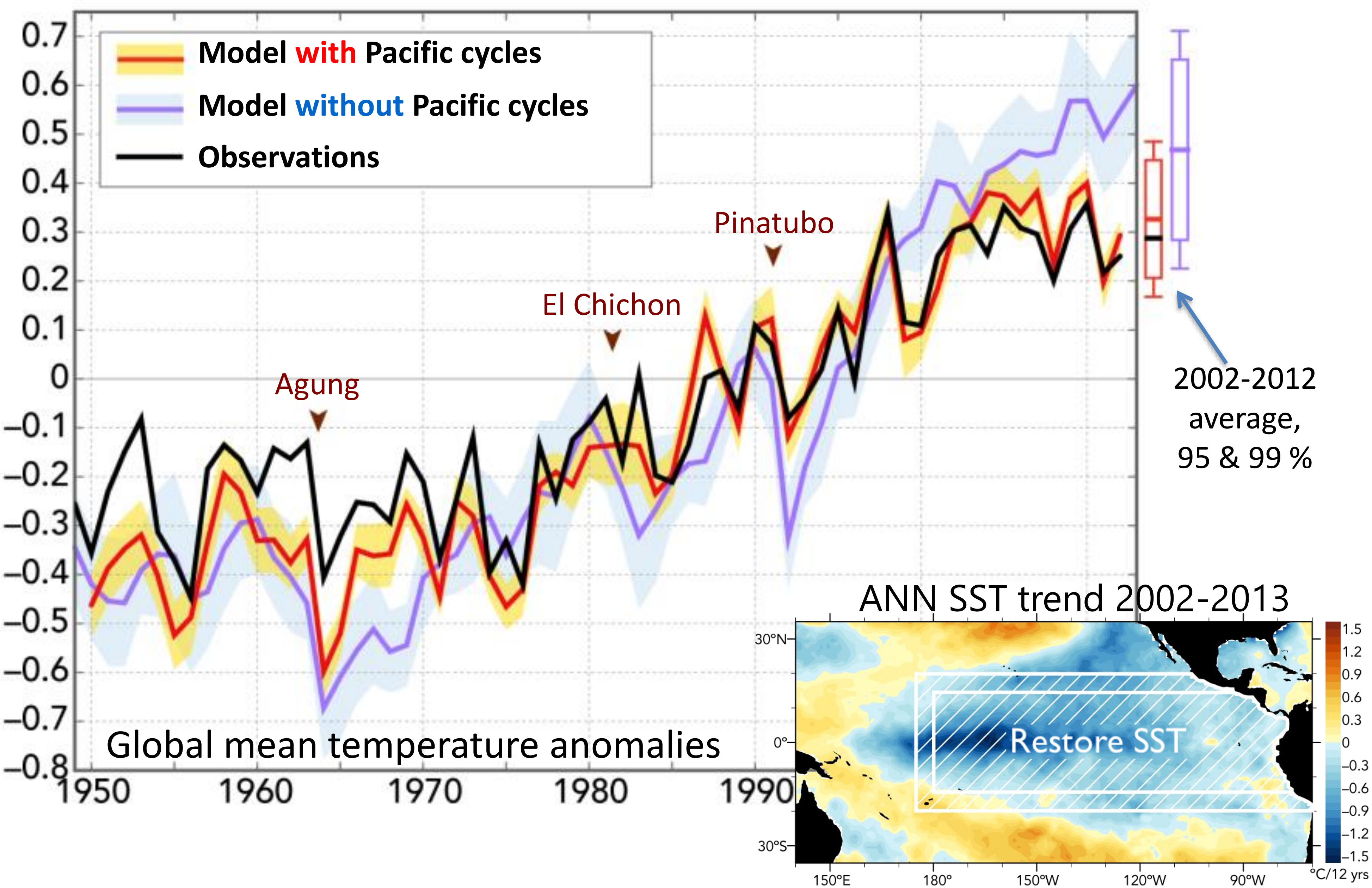
Record heat waves in Europe 2003, Russia 2010, US 2012, China 2013; Record Arctic sea ice loss in 2007 & 2012.

Daily-mean Maua Loa CO2 exceeded 400 ppm for the first time in May 2013.

→ What causes the hiatus?

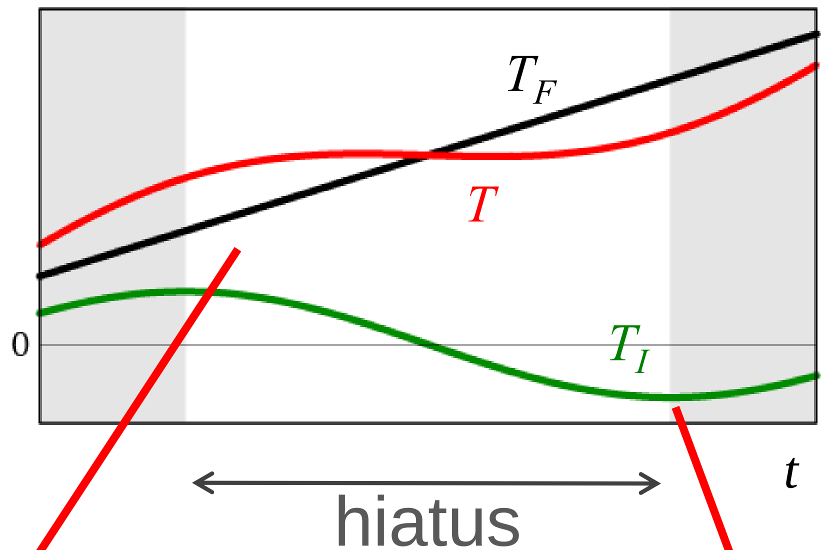
POGA (Pacific Ocean-Global Atmosphere) pacemaker run

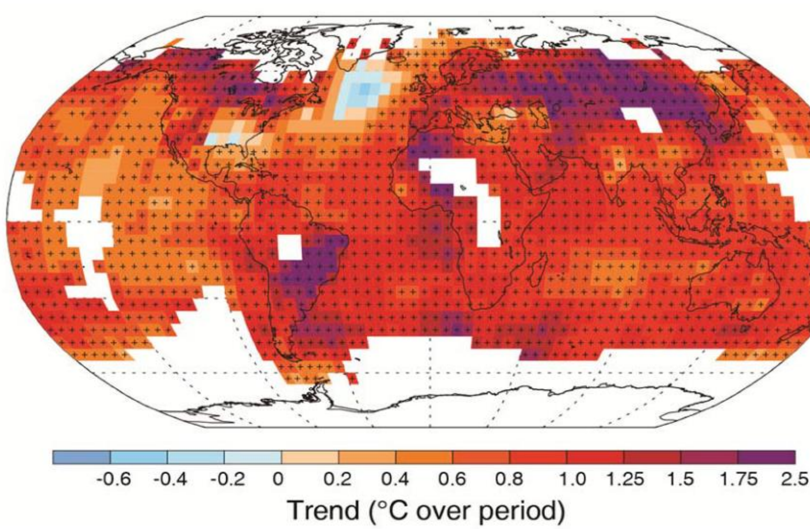
Kosaka & Xie (2013, *Nature*)

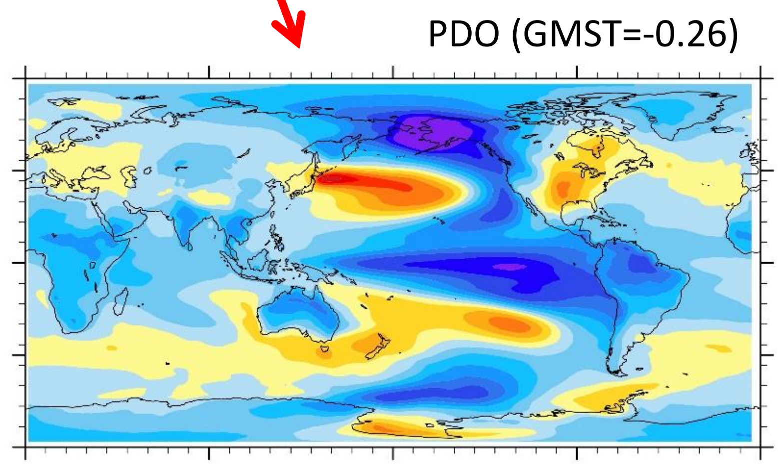


Forced & internal changes in GMST are distinct in pattern, energetics, mechanism & predictability

$$T_{obs} = T_F + T_I$$







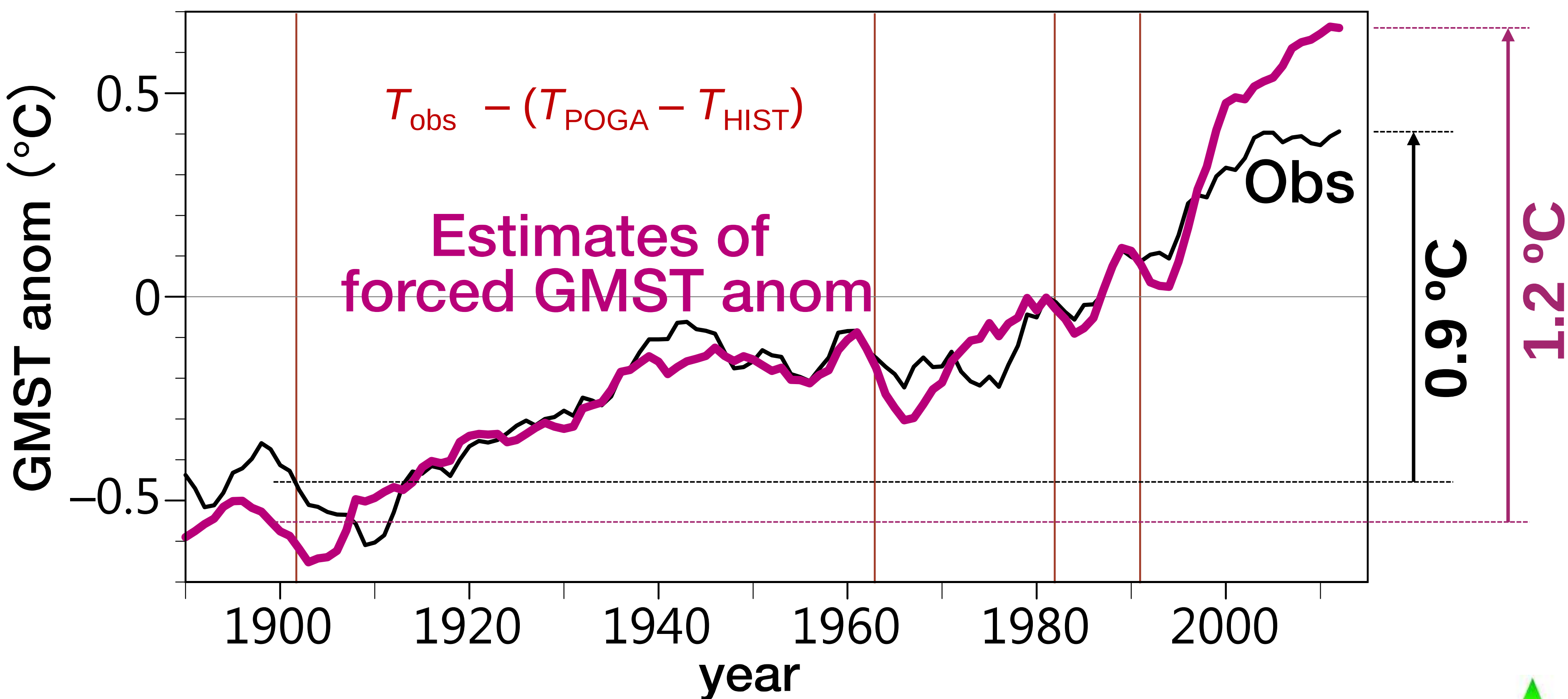
Summary 3

- Tropical Pacific cooling is a major cause of the early 2000s hiatus.
- PDO dominates internal GMST variability, with distinctive seasonal and spatial fingerprints.
- Anthropogenic warming reached 1.2^{o}C.

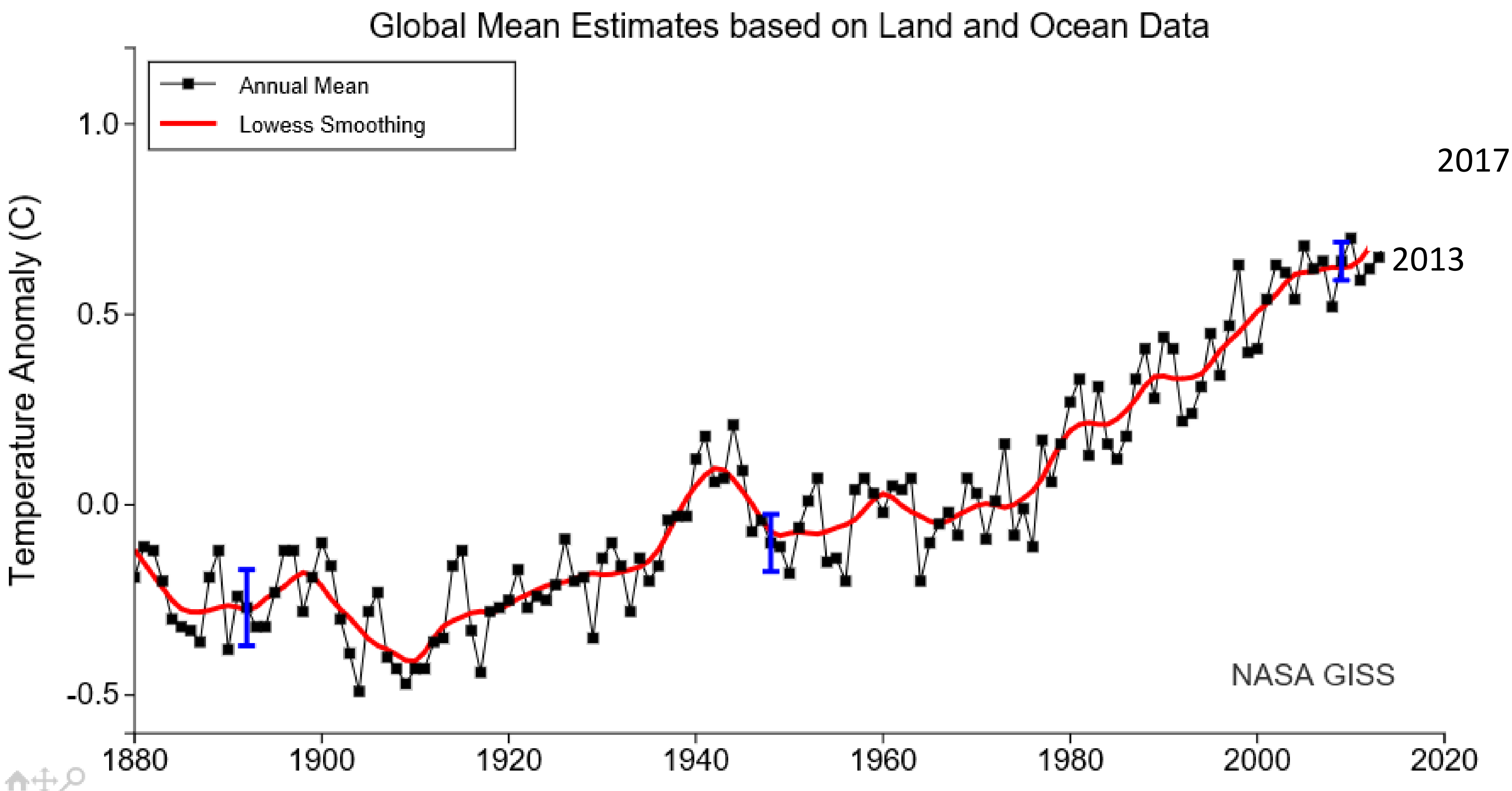
Estimate anthropogenic warming

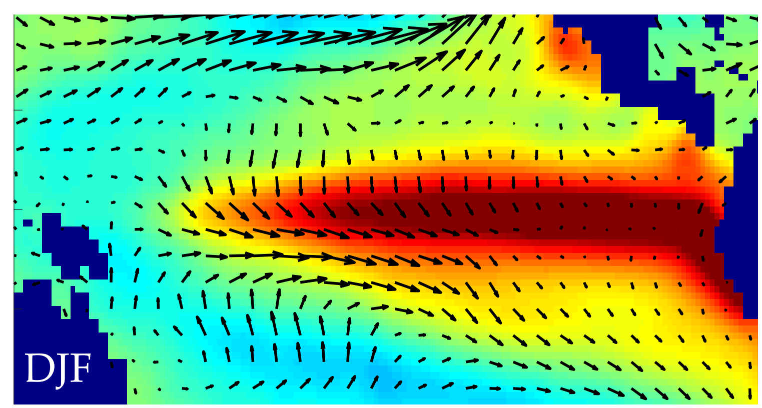
- Use **climate model HIST runs** (e.g., IPCC)
  -downside: uncertainties in radiative forcing & climate feedback
- Use **POGA pacemaker runs**
  -remove internal variability from the model (less affected by the above uncertainties): $T_F = T_{obs} - T_I$

Estimate anthropogenic warming from obs



- Paris agreement: *"holding GMST increase to well below 2°C above pre-industrial levels"*
- Anthropogenic warming already reached 1.2°C.





2015-16 El Nino

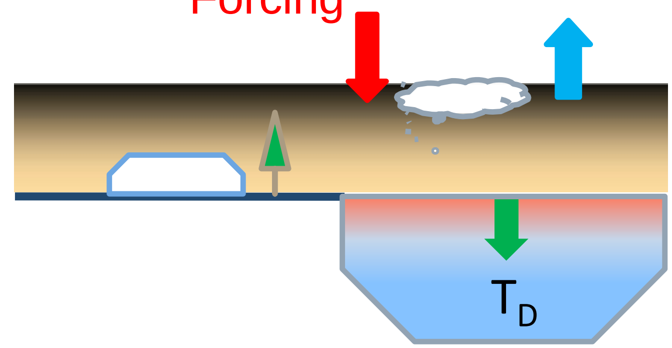
Energy theory $H_t = NTO_A = F - \lambda T$

Ocean heat content change

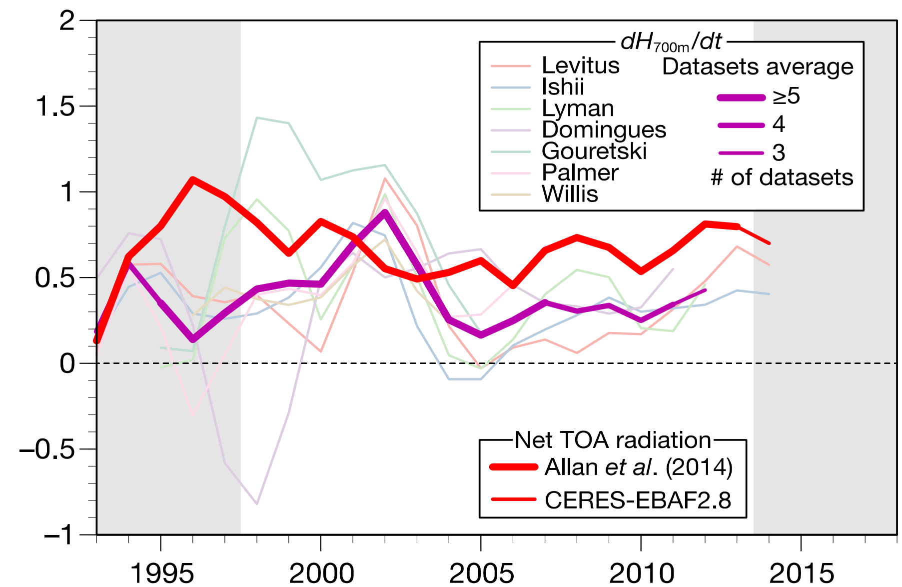
TOA radiative imbalance

Radiative forcing

Climate feedback



Prediction: during the hiatus (T=0), ocean heat uptake accelerates (TOA radiative imbalance increases).



TOA radiative imbalance (0.7 W/m^2) from CERES satellite (2000-), calibrated against Argo data.