Review of SST Pattern Evolution in the Instrumental Record of the 20th Century

Kris Karnauskas
University of Colorado Boulder
kristopher.karnauskas@colorado.edu
@OceansClimateCU

'Pattern Effect' Workshop
Boulder, CO | May 2022

Review of SST Pattern Evolution in the Instrumental Record of the 20th Century

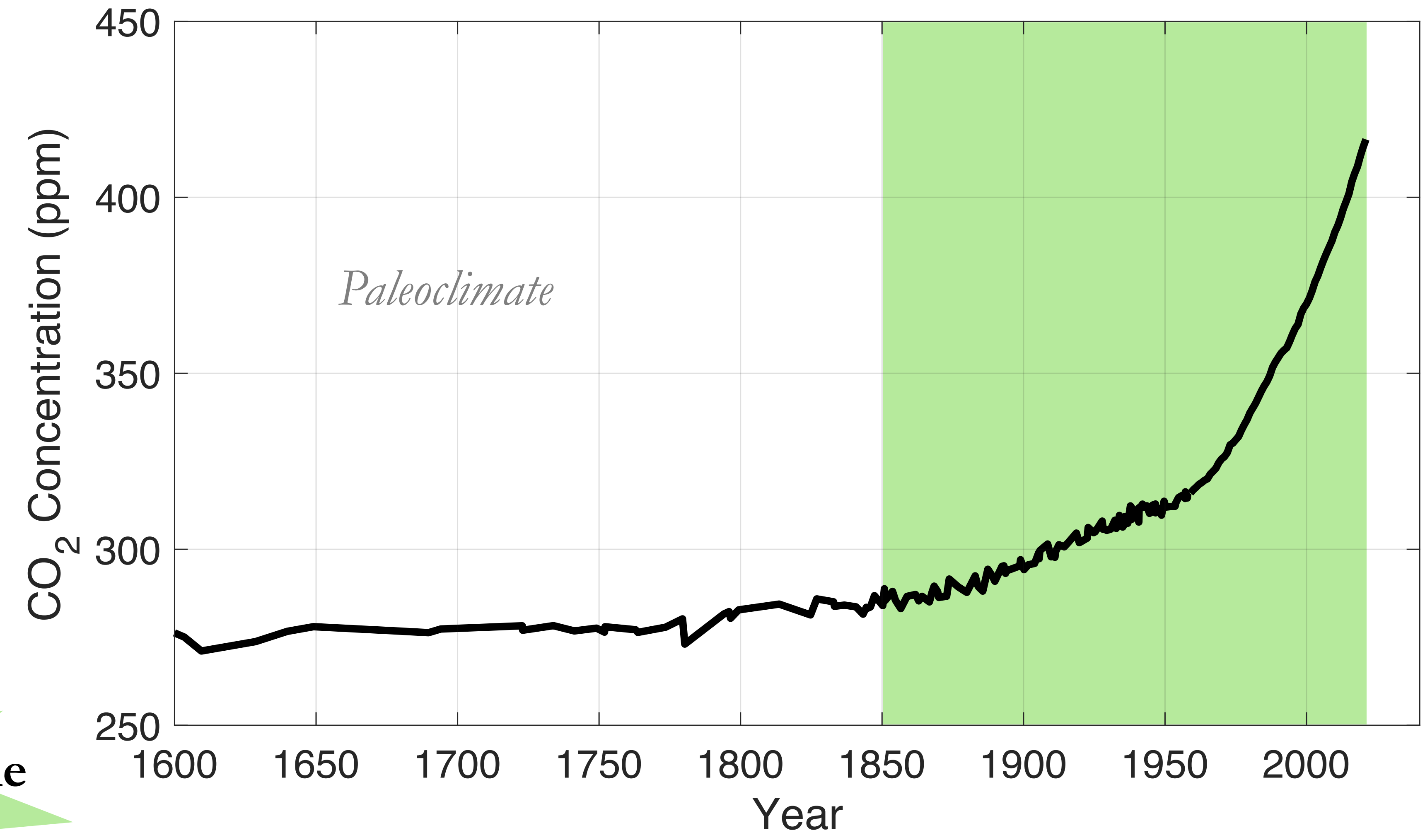
- Some relevant background on instrumental SST records
- Updated comparison of SST trends between different instrumental records and over different periods of time
  A closer look at the tropical Pacific Ocean
- Quick look at SST trends in CMIP6 models & comparison to instrumental records
- Some thoughts on physical mechanisms and related issues in models
  A focus on the circulation of the equatorial Pacific Ocean
- Outlook & open questions to stimulate discussion and further research

Globally, monthly, gridded data sets suitable for characterizing SST variability and change

1854 Internationally organized system for recording shipboard observations

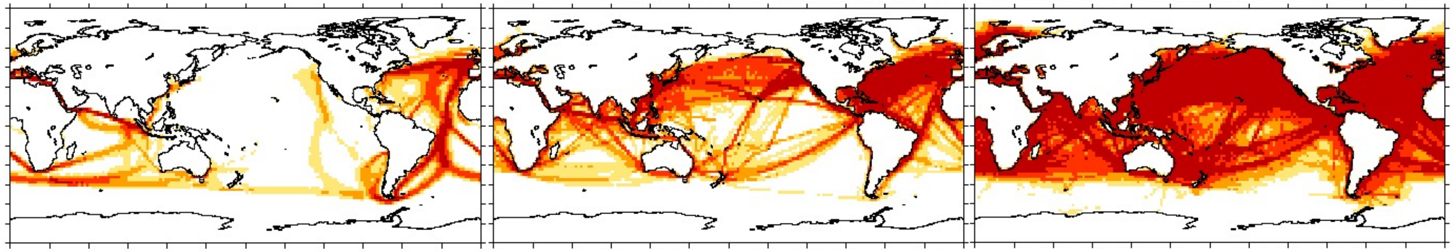
Globally, monthly, gridded data sets suitable for characterizing SST variability and change

1854 Internationally organized system for recording shipboard observations



Globally, monthly, gridded data sets suitable for characterizing SST variability and change

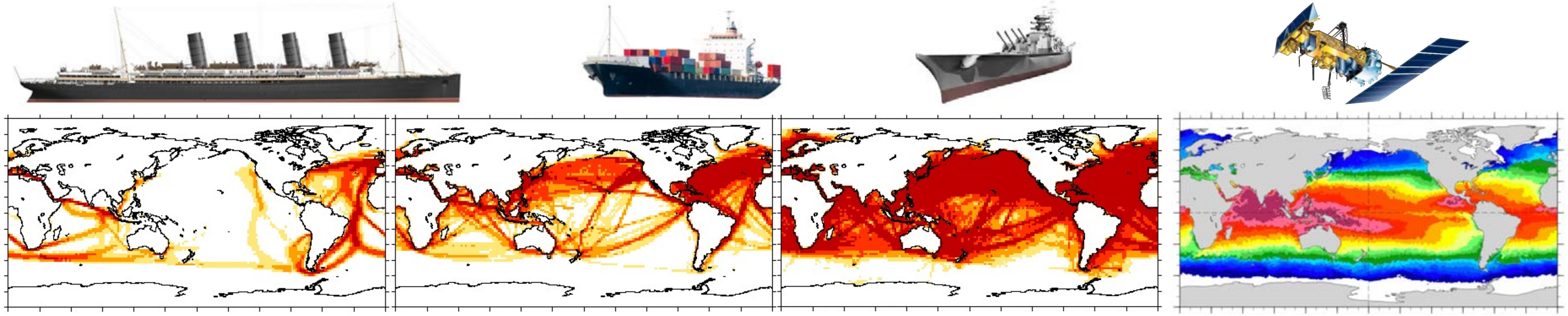
1854 Internationally organized system for recording shipboard observations



Globally, monthly, gridded data sets suitable for characterizing SST variability and change

1854 Internationally organized system for recording shipboard observations

1981 AVHRR on NOAA polar orbiting satellites



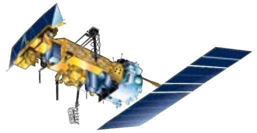
…

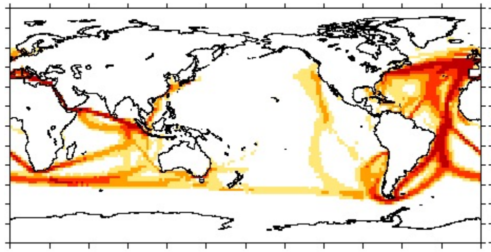
Globally, monthly, gridded data sets suitable for characterizing SST variability and change

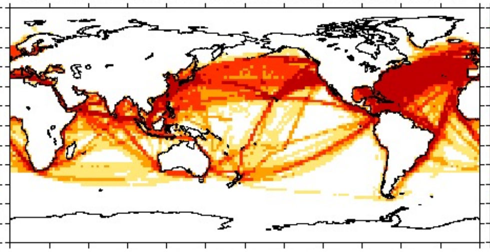
1854 Internationally organized system for recording shipboard observations

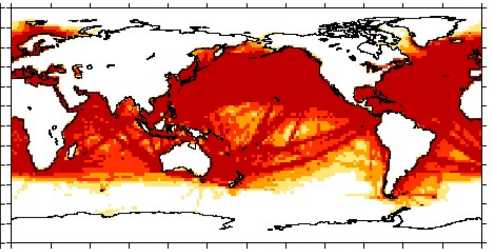
1981 AVHRR on NOAA polar orbiting satellites

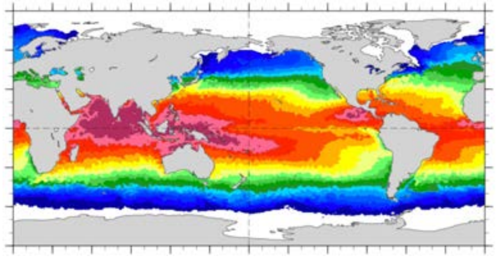
1980s Moored arrays begin to fill out



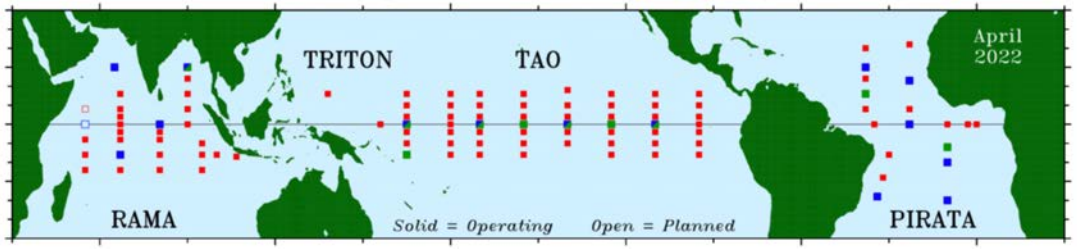








…



Globally, monthly, gridded data sets suitable for characterizing SST variability and change

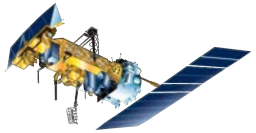
1854 Internationally organized system for recording shipboard observations

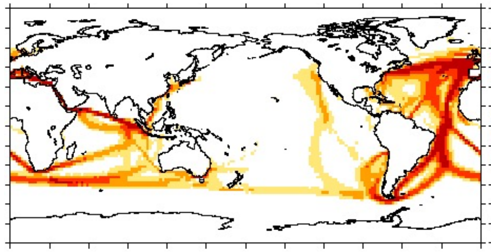
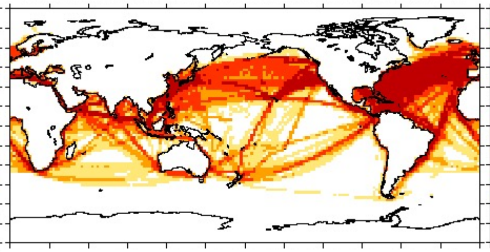
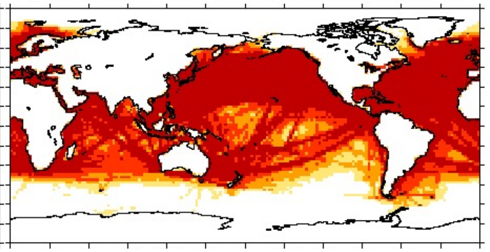
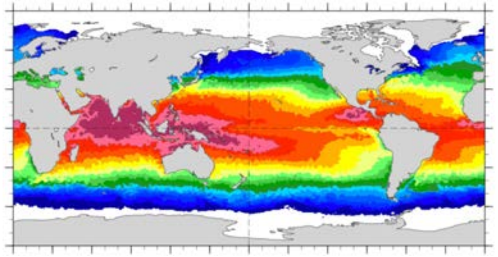
1981 AVHRR on NOAA polar orbiting satellites

1980s Moored arrays begin to fill out

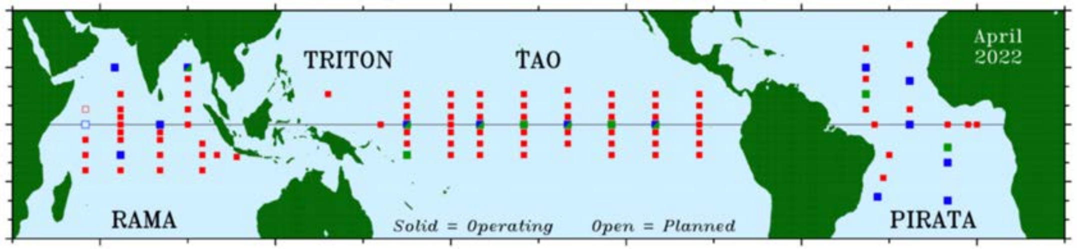
1999 Argo floats deployed

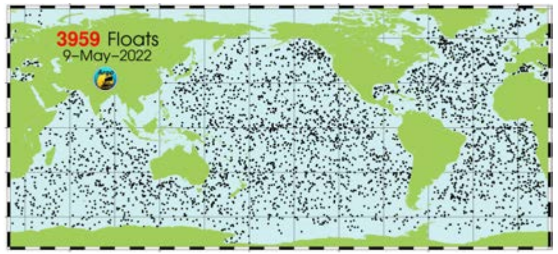


…

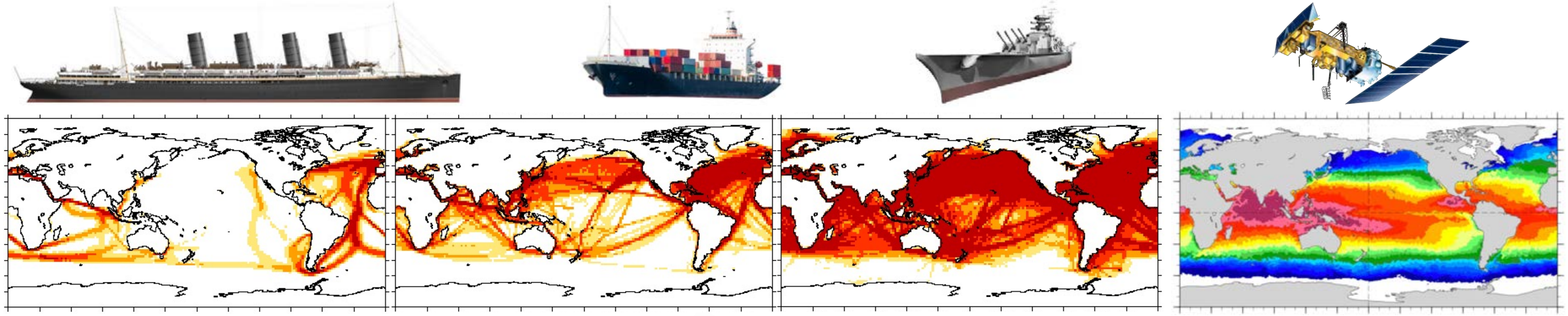
Globally, monthly, gridded data sets suitable for characterizing SST variability and change

1854 Internationally organized system for recording shipboard observations

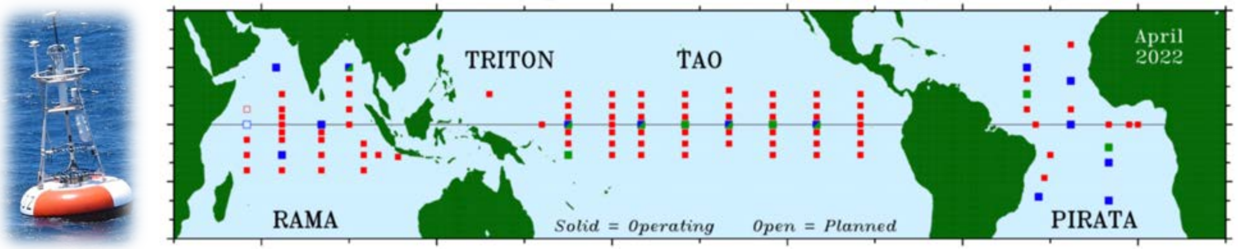
1981 AVHRR on NOAA polar orbiting satellites

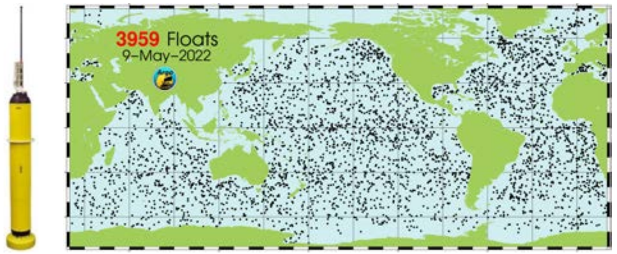
1980s Moored arrays begin to fill out

1999 Argo floats deployed



...





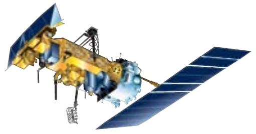
Globally, monthly, gridded data sets suitable for characterizing SST variability and change

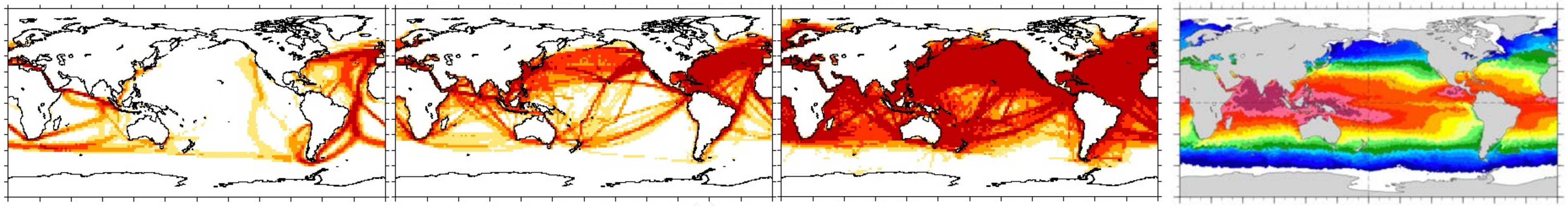
1854 Internationally organized system for recording shipboard observations

1981 AVHRR on NOAA polar orbiting satellites

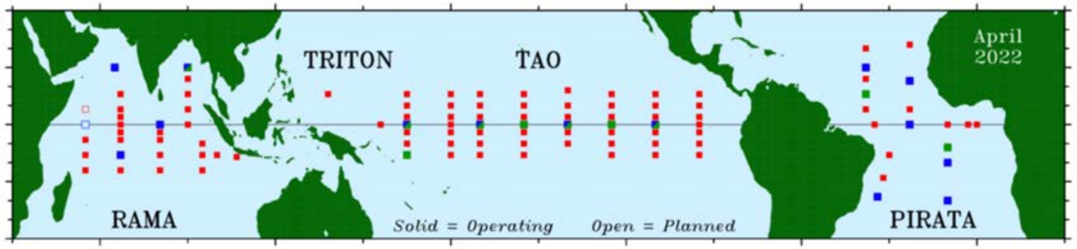
1980s Moored arrays begin to fill out

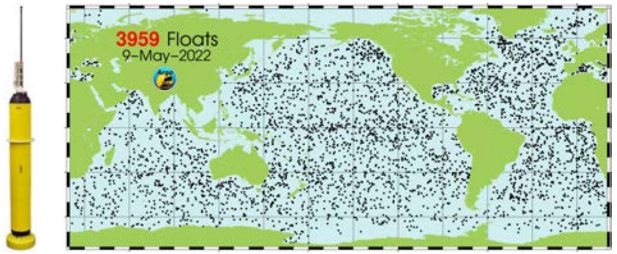
1999 Argo floats deployed





…





Choices in methodology

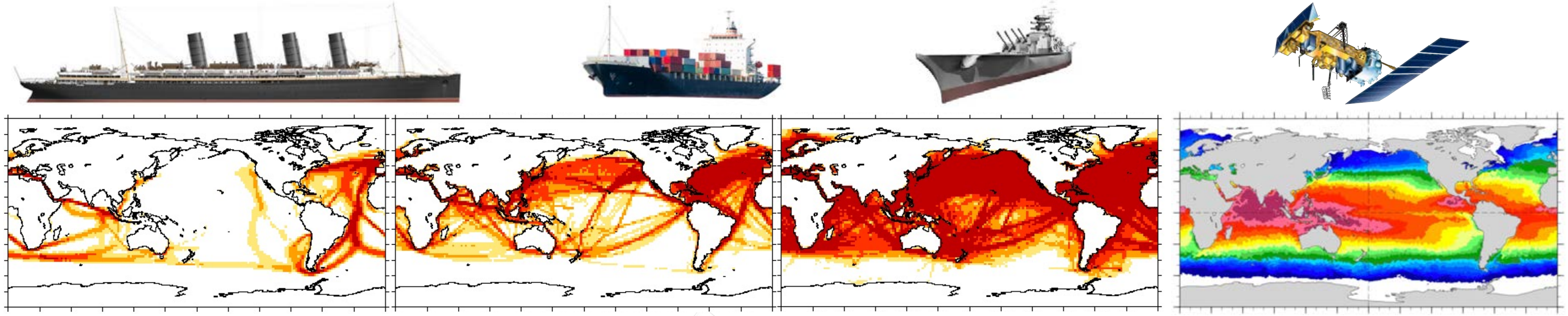
- How to choose **which data sets** to include?
- How to interpolate/**fill gaps** in time and horizontal space?
- How **little data** is *too* little data (*e.g.*, Southern Ocean)?
- How to **quality control** the raw/input data?
- How to introduce data from **new observing platforms** coming online over time?
- How to deal with **spatial aliasing** (*e.g.*, observations taken within eddies)?
- How to deal with **temporal aliasing** (*e.g.*, observations at different points in the diurnal cycle)?
- How to account for **vertical differences** of measurement (*i.e.*, skin, 1 m, ~5 m, …)?
- How to correct for other biases due to **changes in observing method** over time (*e.g.*, bucket vs. intake)?
- Apparently, even a ship's **country of origin** introduces systematic biases (Chan and Huybers 2019).
- How to quantify and convey **uncertainties**?

1854 Internationally organized system for recording shipboard observations

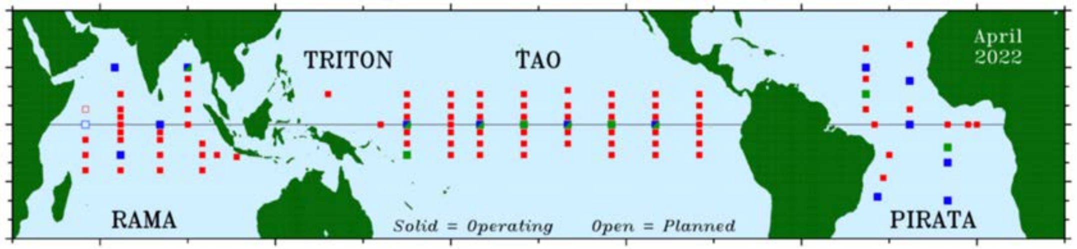
1981 AVHRR on NOAA polar orbiting satellites

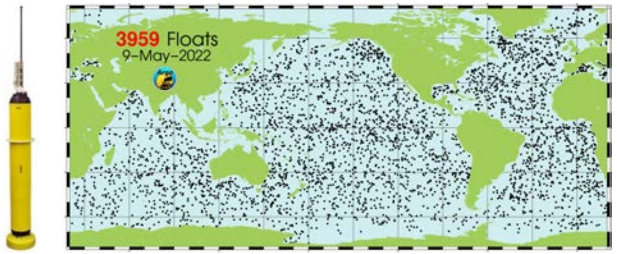
1980s Moored arrays begin to fill out

1999 Argo floats deployed



…





Choices in methodology

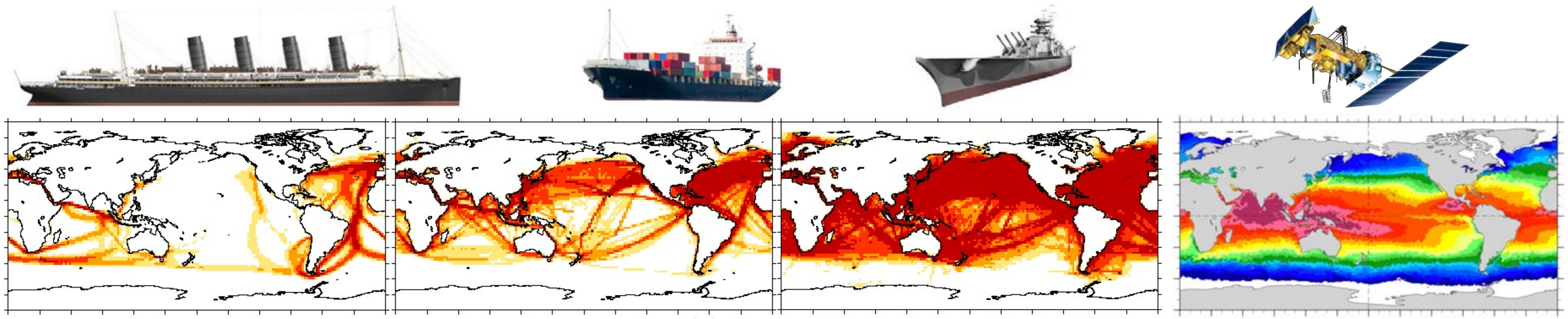
- How to choose **which data sets** to include?
- How to interpolate/**fill gaps** in time and horizontal space?
- How **little data** is *too* little data (*e.g.*, Southern Ocean)?
- How to **quality control** the raw/input data?
- How to introduce data from **new observing platforms** coming online over time?
- How to deal with **spatial aliasing** (*e.g.*, observations taken within eddies)?
- How to deal with **temporal aliasing** (*e.g.*, observations at different points in the diurnal cycle)?
- How to account for **vertical differences** of measurement (*i.e.*, skin, 1 m, ~5 m, …)?
- How to correct for other biases due to **changes in observing method** over time (*e.g.*, bucket vs. intake)?
- Apparently, even a ship's **country of origin** introduces systematic biases (Chan and Huybers 2019).
- How to quantify and convey **uncertainties**?

1854 Internationally organized system for recording shipboard observations

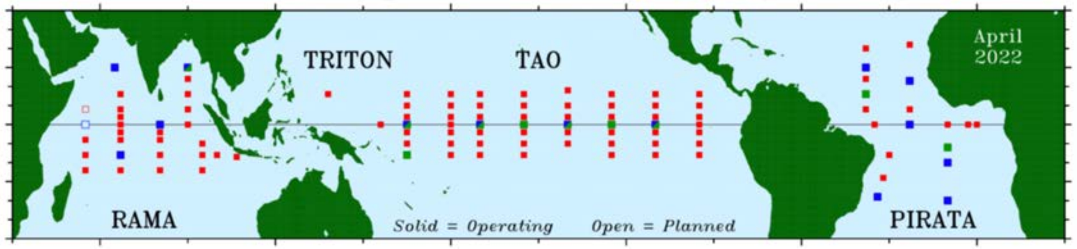
1981 AVHRR on NOAA polar orbiting satellites

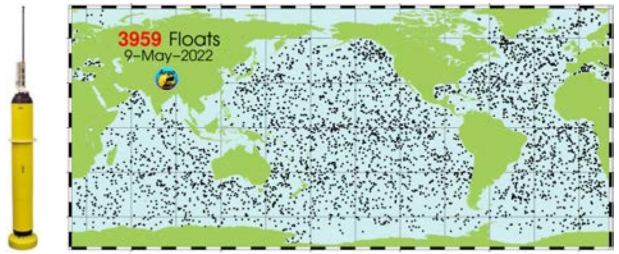
1980s Moored arrays begin to fill out

1999 Argo floats deployed



. . .





Choices in methodology

- How to choose **which data sets** to include?
- How to interpolate/**fill gaps** in time and horizontal space?
- How **little data** is *too* little data (*e.g.*, Southern Ocean)?

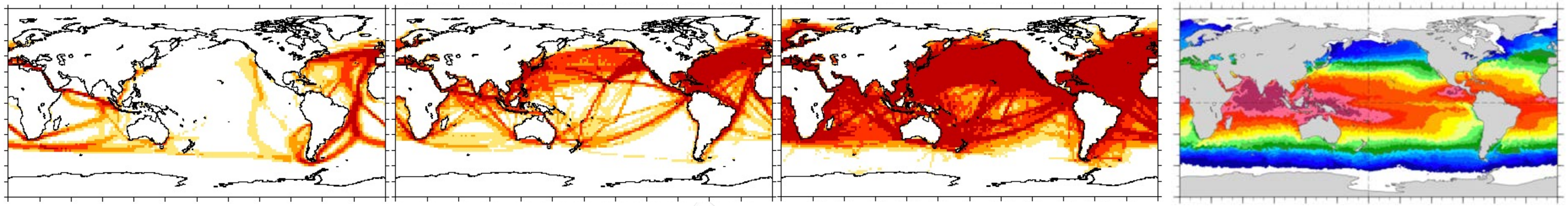
HadSST3-4	In situ only
COBE1-2	In situ only
NOAA ERSST4	In situ only
NOAA ERSST5	In situ only (including Argo)
HadISST1	In situ + satellite
Kaplan ESST2	In situ + satellite

1854 Internationally organized system for recording shipboard observations

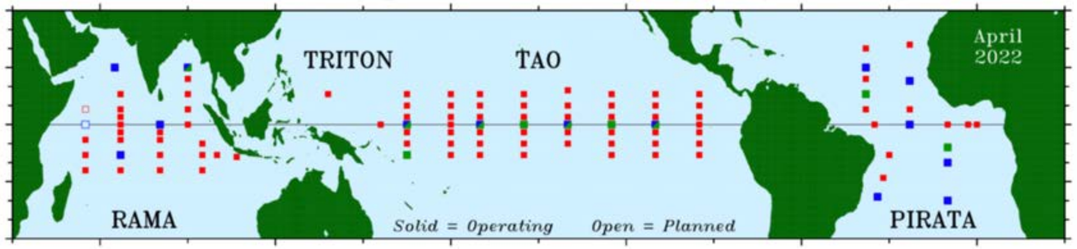
1981 AVHRR on NOAA polar orbiting satellites

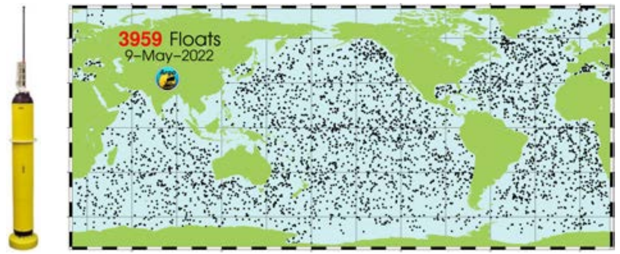
1980s Moored arrays begin to fill out

1999 Argo floats deployed



…





Choices in methodology

- How to choose **which data sets** to include?
- How to interpolate/**fill gaps** in time and horizontal space?
- How **little data** is *too* little data (*e.g.*, Southern Ocean)?

HadSST3-4	Not "filled" (but very large area averages)
COBE1-2	EOF*
NOAA ERSST4	EOF*
NOAA ERSST5	EOF*
HadISST1	EOF*
Kaplan ESST2	EOF*

** Some combination of empirical orthogonal functions (EOFs), reduced space optimal interpolation, Kalman filtering, and optimal smoothing… and each of these techniques comes with an abundance of choices (e.g., how many EOFs, what data to use for construction of EOFs).*

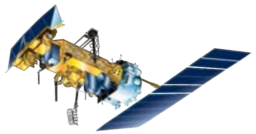
1854 Internationally organized system for recording shipboard observations

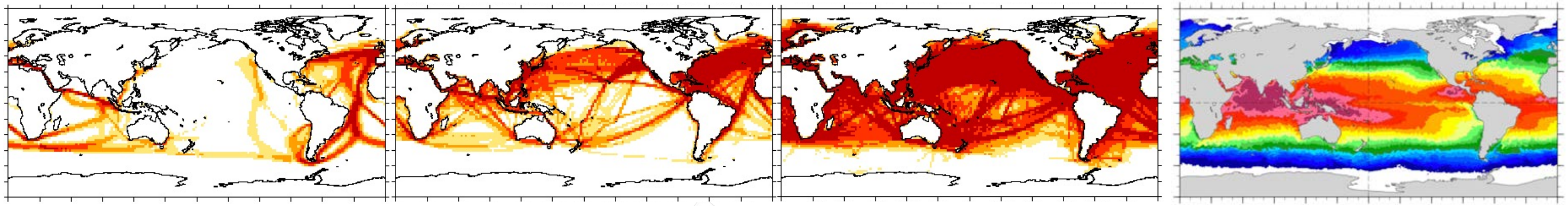
1981 AVHRR on NOAA polar orbiting satellites

1980s Moored arrays begin to fill out

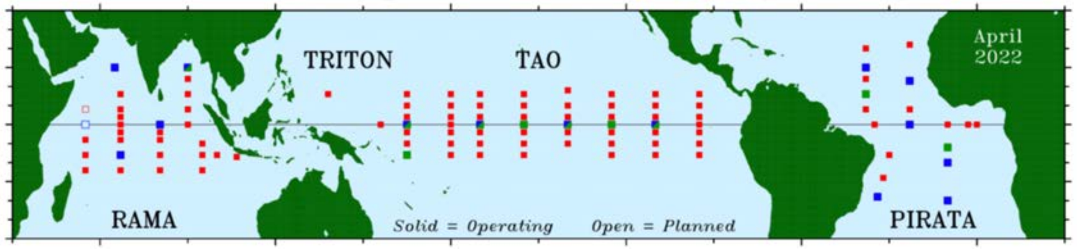
1999 Argo floats deployed



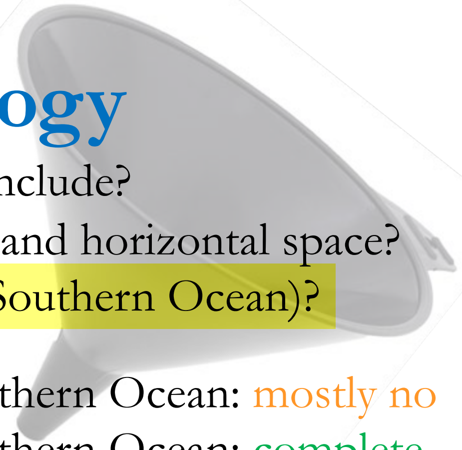





. . .

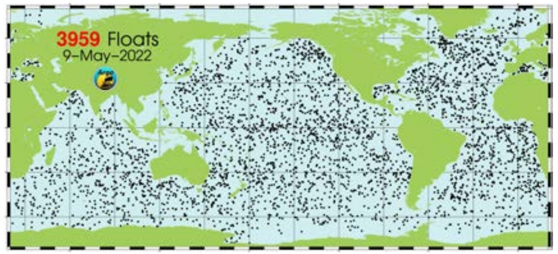


Choices in methodology



- How to choose **which data sets** to include?
- How to interpolate/**fill gaps** in time and horizontal space?
- How **little data** is *too* little data (*e.g.*, Southern Ocean)?

HadSST3-4	1850	Southern Ocean: mostly no
COBE1-2	1850	Southern Ocean: complete
NOAA ERSST4	1854	Southern Ocean: complete
NOAA ERSST5	1854	Southern Ocean: complete
HadISST1	1870	Southern Ocean: complete
Kaplan ESST2	1856	Southern Ocean: no



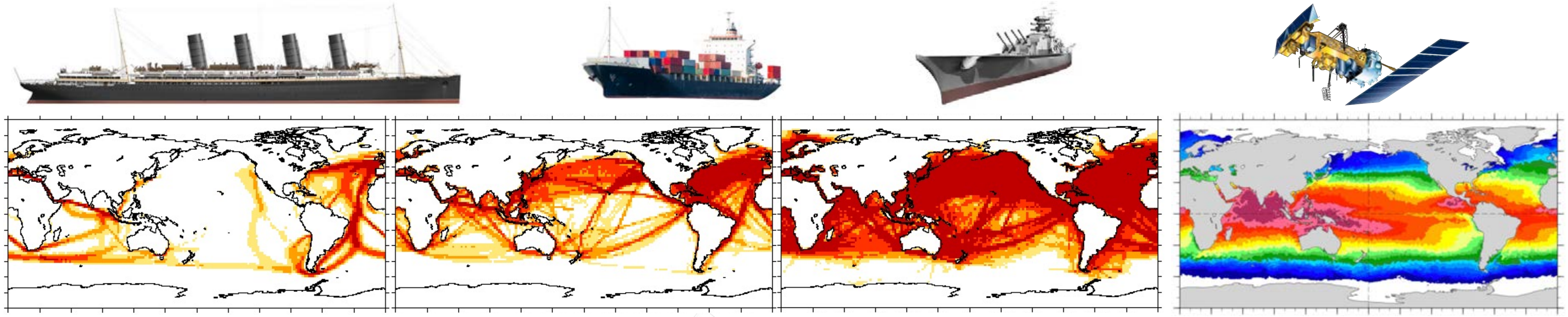
The early decades are very poorly observed, and the Southern Ocean is always poorly observed.

1854 Internationally organized system for recording shipboard observations

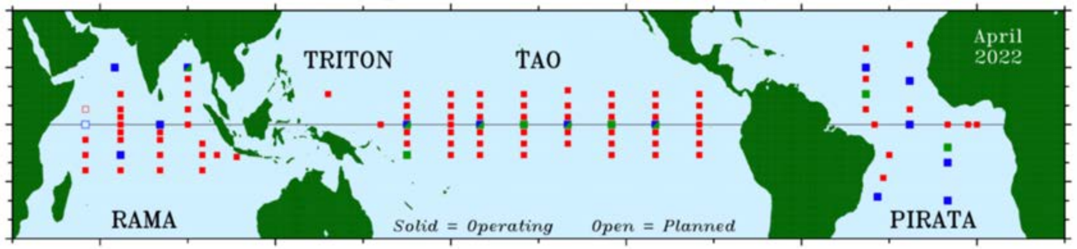
1981 AVHRR on NOAA polar orbiting satellites

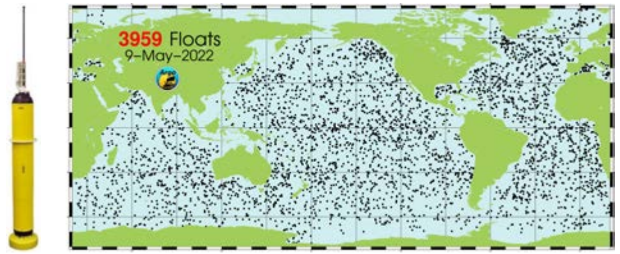
1980s Moored arrays begin to fill out

1999 Argo floats deployed



…



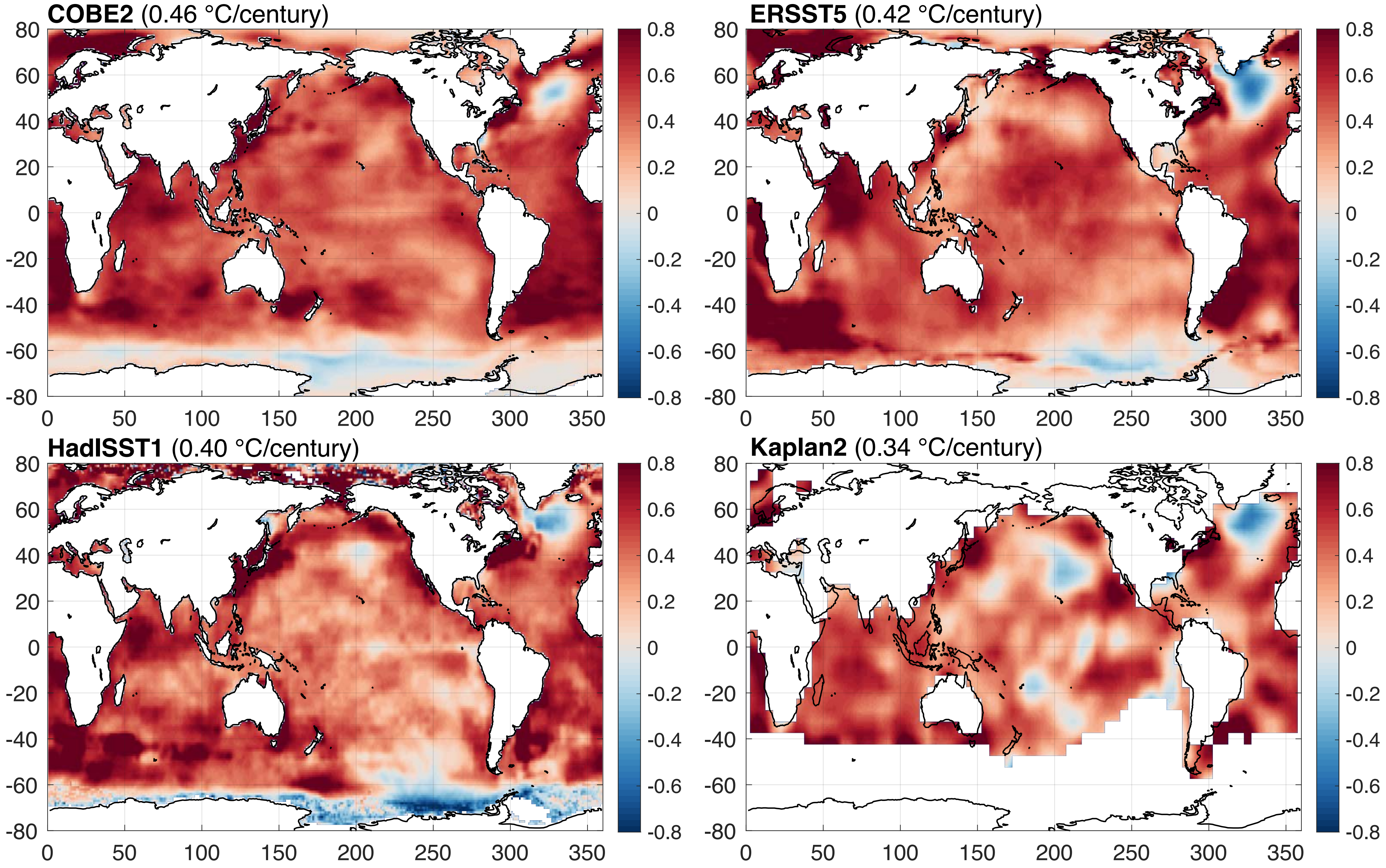


Choices in methodology

- How to choose **which data sets** to include?
- How to interpolate/**fill gaps** in time and horizontal space?
- How **little data** is *too* little data (*e.g.*, Southern Ocean)?
- How to **quality control** the raw/input data?
- How to introduce data from **new observing platforms** coming online over time?
- How to deal with **spatial aliasing** (*e.g.*, observations taken within eddies)?
- How to deal with **temporal aliasing** (*e.g.*, observations at different points in the diurnal cycle)?
- How to account for **vertical differences** of measurement (*i.e.*, skin, 1 m, ~5 m, …)?
- How to correct for other biases due to **changes in observing method** over time (*e.g.*, bucket vs. intake)?
- Apparently, even a ship's **country of origin** introduces systematic biases (Chan and Huybers 2019).
- How to quantify and convey **uncertainties**?

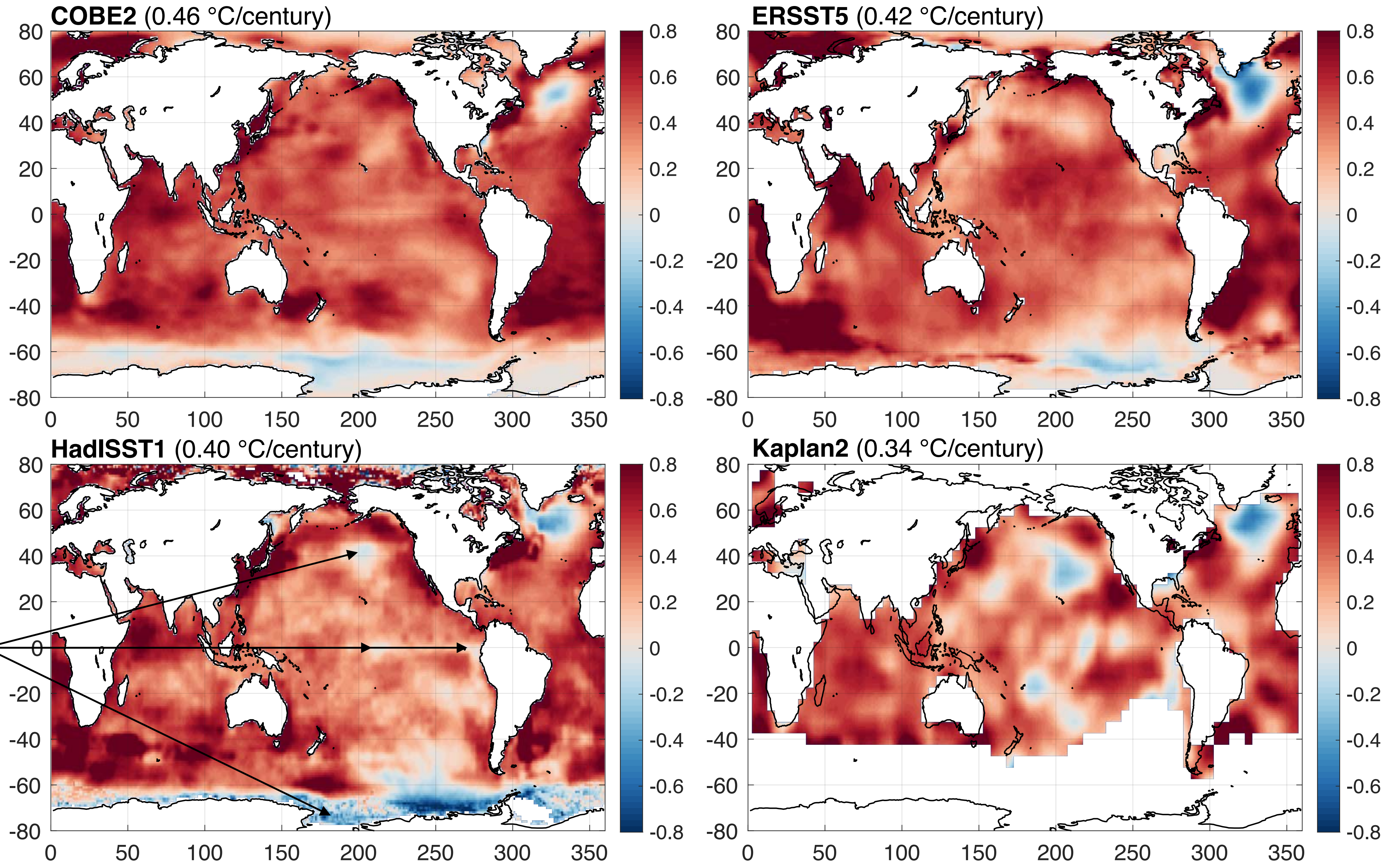
SST Trends (°C/century), **1870**–2019

Note: The global mean trends are all calculated over the same grid cells (the ones that are not blank in Kaplan2).



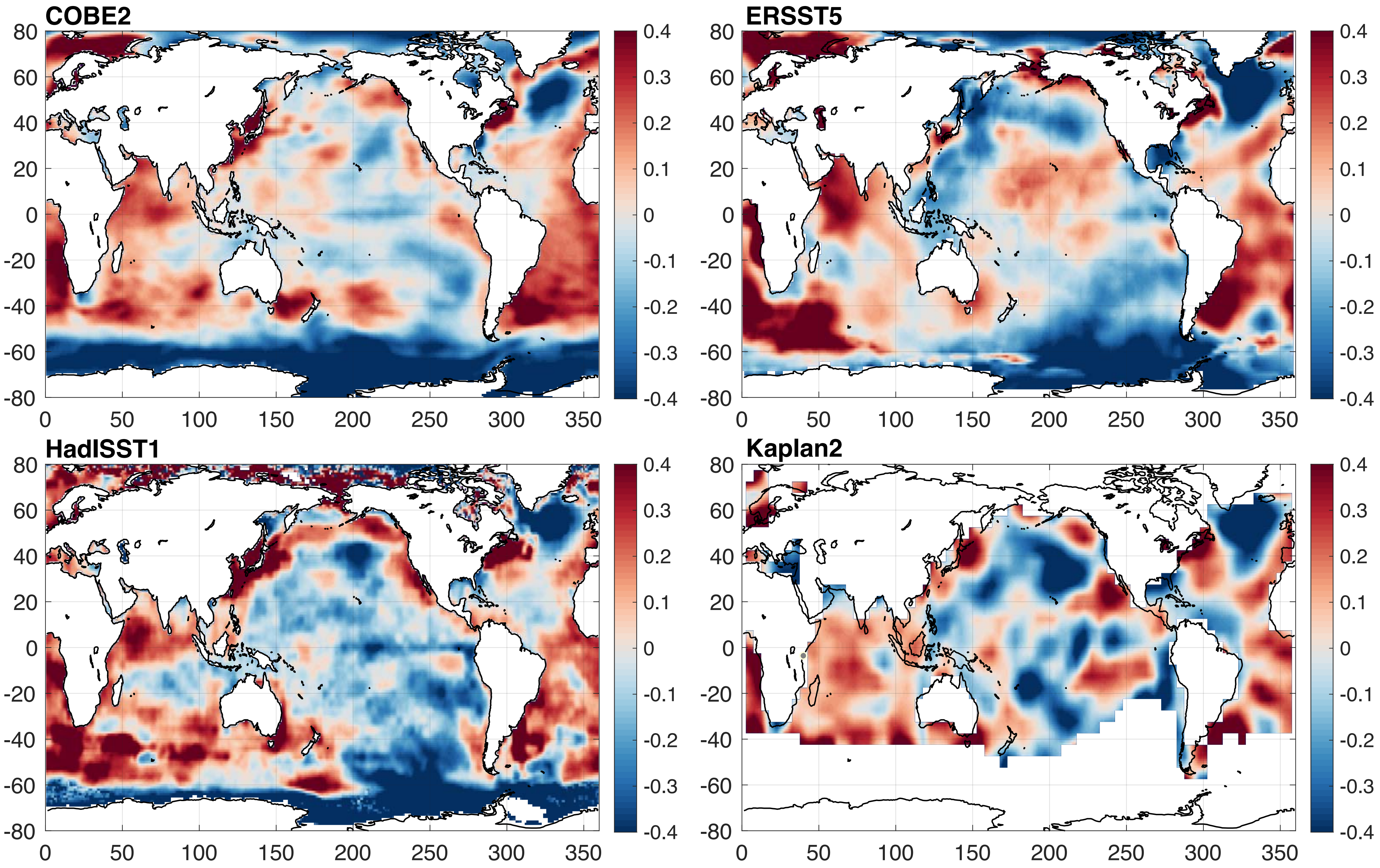
SST Trends (°C/century), **1870**–2019

Note: The global mean trends are all calculated over the <u>same grid cells</u> (the ones that are not blank in Kaplan2).



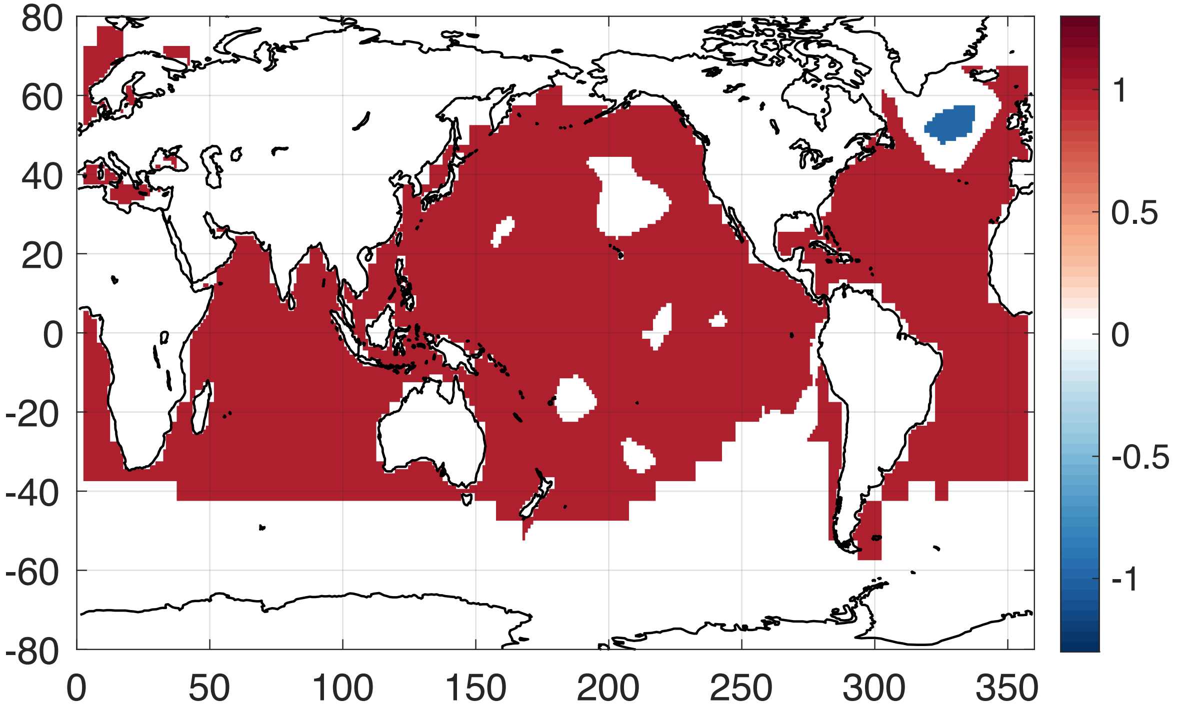
These cooling trends are ***not*** *statistically significant at the 95% confidence level.*
All other trends are significant, but are they significantly ***different from each other?***

SST Trends (°C/century), **1870**–2019, *Global mean trend removed*



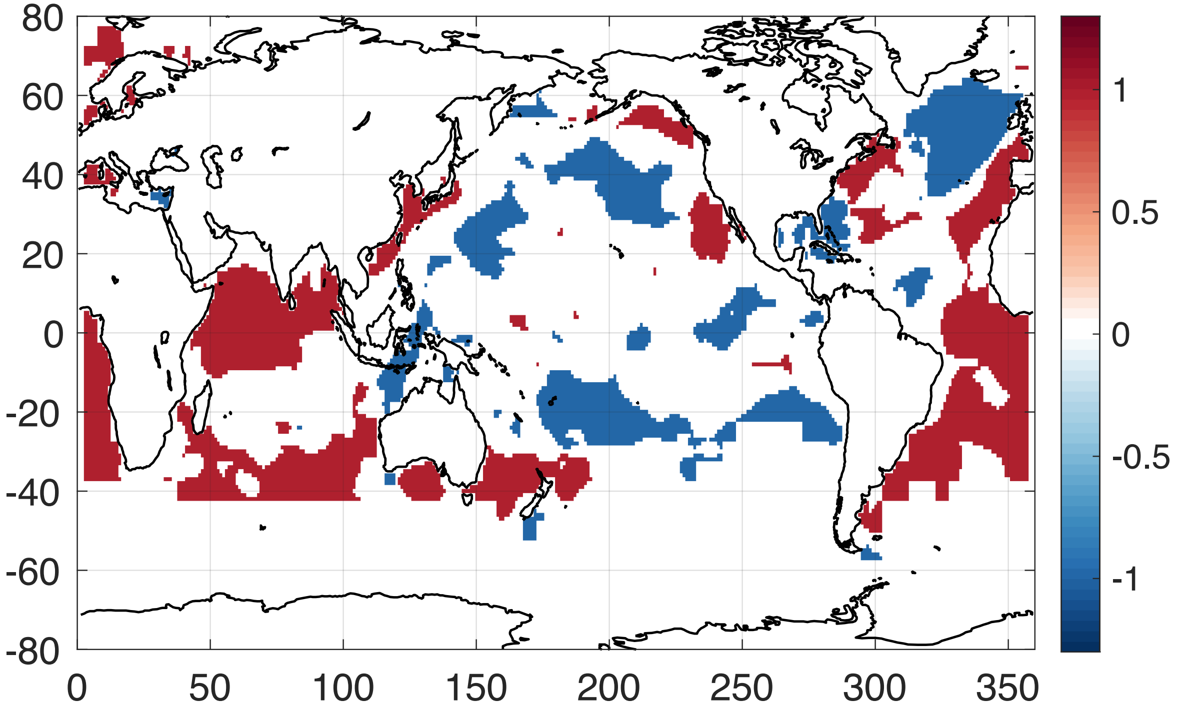
Multi-Record *Agreement* in SST Trends, **1870**–2019

Total trend



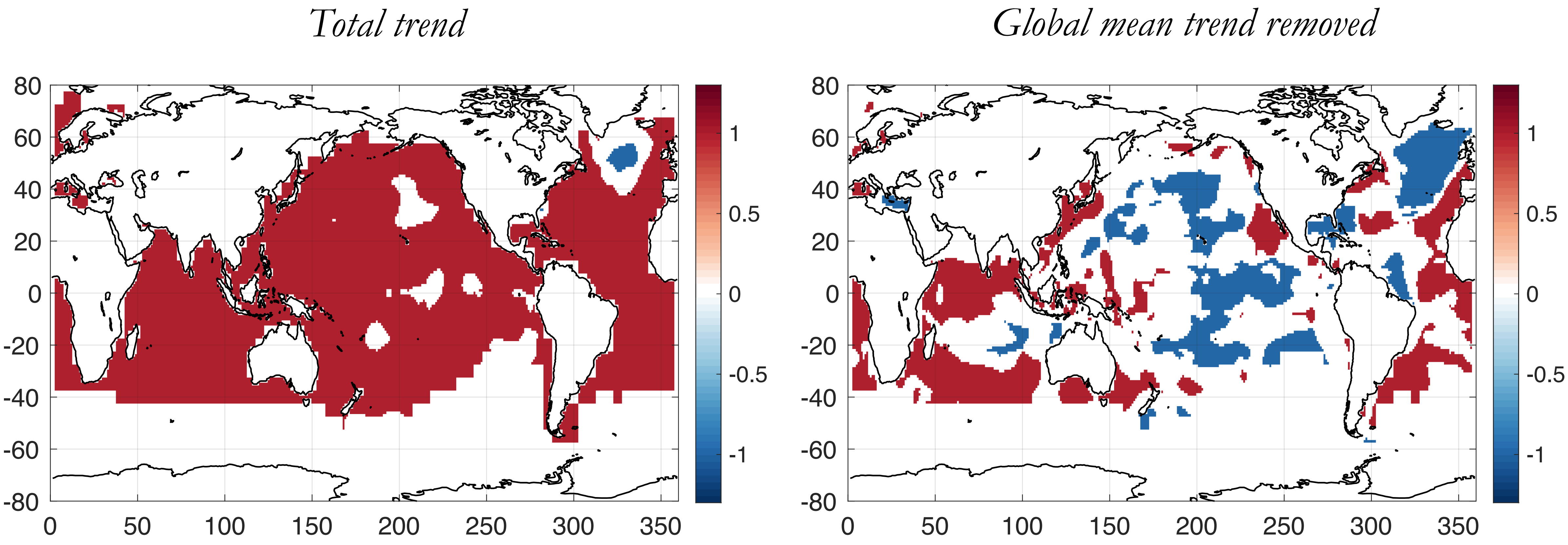
Positive in all four = 1
Negative in all four = –1

Global mean trend removed



Positive in all four = 1
Negative in all four = –1

Multi-Record *Agreement* in SST Trends, **1910**–2019

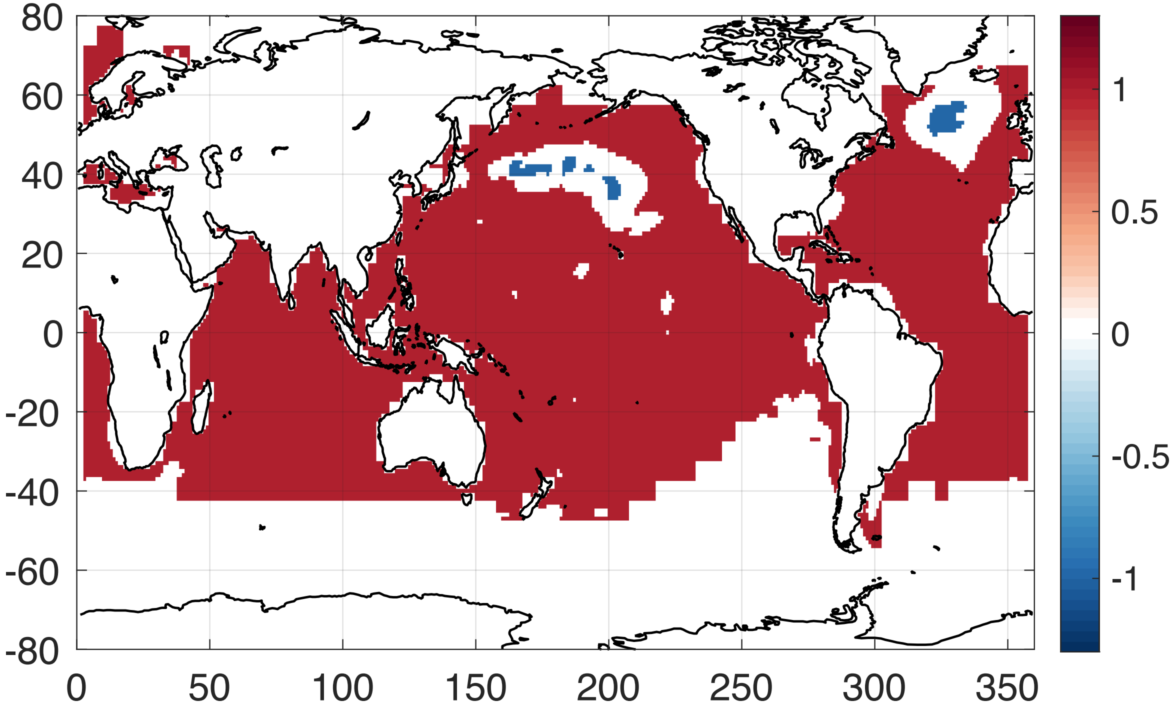


Positive in all four = 1
Negative in all four = –1

Positive in all four = 1
Negative in all four = –1

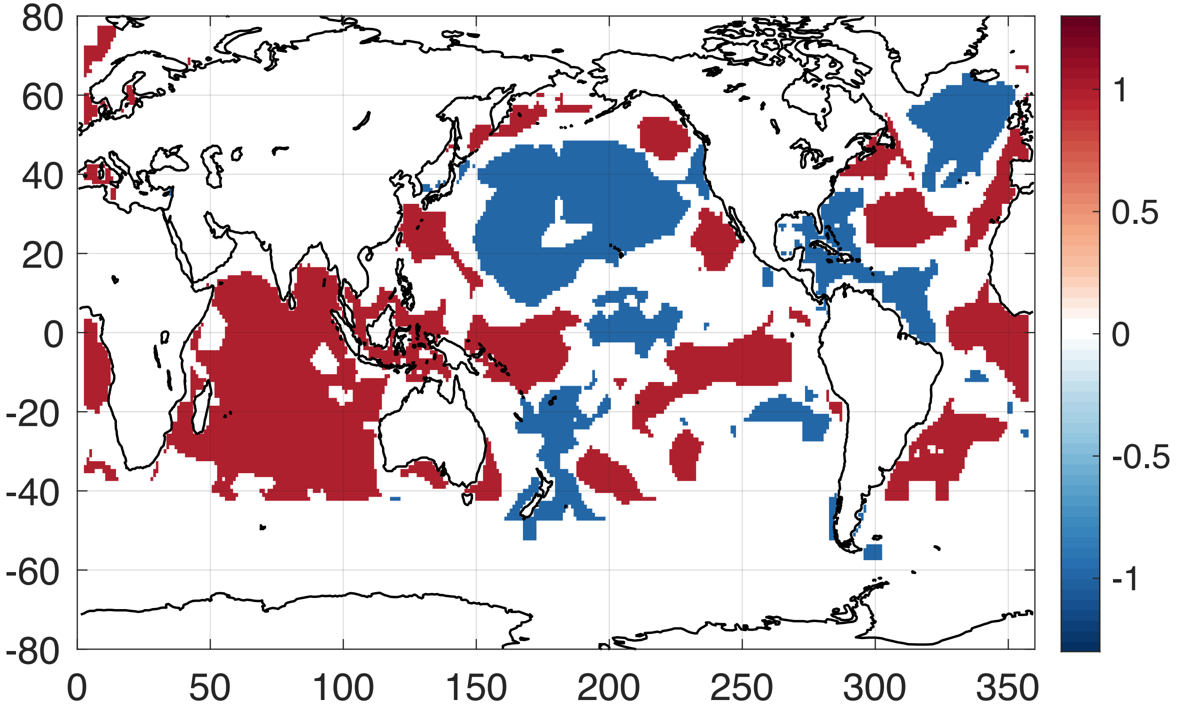
Multi-Record *Agreement* in SST Trends, **1950**–2019

Total trend



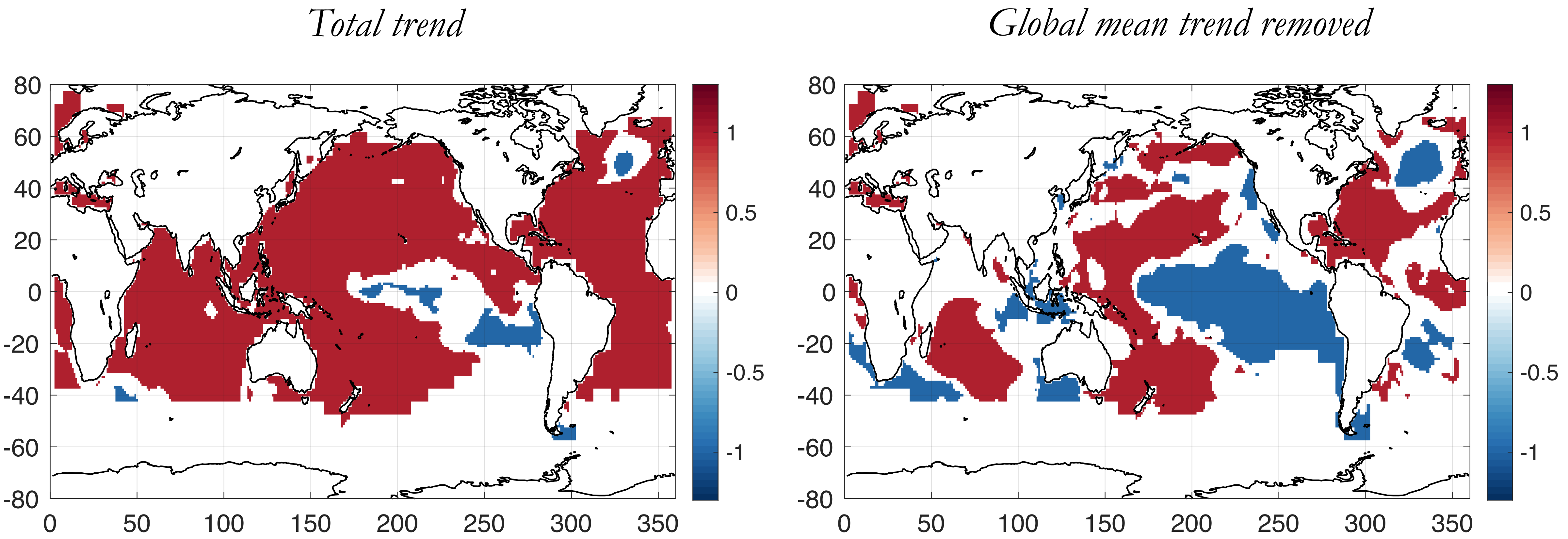
Positive in all four = 1
Negative in all four = –1

Global mean trend removed



Positive in all four = 1
Negative in all four = –1

Multi-Record *Agreement* in SST Trends, **1990**–2019

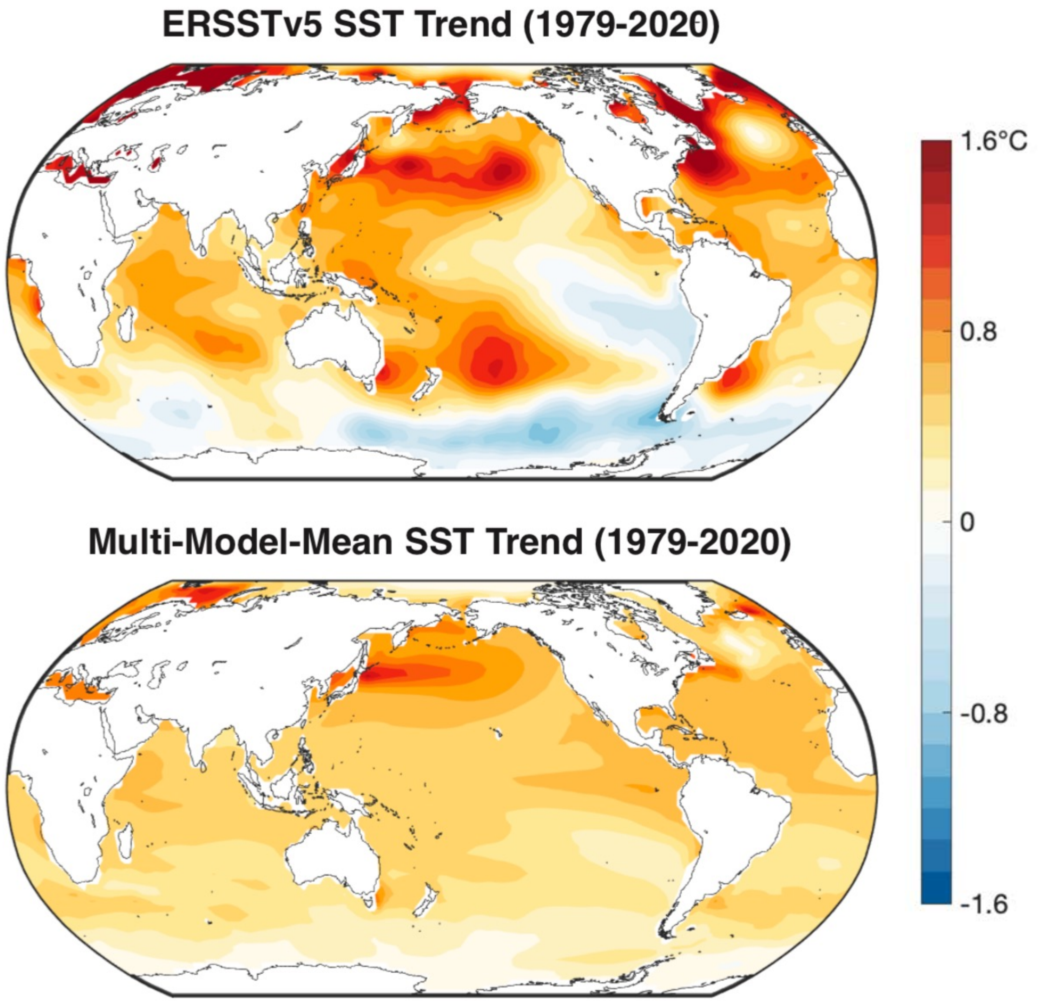


Positive in all four = 1
Negative in all four = –1

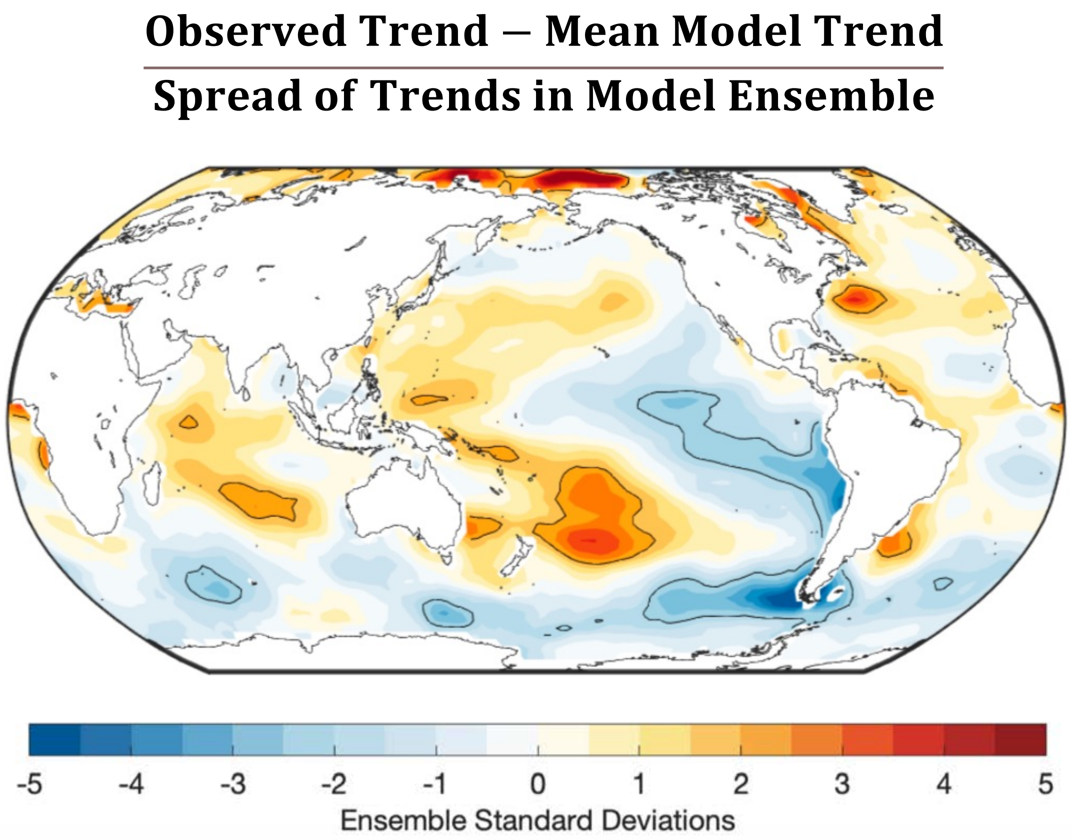
Positive in all four = 1
Negative in all four = –1

Slide contributed by **Robb Wills**

How anomalous are the observed multi-decadal SST trends in the context of internal variability?



16 models, ~600 simulations



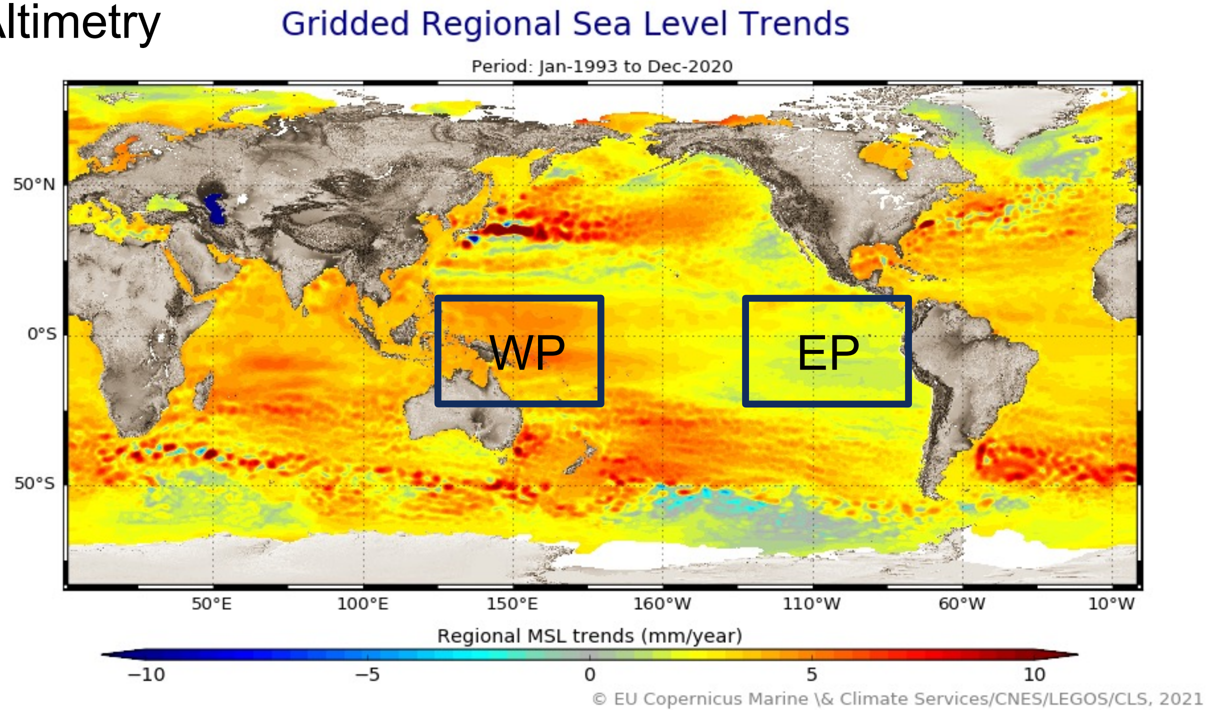
Anomalies greater than ±2 have a less than 5% probability of occurring due to chance

Wills, Dong, Proistosescu et al. (in prep.) – Analysis of Observations and 16 Large Ensembles

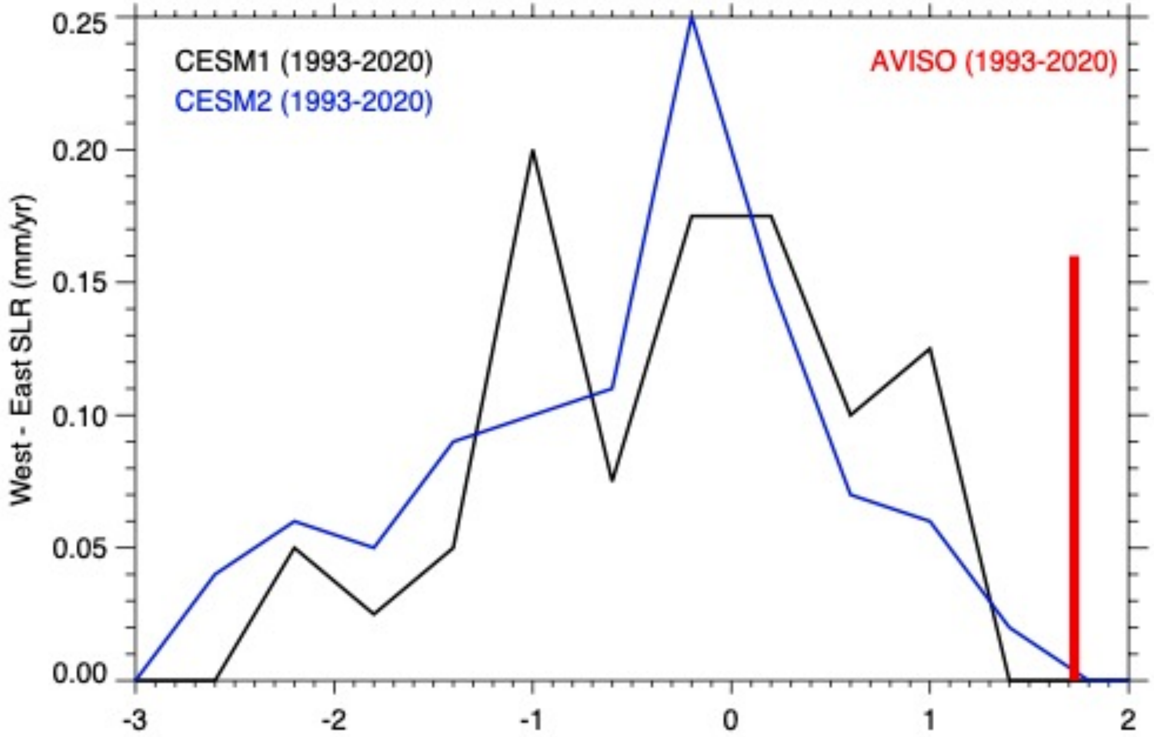
Sea level perspective, courtesy of **John Fasullo**

Altimetry shows greater rates of rise in the western tropical Pacific than in the east whereas CESM1 and CESM2 show greater rates in the east. The difference now exceeds the range that can be explained by internal variability (which is also likely too large).

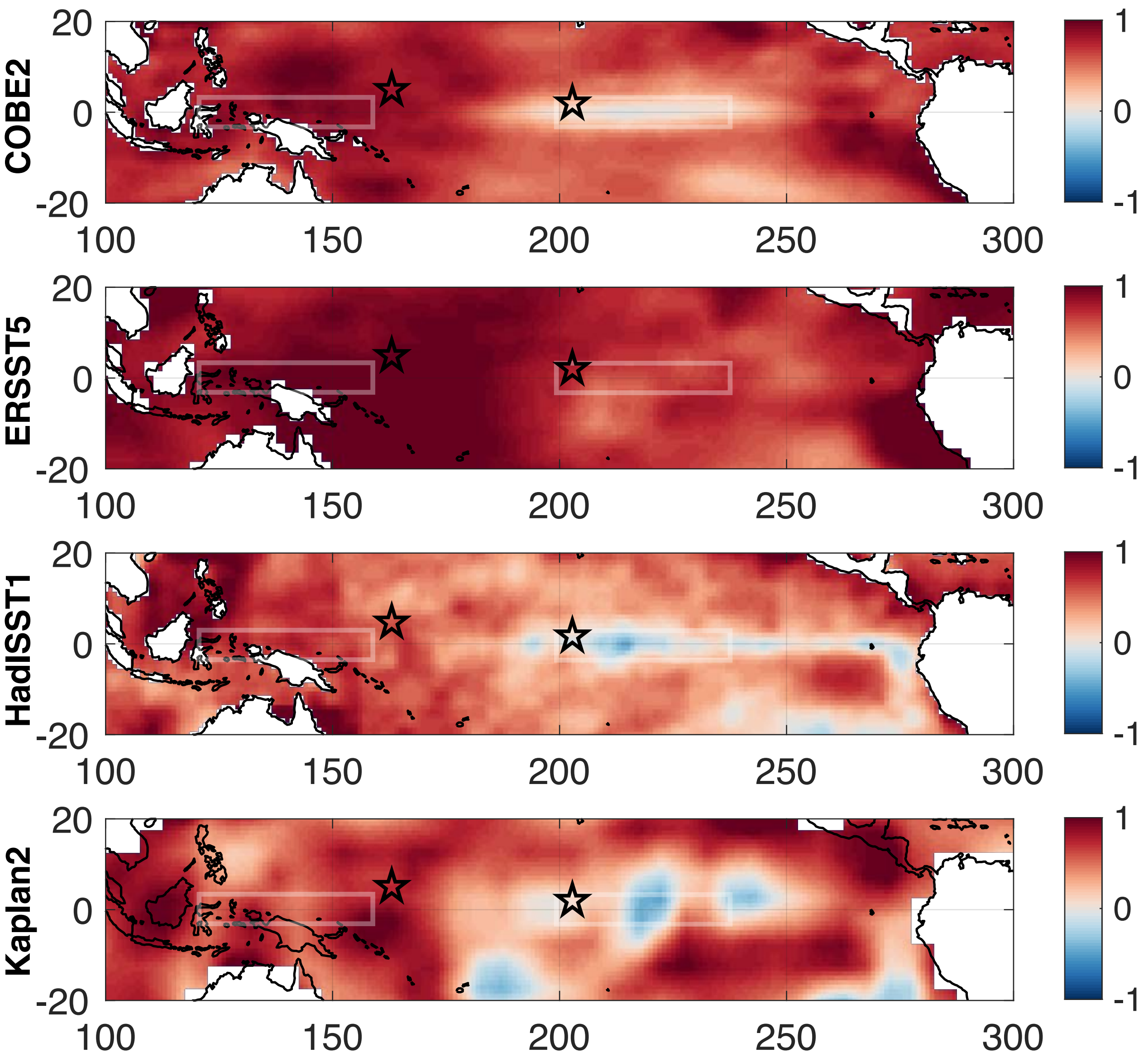
Altimetry

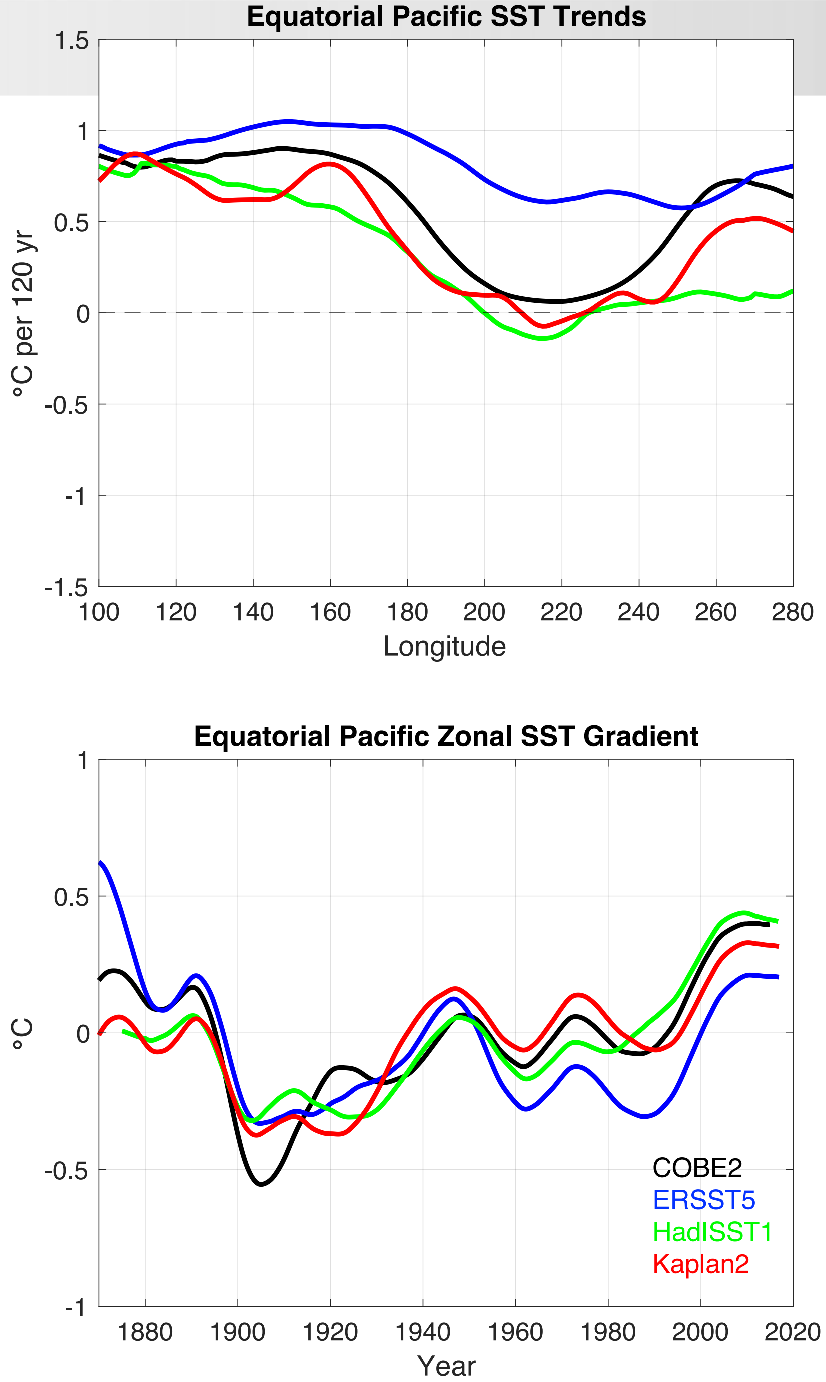


Diff rates of Sea Level Rise



SST Trends (°C/120 yr), **1900**–2019





SST Trends (°C/120 yr), **1900–2010**

nature climate change | ARTICLES
PUBLISHED ONLINE: 8 JULY 2012 | DOI: 10.1038/NCLIMATE1591

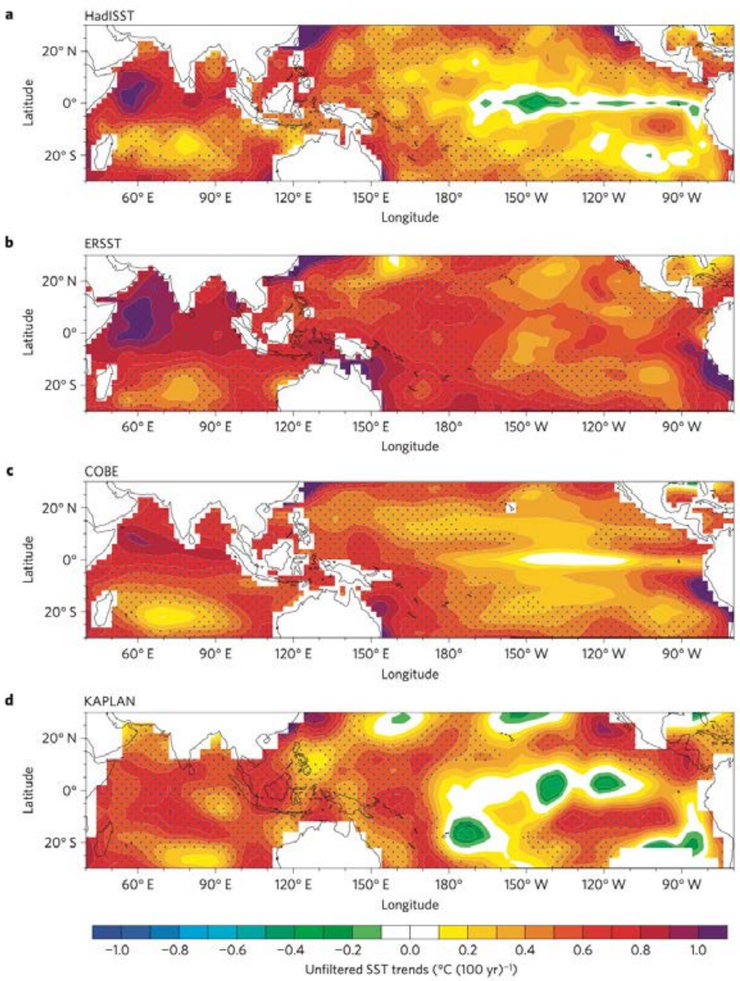
Reconciling disparate twentieth-century Indo-Pacific ocean temperature trends in the instrumental record

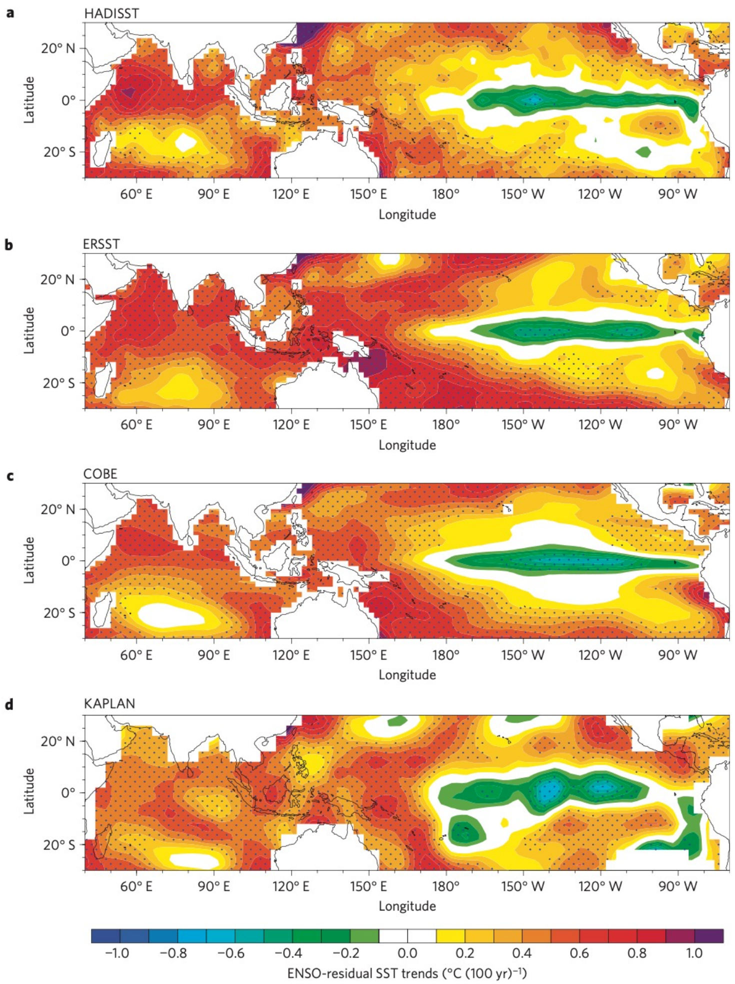
Amy Solomon* and Matthew Newman

"…a more consistent and robust trend among all the reconstructions is found by filtering each data set to remove ENSO …"

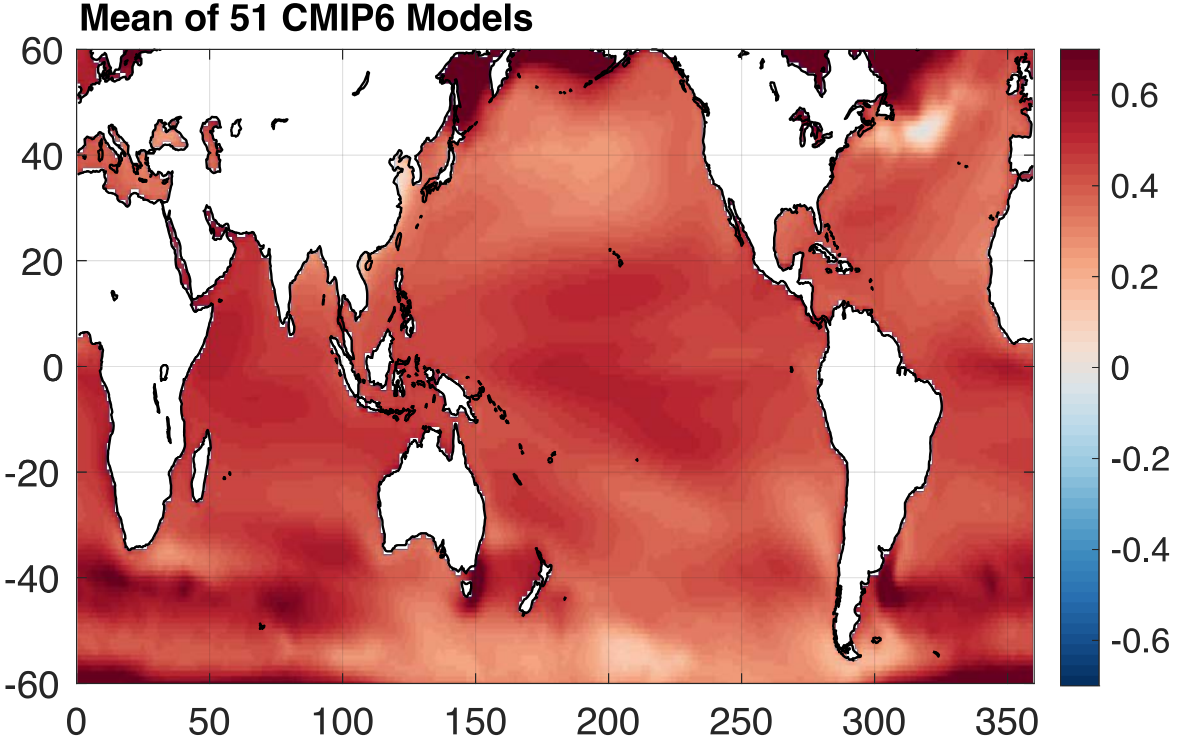
"…discrepancies seem to be largely the result of different estimates of ENSO variability in each reconstruction…"

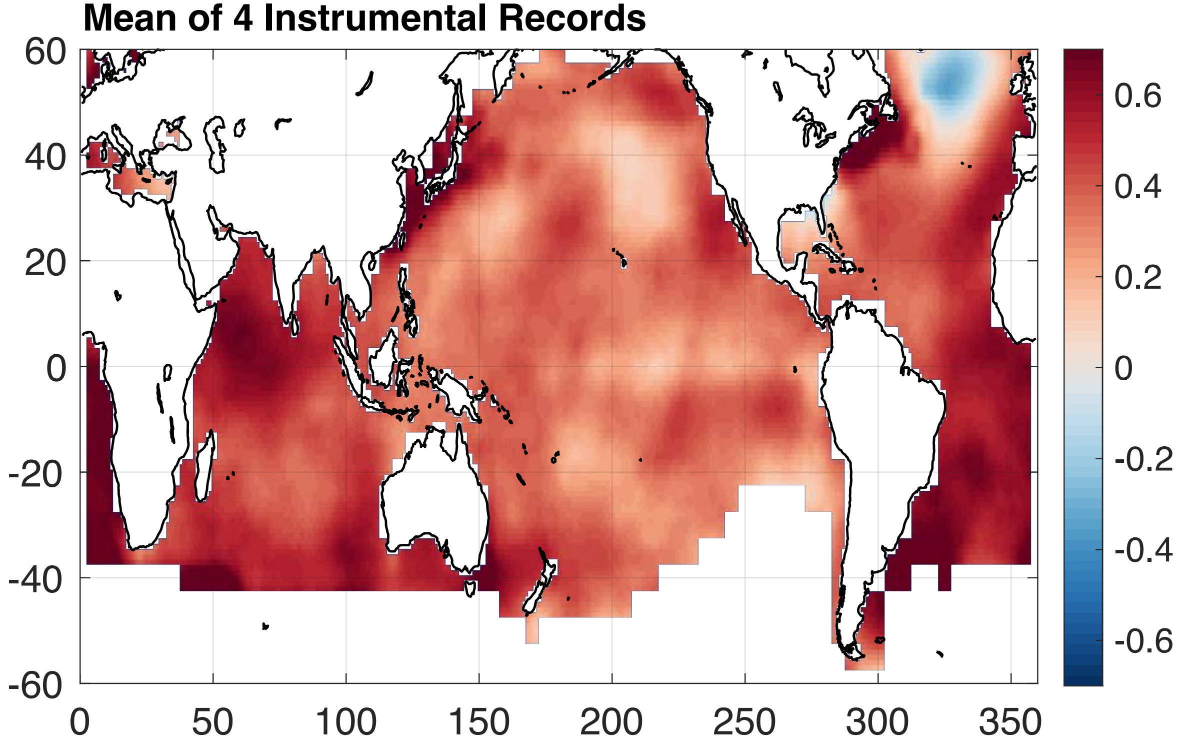
"…trend pattern represents a strengthening of the equatorial Pacific temperature gradient since 1900, owing to a systematic warming trend in the warm pool and weak cooling in the cold tongue"





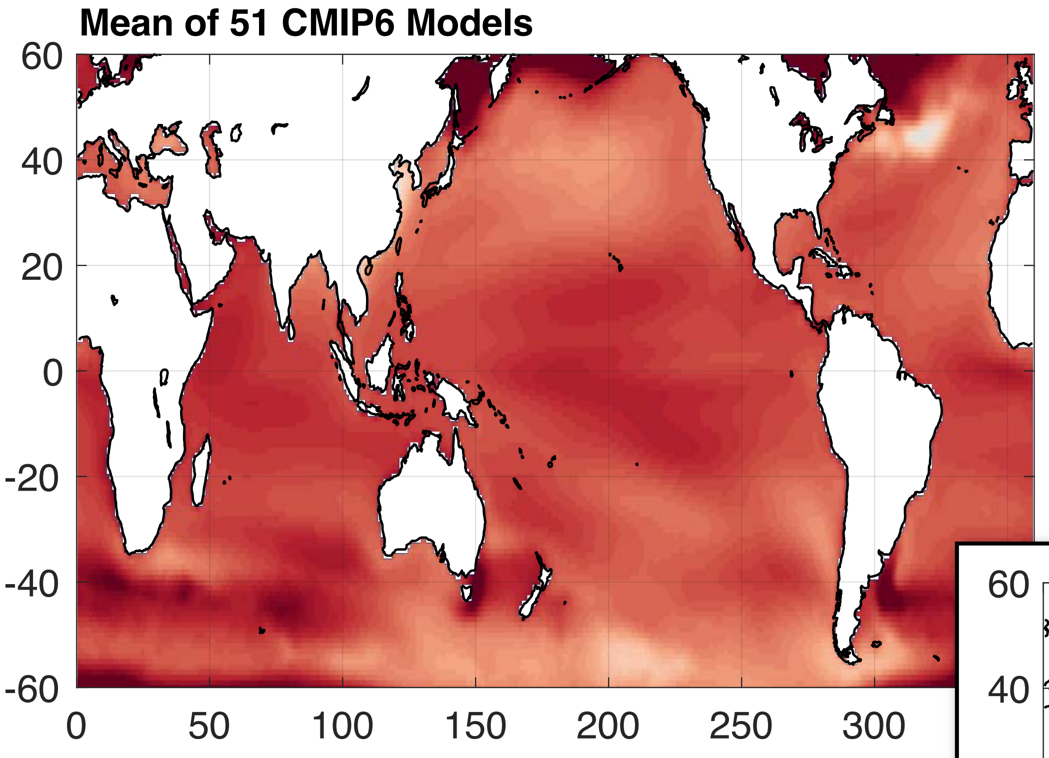
SST Trends (°C/century), **1870–2014**

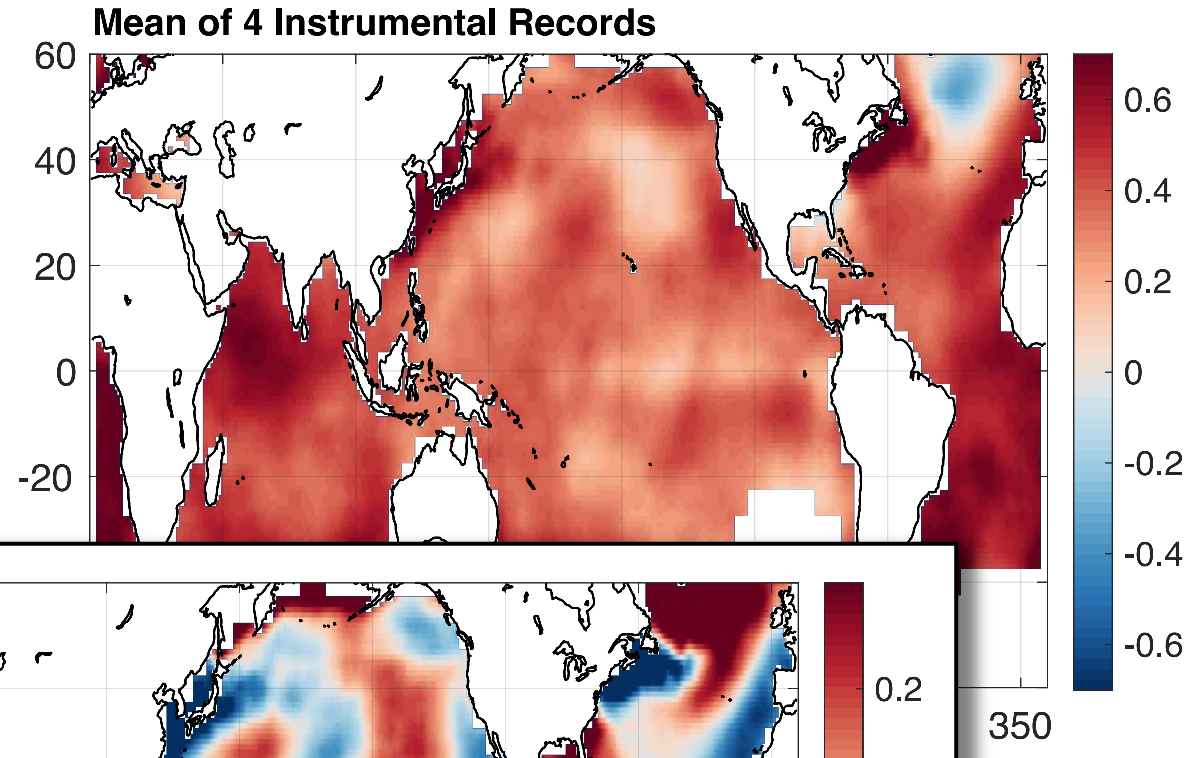


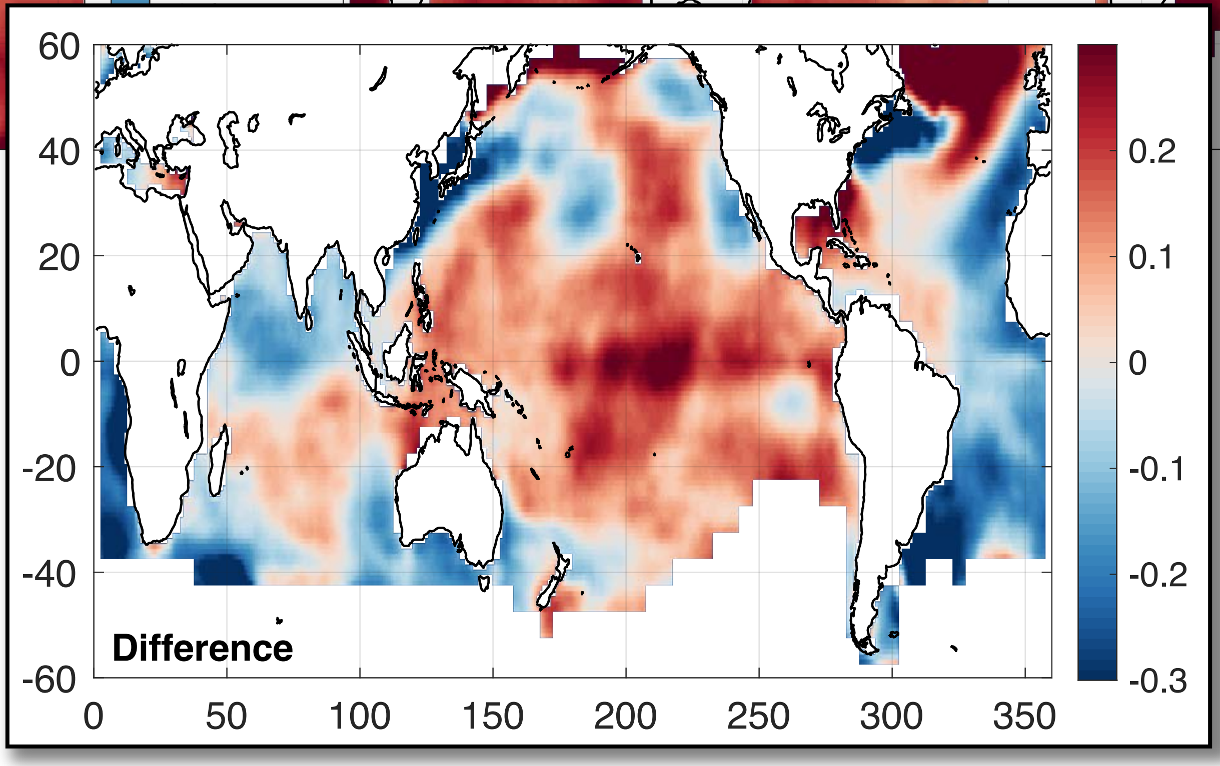


The **global mean** SST trends are *remarkably similar* (0.40 observed vs. 0.43 °C/century modeled), but the regional differences are of the same order of magnitude.

SST Trends (°C/century), **1870–2014**







The **global mean** SST trends are *remarkably similar* (0.40 observed vs. 0.43 °C/century modeled), but the regional differences are of the same order of magnitude.

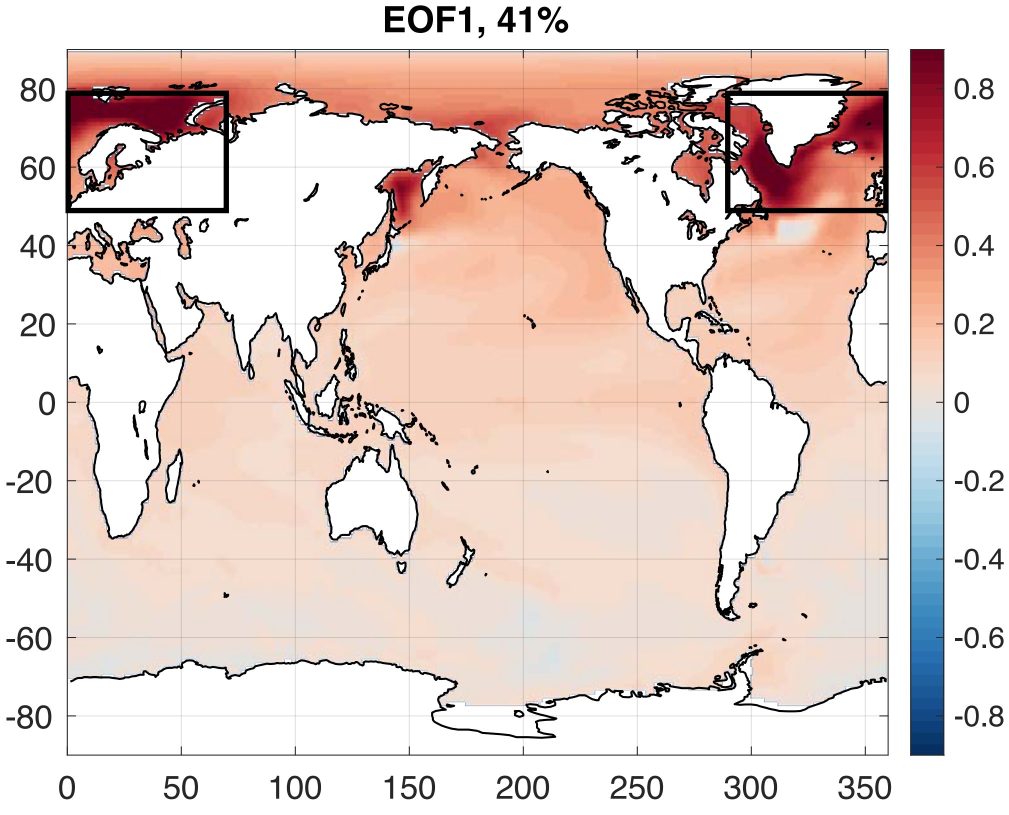
On average, compared to a mean of instrumental records, CMIP6 models exhibit:

- More warming in the tropical Pacific (although it no longer looks like the classic "El Nino-like response" as it did in CMIP3/5…)
- Less warming in the tropical & subtropical Atlantic
- Less warming near the western boundary currents
- *Less cooling* in the high-latitude North Atlantic ("cold blob")

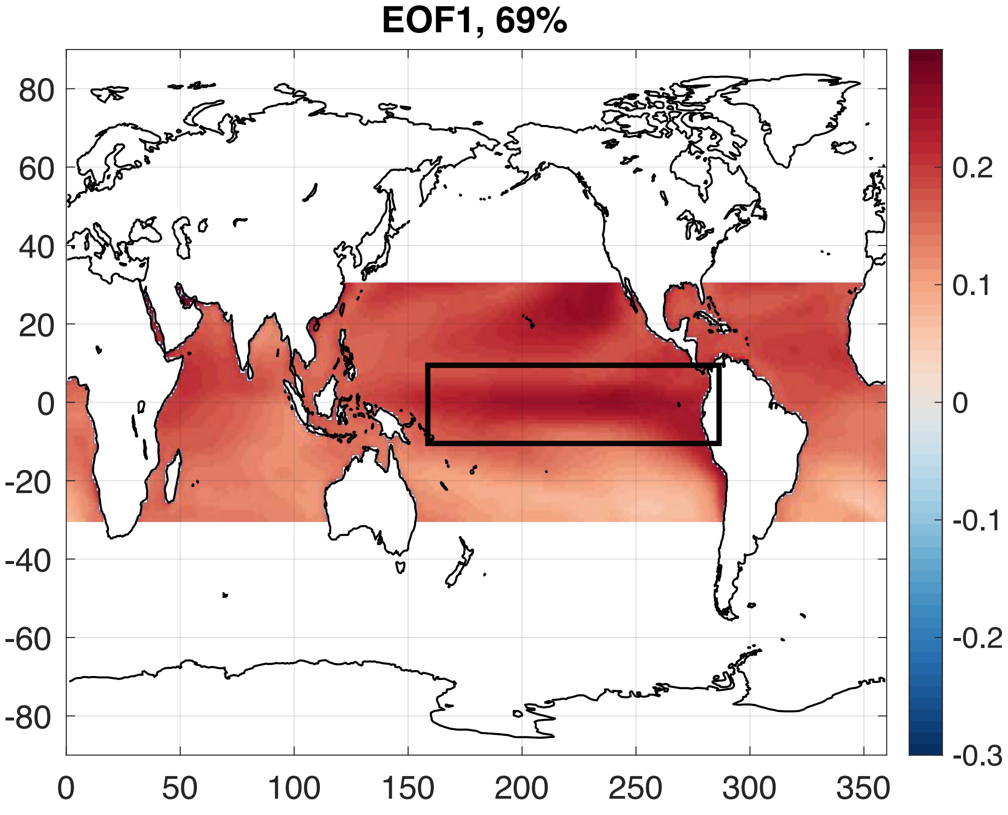
SST Trends (°C/century), **1870–2014**

What are the primary ways the CMIP6 trends **differ** from each other?

As estimated by EOF analysis of the 51 trends (global & tropical domains)

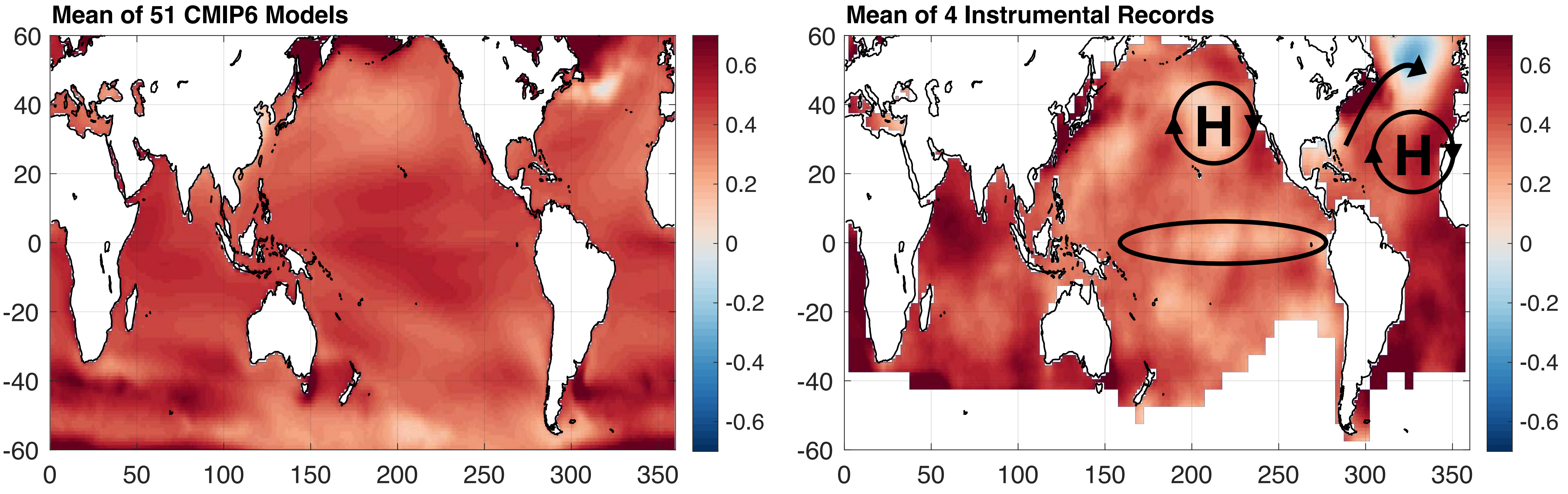


They differ in terms of the amount of warming in the ***high-latitude North Atlantic****.*



They differ in terms of the amount of warming in the ***east–central equatorial Pacific****.*

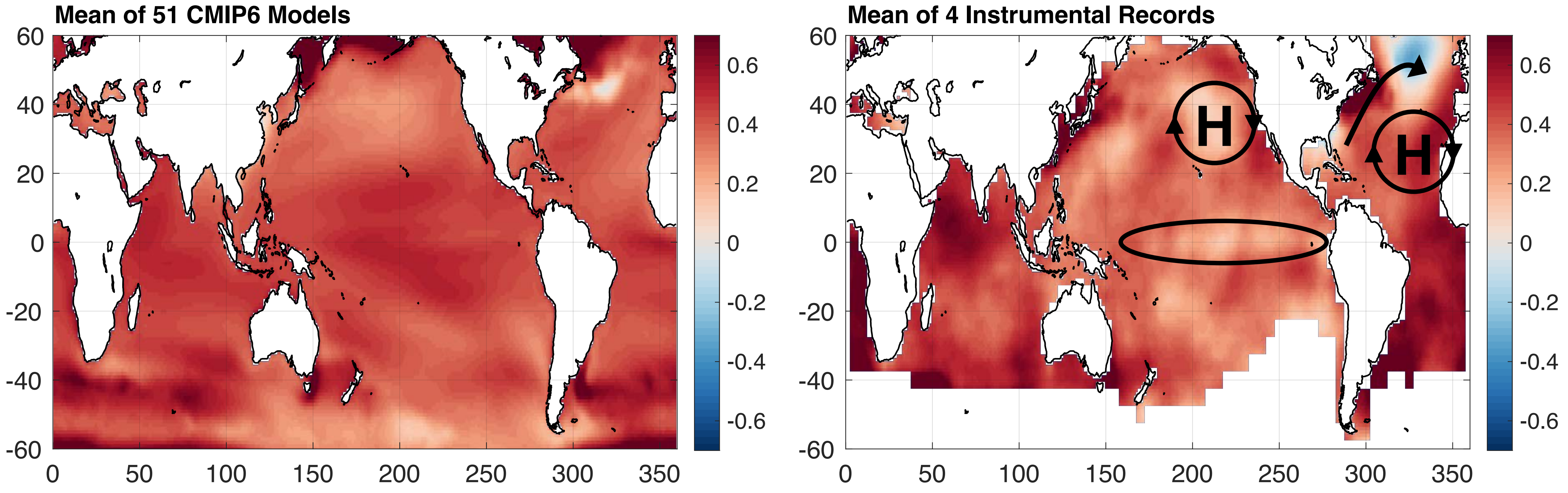
SST Trends (°C/century), **1870–2014**



Just a few potential mechanisms shaping the regional patterns…

- Changes in subtropical highs and associated wind forcing, surface fluxes, *etc.*
- Changes in poleward heat transport by AMOC (buoyancy-driven response)
- Shifts in WBCs associated with Hadley circulation & midlatitude jets
- Buffering of warming by equatorial ocean circulation and coupling

SST Trends (°C/century), **1870–2014**



Just a few potential mechanisms shaping the regional patterns…

- Changes in subtropical highs and associated wind forcing, surface fluxes, *etc.*
- Changes in poleward heat transport by AMOC (buoyancy-driven response)
- Shifts in WBCs associated with Hadley circulation & midlatitude jets
- Buffering of warming by equatorial ocean circulation and coupling

Some mechanistic issues in the **equatorial Pacific**

Are you old enough to remember this look of Eos?

DiNezio, Clement, Vecchi

Eos, Vol. 91, No. 16, 20 April 2010

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 91 NUMBER 16

20 APRIL 2010

PAGES 141–152

Reconciling Differing Views of Tropical Pacific Climate Change

PAGES 141–142

Recent analyses of global warming projections simulated with global climate models (GCMs) suggest that the tropical Pacific does not become El Niño– or La Niña–like in response to increased greenhouse gases (GHGs). Rather, the physical mechanisms that drive tropical Pacific climate change depart substantially from the El Niño–Southern Oscillation (ENSO) analogy often invoked for interpreting future climate changes [e.g., *Knutson and Manabe*, 1995; *Meehl and Washington*, 1996; *Cane et al.*, 1997; *Collins et al.*, 2005; *Meehl et al.*, 2007; *Lu et al.*, 2008; *Cox et al.*, 2004] and past climate changes [e.g. *Lea et al.*, 2001; *Koutavas et al.*, 2002]. This presents an opportunity for reconciling theory, models, and observations.

An ENSO analogy typically is invoked for interpreting tropical Pacific climate change because if an external forcing introduces some east-west asymmetry, this asymmetry can be amplified in the same way as interannual perturbations are, through the posi-

The projected changes in thermocline depth are consistent with the equilibrium response to weaker trade winds, consisting of a zonal mean shoaling of the thermocline in response to the curl of the wind, in addition to the relaxation of the thermocline tilt [*Cane and Sarachik*, 1981; *Clarke*, 2010]. In the eastern equatorial Pacific, the zonal mean shoaling of the thermocline opposes the deepening due to a relaxed tilt, thereby limiting the coupling between changes in winds and sea surface temperature (SST). In addition to this response, increased thermal stratification enhances ocean dynamical cooling [*DiNezio et al.*, 2009] in the eastern basin, putting a brake on SST growth. The increased stratification can be attributed to weaker warming in the subtropical oceans [i.e., *Seager and Murtugudde*, 1997]; however, these mechanisms have not been extensively explored in controlled numerical experiments with IPCC-class coupled GCMs. Because of the weaker Bjerknes feedback, atmo-

Though some questions about the true sensitivity of the hydrological cycle to greenhouse forcing remain [*Wentz et al.*, 2007], it is clear that there are other constraints on the strength of the Walker circulation beyond the zonal SST gradient; hence, a weakened SLP gradient does not necessarily rule out a strengthened SST gradient.

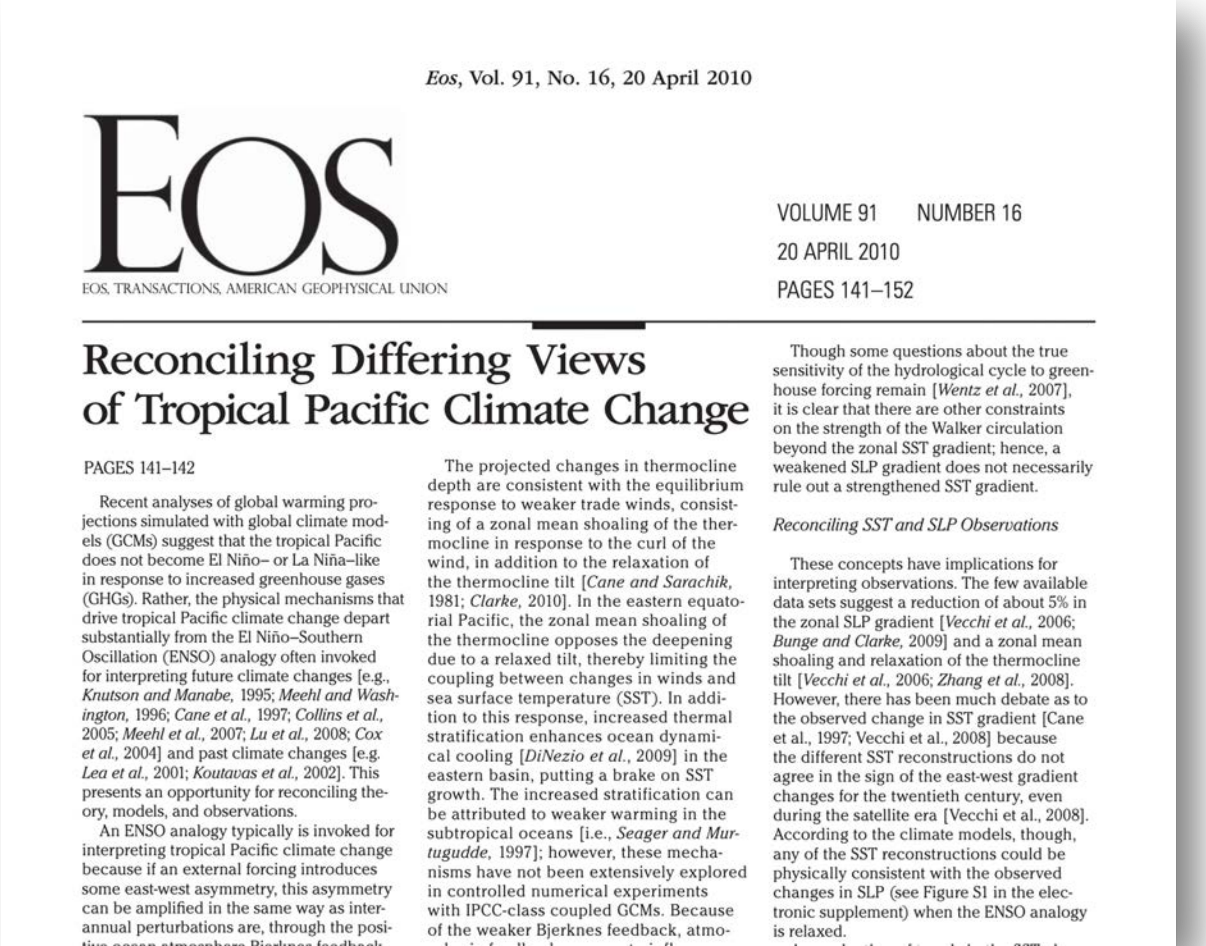
Reconciling SST and SLP Observations

These concepts have implications for interpreting observations. The few available data sets suggest a reduction of about 5% in the zonal SLP gradient [*Vecchi et al.*, 2006; *Bunge and Clarke*, 2009] and a zonal mean shoaling and relaxation of the thermocline tilt [*Vecchi et al.*, 2006; *Zhang et al.*, 2008]. However, there has been much debate as to the observed change in SST gradient [Cane et al., 1997; Vecchi et al., 2008] because the different SST reconstructions do not agree in the sign of the east-west gradient changes for the twentieth century, even during the satellite era [Vecchi et al., 2008]. According to the climate models, though, any of the SST reconstructions could be physically consistent with the observed changes in SLP (see Figure S1 in the electronic supplement) when the ENSO analogy is relaxed.

Some mechanistic issues in the **equatorial Pacific**

Are you old enough to remember this look of Eos?

DiNezio, Clement, Vecchi



Eos, Vol. 91, No. 16, 20 April 2010

EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION
VOLUME 91 NUMBER 16
20 APRIL 2010
PAGES 141–152

Reconciling Differing Views of Tropical Pacific Climate Change

PAGES 141–142

Recent analyses of global warming projections simulated with global climate models (GCMs) suggest that the tropical Pacific does not become El Niño– or La Niña–like in response to increased greenhouse gases (GHGs). Rather, the physical mechanisms that drive tropical Pacific climate change depart substantially from the El Niño–Southern Oscillation (ENSO) analogy often invoked for interpreting future climate changes [e.g., *Knutson and Manabe*, 1995; *Meehl and Washington*, 1996; *Cane et al.*, 1997; *Collins et al.*, 2005; *Meehl et al.*, 2007; *Lu et al.*, 2008; *Cox et al.*, 2004] and past climate changes [e.g. *Lea et al.*, 2001; *Koutavas et al.*, 2002]. This presents an opportunity for reconciling theory, models, and observations.

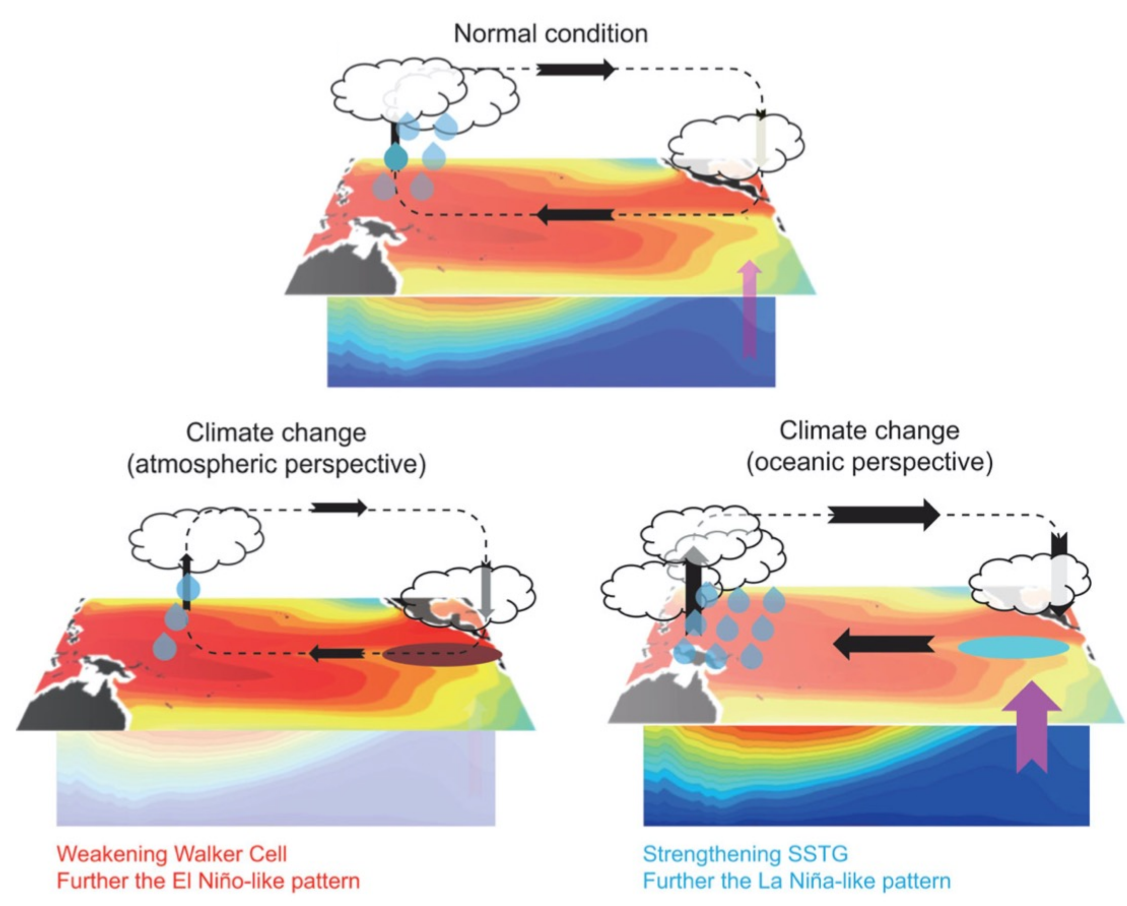
An ENSO analogy typically is invoked for interpreting tropical Pacific climate change because if an external forcing introduces some east-west asymmetry, this asymmetry can be amplified in the same way as interannual perturbations are, through the posi-

The projected changes in thermocline depth are consistent with the equilibrium response to weaker trade winds, consisting of a zonal mean shoaling of the thermocline in response to the curl of the wind, in addition to the relaxation of the thermocline tilt [*Cane and Sarachik*, 1981; *Clarke*, 2010]. In the eastern equatorial Pacific, the zonal mean shoaling of the thermocline opposes the deepening due to a relaxed tilt, thereby limiting the coupling between changes in winds and sea surface temperature (SST). In addition to this response, increased thermal stratification enhances ocean dynamical cooling [*DiNezio et al.*, 2009] in the eastern basin, putting a brake on SST growth. The increased stratification can be attributed to weaker warming in the subtropical oceans [i.e., *Seager and Murtugudde*, 1997]; however, these mechanisms have not been extensively explored in controlled numerical experiments with IPCC-class coupled GCMs. Because of the weaker Bjerknes feedback, atmo-

Though some questions about the true sensitivity of the hydrological cycle to greenhouse forcing remain [*Wentz et al.*, 2007], it is clear that there are other constraints on the strength of the Walker circulation beyond the zonal SST gradient; hence, a weakened SLP gradient does not necessarily rule out a strengthened SST gradient.

Reconciling SST and SLP Observations

These concepts have implications for interpreting observations. The few available data sets suggest a reduction of about 5% in the zonal SLP gradient [*Vecchi et al.*, 2006; *Bunge and Clarke*, 2009] and a zonal mean shoaling and relaxation of the thermocline tilt [*Vecchi et al.*, 2006; *Zhang et al.*, 2008]. However, there has been much debate as to the observed change in SST gradient [Cane et al., 1997; Vecchi et al., 2008] because the different SST reconstructions do not agree in the sign of the east-west gradient changes for the twentieth century, even during the satellite era [Vecchi et al., 2008]. According to the climate models, though, any of the SST reconstructions could be physically consistent with the observed changes in SLP (see Figure S1 in the electronic supplement) when the ENSO analogy is relaxed.



Schematic* from Lian *et al.* (2018)

* I added the EUC.

Some mechanistic issues in the **equatorial Pacific**

Are you old enough to remember this

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL U

Reconciling Diff
of Tropical Pacifi

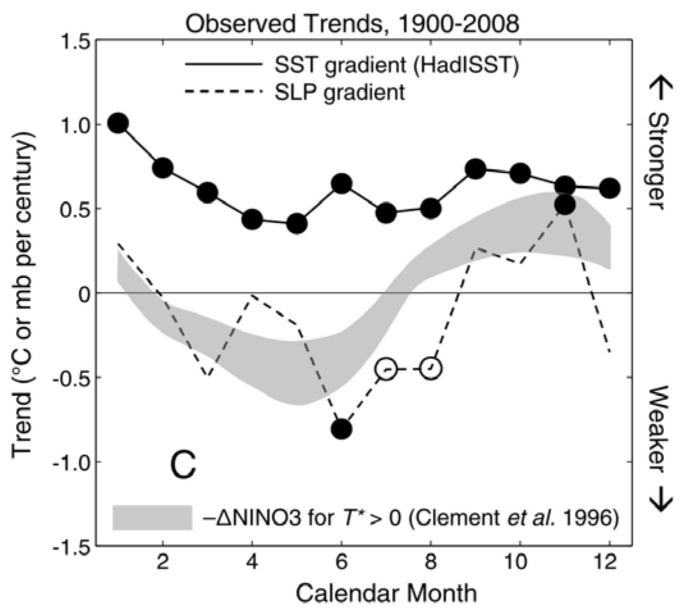
PAGES 141–142

Recent analyses of global warming projections simulated with global climate models (GCMs) suggest that the tropical Pacific does not become El Niño– or La Niña–like in response to increased greenhouse gases (GHGs). Rather, the physical mechanisms that drive tropical Pacific climate change depart substantially from the El Niño–Southern Oscillation (ENSO) analogy often invoked for interpreting future climate changes [e.g., *Knutson and Manabe*, 1995; *Meehl and Washington*, 1996; *Cane et al.*, 1997; *Collins et al.*, 2005; *Meehl et al.*, 2007; *Lu et al.*, 2008; *Cox et al.*, 2004] and past climate changes [e.g. *Lea et al.*, 2001; *Koutavas et al.*, 2002]. This presents an opportunity for reconciling theory, models, and observations.

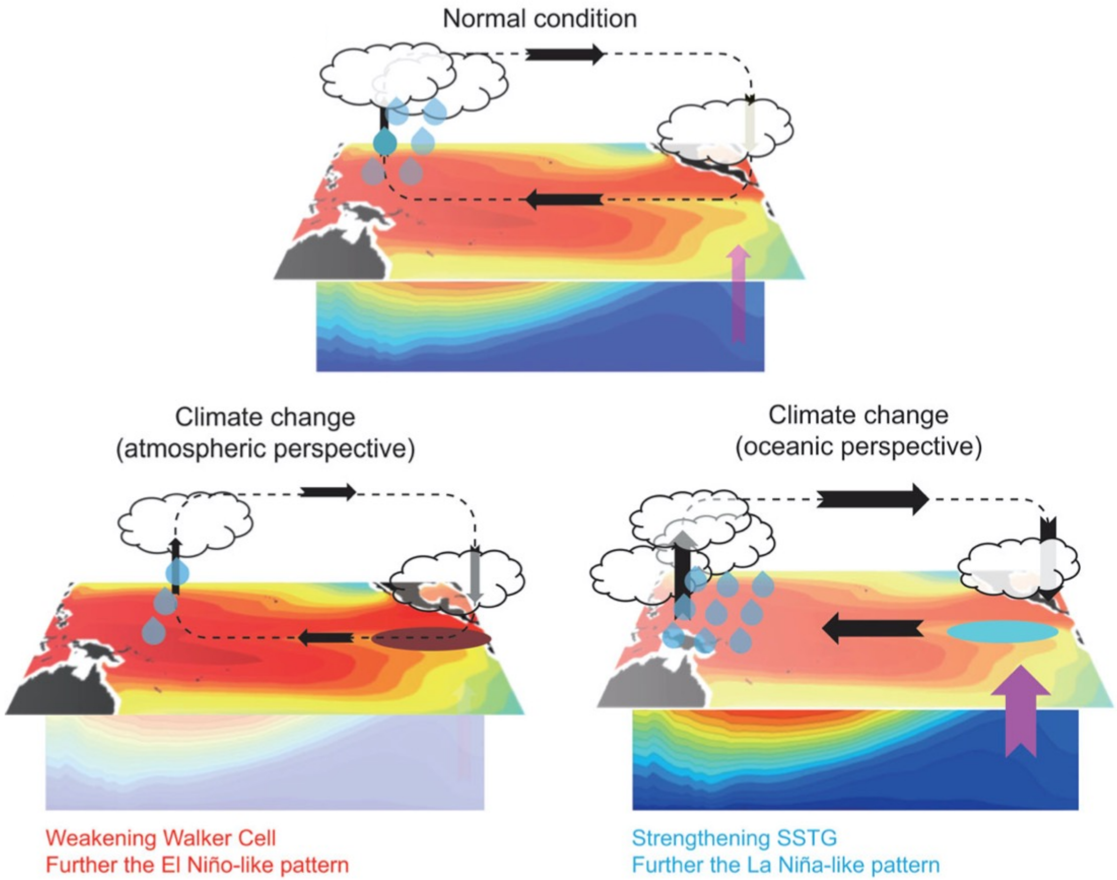
An ENSO analogy typically is invoked for interpreting tropical Pacific climate change because if an external forcing introduces some east-west asymmetry, this asymmetry can be amplified in the same way as interannual perturbations are, through the posi-

mocline in response to the curl of the wind, in addition to the relaxation of the thermocline tilt [*Cane and Sarachik*, 1981; *Clarke*, 2010]. In the eastern equatorial Pacific, the zonal mean shoaling of the thermocline opposes the deepening due to a relaxed tilt, thereby limiting the coupling between changes in winds and sea surface temperature (SST). In addition to this response, increased thermal stratification enhances ocean dynamical cooling [*DiNezio et al.*, 2009] in the eastern basin, putting a brake on SST growth. The increased stratification can be attributed to weaker warming in the subtropical oceans [i.e., *Seager and Murtugudde*, 1997]; however, these mechanisms have not been extensively explored in controlled numerical experiments with IPCC-class coupled GCMs. Because of the weaker Bjerknes feedback, atmo-

These concepts have implications for interpreting observations. The few available data sets suggest a reduction of about 5% in the zonal SLP gradient [*Vecchi et al.*, 2006; *Bunge and Clarke*, 2009] and a zonal mean shoaling and relaxation of the thermocline tilt [*Vecchi et al.*, 2006; *Zhang et al.*, 2008]. However, there has been much debate as to the observed change in SST gradient [Cane et al., 1997; Vecchi et al., 2008] because the different SST reconstructions do not agree in the sign of the east-west gradient changes for the twentieth century, even during the satellite era [Vecchi et al., 2008]. According to the climate models, though, any of the SST reconstructions could be physically consistent with the observed changes in SLP (see Figure S1 in the electronic supplement) when the ENSO analogy is relaxed.



From Coats and Karnauskas (2018), after Karnauskas et al. (2009)



Schematic* from Lian *et al.* (2018)

* I added the EUC.

Some mechanistic issues in the **equatorial Pacific**

Are you old enough to remember this

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL U

Reconciling Diff
of Tropical Pacifi

PAGES 141–142

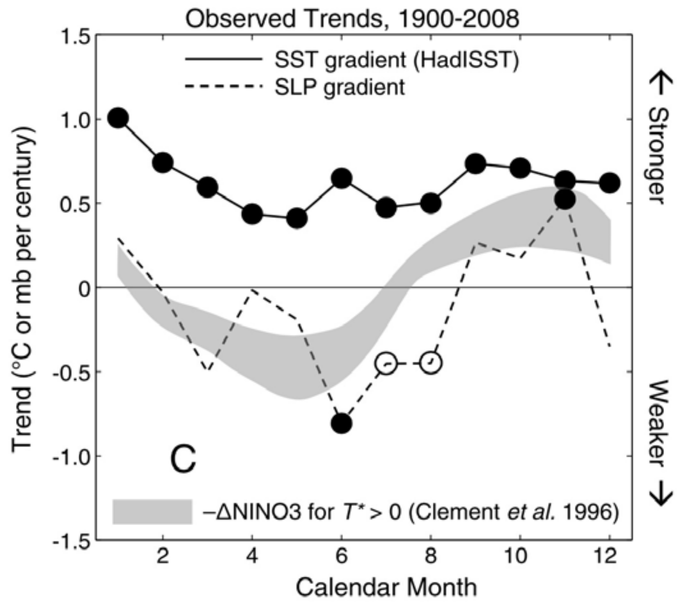
Recent analyses of global warming projections simulated with global climate models (GCMs) suggest that the tropical Pacific does not become El Niño– or La Niña–like in response to increased greenhouse gases (GHGs). Rather, the physical mechanisms that drive tropical Pacific climate change depart substantially from the El Niño–Southern Oscillation (ENSO) analogy often invoked for interpreting future climate changes [e.g., *Knutson and Manabe*, 1995; *Meehl and Washington*, 1996; *Cane et al.*, 1997; *Collins et al.*, 2005; *Meehl et al.*, 2007; *Lu et al.*, 2008; *Cox et al.*, 2004] and past climate changes [e.g. *Lea et al.*, 2001; *Koutavas et al.*, 2002]. This presents an opportunity for reconciling theory, models, and observations.

An ENSO analogy typically is invoked for interpreting tropical Pacific climate change because if an external forcing introduces some east-west asymmetry, this asymmetry can be amplified in the same way as interannual perturbations are, through the posi-

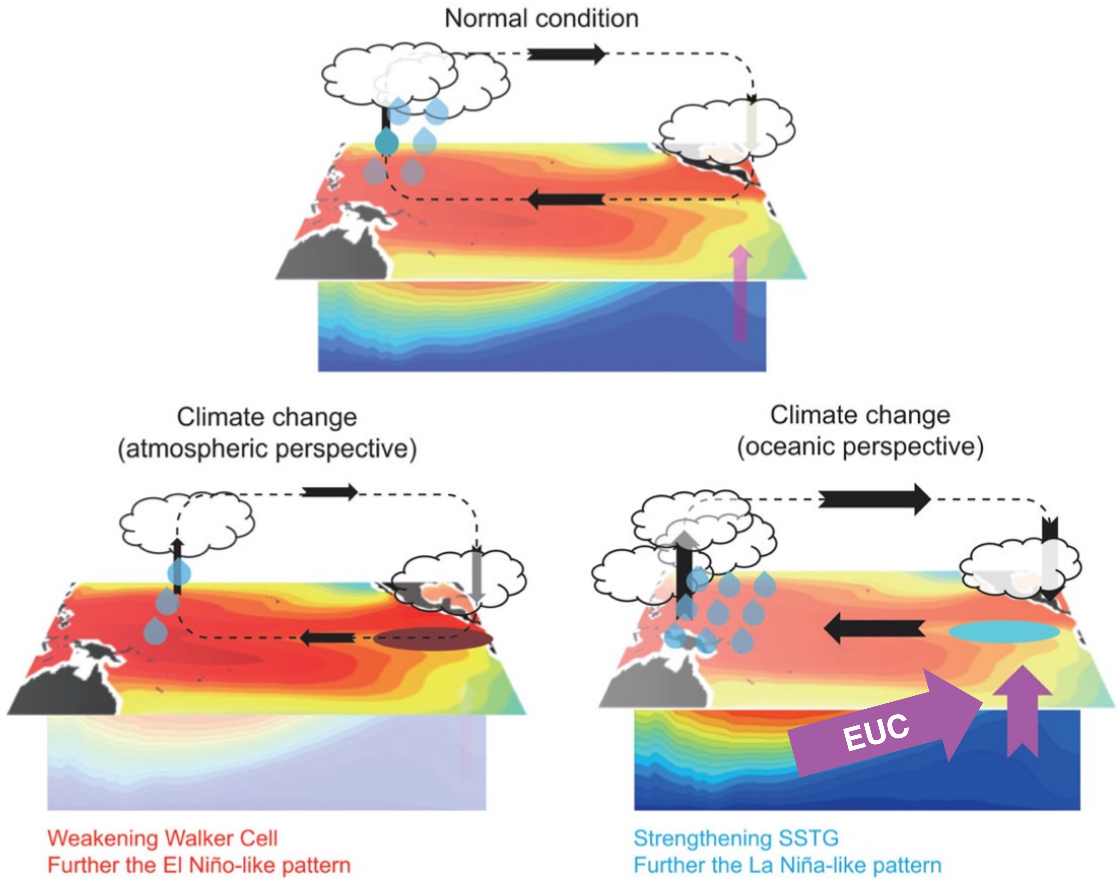
mocline in response to the curl of the wind, in addition to the relaxation of the thermocline tilt [*Cane and Sarachik*, 1981; *Clarke*, 2010]. In the eastern equatorial Pacific, the zonal mean shoaling of the thermocline opposes the deepening due to a relaxed tilt, thereby limiting the coupling between changes in winds and sea surface temperature (SST). In addition to this response, increased thermal stratification enhances ocean dynamical cooling [*DiNezio et al.*, 2009] in the eastern basin, putting a brake on SST growth. The increased stratification can be attributed to weaker warming in the subtropical oceans [i.e., *Seager and Murtugudde*, 1997]; however, these mechanisms have not been extensively explored in controlled numerical experiments with IPCC-class coupled GCMs. Because of the weaker Bjerknes feedback, atmo-

Reconciling SST and SLP Observations

These concepts have implications for interpreting observations. The few available data sets suggest a reduction of about 5% in the zonal SLP gradient [*Vecchi et al.*, 2006; *Bunge and Clarke*, 2009] and a zonal mean shoaling and relaxation of the thermocline tilt [*Vecchi et al.*, 2006; *Zhang et al.*, 2008]. However, there has been much debate as to the observed change in SST gradient [Cane et al., 1997; Vecchi et al., 2008] because the different SST reconstructions do not agree in the sign of the east-west gradient changes for the twentieth century, even during the satellite era [Vecchi et al., 2008]. According to the climate models, though, any of the SST reconstructions could be physically consistent with the observed changes in SLP (see Figure S1 in the electronic supplement) when the ENSO analogy is relaxed.



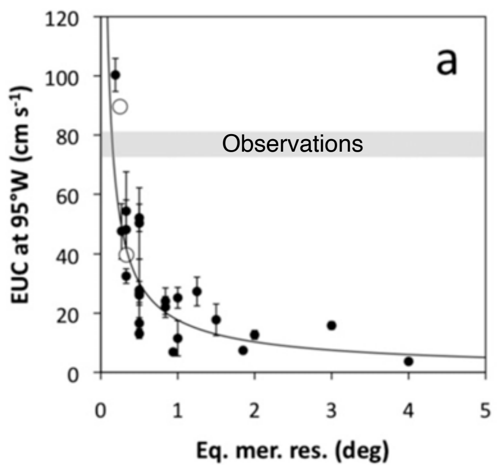
From Coats and Karnauskas (2018), after Karnauskas et al. (2009)



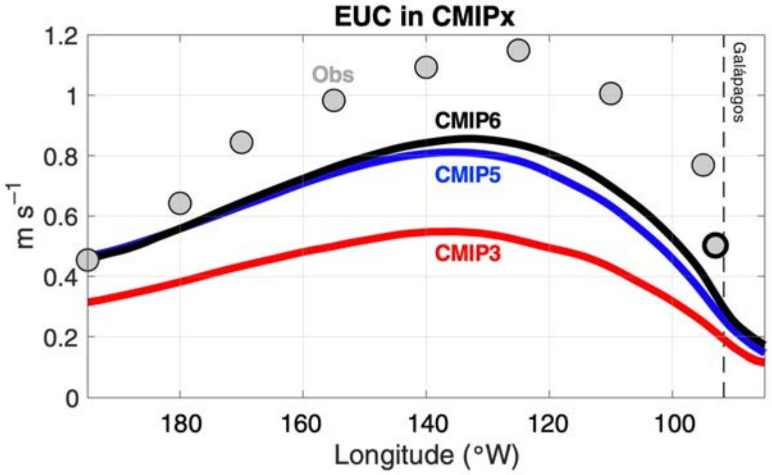
Schematic* from Lian *et al.* (2018)

* I added the EUC.

Some mechanistic issues in the **equatorial Pacific**

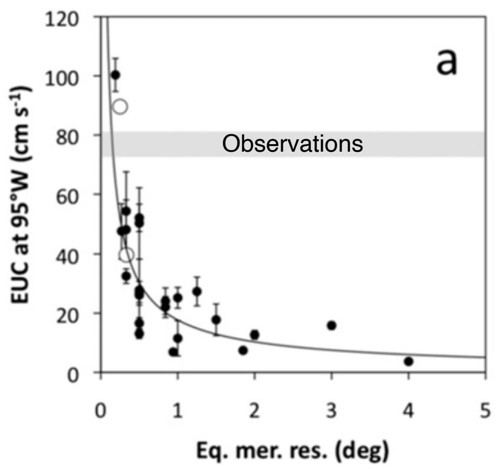


The speed of the Equatorial Undercurrent (EUC) in CMIPx models have a strong ***dependence on ocean model resolution.*** *This is an example from Karnauskas et al. (2012).*

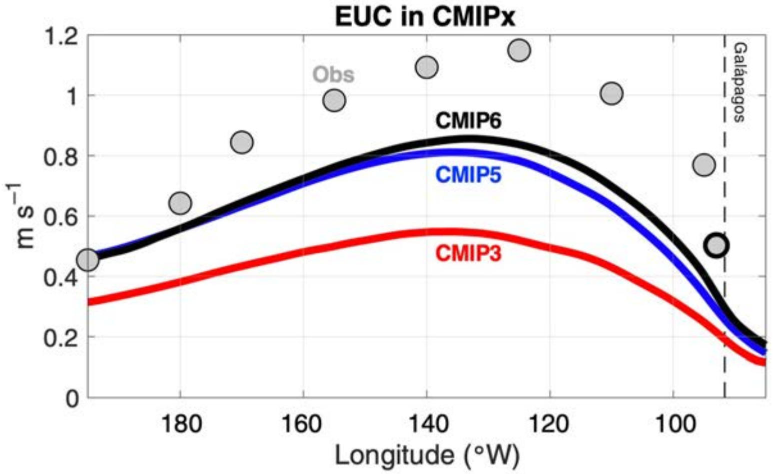


As model resolution has increased from CMIP3 to CMIP6, the EUC has sped up, as predicted, but it is ***still too slow*** *(Karnauskas et al. 2020).*

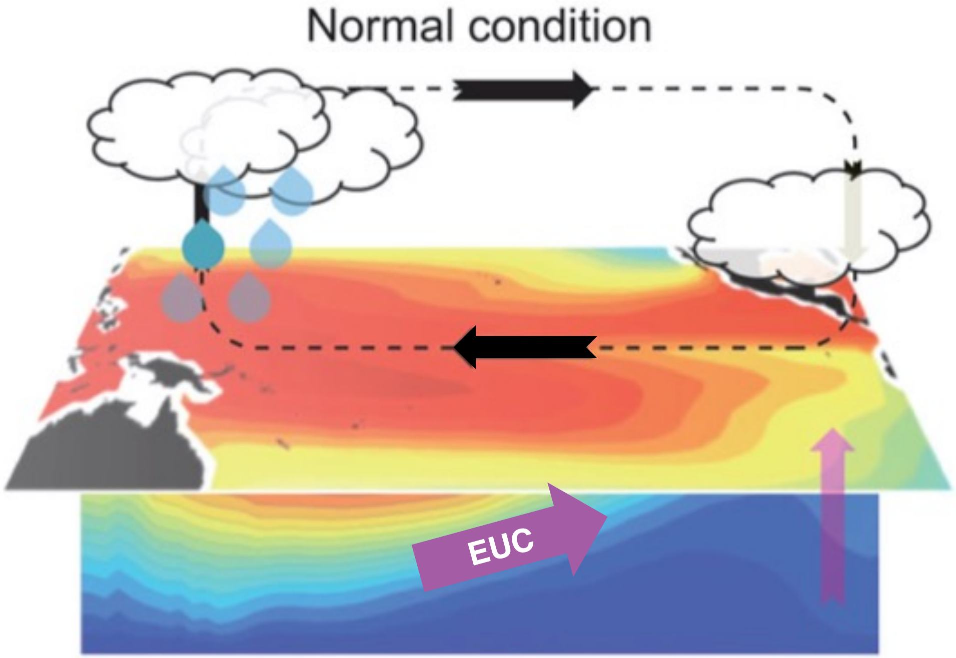
Some mechanistic issues in the **equatorial Pacific**



The speed of the Equatorial Undercurrent (EUC) in CMIPx models have a strong ***dependence on ocean model resolution.*** *This is an example from Karnauskas et al. (2012).*



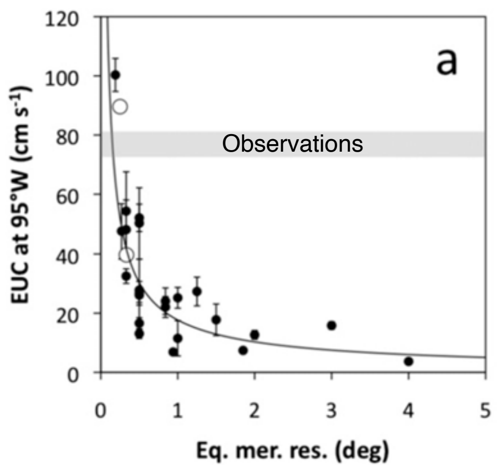
As model resolution has increased from CMIP3 to CMIP6, the EUC has sped up, as predicted, but it is ***still too slow*** *(Karnauskas et al. 2020).*



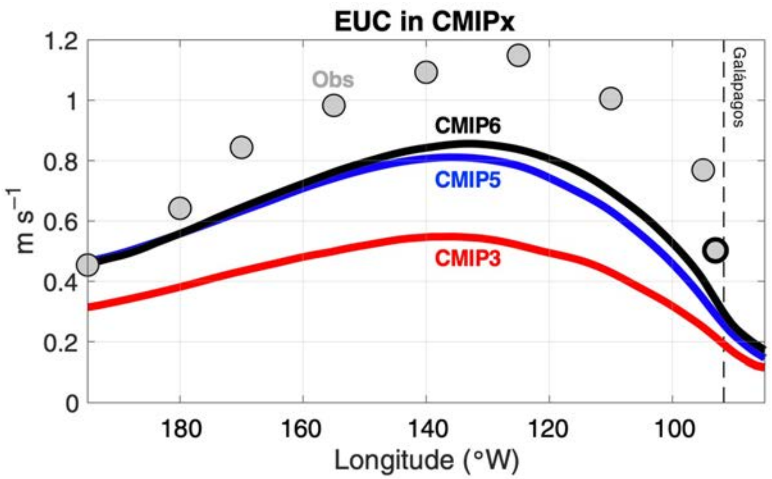
Schematic* from Lian *et al.* (2018)

* I added the EUC.

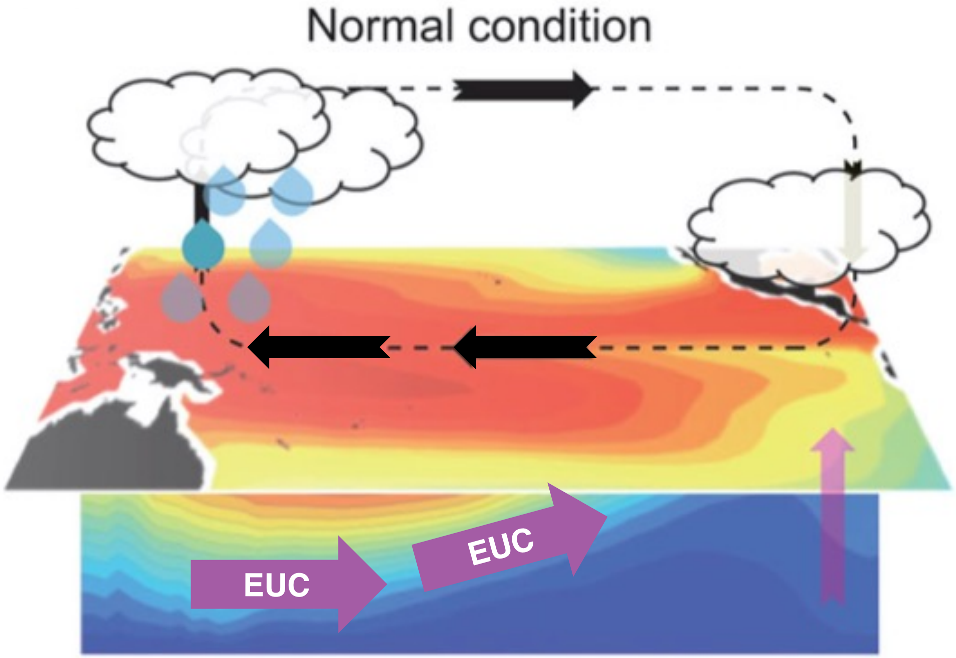
Some mechanistic issues in the **equatorial Pacific**



*The speed of the Equatorial Undercurrent (EUC) in CMIPx models have a strong **dependence on ocean model resolution.** This is an example from Karnauskas et al. (2012).*



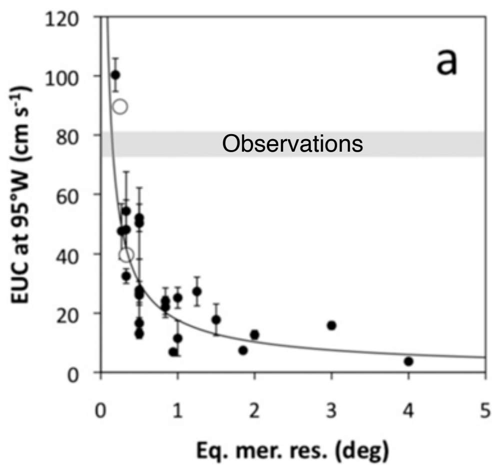
*As model resolution has increased from CMIP3 to CMIP6, the EUC has sped up, as predicted, but it is **still too slow** (Karnauskas et al. 2020).*



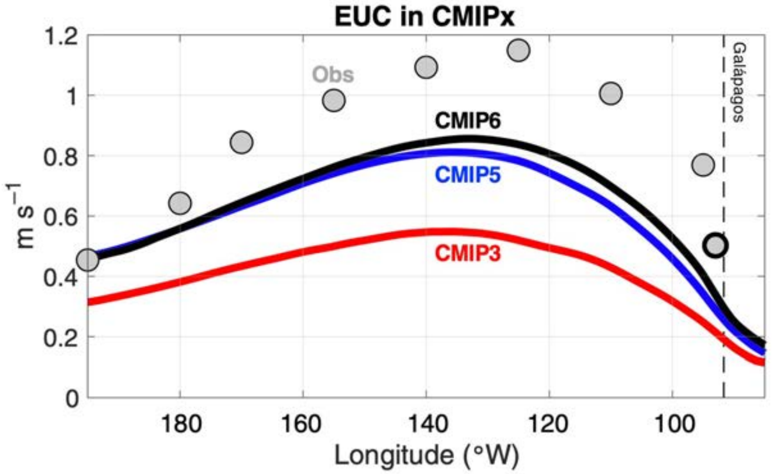
Schematic* from Lian *et al.* (2018)

* I added the EUC.

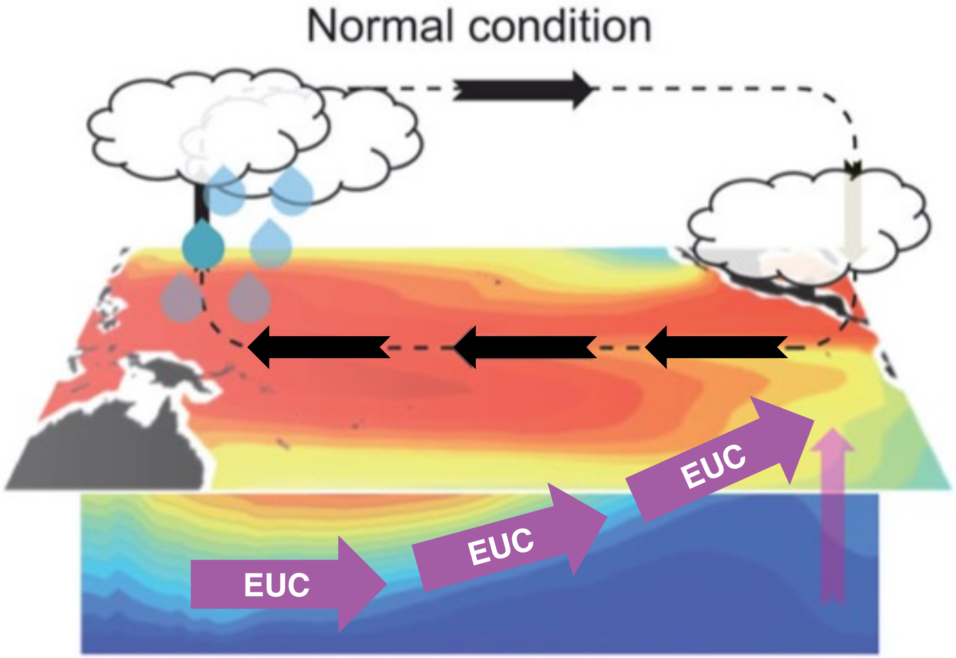
Some mechanistic issues in the **equatorial Pacific**



The speed of the Equatorial Undercurrent (EUC) in CMIPx models have a strong ***dependence on ocean model resolution.*** *This is an example from Karnauskas et al. (2012).*



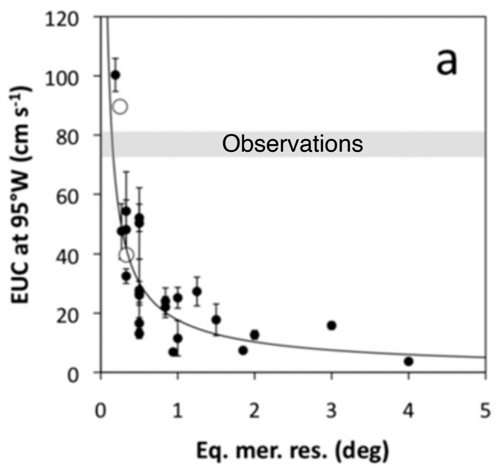
As model resolution has increased from CMIP3 to CMIP6, the EUC has sped up, as predicted, but it is ***still too slow*** *(Karnauskas et al. 2020).*



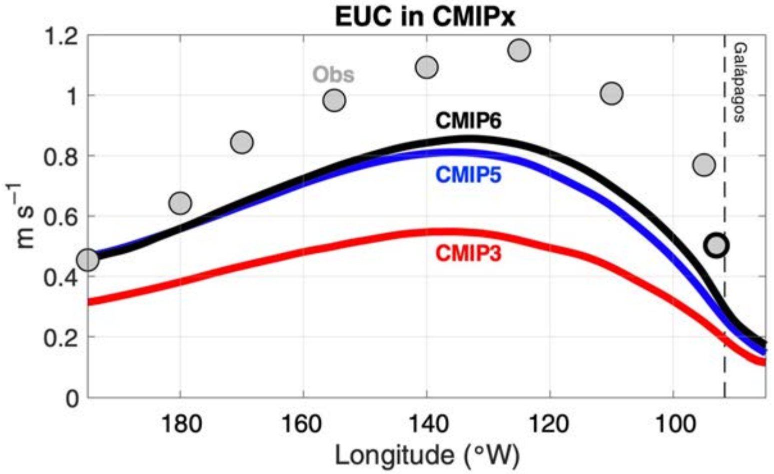
Schematic* from Lian *et al.* (2018)

* I added the EUC.

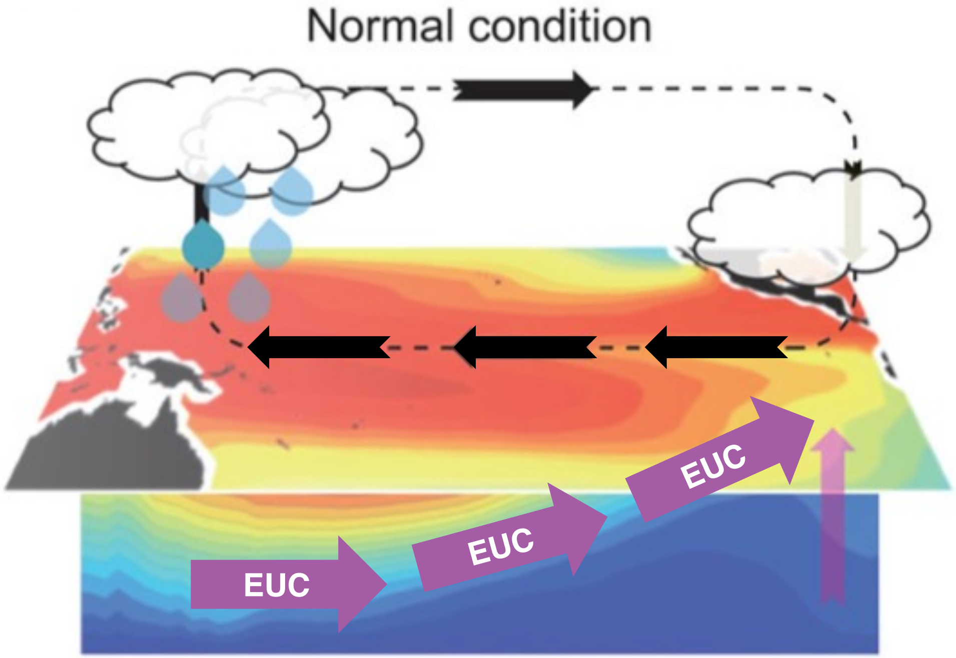
Some mechanistic issues in the **equatorial Pacific**



The speed of the Equatorial Undercurrent (EUC) in CMIPx models have a strong ***dependence on ocean model resolution.*** *This is an example from Karnauskas et al. (2012).*



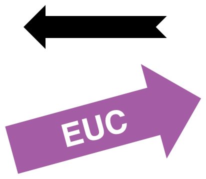
As model resolution has increased from CMIP3 to CMIP6, the EUC has sped up, as predicted, but it is ***still too slow*** *(Karnauskas et al. 2020).*



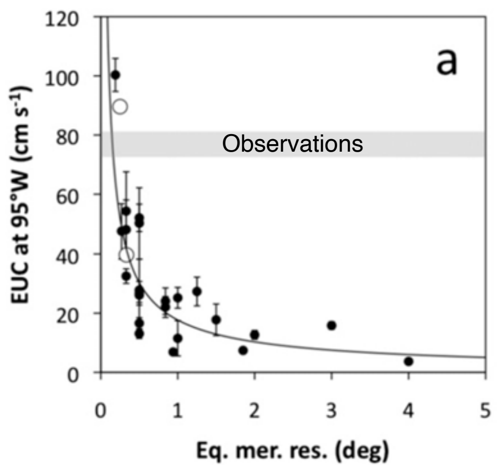
Schematic* from Lian *et al.* (2018)

* I added the EUC.

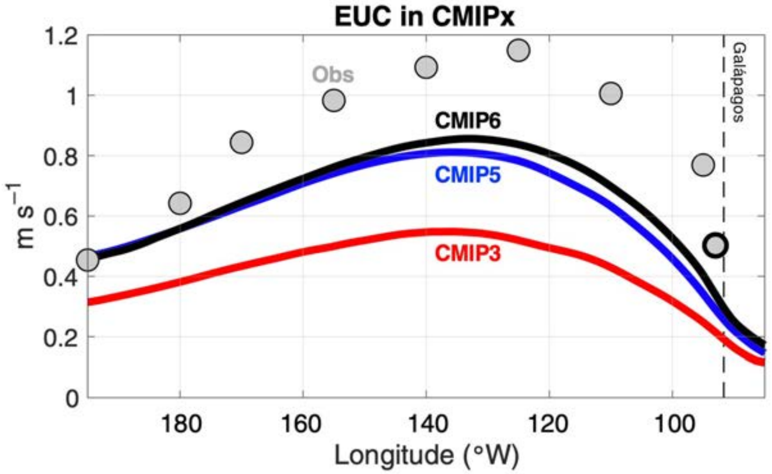
What do you think is sign of the **local** correlation between $-\tau_x$ and u_{EUC} at **different longitudes** along the equator?



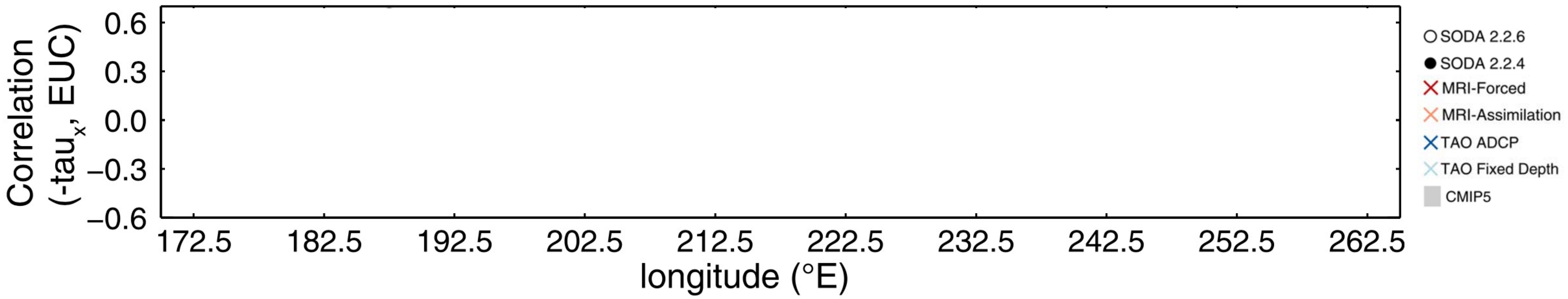
Some mechanistic issues in the **equatorial Pacific**



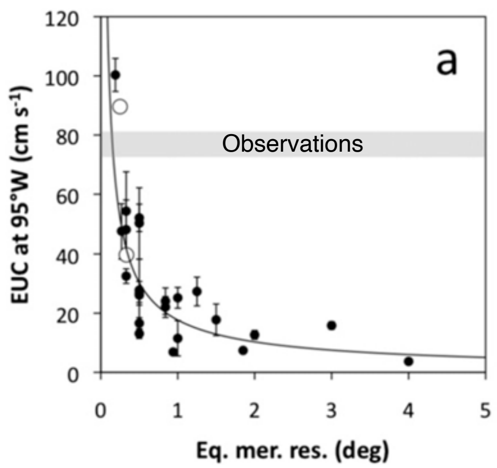
*The speed of the Equatorial Undercurrent (EUC) in CMIPx models have a strong **dependence on ocean model resolution.** This is an example from Karnauskas et al. (2012).*



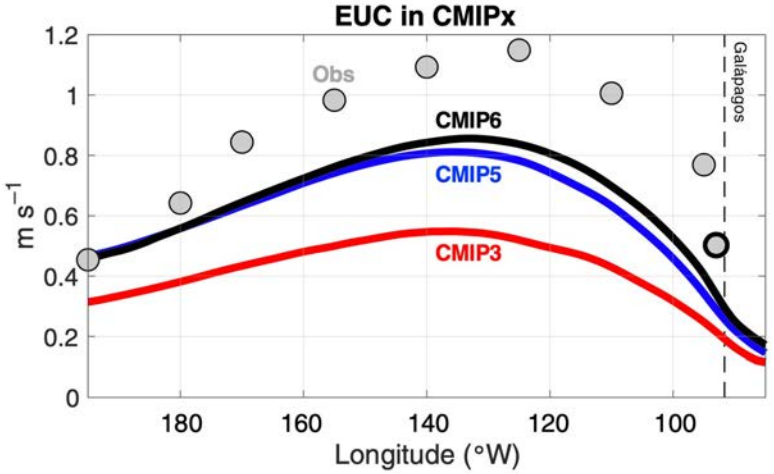
*As model resolution has increased from CMIP3 to CMIP6, the EUC has sped up, as predicted, but it is **still too slow** (Karnauskas et al. 2020).*



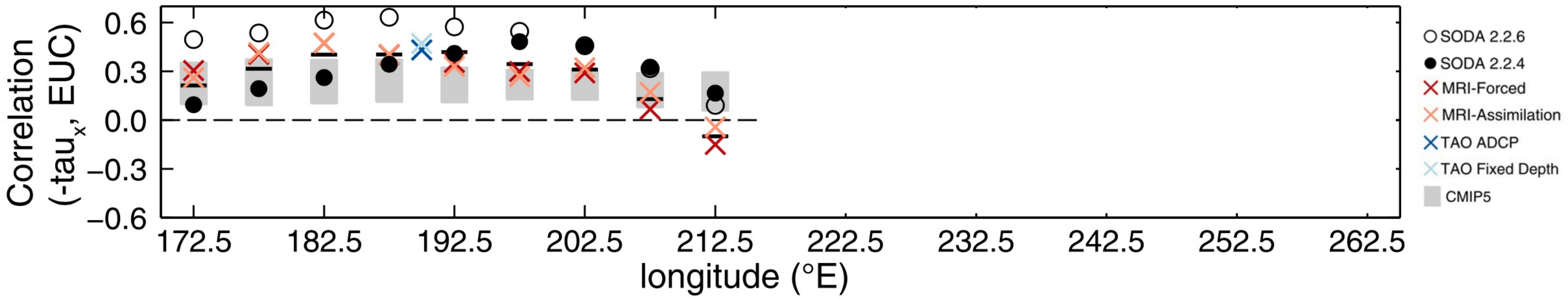
Some mechanistic issues in the **equatorial Pacific**



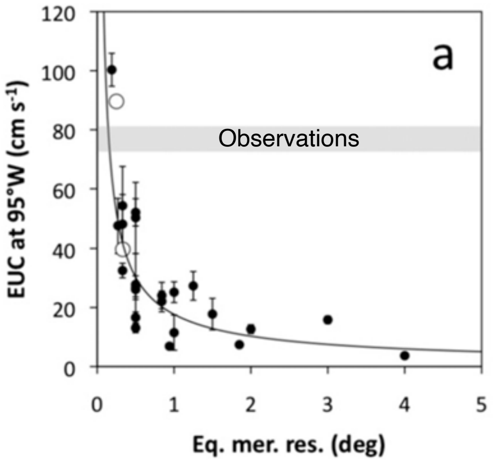
The speed of the Equatorial Undercurrent (EUC) in CMIPx models have a strong ***dependence on ocean model resolution.*** *This is an example from Karnauskas et al. (2012).*



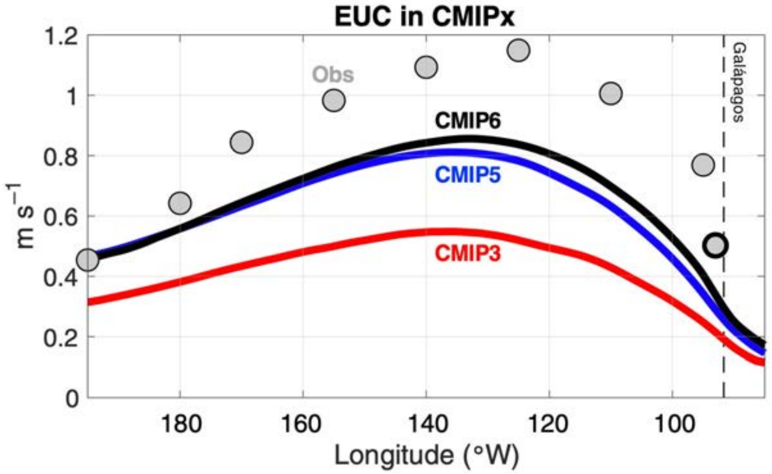
As model resolution has increased from CMIP3 to CMIP6, the EUC has sped up, as predicted, but it is ***still too slow*** *(Karnauskas et al. 2020).*



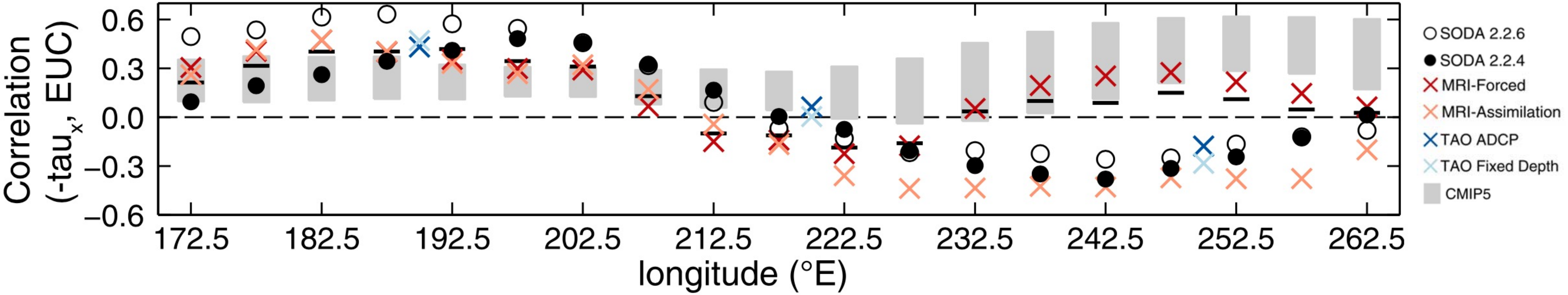
Some mechanistic issues in the **equatorial Pacific**



The speed of the Equatorial Undercurrent (EUC) in CMIPx models have a strong ***dependence on ocean model resolution.*** *This is an example from Karnauskas et al. (2012).*

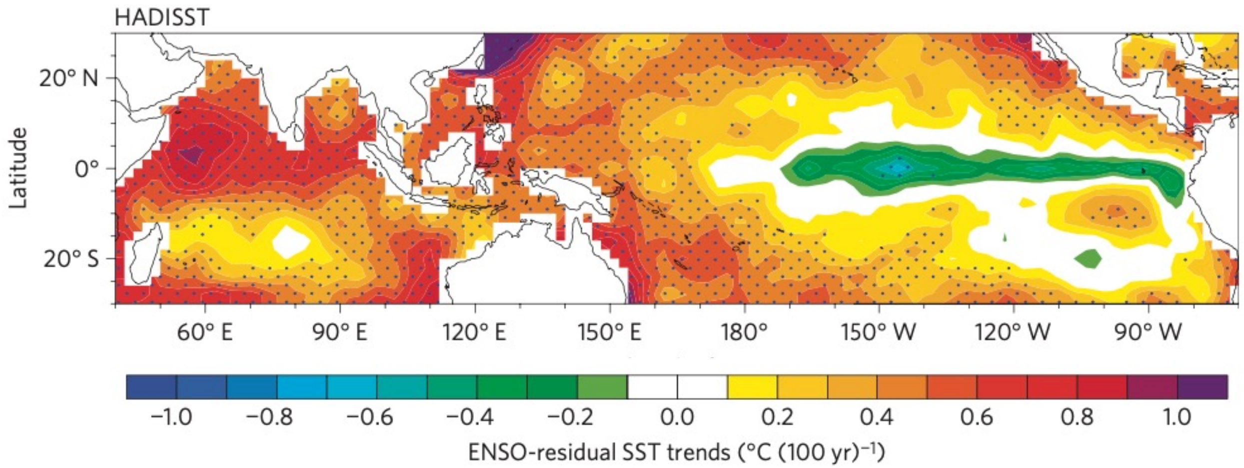


As model resolution has increased from CMIP3 to CMIP6, the EUC has sped up, as predicted, but it is ***still too slow*** *(Karnauskas et al. 2020).*

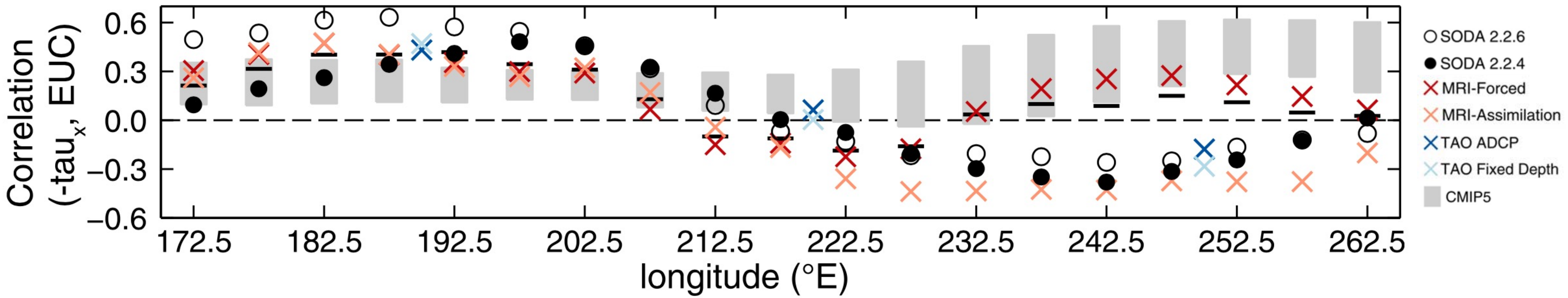


But the mean state does not tell the whole story. An analysis of CMIP5 models revealed that coupled models (and even OGCMs without ocean data assimilation) have the ***wrong relationship between zonal wind and EUC velocity*** *in the eastern equatorial Pacific (Coats and Karnauskas 2018).*

Some mechanistic issues in the **equatorial Pacific**



Note: The width of the EUC is about 2°S–2°N, and seasonally *outcrops* (b. spring) east of ~130°W.



But the mean state does not tell the whole story. An analysis of CMIP5 models revealed that coupled models (and even OGCMs without ocean data assimilation) have the ***wrong relationship between zonal wind and EUC velocity*** *in the eastern equatorial Pacific (Coats and Karnauskas 2018).*

Outlook & open questions

- The instrumental records have similar global mean SST trends, but **regional differences are large**, except when the period of analysis begins after ~1950. Unfortunately, that may be when internal variability has a stronger influence on trends than external forcing.

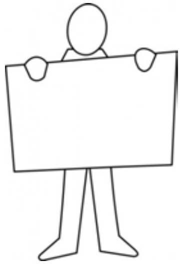
- The **Southern Ocean** is a huge question mark in the instrumental records. For those who dare, it is almost entirely a product of EOF projection (more *extrapolation* than *interpolation*). Will we ever be able to resolve this?

- Are the instrumental records long enough to understand the **role of internal variability** in the observed trends in key regions like the North Atlantic and the tropical Pacific?

- We need to better understand the **uncertainties** in the different instrumental records, and what **methodological choices** lead to differing estimates of long-term SST trends.

Key regions identified in recent work on **Pattern Effect** / ECS / radiative feedbacks are especially plagued by these issues.

Outlook & open questions



- Except for large ensembles, **are historical simulations long enough** in the presence of *very low frequency variability* in the tropical Pacific?

- Much work needs to be done to understand **model biases and representation of physical processes** in key regions of disagreement in terms of SST trends between instrumental records and coupled models.

- Consider **other well-observed variables** such as sea level (now ~30 years of altimetry).

Eos Science News by AGU

SIGN UP FOR NEWSLETTER

ABOUT SPECIAL REPORTS TOPICS PROJECTS NEWSLETTER SUBMIT TO *EOS*

Taking the Pulse of the Planet

How fast is Earth warming? Ocean heat content and sea level rise measurements may provide a more reliable answer than atmospheric measurements.

By L. Cheng, K. E. Trenberth, J. Fasullo, J. Abraham, T. P. Boyer, K. von Schuckmann, and J. Zhu 13 September 2017