

21st Century Projection of Tropical Climate Variability



Agus Santoso

Laoshan Laboratory

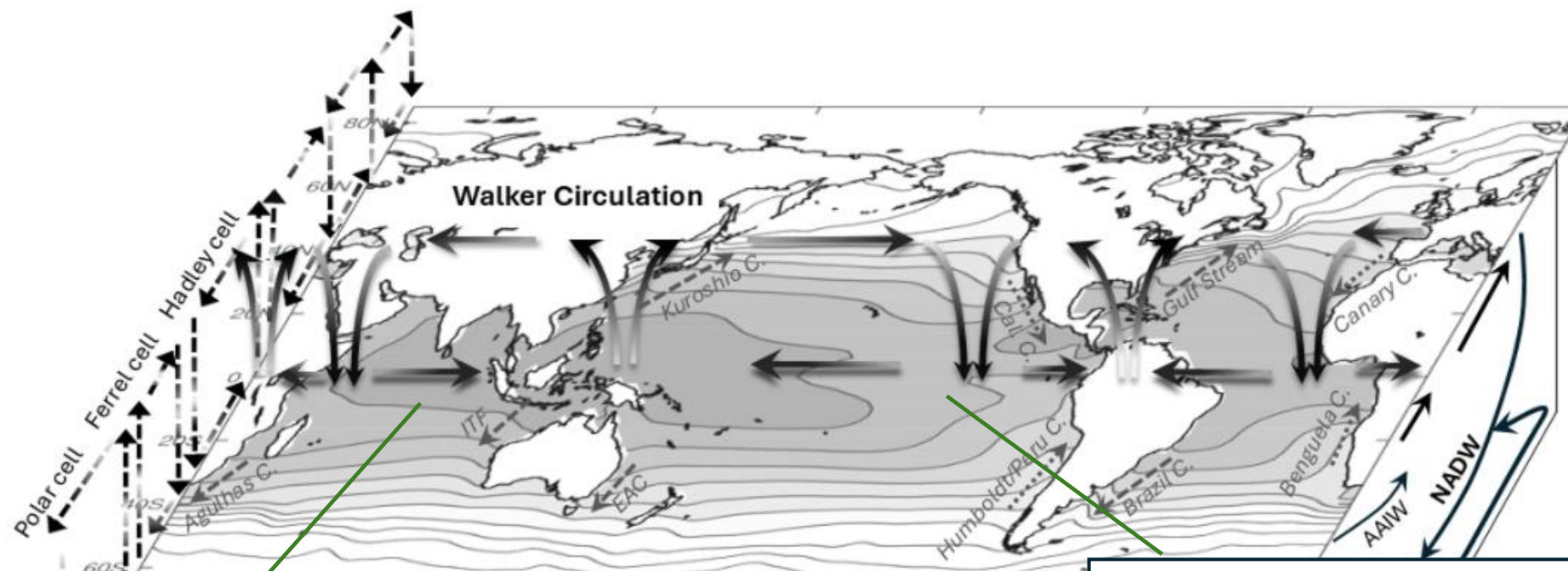
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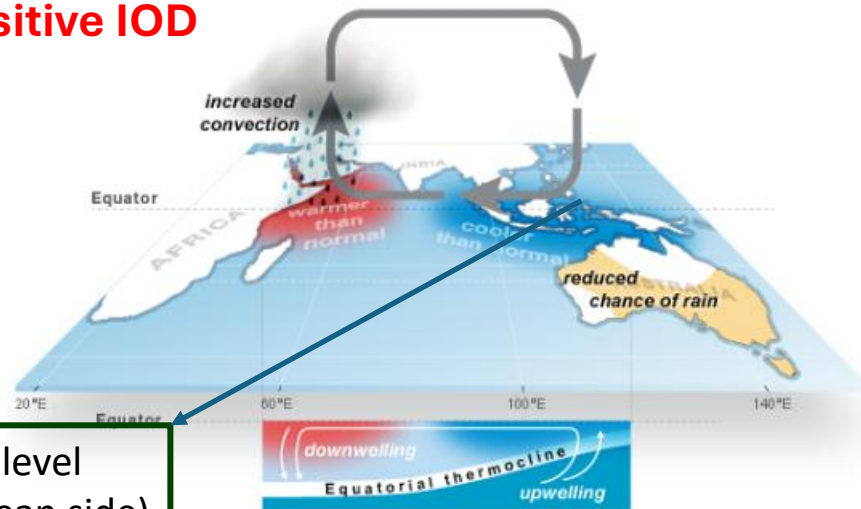


- Background
 - Modes of variability
 - Mechanisms
 - Predictability
 - Impacts
- Future projections
 - ENSO
 - IOD
 - Atlantic Nino
- Uncertainties
- Summary



ITF = Indonesian Throughflow

Positive IOD

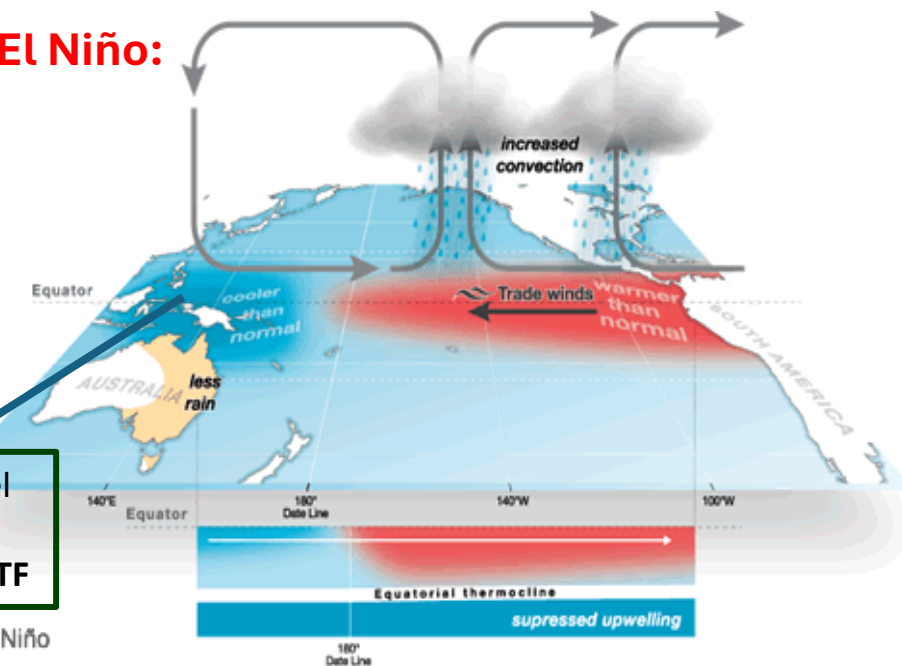


Indian Ocean Dipole (IOD): Positive phase

© Commonwealth of Australia 2013.

Lower sea level
(Indian Ocean side)
-> **increased** ITF

El Niño:

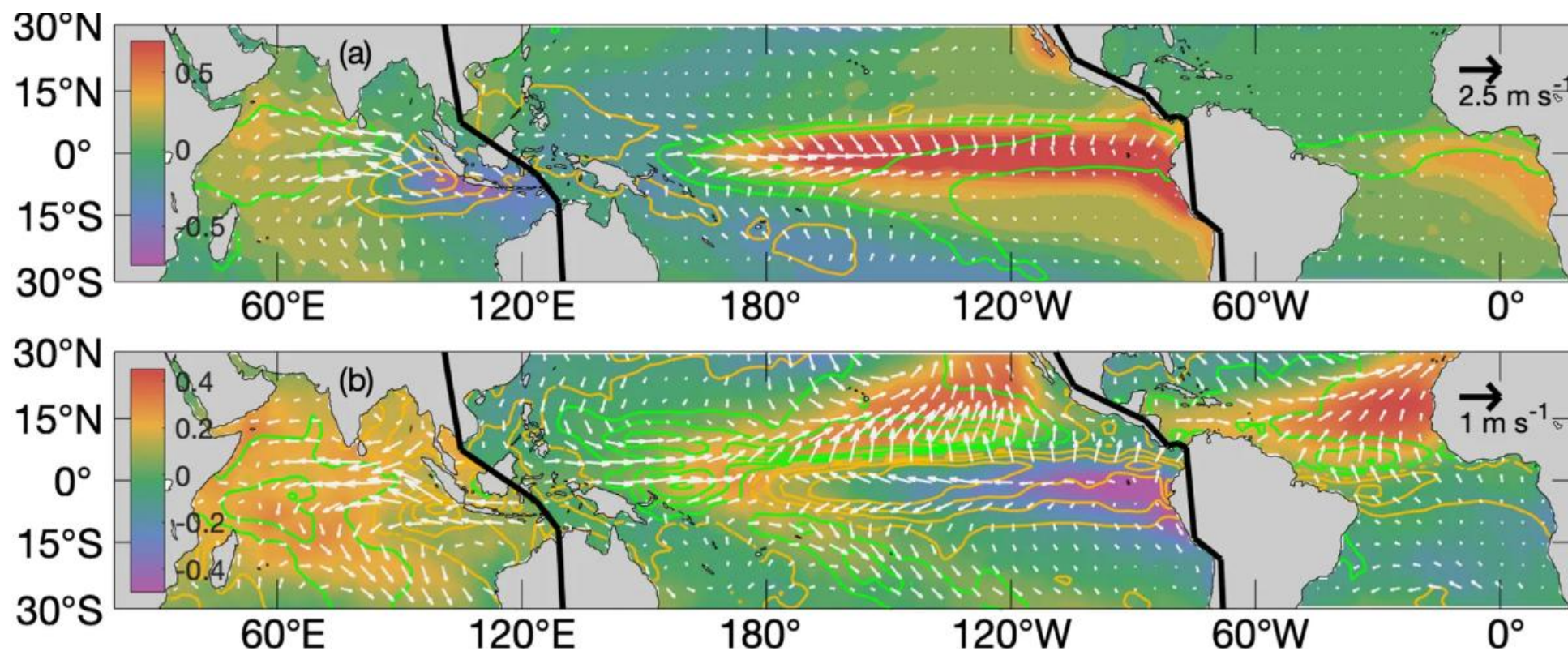


El Niño

Lower sea level
(Pacific side)
-> **decreased** ITF

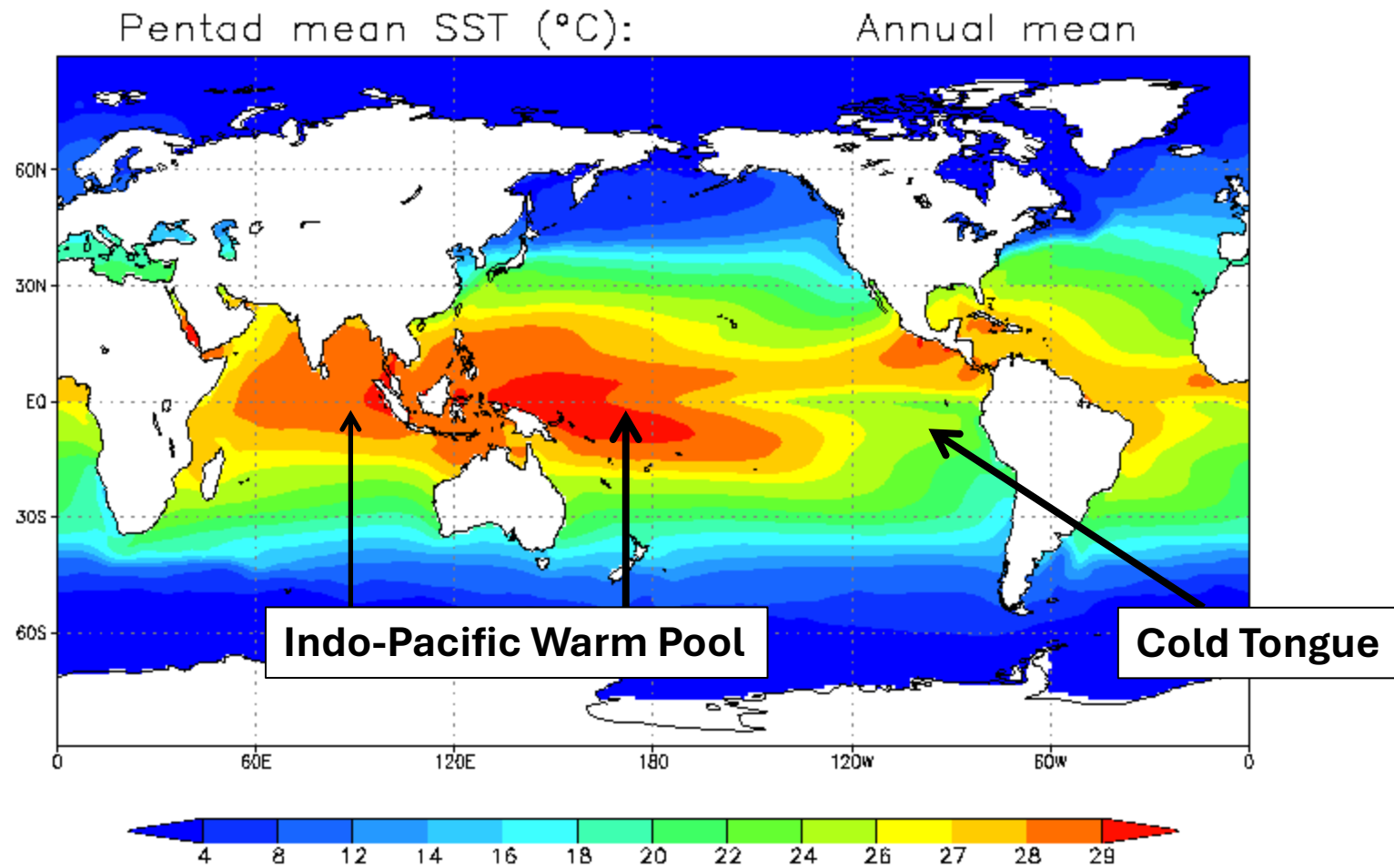
apter 4: Ro
k: Meteor

Toward an integrated pantropical ocean observing system



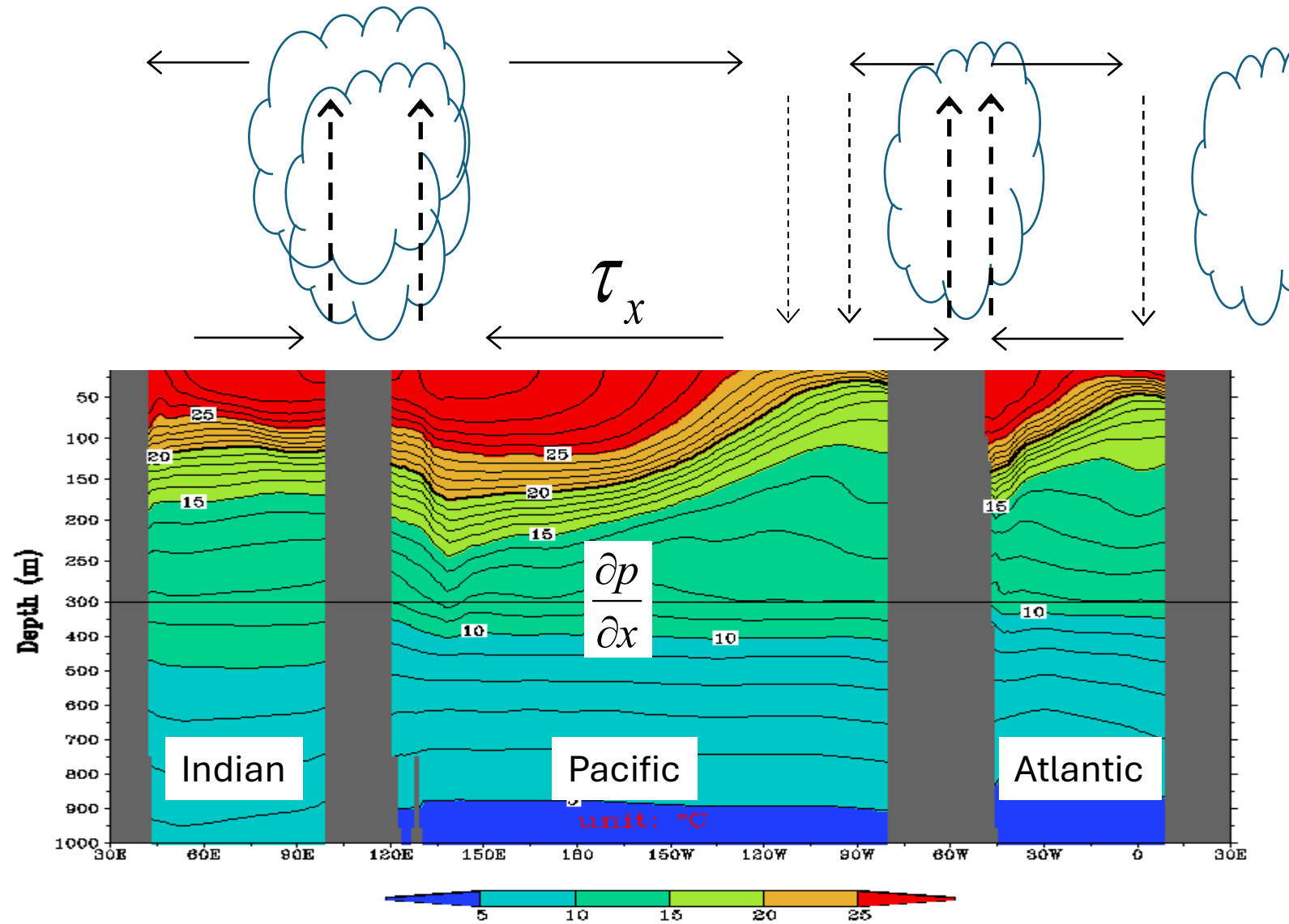
Indian Ocean Basin Mode

Meridional Modes



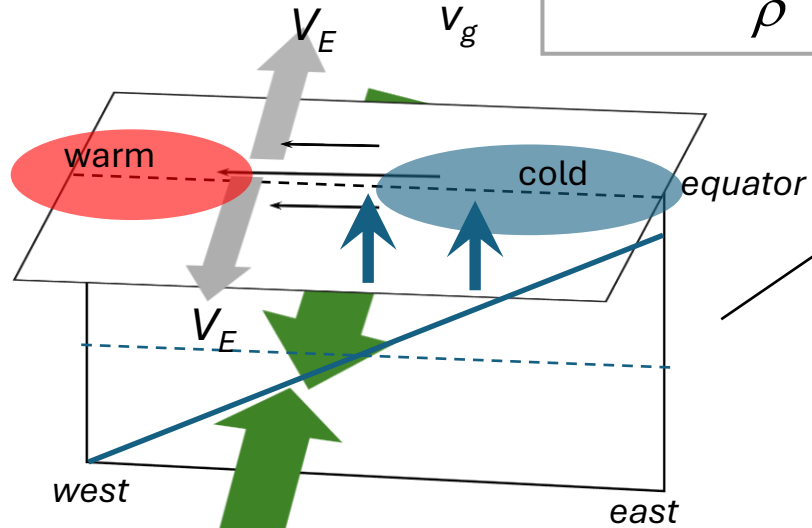
<http://www.cpc.ncep.noaa.gov/products/>

Walker Circulation, Trade Winds, and the ocean thermocline



Ekman transport out of equatorial region, inducing **upwelling**

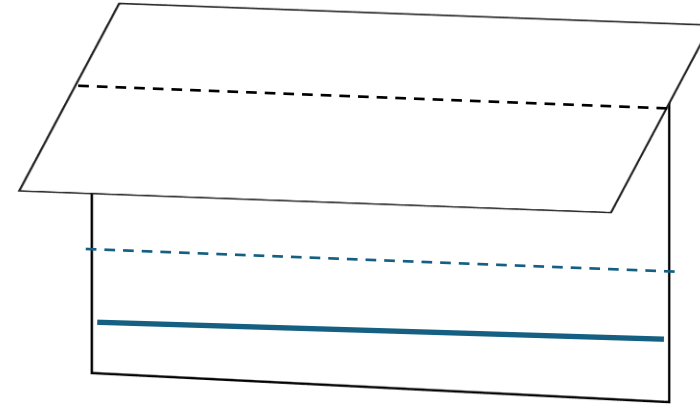
$$fV_E \approx -\frac{\tau_x}{\rho}$$



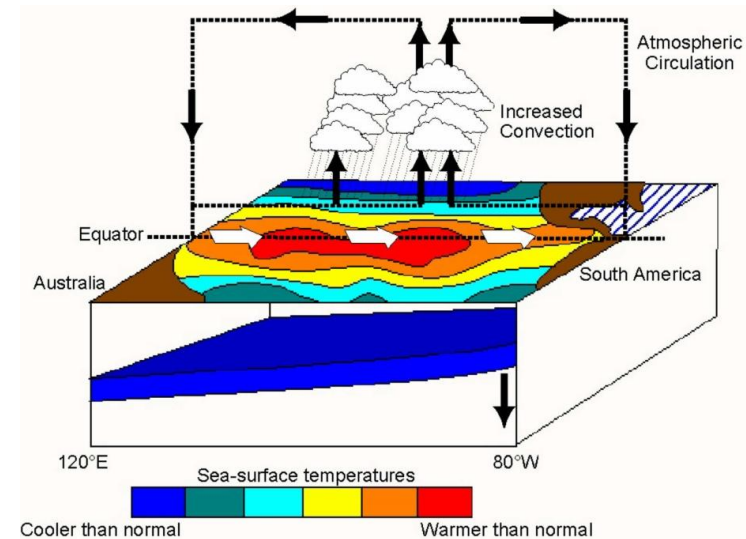
Geostrophic transport into equatorial region

$$fV_g \approx \frac{1}{\rho} \frac{\partial p}{\partial x}$$

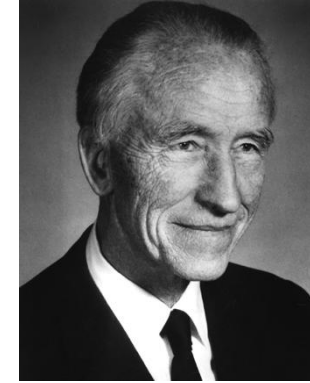
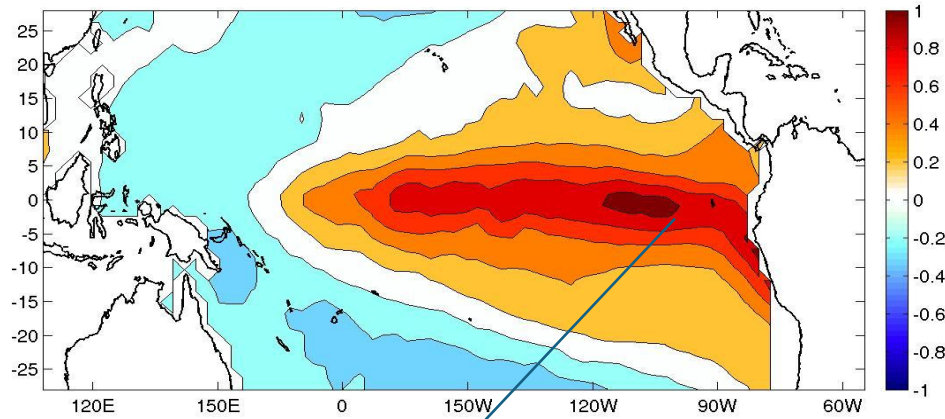
Deep thermocline – High Warm Water Volume (recharge state)



Preconditioning for an El Nino

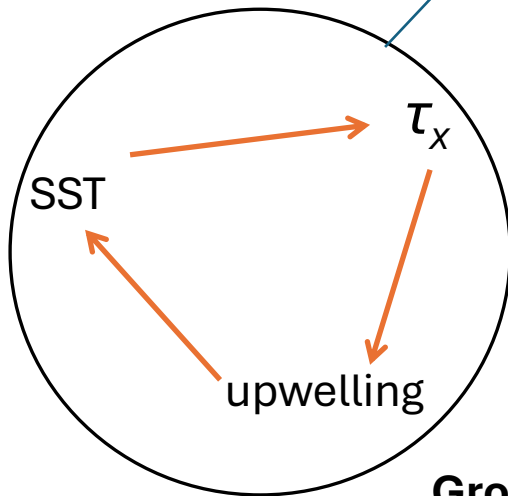


ENSO is a coupled air-sea phenomenon

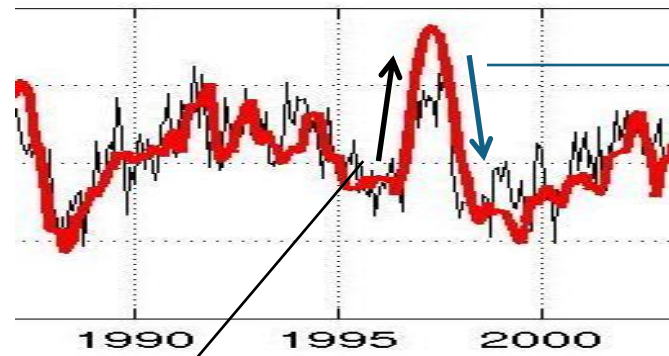


Jacob Bjerknes (1897-1975)

Bjerknes feedback

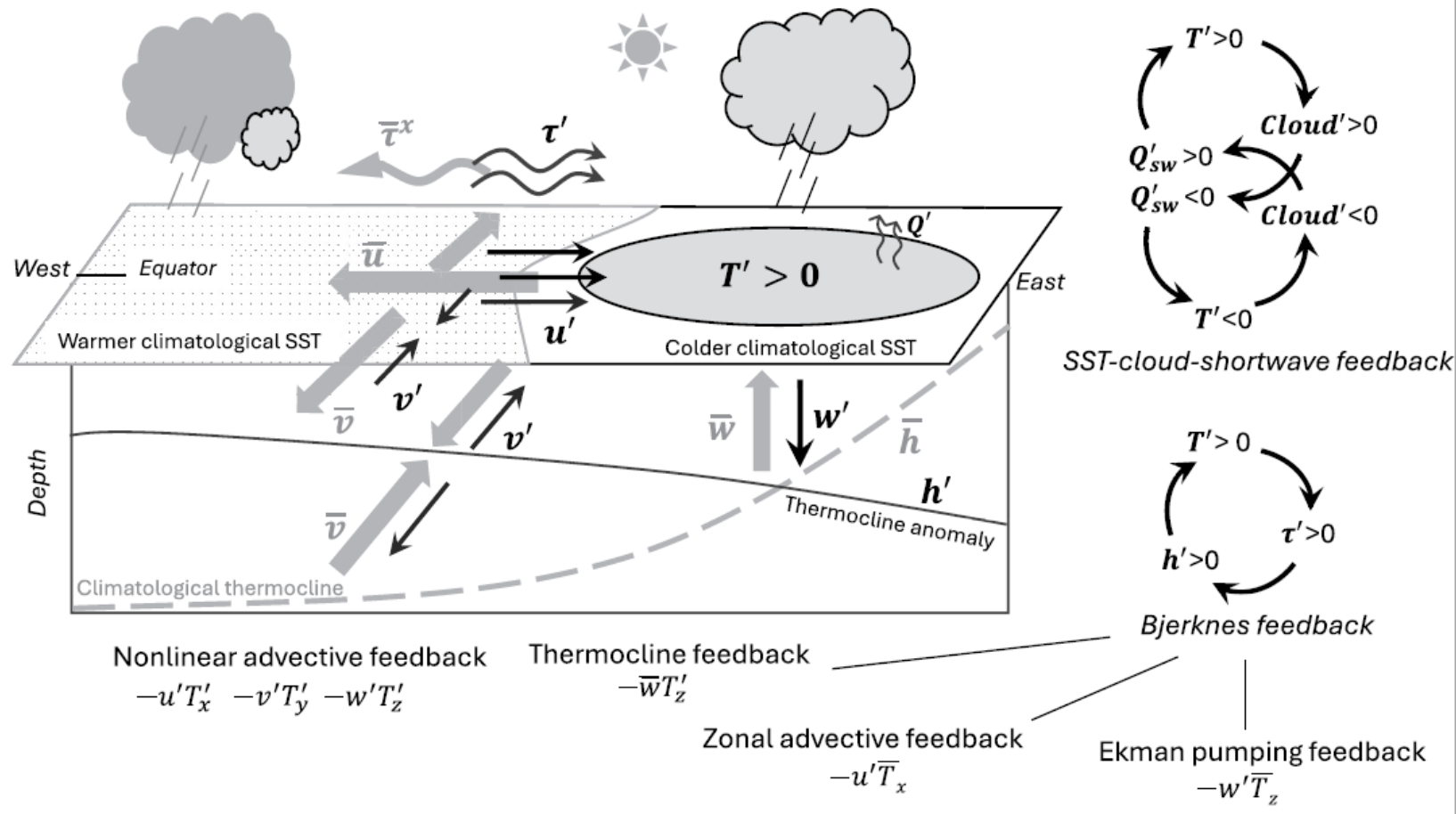


ENSO SST anomalies time series

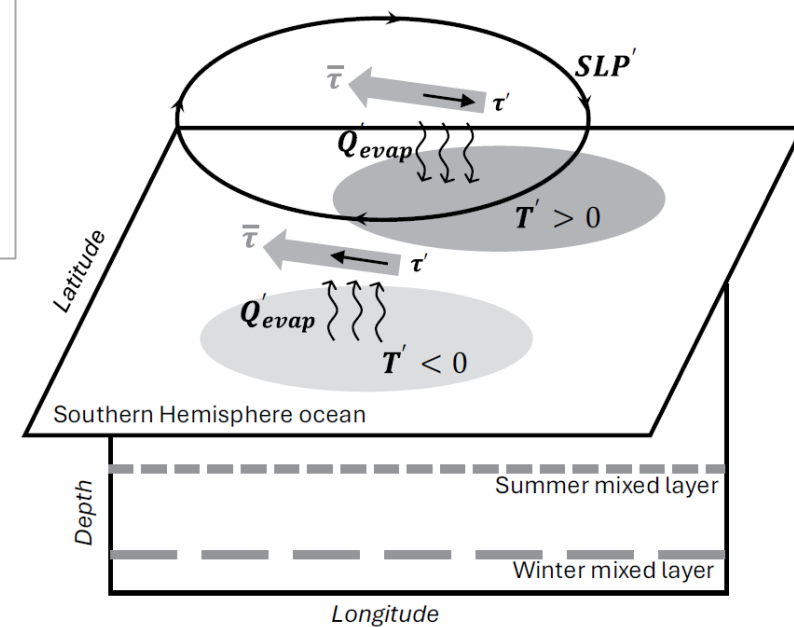


Phase change (via,
e.g., recharge
oscillator, delayed
oscillator)

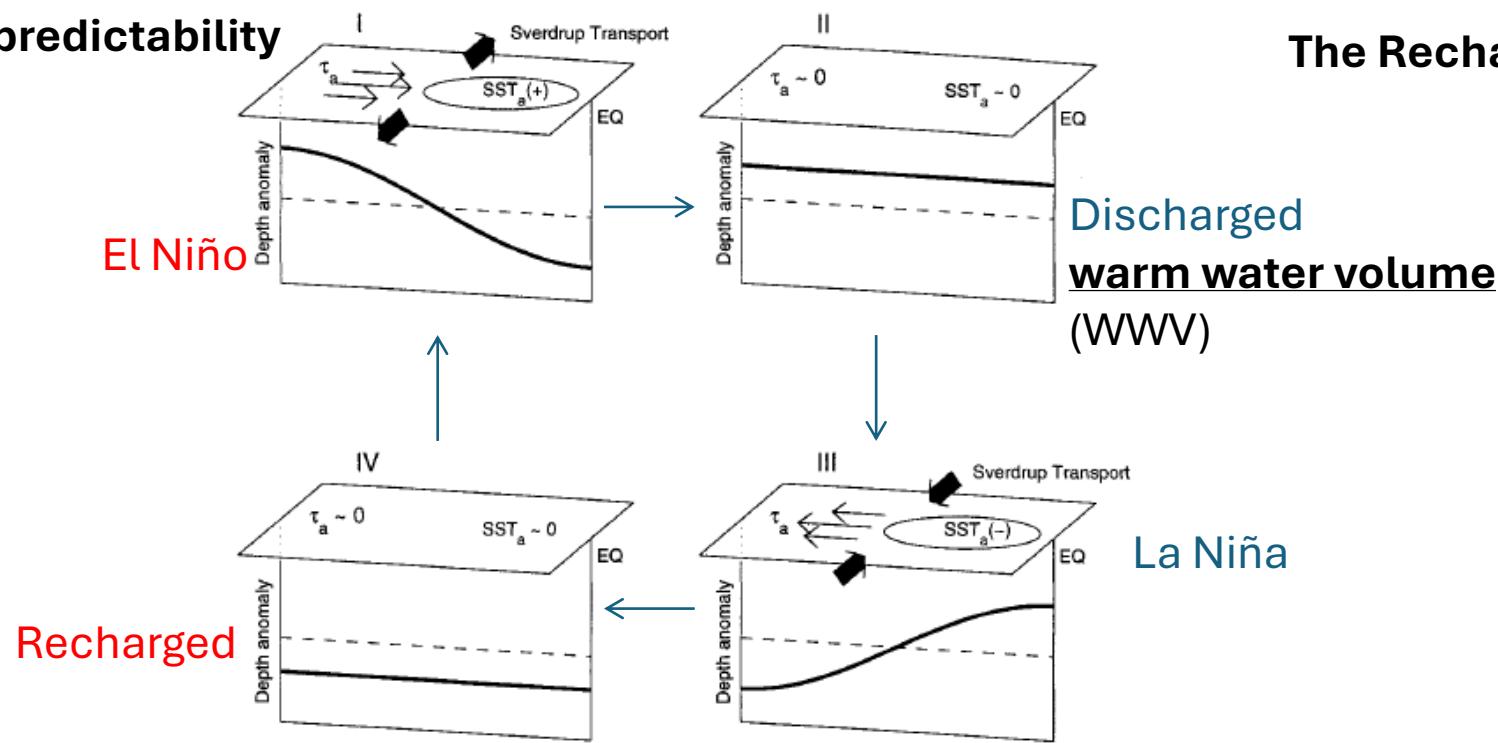
Growth (via Bjerknes +ve feedback)



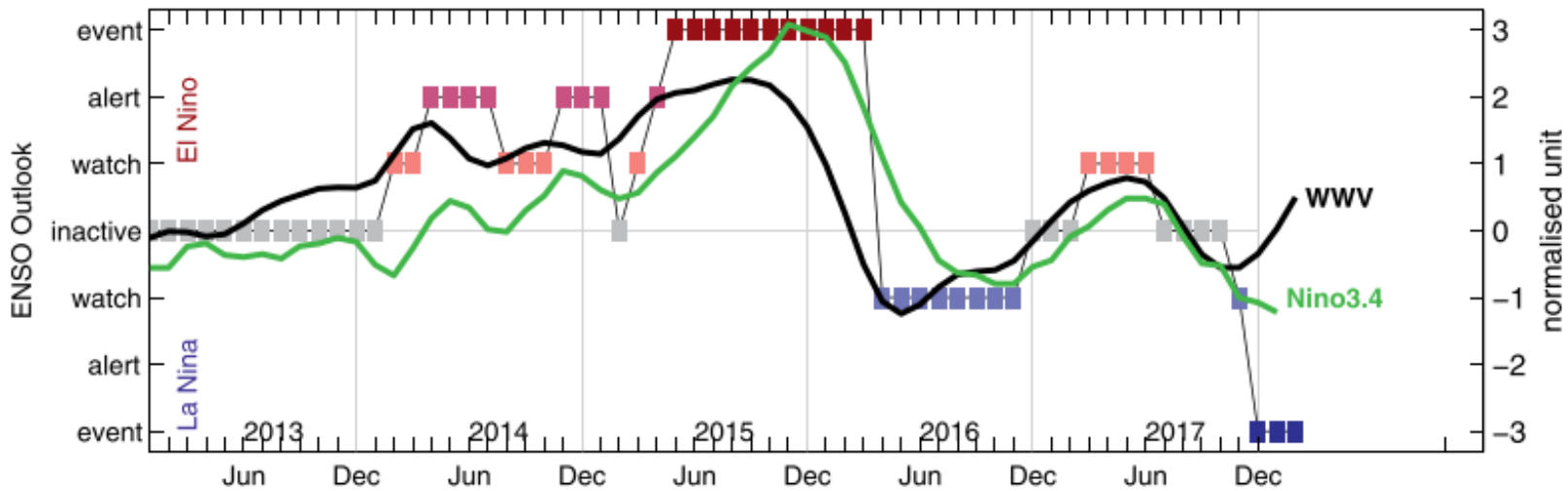
Wind-Evaporation-SST WES Feedback



Source of ENSO predictability

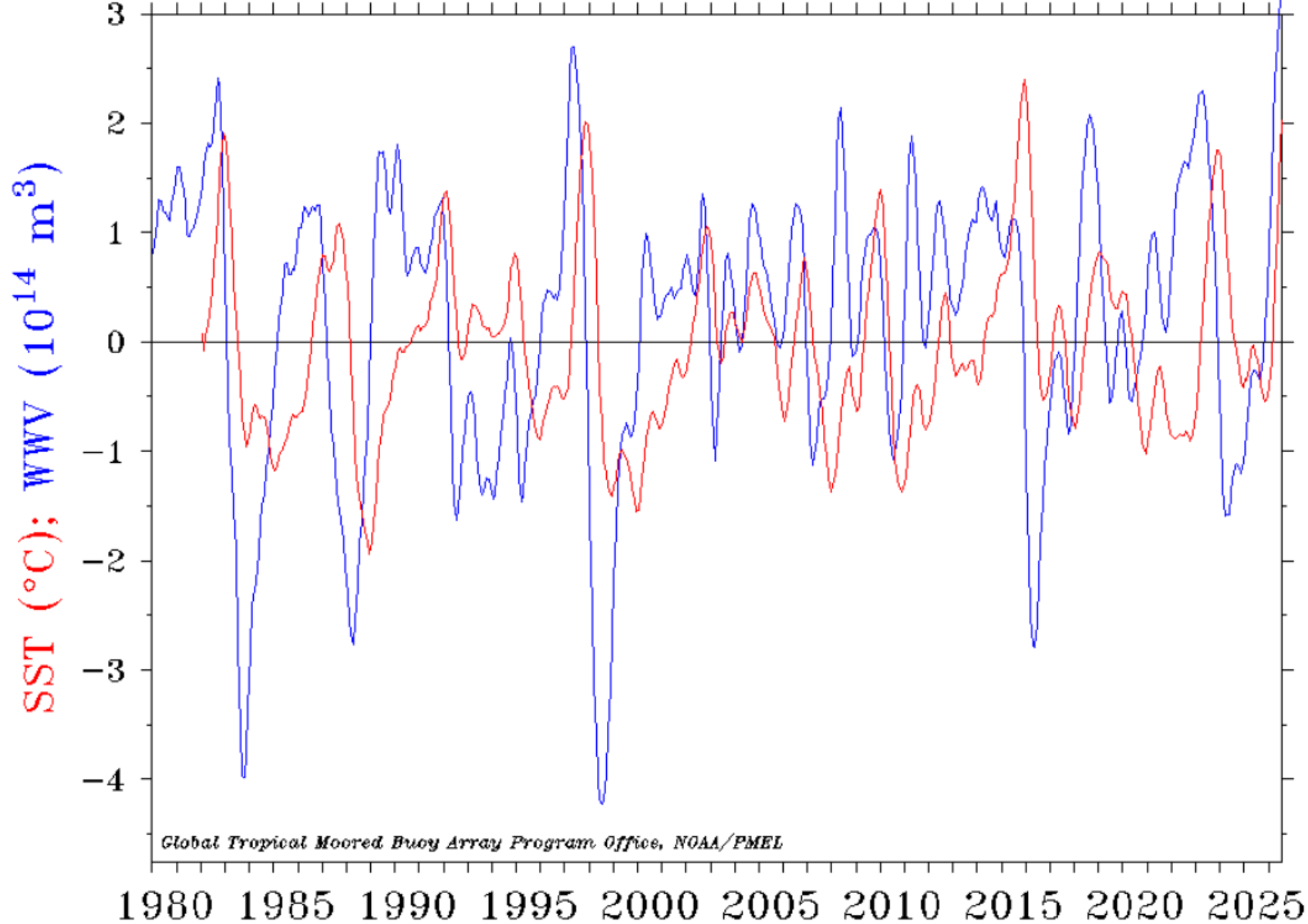


The Recharge Oscillator Paradigm
(Jin 1997)



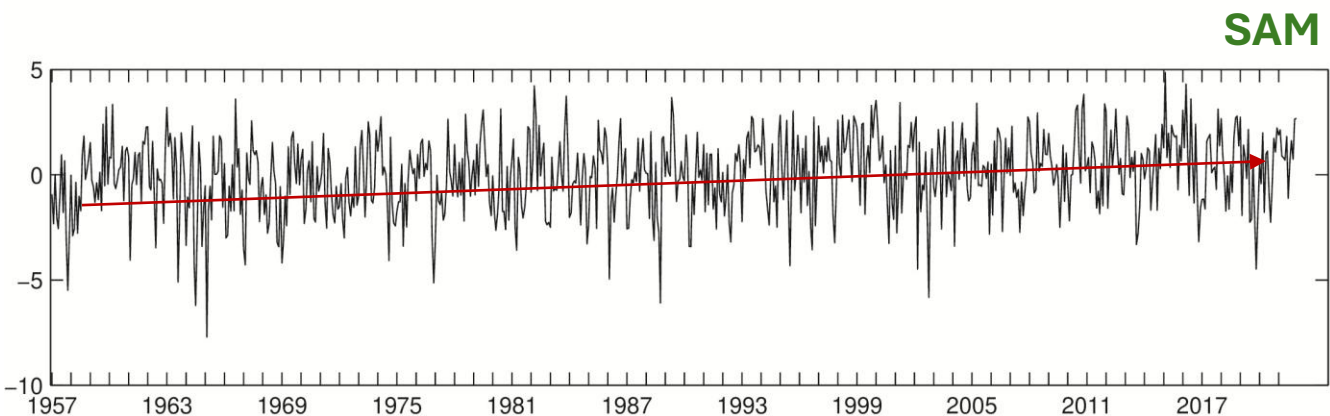
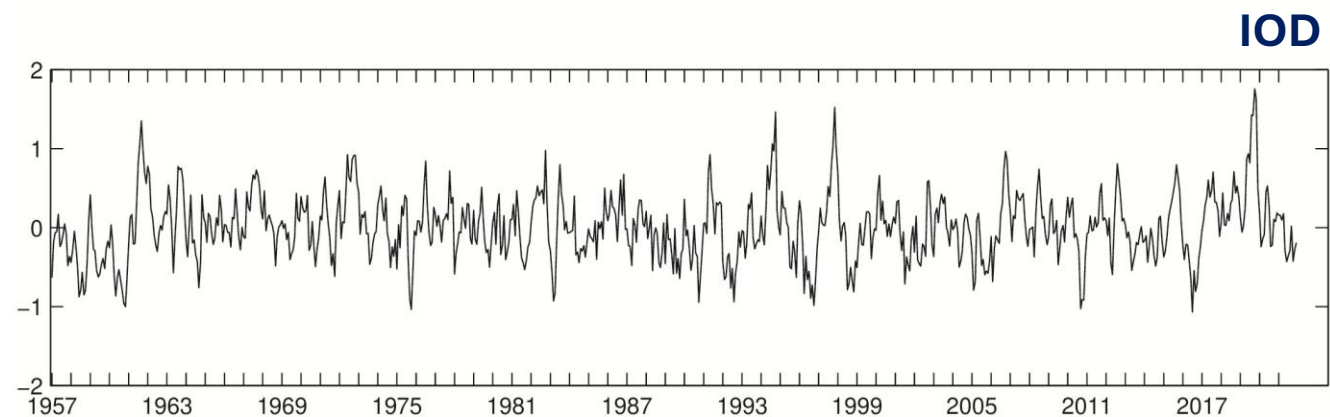
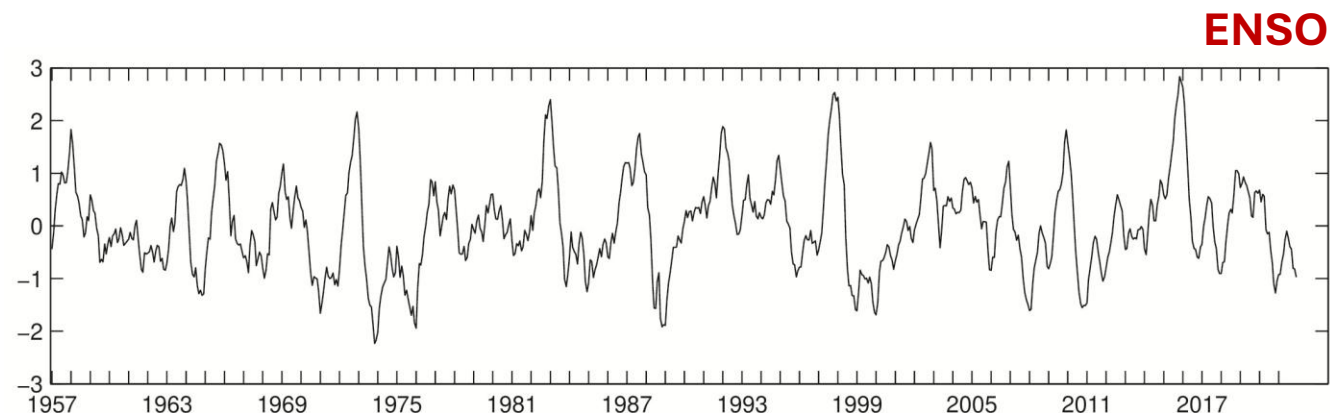
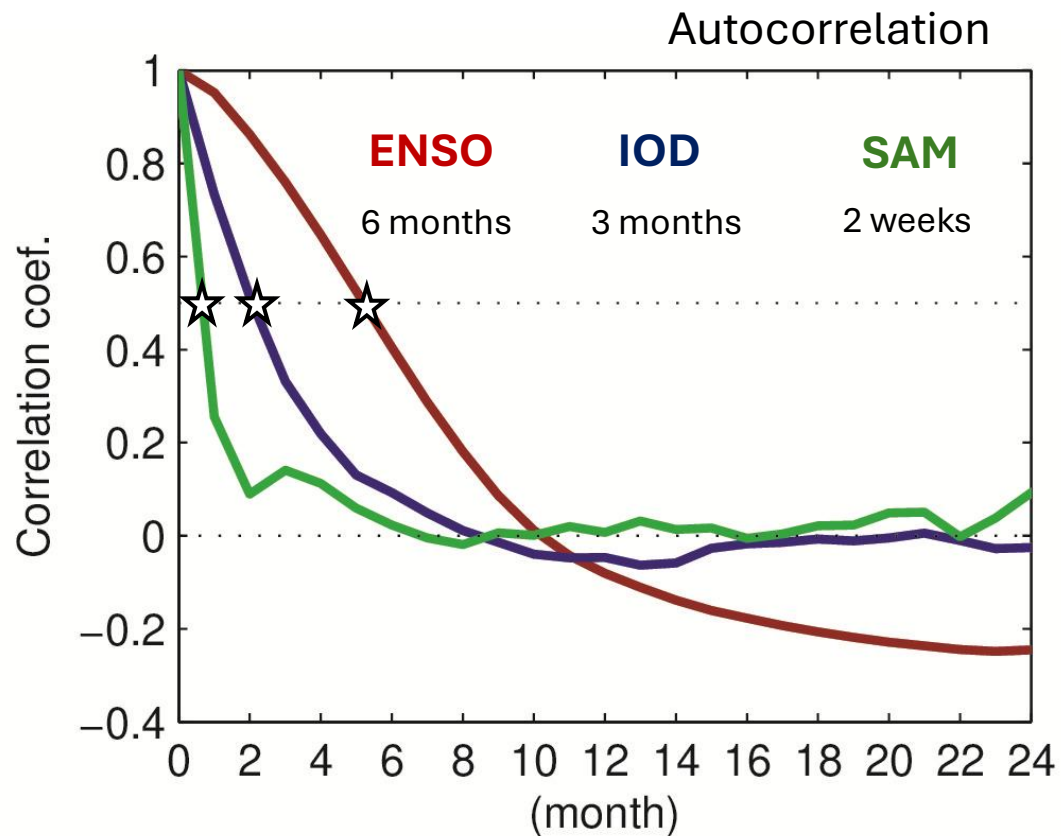
Santoso et al. 2019, BAMS

Warm Water Volume (5°N–5°S, 120°E–80°W) and NINO 3.4 SST Anomaly



Potentially a record
breaking El Nino

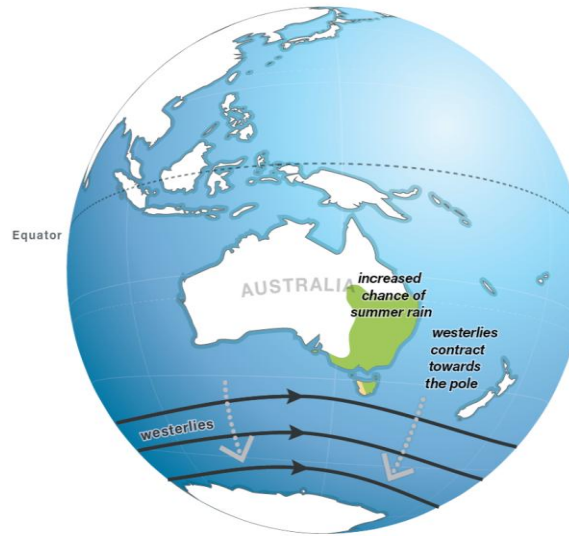
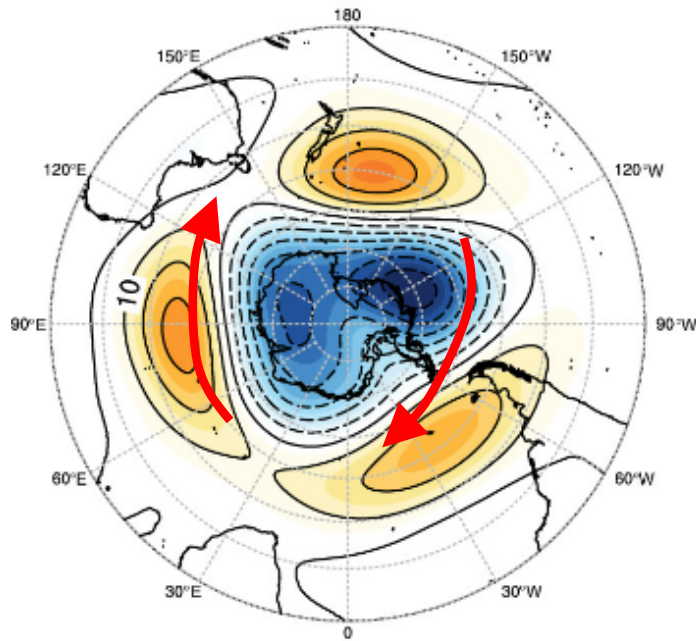
Global Ocean Data Assimilation System (GODAS) produces a real-time gridded ocean temperature dataset as the output of a dynamical global ocean model-based data assimilation scheme that incorporates temperature profiles from TAO moorings, Argo floats, XBTs and other data sets.



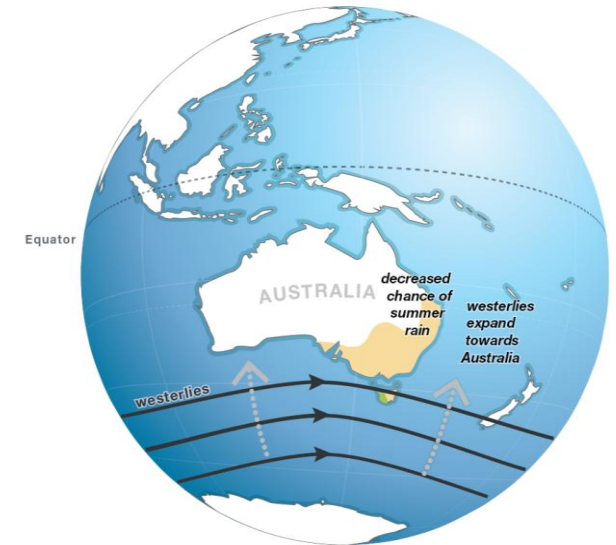
ENSO is most predictable, and is a source of predictability for other climate modes.

Southern Annular Mode (Antarctic Oscillation)

SAM

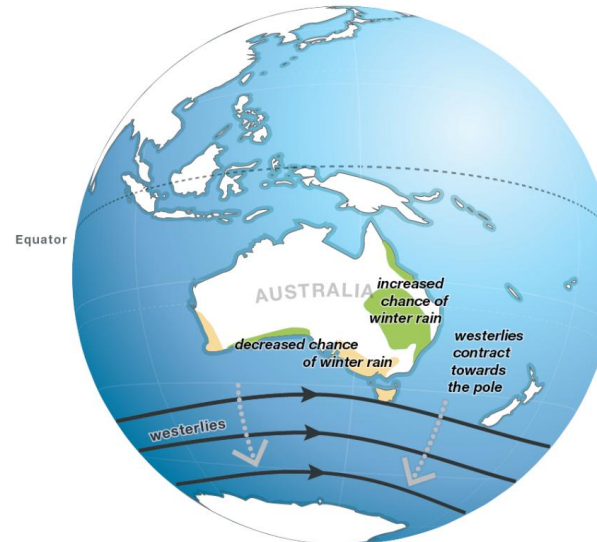


Southern Annular Mode (SAM): Positive phase (summer)

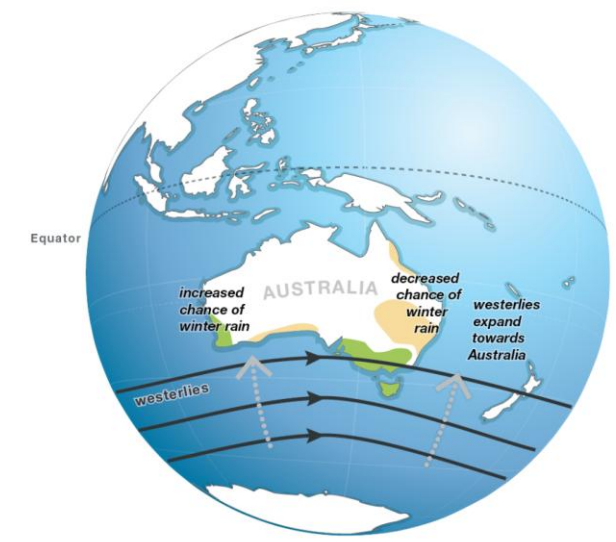


Southern Annular Mode (SAM): Negative phase (summer)

© Commonwealth of Australia 2019.



Southern Annular Mode (SAM): Positive phase (winter)

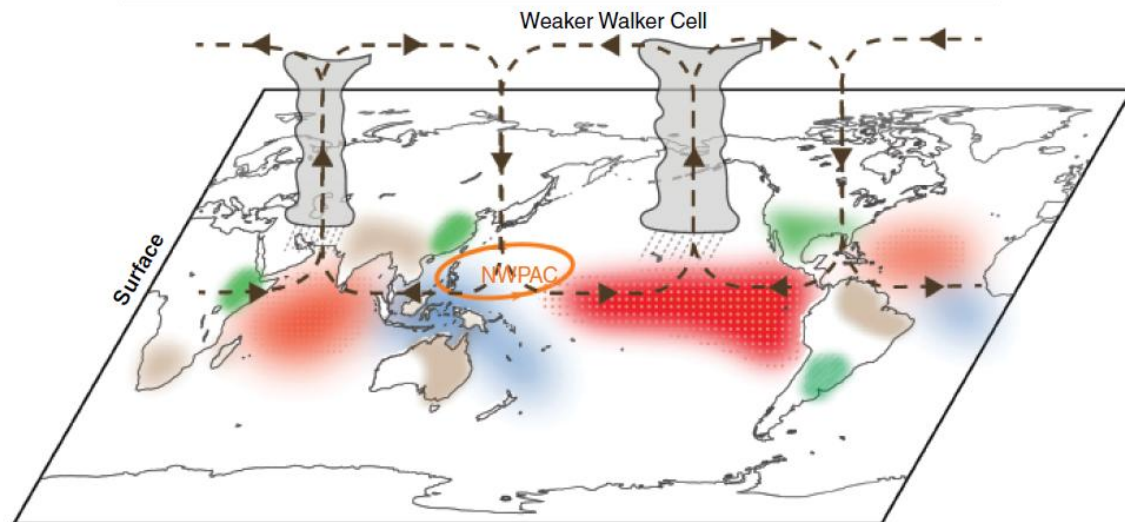
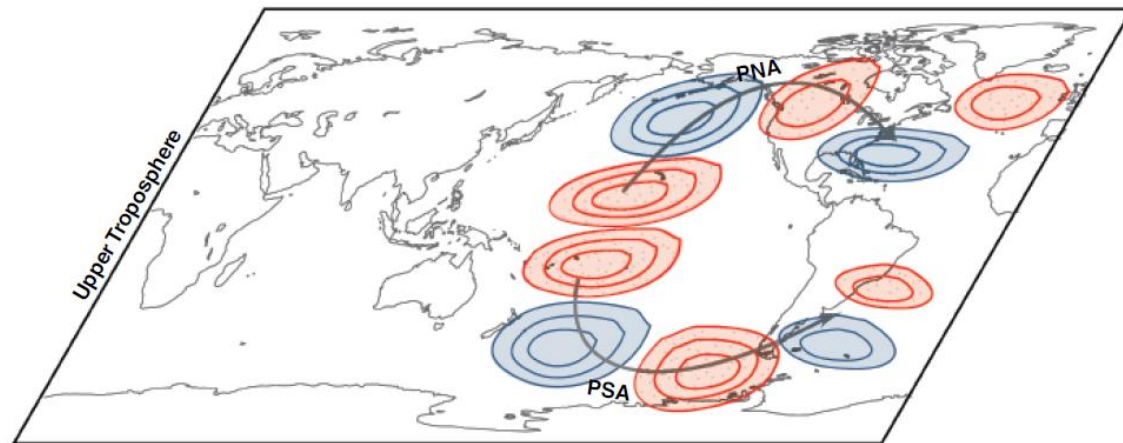


Southern Annular Mode (SAM): Negative phase (winter)

© Commonwealth of Australia 2019.

- SAM - an internal mode of atmospheric variability
- Difference in zonal mean pressure between 40 and 65 °S

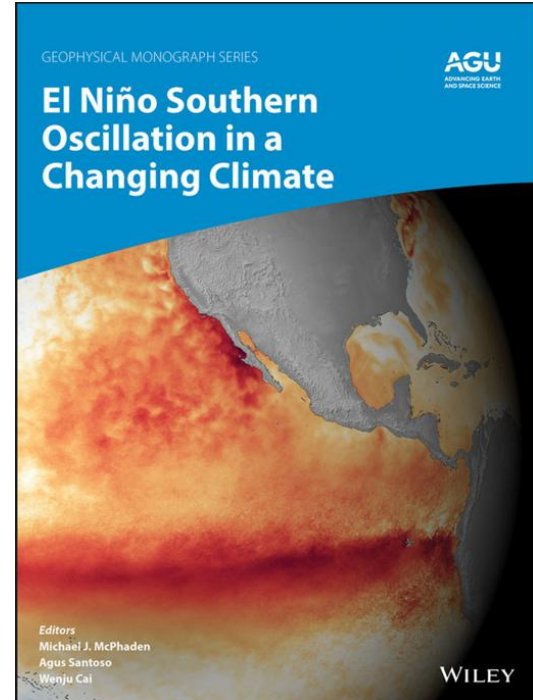
Stratosphere
Strengthened Brewer-Dobson Circulation
and Weaker Polar Vortex



Dry Land
 Wet Land
 Cool Ocean
 Warm Ocean

NWP Anticyclone
 Walker Circulation
 PNA/PSA

Figure 14.1 ENSO atmospheric teleconnections: Schematic of global circulation changes during El Niño. Top: Upper troposphere. Centers of geopotential height representing the Pacific North American (PNA) and Pacific South American (PSA) patterns. Red contours: positive geopotential anomaly. Blue contours: negative geopotential anomaly. Grey arching arrows represent typical PNA and PSA paths. Bottom: surface. Sea surface temperature anomalies (shading), Walker Circulation anomalies (brown dashed arrows), Northwest Pacific Anticyclone (orange contour), and precipitation anomalies (shading over land). Brown: dry. Green: wet. Red: warm. Blue: cool conditions.



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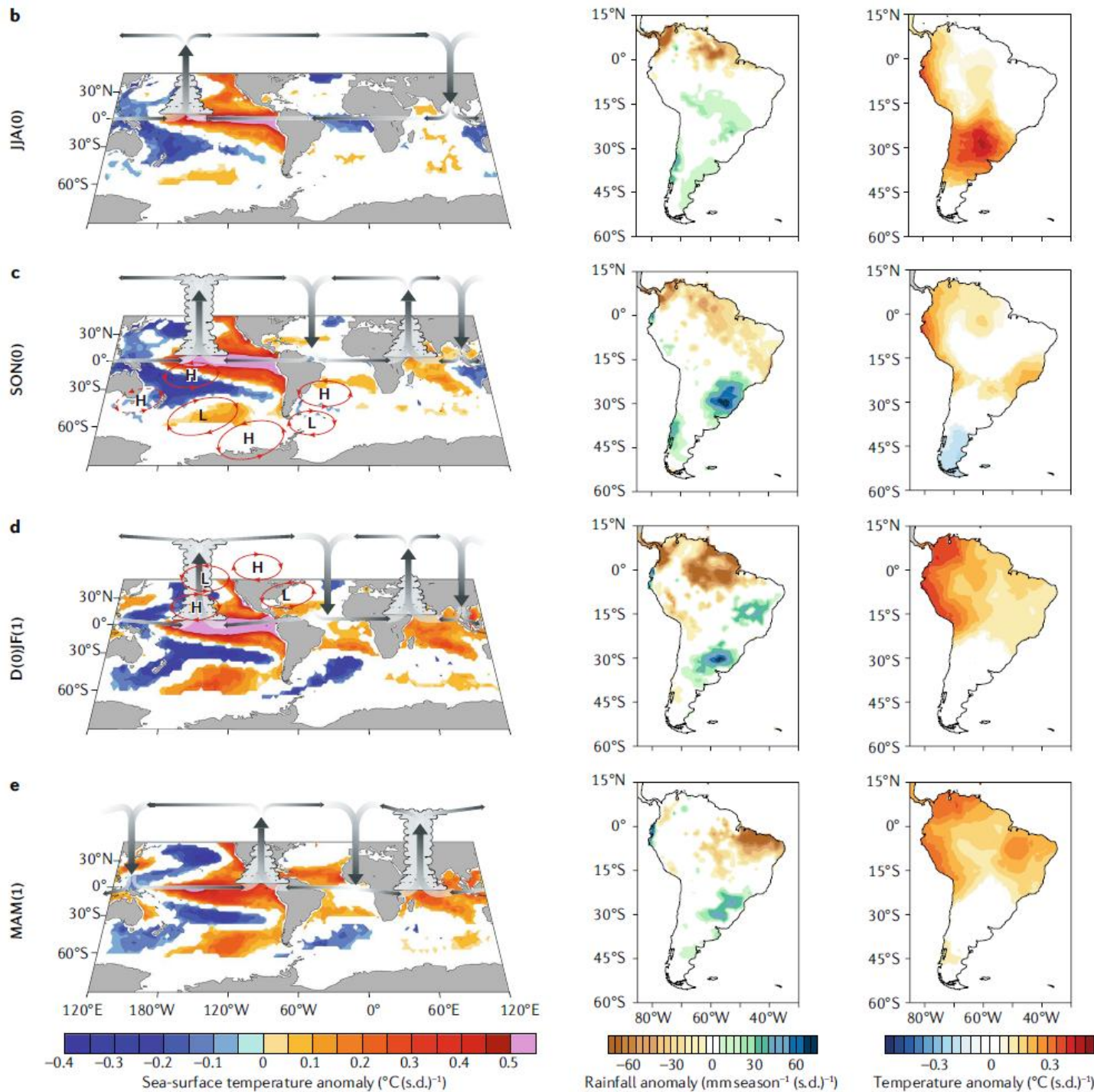
ENSO Atmospheric Teleconnections

Andréa S. Taschetto^{1,2}, Caroline C. Ummerhofer^{2,3}, Malte F. Stuecker⁴, Dietmar Dommenget^{2,5}, Karumuri Ashok⁶, Regina R. Rodrigues⁷, and Sang-Wook Yeh⁸

Climate impacts of the El Niño–Southern Oscillation on South America

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 Marisol Osman^{18,19}, Shujun Li^{1,2}, Lixin Wu¹, Christina Karamperidou²⁰, Ken Takahashi²¹
 and Carolina Vera^{18,19}

ENSO impact on climate is conveyed through changes in the Walker Circulation and atmospheric waves, involving the ocean (e.g., marine heatwaves).

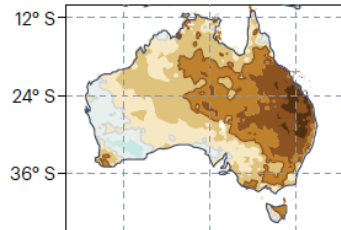


Climate impacts of the El Niño–Southern Oscillation in Africa

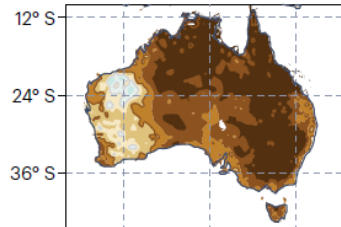
Wenju Cai^{1,2,3}✉, Chris Reason⁴, Elsa Mohino⁵, Belen Rodríguez-Fonseca^{5,6}, Johan Malherbe⁷, Agus Santoso^{8,9}✉, Xichen Li^{10,11}, Hector Chikoo¹², Hyacinth Nnamchi^{13,14}, Michael J. McPhaden¹⁵, Noel Keenlyside^{16,17,18,19}, Andrea S. Taschetto^{9,20,21}, Lixin Wu^{1,3}, Benjamin Ng²², Yi Liu¹, Tao Geng³, Kai Yang²², Guojian Wang²², Fan Jia^{3,23}, Xiaopei Lin^{1,3}, Shujun Li^{1,3}, Yun Yang²⁴, Junkai Wang¹, Li Zhang^{1,3}, Ziguang Li¹, Pokam Wilfried²⁵, Liming Zhou²⁶, Xuebin Zhang²², Francois Engelbrecht²⁷, Zhuoran Li²⁸ & Joseph N. Mutemi²⁹

Nature Reviews Earth & Environment | Volume 6 | August 2025 | 503–520

b JJA(O)



c SON(O)

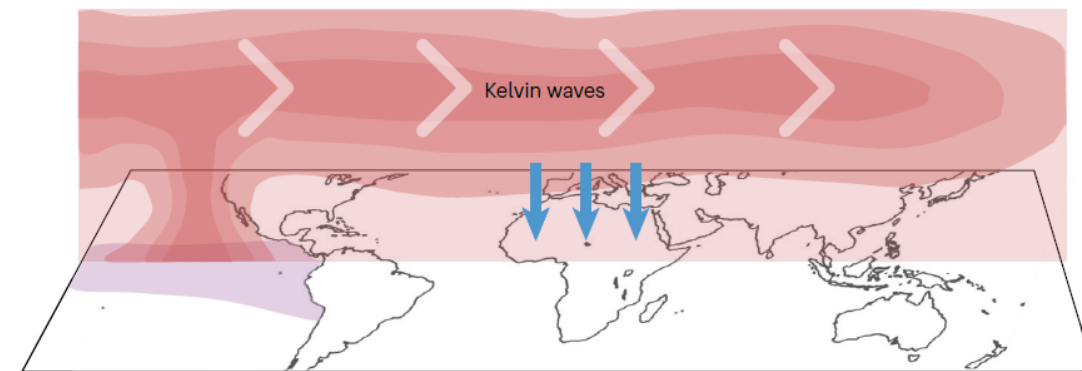


Review article

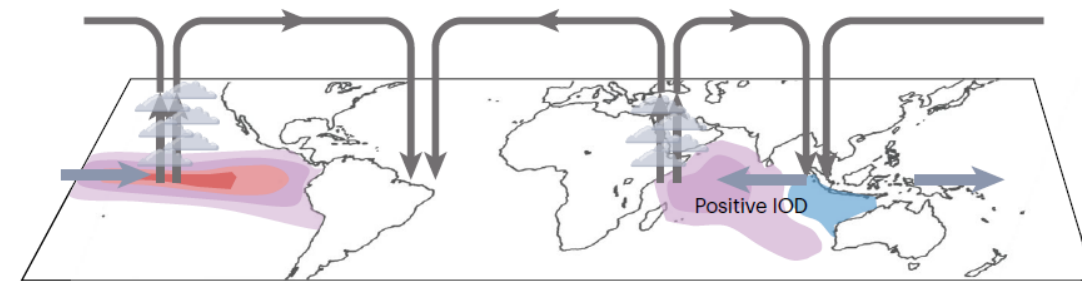
Climate impacts of the El Niño–Southern Oscillation on Australia

Andréa S. Taschetto^{1,2,3,35}✉, Shayne McGregor^{4,5,36}✉, Dietmar Dommenges^{4,6}, Zoe E. Gillett²⁷, Neville Nicholls⁴, Sur Sharmila⁷, Peter van Rensch⁴, Danielle Verdon-Kidd^{8,9}, Ghyslaine Bosch⁷, Christine Chung⁷, Ruby Lieber^{10,11}, Nerilie Abram^{12,13,14,15}, Rob Allan¹⁶, Kathryn Allen^{17,18}, Linden Ashcroft^{10,11}, Josephine R. Brown^{10,19}, Wenju Cai^{20,21,22}, Savin Chand²³, Tim Cowan^{7,24}, Thi Lan Dao^{10,11}, Catherine de Burgh-Day⁷, Mandy B. Freund^{10,19}, Ailie Gallant^{4,5,6}, Joelle Gergis¹⁰, Neil J. Holbrook^{25,26,27}, Hanna Heidemann^{10,11,24}, Chiara Holgate^{12,13}, Pandora Hope⁷, Andrew King^{10,19}, Eun-Pa Lim⁷, John L. McBride^{7,10}, Roseanna C. McKay⁷, Hanh Nguyen⁷, Acacia Pepler²⁸, Sarah Perkins-Kirkpatrick^{15,29}, Scott Power^{4,30,34}, James S. Risbey³¹, Agus Santoso^{1,2,32}, Caroline C. Ummerhofer^{1,2,33}, Guojian Wang³¹ & Xuebin Zhang³¹

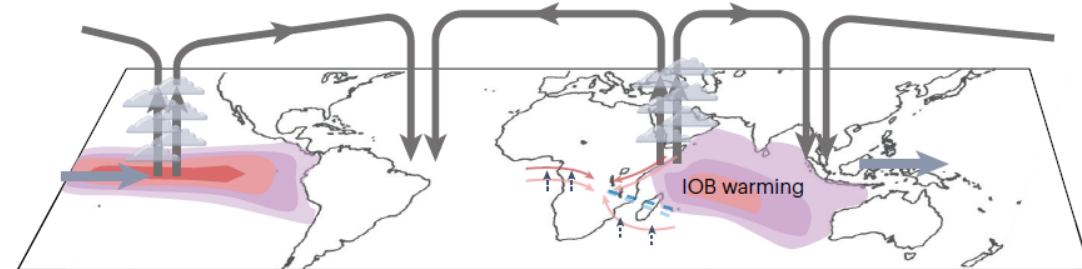
a Tropospheric temperature influence



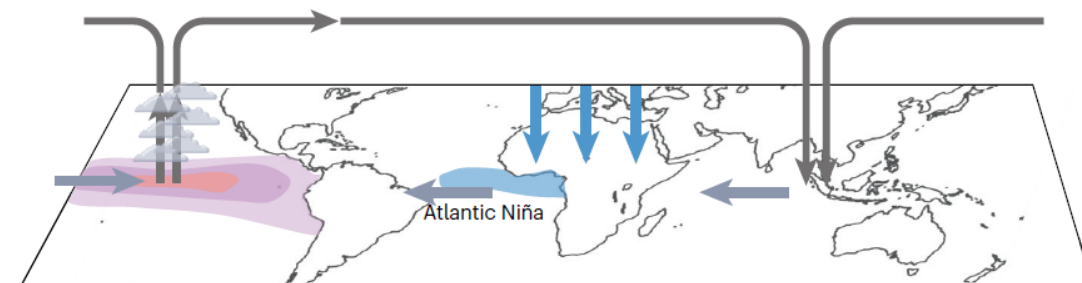
b Indian Ocean influence in SON

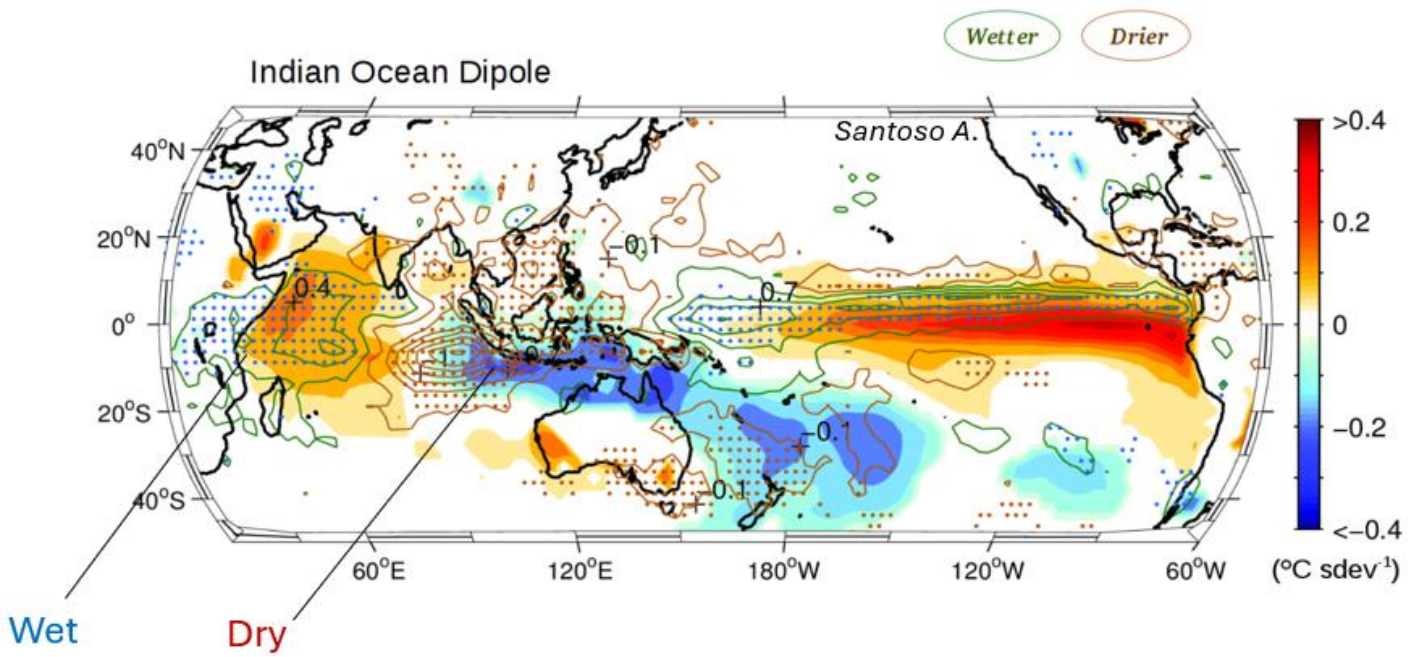


c Indian Ocean influence in DJF



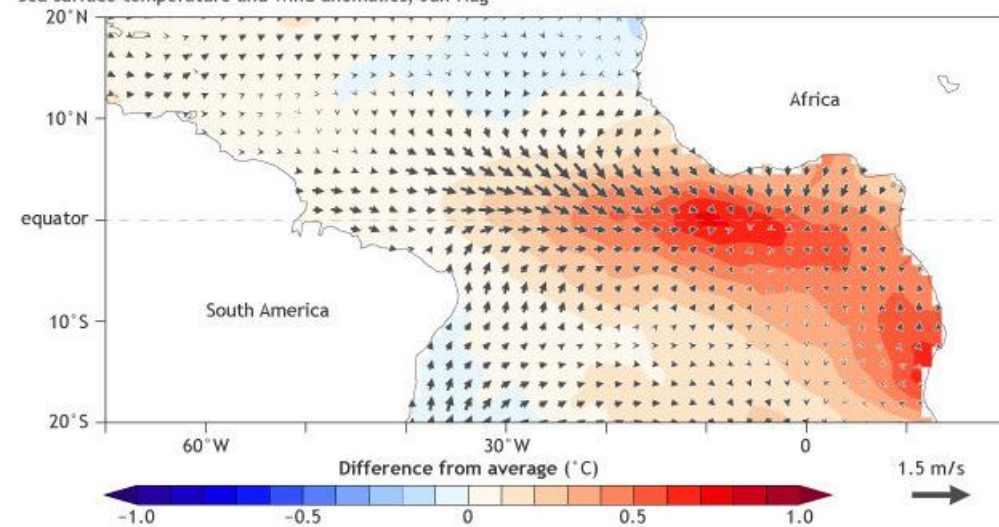
d Atlantic Ocean influence in JJA



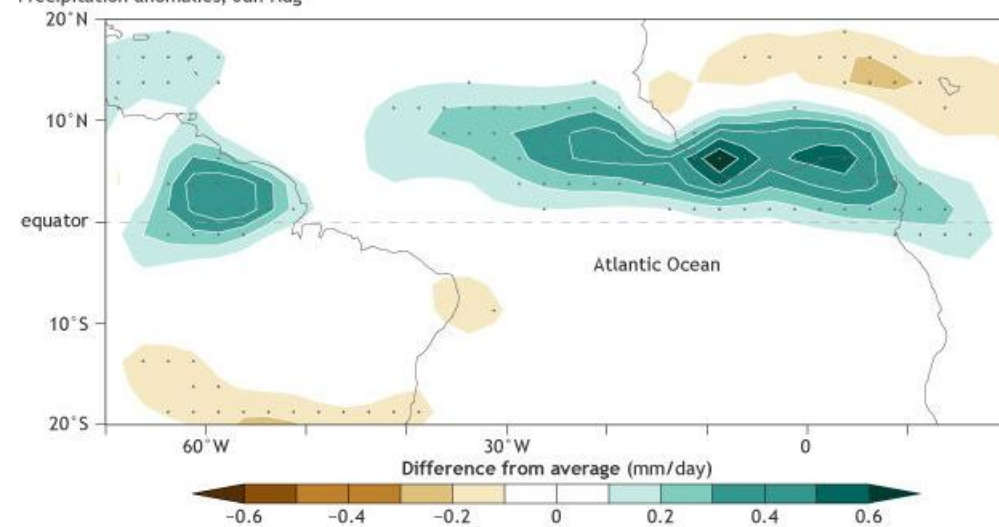


Atlantic Nino: sea surface temperature, wind, and precipitation anomalies

Sea surface temperature and wind anomalies, Jun-Aug



Precipitation anomalies, Jun-Aug



Introduction to El Niño Southern Oscillation in a Changing Climate

Michael J. McPhaden¹, Agus Santoso^{2,3}, and Wenju Cai^{3,4}



Figure 1.3 Images of typical ENSO impacts: Flooding in Peru (top) during the 1997–1998 El Niño (courtesy of the University of Piura); (middle) drought in New South Wales, Australia, early in the 2018–2019 El Niño (photo credit: Graham Jepson); and (bottom) the Thomas wildfire in Southern California in December 2017, during a La Niña winter (photo credit: Kari Greer).

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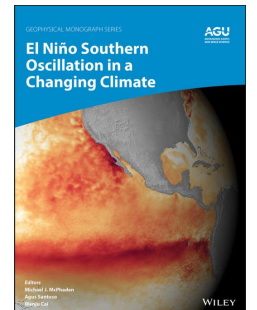
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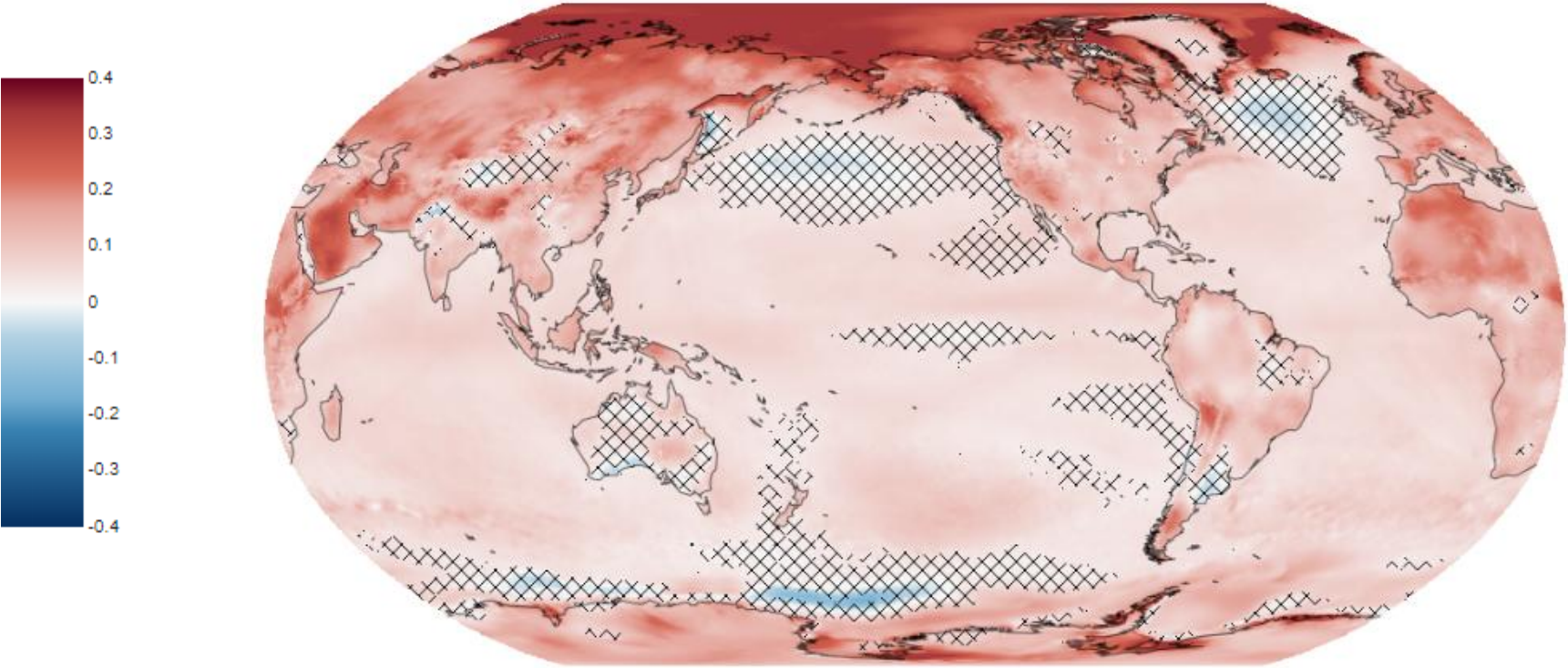
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Mean temperature (°C per decade) - ERA5 - Trend - Historical - 1950-2020 - Annual



PROGRAMME OF THE
EUROPEAN UNION



Global warming

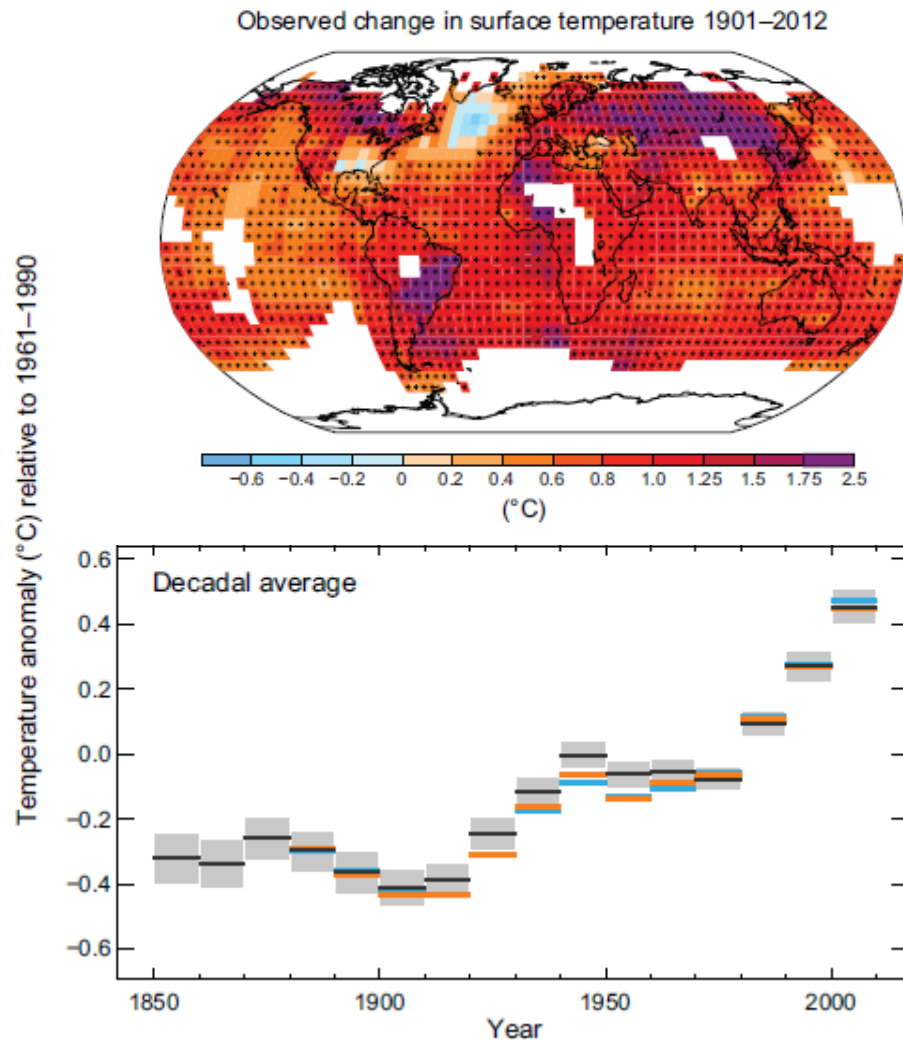
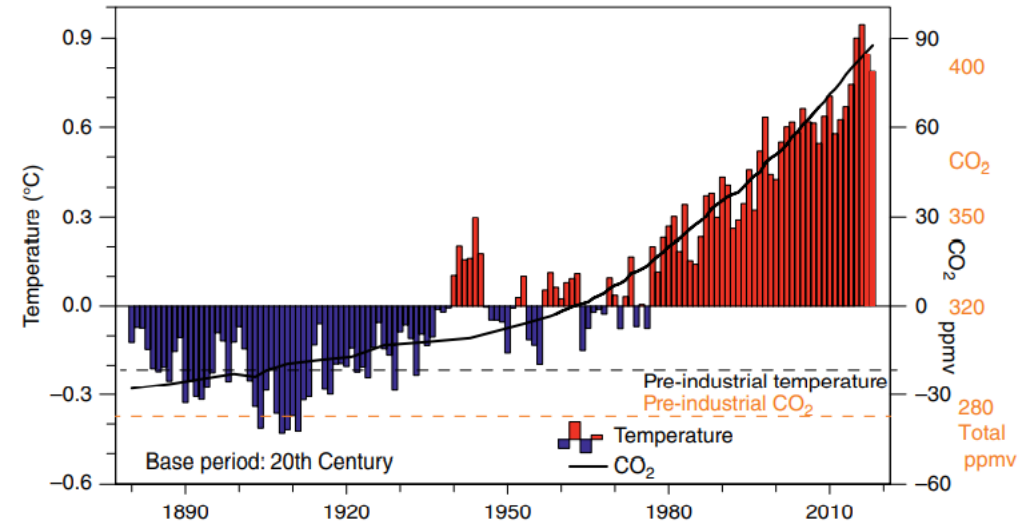


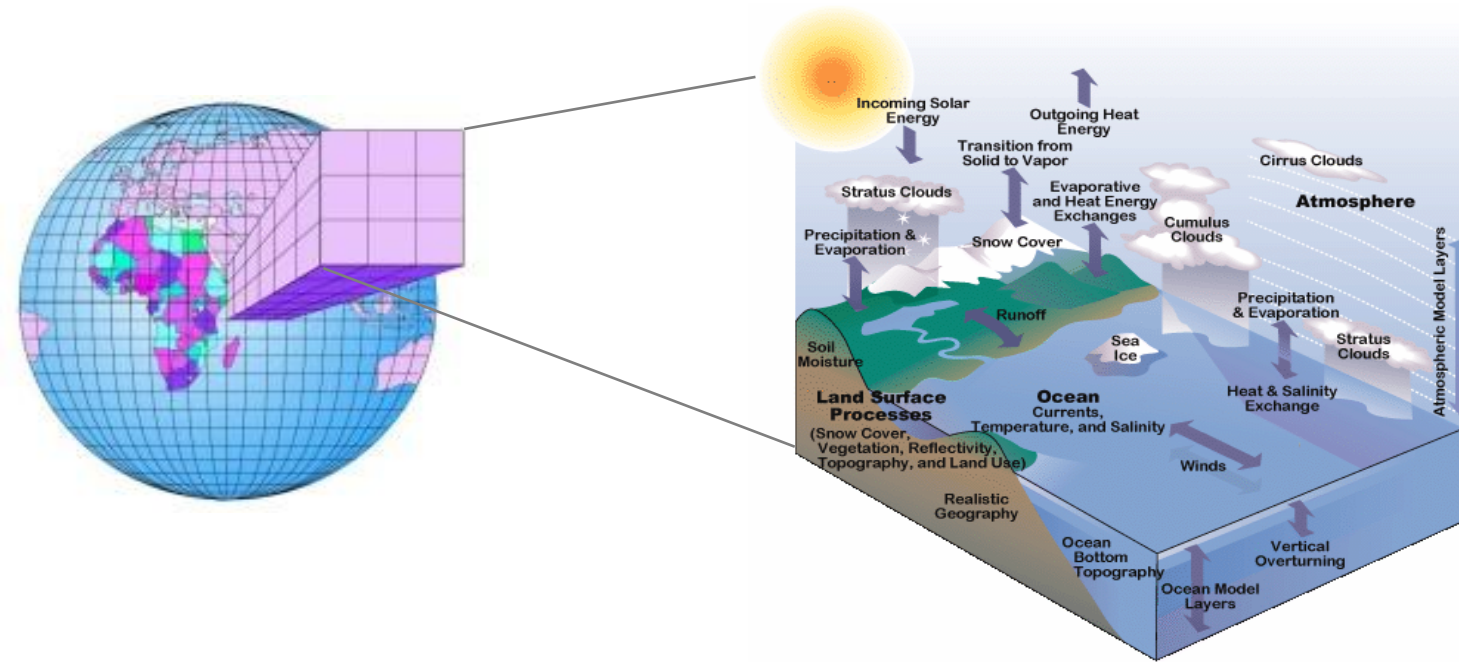
Image source: IPCC AR5



Earth is warming up as greenhouse gas emission continues to climb.

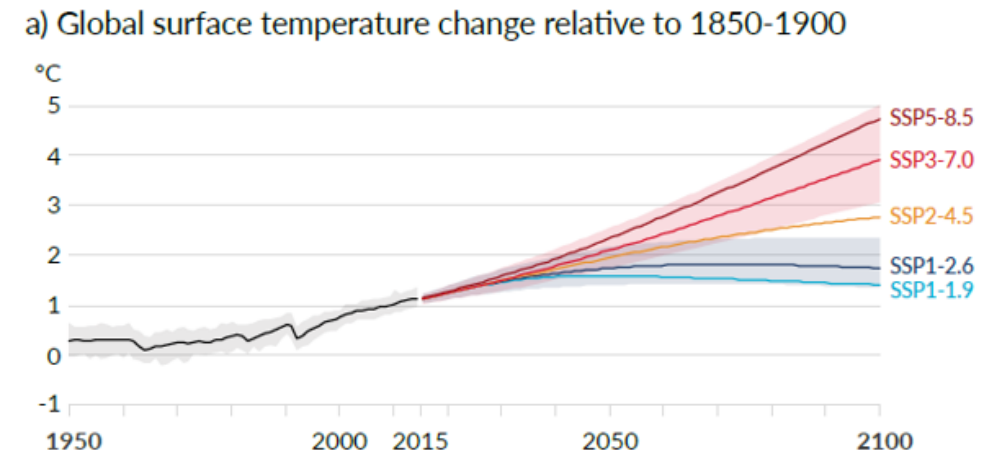
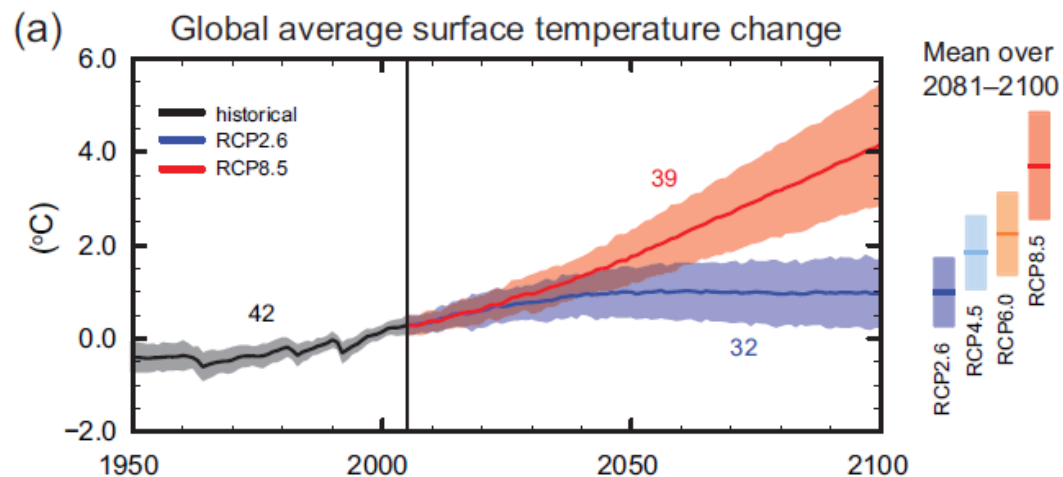
The increase in temperature is not smooth (staircase like) due to internal multi-decadal climate variability (e.g., Interdecadal Pacific Oscillation).

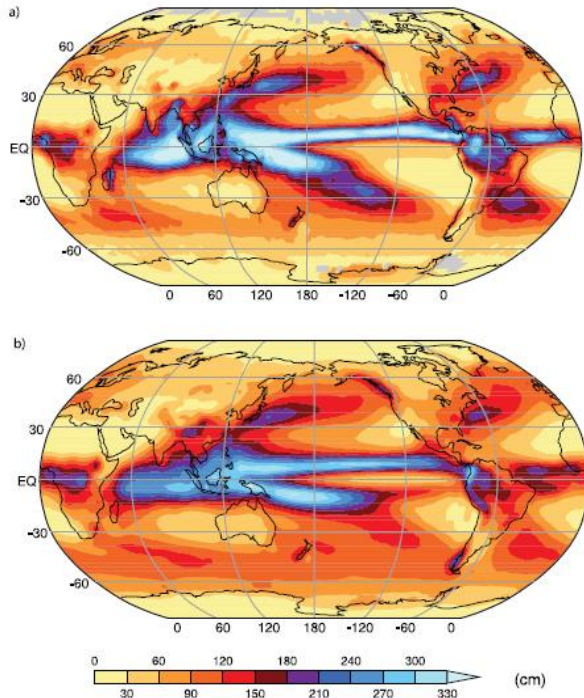
The warming is not distributed equally at all spatial locations.



We use climate models for projecting the future, by subjecting the models to specified emission scenarios.

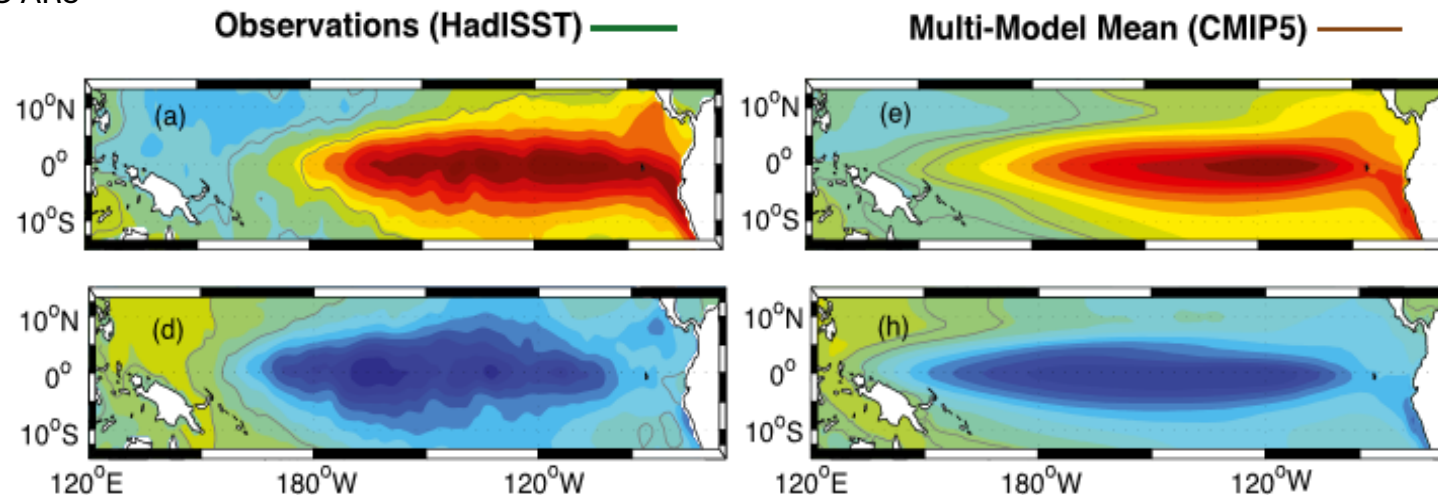
The level of warming depends on how much we emit.





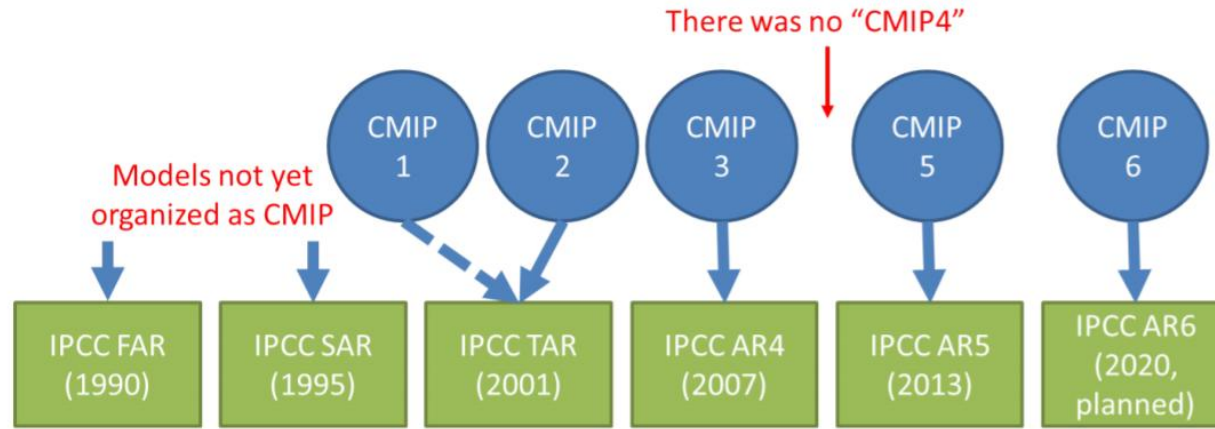
- There are over 60 climate models from about 30 modelling groups all over the world.
- Climate model data are provided under the efforts of Climate Model Intercomparison Project (CMIP)
- They can reasonably simulate the earth climate and modes of variability

IPCC AR5



Coupled Model Intercomparison Project (CMIP)

Progress in climate modeling

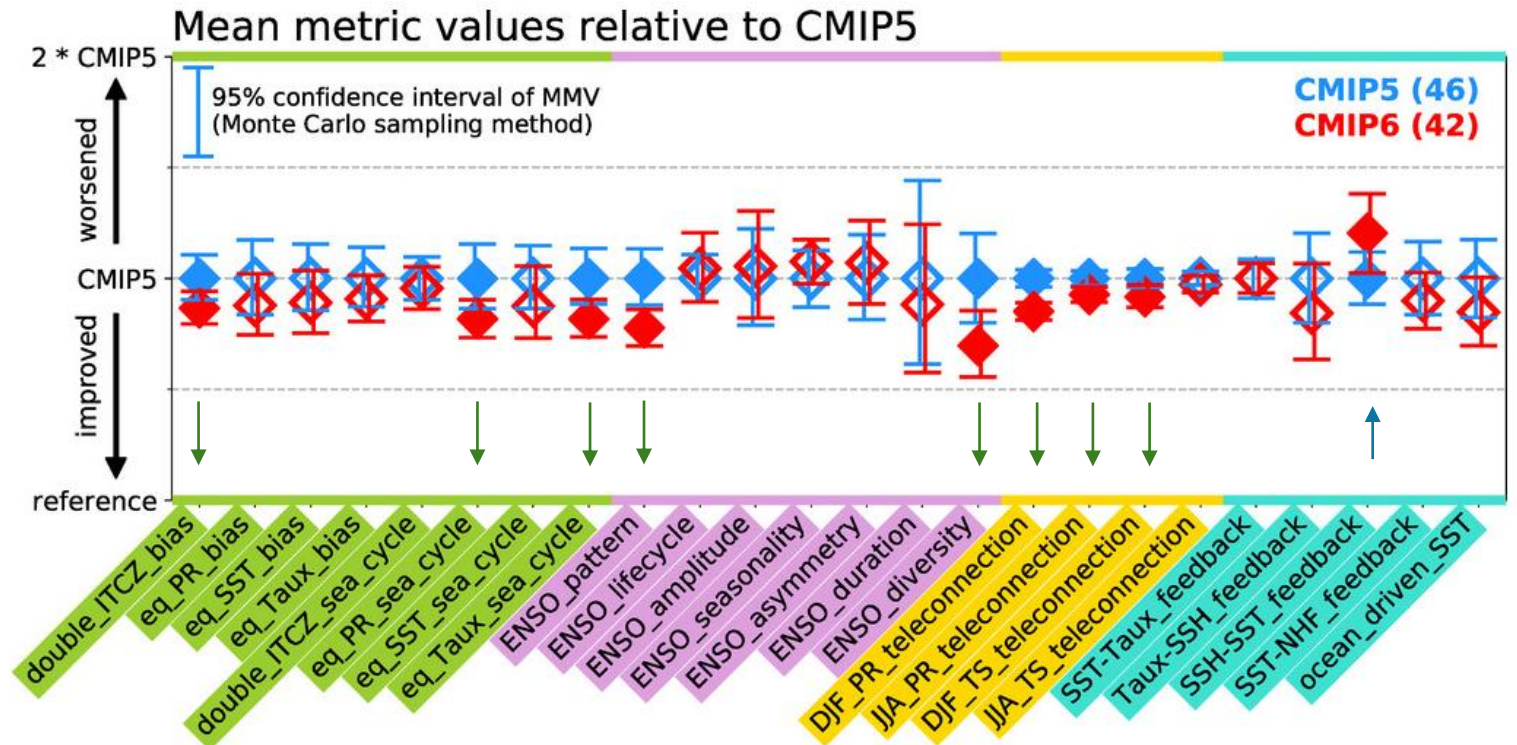


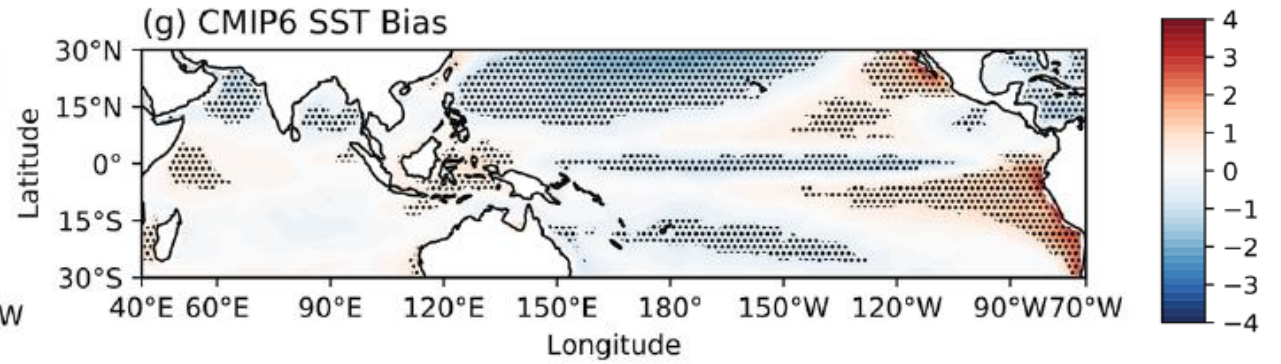
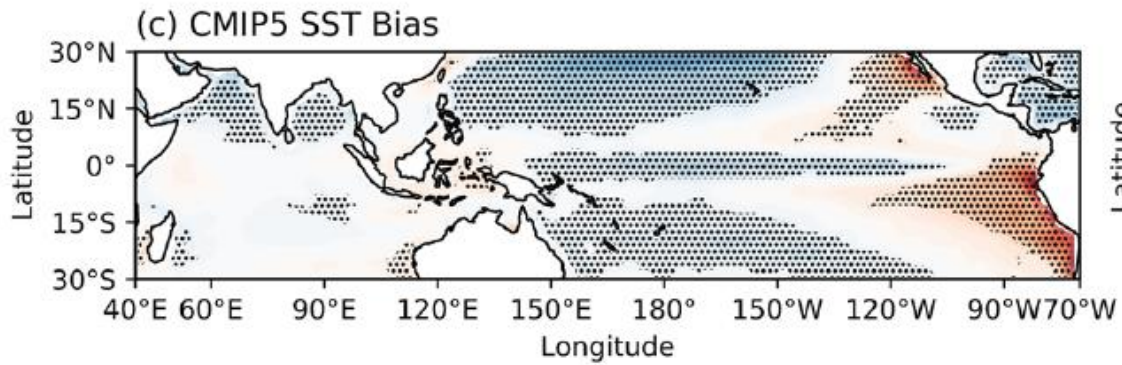
Model inter-comparison

Planton et al. 2021, J. Climate

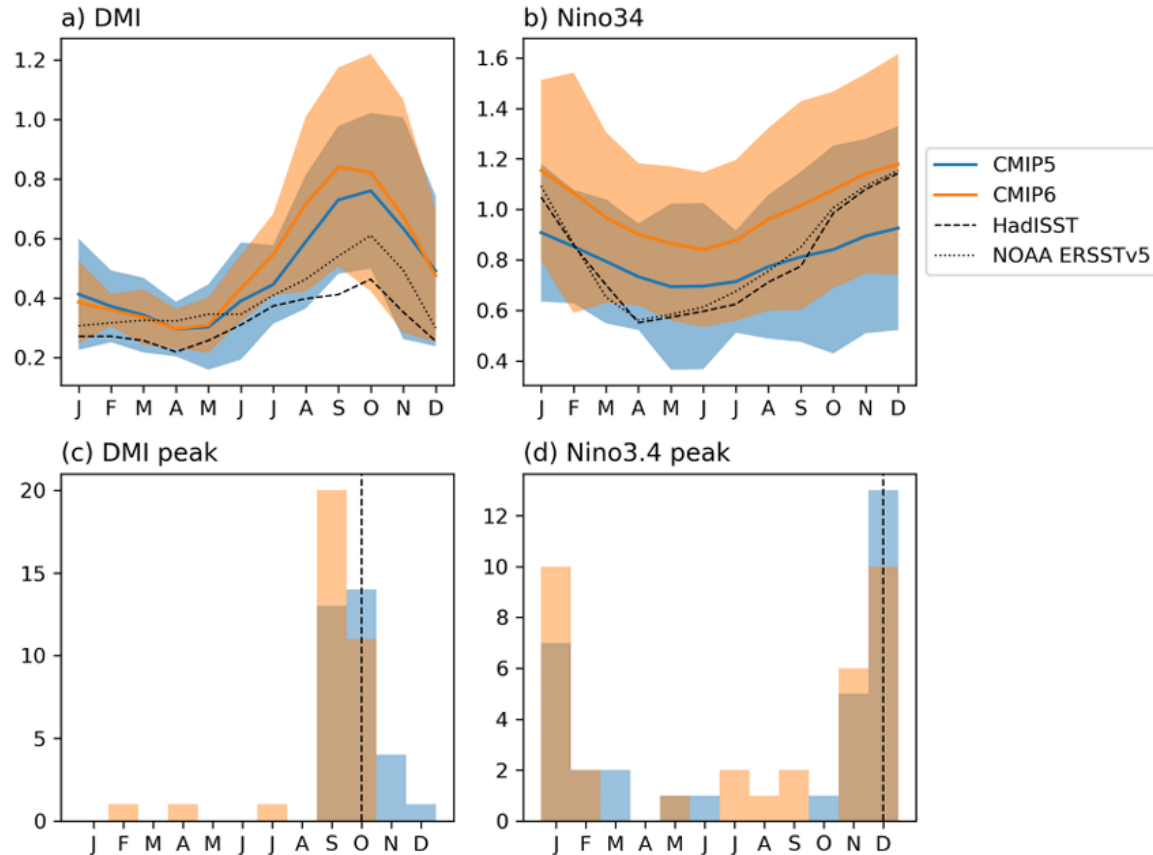
CMIP6 outperforms CMIP5 in 8 out of 24 ENSO metrics (tropical Pacific time-mean, seasonal cycle, ENSO patterns, diversity, and remote teleconnections).

Worse in one metric (coupling between subsurface and surface temperature).





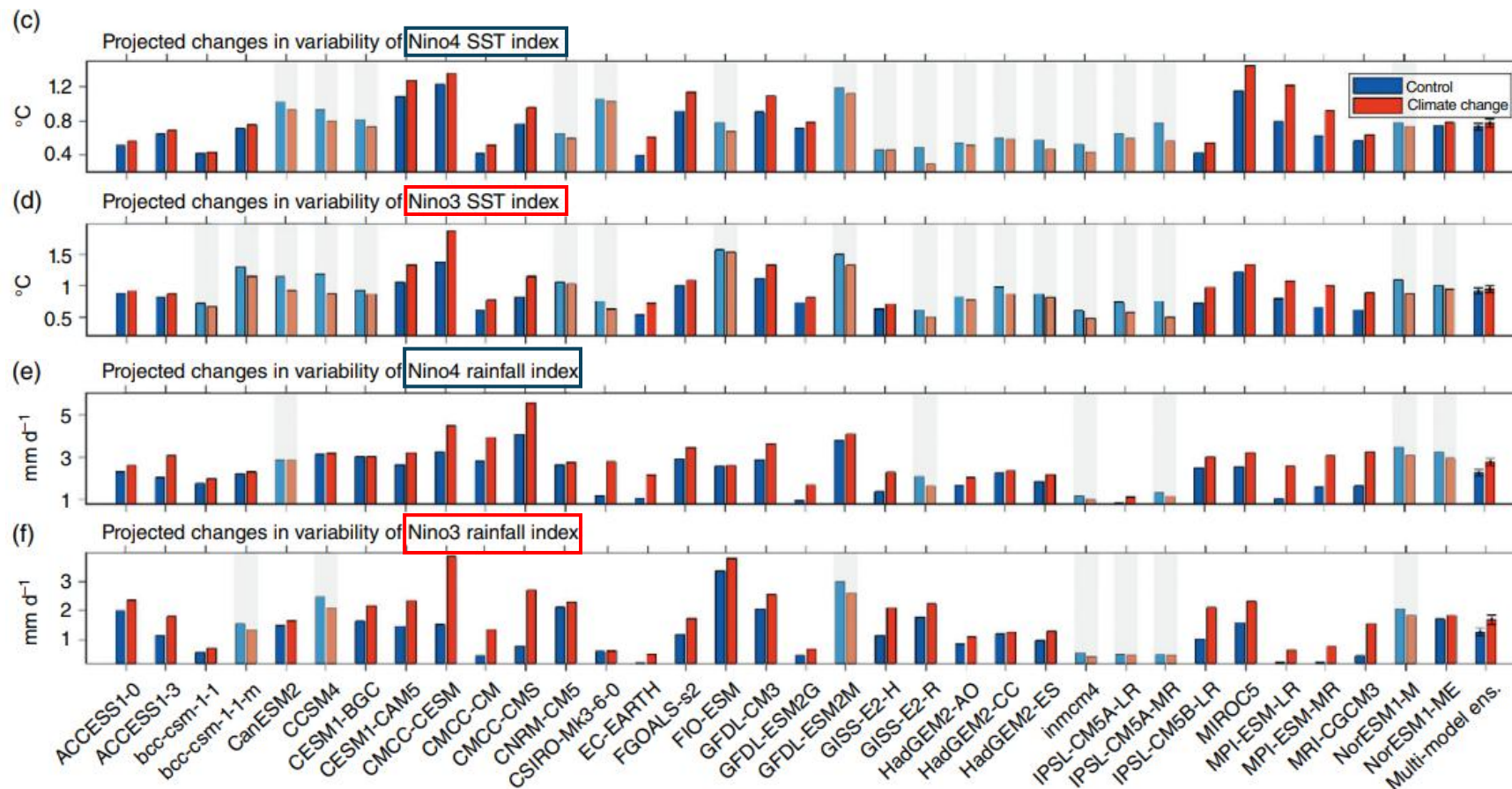
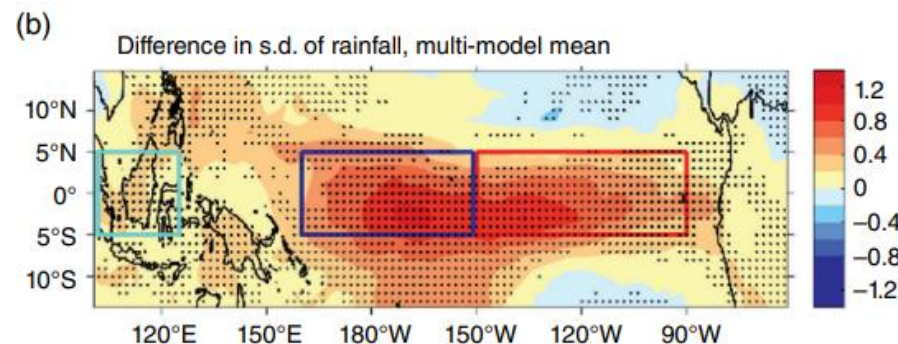
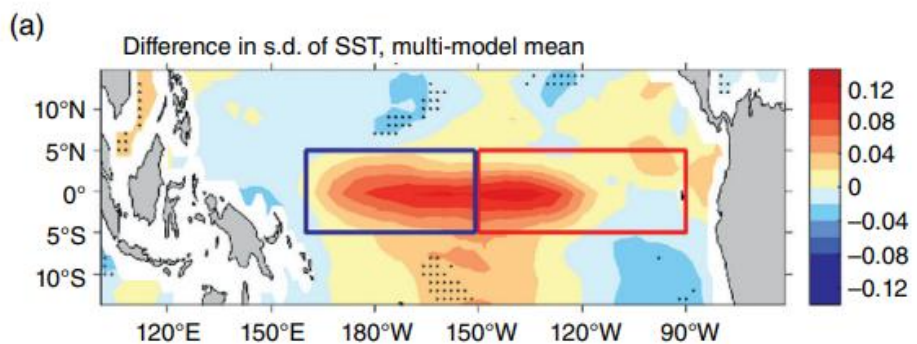
Reduced cold tongue bias



Seasonal Phase Locking is important for teleconnections and prediction.

IOD seasonality is better than ENSO, but the peak amplitude is too strong and seems worse in CMIP6

(McKenna et al. 2020, Scientific Reports)



SST variability change:
low inter-model
agreement

Rainfall variability
change: high inter-model
agreement

$$\frac{\partial T'}{\partial t} = -\underbrace{u' \frac{\partial T'}{\partial x} + v' \frac{\partial T'}{\partial y} + w' \frac{\partial T'}{\partial z}}_{\text{Linear advective terms}} - \underbrace{\cancel{u' \frac{\partial T'}{\partial x}} + \cancel{v' \frac{\partial T'}{\partial y}} + \cancel{w' \frac{\partial T'}{\partial z}}}_{\text{NDH}} + \text{res}$$

$$\frac{\partial \langle T \rangle}{\partial t} \approx - \left(\frac{\langle \bar{u} \rangle}{L_x} + \frac{\langle -2y\bar{v} \rangle}{L_y^2} + \frac{\langle \bar{w} \rangle}{H_m} \right) \langle T \rangle - \langle u \rangle \left\langle \frac{\partial \bar{T}}{\partial x} \right\rangle - \langle w \rangle \left\langle \frac{\partial \bar{T}}{\partial z} \right\rangle + \langle \bar{w} \rangle \frac{\langle T_{sub} \rangle}{H_m} + \langle Q \rangle$$

$$\langle u \rangle = \beta_u \langle \tau_x \rangle + \beta_{uh} [h]$$

$$\langle w \rangle = -\beta_w \langle \tau_x \rangle$$

$$\langle h \rangle - [h] = \beta_h [\tau_x]$$

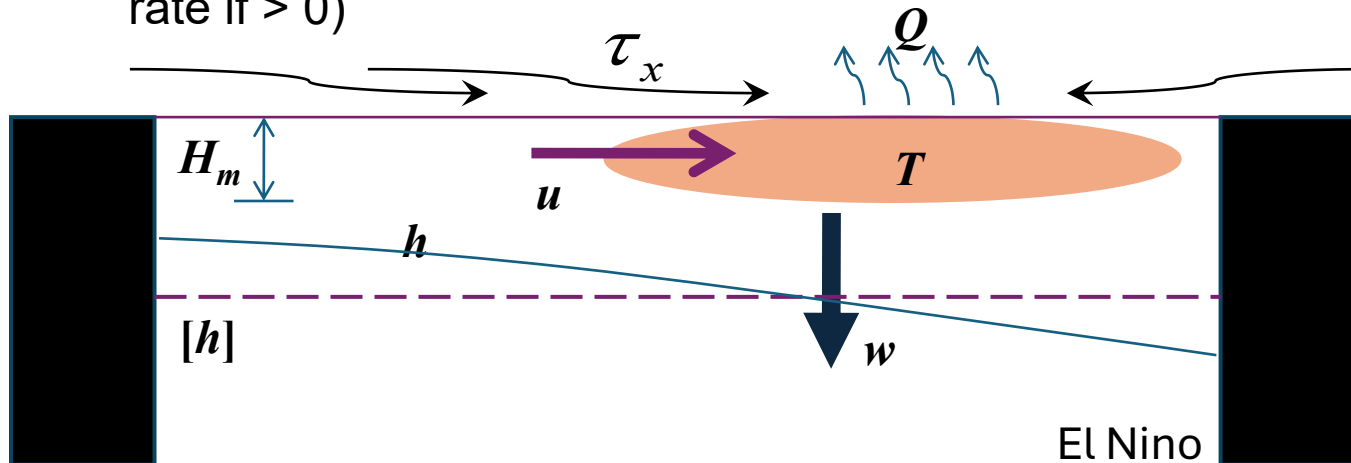
$$\langle Q \rangle = -\alpha \langle T \rangle$$

$$\frac{\partial \langle T \rangle}{\partial t} = 2I_{BJ} \langle T \rangle + \left(-\frac{\partial \bar{T}}{\partial x} \beta_{uh} + \frac{\bar{w}}{H_m} \right) [h]$$

$$2I_{BJ} \approx \underbrace{- \left(\frac{\langle \bar{u} \rangle}{L_x} + \frac{\langle -2y\bar{v} \rangle}{L_y^2} + \frac{\langle \bar{w} \rangle}{H_m} \right)}_{\text{MA}} \underbrace{- \alpha}_{\text{TD}} \underbrace{\left(+ \mu_a \beta_u \left\langle -\frac{\partial \bar{T}}{\partial x} \right\rangle + \mu_a \beta_w \left\langle \frac{\partial \bar{T}}{\partial z} \right\rangle + \mu_a^* \beta_h \left\langle \frac{\bar{w}}{H_m} \right\rangle \right)}_{\text{ZA EK TH}}$$

ENSO interactions
with **Mean State**

Bjerknes (BJ) stability index (Jin et al. 2006, GRL; decay rate if < 0, growth rate if > 0)



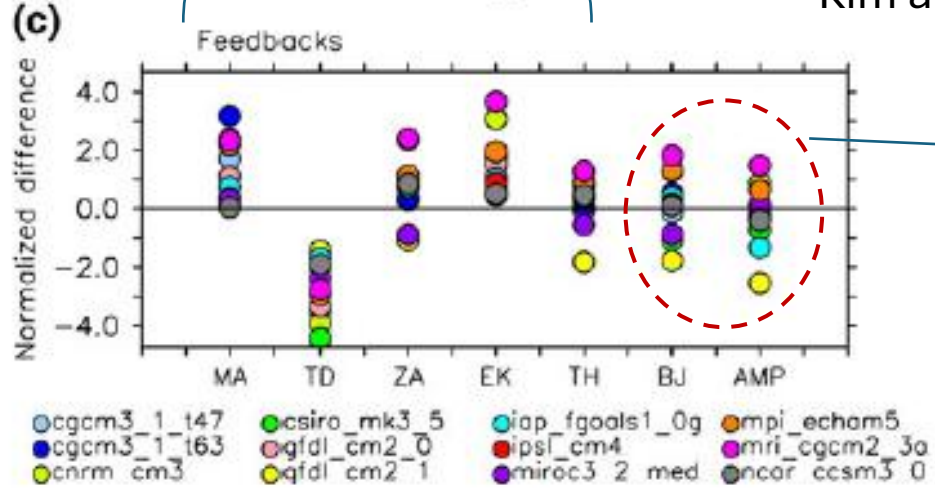
$$[\tau_x] = \mu_a^* \langle T \rangle$$

$$\langle \tau_x \rangle = \mu_a \langle T \rangle$$

$$\langle h \rangle = \frac{\langle T_{sub} \rangle}{a}$$

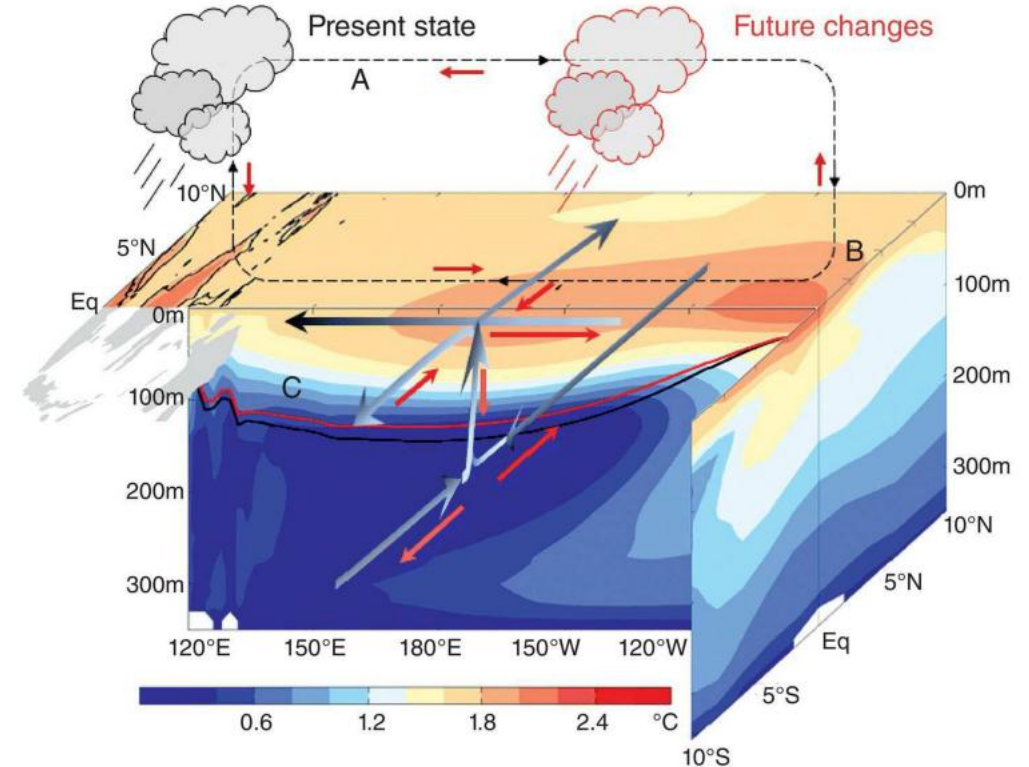
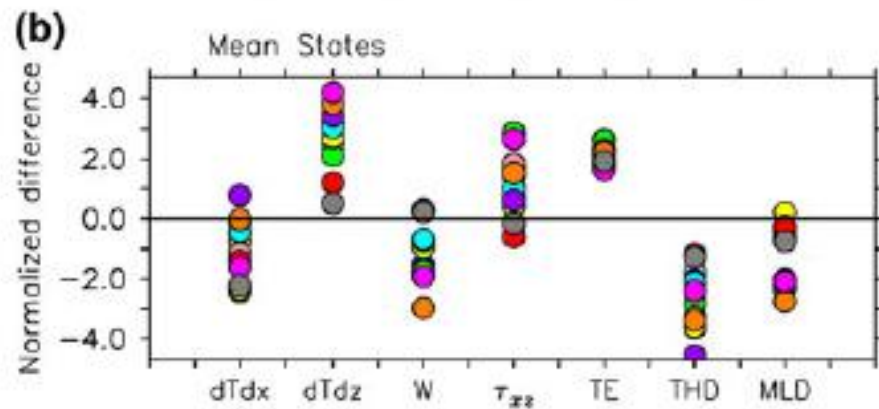
compensating feedbacks

Kim and Jin (2011)



No model consensus in ENSO amplitude change

Despite strong consensus in mean state change: weakened Walker Circulation

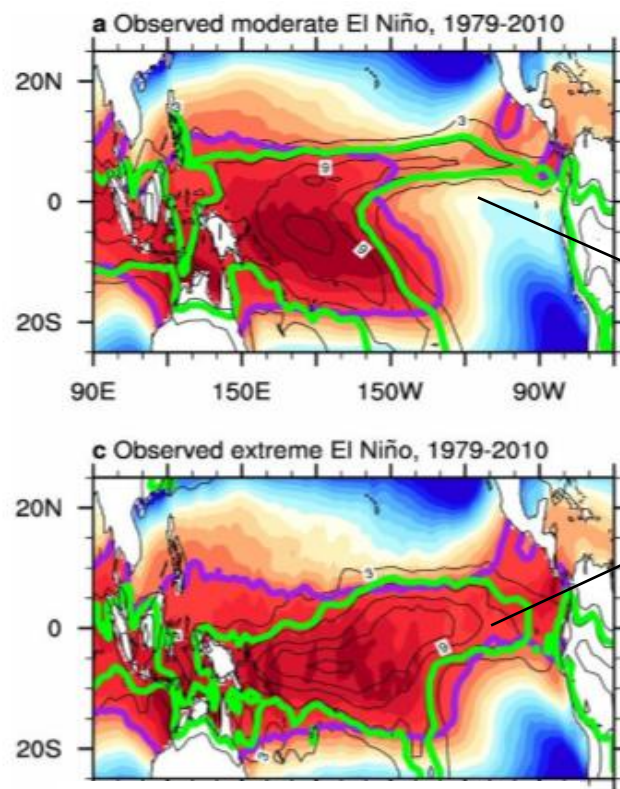


Cai, Santoso, Wang, et al. (2020, ENSO book Chapter 13)

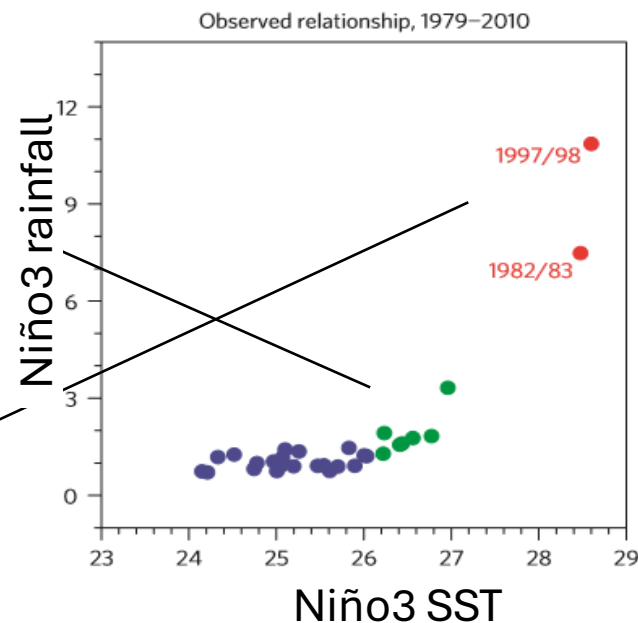
Increasing frequency of extreme El Niño events due to greenhouse warming

Wenju Cai^{1,2*}, Simon Borlace¹, Matthieu Lengaigne³, Peter van Rensch¹, Mat Collins⁴,
Gabriel Vecchi⁵, Axel Timmermann⁶, Agus Santoso⁷, Michael J. McPhaden⁸, Lixin Wu²,
Matthew H. England⁷, Guojian Wang^{1,2}, Eric Guilyardi^{3,9} and Fei-Fei Jin¹⁰

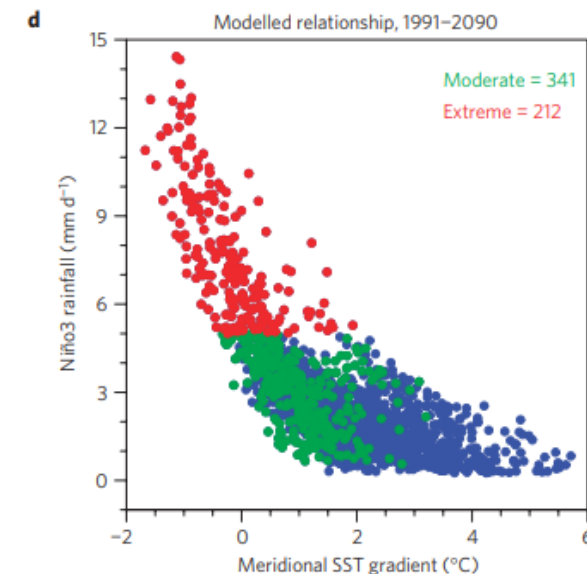
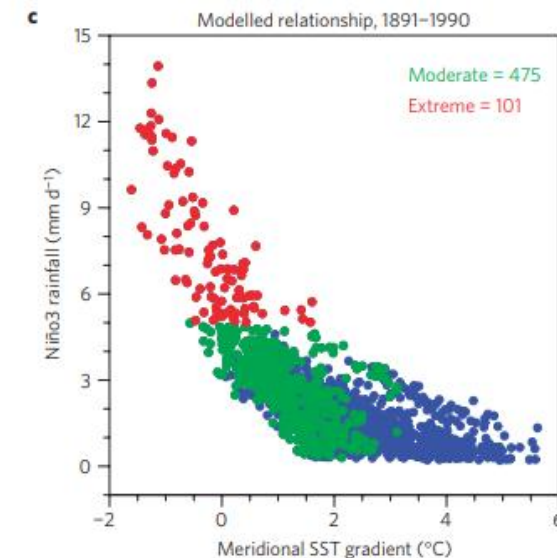
Eastern equatorial Pacific rainfall

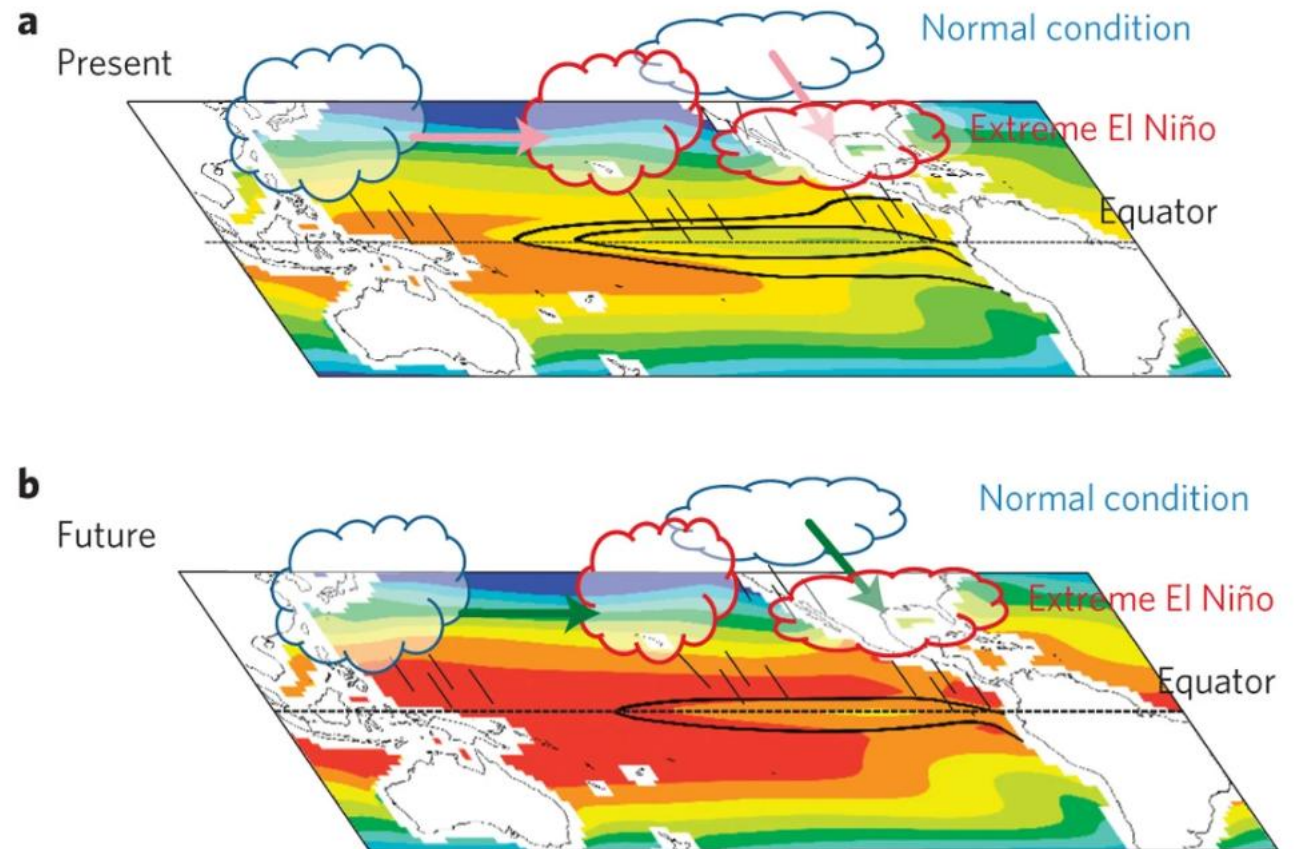
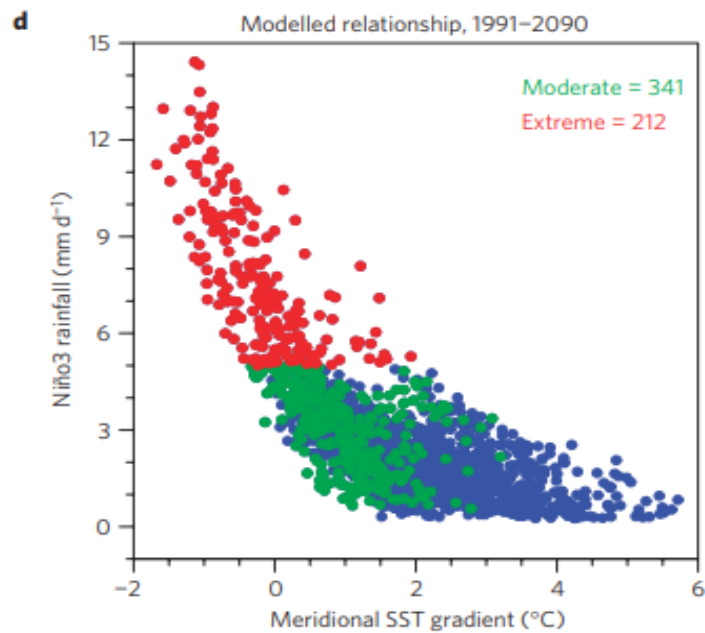
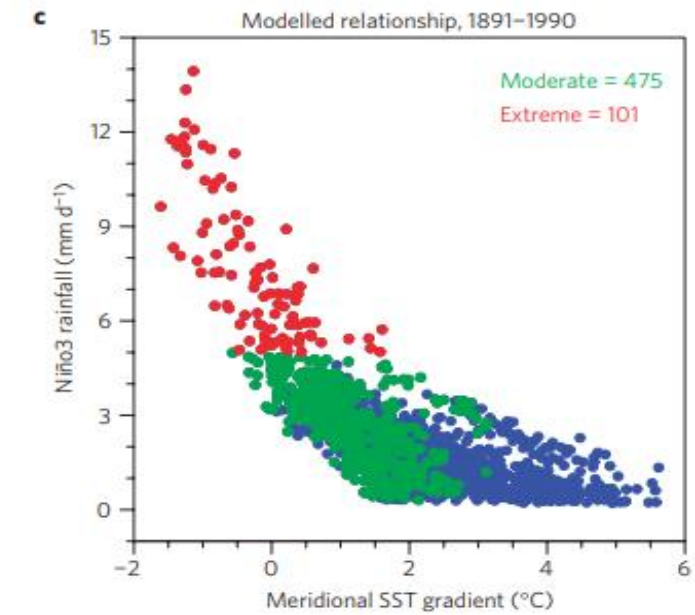


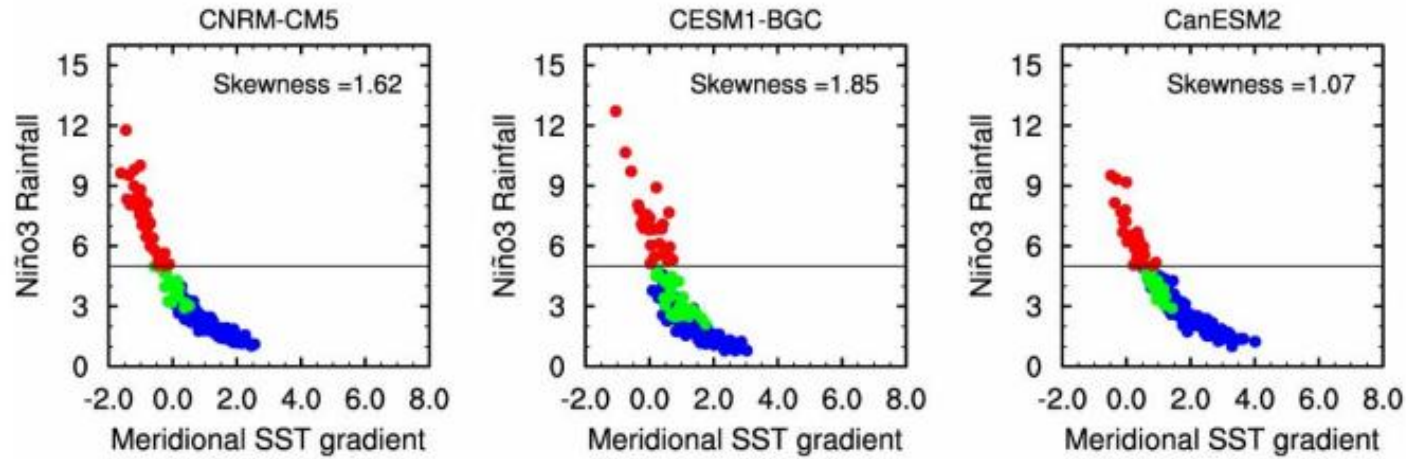
Green 5 mm per day
Purple 28°C isotherm



Define Extreme El Niño: DJF
Niño3 Precip > 5 mm/day

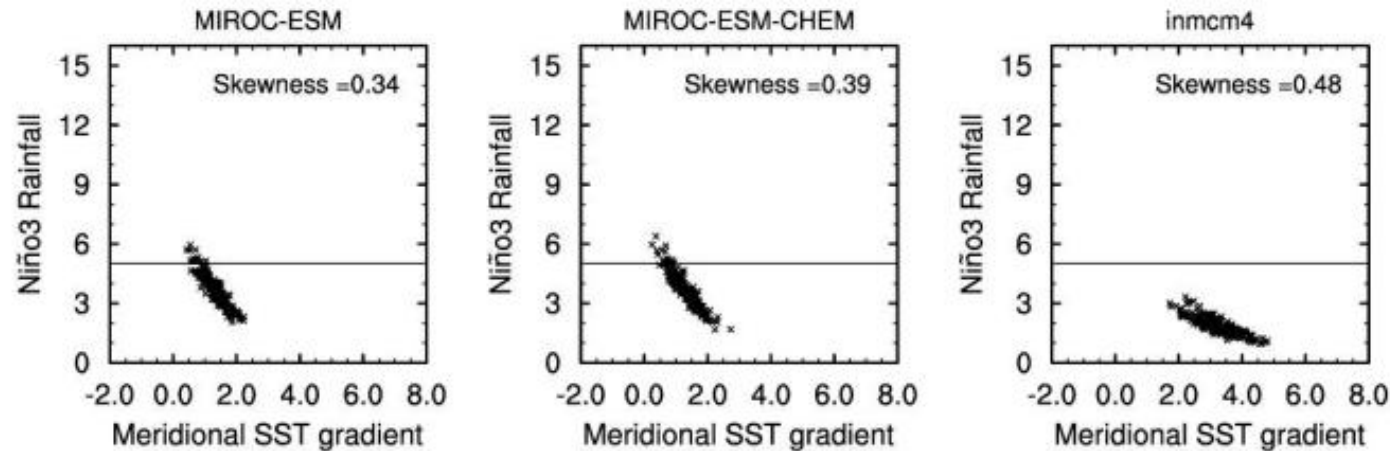






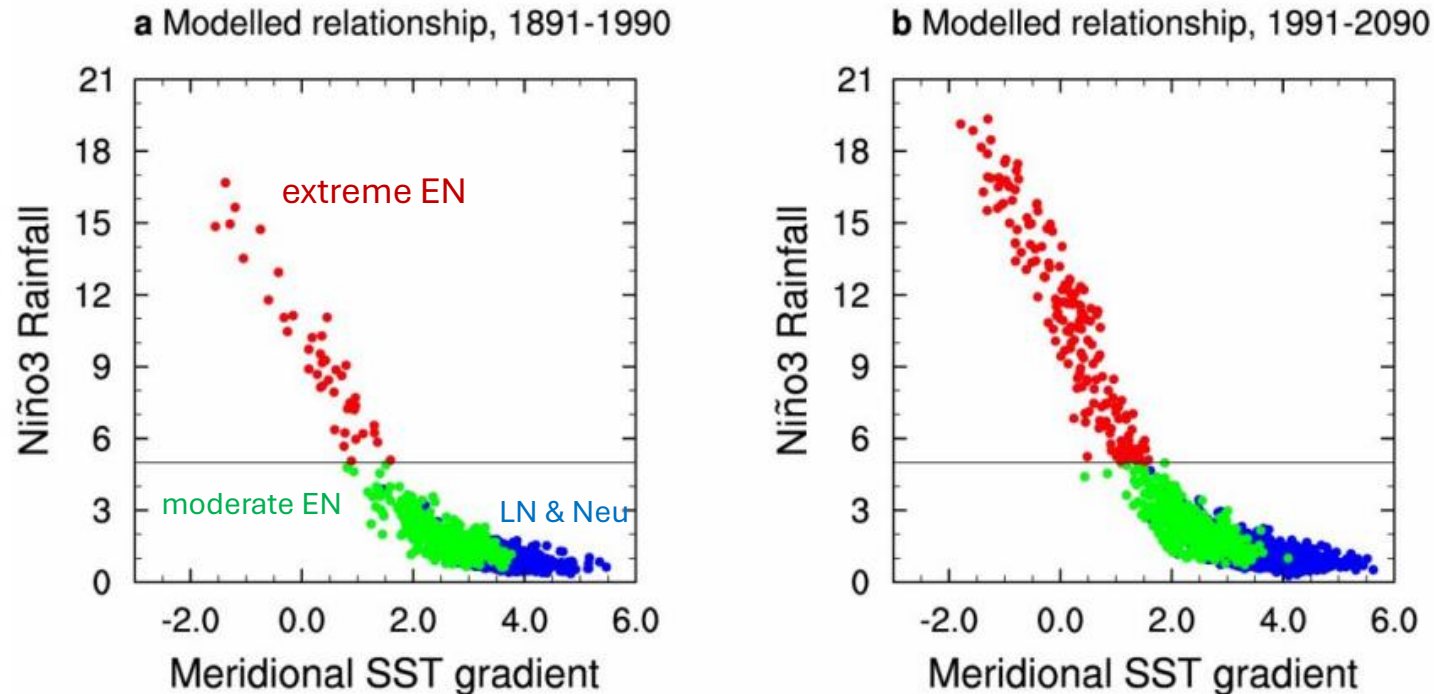
Examples of the selected models

Nino3 rainfall skewness > 1
Able to simulate events with
Nino3 rainfall > 5 mm/day



Examples of the discarded models

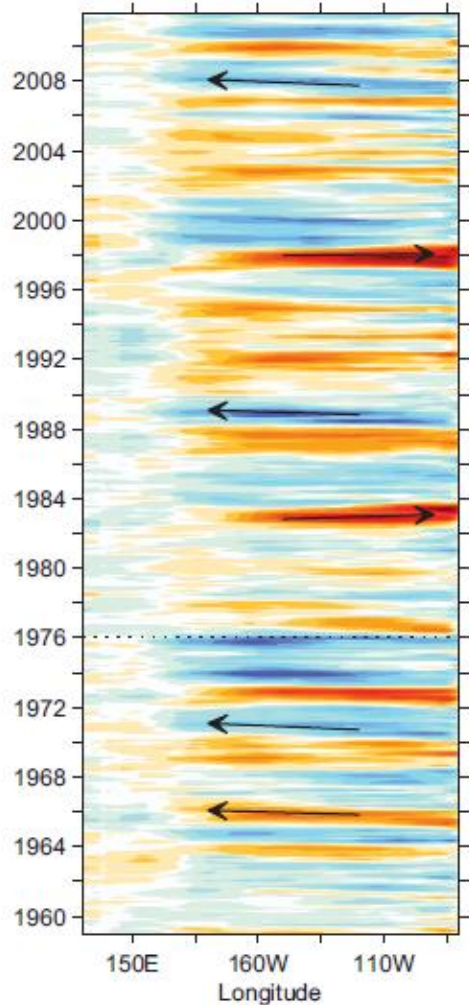
Perturbed Physics Ensemble (PPE): a flux correction strategy applied directly within coupled models to reduce present-day mean-state cold-tongue bias (Collins et al., 2011).



33 SST-bias-corrected PPE experiments, conducted with the HadCM3 CGCM forced with historical radiative perturbations and a 1% per year CO_2 increase for the future climate change runs -> 4 times increase in extreme El Nino events.

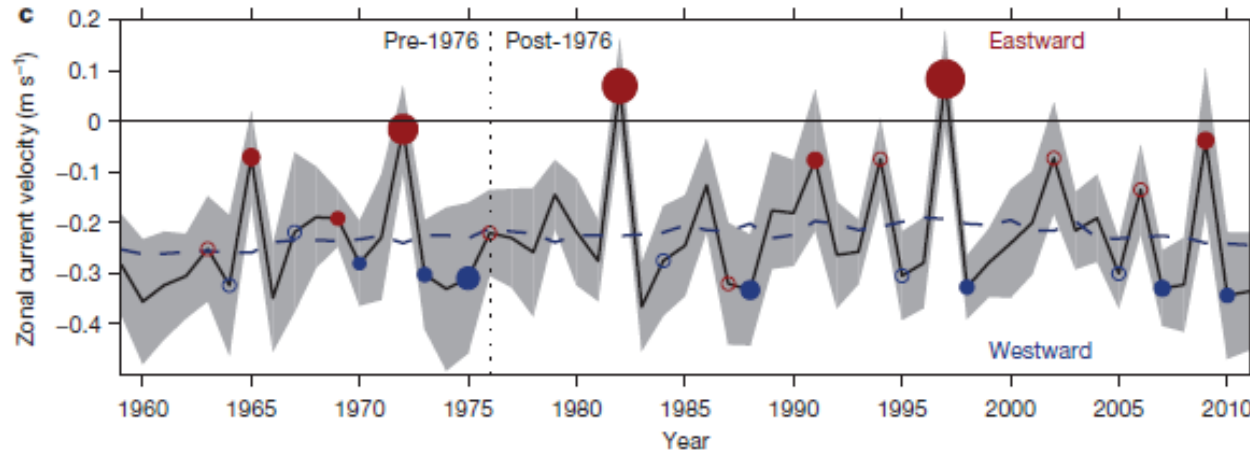
Late-twentieth-century emergence of the El Niño propagation asymmetry and future projections

Agus Santoso¹, Shayne McGregor¹, Fei-Fei Jin², Wenju Cai³, Matthew H. England¹, Soon-Il An⁴, Michael J. McPhaden⁵ & Eric Guilyardi^{6,7}

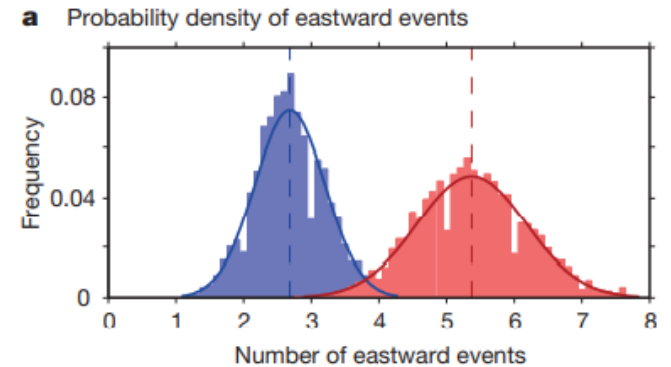
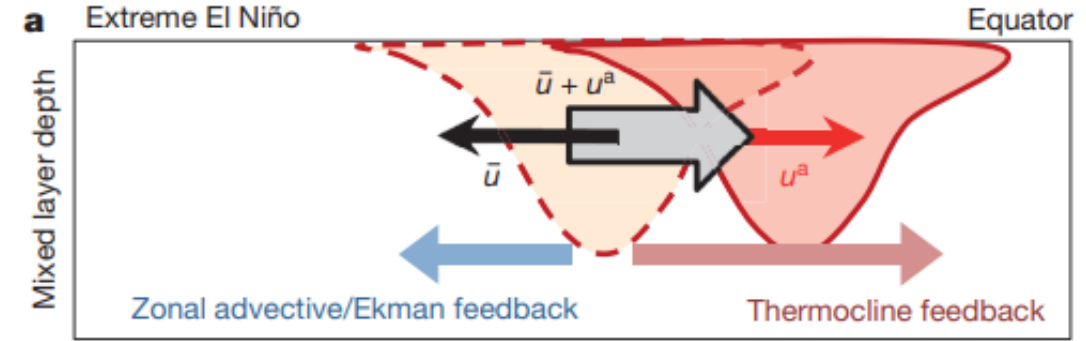


Eastward propagation and strong equatorial current reversal

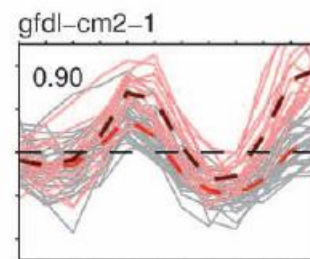
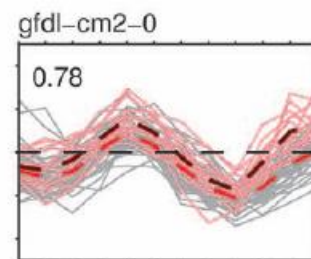
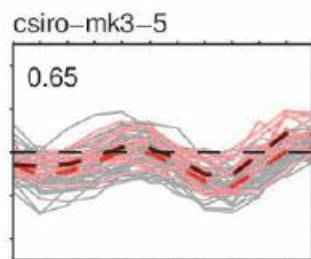
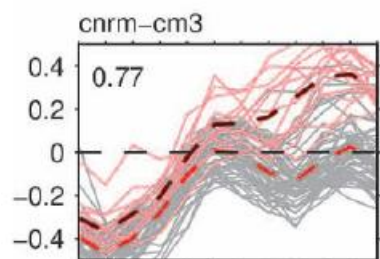
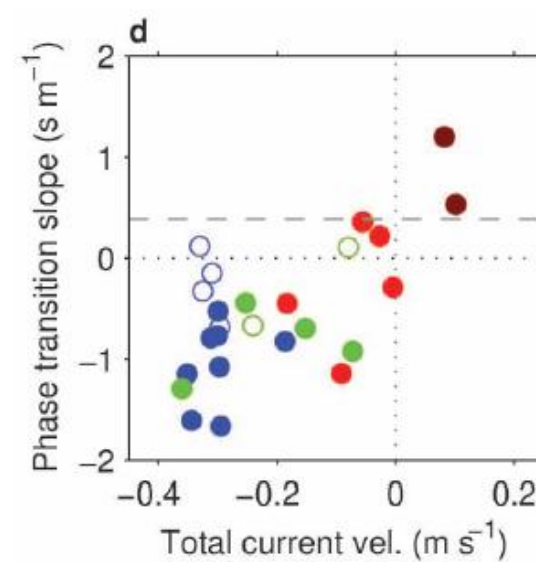
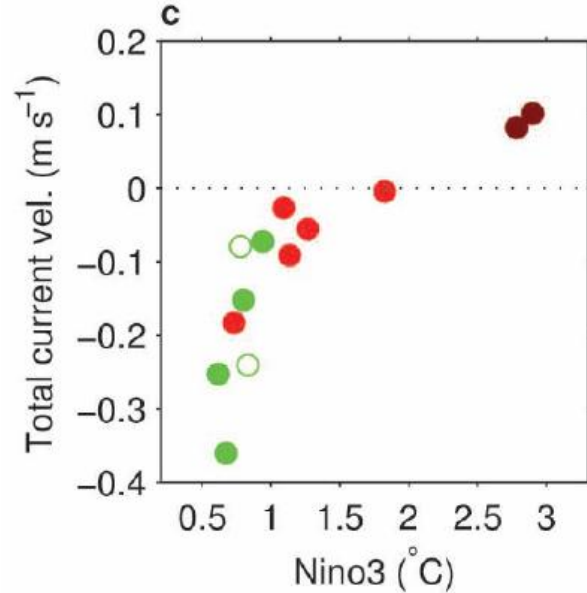
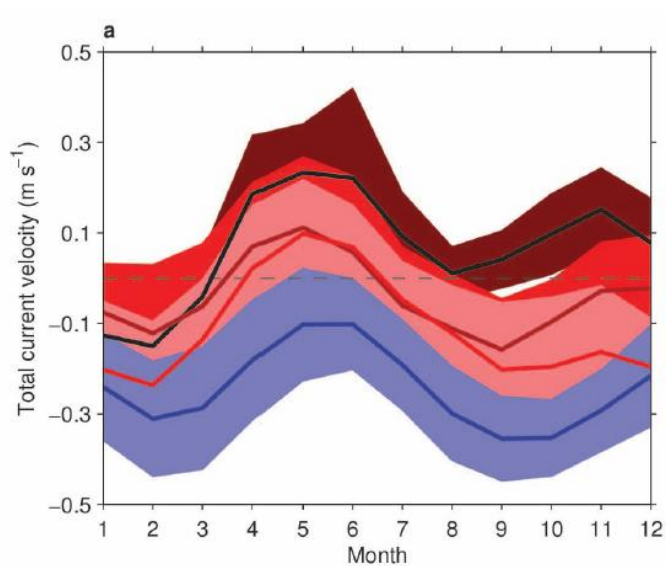
Equatorial current



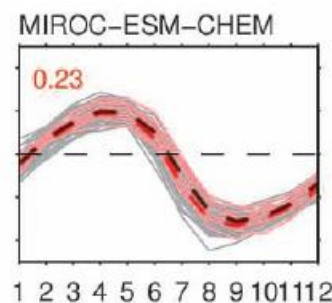
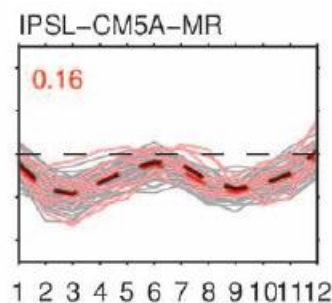
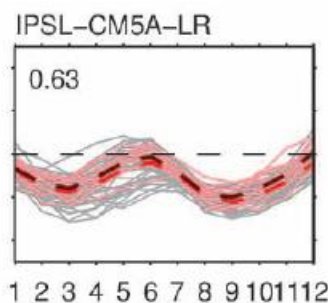
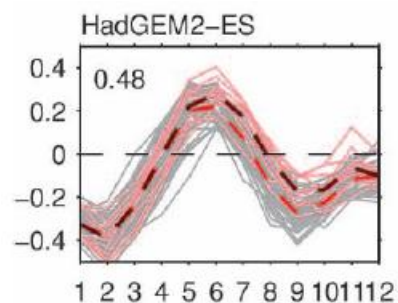
Projected weakening in mean equatorial Pacific surface current -> more occurrences of eastward propagating El Niño



— 1907–1999
— 2006–2098

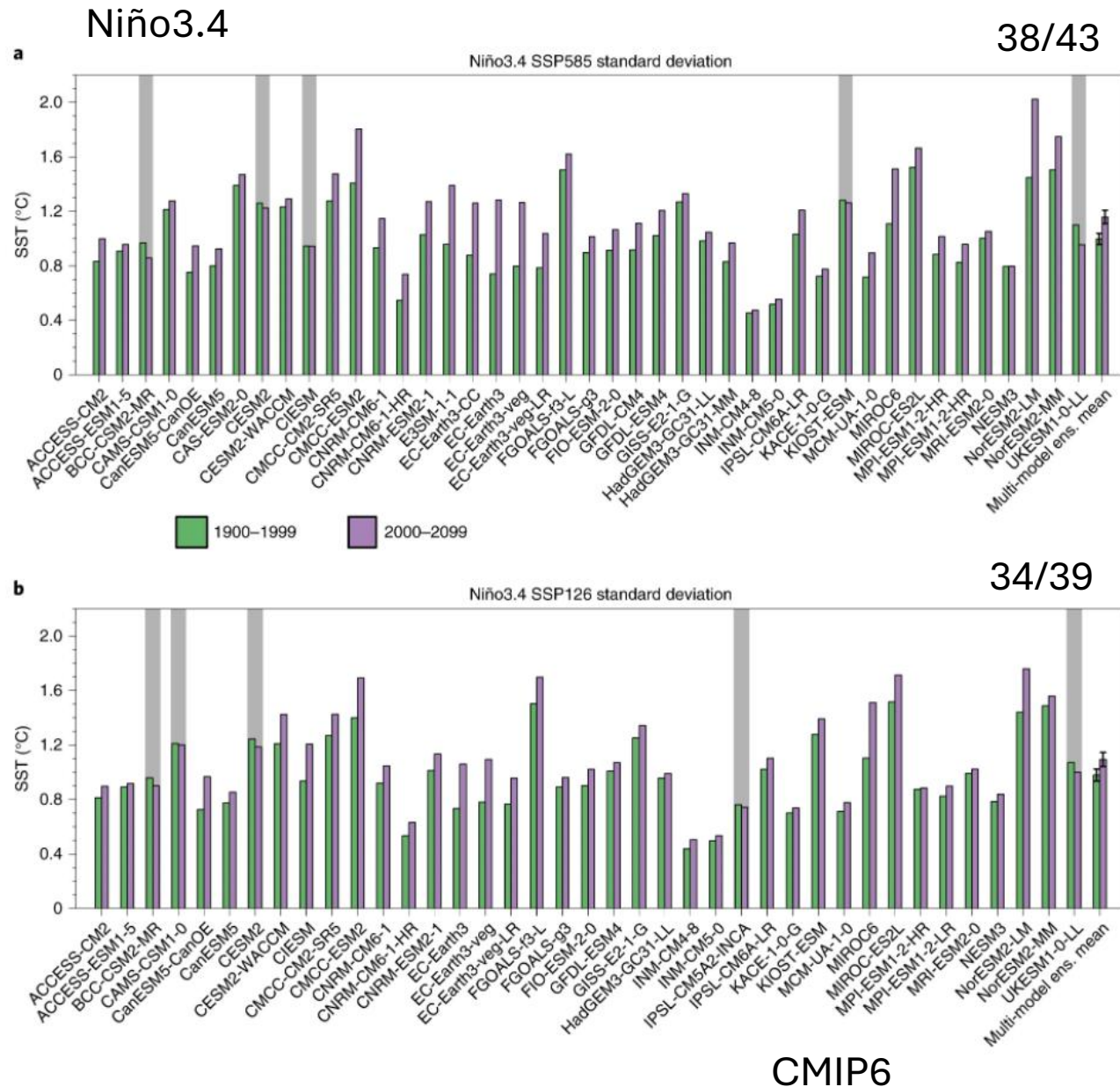


Examples of the selected models



Examples of the discarded models

Comparing 21st and 20th century: 100 years each



BRIEF COMMUNICATION

<https://doi.org/10.1038/s41558-022-01282-z>

nature
climate change

Check for updates

OPEN

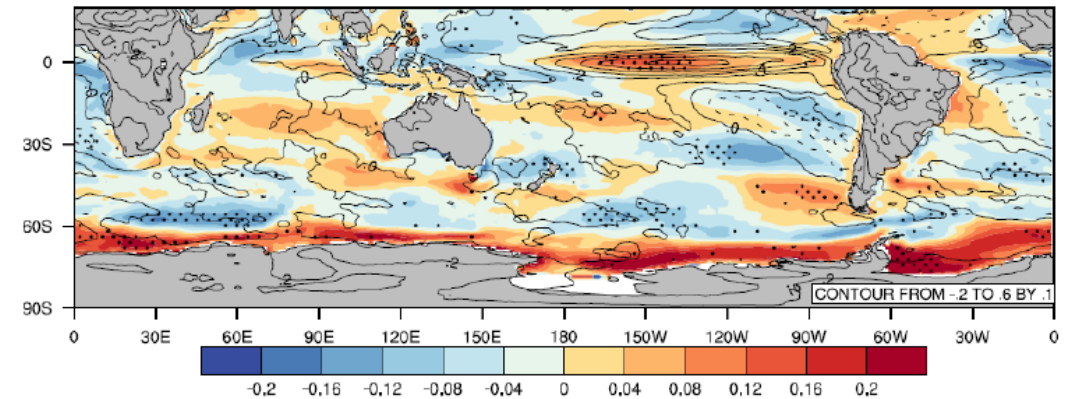
Increased ENSO sea surface temperature variability under four IPCC emission scenarios

Wenju Cai^{1,2}, Benjamin Ng², Guojian Wang^{1,2}, Agus Santoso^{1,2,3}, Lixin Wu¹ and Kai Yang⁴

Abstract

Sea surface temperature (SST) variability of El Niño–Southern Oscillation (ENSO) underpins its global impact, and its future change is a long-standing science issue. In its sixth assessment, the IPCC reports no systematic change in ENSO SST variability under any emission scenarios considered. However, comparison between the 20th and 21st century shows a robust increase in century-long ENSO SST variability under four IPCC plausible emission scenarios.

b) SST&Rainfall s.d. change



Santoso et al. (2025)

Reduction of the Pacific cold tongue bias may lead to stronger increase in future ENSO variability.

Equatorial Pacific Cold Tongue Bias degrades simulation of ENSO Asymmetry due to underestimation of strong Eastern Pacific El Niños

Tobias Bayr, Joke F. Lübbecke, Jérôme Vialard, and Mojib Latif

Online Publication: 27 Aug 2024

DOI: <https://doi.org/10.1175/JCLI-D-24-0071.1>

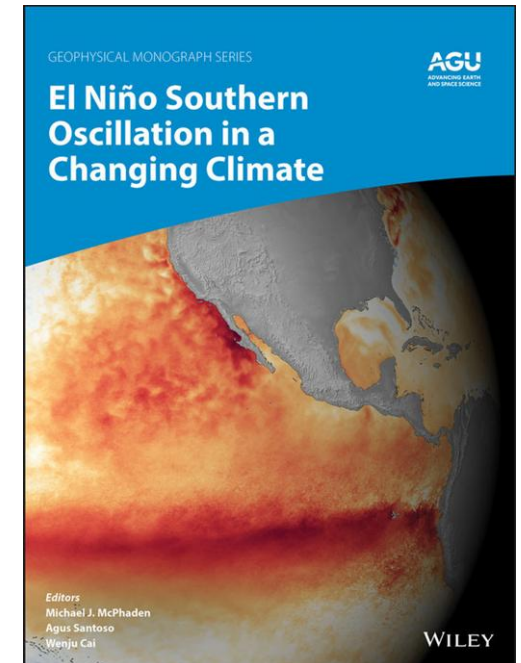


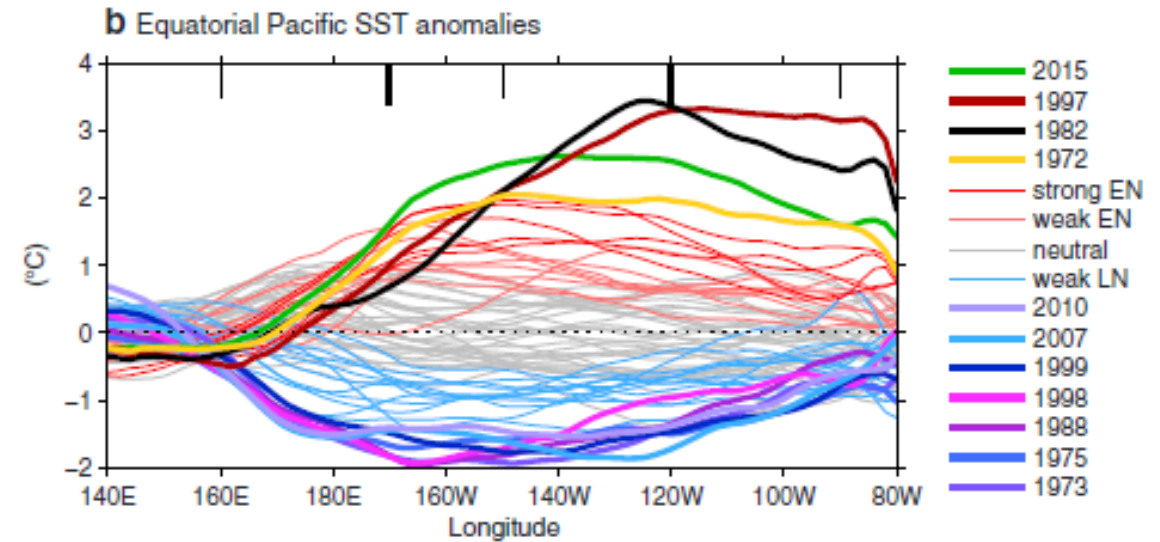
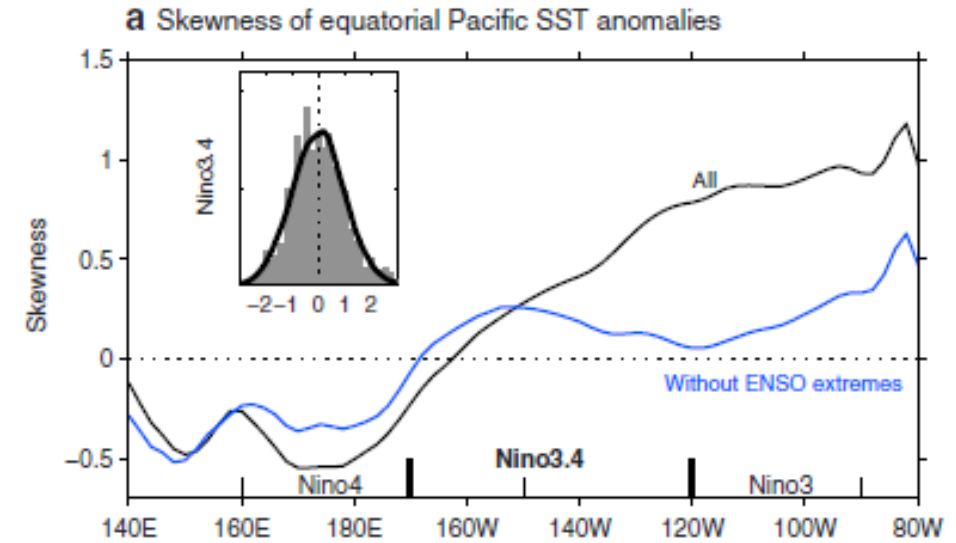
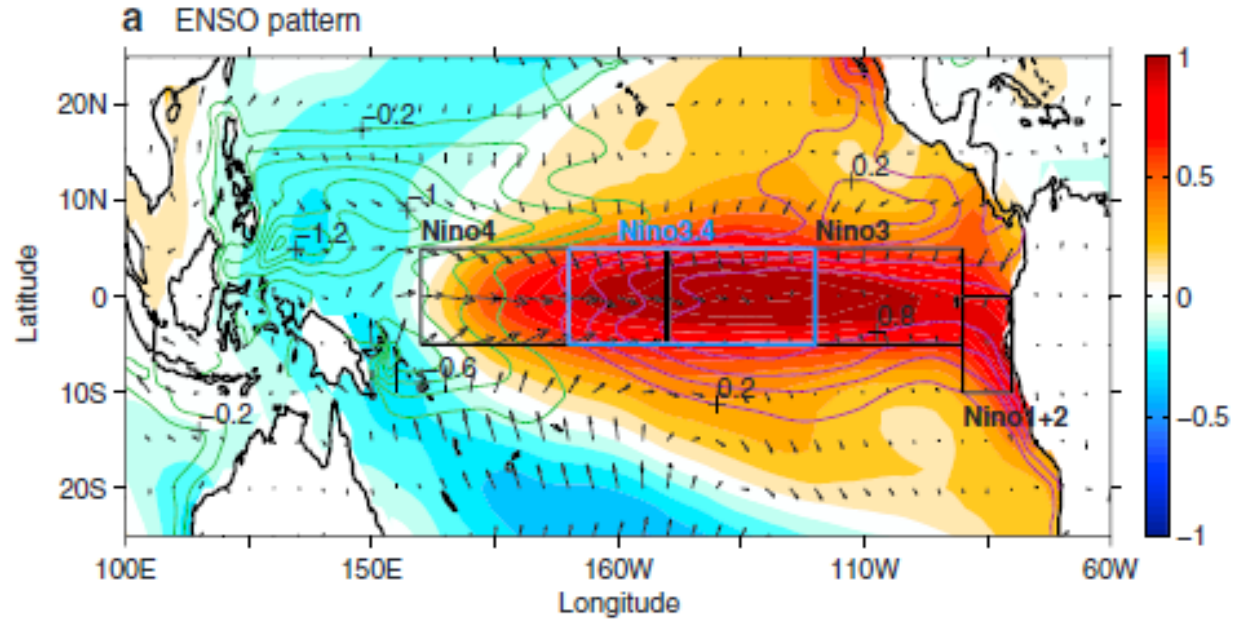
- Models an overly strong Cold Tongue simulate the strongest mean state warming farther west.
- Stronger mean state warming over the eastern equatorial Pacific facilitates a southward shift of the ITCZ, promoting an increase of strong Easter Pacific El Niño events and ENSO amplitude under global warming.
- Reducing the Cold Tongue bias should further enhance ENSO variability in the 21st century.

13

ENSO Response to Greenhouse Forcing

Wenju Cai^{1,2}, Agus Santoso^{1,3}, Guojian Wang^{1,2}, Lixin Wu², Mat Collins⁴, Matthieu Lengaigne^{5,6}, Scott Power^{7,8}, and Axel Timmermann^{9,10}





ENSO nonlinearity

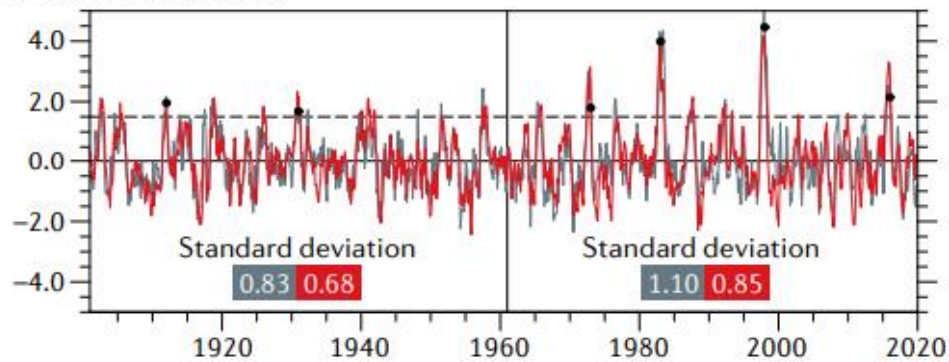
Positive skewness in Nino3 due to extreme El Nino

Negative skewness in Nino4 due to extreme La Nina

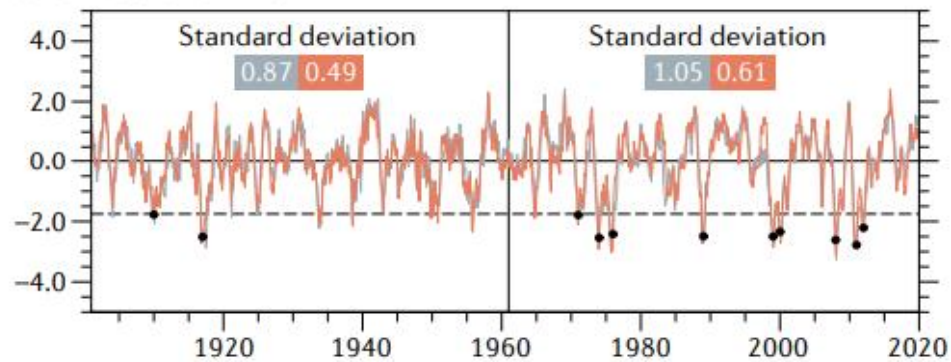
Observations. Approx. **20% increase** between pre-1960 and post-1960 in Eastern Pacific (EP) and Central Pacific (CP) ENSO variability.

Increase in EP and CP variability after 1960 is characterised by more frequent extreme El Niño and extreme La Niña events, respectively.

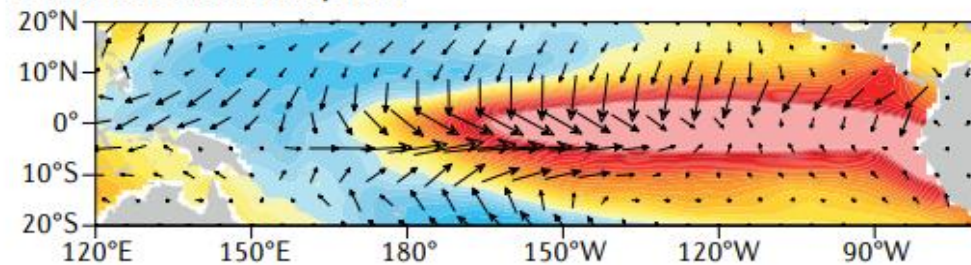
a E-index and Niño3



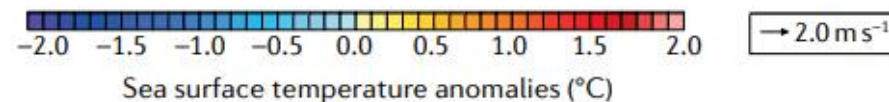
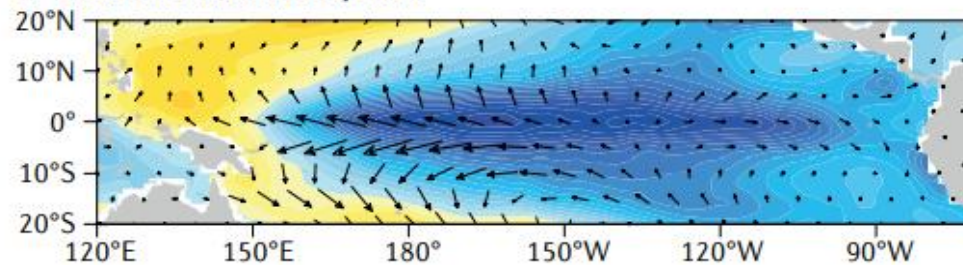
b C-index and Niño4



c Extreme El Niño composite



d Extreme La Niña composite

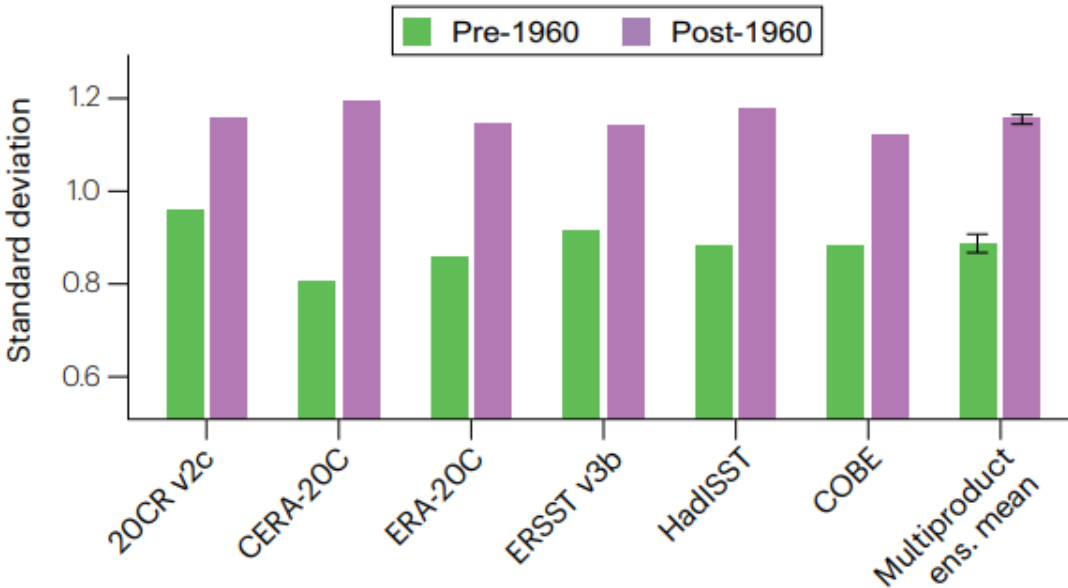


Anthropogenic impacts on twentieth-century ENSO variability changes

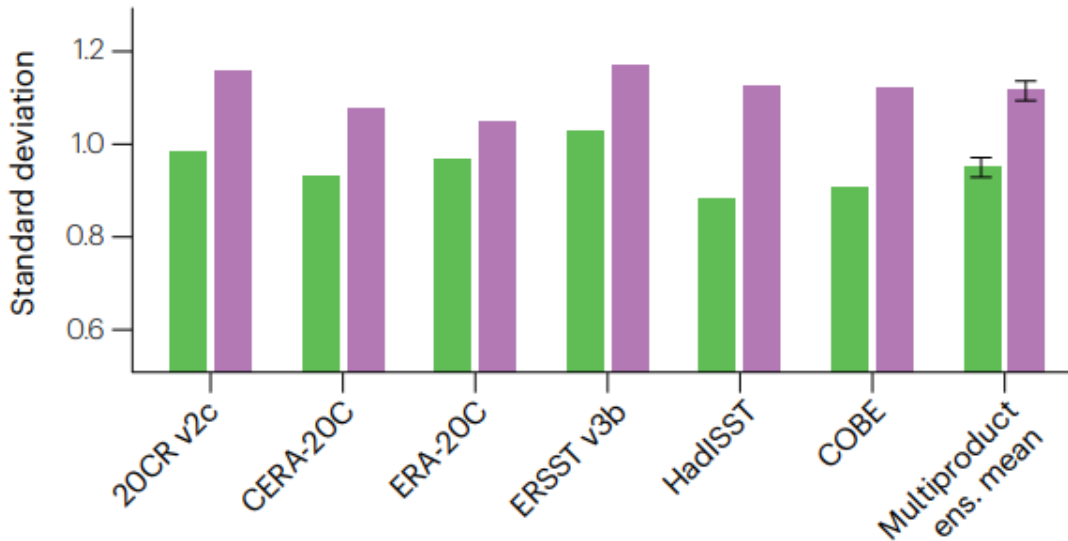
Wenju Cai^{1,2}✉, Benjamin Ng^{1,3}, Tao Geng^{1,3}, Fan Jia⁴, Lixin Wu^{1,3}✉, Guojian Wang^{1,2}, Yu Liu⁵, Bolan Gan^{1,3}, Kai Yang⁶, Agus Santoso^{1,2,7}, Xiaopei Lin^{1,3}, Ziguang Li^{1,3}, Yi Liu¹, Yun Yang⁸, Fei-Fei Jin⁹, Mat Collins¹⁰ & Michael J. McPhaden¹¹

This study provides an argument that the observed increase in EP and CP ENSO variability after 1960 could be due to greenhouse warming.

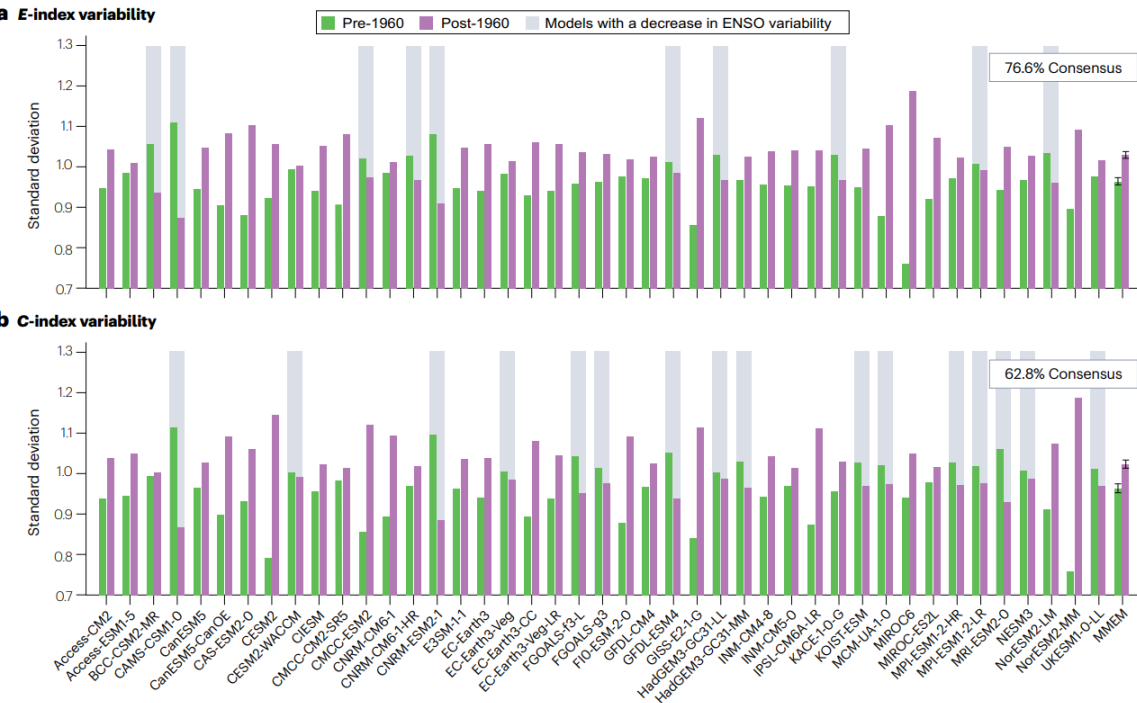
e Reanalysis *E*-index variability



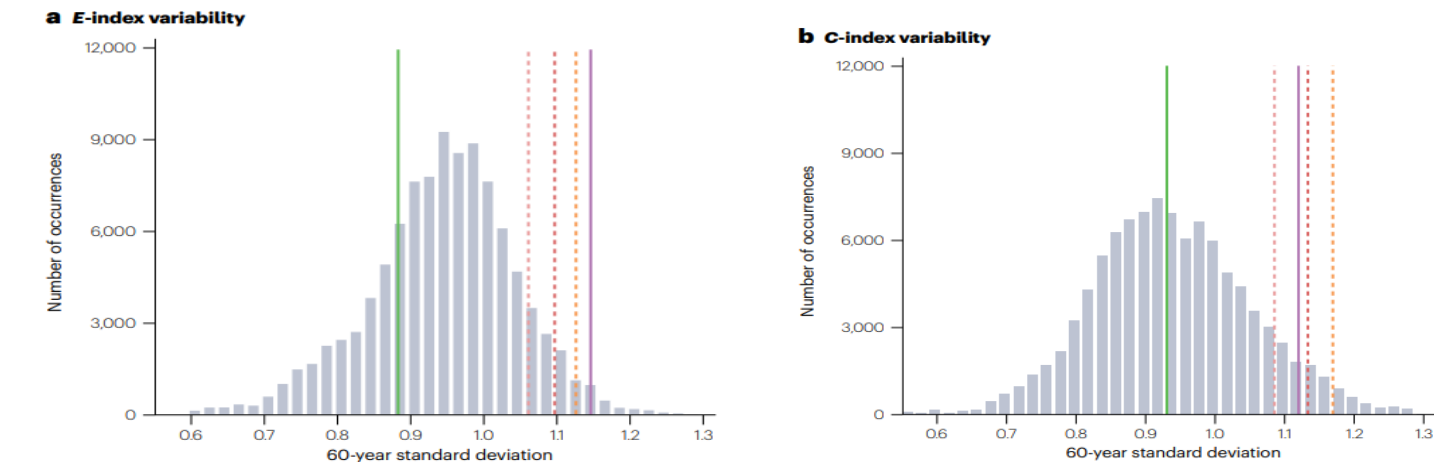
f Reanalysis *C*-index variability



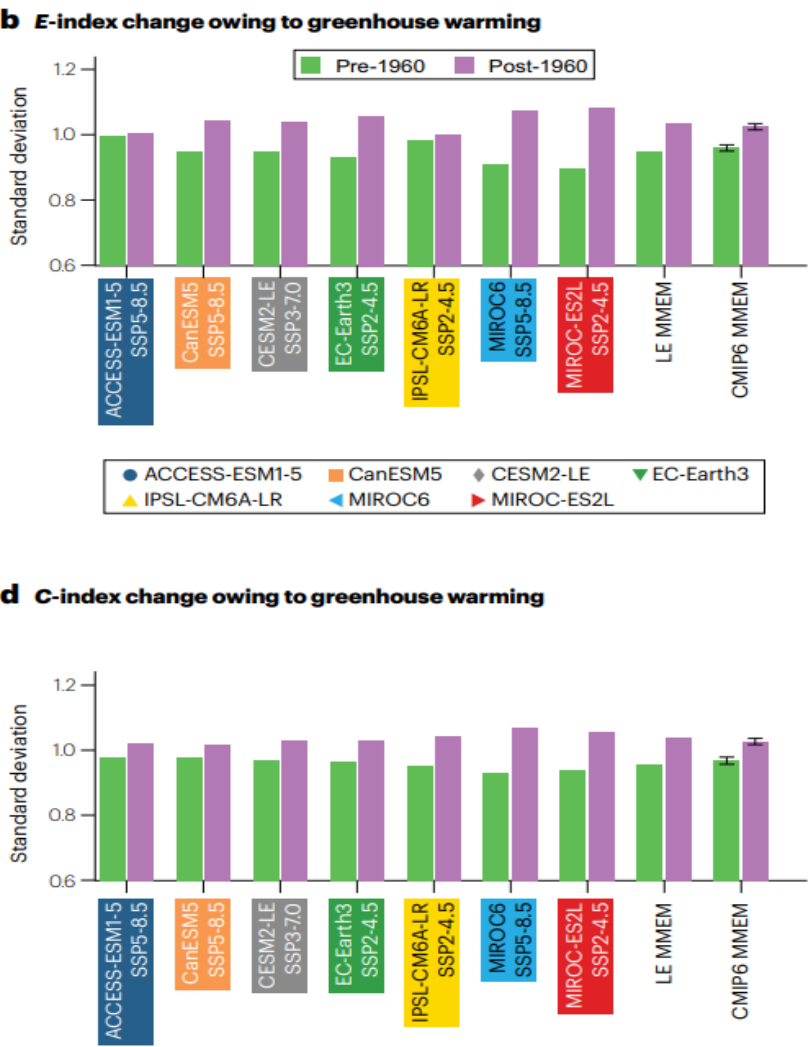
Approach 1: 43 CMIP6 models



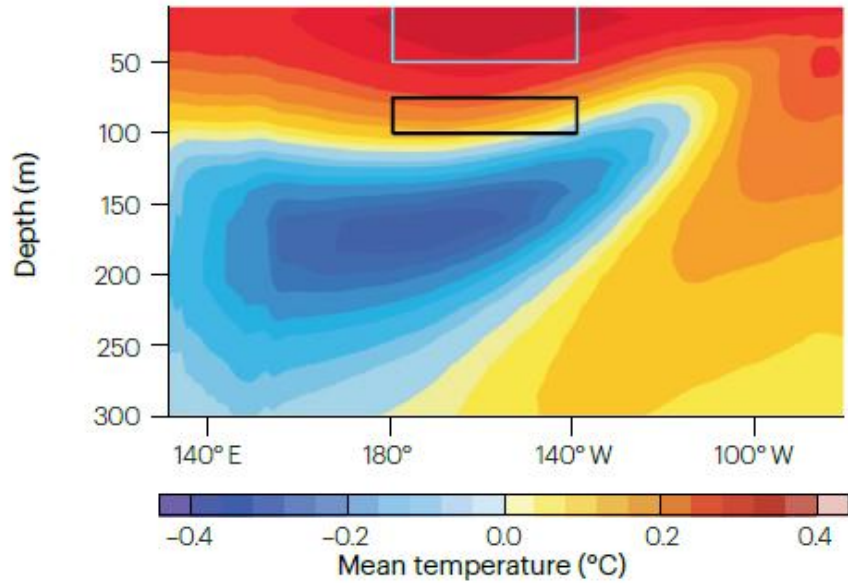
Approach 3: 39 CMIP6 models that have multi-century simulation with CO2 concentration set at pre-industrial level



Approach 2: 7 CMIP6 models, each with at least 10 ensemble members

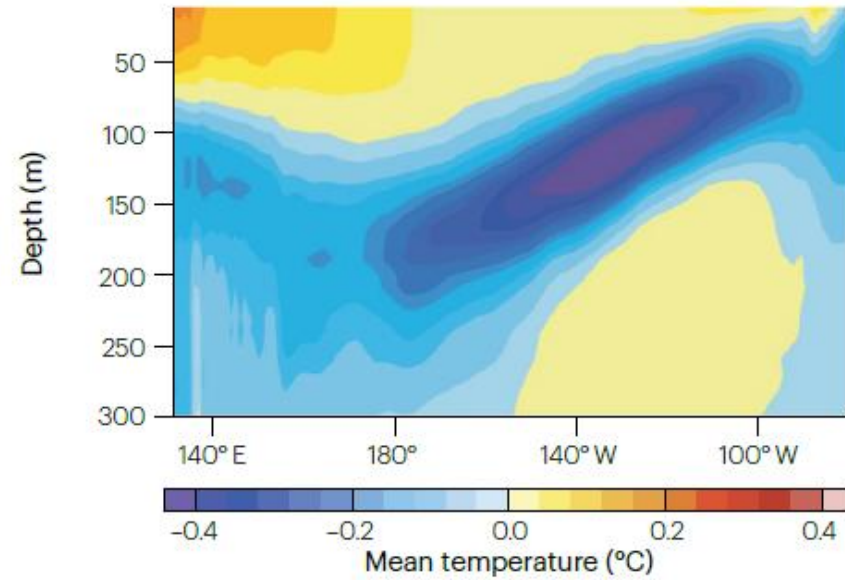


a Multimodel ensemble



1961-2020 minus 1901-1960

b Observation



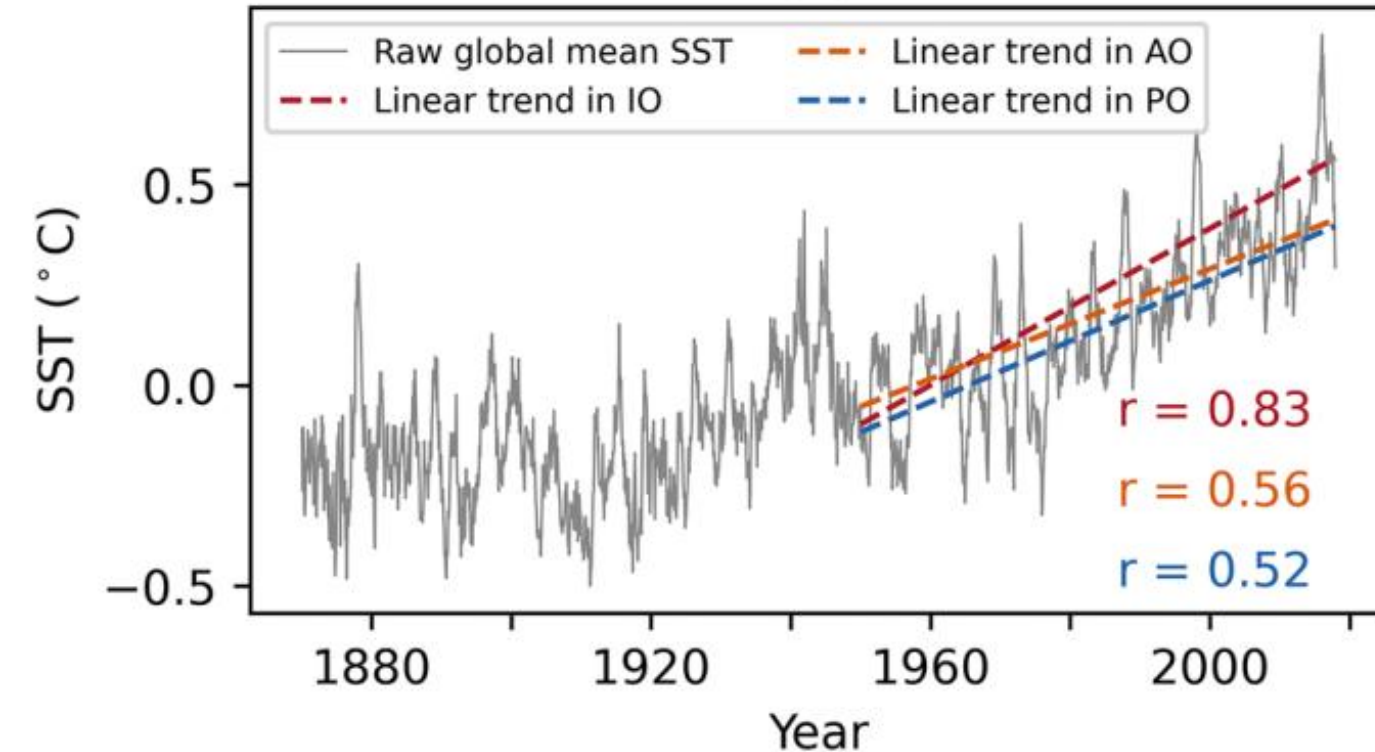
Trend (1958-2017)

Increased upper ocean stratification promotes air-sea coupling essential for the growth of ENSO events

Indian Ocean warming most rapid among tropical oceans

Emergence of positive IOD-like warming pattern driven by greenhouse gases and anthropogenic aerosols during the recent four decades

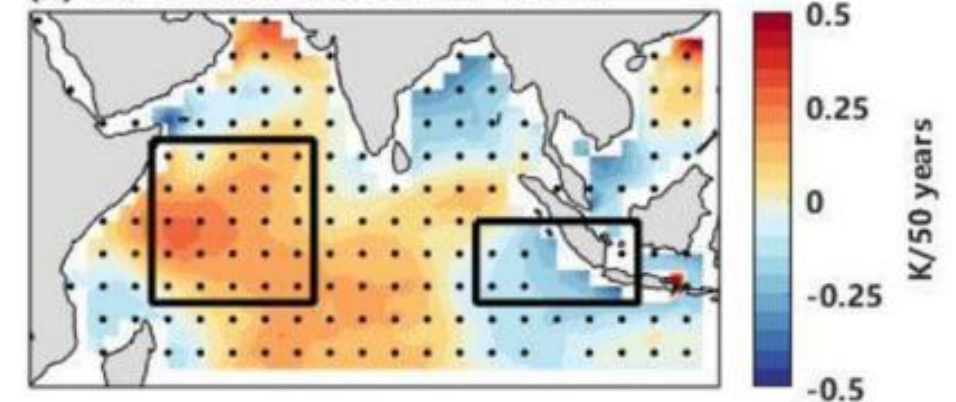
Shengyao Xin¹ · Lu Dong^{1,2} · Lixin Wu^{1,3} · Fengfei Song^{1,3} · Agus Santoso^{4,5} · Xiaotong Zheng⁶ · Bolan Gan^{1,2} · Shichu Liu^{1,7}



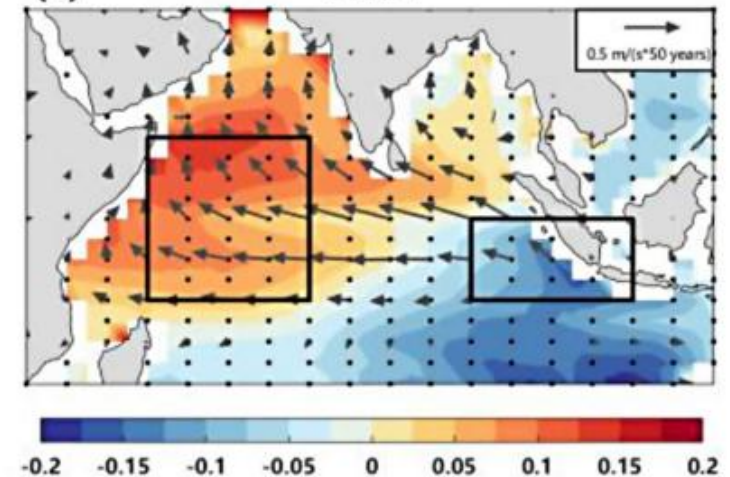
Indian Ocean warming modulates global atmospheric circulation trends

Shreya Dhame¹ · Andréa S. Taschetto¹ · Agus Santoso^{1,2} · Katrin J. Meissner¹

(d) OBS Mean Relative SST Trend



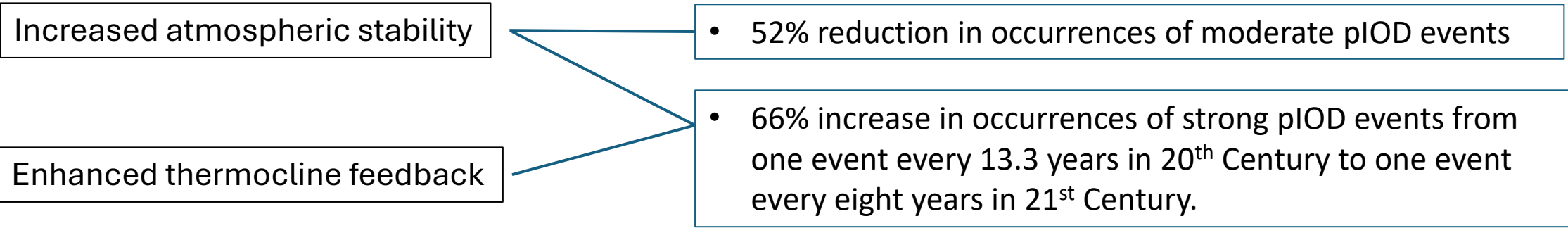
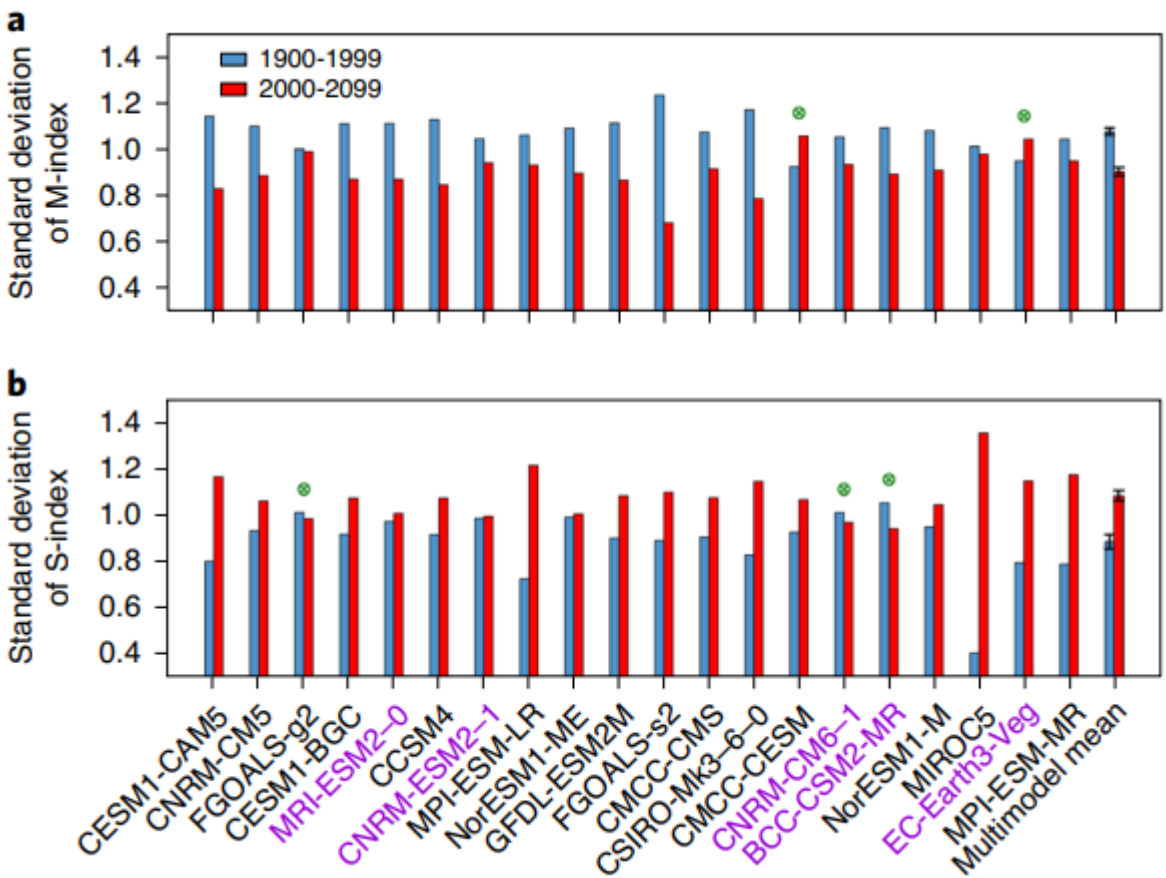
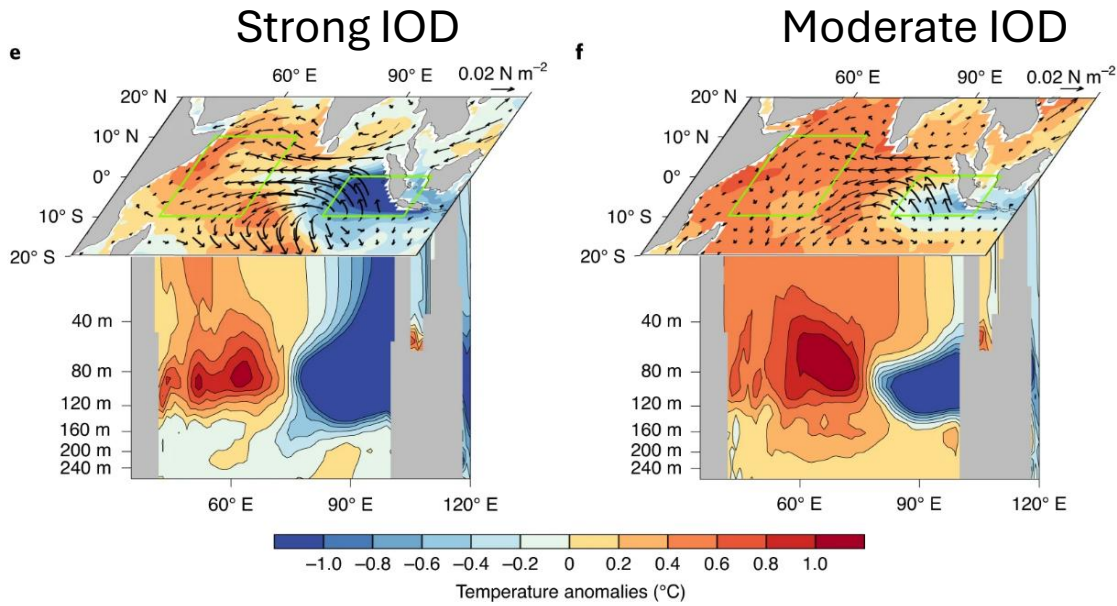
(b) GHG



Opposite response of strong and moderate positive Indian Ocean Dipole to global warming

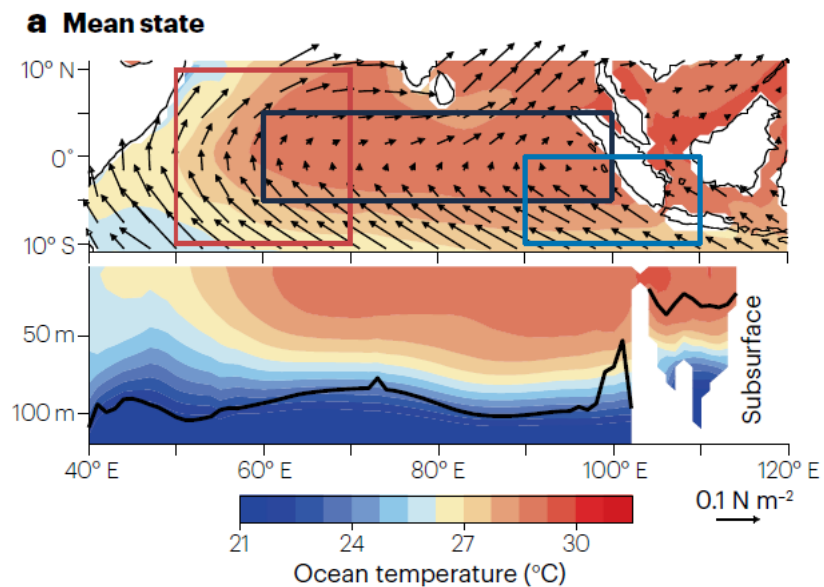
Wenju Cai, Kai Yang, Lixin Wu, Gang Huang, Agus Santoso, Benjamin Ng, Guojian Wang & Toshio Yamagata

Nature Climate Change 11, 27–32 (2021)

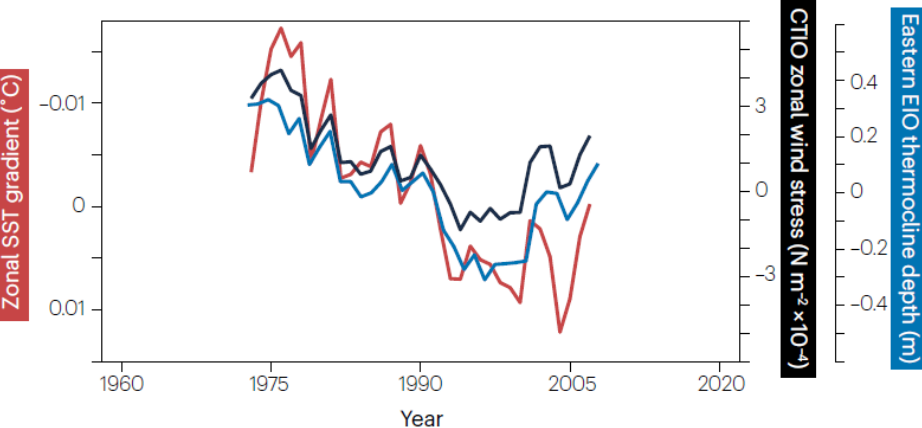


The Indian Ocean Dipole in a warming world

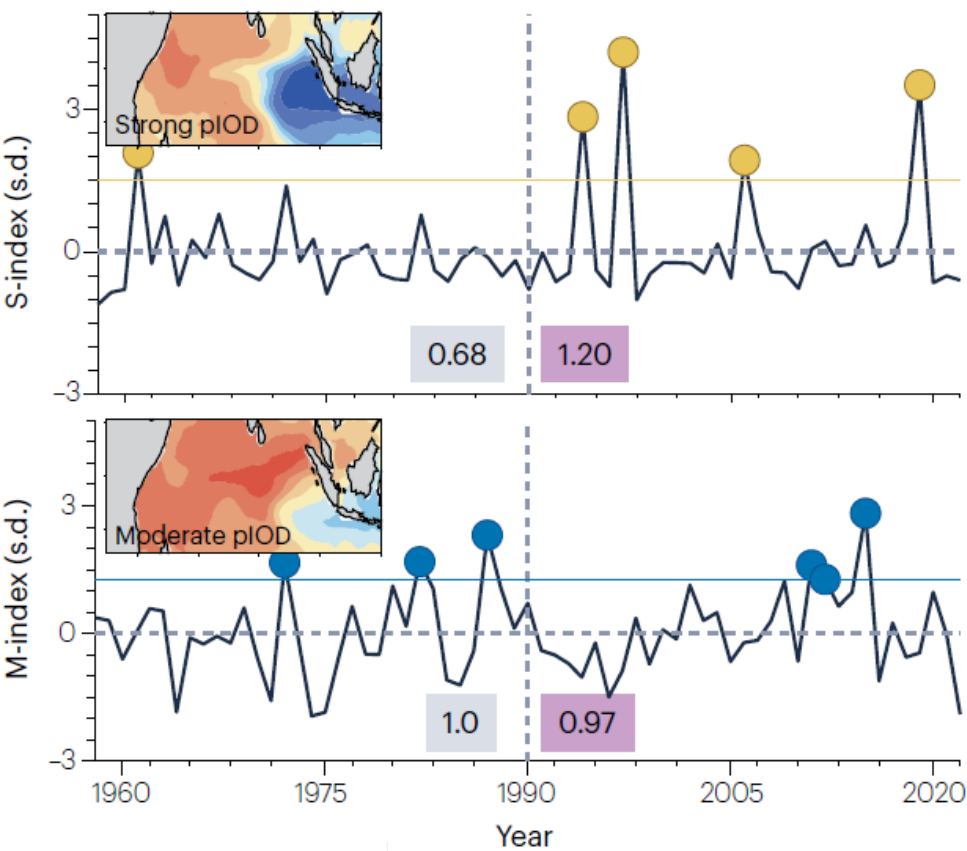
Guojian Wang¹✉, Wenju Cai^{2,3,4,5}✉, Agus Santoso^{1,6,7}, Nerilie Abram^{8,9,10}, Benjamin Ng¹, Kai Yang^{1,11}, Tao Geng^{2,3}, Takeshi Doi¹², Yan Du^{13,14}, Takeshi Izumo¹⁵, Karumuri Ashok^{16,17}, Jianping Li^{3,18}, Tim Li^{19,20}, Sebastian McKenna⁶, Shuangwen Sun^{21,22,23}, Tomoki Tozuka²⁴, Xiaotong Zheng^{2,3}, Yi Liu^{1,2}, Lixin Wu^{2,3}, Fan Jia^{3,25}, Shijian Hu^{3,25} & Xichen Li²⁶



f 31-year sliding trend



d S- and M- IOD indices

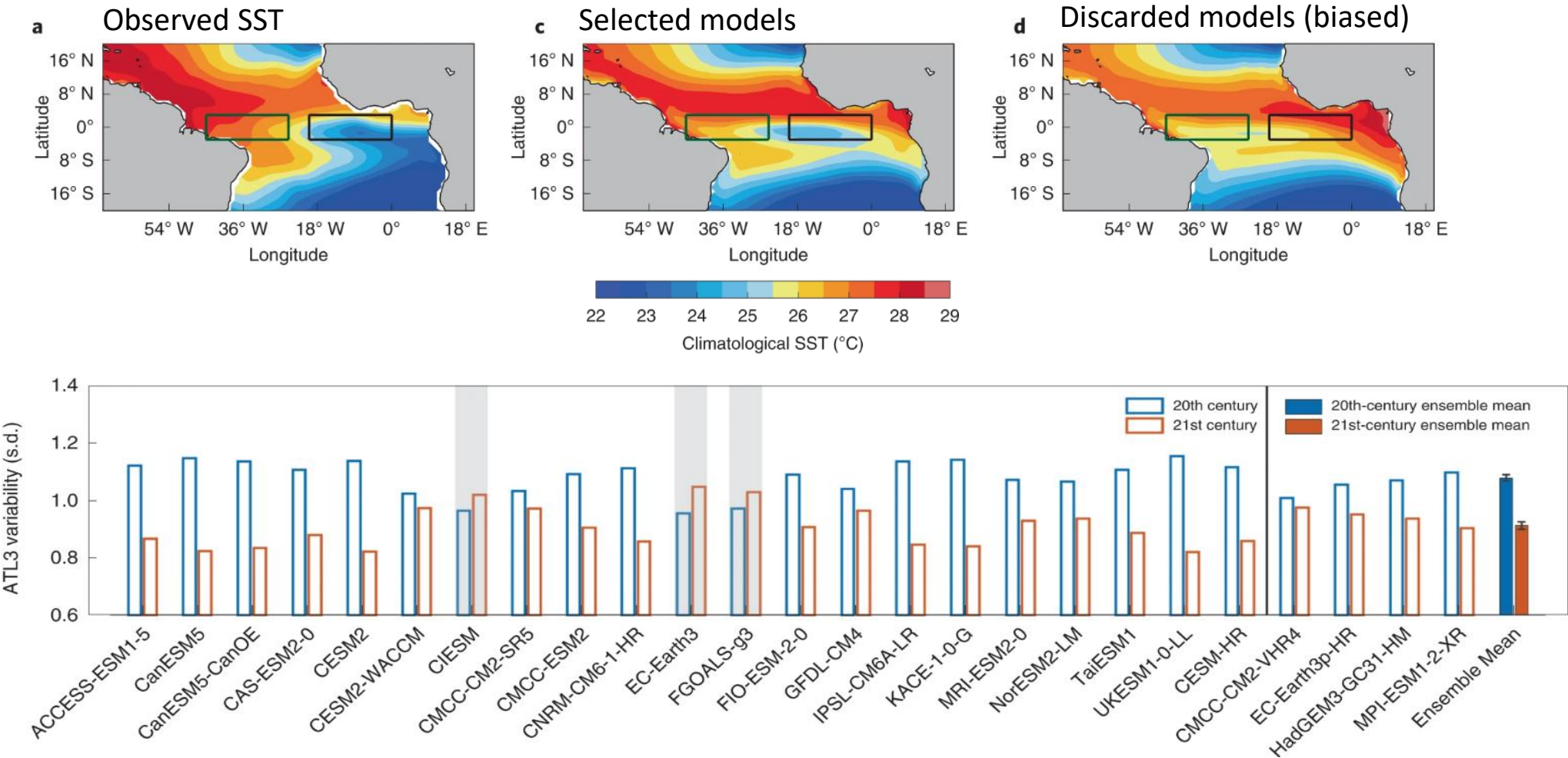


Linked to a more positive IOD-like mean state change

Suppressed Atlantic Niño/Niña variability under greenhouse warming

Yun Yang, Lixin Wu, Wenju Cai, Fan Jia, Benjamin Ng, Guojian Wang & Tao Geng

Nature Climate Change **12**, 814–821 (2022)



Declining tropical sea surface temperature variability under post-2050s greenhouse warming

Received: 18 September 2025

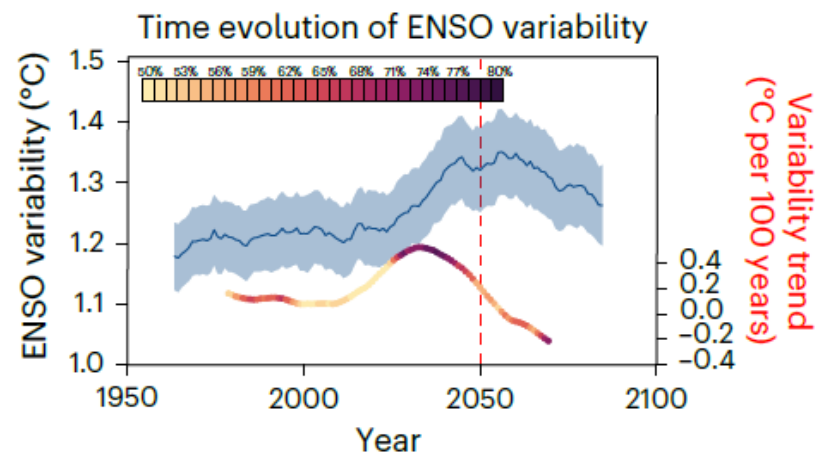
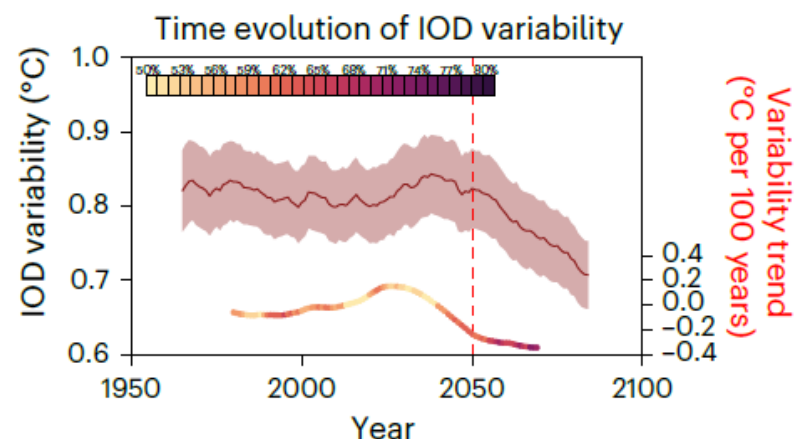
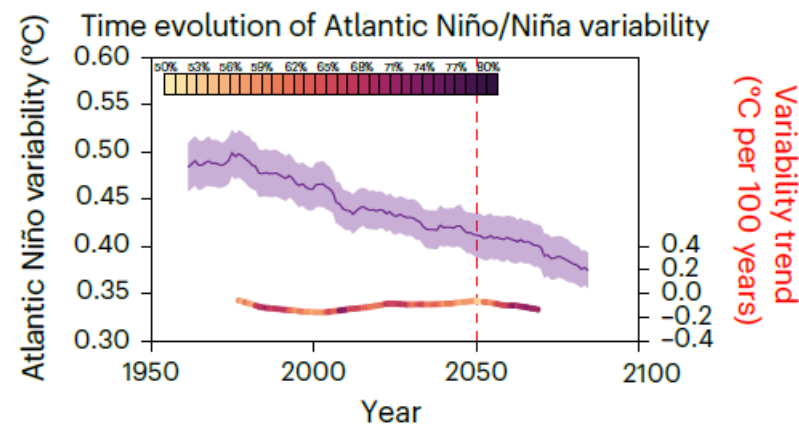
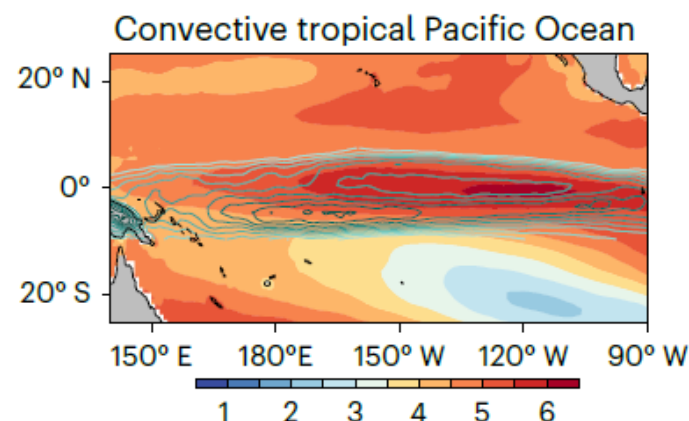
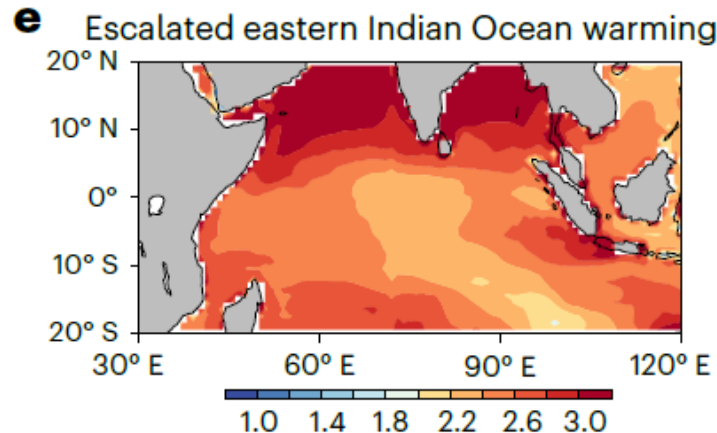
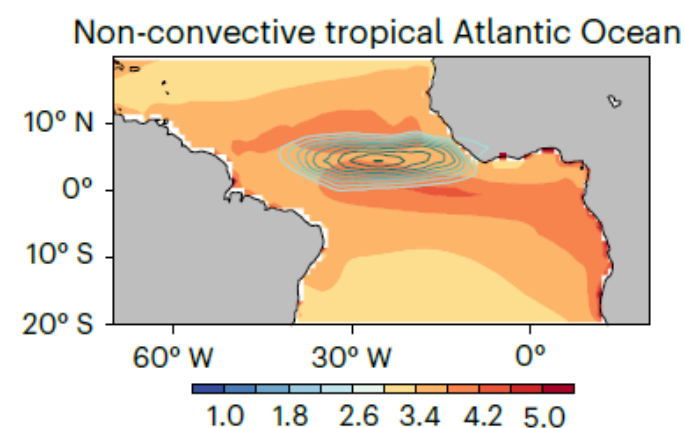
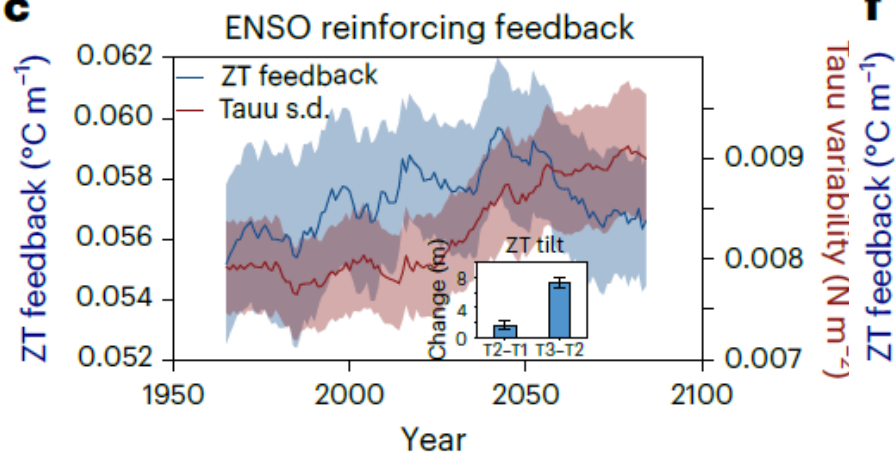
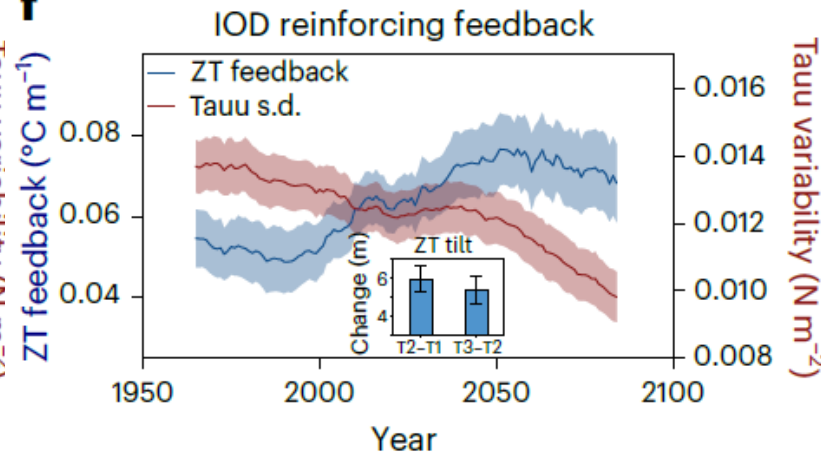
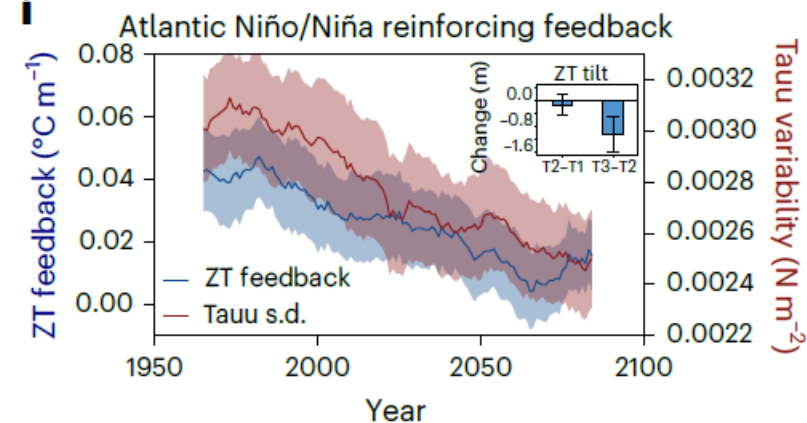
Accepted: 29 May 2026

Published online: 25 June 2026

 Check for updates

Guojian Wang ^{1,2,3}✉ & Agus Santoso ^{1,2,4}

Tropical climate variability, including the El Niño–Southern Oscillation, Indian Ocean Dipole and Atlantic Niño/Niña variability, has long governed global interannual climate fluctuations. Understanding how their influence may change in the next few decades is critically important for climate prediction and adaptation. Here we show that tropical interannual sea surface temperature variability could start to weaken in the next few decades, even if greenhouse warming intensifies.

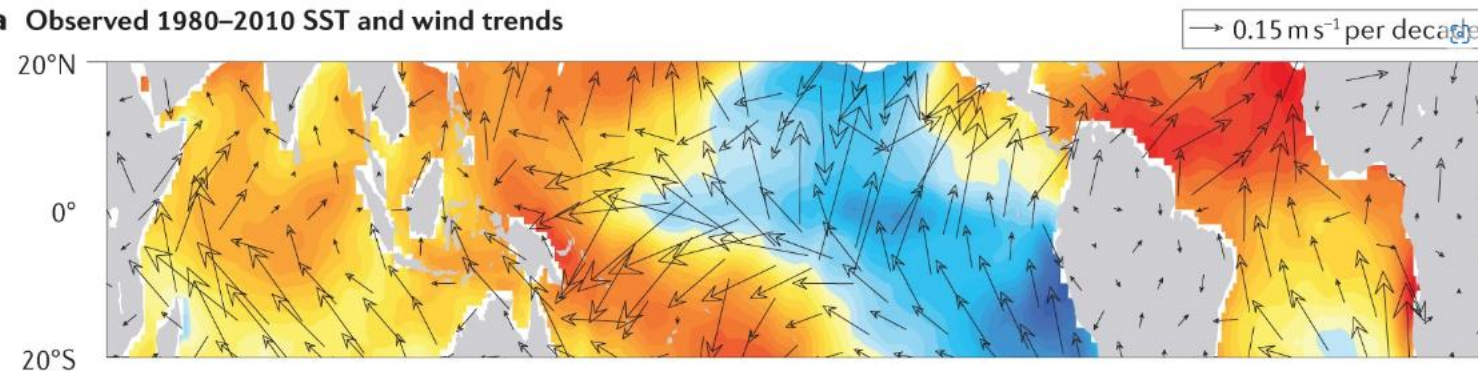
a**d****g****b****e****h****c****f****i**

Despite the projected decline in tropical SST variability after the 2050s, its impacts are not necessarily expected to decline, as the impacts of weak SST anomalies can be magnified by changes in the mean state.

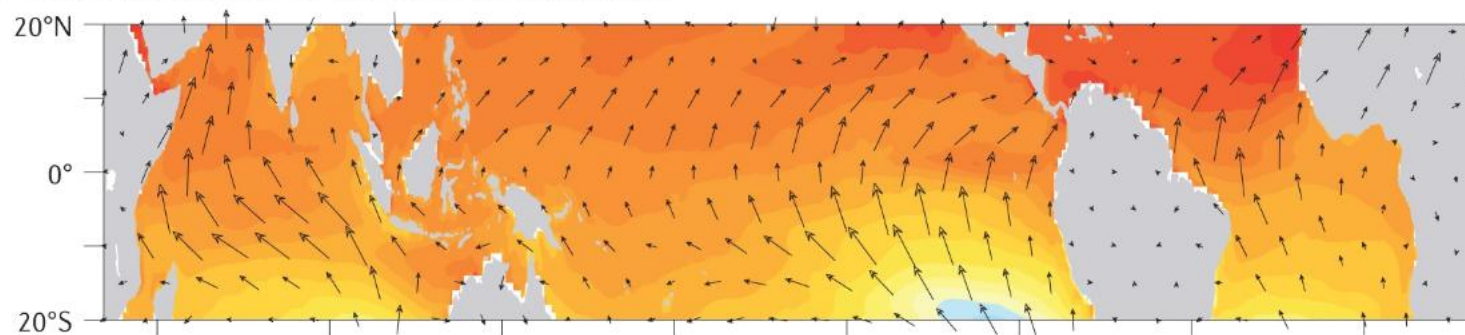
A decline in tropical SST variability after the 2050s highlights the need to revisit climate predictability frameworks, which are closely associated with the magnitude of tropical climate modes.

The transition to a regime of weak tropical SST variability marks a critical inflection point in anthropogenic climate change for environmental and societal risk management.

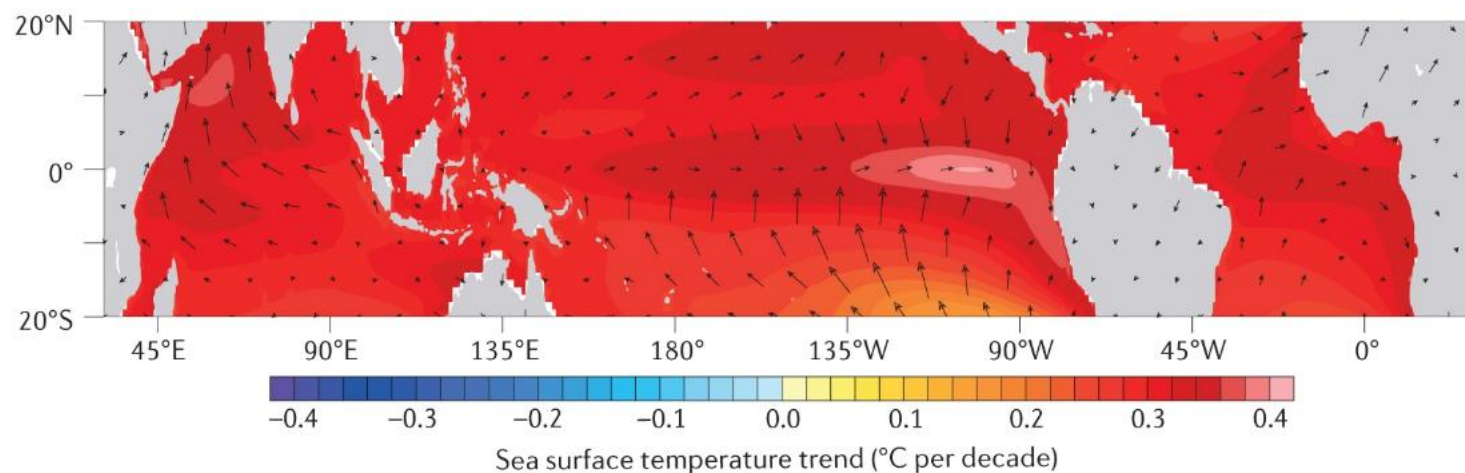
a Observed 1980–2010 SST and wind trends



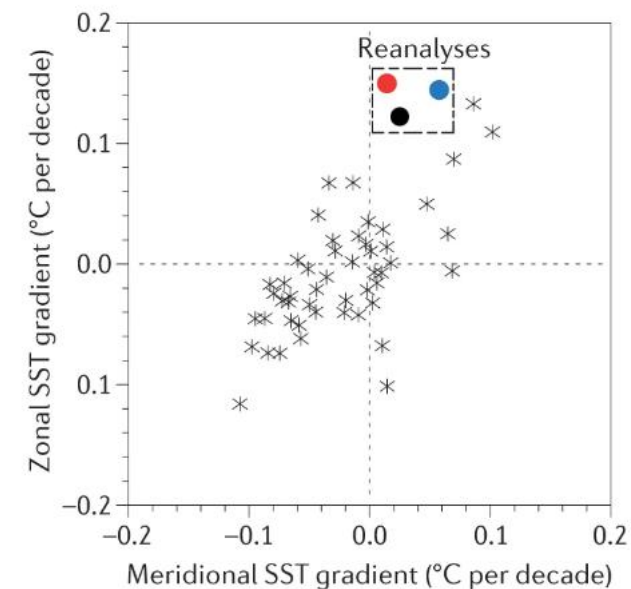
b CMIP5 and CMIP6 1980–2010 SST and wind trends



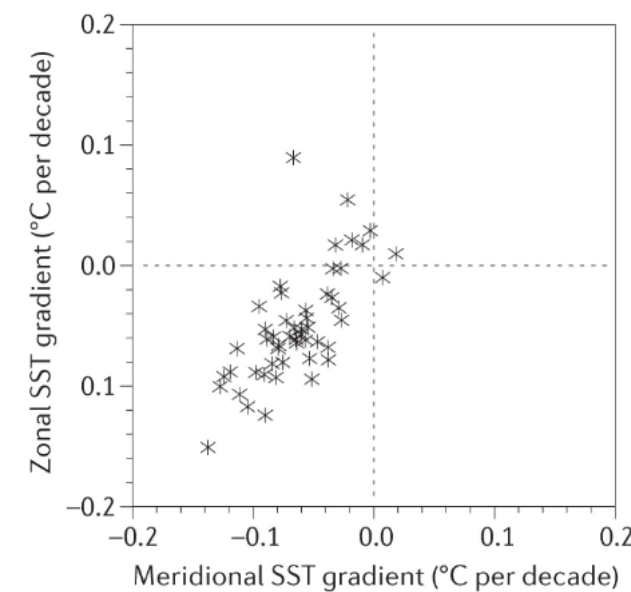
c CMIP5 and CMIP6 1980–2099 SST and wind trends



e 1980–2019 SST gradient trend



f 2020–2099 SST gradient trend



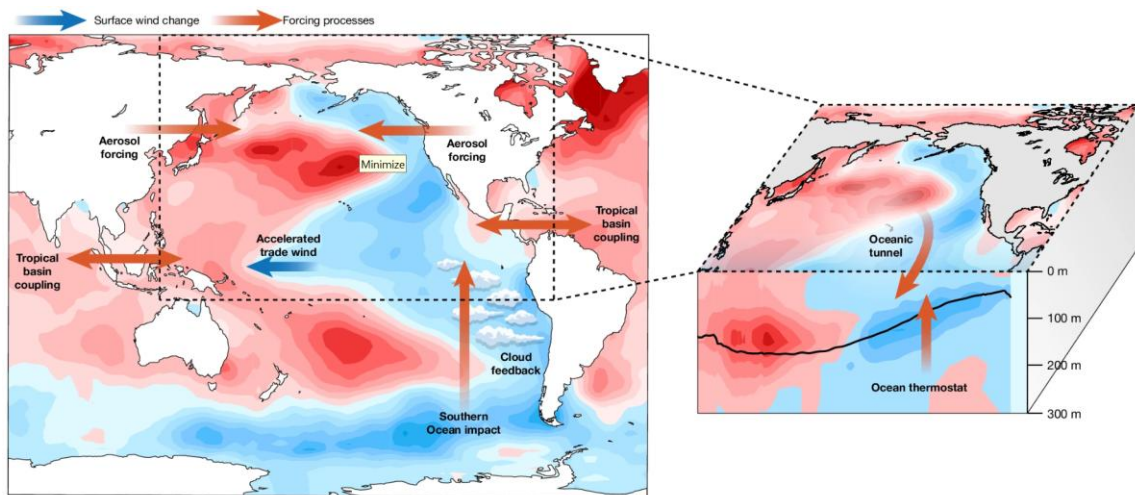
Possible differences between models and observations:

- **Internal variability** (e.g., IPO) – some models/ensemble members capture the observed strengthening of Walker Circulation (Chung et al. 2019, NCC) and equatorial zonal SST gradients (Watanabe et al. 2021, NCC).
- **Evaporative damping differentials** (Knutson et al. 1995; Liu et al. 2005; Xie et al. 2010, JCLIM)
- **Ocean thermostat** (Clement et al. 1996 JCLIM)
- **Inter-basin interactions**

Perspective *Nature* 630, 315–324 (2024)

Possible shift in controls of the tropical Pacific surface warming pattern

Masahiro Watanabe¹, Sarah M. Kang², Matthew Collins³, Yen-Ting Hwang⁴,
Shayne McGregor⁵ & Malte F. Stuecker⁶



NREE, 2023

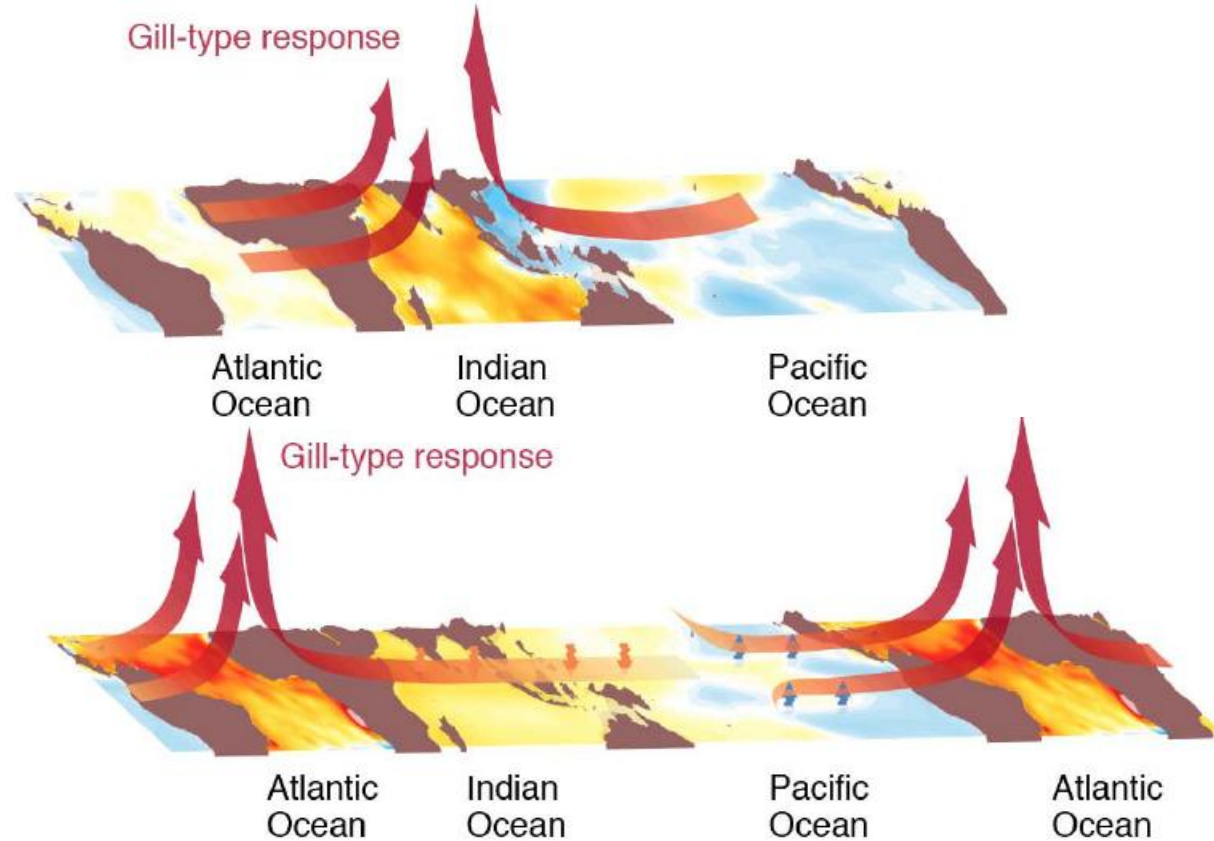
Review article

Mechanisms of tropical Pacific decadal variability

Antonietta Capotondi^{1,2}, Shayne McGregor^{3,4}, Michael J. McPhaden⁵, Sophie Cravatte^{6,7}, Neil J. Holbrook^{8,9}, Yukiko Imada¹⁰, Sara C. Sanchez¹¹, Janet Sprintall¹², Malte F. Stuecker^{13,14}, Caroline C. Ummenhofer^{15,16}, Mathias Zeller¹⁷, Riccardo Farneti¹⁸, Giorgio Graffino¹⁹, Shijian Hu²⁰, Kristopher B. Karnauskas¹, Yu Kosaka²¹, Fred Kucharski¹⁸, Michael Mayer^{22,23}, Bo Qiu¹³, Agus Santoso^{16,24}, Andréa S. Taschetto^{16,24}, Fan Wang²⁰, Xuebin Zhang²⁵, Ryan M. Holmes²⁶, Jing-Jia Luo²⁷, Nicola Maher^{1,11,28,29}, Cristian Martinez-Villalobos^{30,31}, Gerald A. Meehl³², Rajashree Naha³, Niklas Schneider^{13,14}, Samantha Stevenson³³, Arnold Sullivan³⁴, Peter van Rensch³ & Tongtong Xu^{1,2}

Pantropical climate interactions

Wenju Cai^{1,2}, Lixin Wu^{1*}, Matthieu Lengaigne^{3,4}, Tim Li⁵, Shayne McGregor^{6,7}, Jong-Seong Kug⁸, Jin-Yi Yu⁹, Malte F. Stuecker^{10,11}, Agus Santoso^{2,12}, Xichen Li¹³, Yoo-Geun Ham¹⁴, Yoshimitsu Chikamoto¹⁵, Benjamin Ng², Michael J. McPhaden¹⁶, Yan Du^{17,18}, Dietmar Dommenges¹⁹, Fan Jia²⁰, Jules B. Kajtar²¹, Noel Keenlyside^{22,23}, Xiaopei Lin¹, Jing-Jia Luo²⁴, Marta Martín-Rey^{25,26}, Yohan Ruprich-Robert²⁷, Guojian Wang^{1,2}, Shang-Ping Xie²⁸, Yun Yang²⁹, Sarah M. Kang³⁰, Jun-Young Choi¹⁴, Bolan Gan¹, Geon-Il Kim⁸, Chang-Eun Kim⁸, Sunyoung Kim⁸, Jeong-Hwan Kim¹⁴, Ping Chang³¹

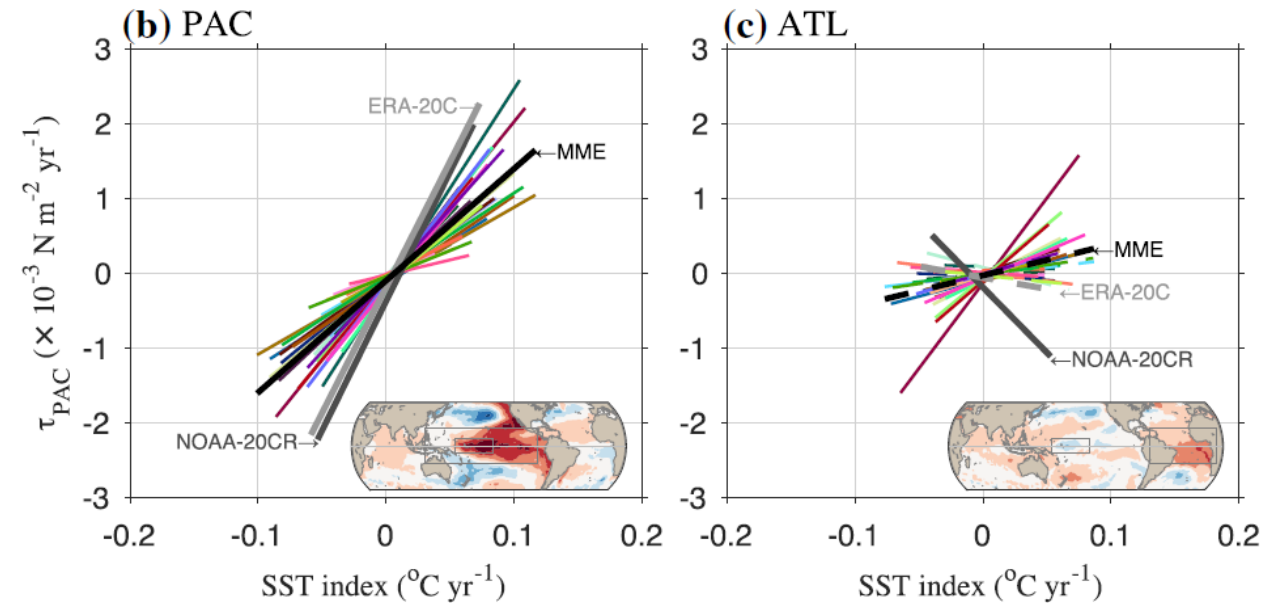


Clim Dyn (2018) 50:1471–1484

DOI 10.1007/s00382-017-3699-5

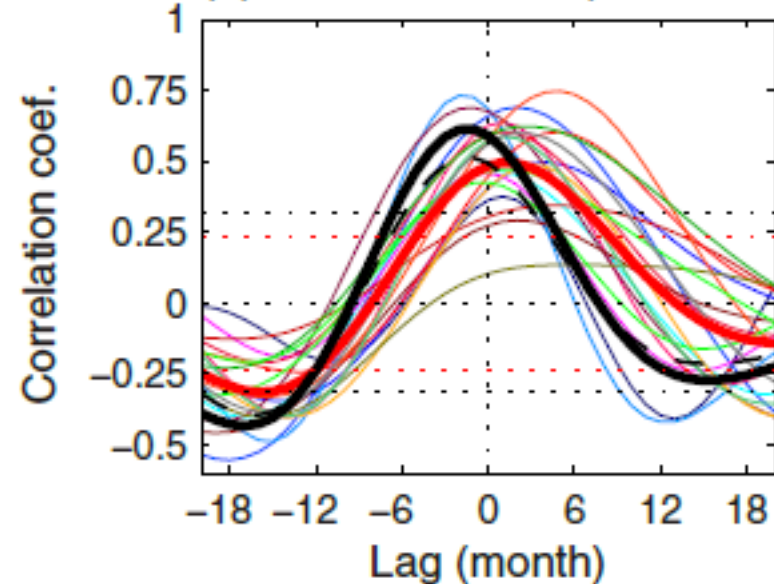
Model under-representation of decadal Pacific trade wind trends and its link to tropical Atlantic bias

Jules B. Kajtar^{1,2,3} · Agus Santoso^{1,2} · Shayne McGregor^{1,4} · Matthew H. England^{1,2} · Zak Baillie^{1,2}

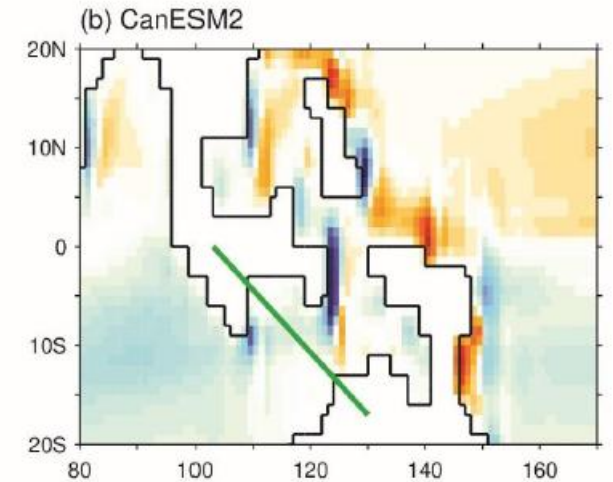
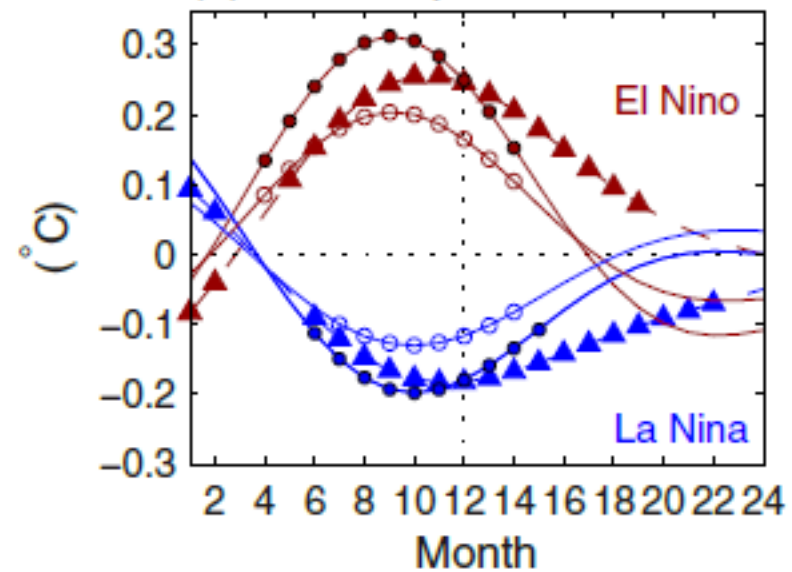




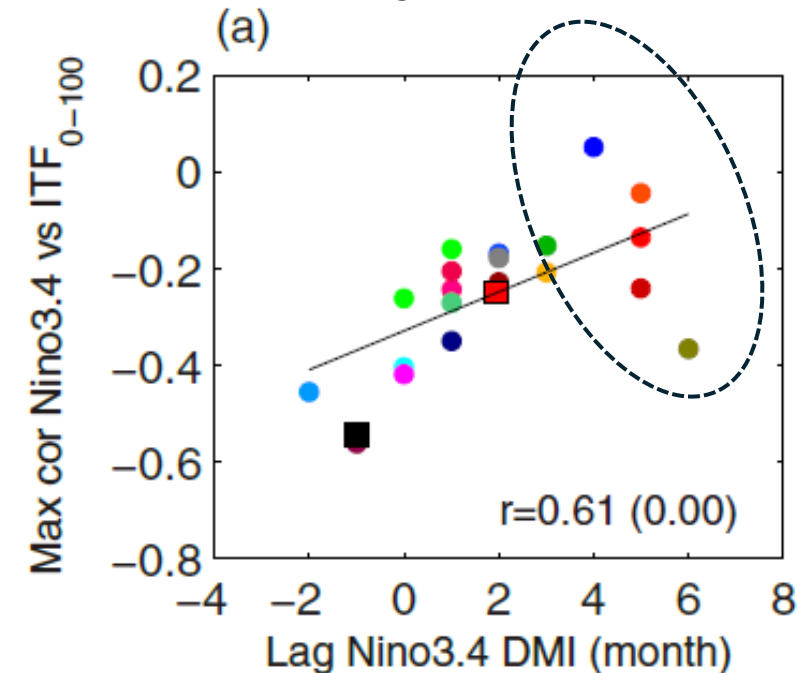
(a) Nino3.4 vs DMI (interannual)



(b) DMI composite



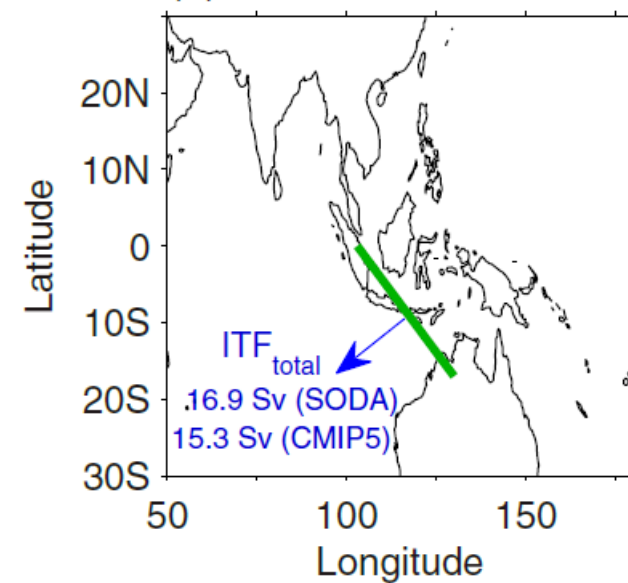
Coarse resolution models



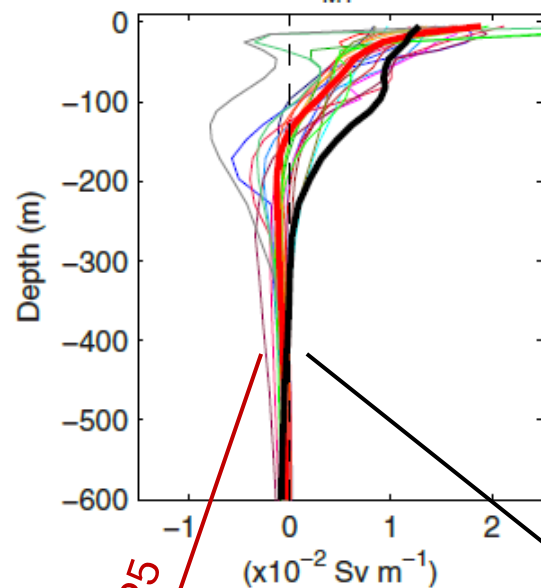
- IOD tends to lead ENSO by a season, but in 15/20 CMIP5 models ENSO instead leads IOD by an average of 3 months.
- This bias is related to the simulated ENSO teleconnection.
- This delayed ENSO-IOD teleconnection explains why ENSO-IOD correlation appears weaker in models and reflects prolonged IOD events.

The longer the IOD lags ENSO, the weaker the ENSO influence is on the ITF surface-intensified transport

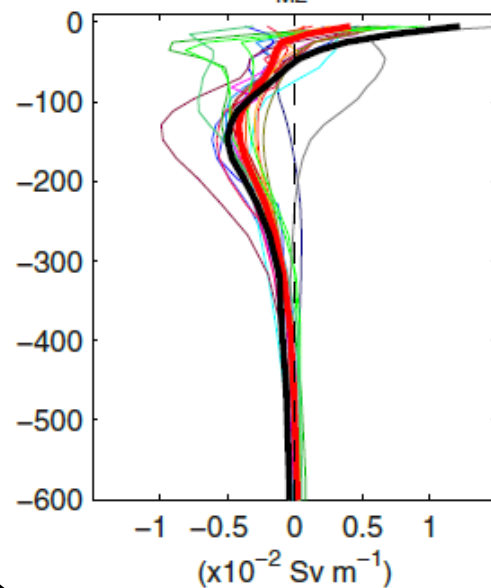
(a) Transect location



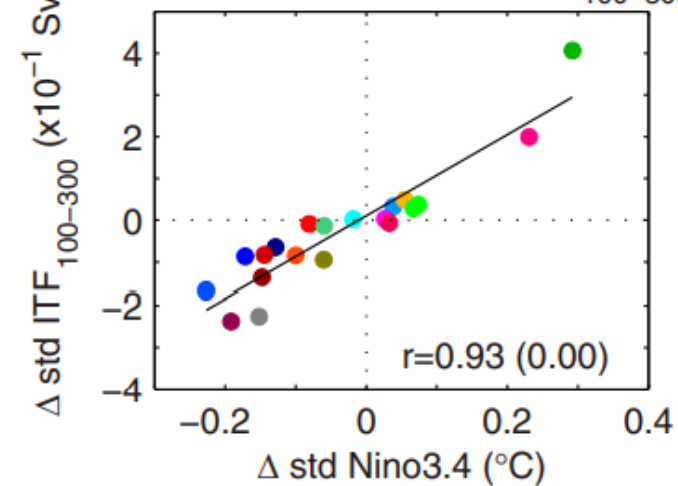
(b) EOF1 (ITF_{M1})



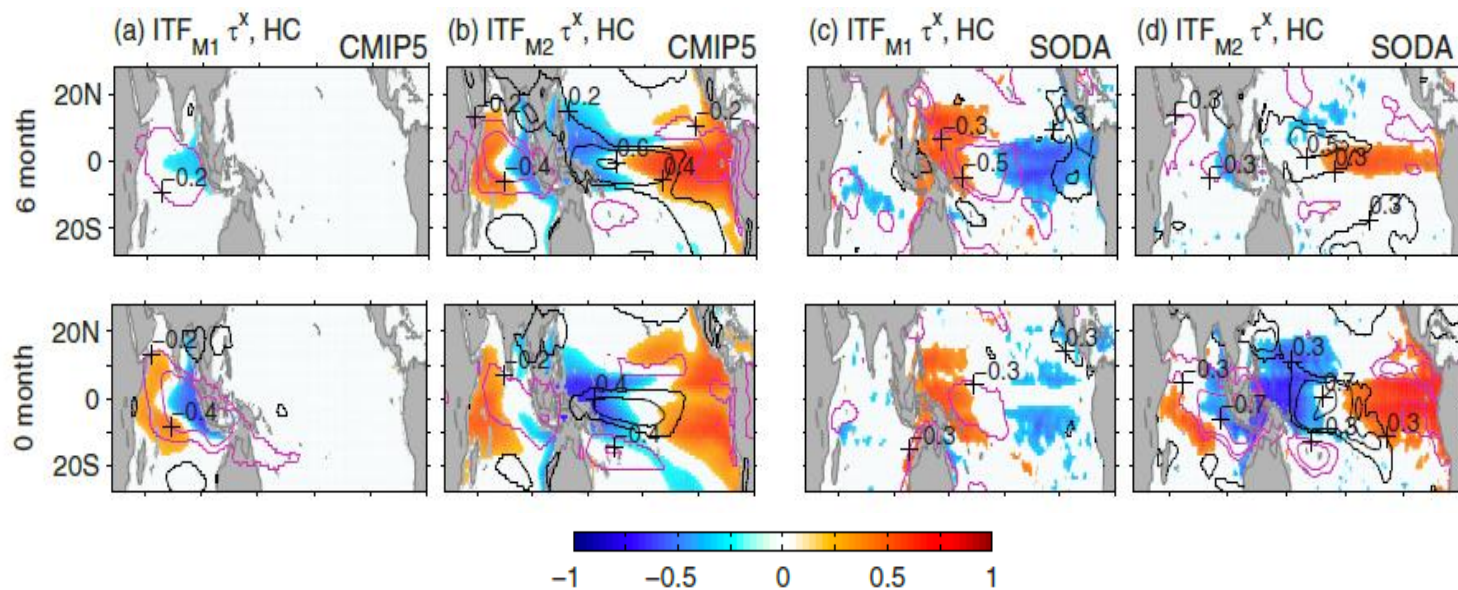
(c) EOF2 (ITF_{M2})



(d) Variability dif. (ENSO vs ITF₁₀₀₋₃₀₀)



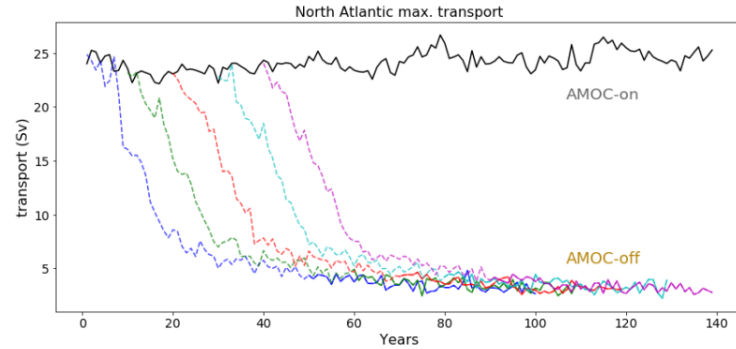
Projected changes in subsurface ITF variability linked to ENSO future change.



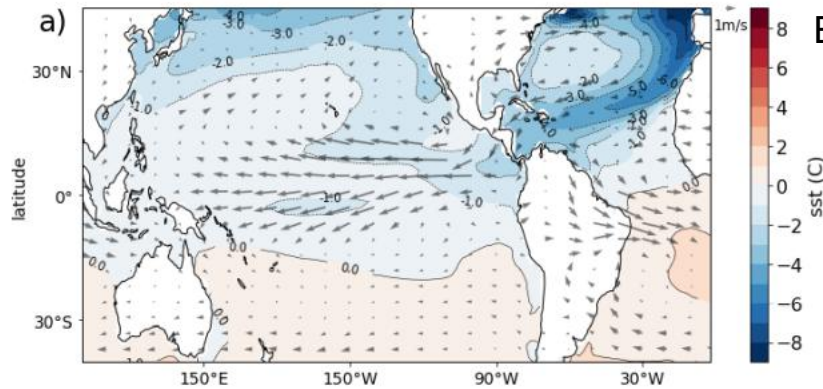
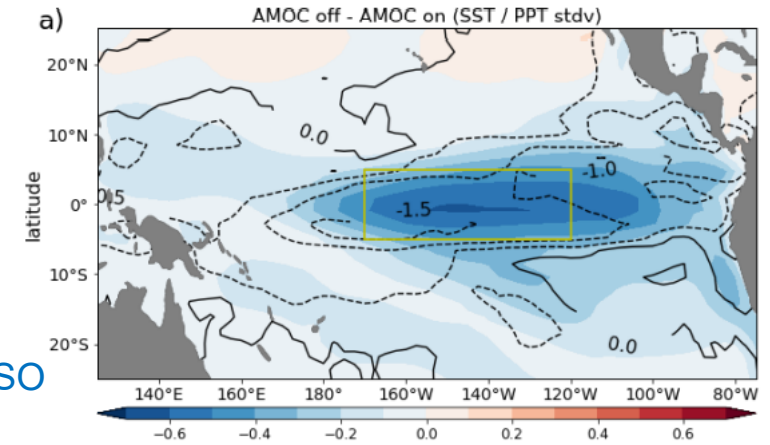
Reduced ENSO variability due to a collapsed Atlantic Meridional Overturning Circulation

Orihuela-Pinto, Santoso, England, Taschetto (2022, J. Climate, 35)

NA freshwater hosing (CESM 1.2)

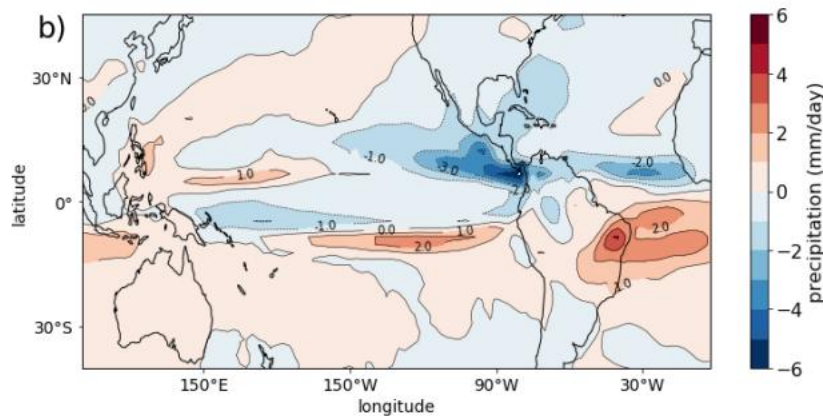


Reduced ENSO



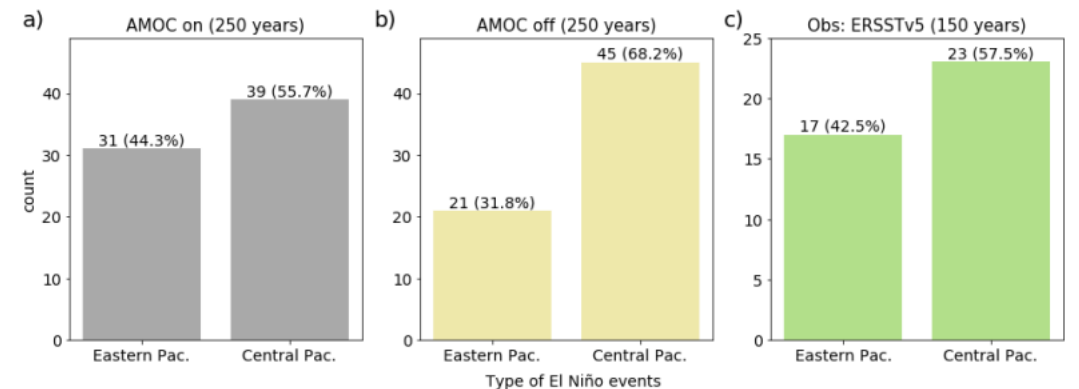
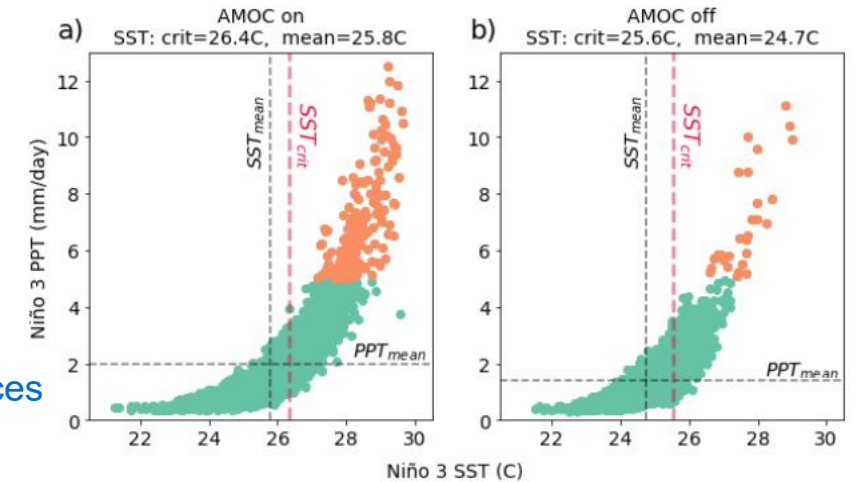
Enhanced Walker Circulation

Reduced extreme El Nino occurrences



Reduced equatorial Pacific rainfall

More CP El Ninos, less EP El Ninos



Key Points:

- Tropical Pacific cooling can drive a strengthening of the Atlantic Meridional Overturning Circulation (AMOC)
- The Pacific–North Atlantic teleconnection occurs via both atmospheric and oceanic planetary waveguides
- Pacific–AMOC teleconnections can be induced on a multidecadal time-scale

Coupled Feedbacks From the Tropical Pacific to the Atlantic Meridional Overturning Circulation

Bryam Orihuela-Pinto^{1,2} , Agus Santoso^{1,2} , Matthew H. England^{1,3} , and Andréa S. Taschetto^{1,2} 

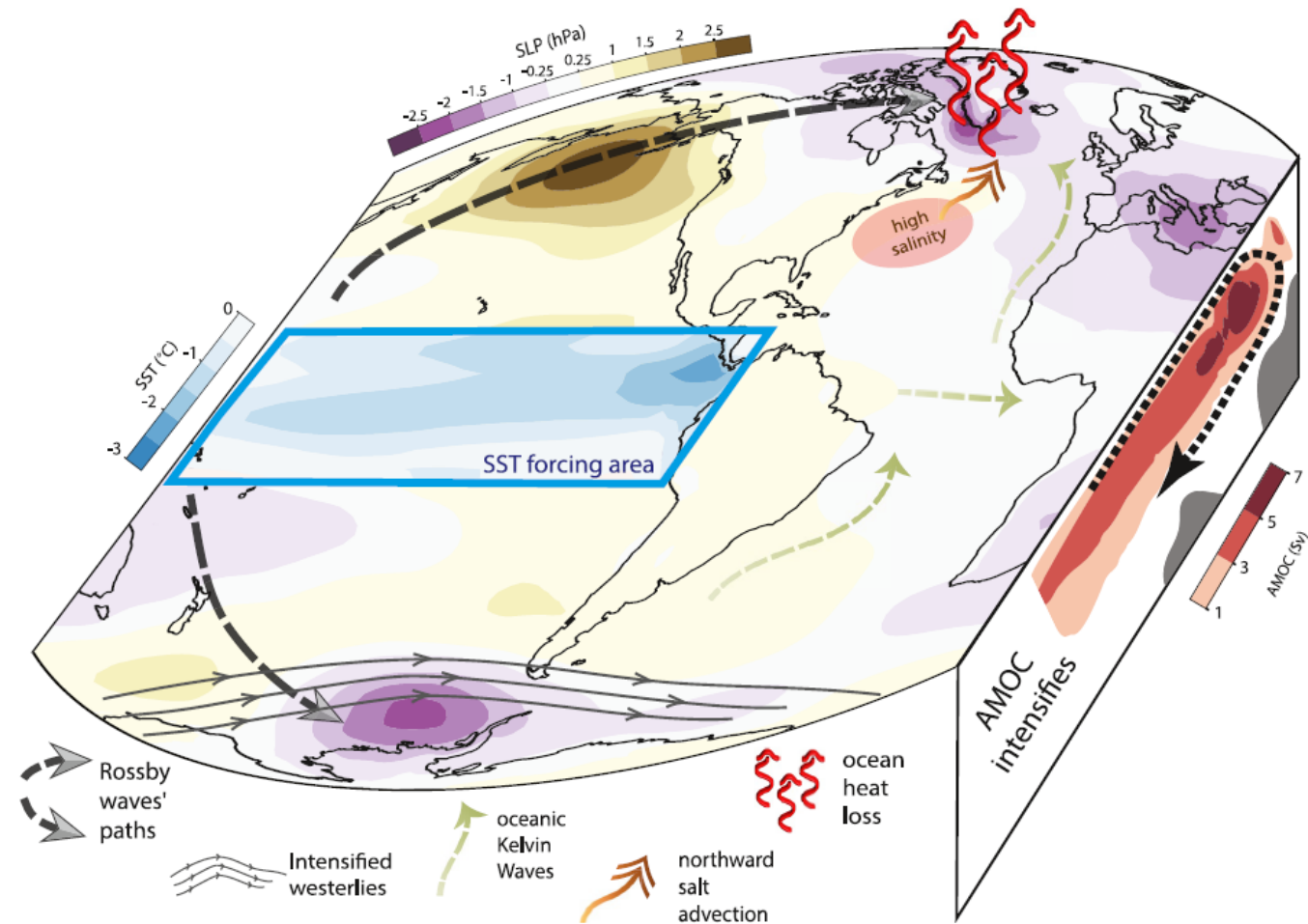


Figure 5. Schematic of the mechanisms wherein Pacific cooling causes AMOC strengthening in our simulation. The tropical Pacific Ocean cooling triggers Rossby wave propagation to the extratropics. In the North Atlantic, it increases local winds and ocean heat loss from the subpolar gyre, favoring enhanced oceanic convection, thus strengthening the AMOC. The AMOC is also intensified later by anomalous northward advection of salinity anomalies in the Atlantic, and oceanic wave adjustment triggered by increased surface westerlies over the Southern Ocean.

Tropical Pacific trends explain the discrepancy between observed and modelled rainfall change over the Americas

Weiteng Qiu¹✉, Matthew Collins¹, Adam A. Scaife^{1,2} & Agus Santoso^{3,4}

Adjustment of precipitation trends based on ENSO teleconnection

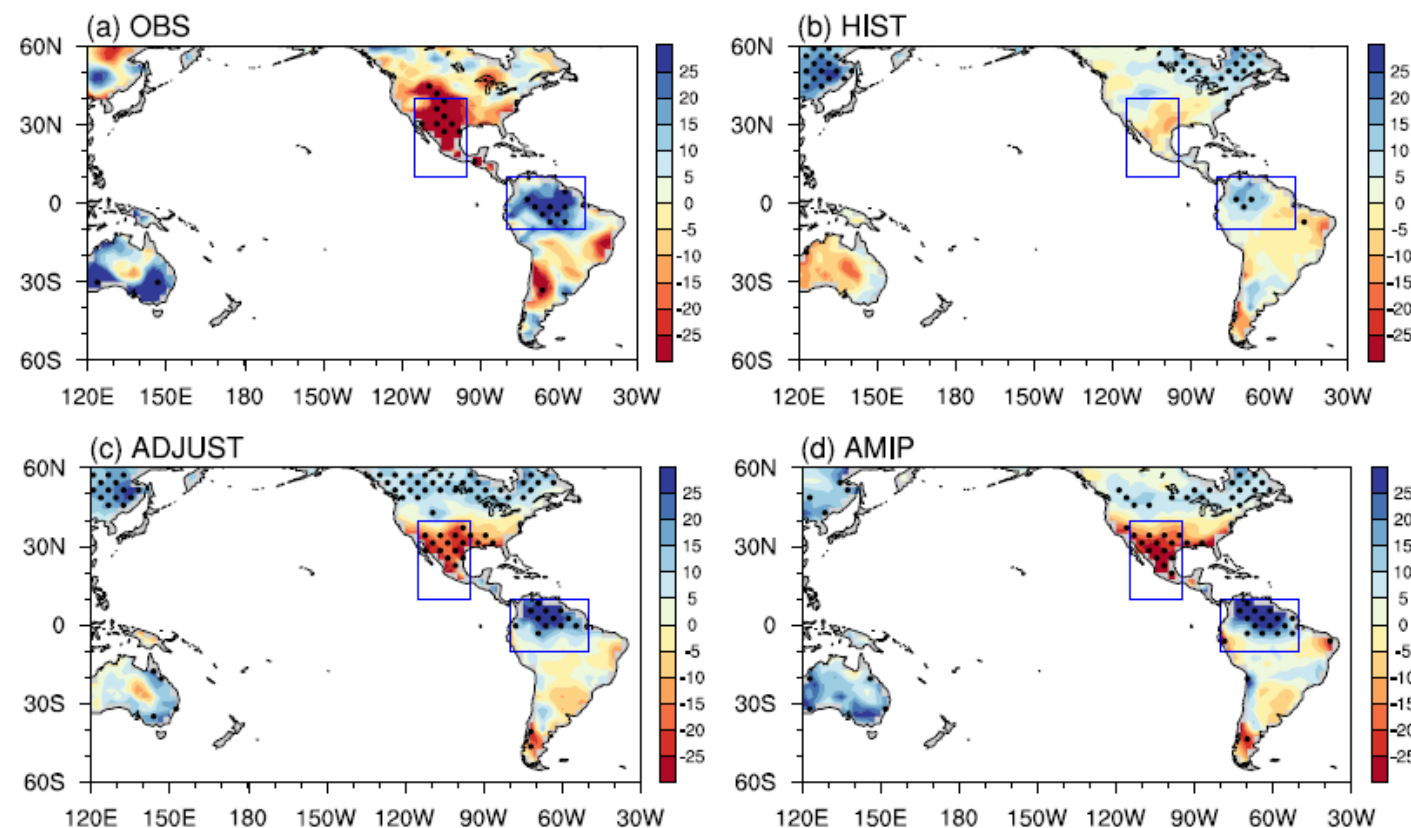
$$\frac{\partial Pr_{hist_adj}}{\partial t} = \frac{\partial Pr_{hist}}{\partial t} + \frac{\partial Pr_{ENSO_adj}}{\partial t}$$

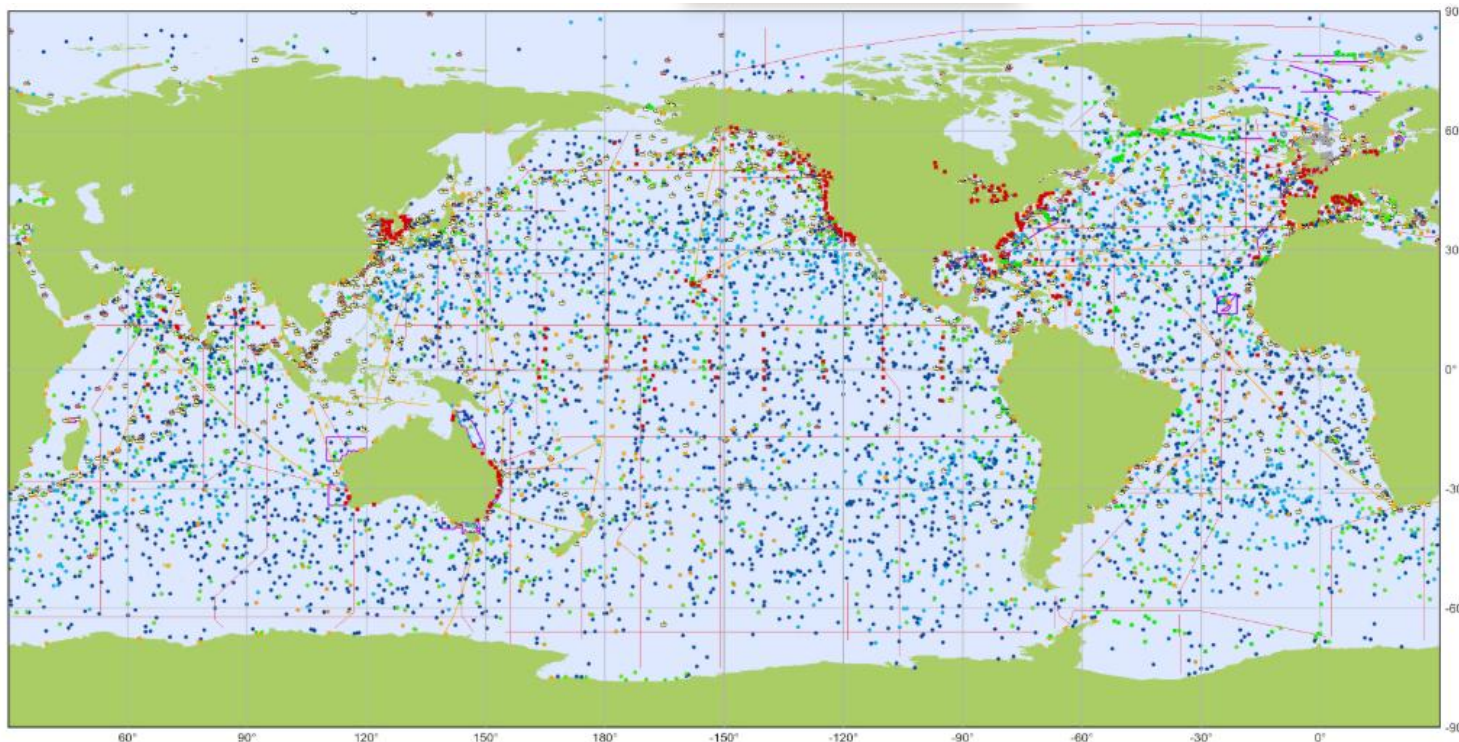
$$\frac{\partial Pr_{ENSO_adj}}{\partial t} = r_{Pr,U} \cdot \frac{\partial U_{obs}}{\partial t} \quad (\text{Observed Nino4 wind trend})$$

$$r_{Pr,U} = \frac{\partial Pr_{hist}}{\partial U_{hist}}$$

(interannual regression between Nino4 wind vs precipitation in each **CMIP** model)

Precipitation trends 1979-2014





Global ocean observing system

In situ operational platforms monitored by OceanOPS

August 2026

Mobile systems

- Core floats - Argo
- Deep floats - Argo
- Biogeochemistry floats - Argo
- Underwater gliders - OceanGliders
- Drifting buoys - DBCP

Fixed systems

- Polar buoys - DBCP
- Animal borne sensors
- Tsunamieters - DBCP
- Offshore platforms - DBCP
- Moored buoys - DBCP

Ship based measurements

- Ocean reference stations - OceanSITES
- Sea level gauges -GLOSS
- High Frequency radars
- Manned weather stations - SOT/VOS
- Automated weather stations - SOT/VOS

Reference lines and areas

- Radiosondes - SOT/ASAP
- Repeat hydrography - GO-SHIP
- eXpendable BathyThermographs - SOT/SOOP
- Sampled sites - OceanGliders

Generated by ocean-ops.org, 2026-09-06
Projection: World Plate Carree (-150.0000)



COVID Impacts Cause Critical Gaps in the Indian Ocean Observing System

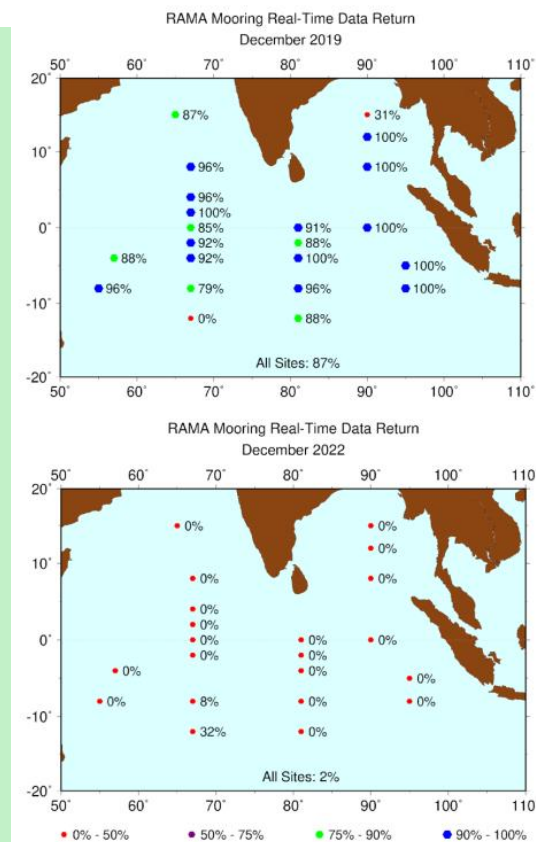
Janet Sprintall, Motoki Nagura, Juliet Hermes, M. K. Roxy, Michael J. McPhaden, E. Pattabhi Rama Rao, Srinivasa Kumar Tummala, Sidney Thurston, Jing Li, Mathieu Belbeoch, and Victor Turpin

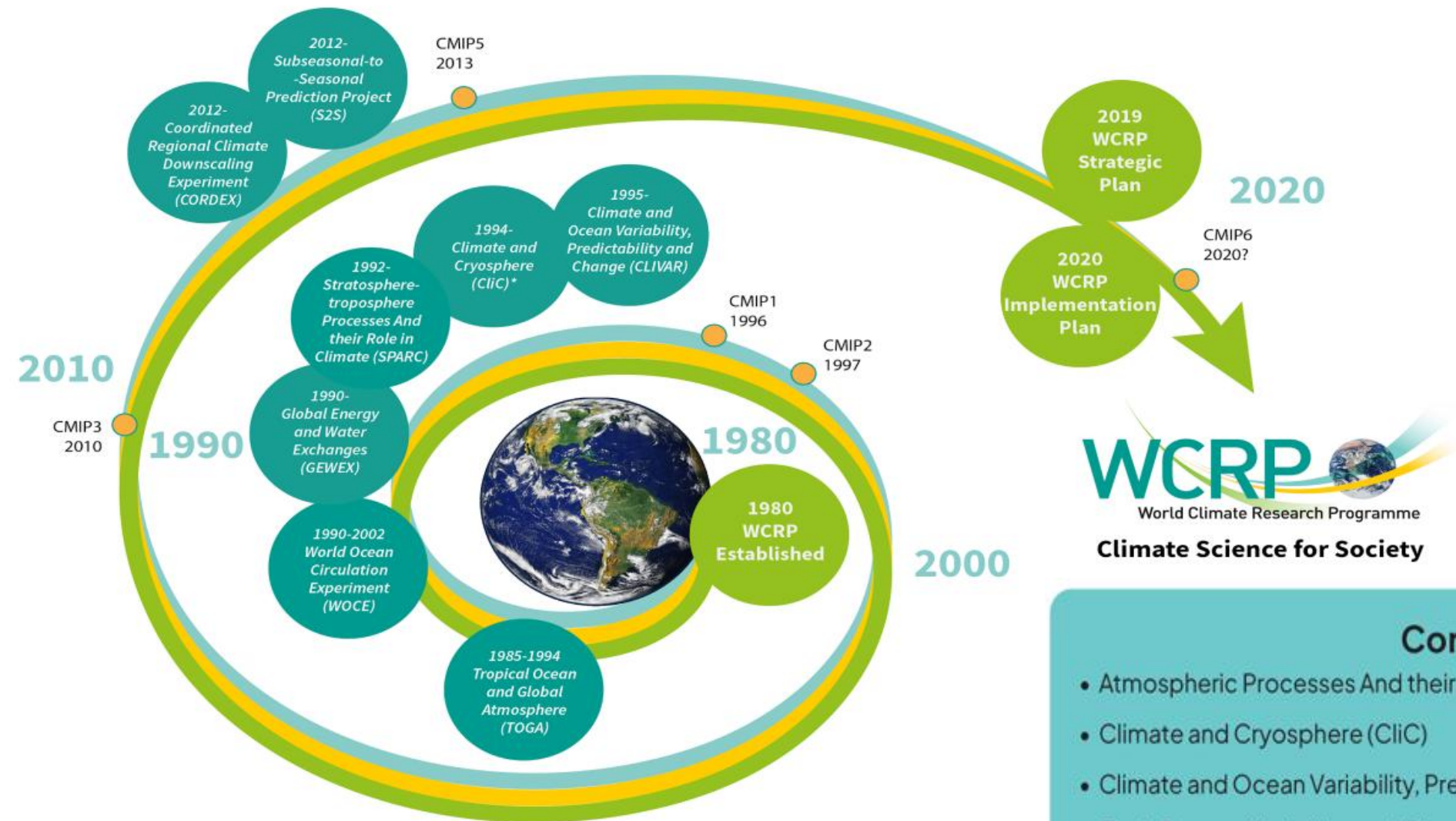
Online Publication: 15 Feb 2024

DOI: <https://doi.org/10.1175/BAMS-D-22-0270.1>

The CLIVAR Indian Ocean Region Panel led an article in *BAMS* documenting the challenges in sustaining IndOOS in the face of the ongoing pandemic and provided insights on the way forward.

Also formed a New Task Team (QIndOOS - Quantitative evaluation of the Indian Ocean Observing System to improve climate forecasts).





Core Projects

- Atmospheric Processes And their Role in Climate (APARC)
- Climate and Cryosphere (CliC)
- Climate and Ocean Variability, Predictability and Change (CLIVAR)
- Earth System Modelling and Observations (ESMO)
 - ▶ including the Coupled Model Intercomparison Project (CMIP)
- Global Energy and Water Exchanges (GEWEX)
- Regional Information for Society (RIfS)
 - ▶ including the Coordinated Regional Climate Downscaling Experiment (CORDEX)

Summary

- Projecting tropical climate variability is a challenging task, as it is linked to progress in climate modeling.
- The current standing is that there is an inter-model consensus among the latest generation of climate models (i.e., CMIP6): increased ENSO and IOD variability, manifesting in more frequent extreme El Nino, extreme La Nina events, stronger positive IODs, but weaker moderate IODs and Atlantic Nino/Nina.
- Projection uncertainties are linked to the projection of the mean climate. Model biases/deficiencies (e.g., cold tongue and associated biases, underestimated inter-basin interactions) and relatively short observations remain important source of these uncertainties.
- Regardless, society needs to be prepared for intensified (and possibly less predictable) impacts of tropical climate variability which operates in a warming ocean.