HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

GEOMAR

Interannual variability in the tropical Atlantic

Deutsche Forschungsgemeinschaft
German Research Foundation

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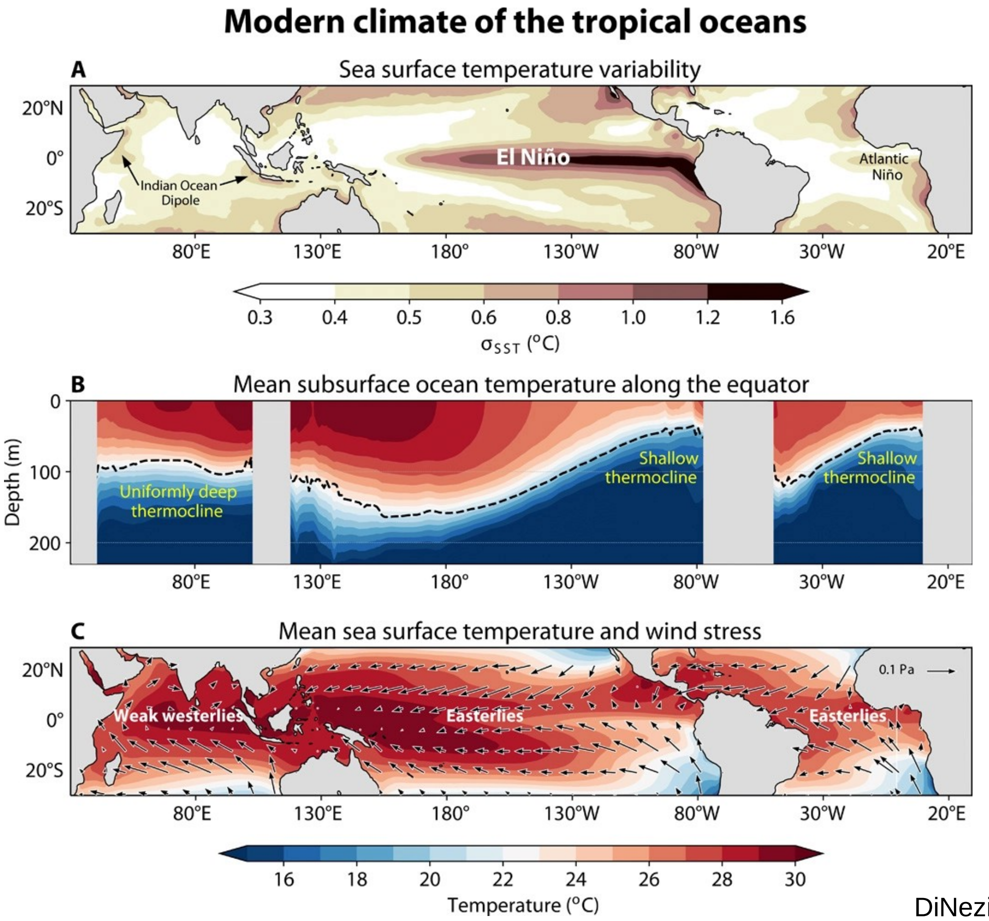
Background

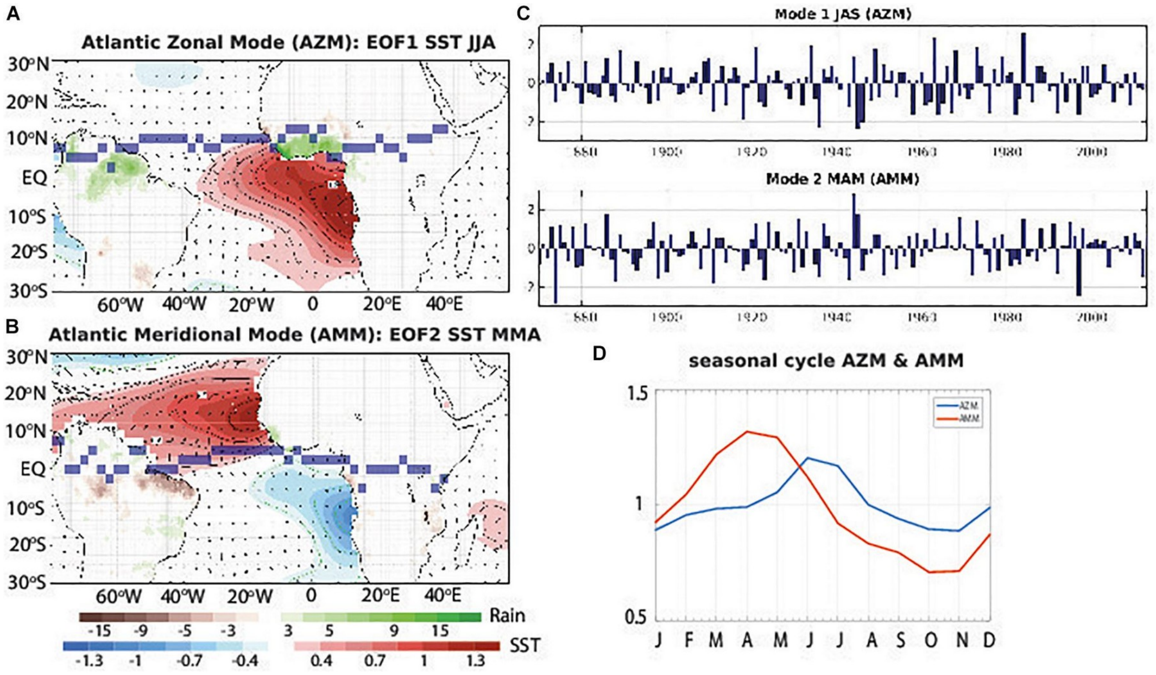
- **Modes of variability as perturbation of the mean state.**



DiNezio et al 2020, *Sci. Adv.*

Background

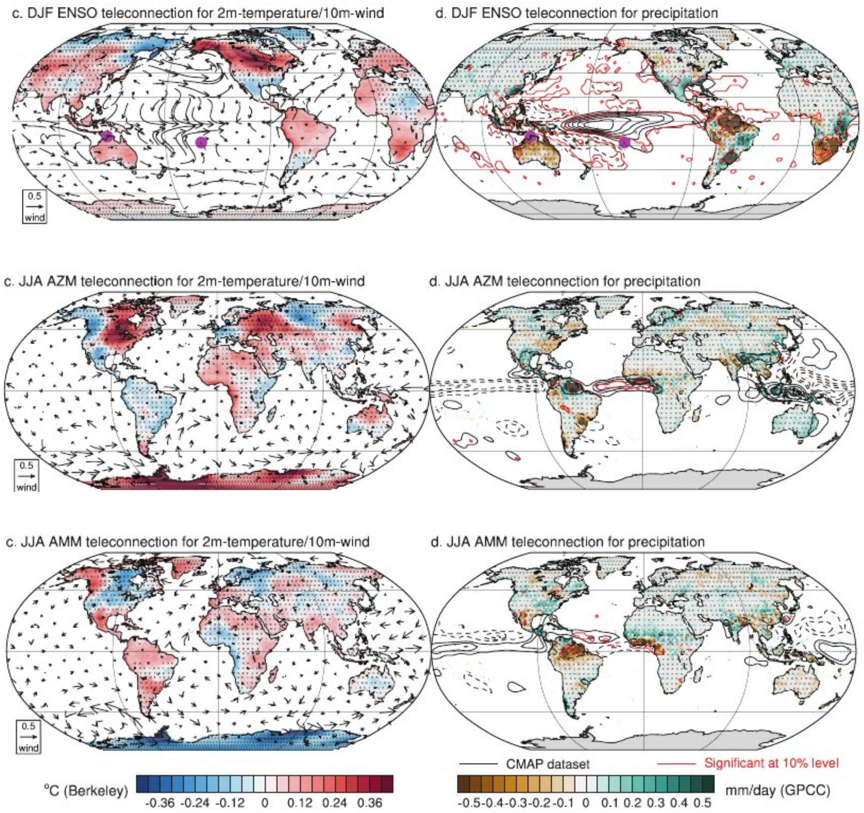
- Two leading modes in the tropical Atlantic.
- **Atlantic Niño or zonal mode** peaks in summer, the **meridional mode** peaks in spring.



Foltz et al 2019, Front. Mar. Sc.

Background

- **Climatic impacts**
- Profound impacts on regional and global climates.
- Important for seasonal climate prediction.



ENSO

Atlantic Niño

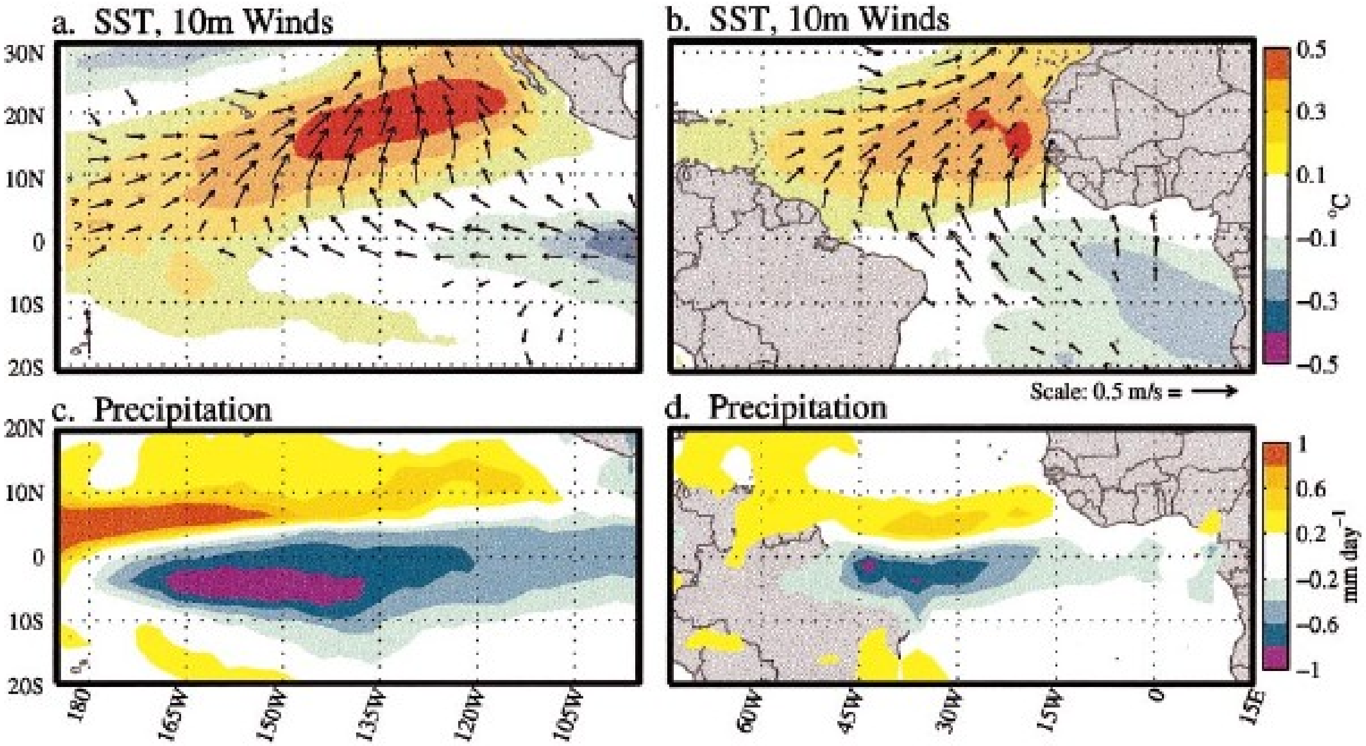
Atlantic meridional mode

IPCC AR6 2021, *Annex IV*

Part I

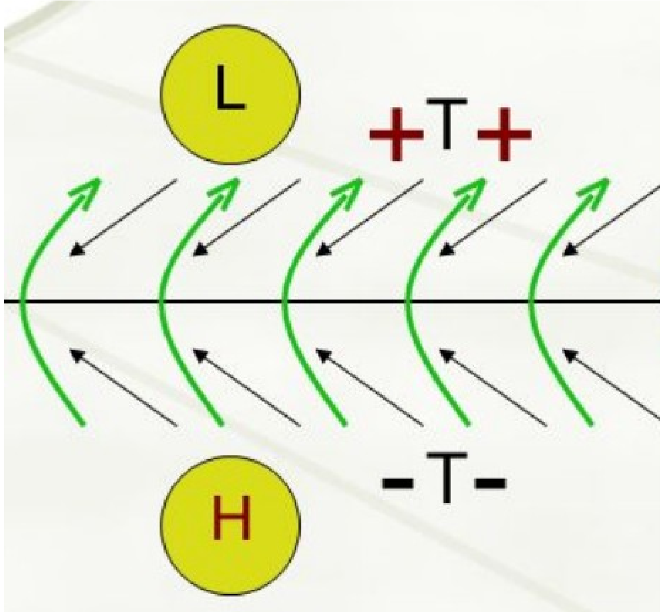
- **Atlantic meridional mode**

1| Atlantic meridional mode

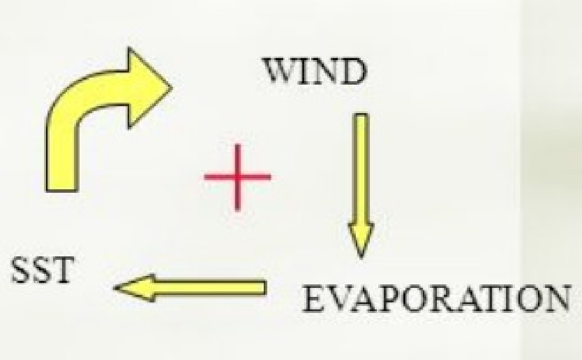


Chiang and Vimont, 2004, J. Climate

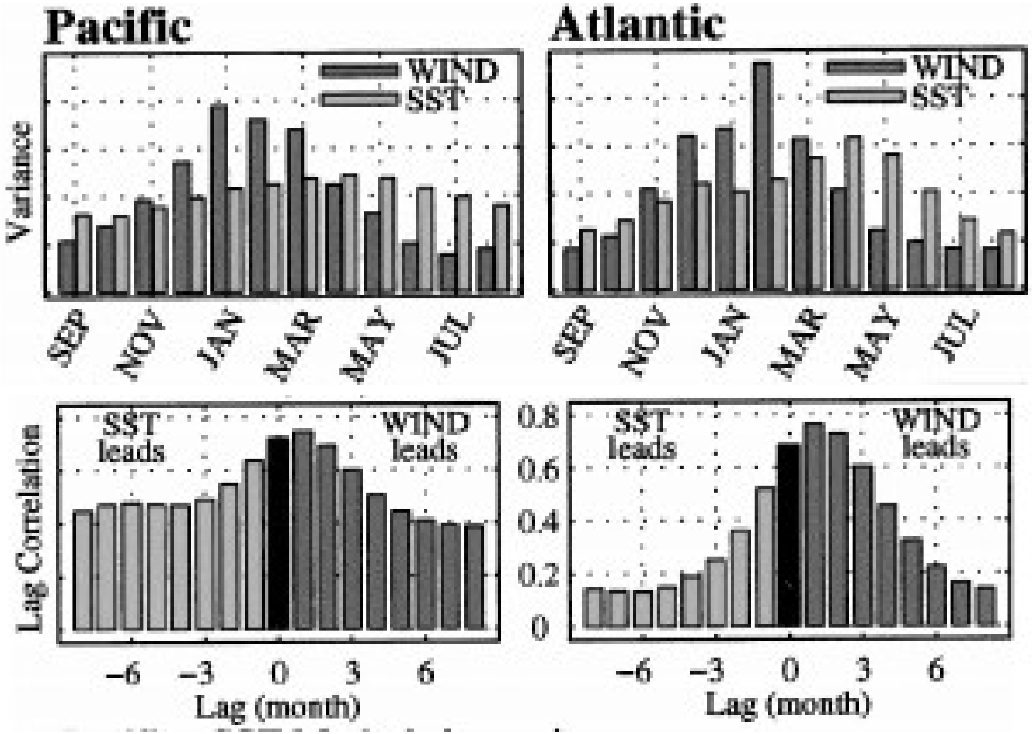
Pattern is driven by Wind-Evaporation-SST (WES) feedback



black arrow = mean
green arrows = anomalies

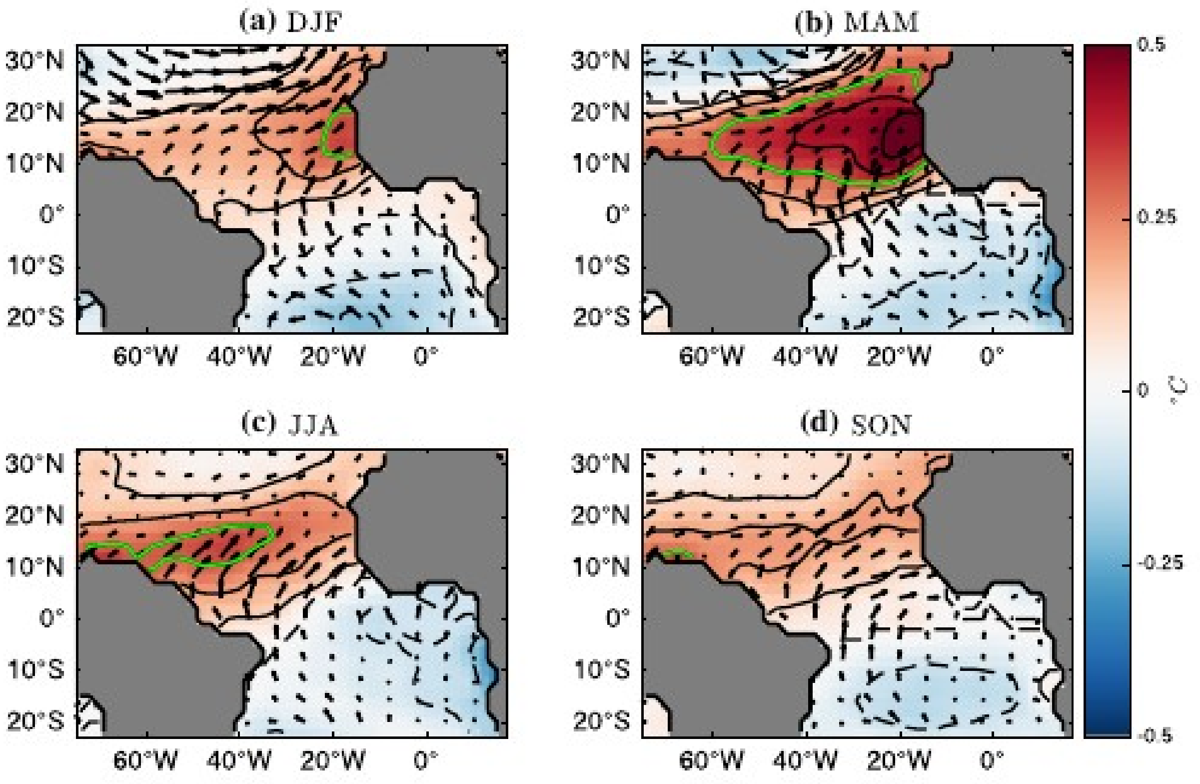


Peaks in boreal spring, winds leads SST anomalies



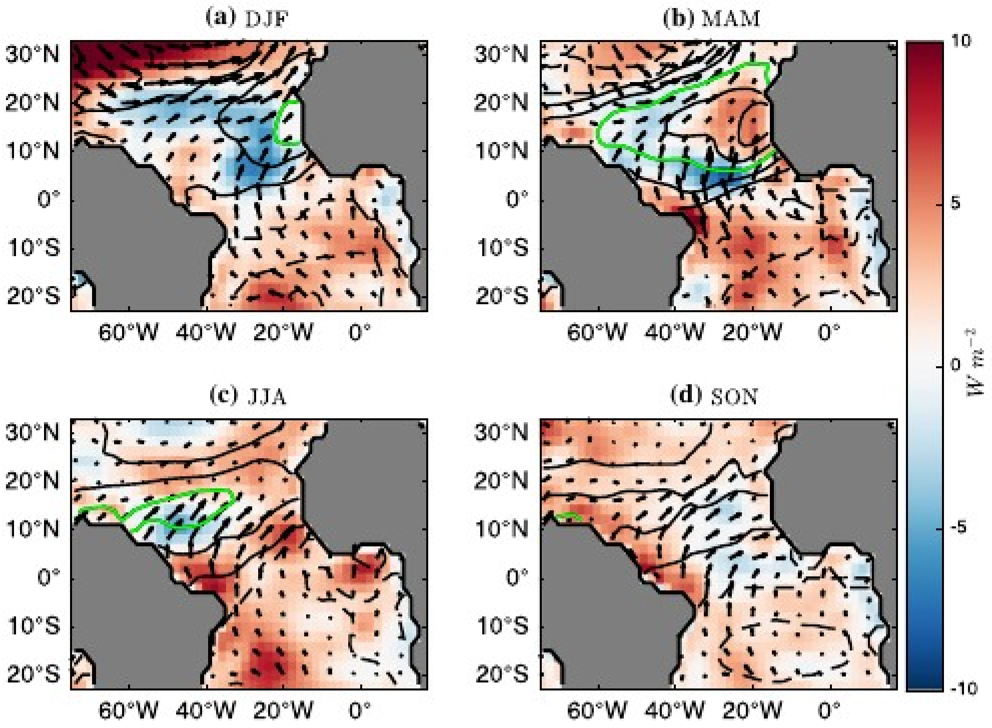
Chiang and Vimont, 2004, J. Climate.

Peaks in boreal spring, wind leads SST anomalies



Amaya, 2017, Clim. Dyn.

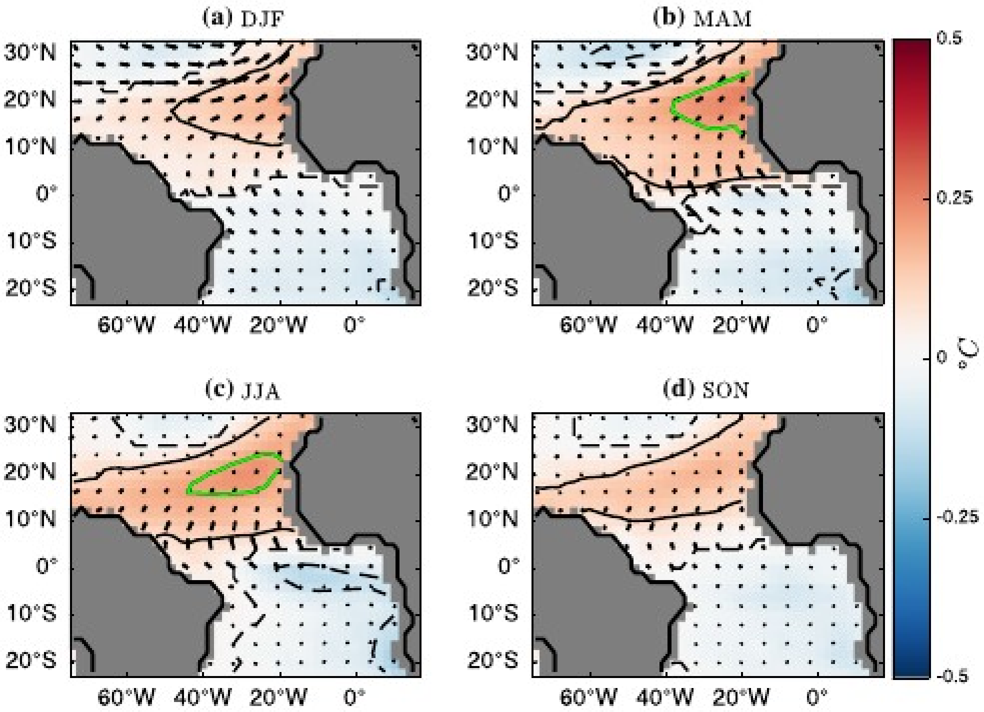
WES feedback shown in observations of latent heat flux (shading), wind (arrows), SST (contour)



Amaya, 2017, Clim. Dyn.

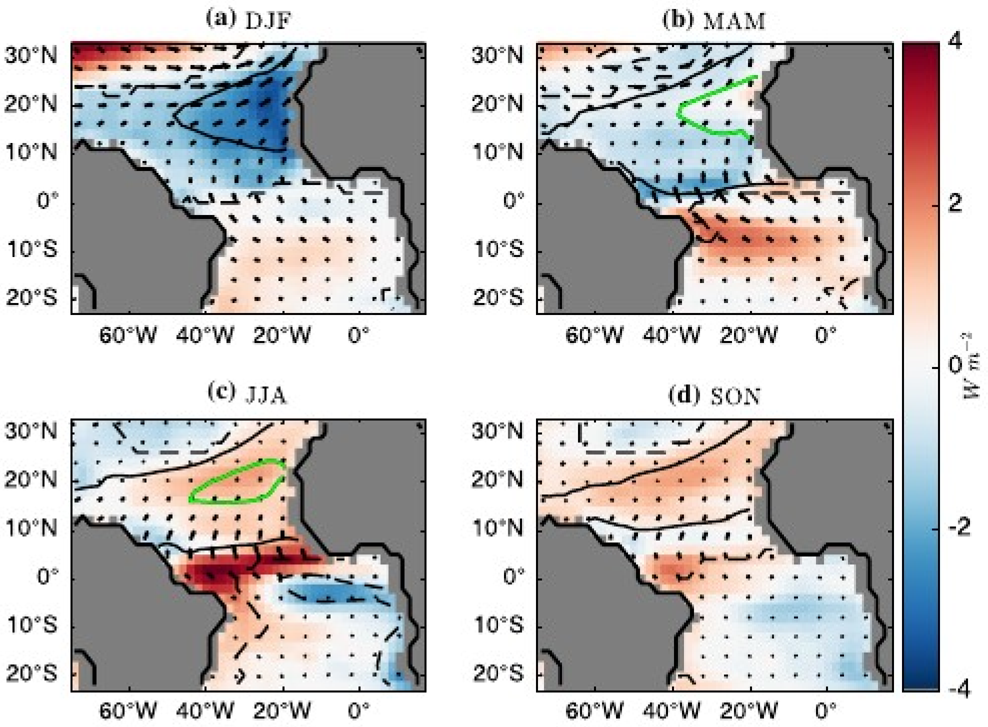
Negative = ocean warming
Positive = ocean cooling

CMIP5 ensemble/17 members



Amaya, 2017, Clim. Dyn.

WES feedback in CMIP5 ensemble/17 members

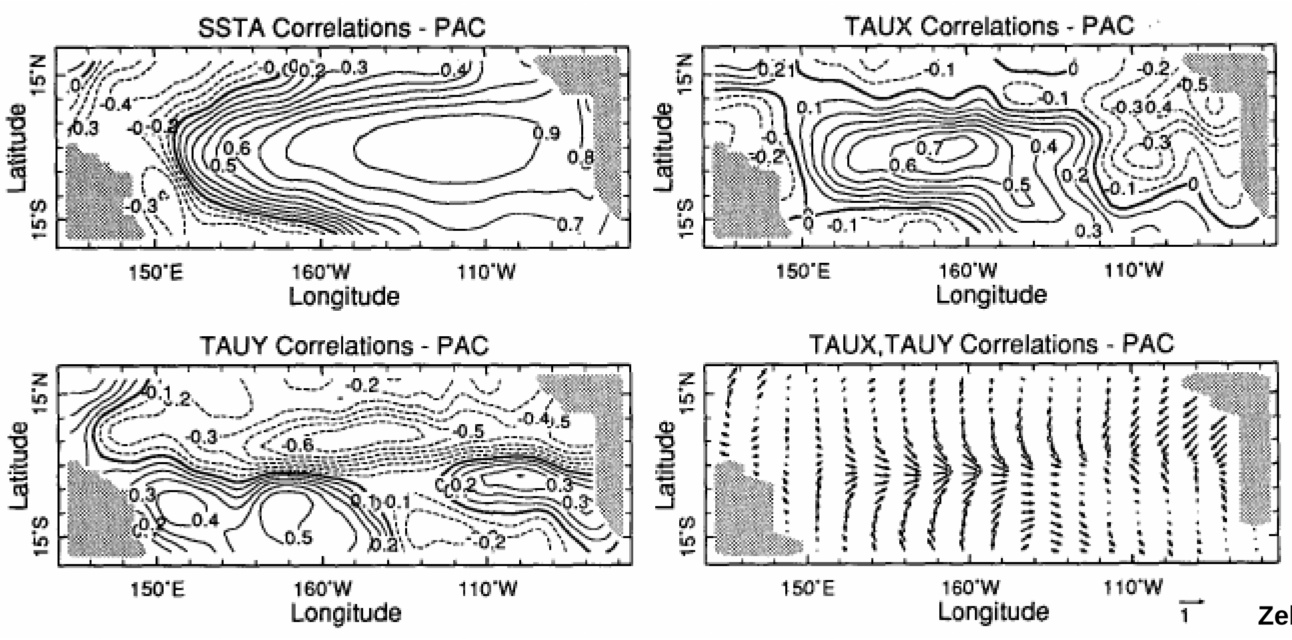


Amaya, 2017, Clim. Dyn.

Part II

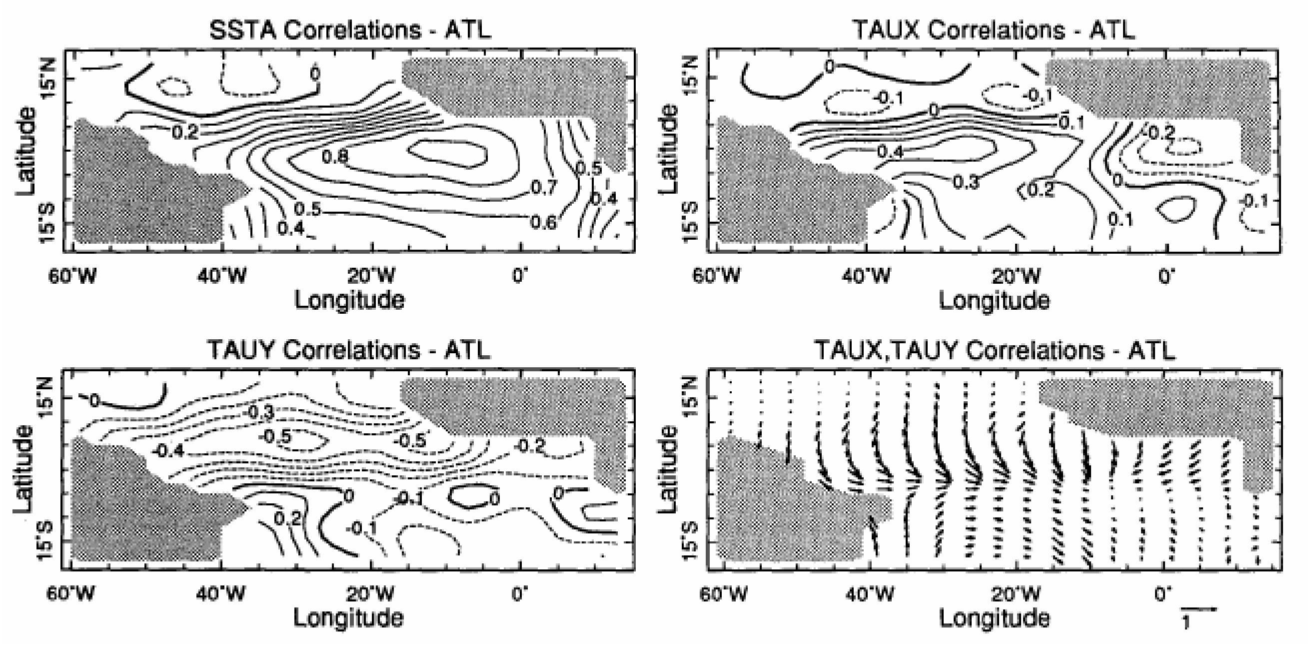
- **Atlantic Niño**

Initial ideas from the tropical Pacific El Nino



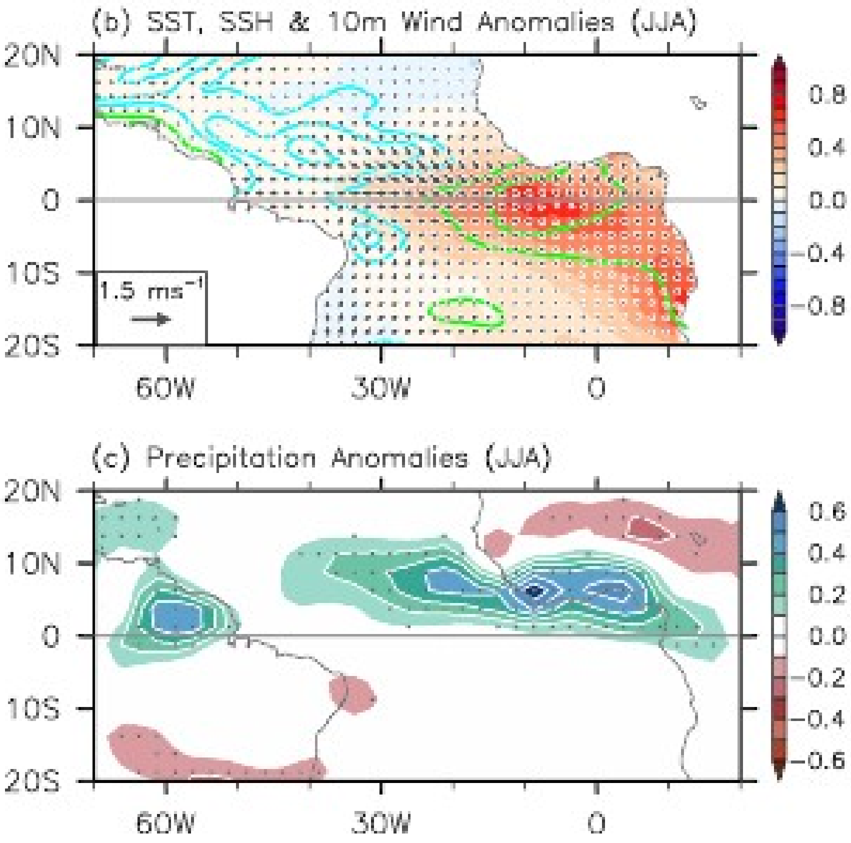
Zebiak, 1993, J. Climate

Similar patterns found in the equatorial Atlantic



Zebiak, 1993, J. Climate

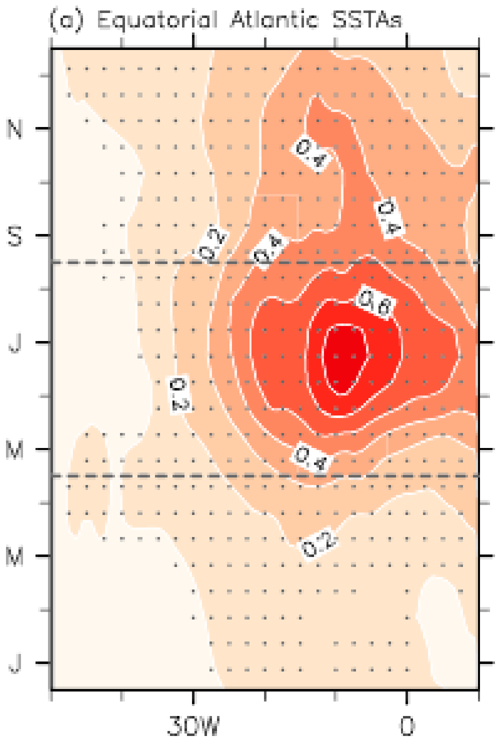
Air-sea coupling and impacts



Vallès-Casanova et al 2019, GRL

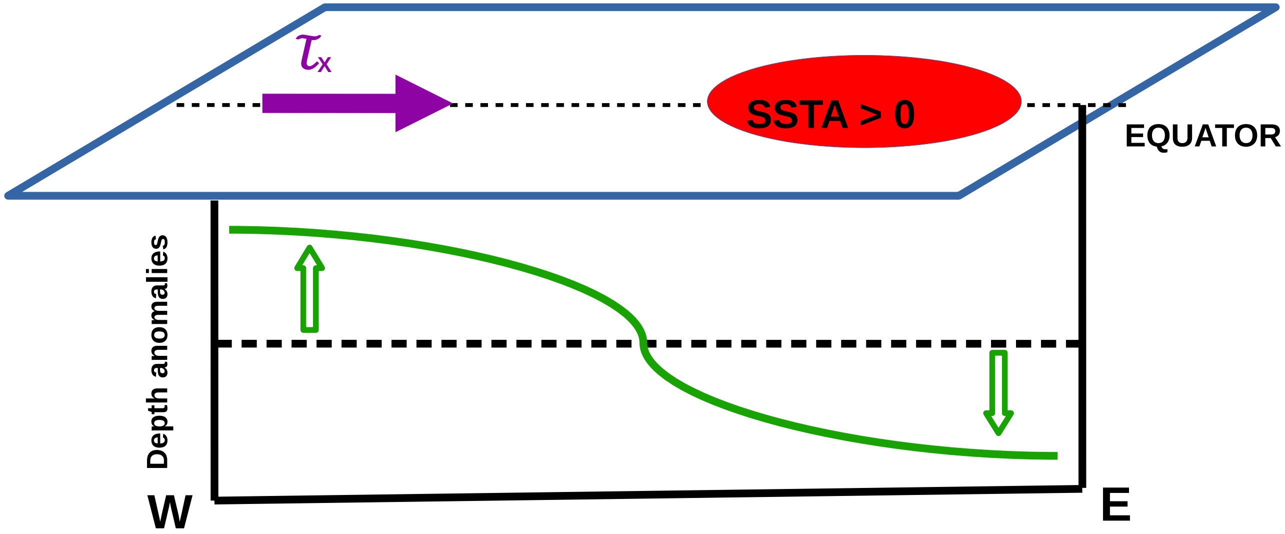
Atlantic Niño: differences from ENSO

- Occurs more often, every 2-5 years
- Typical amplitude of the order of 0.6K
- Peaks in boreal summer, with a secondary peak in winter
- Weaker ocean-atmosphere
- Less predictable
- Smaller impacts; nevertheless, profound impacts on the adjacent continents



Vallès-Casanova et al 2019, *GRL*

Thermocline feedback as the primary driver



Bjerknes feedback

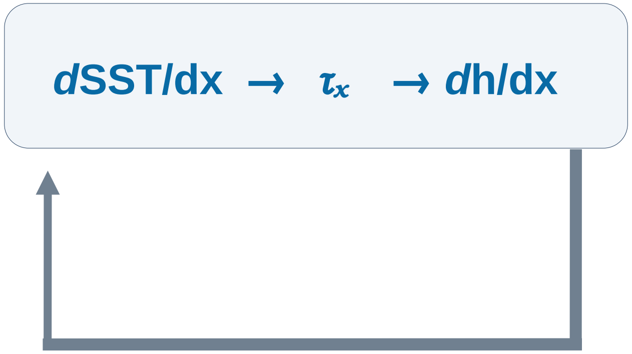
Three elements of the Bjerknes feedback loop

Coupling between:

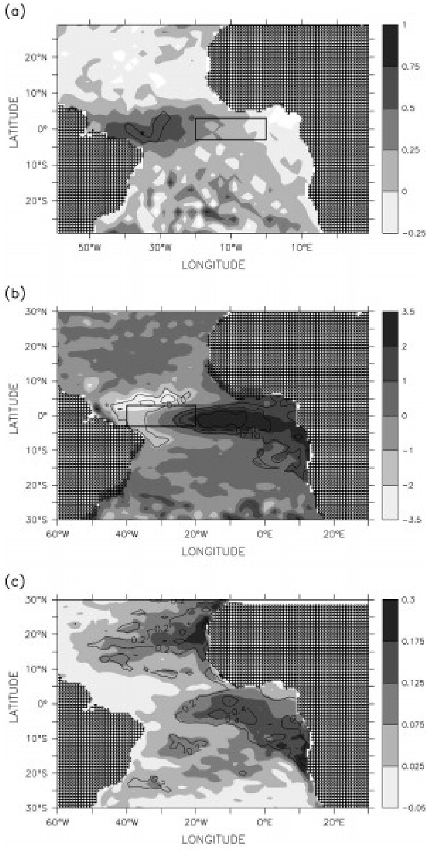
1] SST & wind stress

2] Wind stress & thermocline

3] Thermocline and SST



Bjerknes feedback in observations



SST vs winds

winds vs heat content

Heat content vs SST

Keenlyside & Latif, 2007, J. Clim.

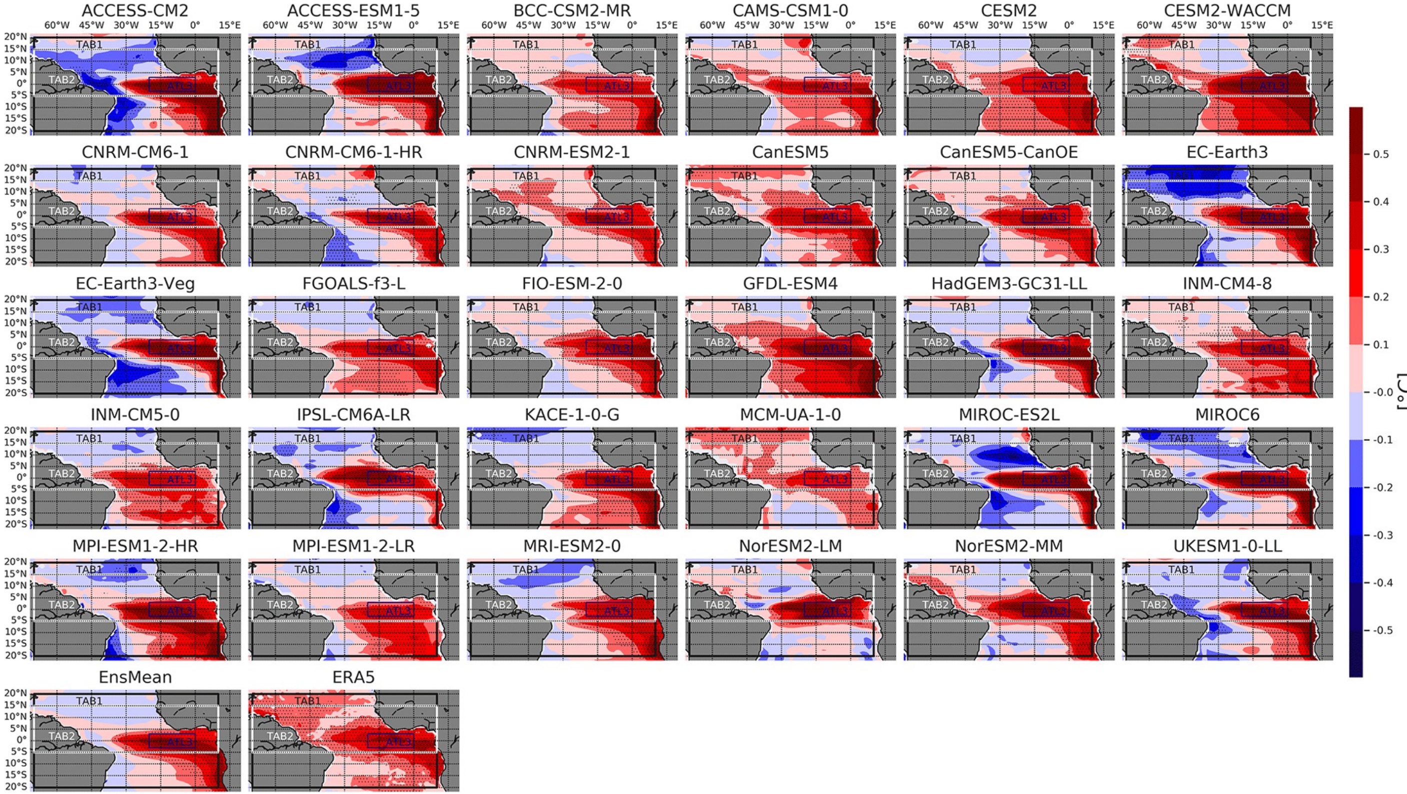
Bjerknes feedback in observations

TABLE 1. Statistical analysis of the Bjerknes feedback in the Atlantic and Pacific. Listed are the dependent (X) and independent (Y) variables, data period, correlation (r) and regression (a) values, regression value units, lag in months of maximum correlation (l), maximum correlation (r_l) and regression (a_l) values, and the 95% significance level for correlation. The indices used are the Atlantic3 (Atl3; 3°S–3°N, 20°W–0°), western equatorial Atlantic (WAtl; 3°S–3°N, 40°–20°W), Niño-3, and Niño-4. SST data are from HadISST, 10-m zonal winds (U10) are from COADS, zonal surface stress (Ustr) are from the NCEP–NCAR reanalysis, sea level anomalies (SLAs) are derived from satellite measurements, 400-m HSTs are from JEDA, and 400-m average temperature anomalies (Tave) are from a forced OGCM simulations. All data and statistical techniques are described in section 2.

X	Y	Period	r_0	a_0	$[a]$	l	r_l	a_l	r_{95}
				SST–Surface zonal wind					
				Atlantic					
Atl3–SST	WAtl–U10	1950–1997	0.48	0.55	m s^{-1} °C^{-1}	−1	0.52	0.60	0.28
Atl3–SST	WAtl–Ustr	1950–2002	0.52	0.75	10^{-2} Pa °C^{-1}	0	0.52	0.75	0.27
				Pacific					
Niño-3–SST	Niño-4–U10	1950–1997	0.66	0.84	M s^{-1} °C^{-1}	−2	0.67	0.86	0.28
Niño-3–SST	Niño-4–Ustr	1950–2002	0.68	0.74	10^{-2} Pa °C^{-1}	−1	0.70	0.76	0.28
				Surface zonal wind–HC					
				Atlantic					
WAtl–Ustr	Atl3–SLA	1993–2002	0.59	2.2	cm $(10^{-2}$ Pa$)^{-1}$	0	0.59	2.2	0.53
WAtl–U10	Atl3–HST	1970–1997	0.22	1.4	10^8 J $m^{-1}s^{-1}$	1	0.22	1.4	0.28
Watl–Ustr	Atl3–Tave	1950–2001	0.58	0.27	°C $(10^{-2}$ Pa$)^{-1}$	1	0.62	0.29	0.31
				Pacific					
Niño-4–Ustr	Niño-3–SLA	1993–2002	0.82	6.0	cm $(10^{-2}$ Pa$)^{-1}$	1	0.87	6.3	0.63
Niño-4–U10	Niño-3–HST	1970–1997	0.71	3.8	10^8J m^{-1} s^{-1}	1	0.74	4.0	0.32
Niño-4–Ustr	Niño-3–Tave	1950–2001	0.73	0.44	°C $(10^{-2}$ Pa$)^{-1}$	1	0.80	0.49	0.31
				HC–SST					
				Atlantic					
Atl3–SST	Atl3–SLA	1993–2002	0.69	0.17	°C cm^{-1}	1	0.73	0.18	0.6
Atl3–SST	Atl3– HST	1970–2002	0.43	0.06	°C $(10^8$ J$)^{-1}$	1	0.46	0.06	0.34
				Pacific					
Niño-3–SST	Niño-3–SLA	1993–2002	0.90	0.12	°C cm^{-1}	1	0.94	0.12	0.6
Niño-3–SST	Niño-3– HST	1970–2002	0.81	0.12	°C $(10^8$ J$)^{-1}$	1	0.83	0.12	0.34

Keenlyside & Latif, 2007, J. Climate

Atlantic Nino in CMIP6 models



Worou et al., 2022, ESD

Bjerknes feedback in CMIP5 models

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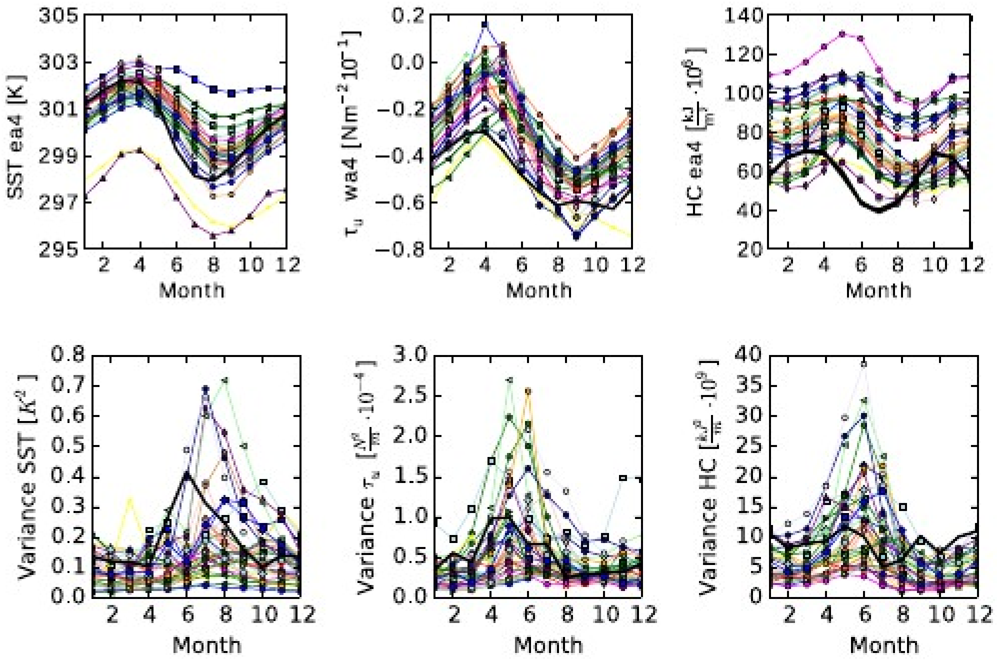
SST **Wind stress** **Heat content**

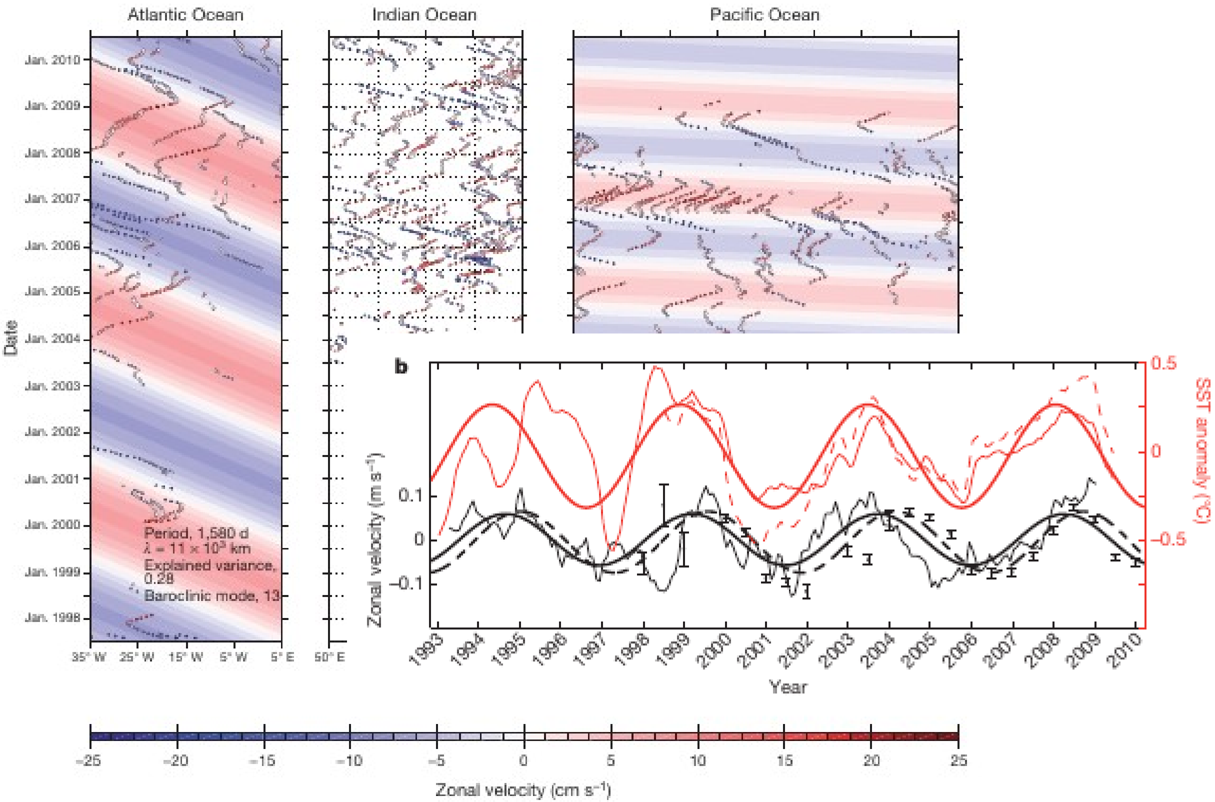


Deppenmeier et al, 2016, Clim. Dyn.

Bjerknes feedback in the equatorial Atlantic

- Atlantic Niño can be driven by factors other than the Bjerknes feedback:
- -Deep equatorial jets (Brandt et al., 2011; *Nature*)
- -Advection of the North Tropical Atlantic (Richter et al., 2013; *Nature Geoscience*)
- The classical Bjerknes observed in the Pacific is modified in the Atlantic, more important role for the atmosphere

Bjerknes feedback NOT required [1]:
Deeep equatorial jets

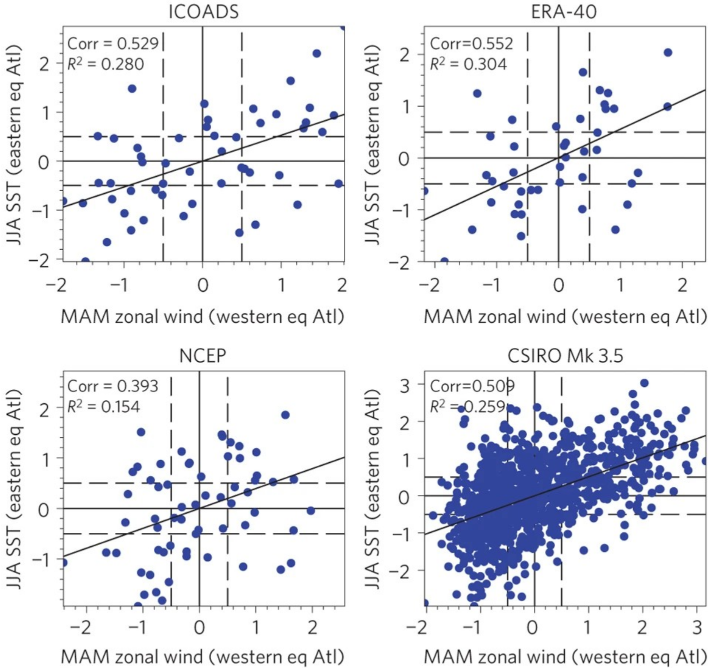


Deep equatorial jets:

- propagate energy upward towards the surface
- governed by intrinsic ocean dynamics **NOT** coupled to the atmosphere

Brandt et al.,
(2011), *Nature*

Bjerknes feedback NOT required [2]: Advection from North Tropical Atlantic



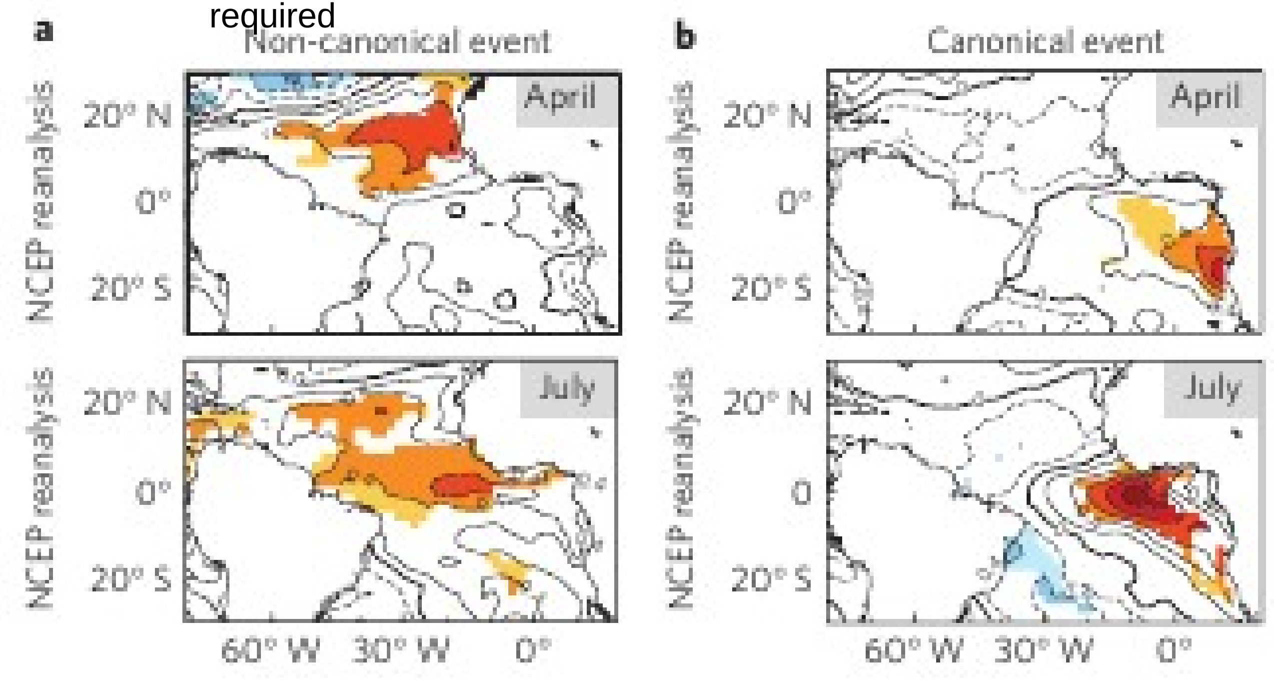
Bjerknes feedback explains only 15-30% of the Atlantic Nino variance

Richter et al., 2013, *Nat. Geosc.*

Bjerknes feedback NOT required [2]: Advection from North Tropical Atlantic

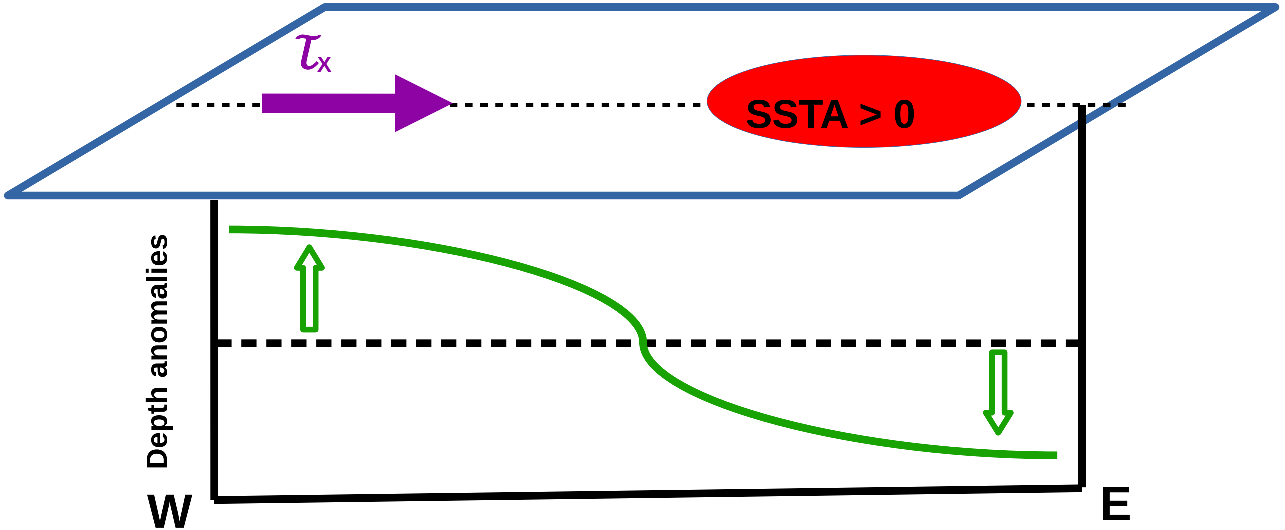
Berknes feedback **NOT** required

Bjerknes feedback **IS** required



Richter et al., 2013; *Nat. Geosc.*

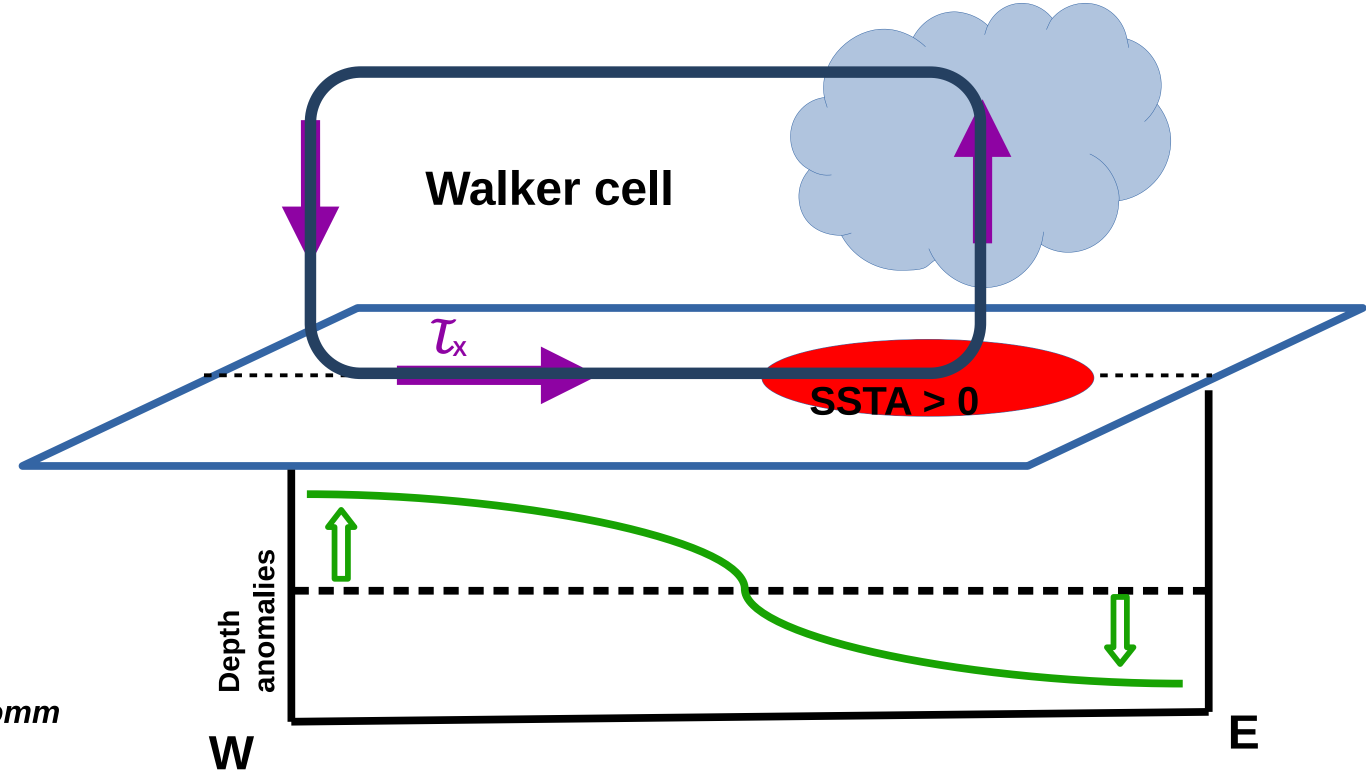
Can you suggest what is missing here?



$d\text{SST}/dx \rightarrow \tau_x \rightarrow dh/dx$

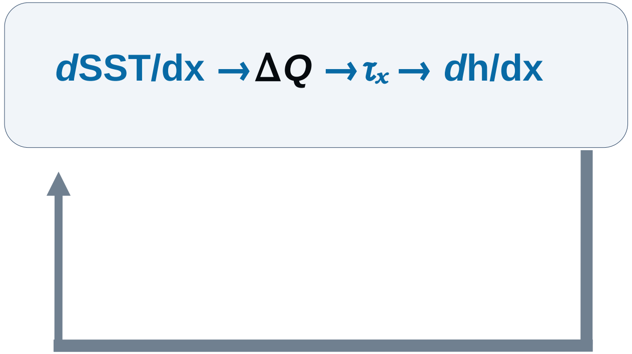
Bjerknes feedback

The atmospheric profile?



Nnamchi et al, 2021, *Nature Comm*

Introduce a measure of convection in the atmosphere

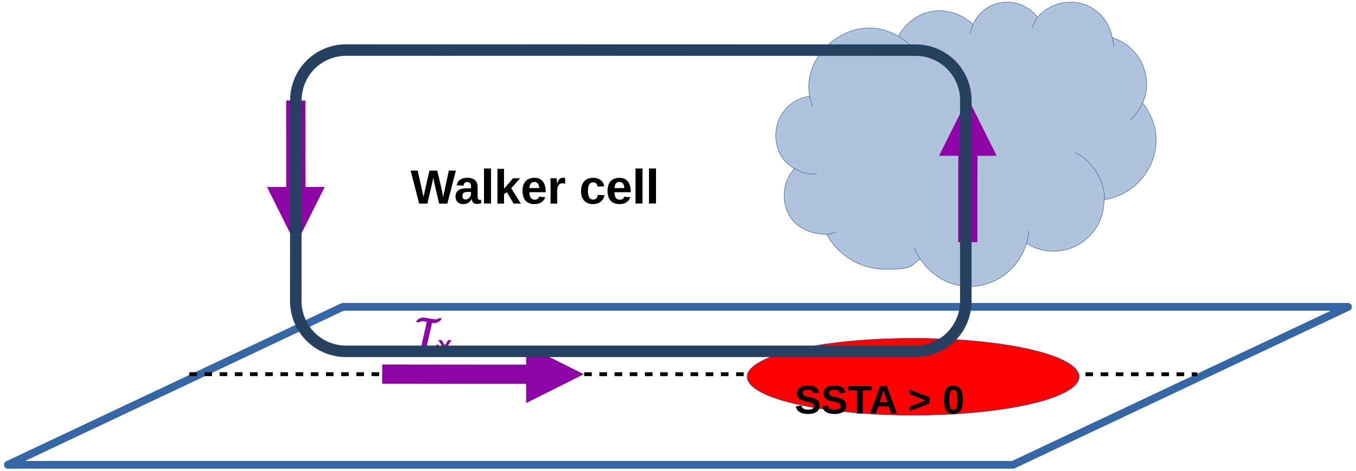


Nnamchi et al, 2015, 2021; *Nature Comm*

In a modelling framework:

Slab-coupled system.

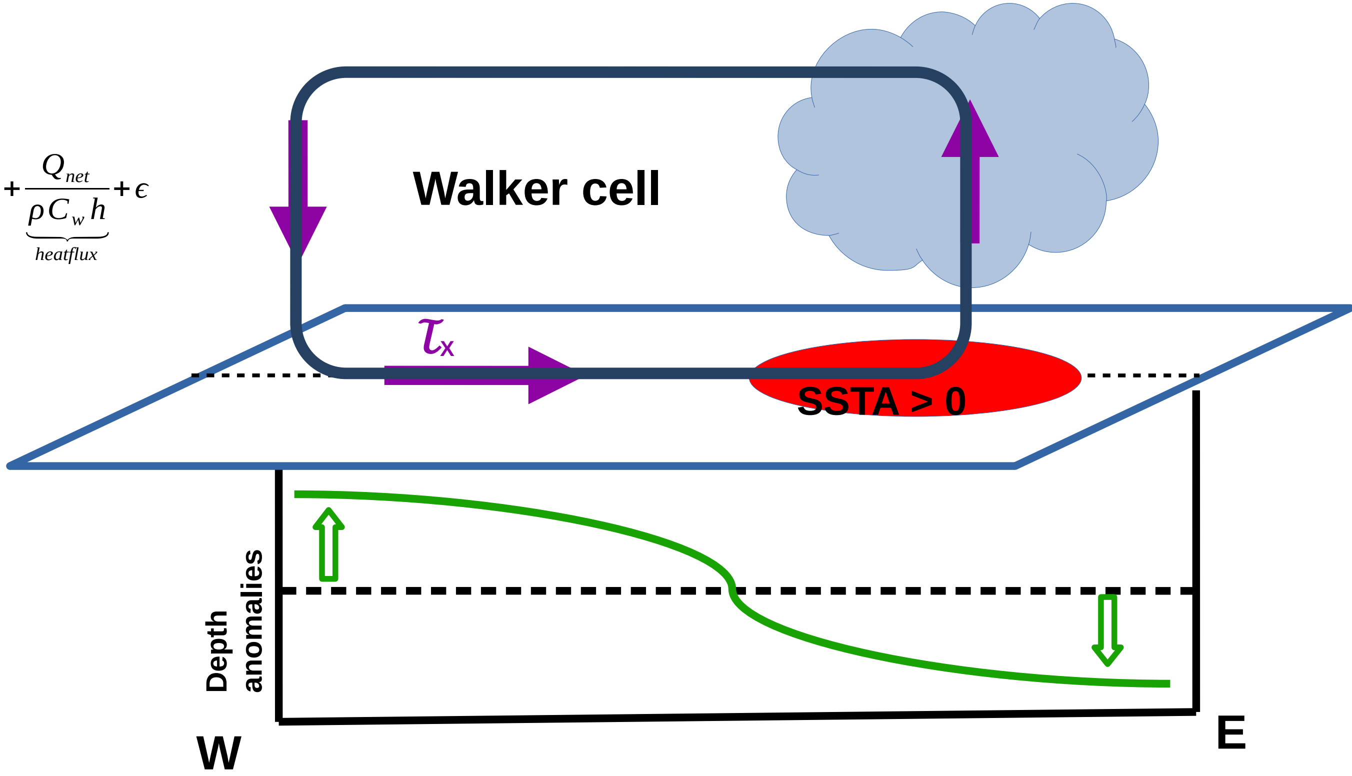
$$\frac{\partial T}{\partial t} = \frac{Q_{net}}{\rho C_w h}$$



Nnamchi et al, 2021; *Nature Comm*

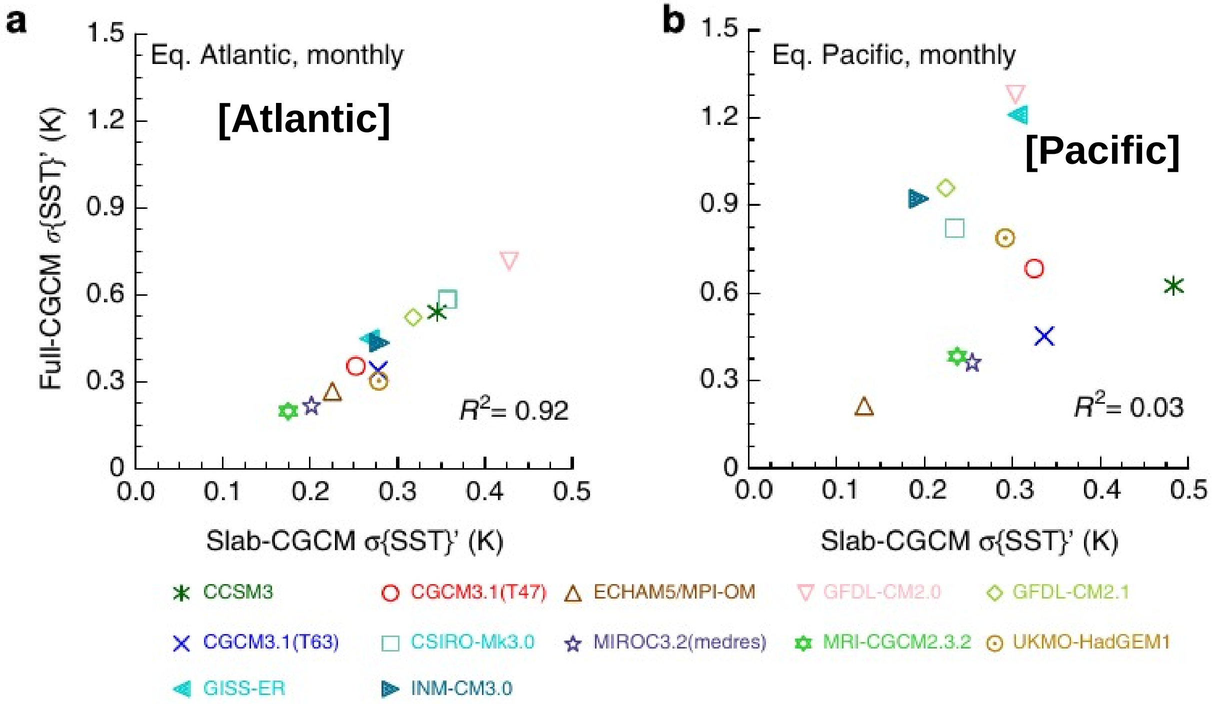
Fully-coupled system.

$$\frac{\partial\langle T\rangle}{\partial t}=\underbrace{\left\langle u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right\rangle}_{horizontal\ advection}+\underbrace{\frac{1}{h}\left[\langle T\rangle-T_{-h}\right]w_e}_{entrainment}+\underbrace{\frac{Q_{net}}{\rho C_w h}}_{heatflux}+\epsilon$$



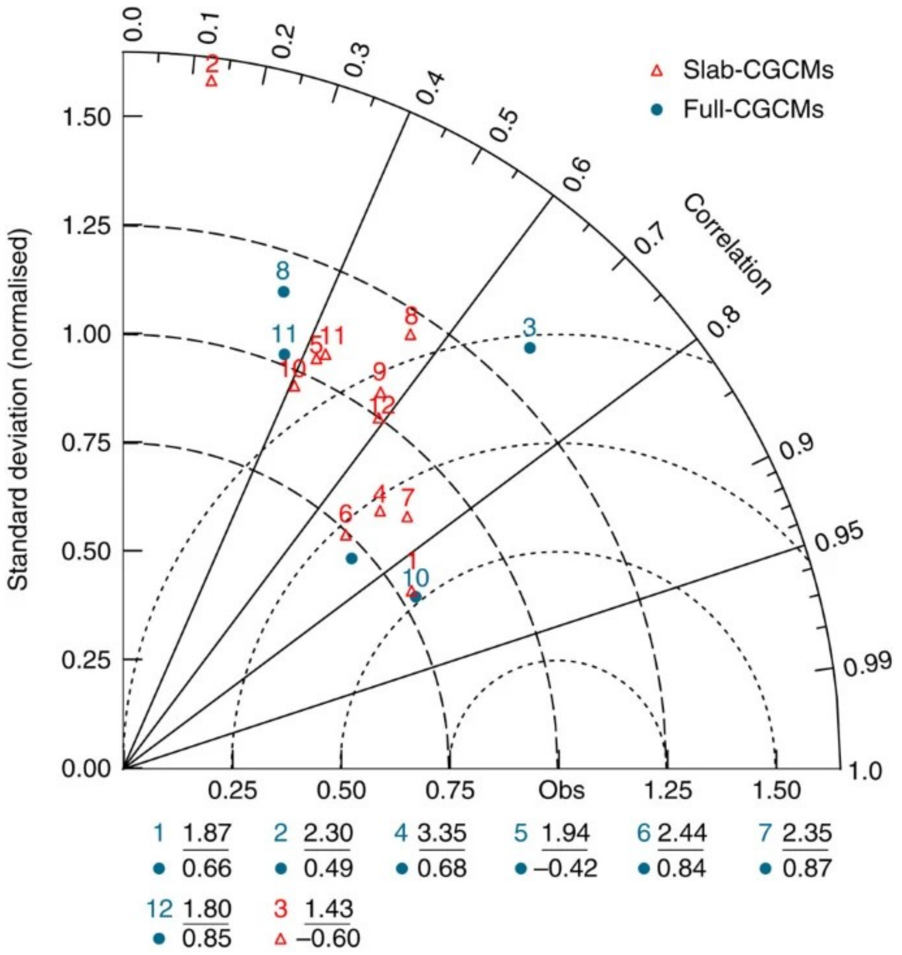
Nnamchi et al, 2021

Atlantic Niño as a function of slab processes.



Nnamchi et al., 2015.

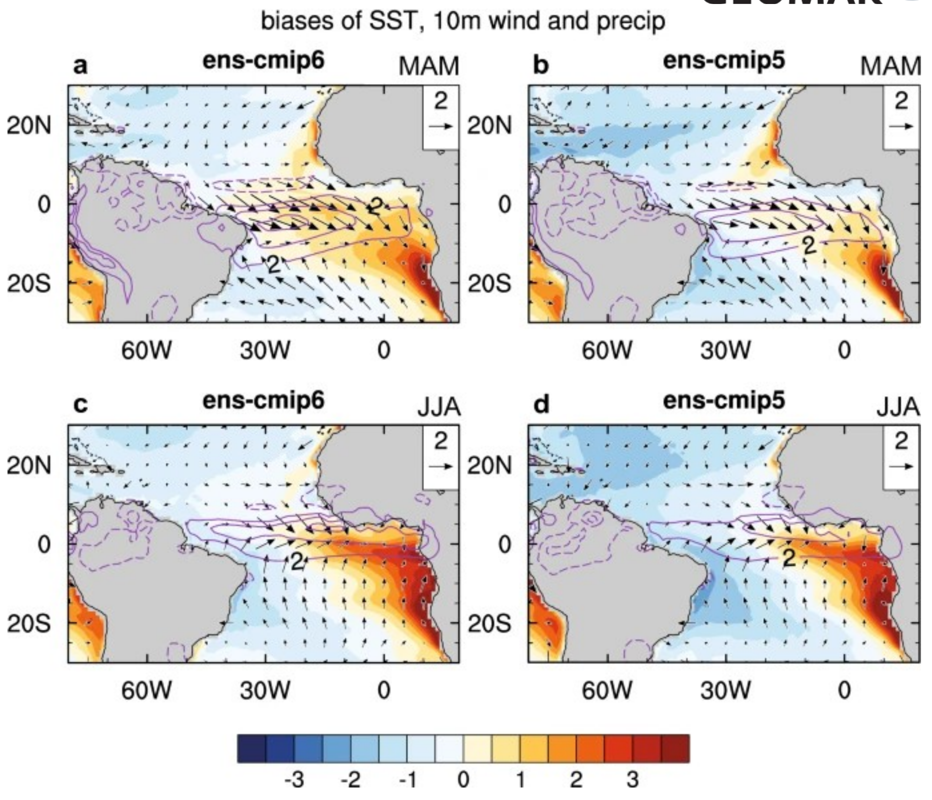
Fully-coupled models no better than the models



Nnamchi et al., 2015.

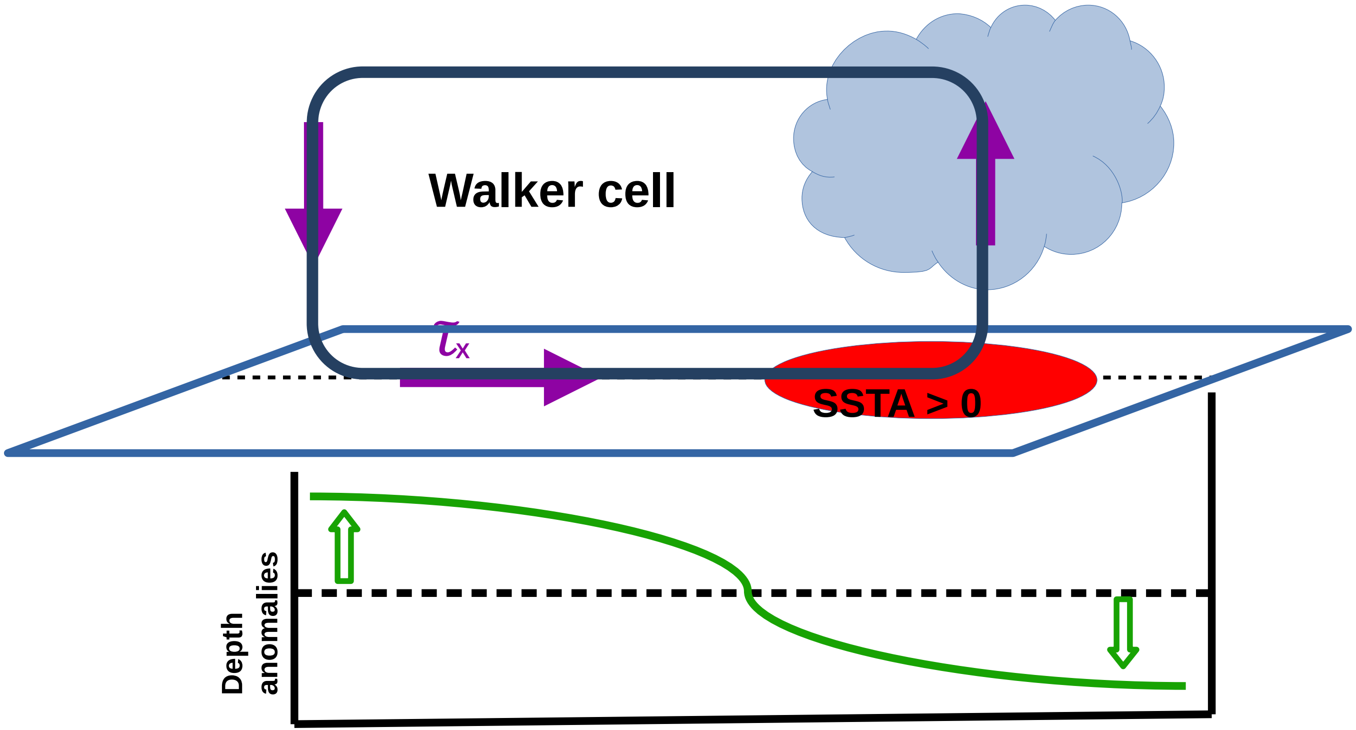
Mean state model biases

- Too **warm** in the cold tongue region
- Too **weak** easterly trade winds
- Too much precipitation/stagnation of the ITCZ in the equatorial Atlantic
-

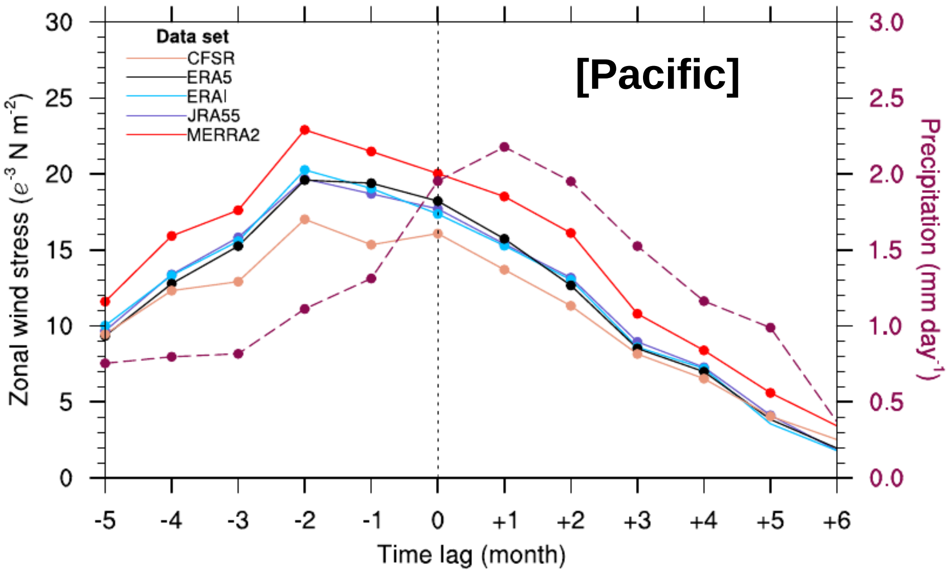


Richter & Tokinaga, 2020, *Clim. Dyn.*

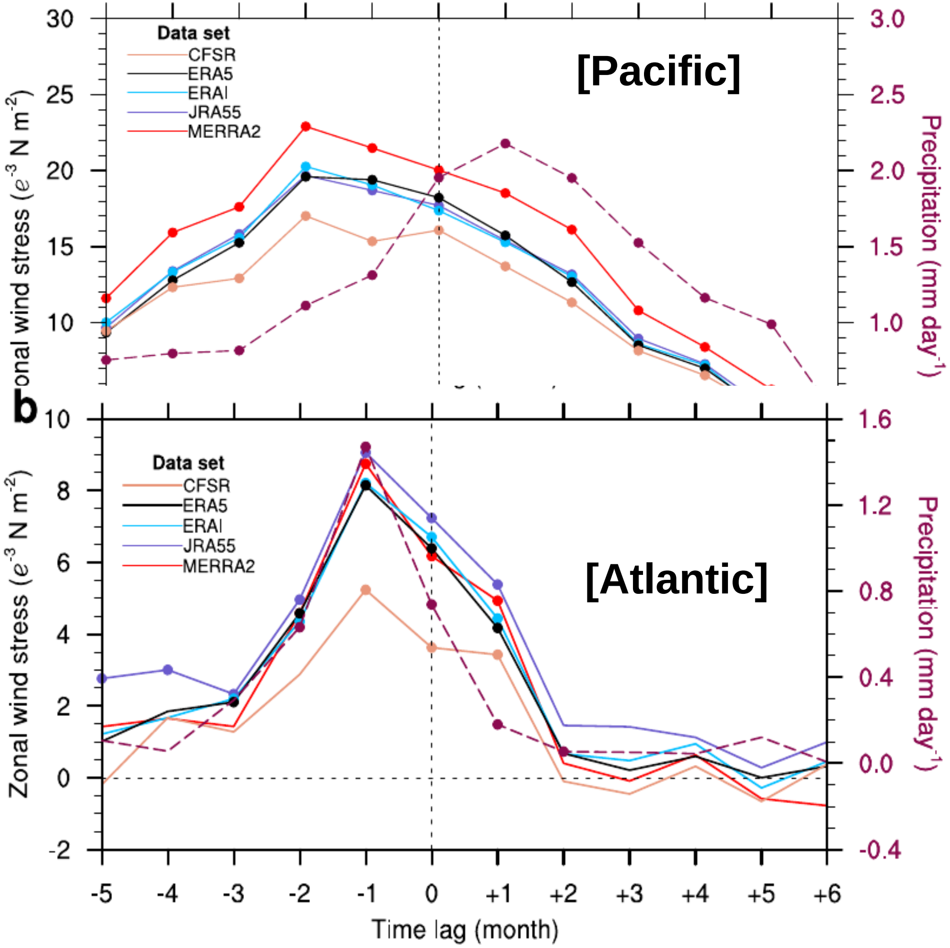
Revisiting observations.



Nnamchi et al., 2021



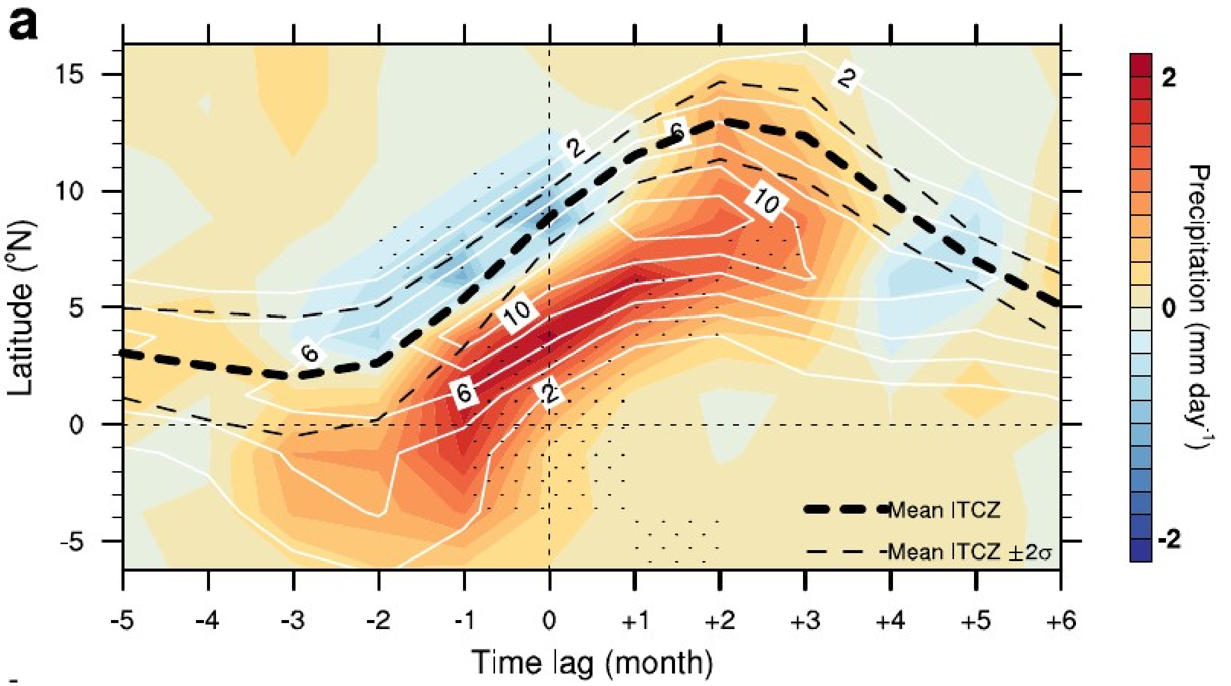
Nnamchi et al., 2021.



Nnamchi et al., 2021.

- Precipitation leads SST in the Atlantic
- Inconsistent with the Bjerknes mechanism
-

- **Seasonal migration of the ITCZ as a pacesetter for the interannual variability**



Nnamchi et al., 2021

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- **Summary**
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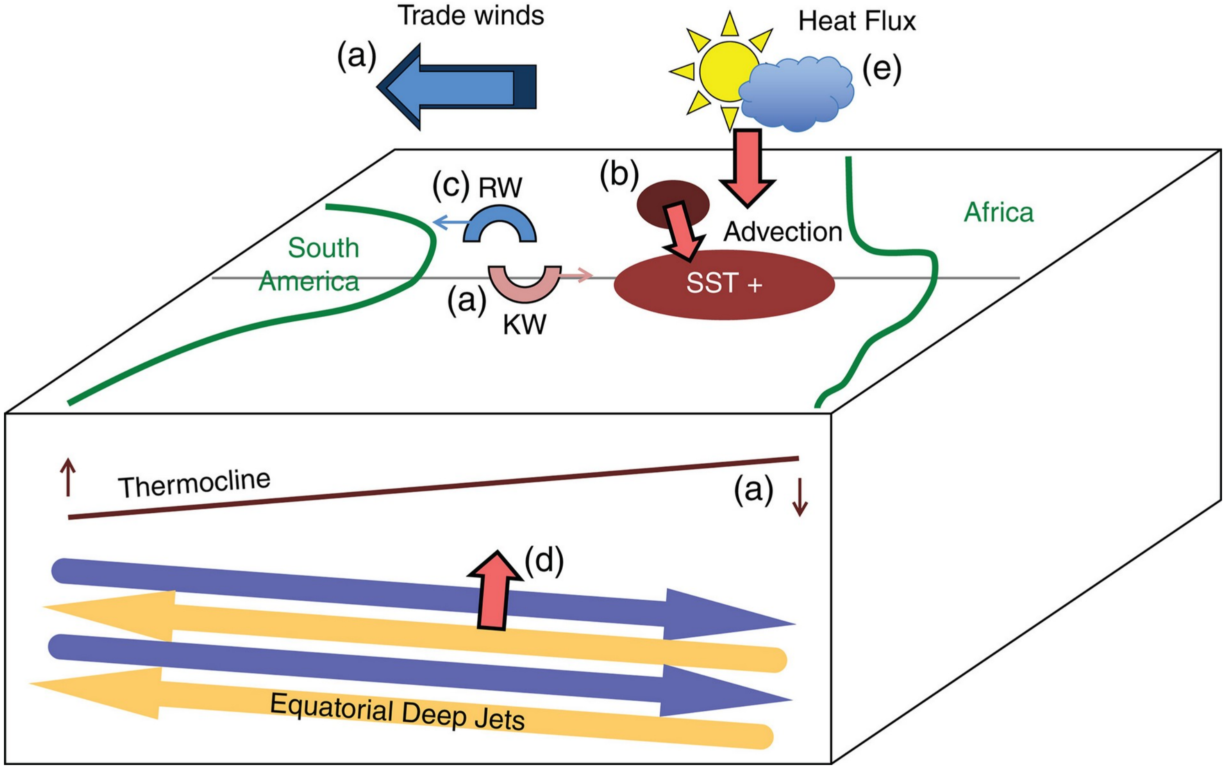
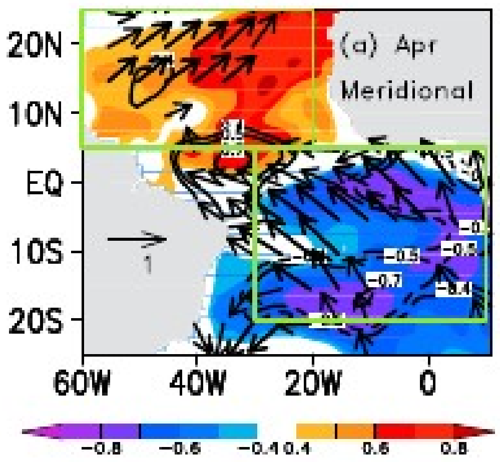


Lübbecke et al., 2018, *WIREs Clim Change*

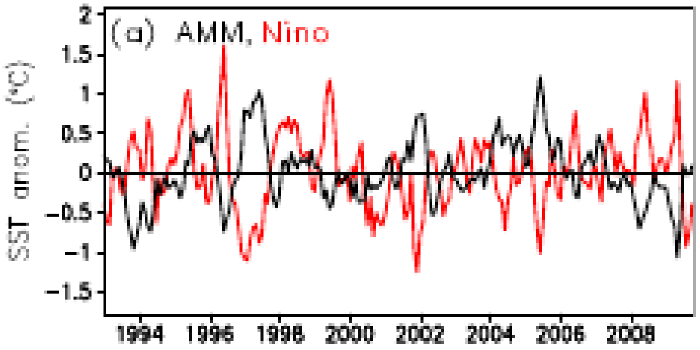
Part III

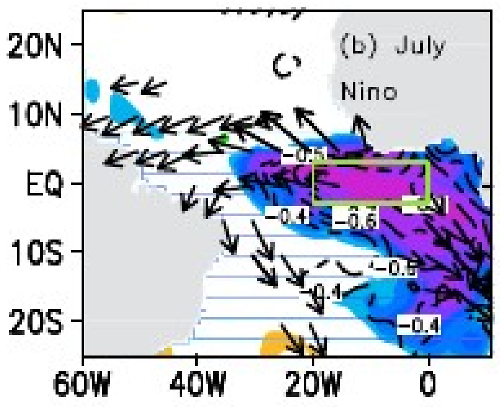
- **Interactions between the Atlantic Niño and meridional mode**

Atlantic meridional mode in *spring* forces Atlantic Niño the following *summer*.



Correlations of SST (shading), wind stress (vectors), and sea level (contours) with AMM in **April.**

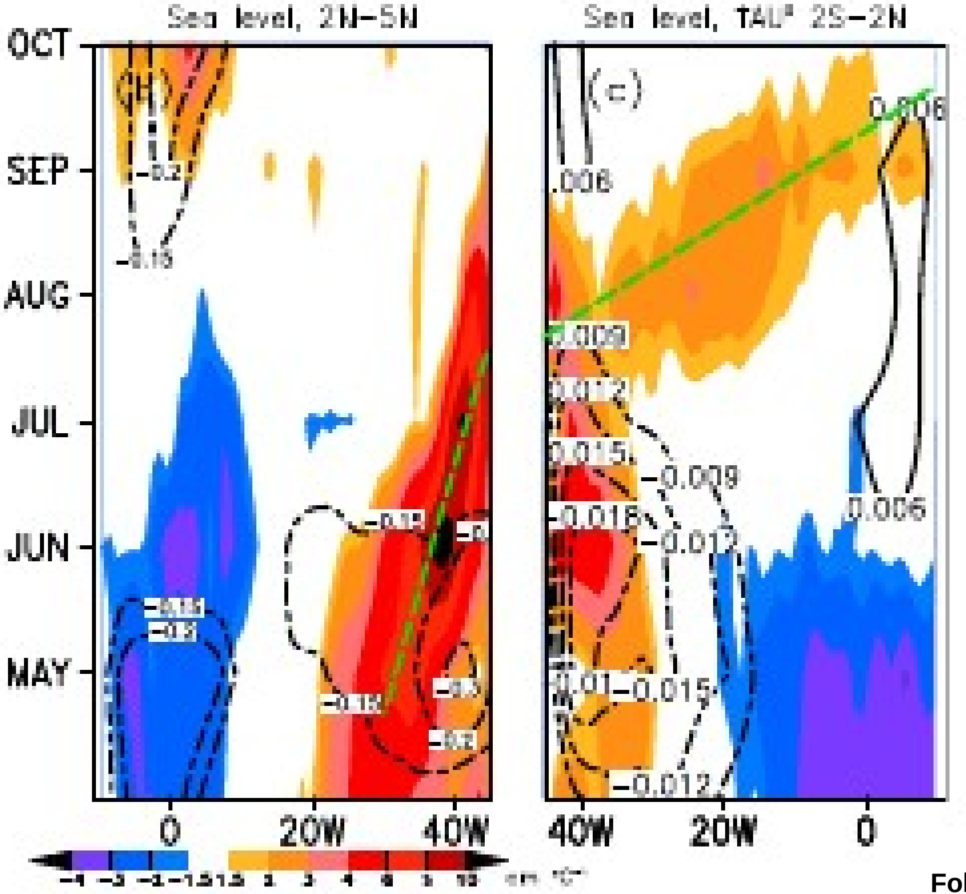




Correlations with Atlantic Niño in **July.**

Foltz & McPhaden, 2010; *GRL*

Wind-forced Rossby wave propagation is reflected at the western boundary into eastward propagating Kelvin waves



Evolution of **sea level** (shaded) and **Ekman pumping velocity** (contours, negative downward). The longitude axis has been reversed to show reflection at the westernboundary.

Foltz & McPhaden, 2010

Atlantic meridional mode (***dashed line***) is related to the (***dashed/dotted***), and thermocline (***solid***).

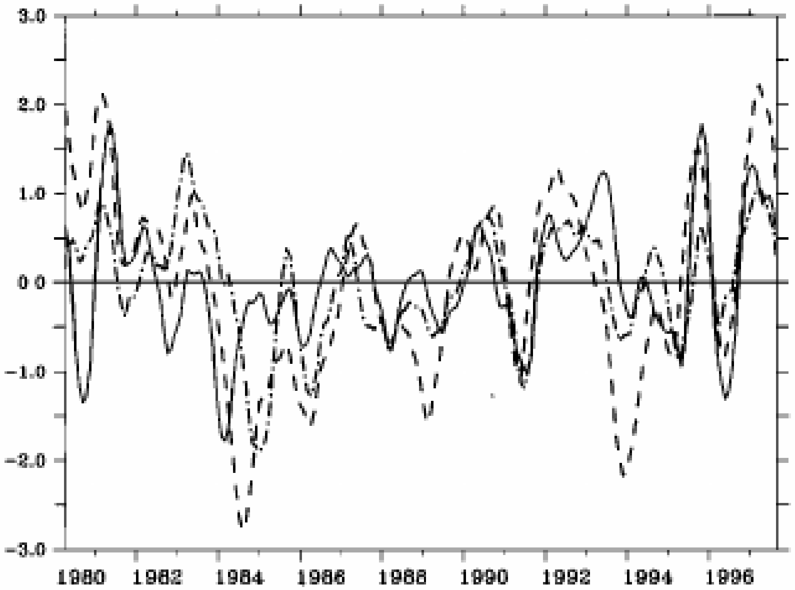
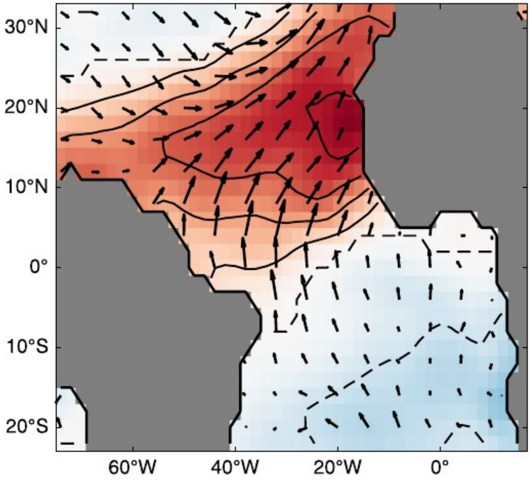


Figure 3. Monthly time series of ΔZ20 (solid line), ΔSST (dashed line), and ΔITCZ (dashed/dotted line) from the observations for the period 1980–1997. ΔZ20 is an index of the changes in the equatorial thermocline west-east slope, ΔSST measures the north-south SST gradient, ΔITCZ identifies the changes in the latitudinal position of ITCZ. Each time series is smoothed by a 6-month running-mean filter.

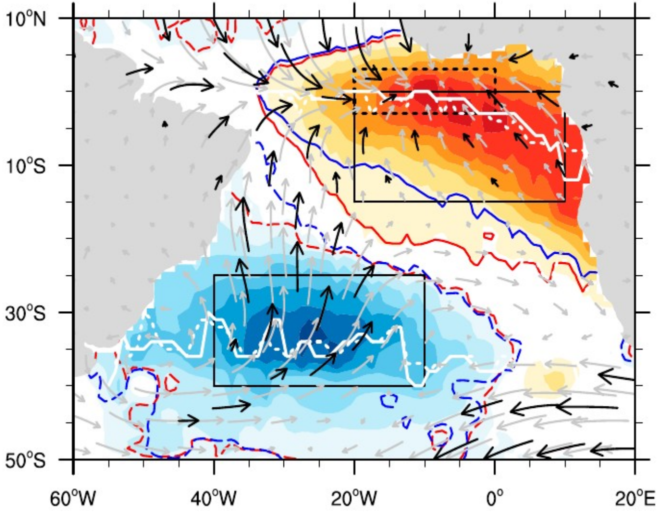
Servain et al., 1999, *GRL*

Tropical Atlantic



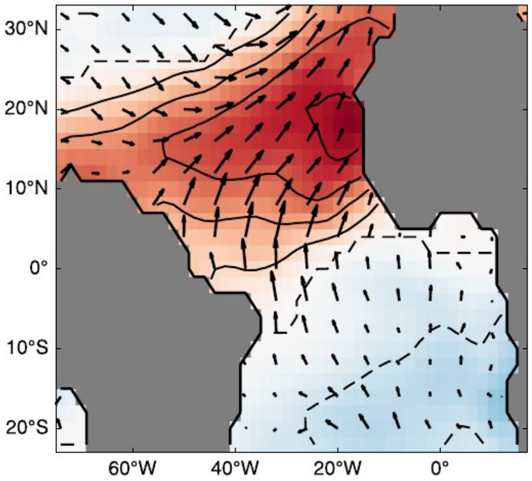
Amaya et al., 2016.

South Atlantic



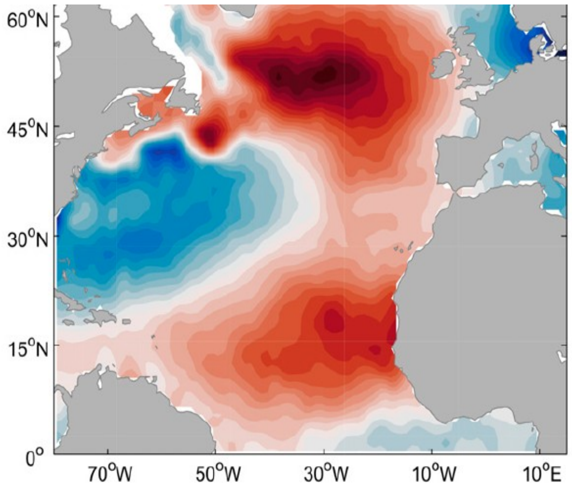
Nnamchi et al., 2016. *J. Climate*

Tropical Atlantic



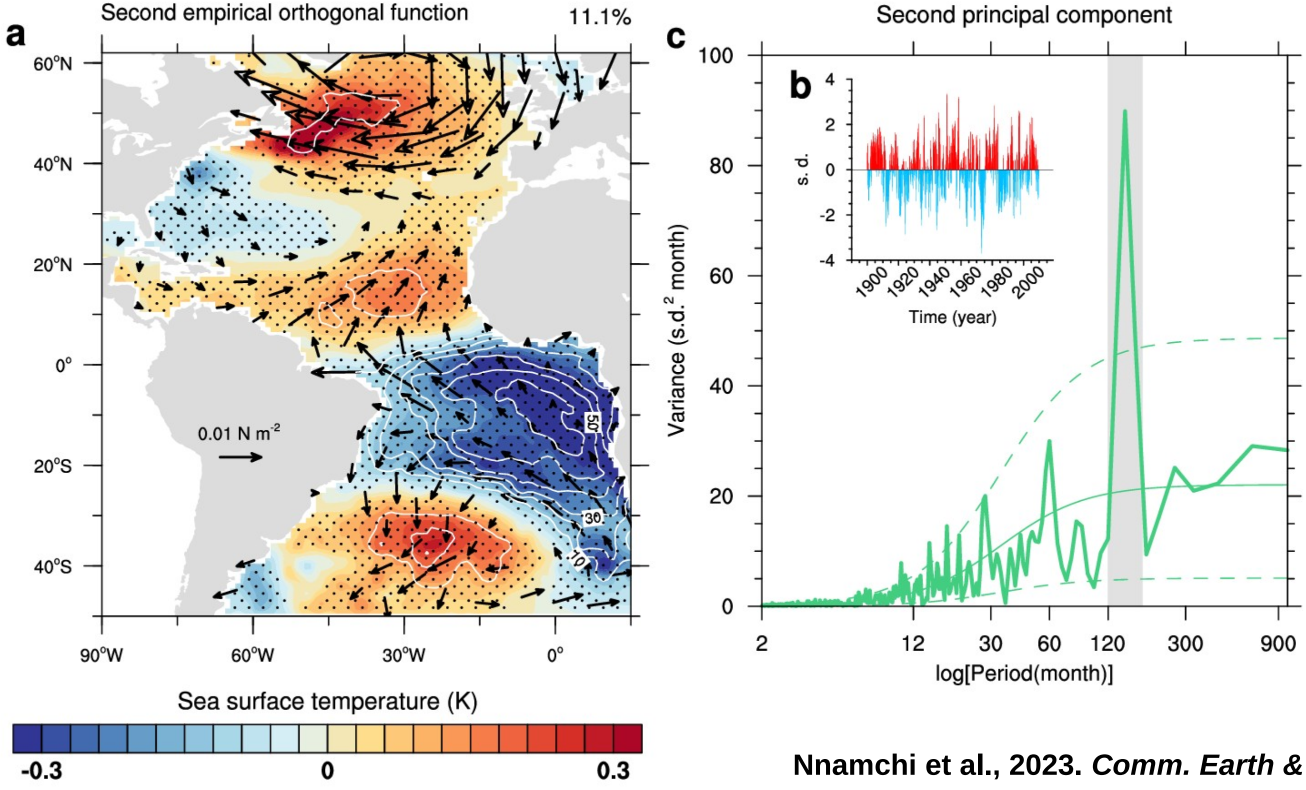
Amaya et al., 2016. *Clim. Dyn.*

North Atlantic

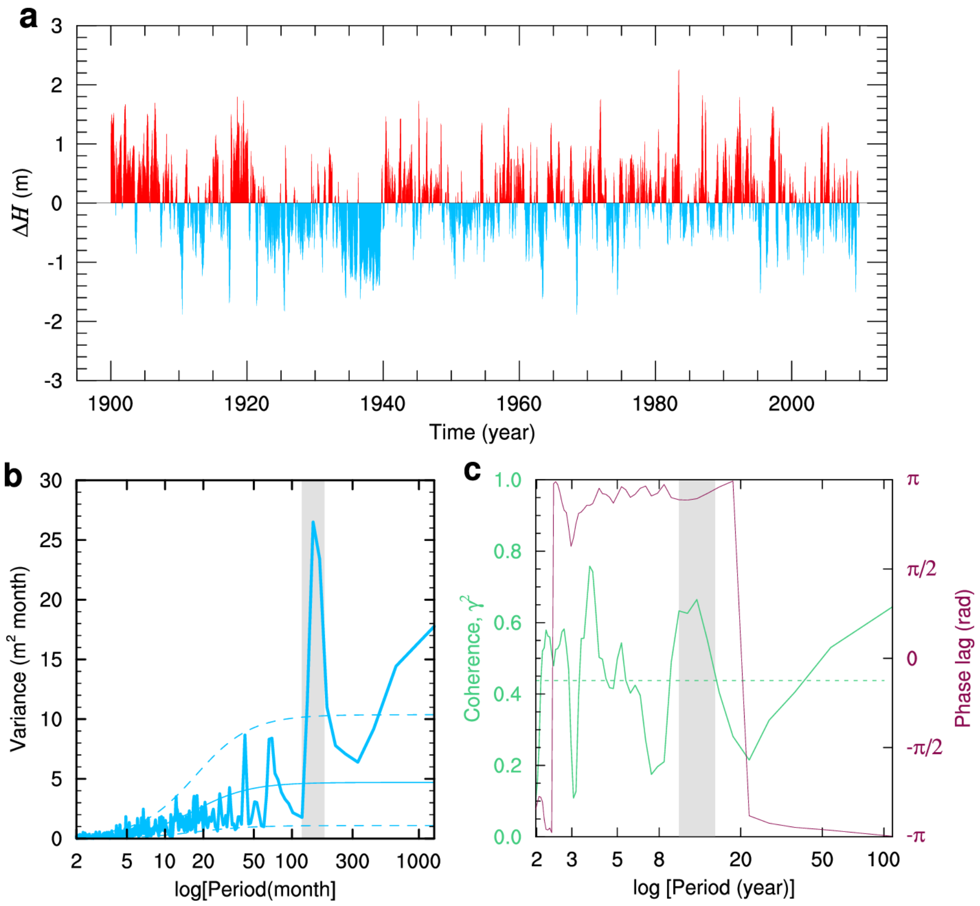


Ãrthun et al., 2021. *J. Climate*

Atlantic-scale pattern of variability on interannual to decadal timescales



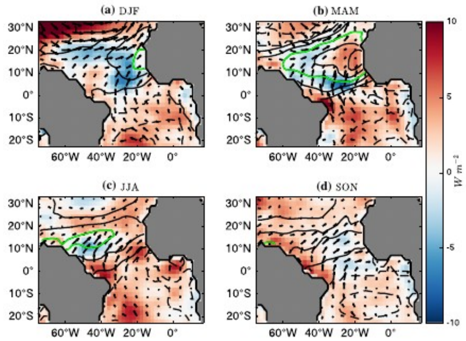
Nnamchi et al., 2023. *Comm. Earth & Environ.*



Strong interannual to decadal variability resides in the Atlantic Nino region.

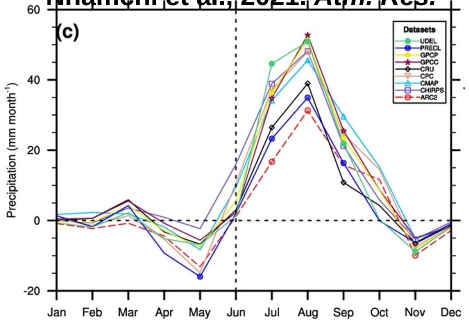
Closing perspectives

Amaya et al., 2017. *Clim. Dyn.*



- First two modes of tropical Atlantic variability are oriented in the zonal and meridional directions respectively.
- Atlantic Niño is driven by other mechanisms, in addition to the Bjerknes feedback. Is the meridional mode fully explained by the WES feedback?
-
- The classical Bjerknes feedback loop (as seen in the tropical Pacific) is modified in the Atlantic by the seasonal migrations of the ITCZ.
- The ITCZ as a pacesetter for seasonal climate in the tropical Atlantic, linking the two modes and the continents.
- Strong interannual to decadal variability resides in the cold tongue region, potentially related to other parts of the basin. The underlying mechanism remains an open question.

Nnamchi et al., 2021. *Atm. Res.*

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Thank you
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References

- DiNezio, P. N., Puy, M., Thirumalai, K., Jin, F.-F., & Tierney, J. E. (2020). Emergence of an equatorial mode of climate variability in the Indian Ocean. Science Advances, 6(19), eaay7684. https://doi.org/10.1126/sciadv.aay7684

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