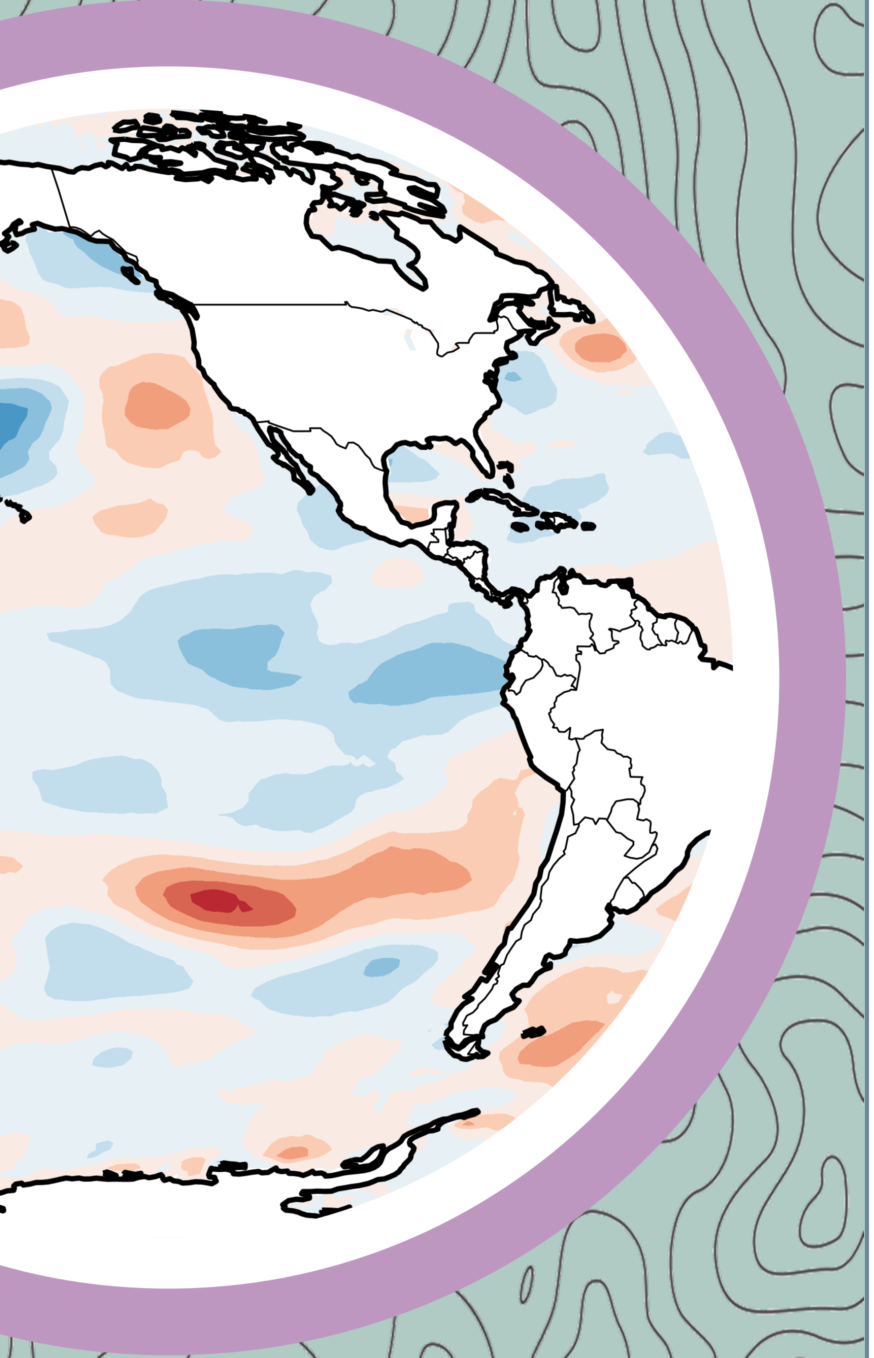

The critical role of atmospheric nonlinearities in producing ENSO asymmetry

Jacob Stuivenvolt-Allen and Alexey Fedorov

1. Introduction of the problem
2. A hybrid-coupled model in CESM2
3. Ocean versus atmos. nonlinearities
4. Conclusions and implications

NCAR RAL

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Yale Earth & Planetary Sciences

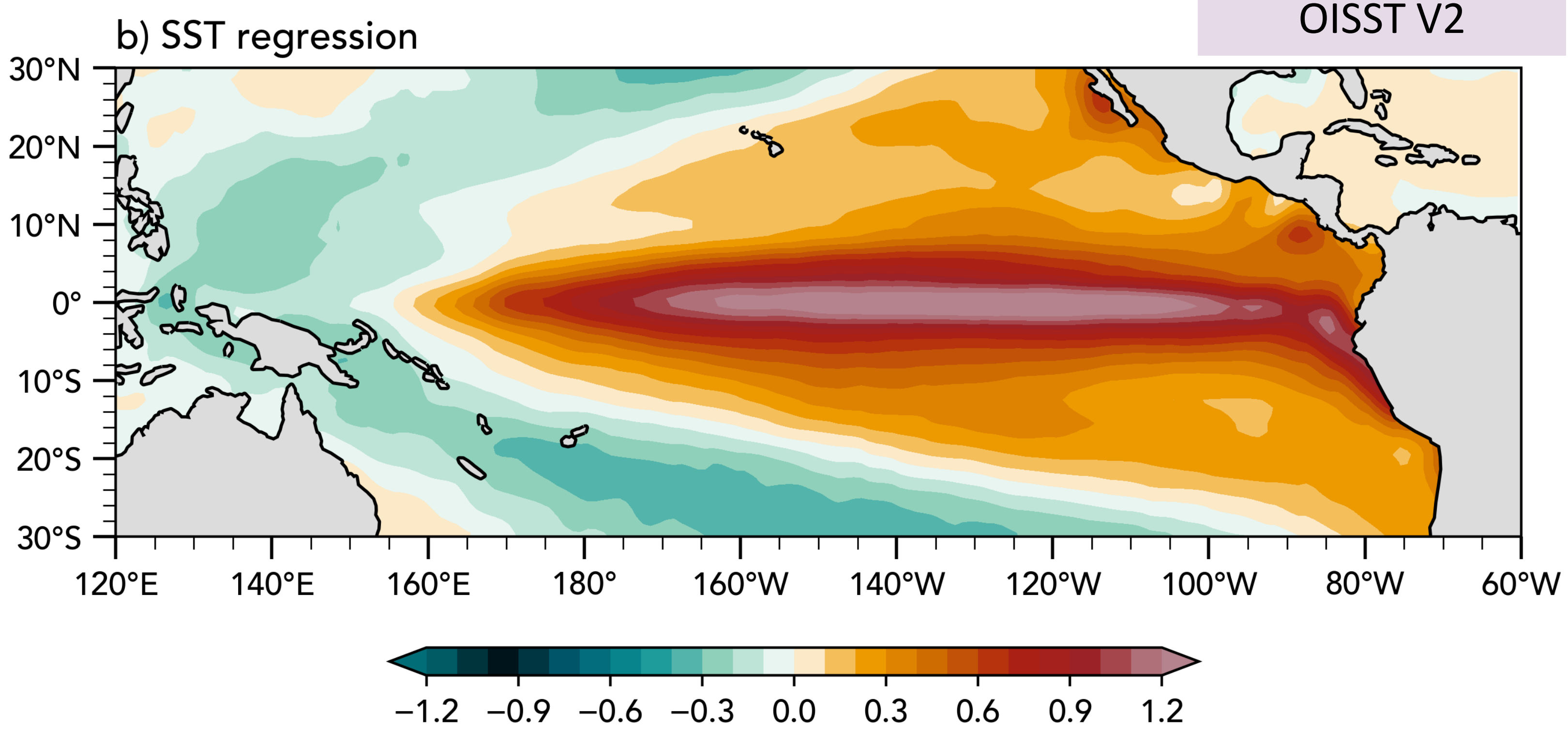
Atmosphere, Ocean, Climate Dynamics

Introduction

ENSO in observations

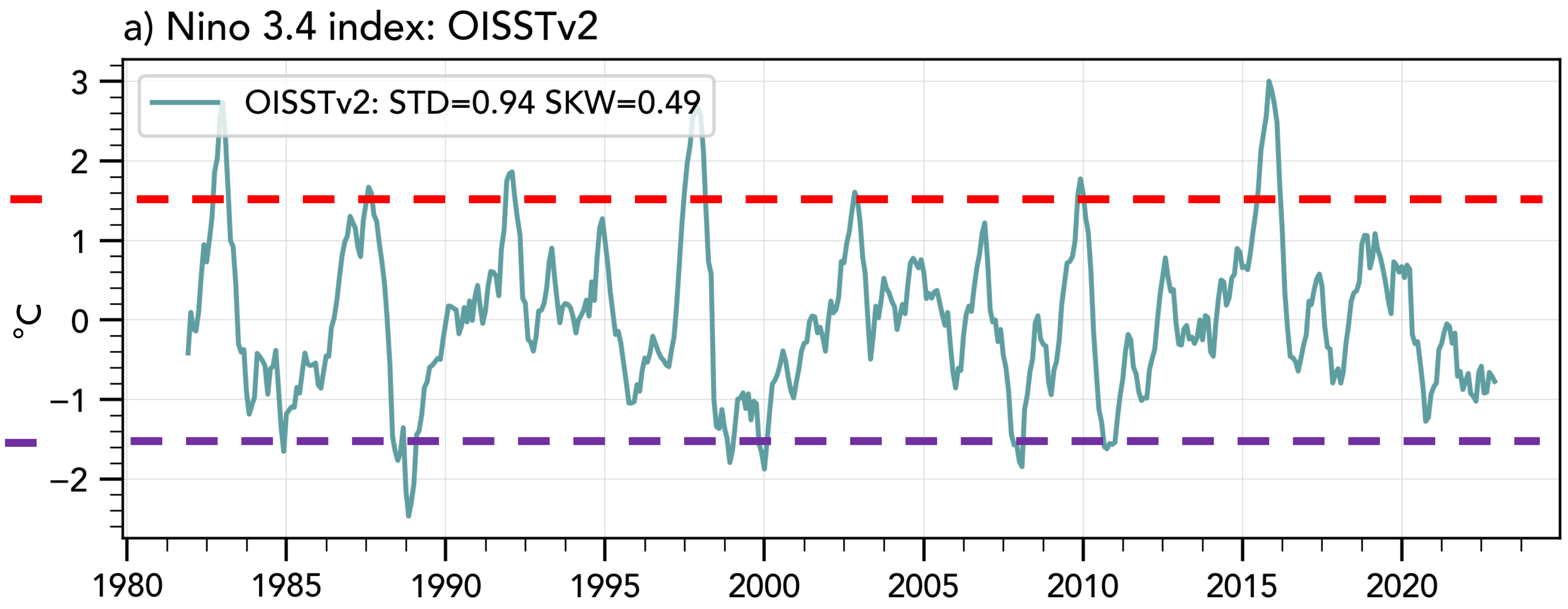
El Niño and La Niña are not mirror images of each other!

OISST V2



Strong El Niño

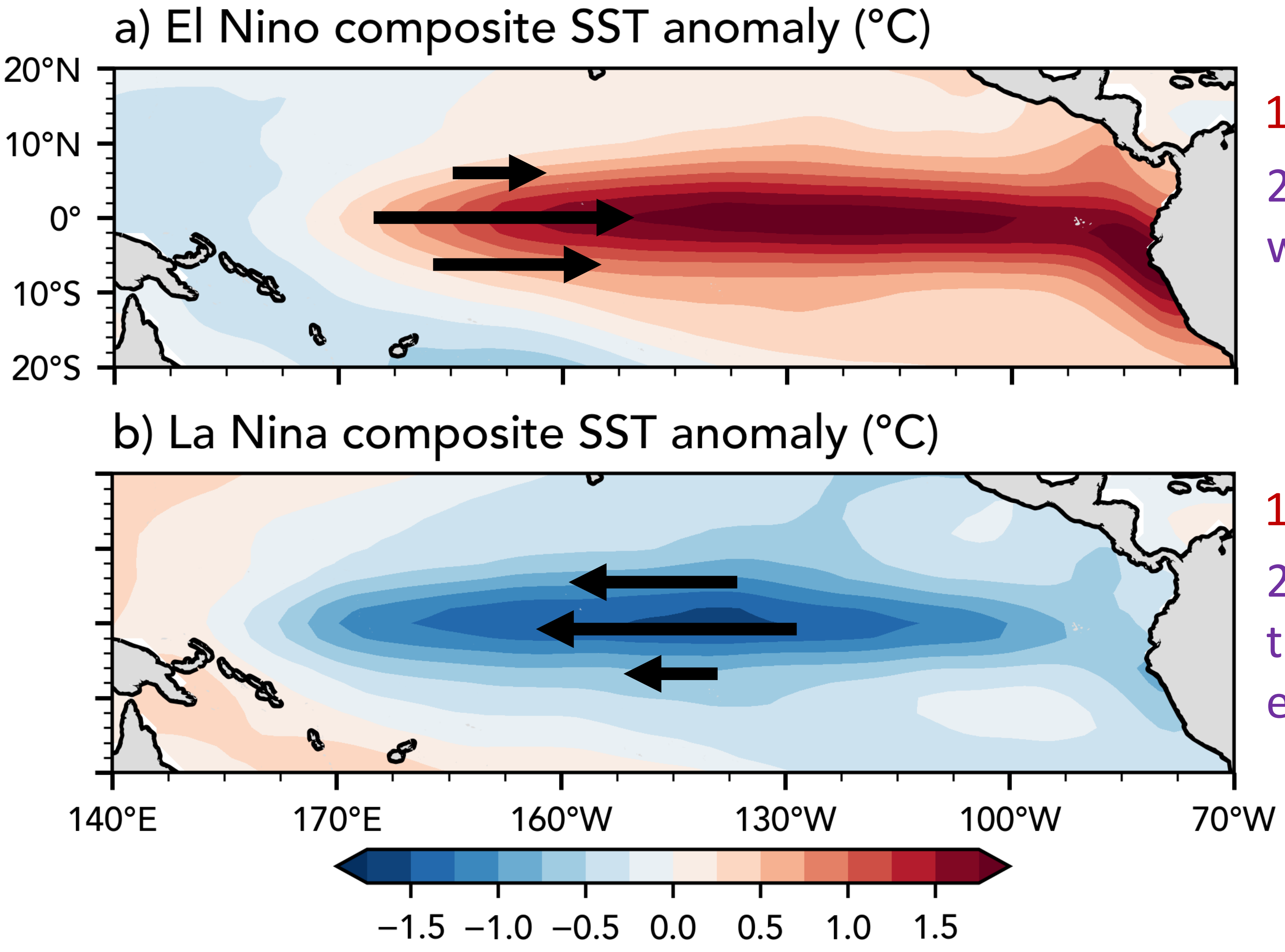
Strong La Niña



Introduction

The fundamental ENSO asymmetry

OISST V2



1. Westerly wind anomalies
2. Thermocline shoals in the west and deepens in the east

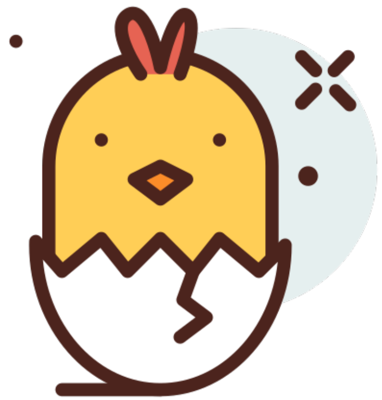
1. Easterly wind anomalies
2. Thermocline deepens in the west and shoals in the east

An et al., 2000a;2000b;2001;2004, Hayashi et al. 2021; Liu et al., 2024

The fundamental ENSO asymmetry

OISST V2

Atmosphere	**VS.**	**Ocean**
1. Westerly wind bursts 2. Nonlinear response of wind-stress to SST		1. Nonlinear heat advection 2. Thermocline adjustment



The range of ENSO skewness in CMIP6 is -0.5 to 1.15!!

An et al., 2000a;2000b;2001;2004, Hayashi et al. 2021; Liu et al., 2024

Experiment design – a hybrid-couped model of ENSO

If we linearize atmospheric wind-stress…

The resulting ENSO asymmetry will be what the ocean produces itself!

If we add it appropriate nonlinearities in wind-stress…

We can identify how important the nonlinear wind-stress response is.

CESM2 experiments

Experiment design – a hybrid-couped model of ENSO

Step 1:

Take wind-stress anomalies from obs. and climatology from CESM2 Control

Step 2:

Edit source code in the coupler to manipulate the zonal surface momentum flux – give it the patterns of ENSO τ_x from Step 1.

Linear

$$\tau_x = \overline{\tau_x^{piC}} + \boxed{\tau'_x(Niño_{3.4}^{\mathrm{Internal}})}$$

Linear **Nonlinear**

$$\tau_x = \overline{\tau_x^{piC}} + \boxed{\tau'_{x1}\left(Niño_{3.4}^{Internal}\right)} + \boxed{\tau'_{x2}\left(\mathrm{Niño}_{3.4}^{Internal}\right)^2}$$

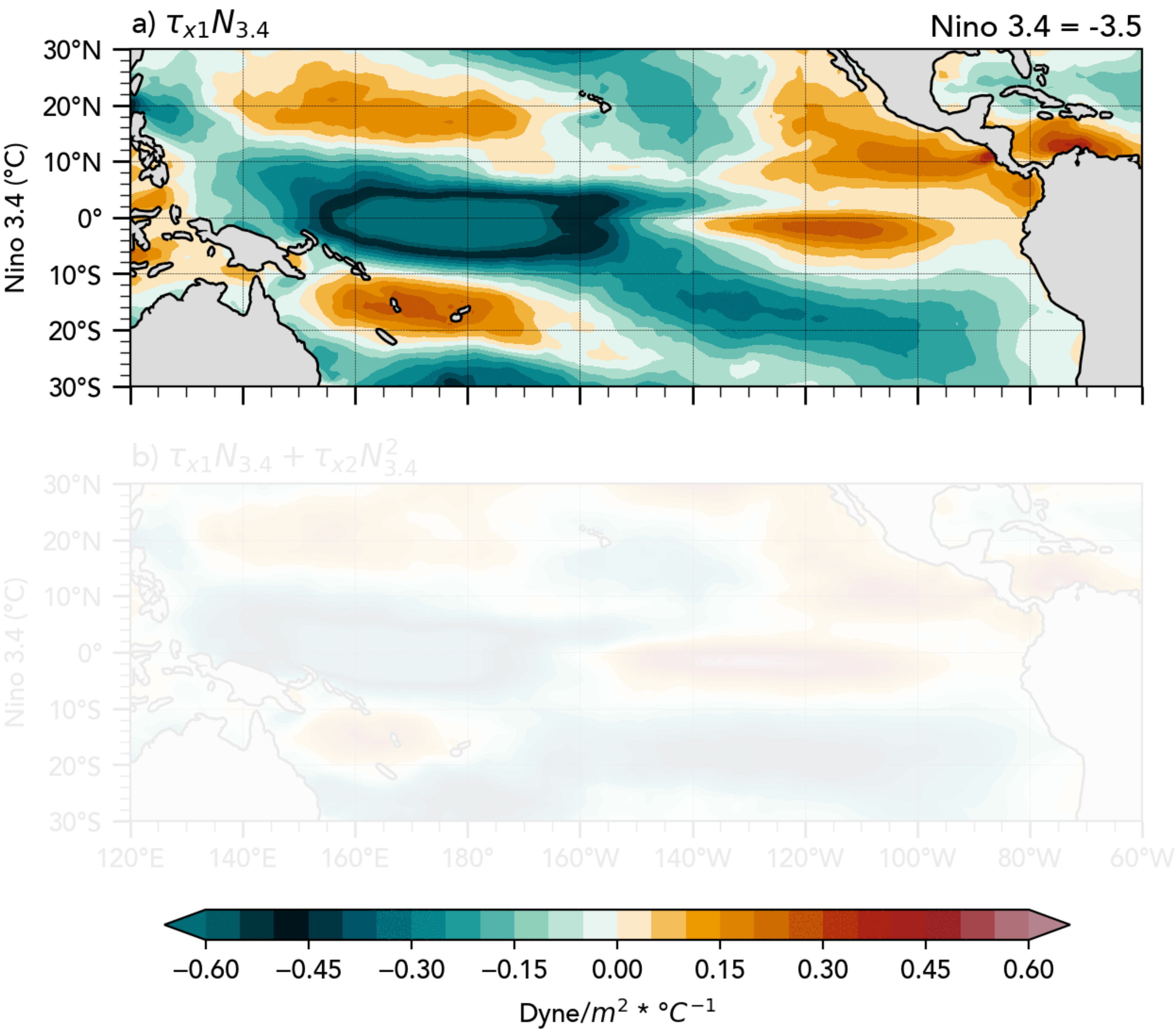
CESM2 experiments

Adding the observed wind-stress pattern

Blue is easterly!

Red is westerly!

2^{nd} order least squares fitting of ERA5 τ_x' onto observed Niño 3.4 index!



CESM2 experiments

Adding the observed wind stress pattern

Blue is easterly!

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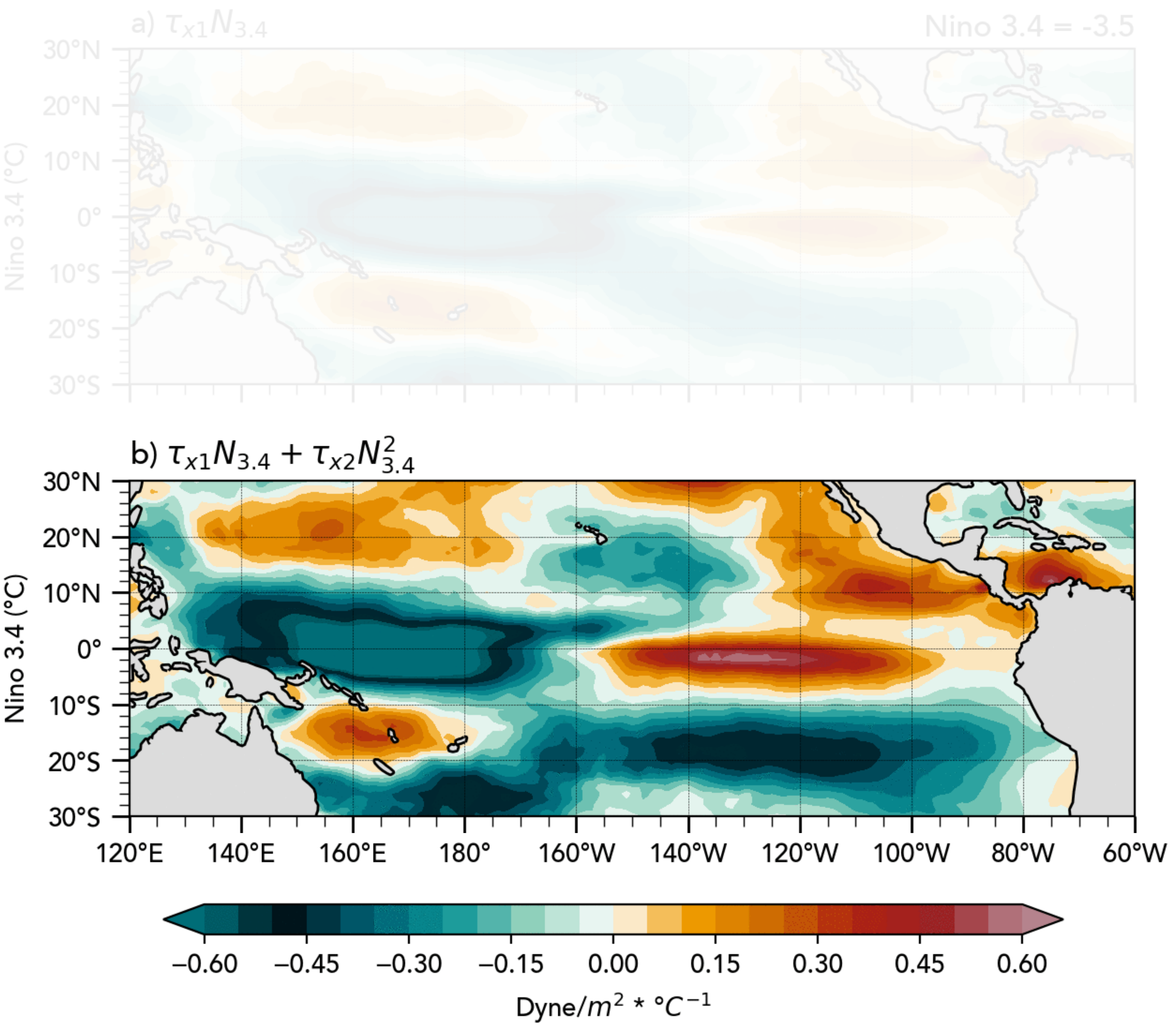


CESM2 experiments

Experiment tables

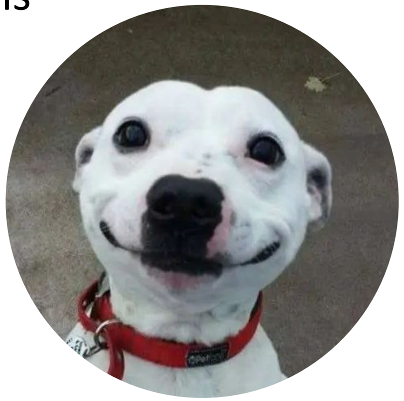
Simulation name	Formulaic expression for τ_x'
Linear	$\tau_{x1}' \times \mathrm{Nino}_{3.4}$
Amplified linear	$^3/_2\,(\tau_{x1}' \times \mathrm{Nino}_{3.4})$
Reduced nonlinear	$\tau_{x1}' \times \mathrm{Nino}_{3.4} + {}^4/_5\,(\tau_{x2}' \times \mathrm{Nino}_{3.4}^2)$
Nonlinear	$\tau_{x1}' \times \mathrm{Nino}_{3.4} + (\tau_{x2}' \times \mathrm{Nino}_{3.4}^2)$

Simulation name	Reason for running
Linear	*Can ocean nonlinearities alone create asymmetry?*
Amplified linear	*Do ocean nonlinearities depend on coupling strength?*
Reduced nonlinear	*Does adding nonlinear τ_x improve ENSO asymmetry?*
Nonlinear	*How strong of a τ_x nonlinearity is needed?*

Ocean versus Atmos.

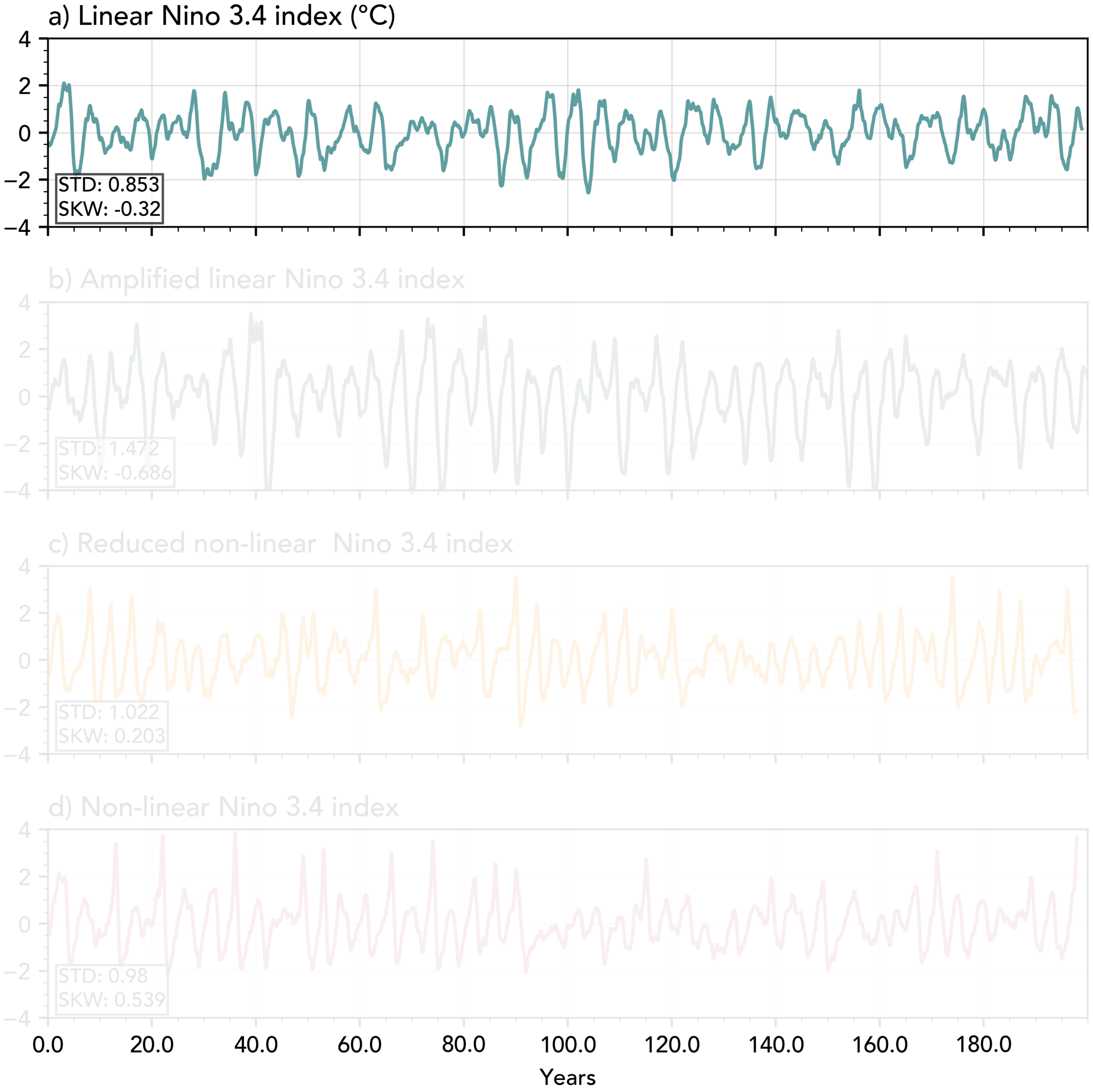
Niño 3.4 index and stats

- 2.7 – 5 year dominant variability
- Irregular and chaotic behavior
- Realistic amplitudes and spatial patterns



Linear experiments produce negative ENSO asymmetry

Nonlinear experiments produce positive ENSO asymmetry



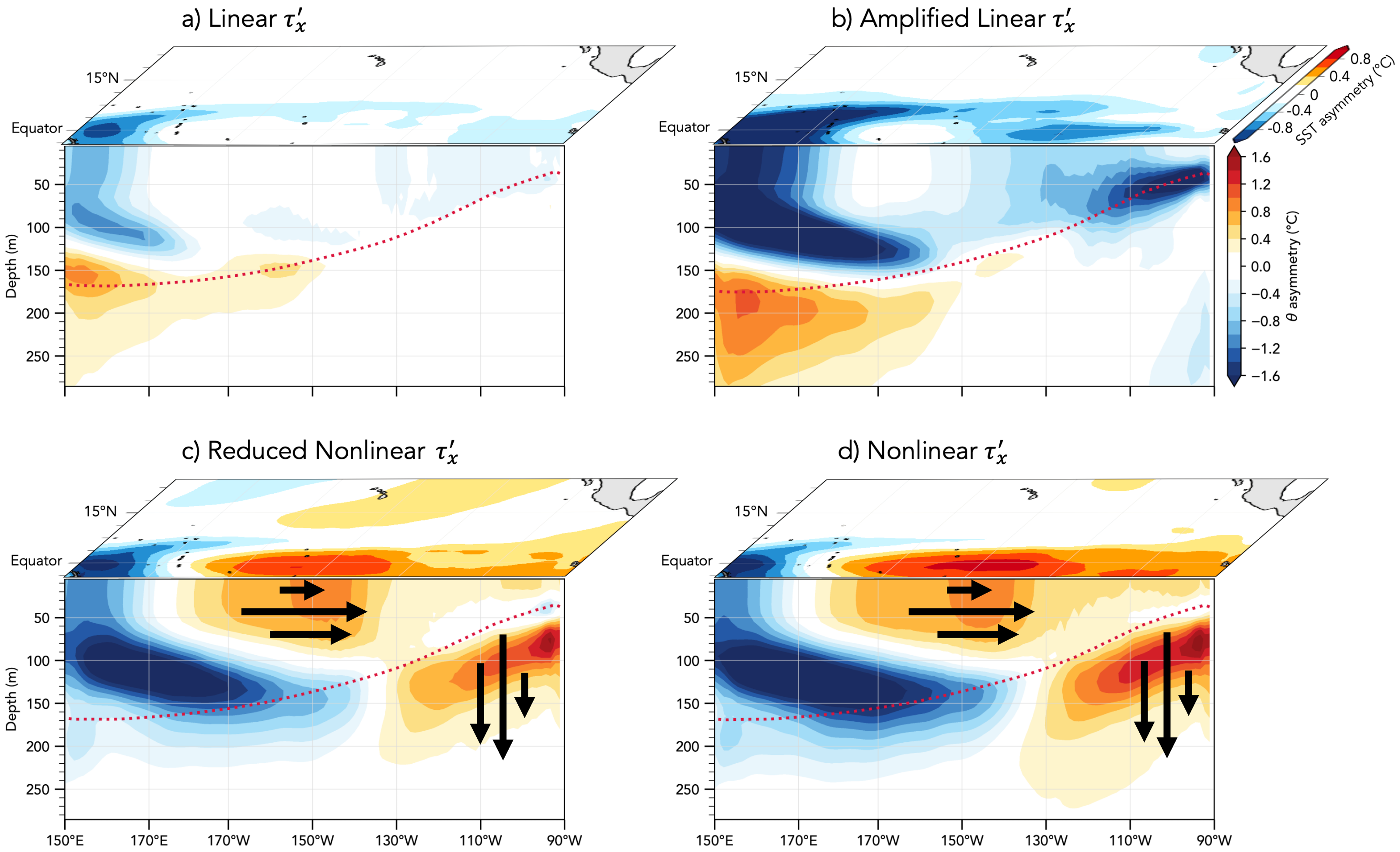
Ocean versus Atmos.

Resulting ENSO asymmetry

Hybrid-coupled CESM2 exps.

Red shading = positive asymmetry (El Niño anomaly > La Niña anomaly)

Blue shading = negative asymmetry (La Niña anomaly > El Niño anomaly)



Liu et al., 2024 ; Srinivas et al., 2024

Conclusions and implications

Ocean versus Atmos.

Can ocean nonlinearities alone create asymmetry?

Not the correct one! Without τ_x nonlinearities, ENSO is negatively skewed!

Do ocean nonlinearities depend on coupling strength?

Increasing linear coupling strength exacerbates negative skewness.

Does adding τ_x nonlinearities improve ENSO asymmetry?

YES**.** With atmos. nonlinearities, the ocean nonlinearities follow.

How strong of a τ_x nonlinearity is needed?

Only with the full strength τ_x nonlinearity do we get ENSO statistics like OBS.

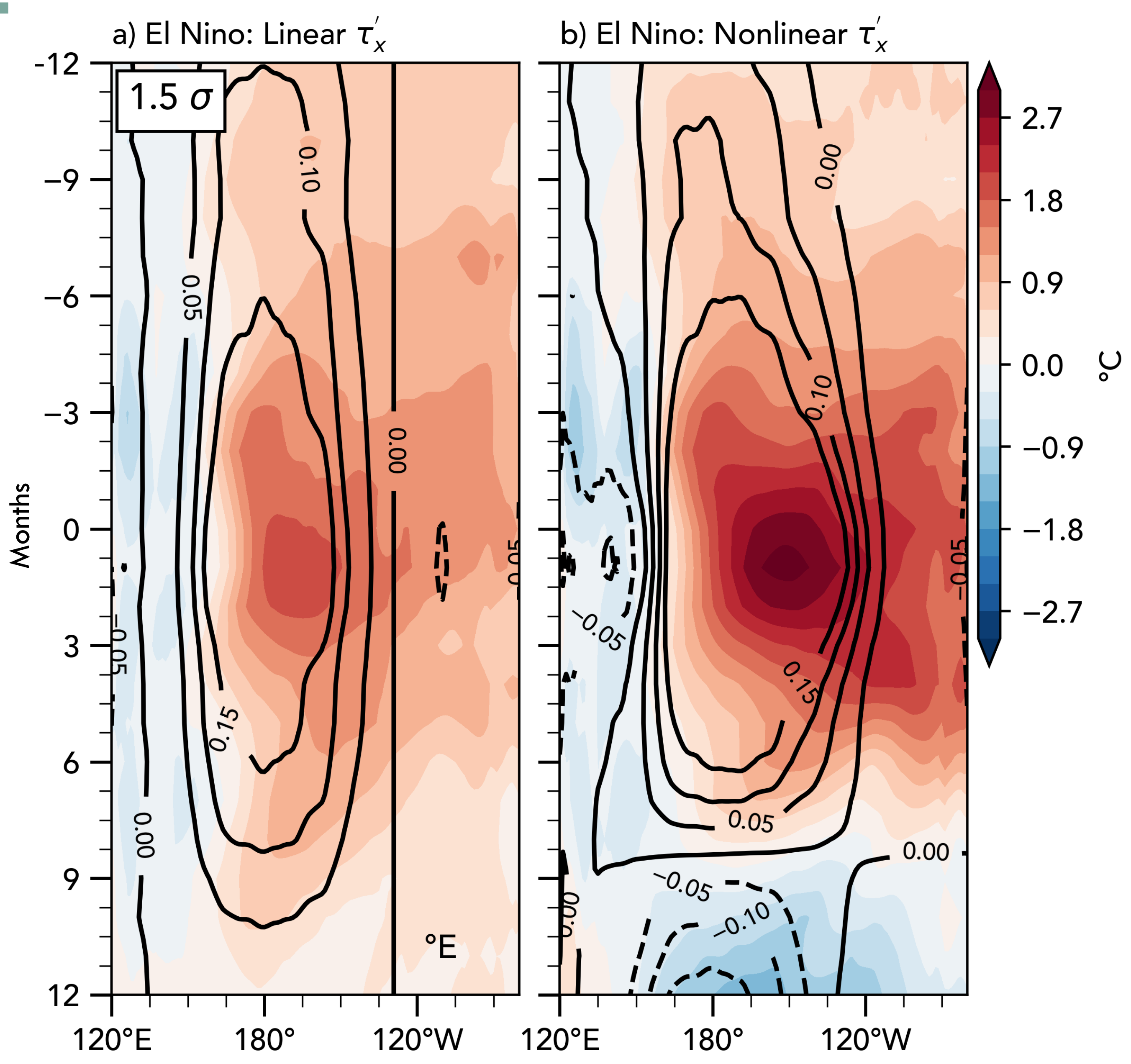
Conclusions

Conclusions and implications

Issues with ENSO skewness in GCMs comes from atmospheric nonlinearities

ENSO skewness problem remains in GCMs with high-resolution oceans

ENSO temporal evolution also depends on atmospheric nonlinearities!



Thanks! Questions?