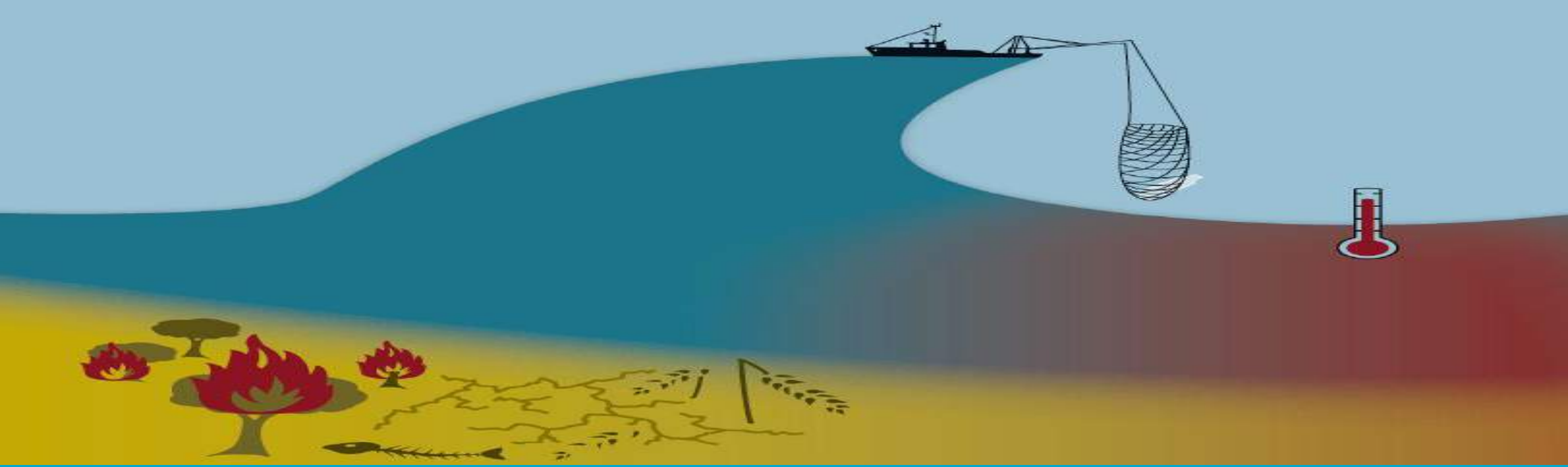
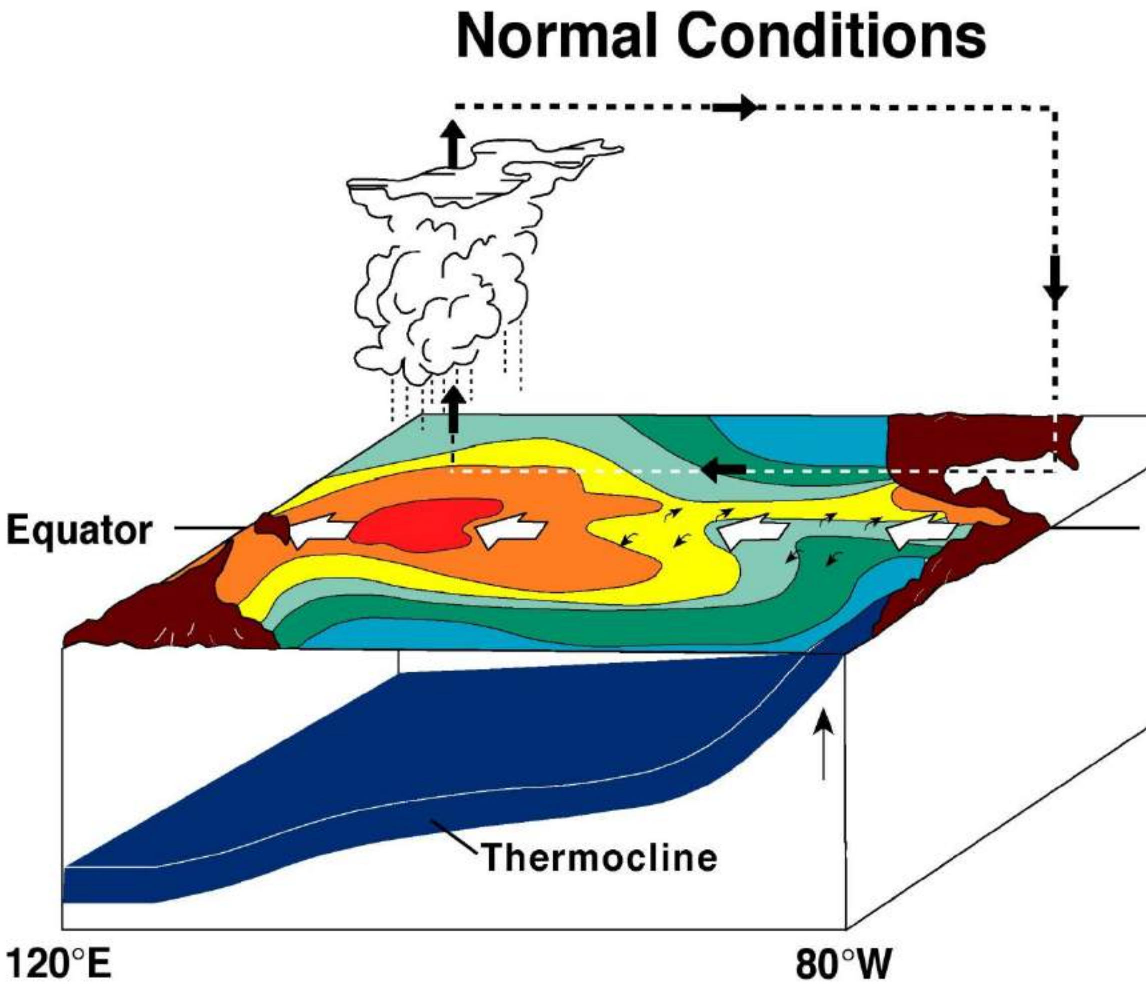


Response of El Niño/La Niña to greenhouse warming

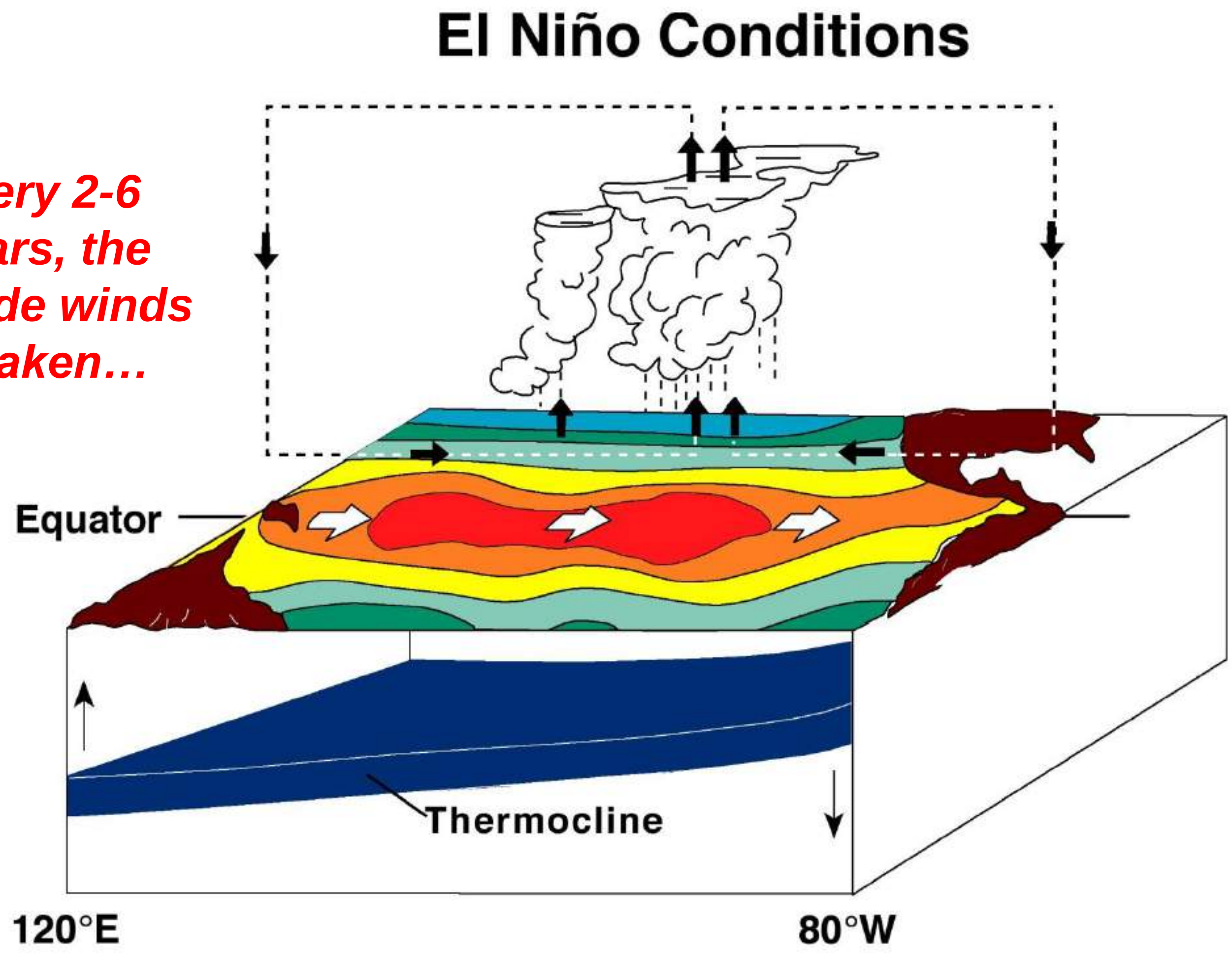
Dr Wenju Cai, CSIRO

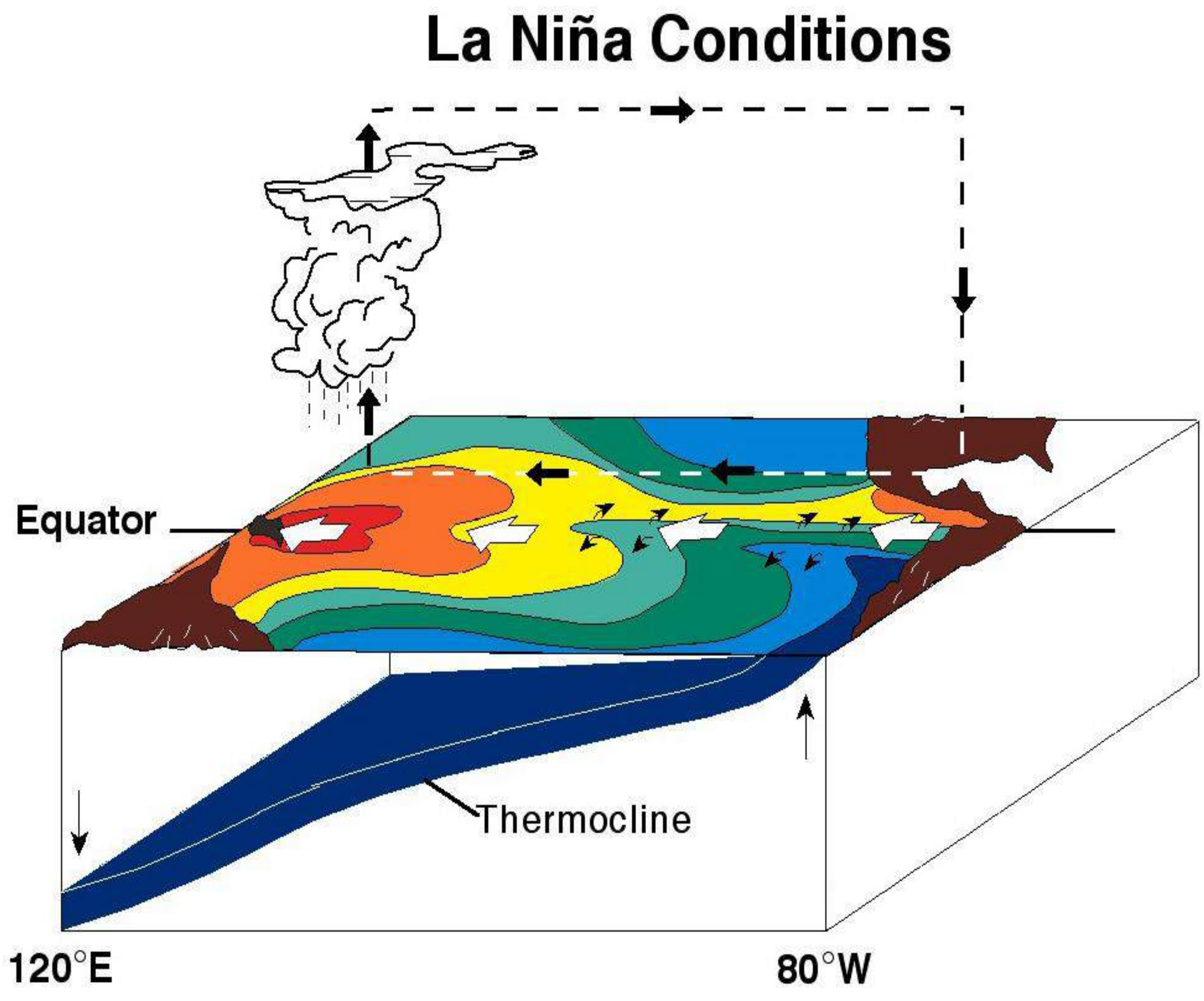
Collaboration with: Lixin Wu, Guojian Wang, Boris Dewitte, Agus Santoso, Ken Takahashi, Yun Yang, Aude Carreric, Michael J. McPhaden, and **many more …**

El Niño/Southern Oscillation (ENSO): Walker Circulation



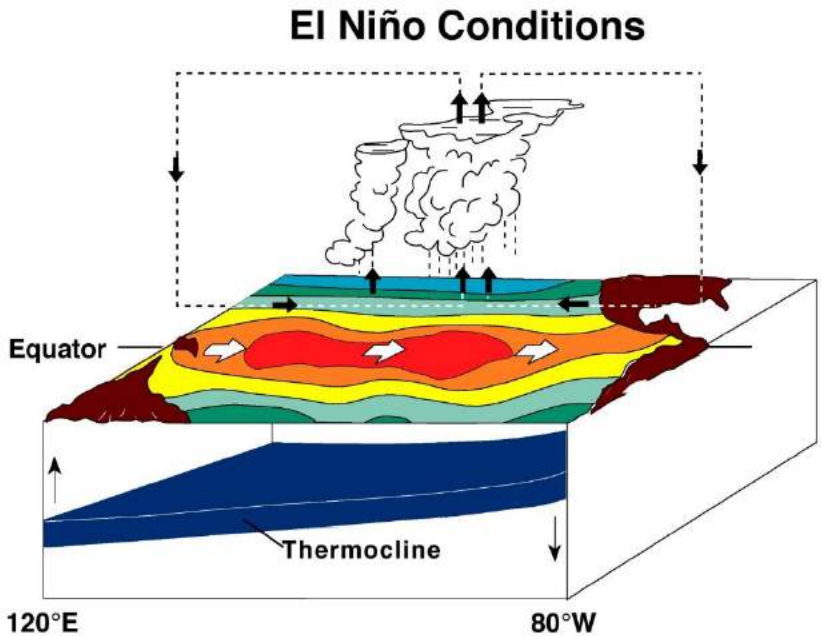
Every 2-6 years, the trade winds weaken…




La Niña Conditions
Equator
Thermocline
120°E
80°W

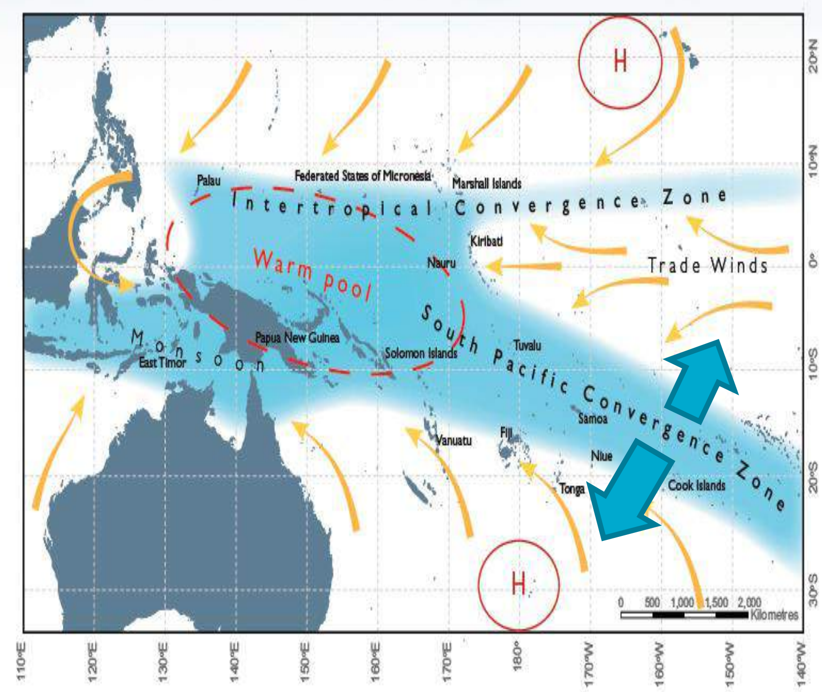
Impact of extreme El Niño events

January 1998, Peru


El Niño Conditions
Equator
Thermocline
120°E
80°W


Melbourne dust storm, 8 February 1983
caused by dust from rural areas


Ash Wednesday 1983
(c) DSE


H
Palau
Federated States of Micronesia
Marshall Islands
Intertropical Convergence Zone
Kiribati
Nauru
Warm pool
Trade Winds
South Pacific Convergence Zone
Papua New Guinea
Solomon Islands
Tuvalu
Monsoon
East Timor
Samoa
Vanuatu
Fiji
Niue
Tonga
Cook Islands
H
0 500 1,000 1,500 2,000
Kilometres
20°N
10°N
0°
10°S
20°S
30°S
110°E
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130°E
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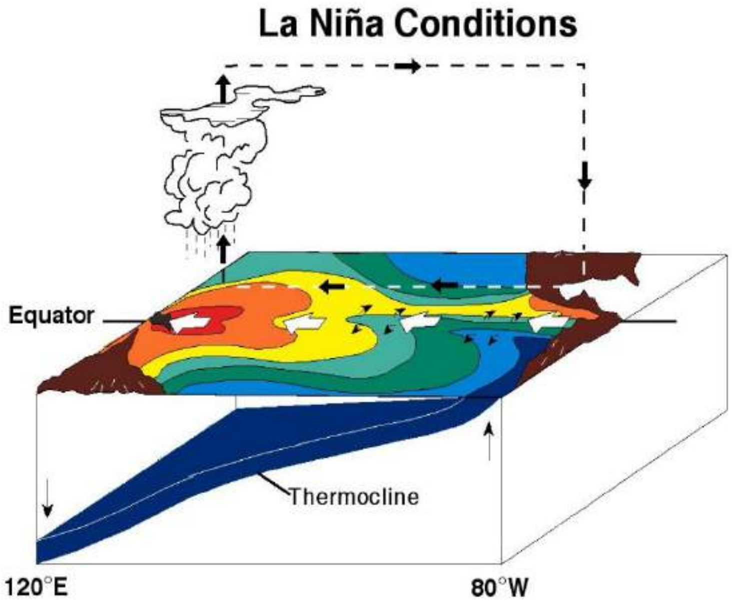
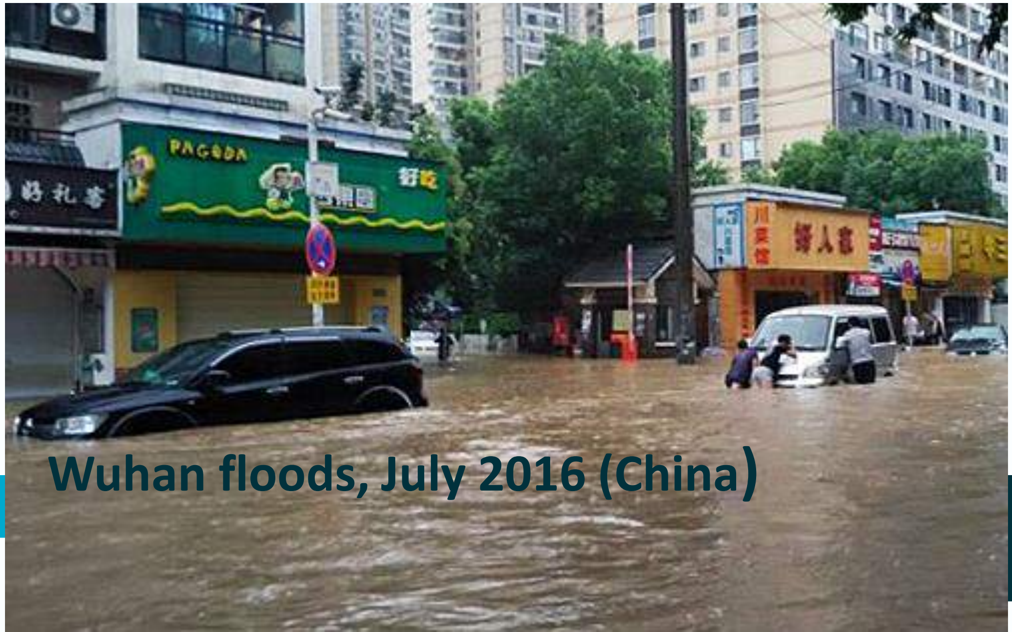
180°
170°W
160°W
150°W
140°W



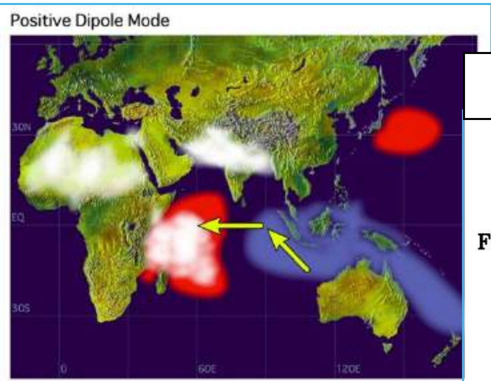
1998/1999 Extreme La Niña, Brisbane floods, 10 January 1999 (Australia)

China 1998 floods, killing 1000s, and displacing 200m



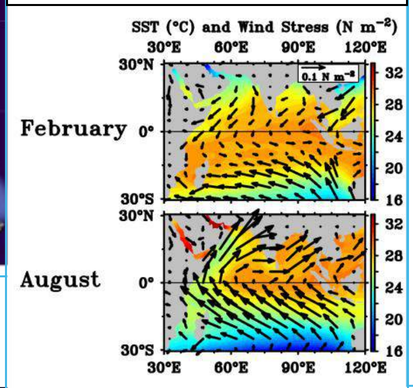
Wuhan floods, July 2016 (China)

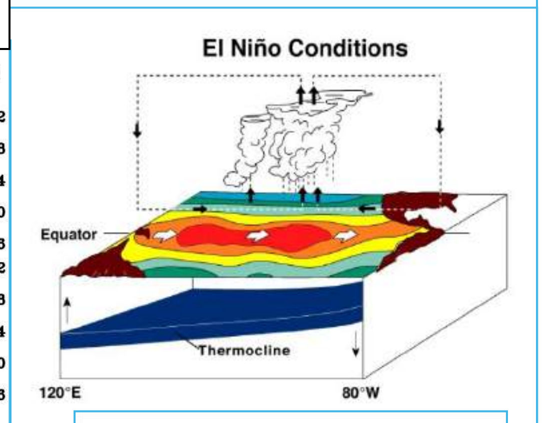
Global Impacts

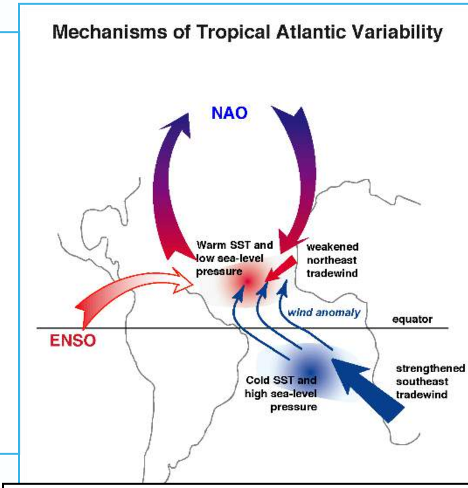


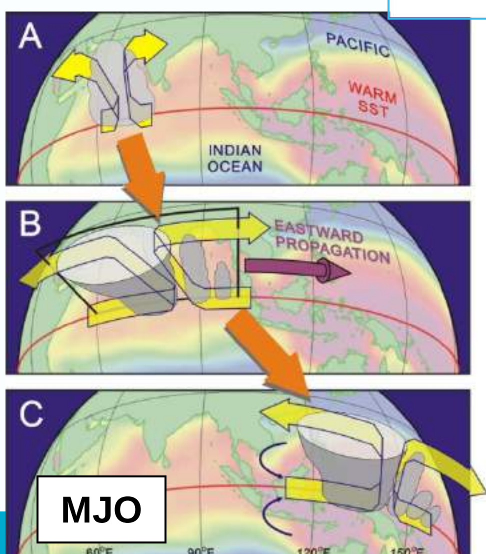
Indian Ocean Dipole

Monsoons

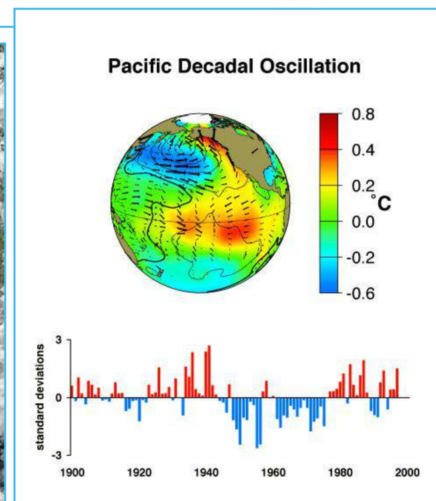


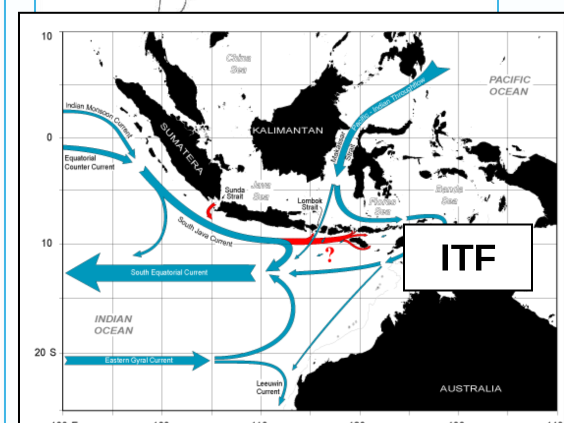




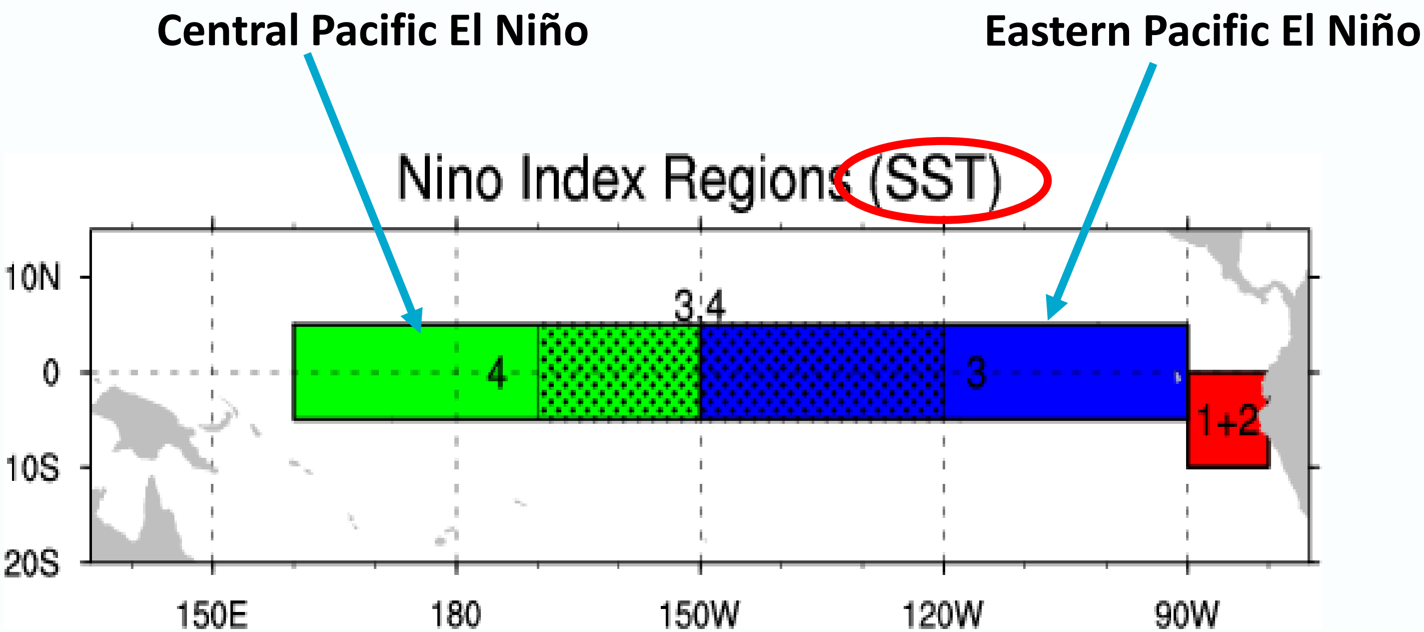


Typhoons, Cyclones & Hurricanes





Courtesy of Mike McPhaden



How ENSO will respond to greenhouse warming has challenged scientists for many years.

nature geoscience

REVIEW ARTICLE

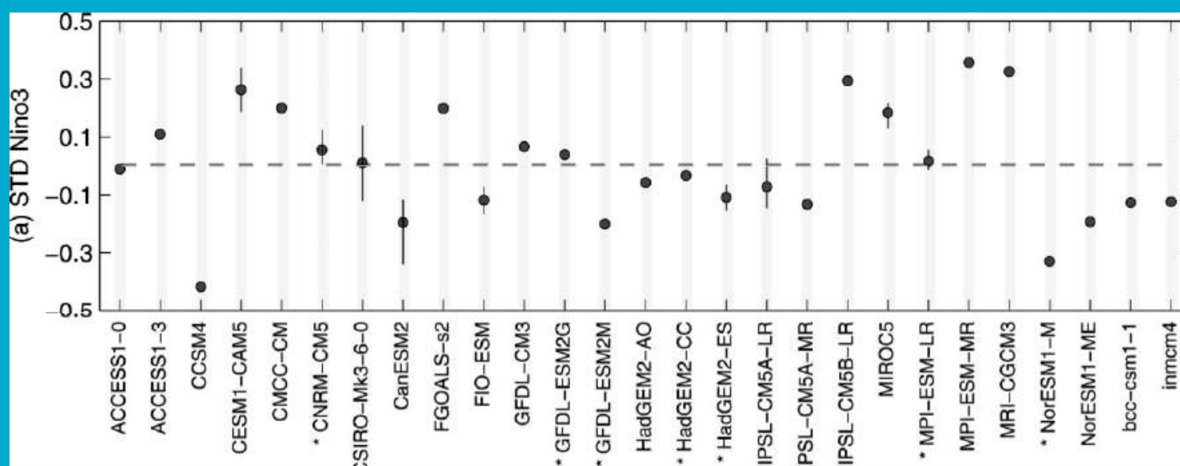
PUBLISHED ONLINE: 23 MAY 2010 | DOI: 10.1038/NGEO868

2010

The impact of global warming on the tropical Pacific Ocean and El Niño

Mat Collins[1]*, Soon-Il An[2], Wenju Cai[3], Alexandre Ganachaud[4], Eric Guilyardi[5], Fei-Fei Jin[6], Markus Jochum[7], Matthieu Lengaigne[8], Scott Power[9], Axel Timmermann[10], Gabe Vecchi[11] and Andrew Wittenberg[11]

The El Niño–Southern ... cific region and affects ecosystem ... er the influ- ence of global wa ... al easterly trade winds are ... and more slowly farther aw ... eeper lay- ers is expected t ... ar-to-year ENSO variability ... sical proc- esses that are re ... Therefore, despite consider ... ntribute to El Niño variabilit ... of events will change.



Anthropogen... global issu... of the prin... with anthropogeni... exaggeration of, pr... the average distributio... values, this can mean that thresholds to flooding or drought are crossed more often. One of the most important sources of natural climatic variability is ENSO. On a timescale of two to seven years, the eastern equatorial Pacific climate varies between anomalously cold (La Niña) and warm (El Niño) conditions. These swings in

... n if ENSO ... have devel- ... s and proc- ... nathematical ... energetics, linear stability and nonlinearity of ENSO[2–5]. Complex coupled global circulation models (CGCMs) have become powerful tools for examining ENSO dynamics and the interactions between global warming and ENSO[6]. ENSO is now an emergent property of many CGCMs, that is, it is generated spontaneously as a result of the complex interplay of

nature climate change

REVIEW ARTICLE

PUBLISHED ONLINE: 17 AUGUST 2015 | DOI: 10.1038/NCLIMATE2743

2015

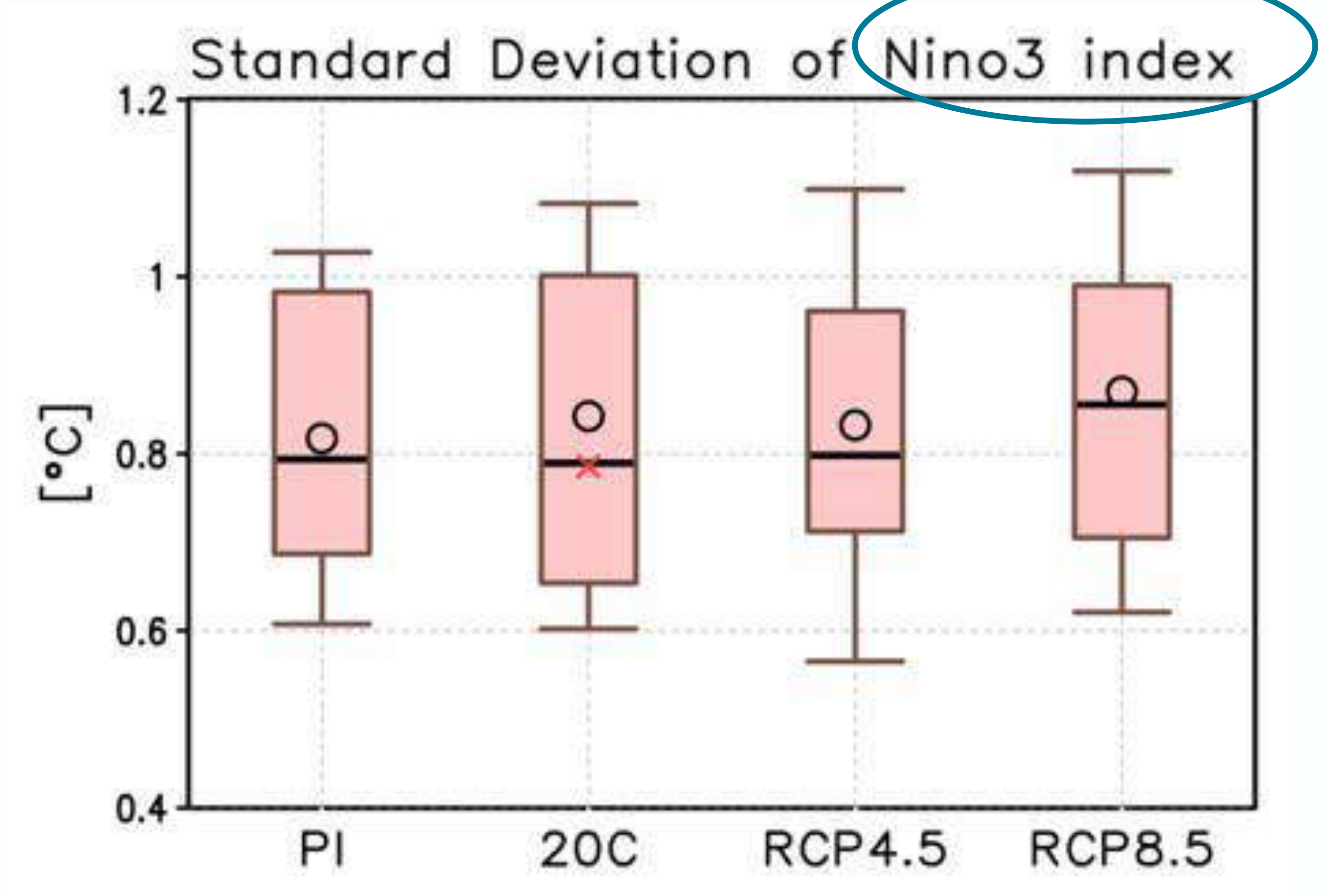
ENSO and greenhouse warming

Wenju Cai[1,2*], Agus Santoso[3], Guojian Wang[1], Sang-Wook Yeh[4], Soon-Il An[5], Kim M. Cobb[6], Mat Collins[7], Eric Guilyardi[8,9], Fei-Fei Jin[10], Jong-Seong Kug[11], Matthieu Lengaigne[8], Michael J. McPhaden[12], Ken Takahashi[13], Axel Timmermann[14], Gabriel Vecchi[15], Masahiro Watanabe[16] and Lixin Wu[2]

The El Niño/Southern Oscillation (ENSO) is the dominant climate phenomenon affecting extreme weather conditions worldwide. Its response to greenhouse warming has challenged scientists for decades, despite model agreement on projected changes in mean state. Recent studies have provided new insights into the elusive links between changes in ENSO and in the mean state of the Pacific climate. The projected slow-down in Walker circulation is expected to weaken equatorial Pacific Ocean currents, boosting the occurrences of eastward-propagating warm surface anomalies that characterize observed extreme El Niño events. Accelerated equatorial Pacific warming, particularly in the east, is expected to induce extreme rainfall in the eastern equatorial Pacific and extreme equatorward swings of the Pacific convergence zones, both of which are features of extreme El Niño. The frequency of extreme La Niña is also expected to increase in response to more extreme El Niños, an accelerated maritime continent warming and surface-intensified ocean warming. ENSO-related catastrophic weather events are thus likely to occur more frequently with unabated greenhouse-gas emissions. But model biases and recent observed strengthening of the Walker circulation highlight the need for further testing as new models, observations and insights become available.

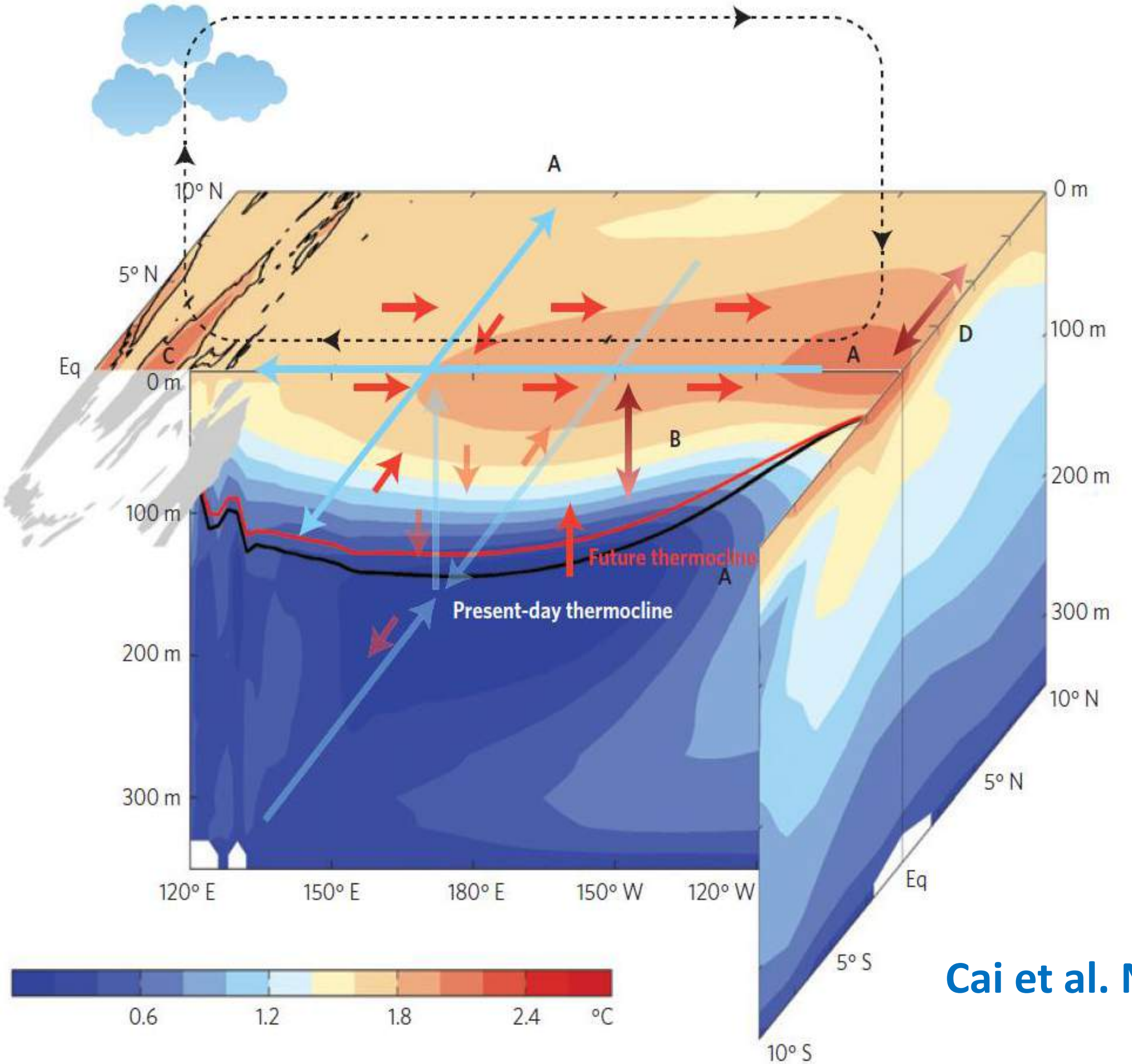
The impacts of anthropogenic climate change may be felt through changes in modes of natural climatic variability. ENSO is the most important year-to-year fluctuation of the climate system on the planet[1], varying between anomalously cold (La Niña) and warm (El Niño) conditions. Underpinning occurrences of ENSO events is the positive feedback between trade wind intensity and zonal contrasts in sea surface temperature (SST), referred to as the Bjerknes feedback. The trade winds normally pile up warm surface water in the western Pacific while upwelling colder subsurface water

During the 1982/1983 and 1997/1998 extreme El Niño events[6,8], surface warming anomalies propagated eastward in an uncharacteristic fashion[13,14], and massive surface warm anomalies in the eastern equatorial Pacific exceeding 3 °C caused an equatorward shift of the Intertropical Convergence Zone (ITCZ). Catastrophic floods occurred in the eastern equatorial region of Ecuador and northern Peru[6,8]. The South Pacific Convergence Zone (SPCZ), the largest rain band in the Southern Hemisphere, shifted equatorward by up to 1,000 km (an event referred to as zonal SPCZ[10]), spurring



IPCC AR5, 2013; Cai 2015 NCC Review

Mean circulation



A: Weakening Walker C faster warming in E. Pacific

B: Increasing vertical temperature gradients

C: Faster warming in M. C.

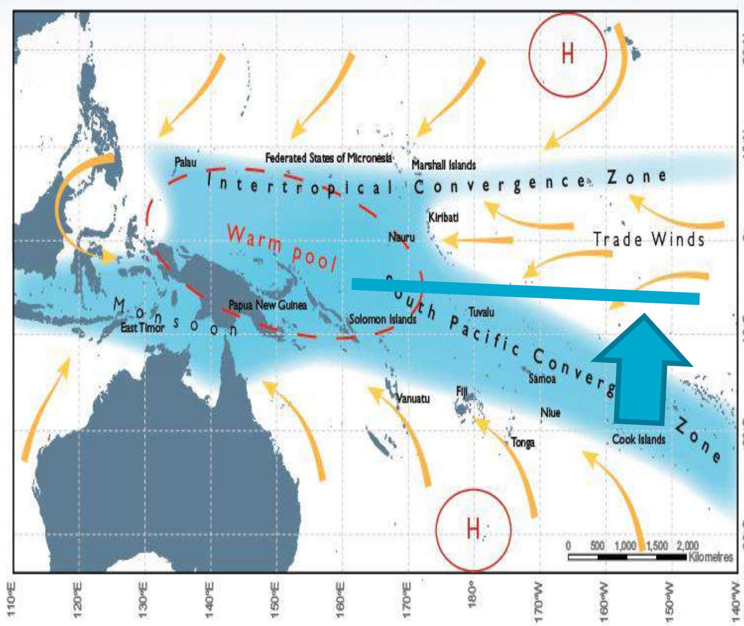
D: Faster warming in the equatorial than the off equatorial Pacific.

Cai et al. Nature Climate Change, 2015

In terms of rainfall variability ……

Frequency of swings doubles

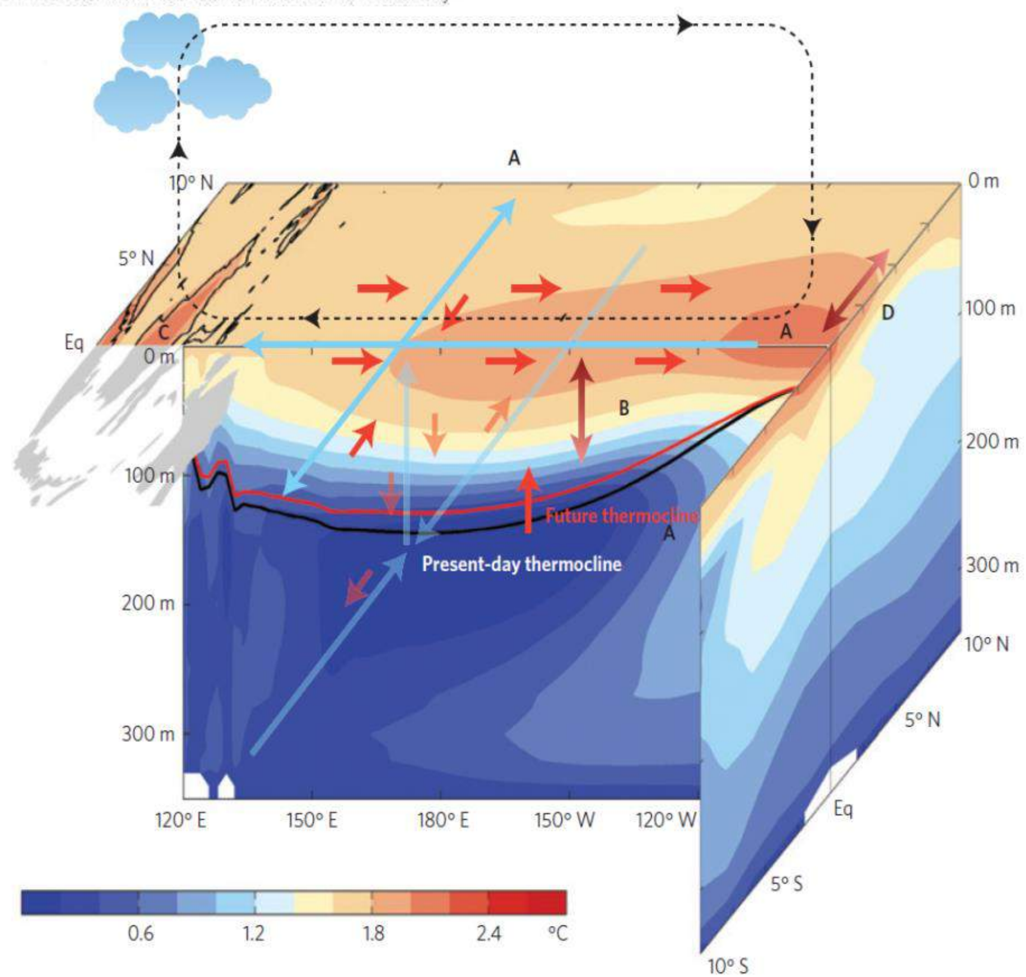
1982/83,1997/98, 1991/92



nature

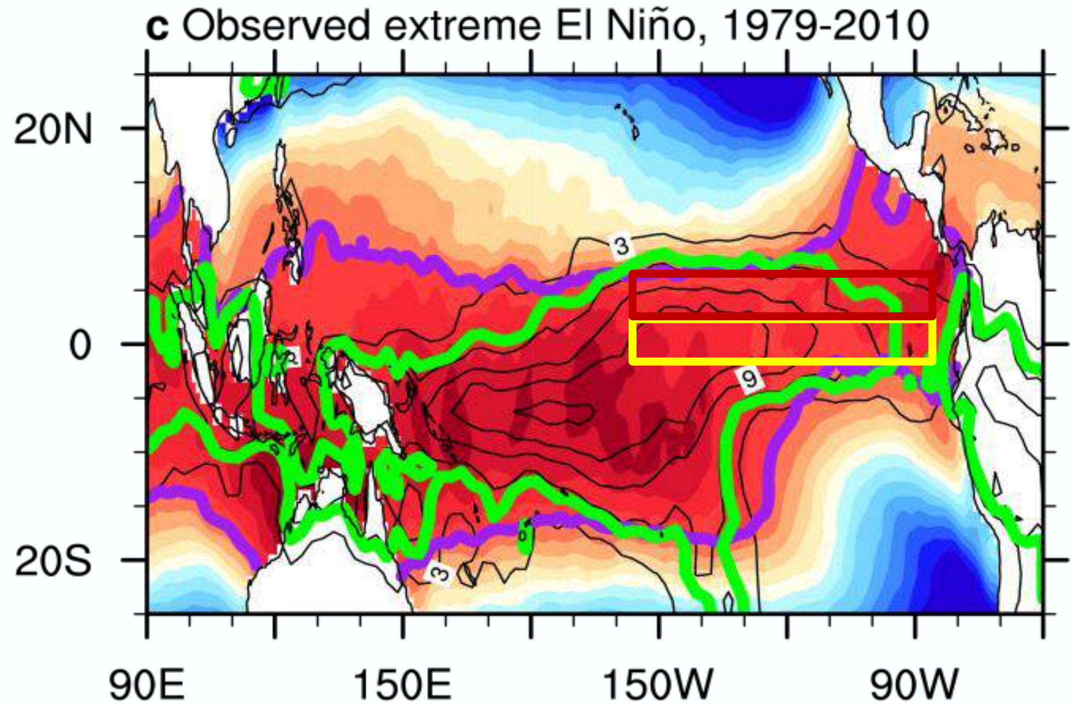
More Extreme Swings of the South Pacific Convergence Zone Due to Greenhouse Warming

Wenju Cai, Matthieu Lengaigne, Simon Borlace, Matthew Collins, Tim Cowan, Michael J. McPhaden, Axel Timmermann, Scott Power, Josephine Brown, Christophe Menkes, Arona Ngari, Emmanuel M. Vincent and Matthew J. Widlansky



Characteristics of extreme El Niños: DJF rainfall and SST

Green 5 mm per day
Purple 28^{o}C isotherm

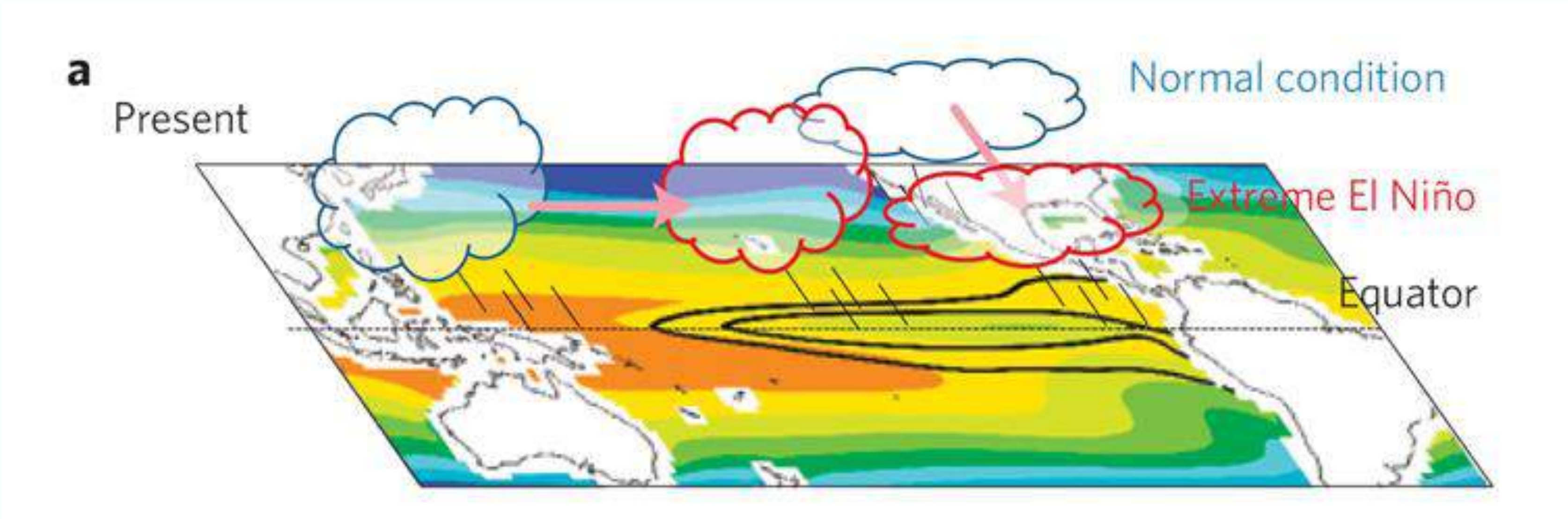


Warm pool (purple, SST) and heavy rain (green) extend to the east Pacific

Meridional gradient: Box 1 SST – Box 2 SST < 0

The ITCZ moves to the eastern equatorial Pacific

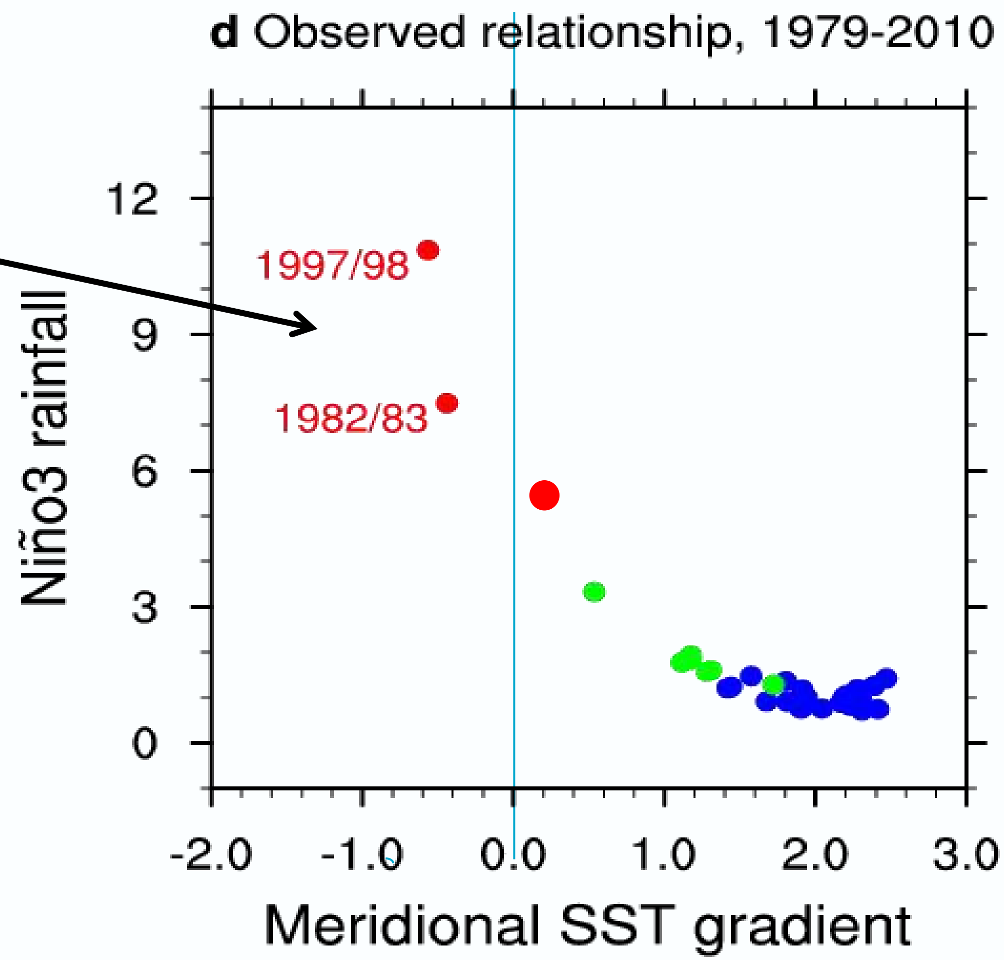
Cai et al. NCC, 2014

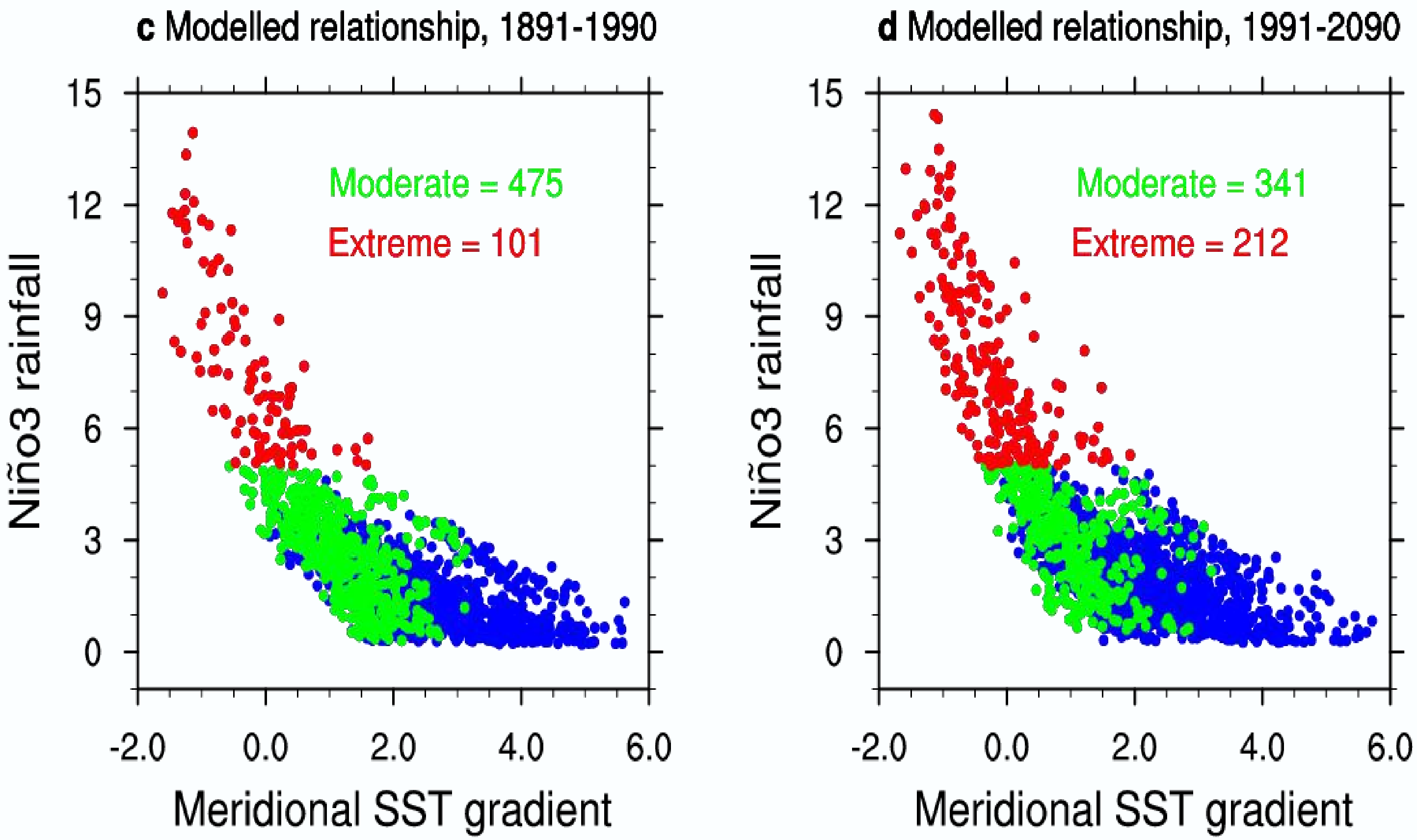

a
Present
Normal condition
Extreme El Niño
Equator

Characteristics of extreme El Niños

Rainfall in the eastern Eq. Pacific reaches > 5 mm per day, which we define as an extreme El Niño

Rainfall
Skewness: 2.7





There is a doubling of extreme El Niño events 17/20 showing an increase.

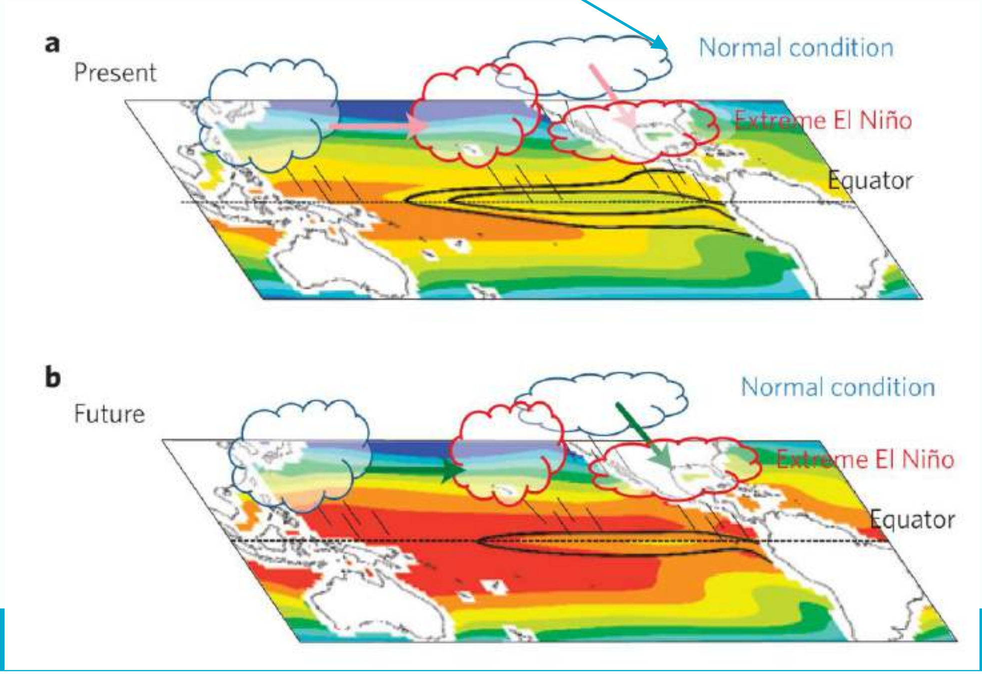
Extreme El Niño with the ITCZ in the equatorial E. Pacific

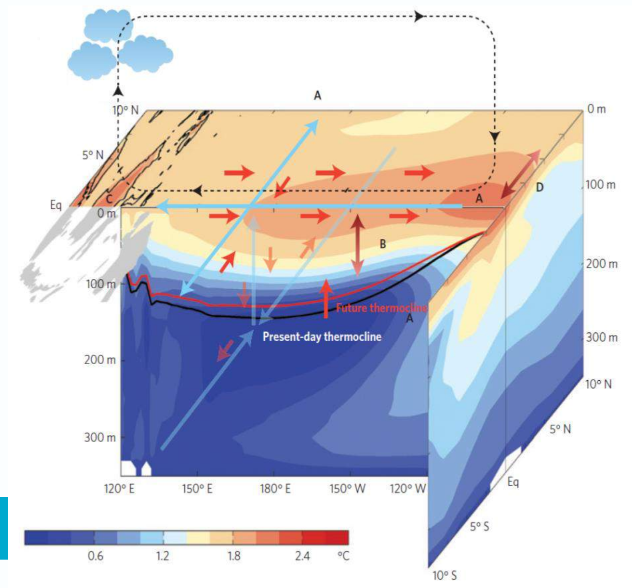
nature climate change
LETTERS
PUBLISHED ONLINE: 19 JANUARY 2014 | DOI: 10.1038/NCLIMATE2100

Increasing frequency of extreme El Niño events due to greenhouse warming

Wenju Cai[1,2]*, Simon Borlace[1], Matthieu Lengaigne[3], Peter van Rensch[1], Mat Collins[4], Gabriel Vecchi[5], Axel Timmermann[6], Agus Santoso[7], Michael J. McPhaden[8], Lixin Wu[2], Matthew H. England[7], Guojian Wang[1,2], Eric Guilyardi[3,9] and Fei-Fei Jin[10]

ITCZ moves to the equator





Continued increase of extreme El Niño frequency long after 1.5 °C warming stabilization

Guojian Wang, Wenju Cai, Bolan Gan, Lixin Wu, Agus Santoso, Xiaopei Lin, Zhaohui Chen & Michael J. McPhaden

Affiliations | Contributions | Corresponding authors

Nature Climate Change 7, 568–572 (2017) | doi:10.1038/nclimate3351
Received 13 December 2016 | Accepted 22 June 2017 | Published online 24 July 2017

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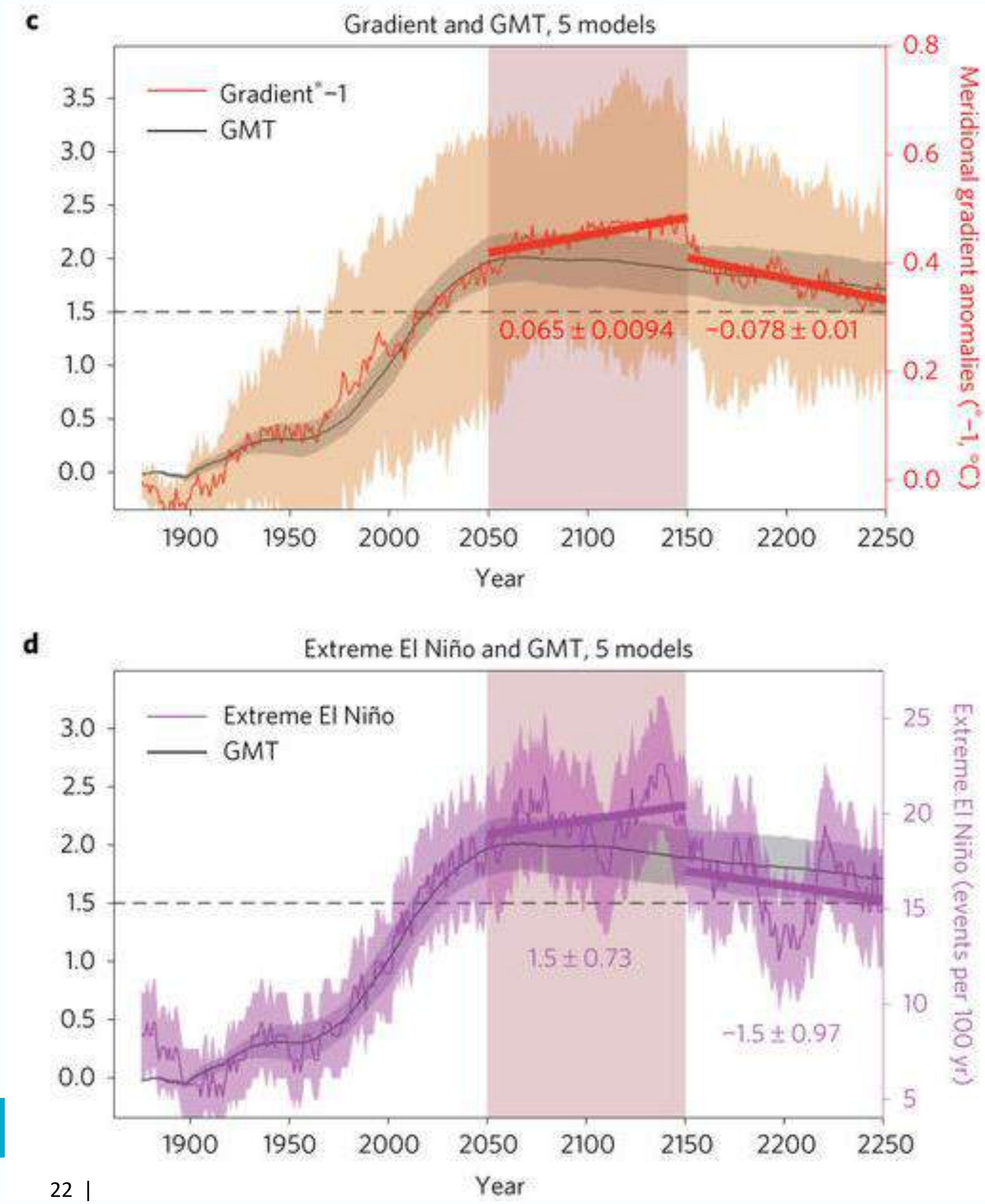
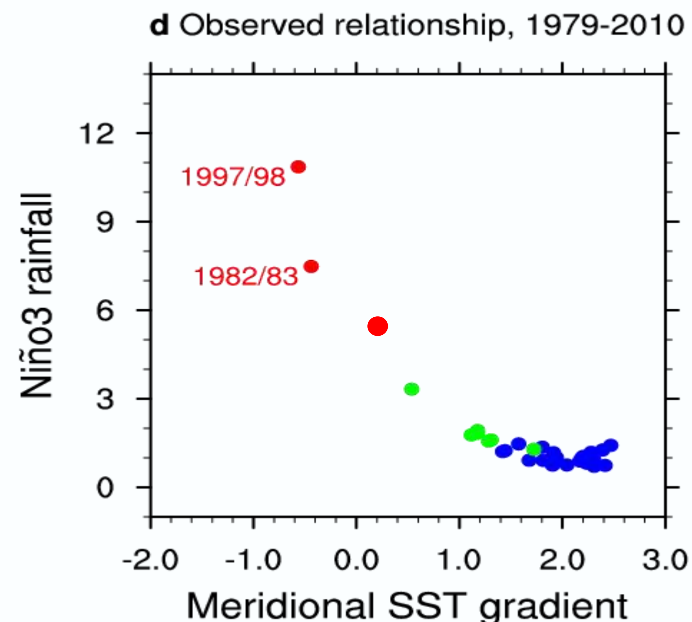
The Paris Agreement aims to constrain global mean temperature (GMT) increases to 2 °C above pre-industrial levels, with an aspirational target of 1.5 °C. However, the pathway to these targets[1, 2, 3, 4, 5, 6] and the impacts of a 1.5 °C and 2 °C warming on extreme El Niño and La Niña events—which severely influence weather patterns, agriculture, ecosystems, public health and economies[7, 8, 9, 10, 11, 12, 13, 14, 15, 16]—is little known. Here, by analysing

Temporal evolution: 5-model ensemble average, RCP2.6



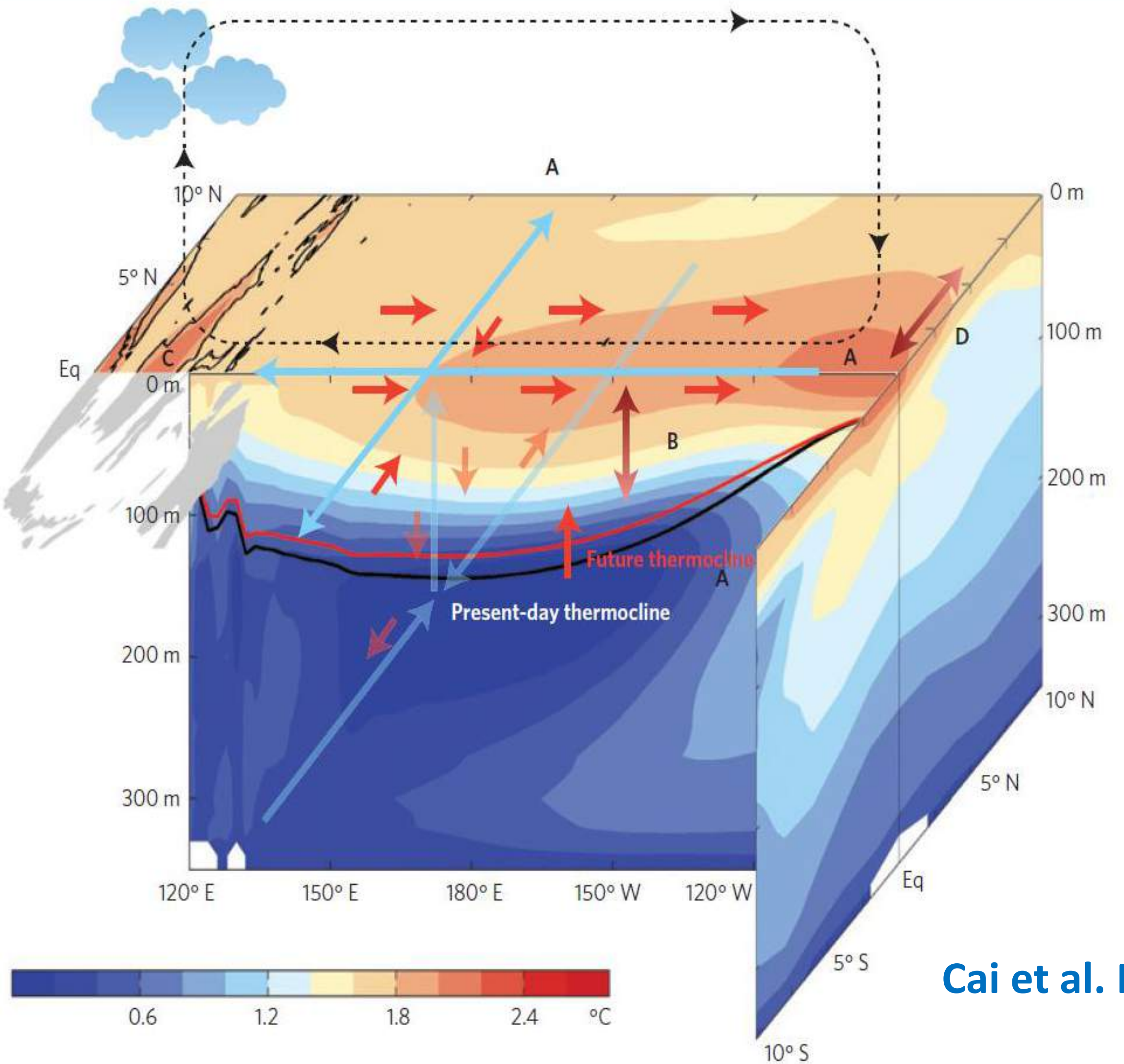
Wang et al. NCC 2017



Under GW, rainfall sensitivity to SST increases even if SST variability does not change

In terms of response of SST variability …

Mean circulation



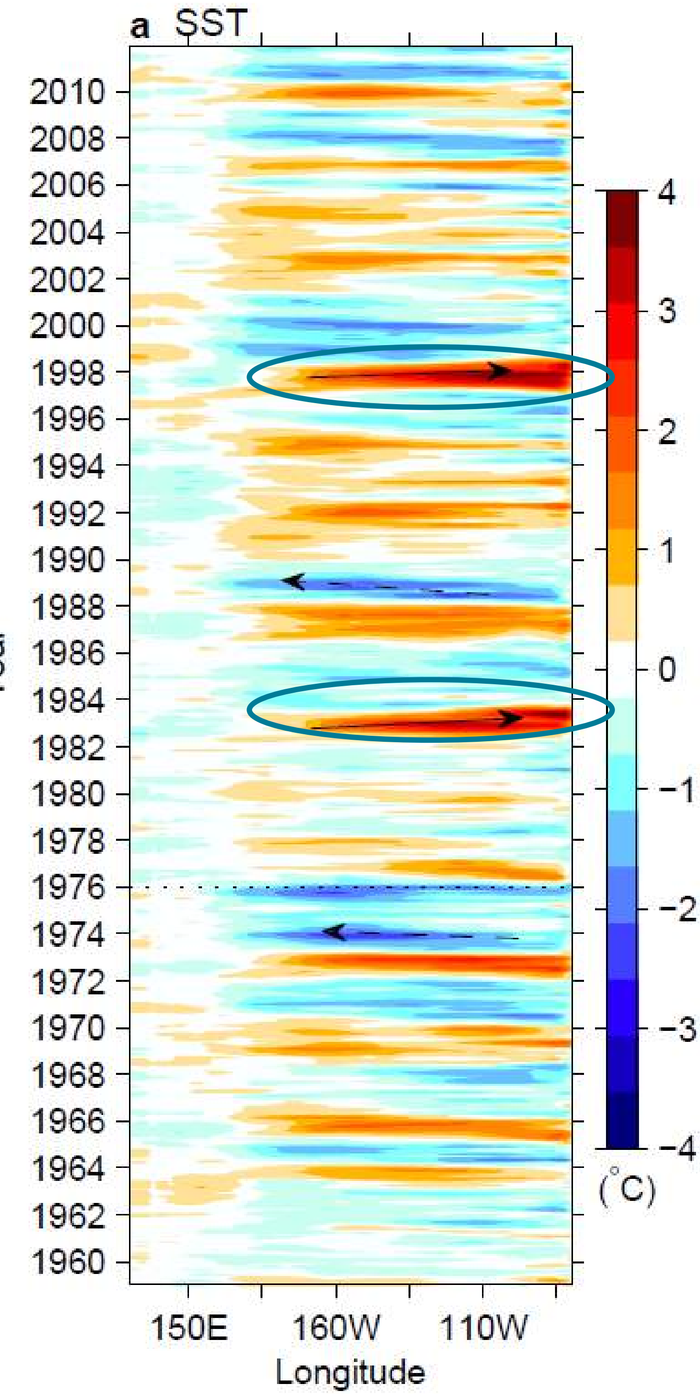
A: Weakening Walker C faster warming in E. Pacific

B: Increasing vertical temperature gradients

C: Faster warming in M. C.

D: Faster warming in the equatorial than the off equatorial Pacific.

Cai et al. Nature Climate Change, 2015

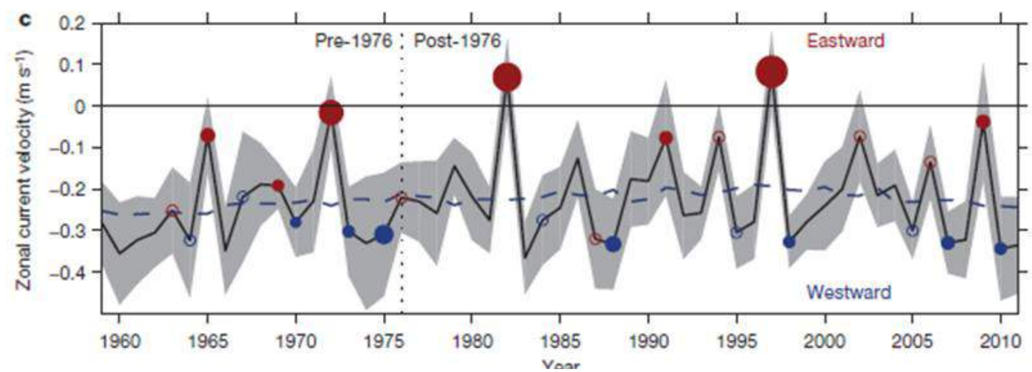


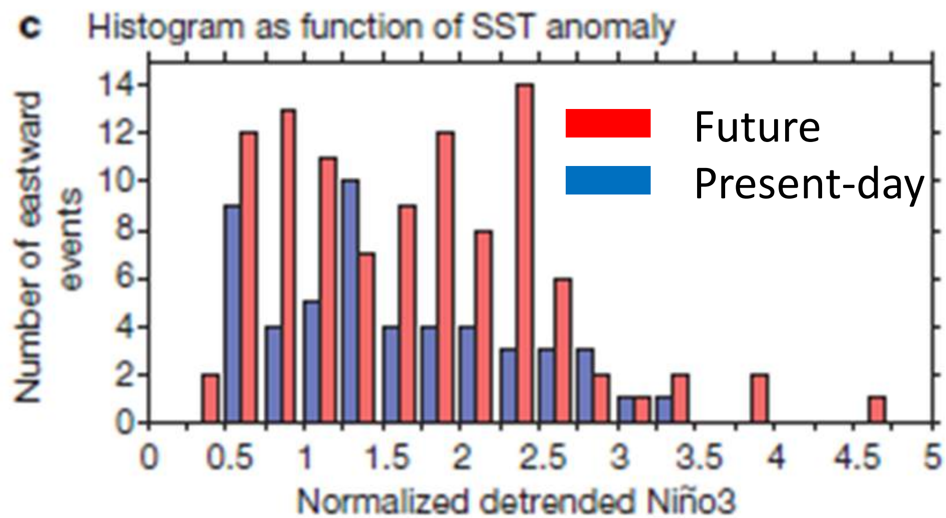
LETTER

doi:10.1038/nature12683

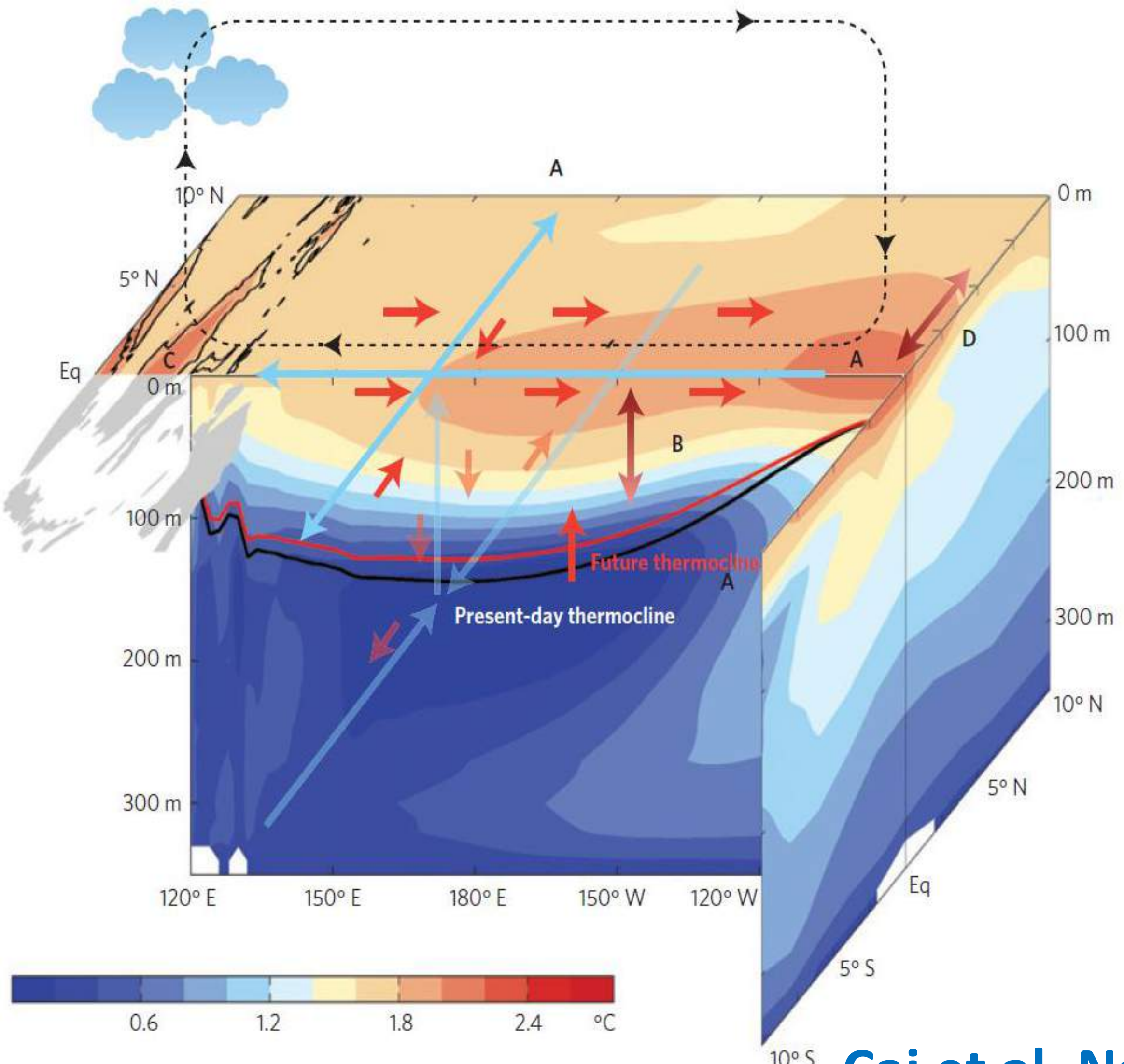
Late-twentieth-century emergence of the El Niño propagation asymmetry and future projections

Agus Santoso[1], Shayne McGregor[1], Fei-Fei Jin[2], Wenju Cai[3], Matthew H. England[1], Soon-Il An[4], Michael J. McPhaden[5] & Eric Guilyardi[6,7]





Mean circulation



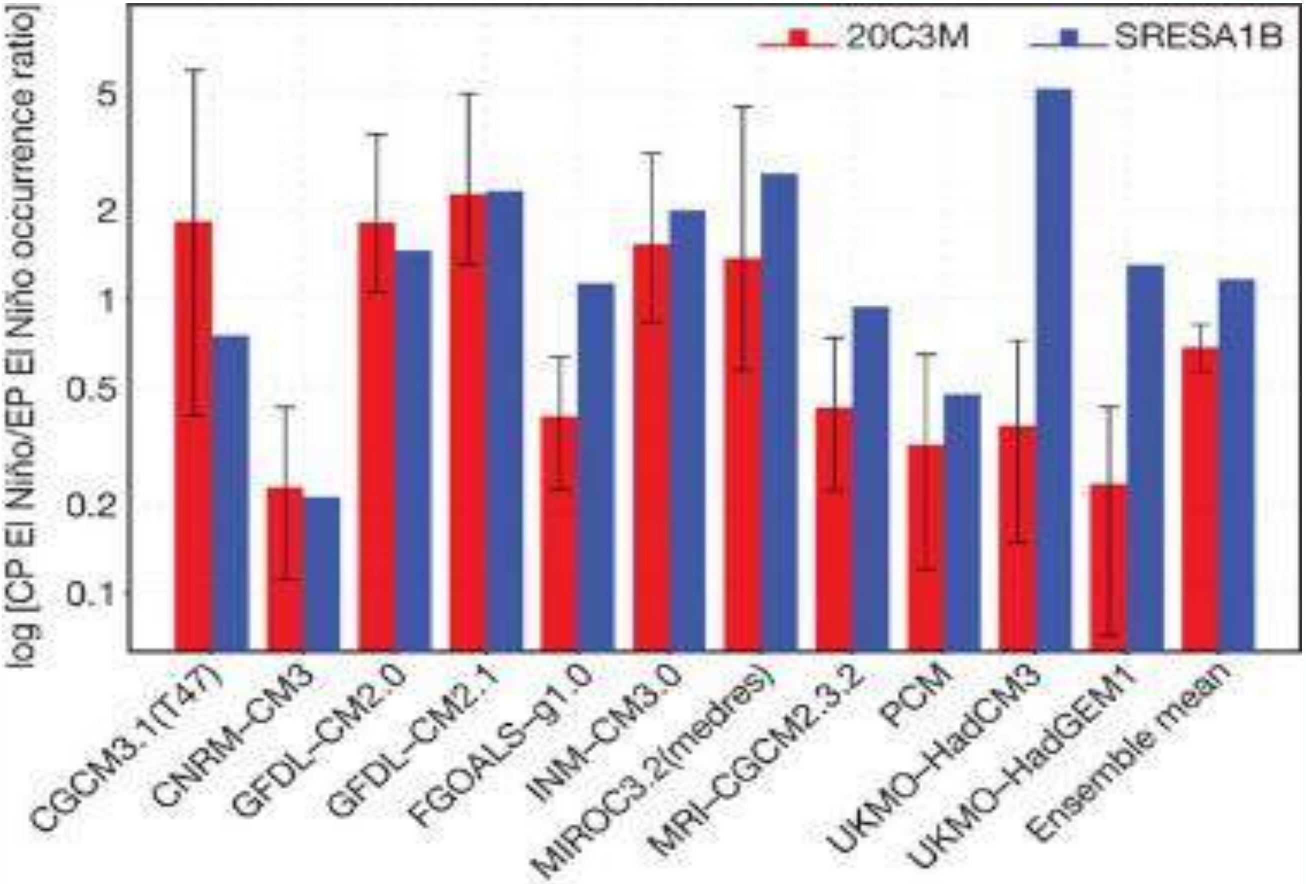
A: Weakening Walker C

B: Increasing vertical temperature gradients shallowing thermocline

C: Faster warming in M. C.

D: Faster warming in the equatorial than the off equatorial Pacific.

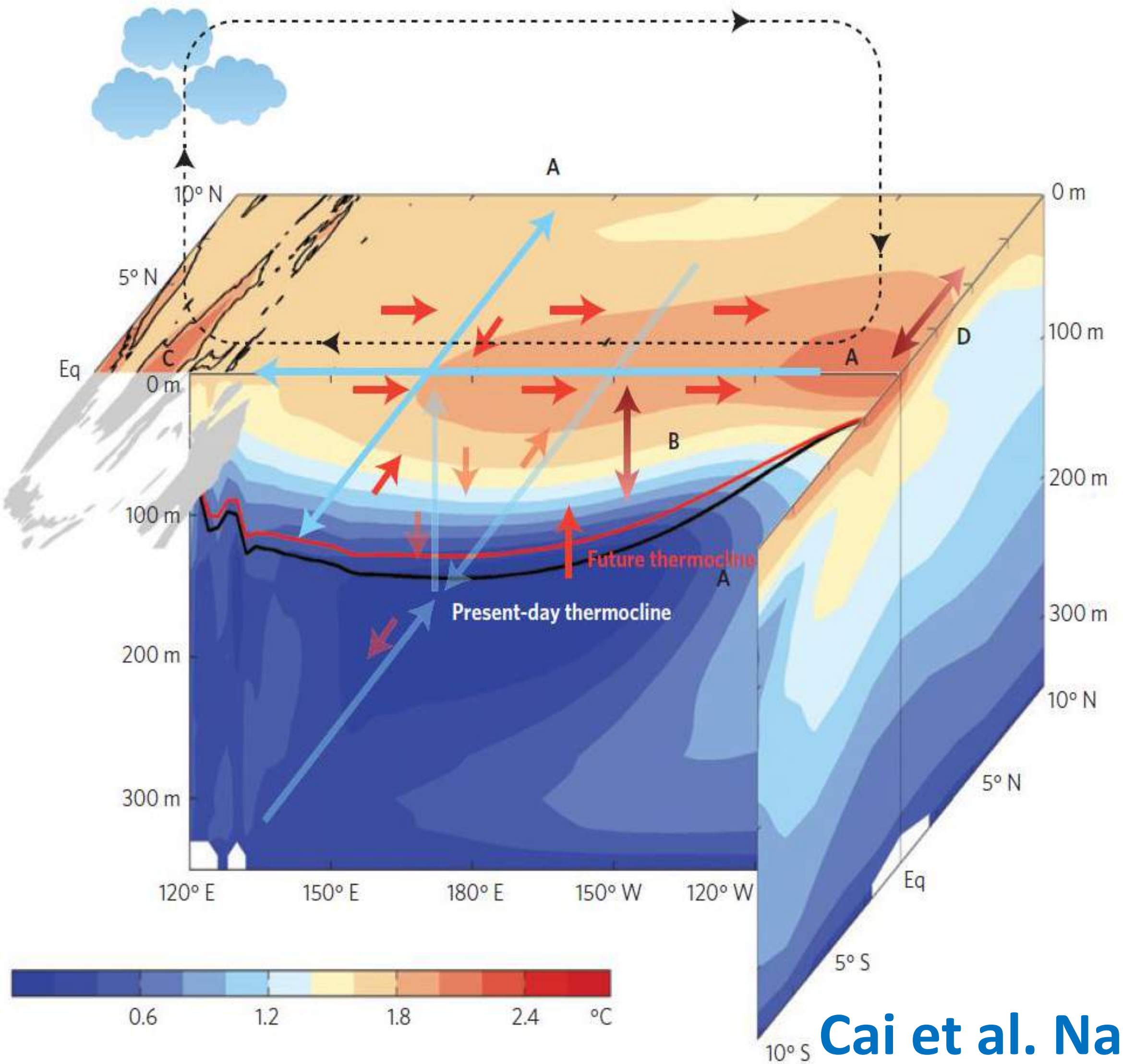
Cai et al. Nature Climate Change, 2015



✓ The frequency of CP El Niño (relative to EP) increases under GW

Yeh et al. Nature 2009

Mean circulation



A: Weakening Walker C faster warming in E. Pacific

B: Increasing vertical temperature gradients shallowing thermocline

C: Faster warming in M. C.

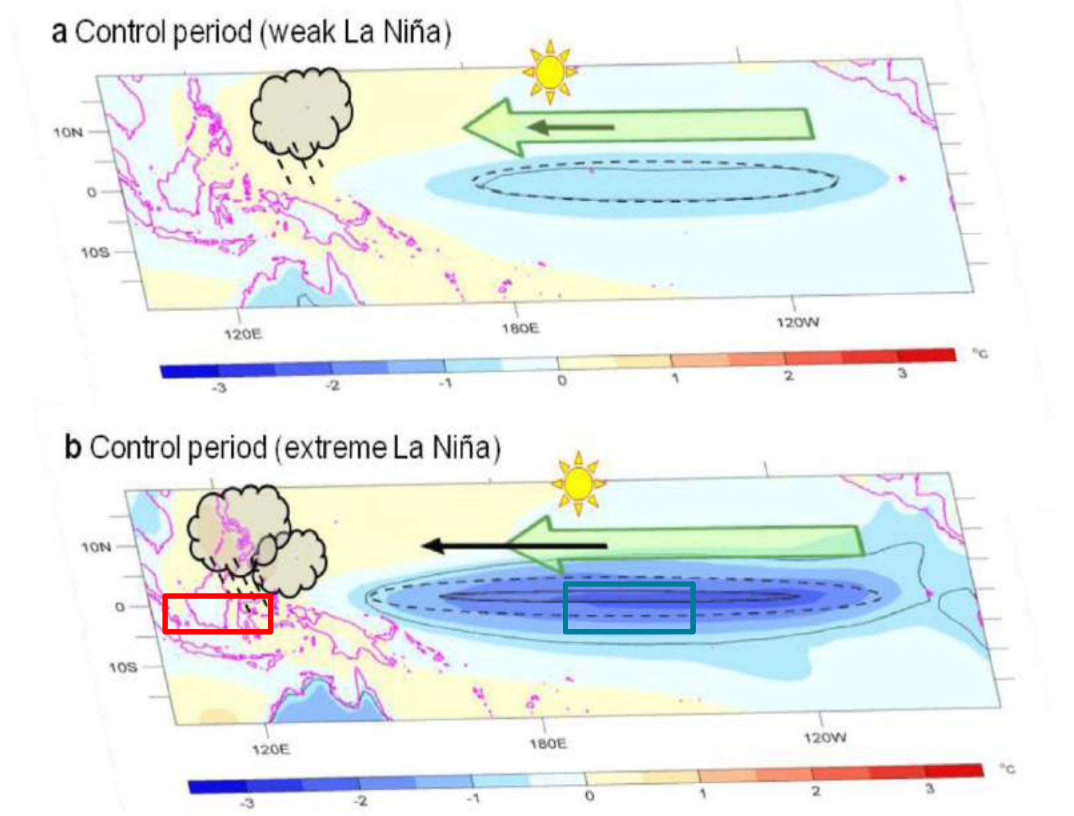
D: Faster warming in the equatorial than the off equatorial Pacific.

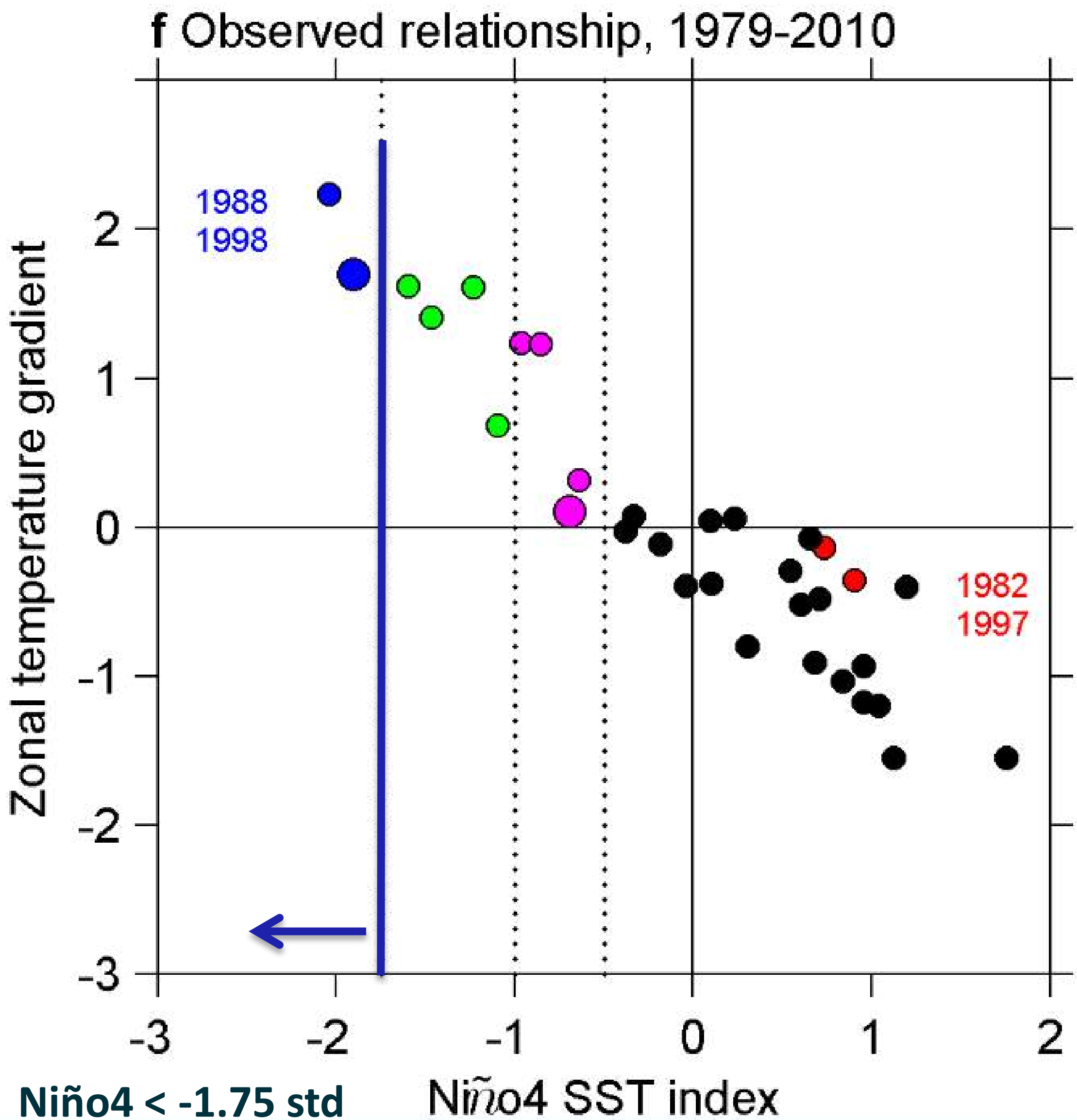
Cai et al. Nature Climate Change, 2015

LETTERS
PUBLISHED ONLINE: 26 JANUARY 2015 | DOI: 10.1038/NCLIMATE2492
nature climate change

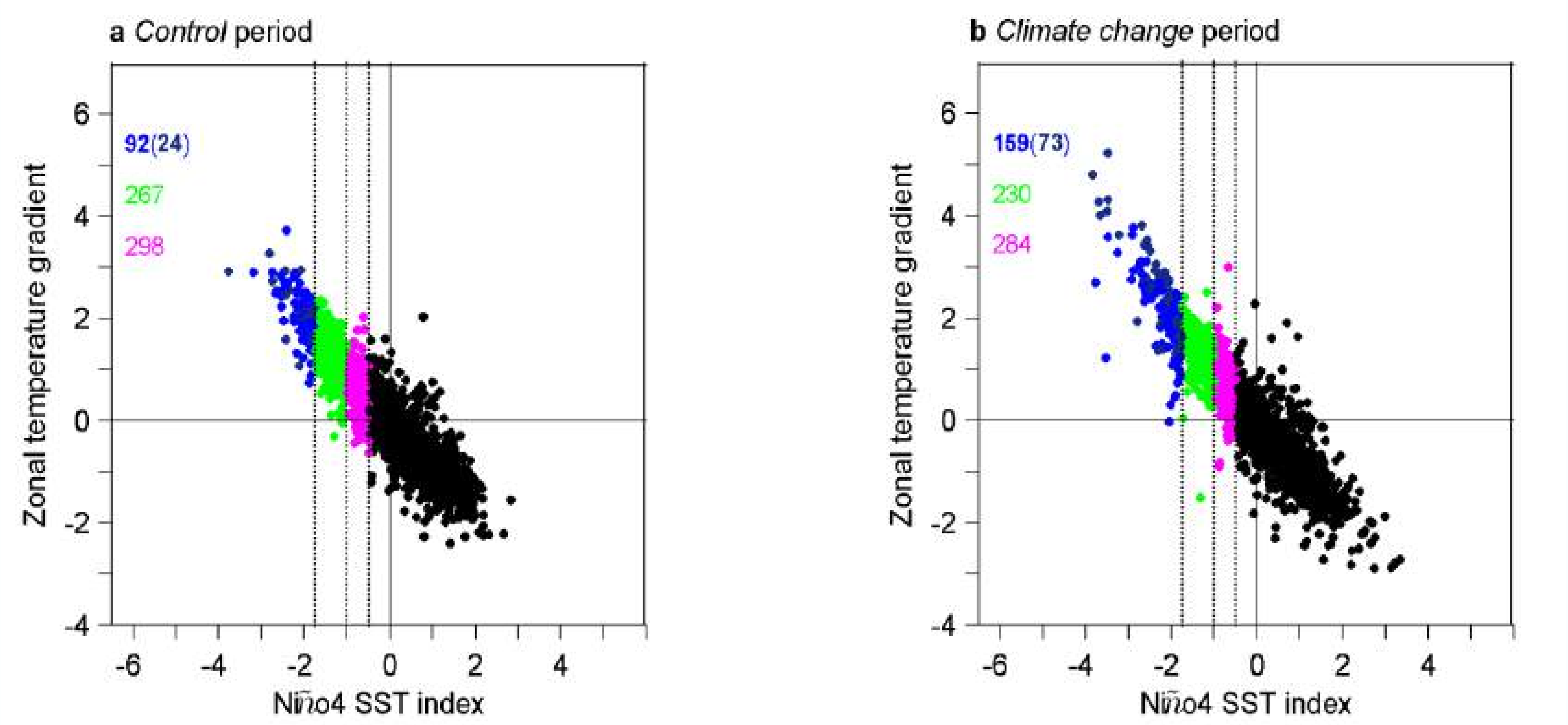
Increased frequency of extreme La Niña events under greenhouse warming

Wenju Cai[1,2★], Guojian Wang[1,2], Agus Santoso[3], Michael J. McPhaden[4], Lixin Wu[2], Fei-Fei Jin[5], Axel Timmermann[6], Mat Collins[7], Gabriel Vecchi[8], Matthieu Lengaigne[9], Matthew H. England[3], Dietmar Dommenget[10], Ken Takahashi[11] and Eric Guilyardi[9,12]



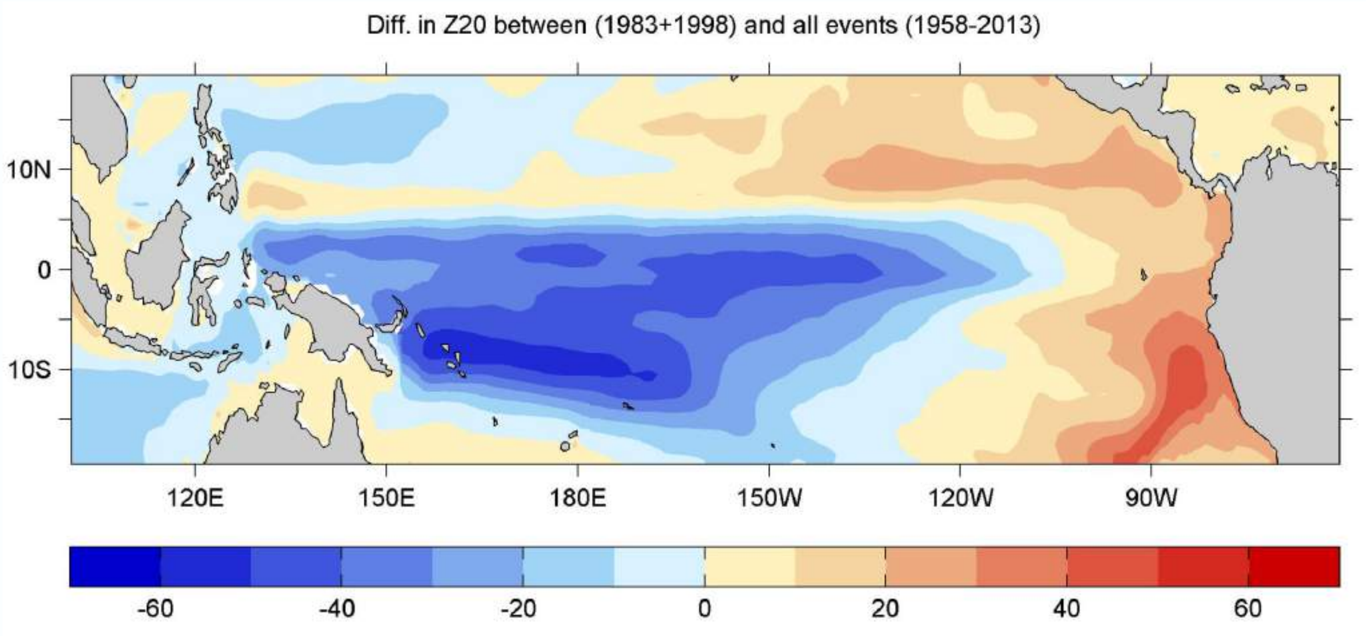


Niño4 < -1.75 std



17 out of 21 models produce an increase

Thermocline anomalies after extreme El Niño



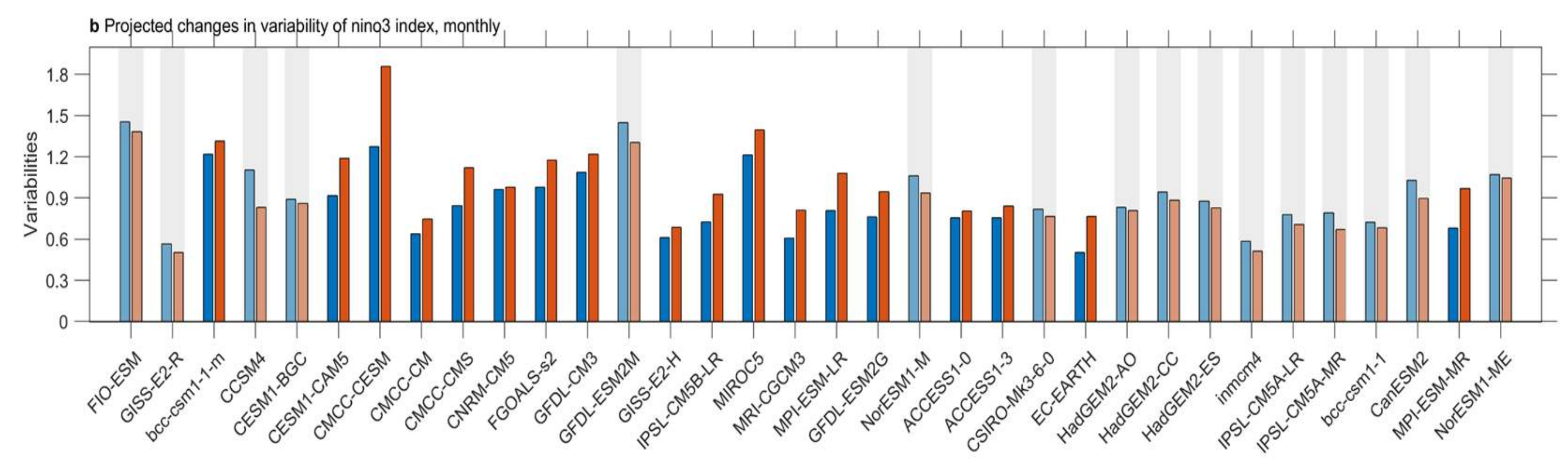
The long-standing challenge

How ENSO SST variability responds to greenhouse warming has been one of the most critical issues in climate change science.

For several model generations, there is **no inter-model consensus on its future change** using conventional ENSO indices.

But the response of Eastern Pacific ENSO is still an open question

16 out of 34 models generate a decreased variance In Niño3



What is it implied by using Niño3?

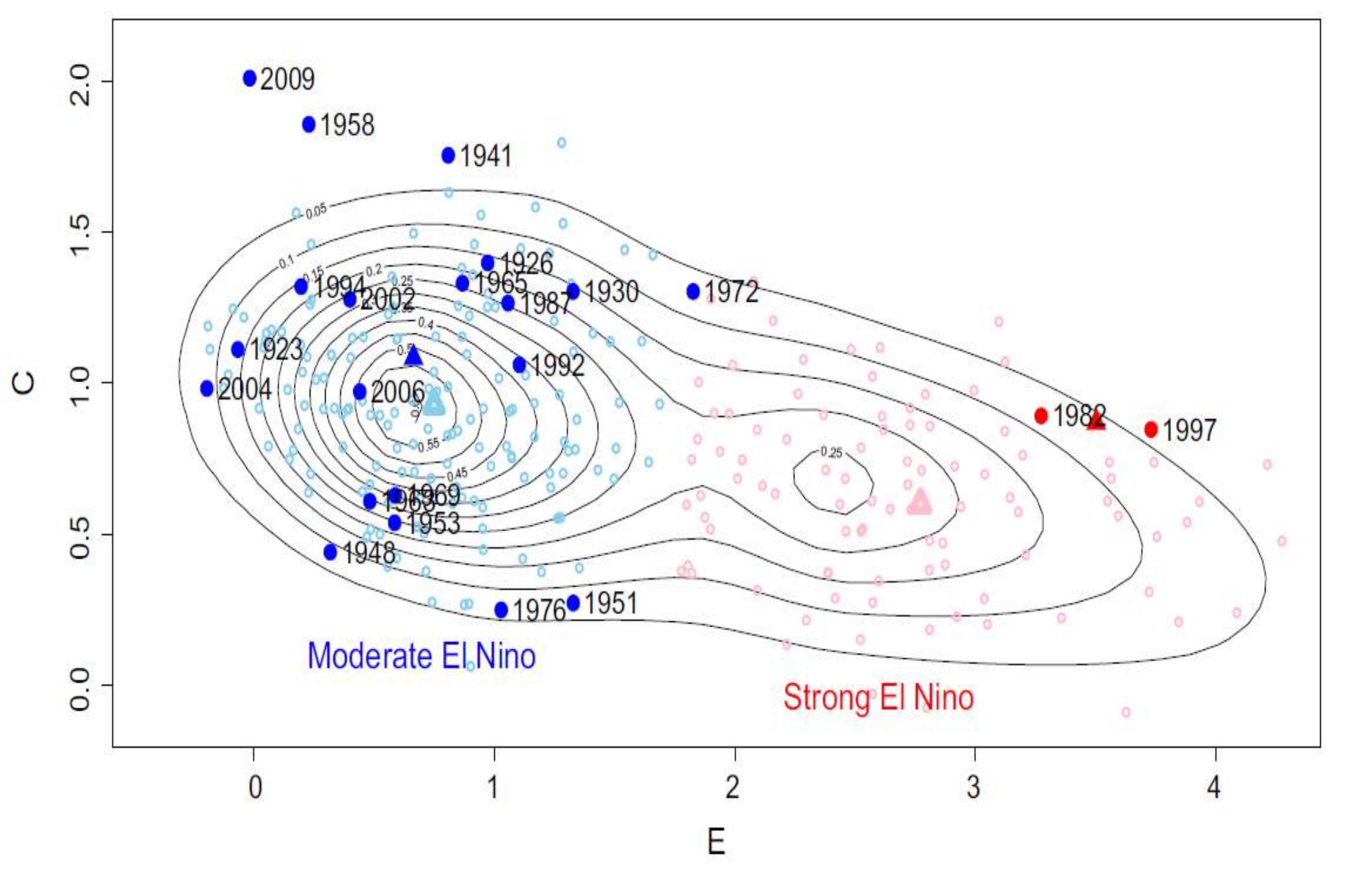
ARTICLE

https://doi.org/10.1038/s41586-018-0776-9

Increased variability of eastern Pacific El Niño under greenhouse warming

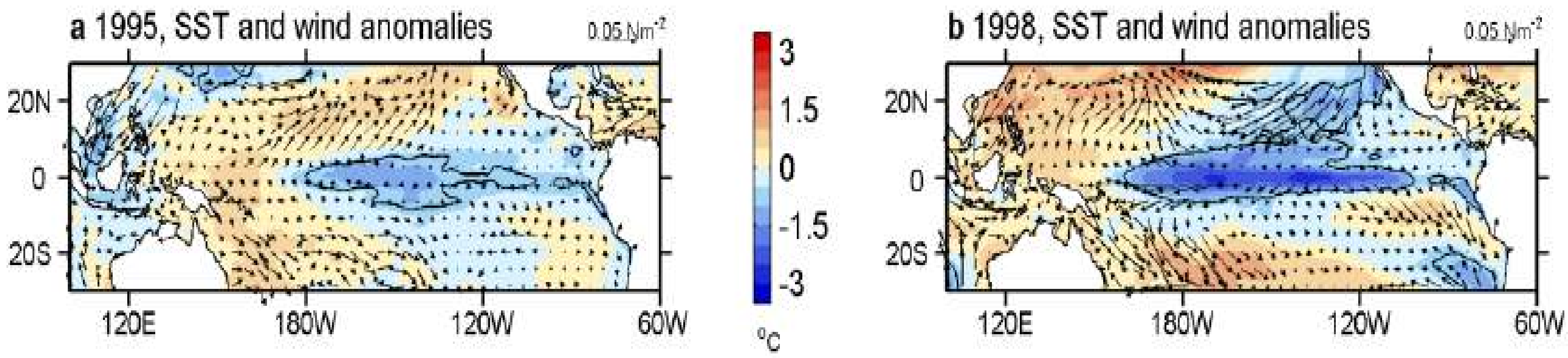
Wenju Cai[1,2]*, Guojian Wang[1,2], Boris Dewitte[3,4,5,6], Lixin Wu[1]*, Agus Santoso[2,7], Ken Takahashi[8], Yun Yang[9], Aude Carreric[6] & Michael J. McPhaden[10]

The El Niño–Southern Oscillation (ENSO) is the dominant and most consequential climate variation on Earth, and is characterized by warming of equatorial Pacific sea surface temperatures (SSTs) during the El Niño phase and cooling during the La Niña phase. ENSO events tend to have a centre—corresponding to the location of the maximum SST anomaly—in either the central equatorial Pacific (5° S–5° N, 160° E–150° W) or the eastern equatorial Pacific (5° S–5° N, 150°–90° W); these two distinct types of ENSO event are referred to as the CP-ENSO and EP-ENSO regimes, respectively. How the ENSO may change under future greenhouse warming is unknown, owing to a lack of inter-model agreement over the response of SSTs in the eastern equatorial Pacific to such warming. Here we find a robust increase in future EP-ENSO SST variability among CMIP5 climate models that simulate the two distinct ENSO regimes. We show that the EP-ENSO SST anomaly pattern and its centre differ greatly from one model to another, and therefore cannot be well represented by a single SST 'index' at the observed centre. However, although the locations of the anomaly centres differ in each model, we find a robust increase in SST variability at each anomaly centre across the majority of models considered. This increase in variability is largely due to greenhouse-warming-induced intensification of upper-ocean stratification in the equatorial Pacific, which enhances ocean-atmosphere coupling. An increase in SST variance implies an increase in the number of 'strong' eastern Pacific El Niño events (corresponding to large SST anomalies) and associated extreme weather events.

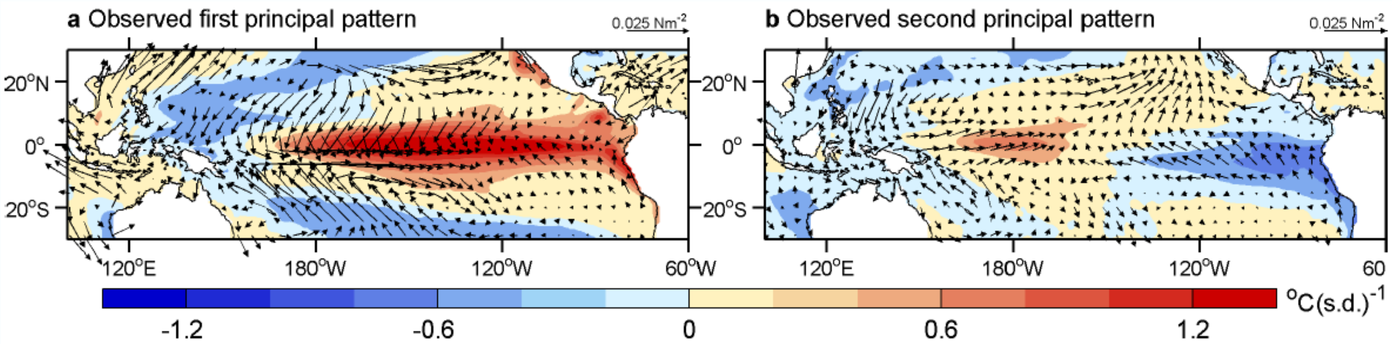


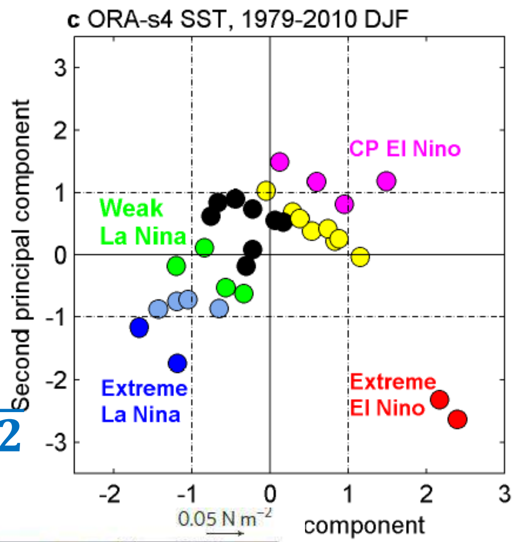
Takahashi and Dewitte, Clim Dyn. 2016

Difference between weak and strong La Niña



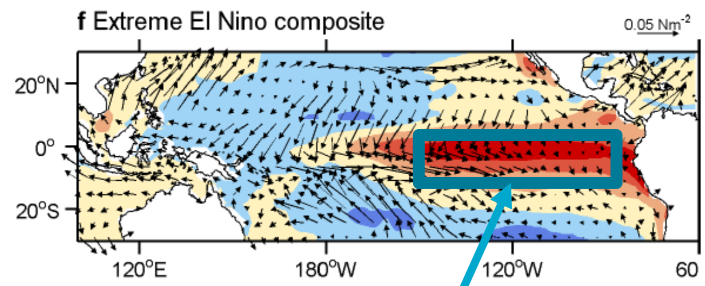
Cai et al. NCC, 2015



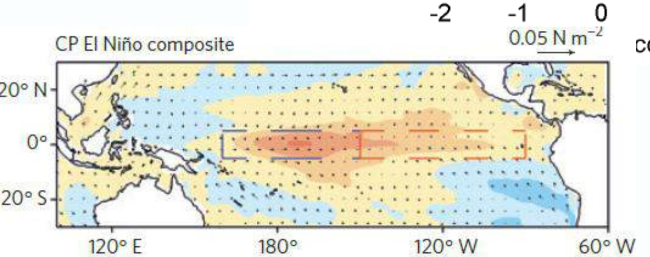


$C=(PC1+PC2)/\sqrt{2}$

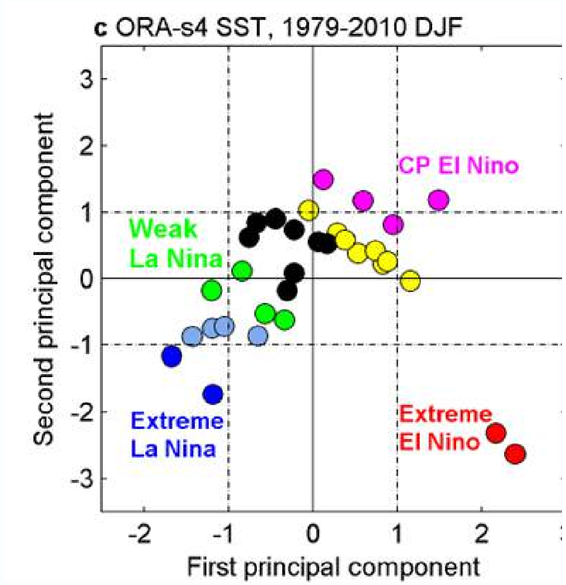
$E=(PC1-PC2)/\sqrt{2}$

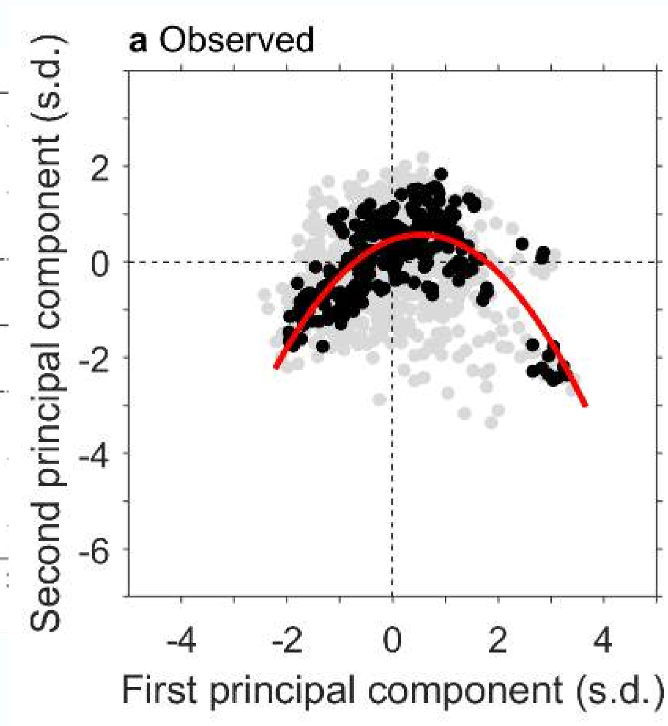


Niño3 may represent Eastern Pacific El Niño



Using five (5) reanalysis products

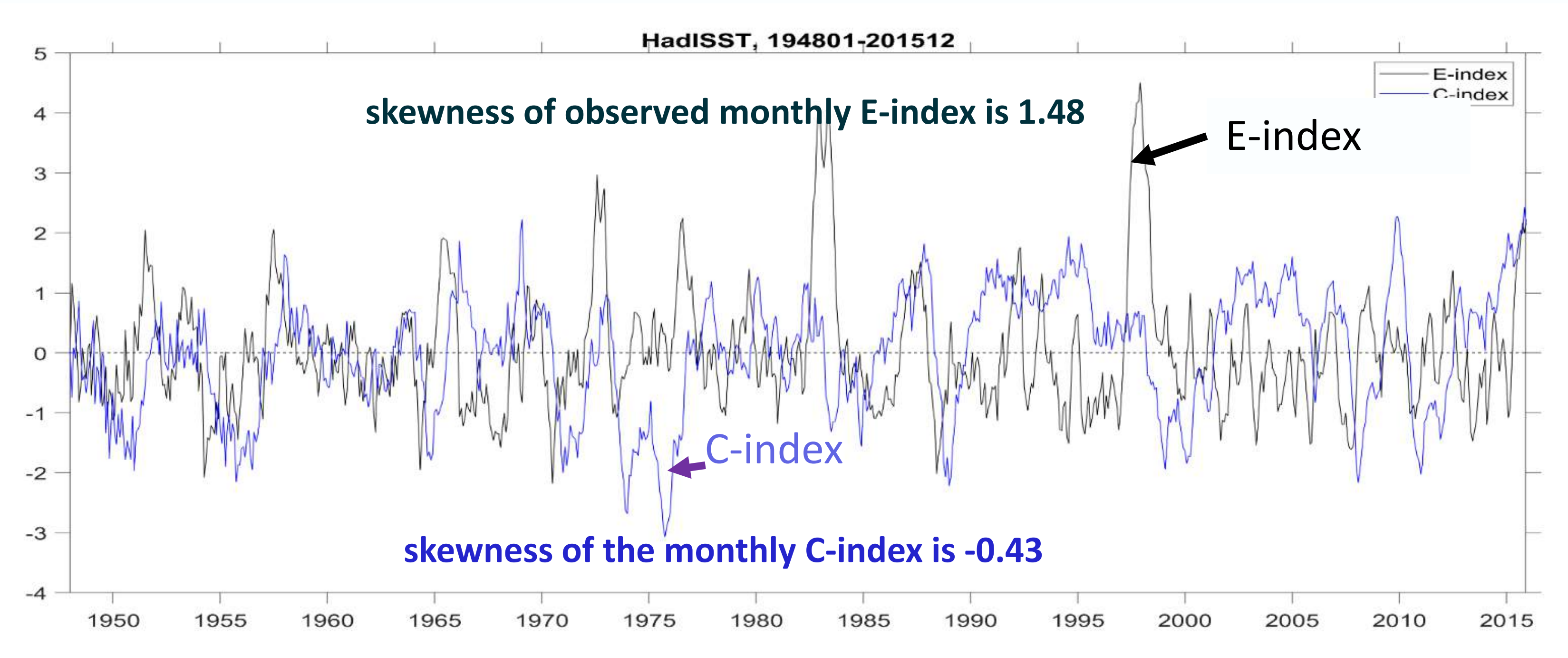




The nonlinearity can be measured by a quadratic relationship

$$\mathrm{PC2}(t) = \alpha[\mathrm{PC1}(t)]^2 + \beta\mathrm{PC1}(t) + \gamma$$

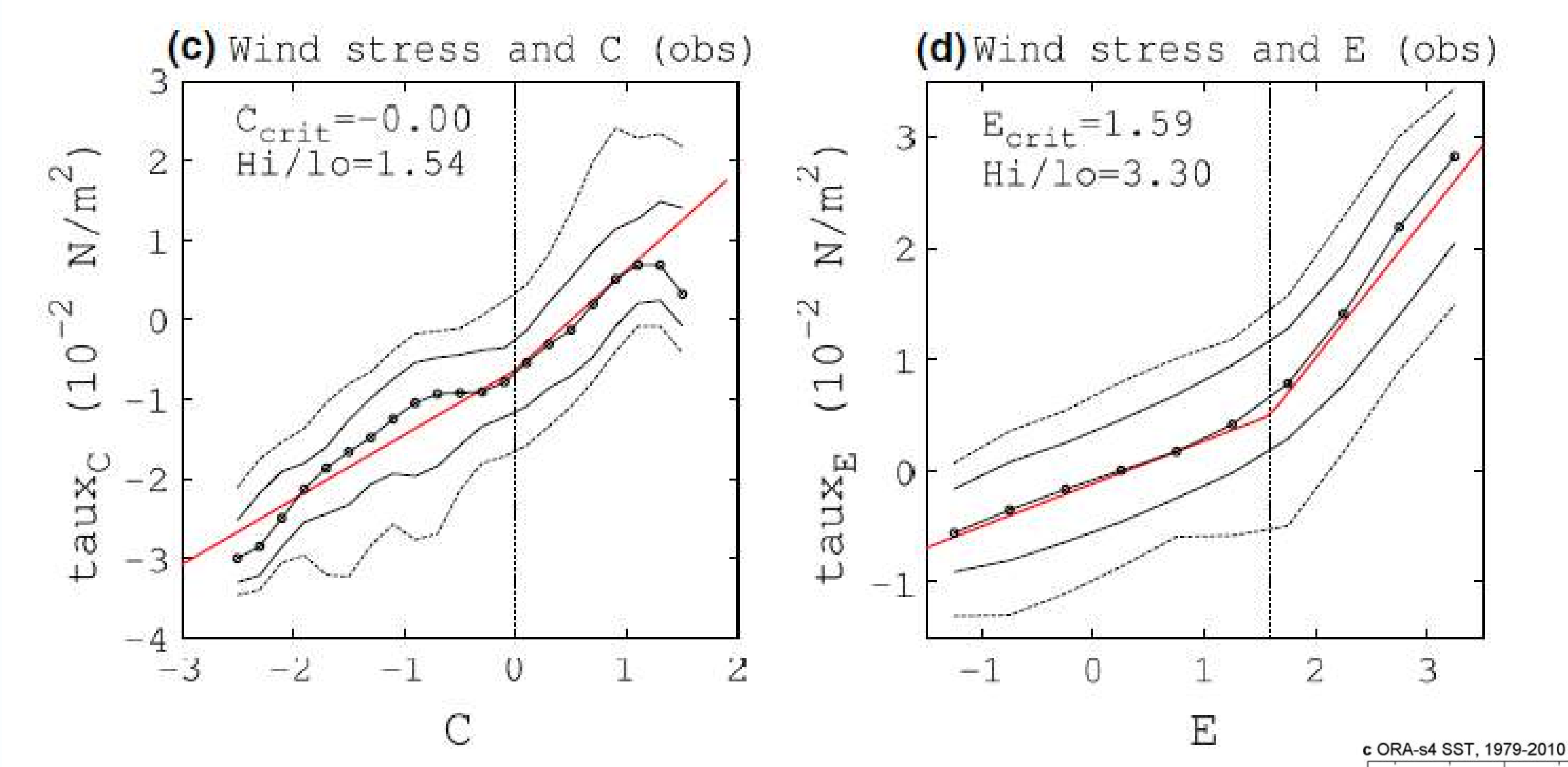
***α* = -0.31**



Centre of positive skewness is the centre for EP-ENSO;

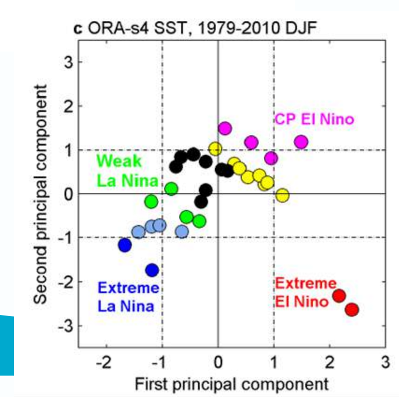
Centre of negative skewness is the centre for CP-ENSO

Dynamics responsible for the skewness



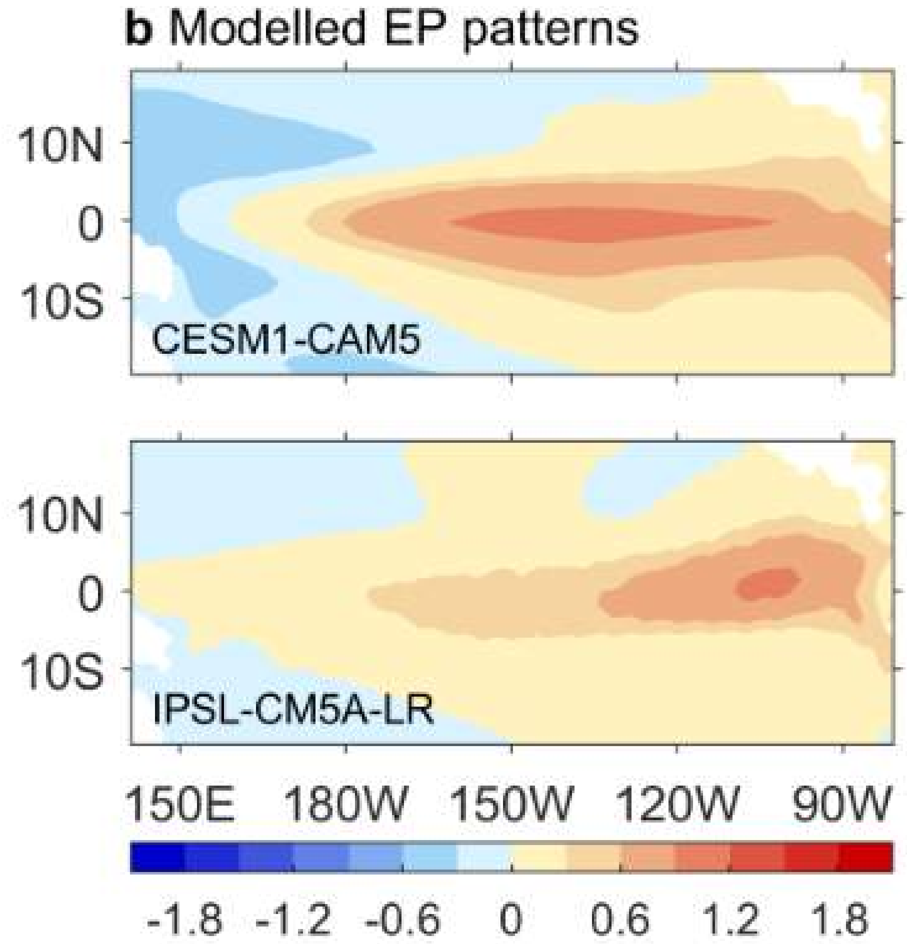
Takahashi and Dewitte Clim Dyn. 2016

Dommenget et al. 2013



Across 34 models

Applying EOF
Construct E-index



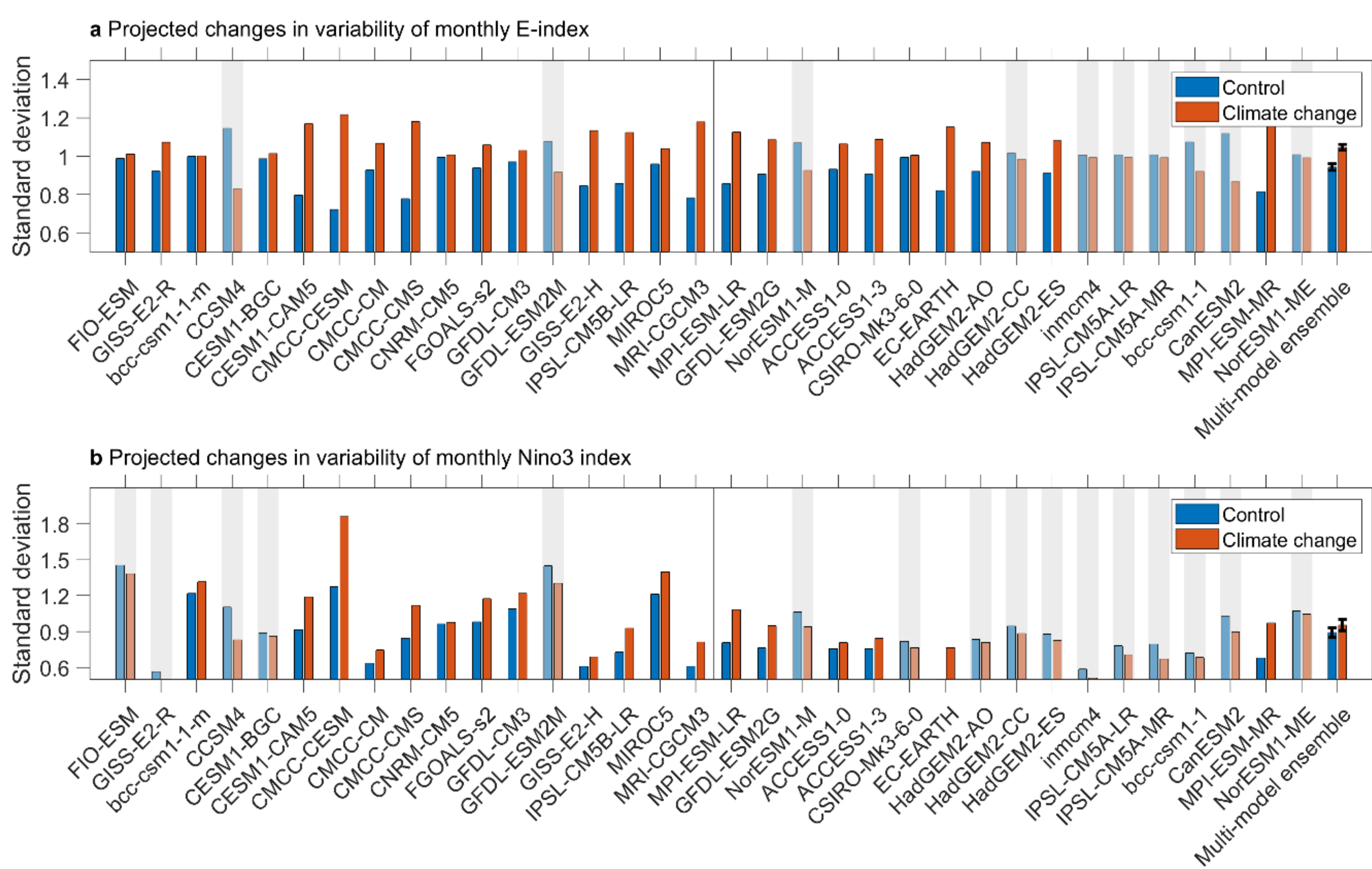
Huge difference in the centre.

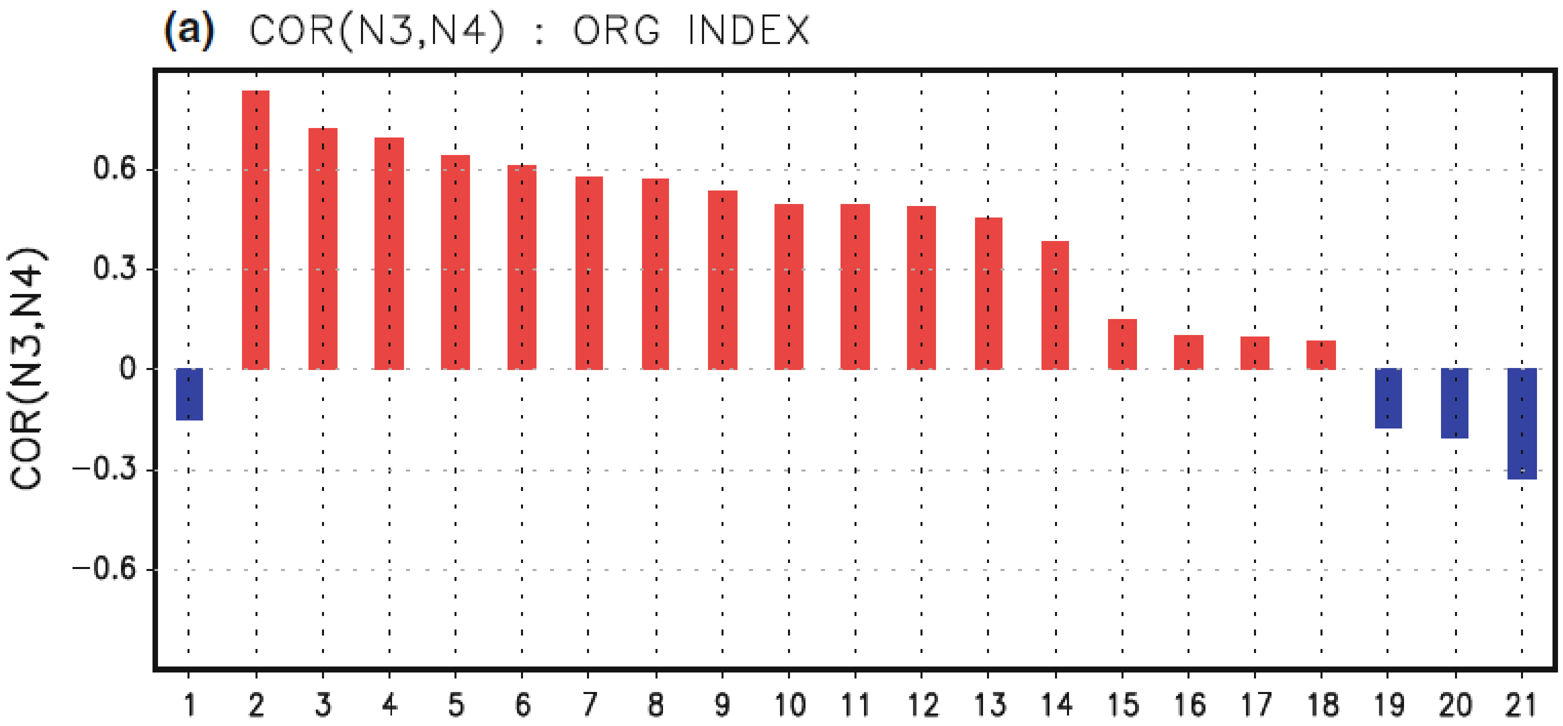
Not appropriate to be represented by Niño3

But should be represented by E index

E-index change

24/34 models generating an increase





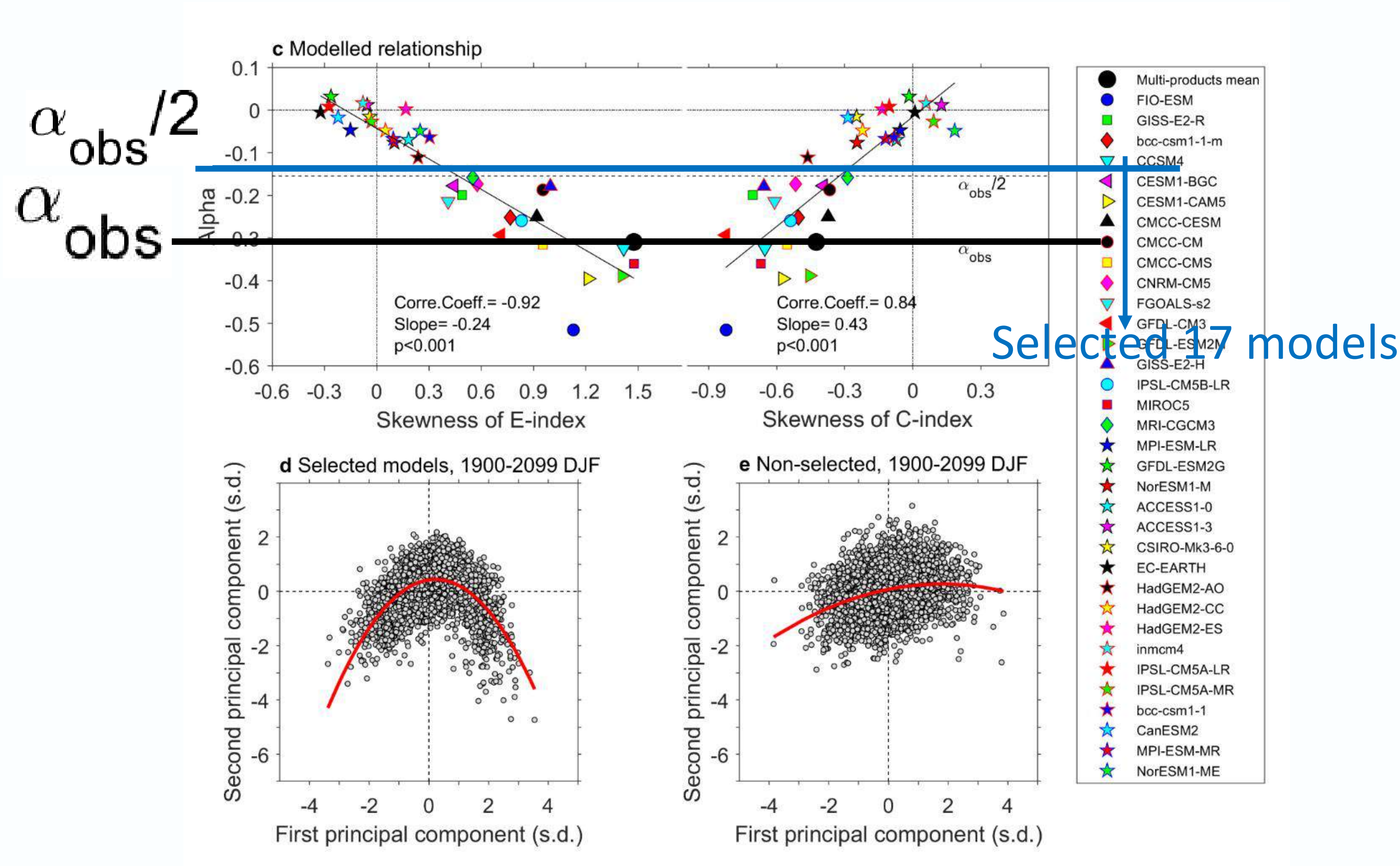
(Ham and Kug, Climate Dynamics , 2012)

Many models are not able to simulate well distinguishable CP and EP anomaly centres

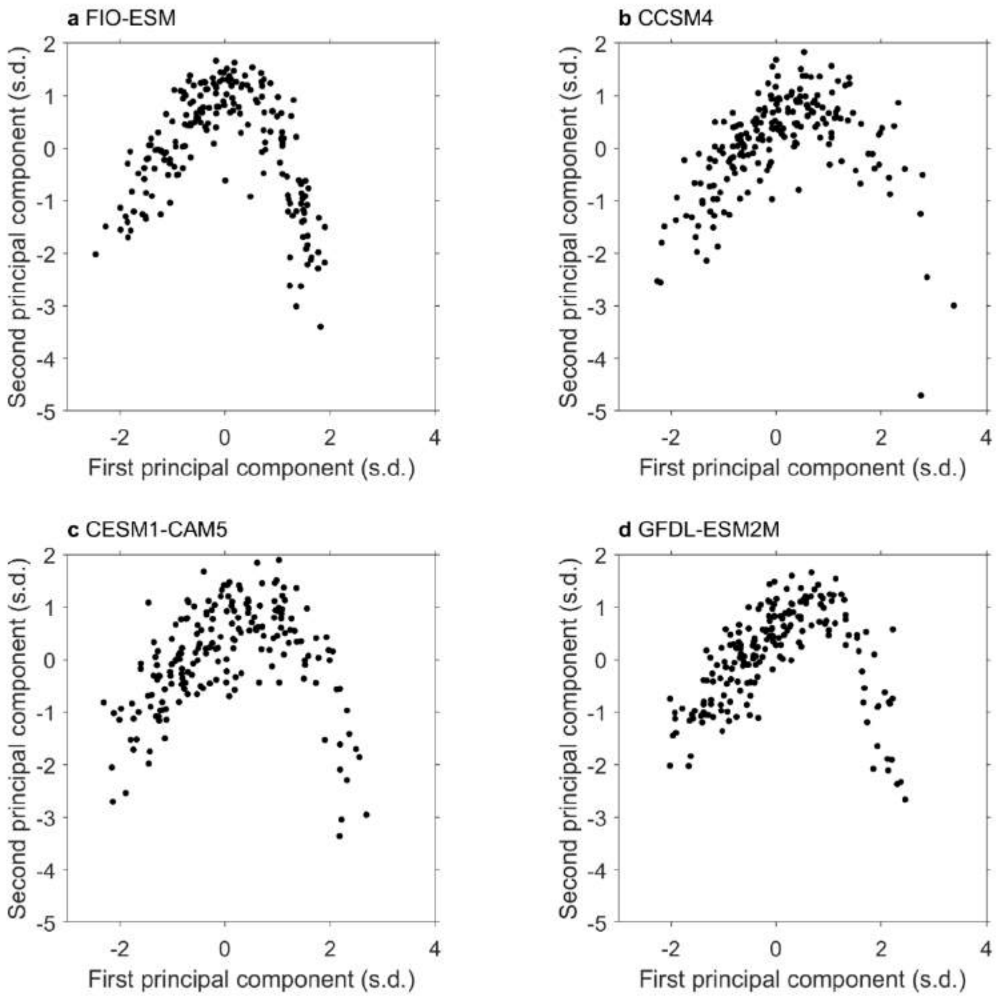
This can be measured by a model's ability to simulate the nonlinearity

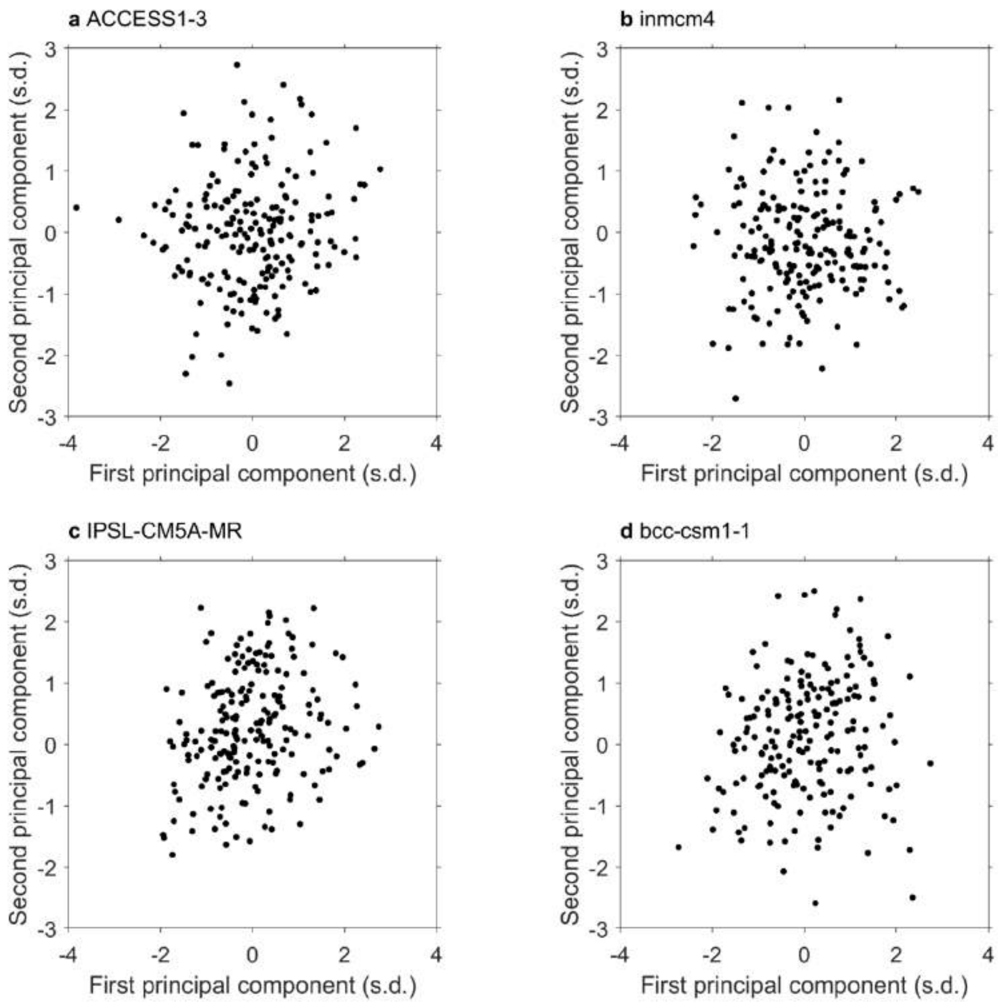
For obs the link between … is not clear, but…

- α = -0.31
- E-index skewness +1.4
- C-index skewness -0.41

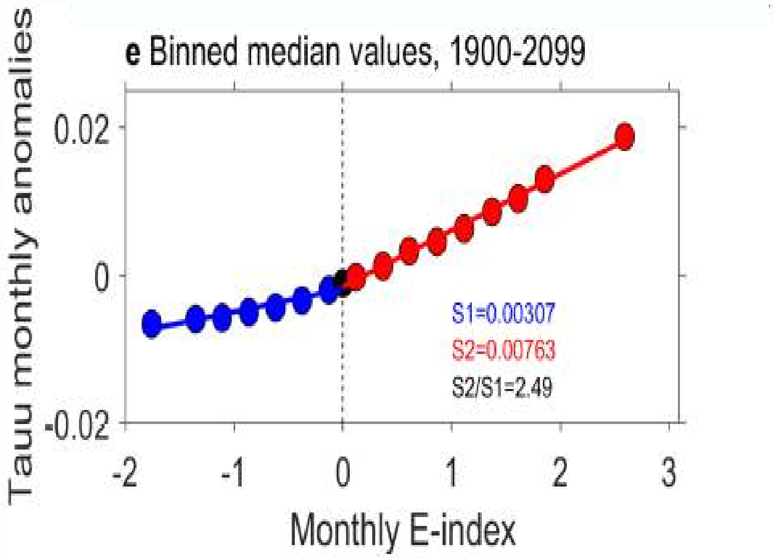


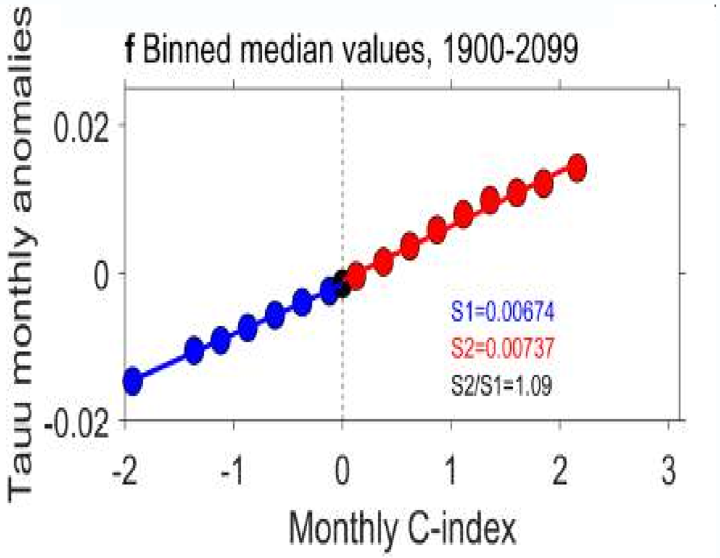
α links the two skewness


a FIO-ESM
b CCSM4
c CESM1-CAM5
d GFDL-ESM2M
Second principal component (s.d.)
First principal component (s.d.)


a ACCESS1-3
b inmcm4
c IPSL-CM5A-MR
d bcc-csm1-1
Second principal component (s.d.)
First principal component (s.d.)
3
2
1
0
-1
-2
-3
-4
-2
0
2
4

Selected models

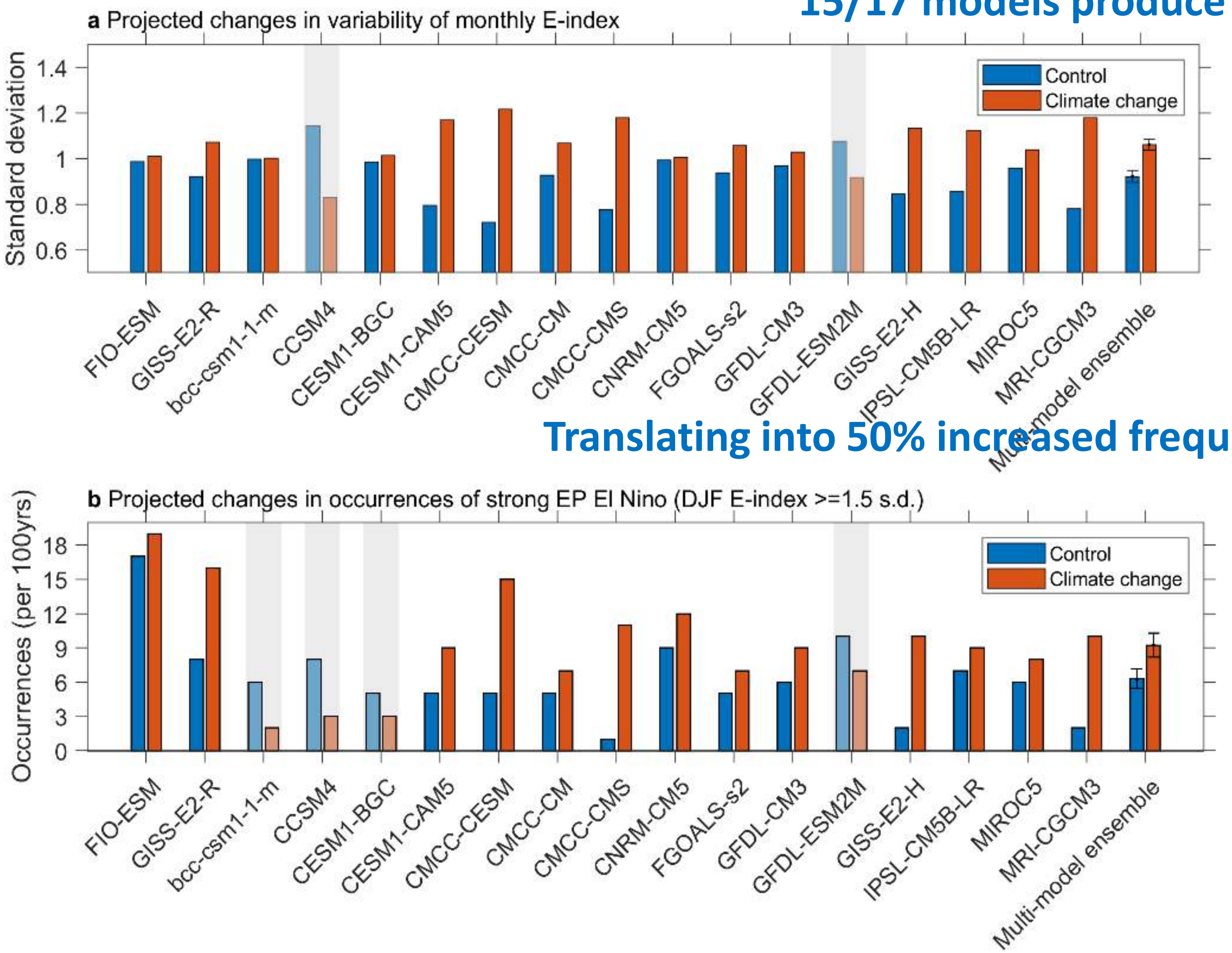




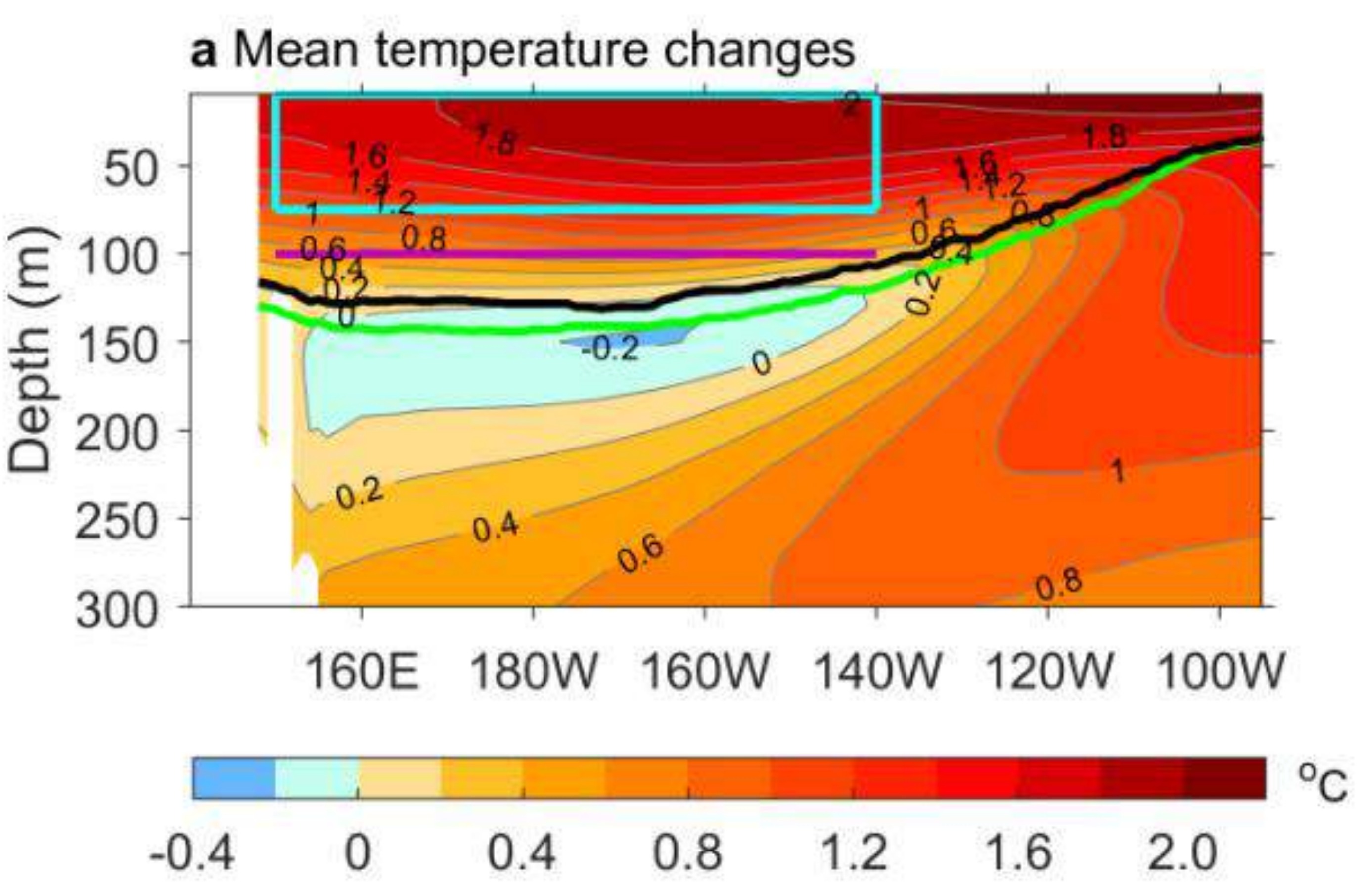
Enhanced consensus in selected models

15/17 models produce an increased variability

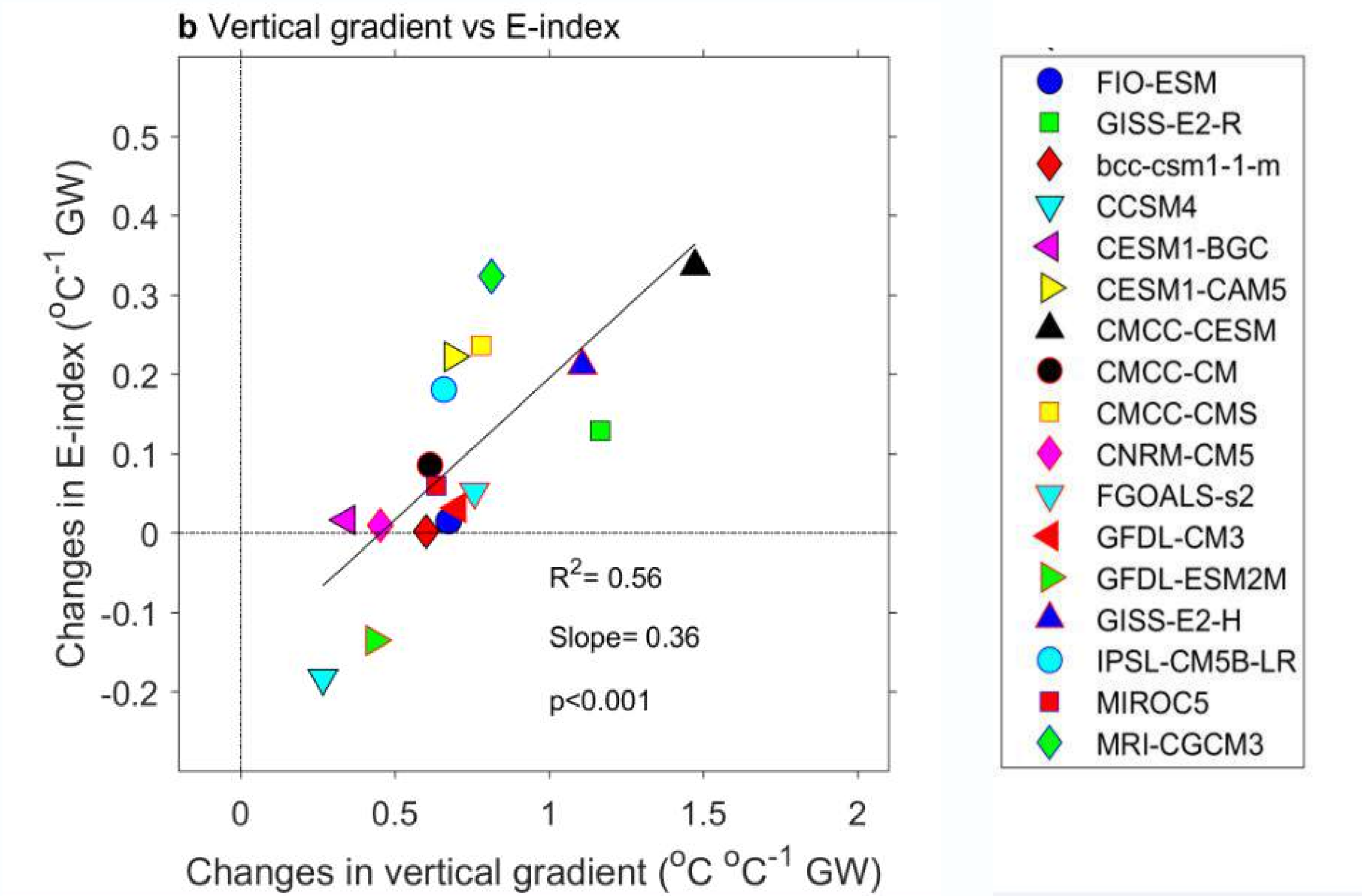
Translating into 50% increased frequency of extreme El Niño



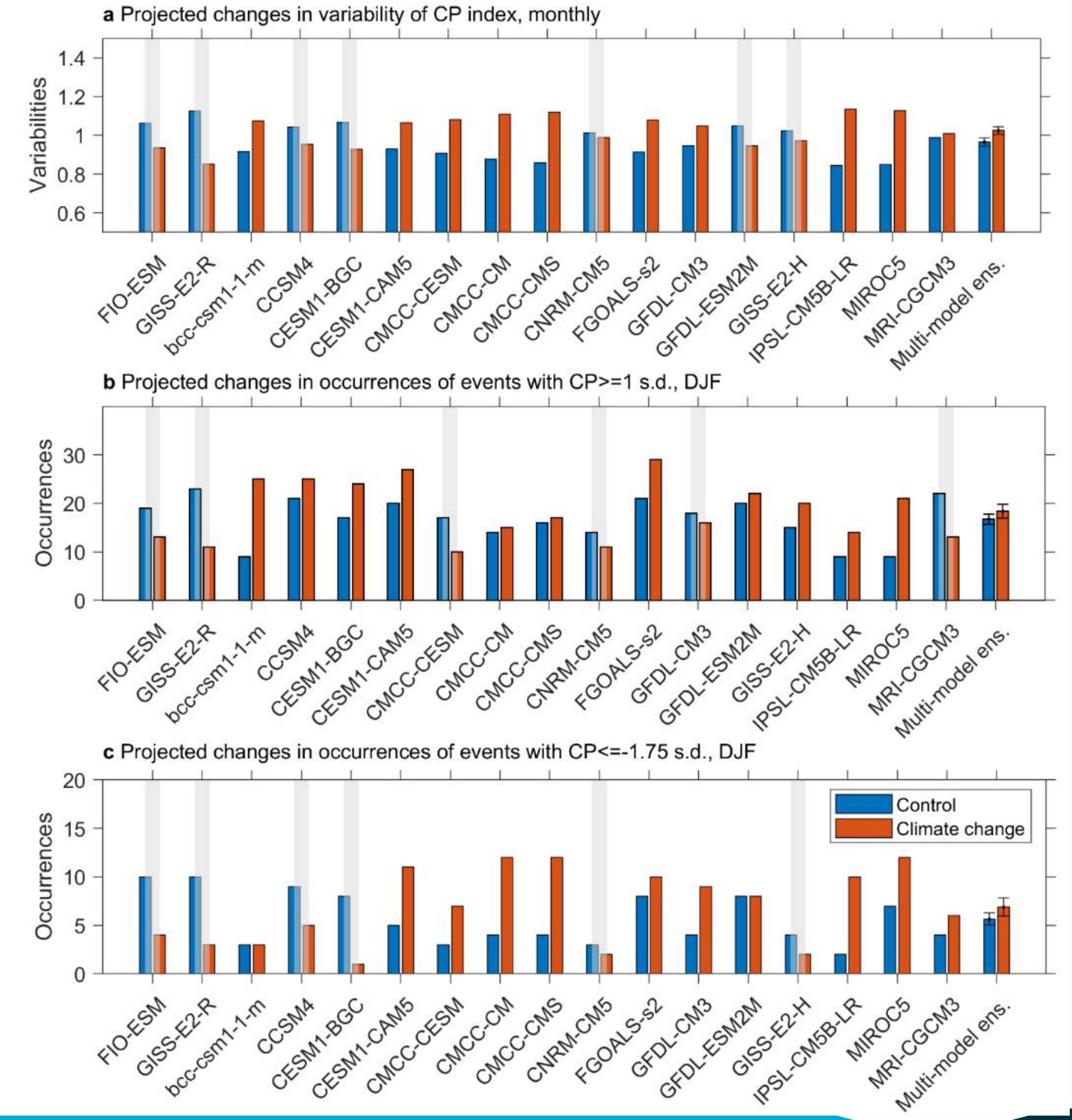
Mechanism



This increases the ocean and atmosphere coupling coefficient


b Vertical gradient vs E-index
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
Changes in E-index (°C°C⁻¹ GW)
0
0.5
1
1.5
2
Changes in vertical gradient (°C °C⁻¹ GW)
R²= 0.56
Slope= 0.36
p<0.001
FIO-ESM
GISS-E2-R
bcc-csm1-1-m
CCSM4
CESM1-BGC
CESM1-CAM5
CMCC-CESM
CMCC-CM
CMCC-CMS
CNRM-CM5
FGOALS-s2
GFDL-CM3
GFDL-ESM2M
GISS-E2-H
IPSL-CM5B-LR
MIROC5
MRI-CGCM3

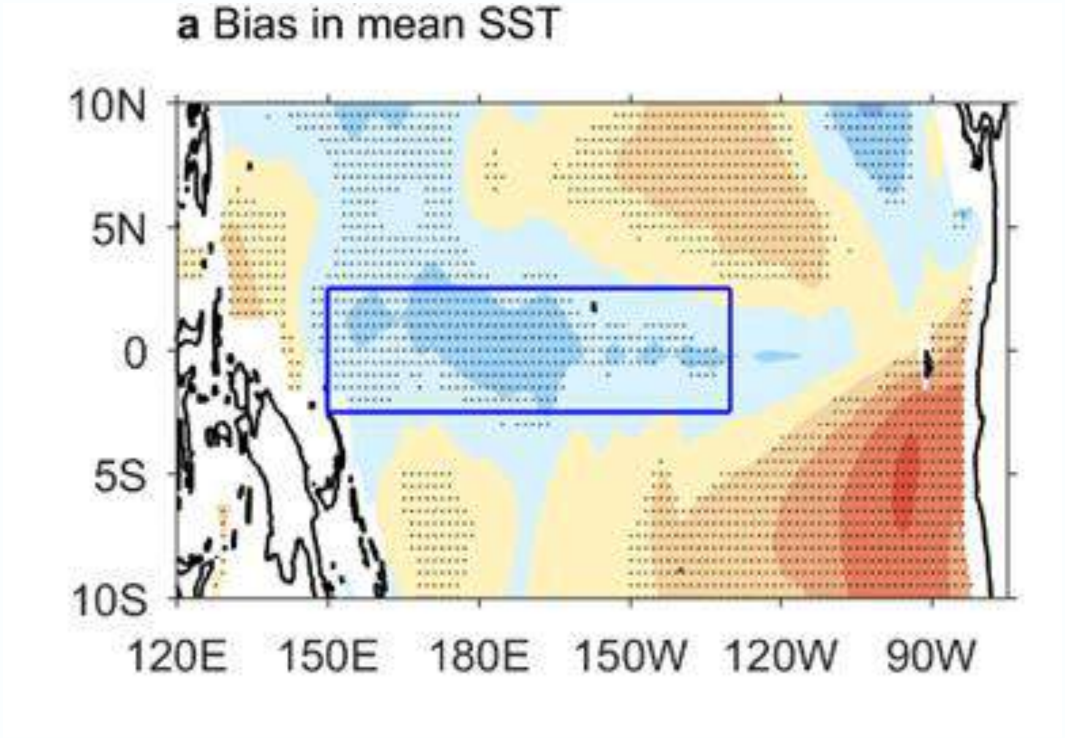
CP-index



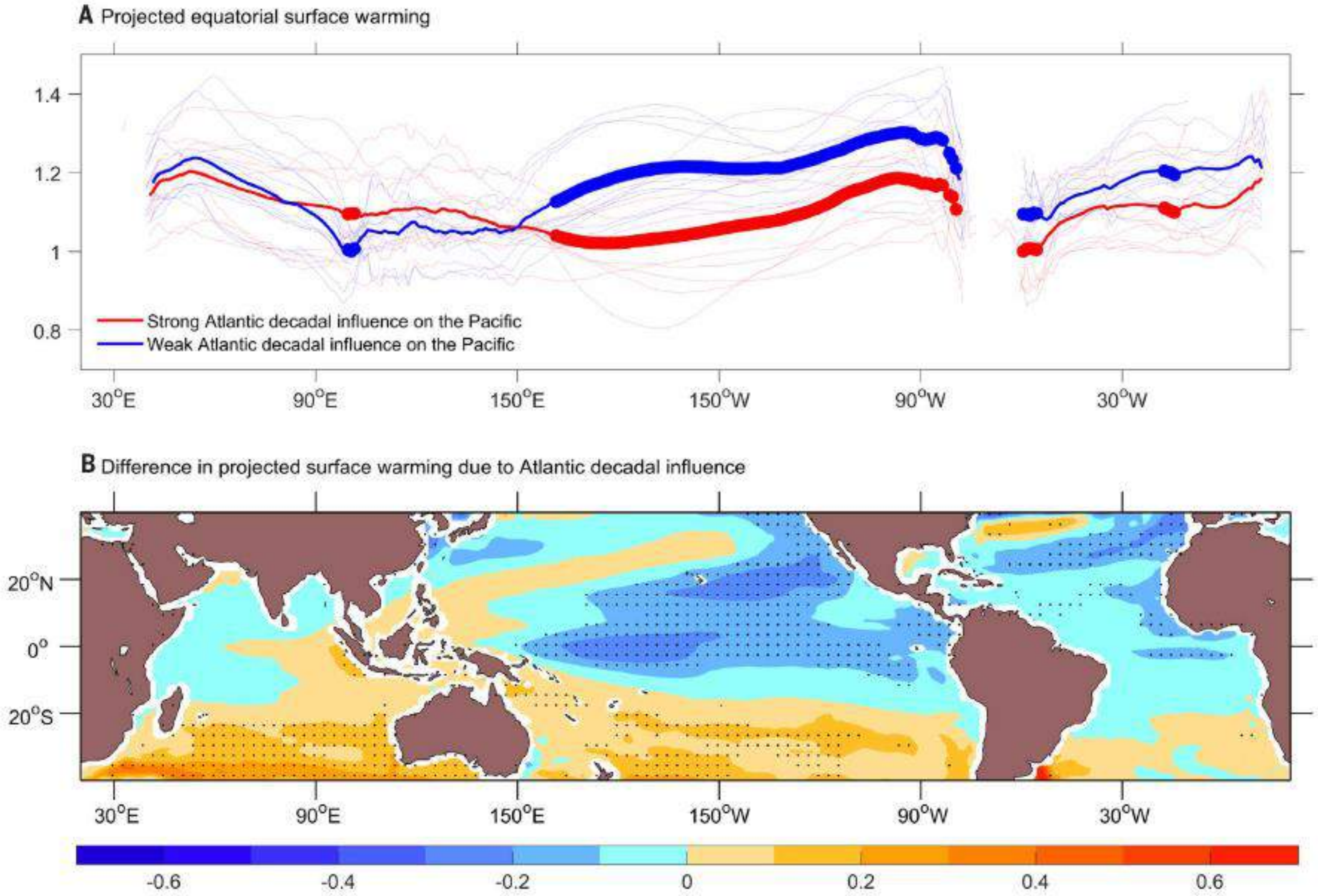
a Projected changes in variability of CP index, monthly
Variabilities
b Projected changes in occurrences of events with CP>=1 s.d., DJF
Occurrences
c Projected changes in occurrences of events with CP<=-1.75 s.d., DJF
Occurrences
Control
Climate change
FIO-ESM
GISS-E2-R
bcc-csm1-1-m
CCSM4
CESM1-BGC
CESM1-CAM5
CMCC-CESM
CMCC-CM
CMCC-CMS
CNRM-CM5
FGOALS-s2
GFDL-CM3
GFDL-ESM2M
GISS-E2-H
IPSL-CM5B-LR
MIROC5
MRI-CGCM3
Multi-model ens.

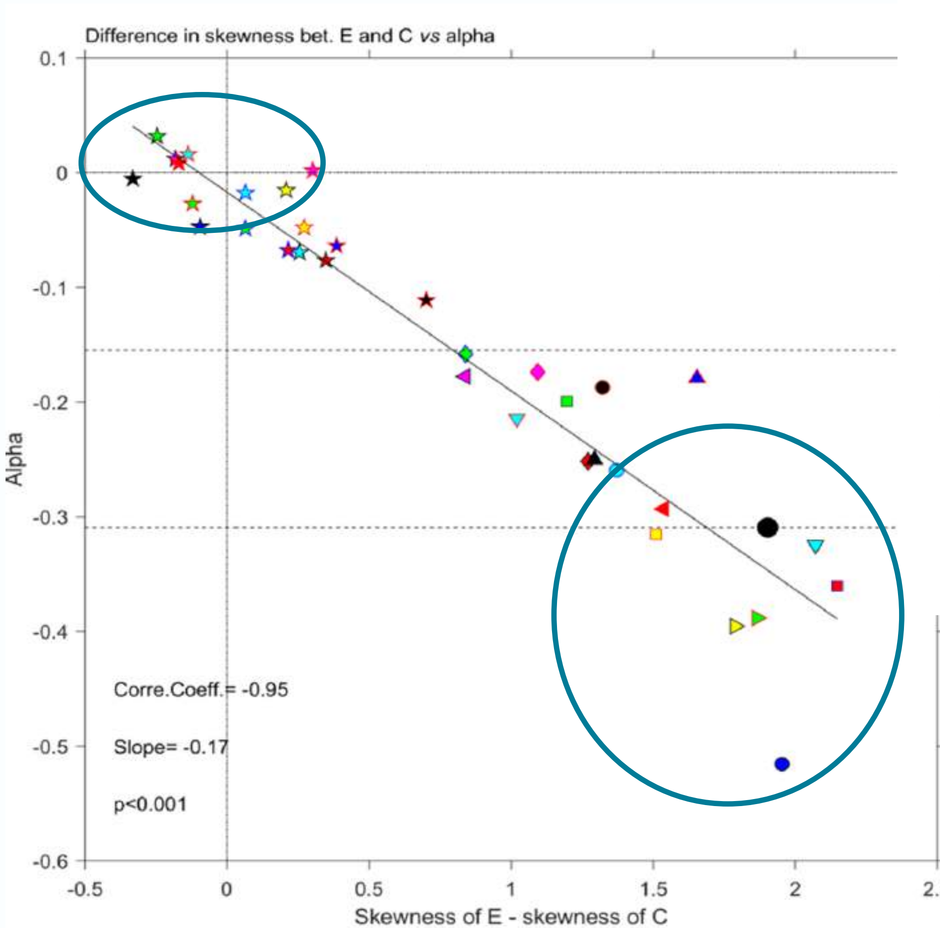
Uncertainties

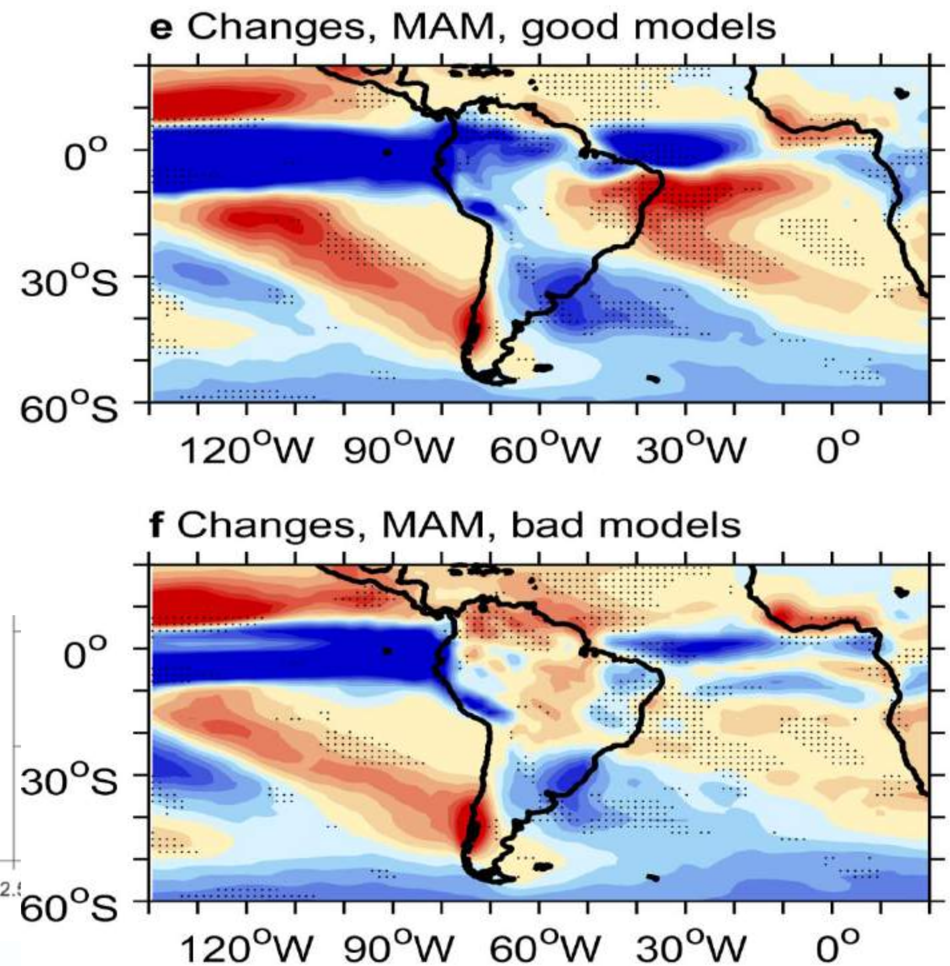
1. Cold tongue bias leads to higher

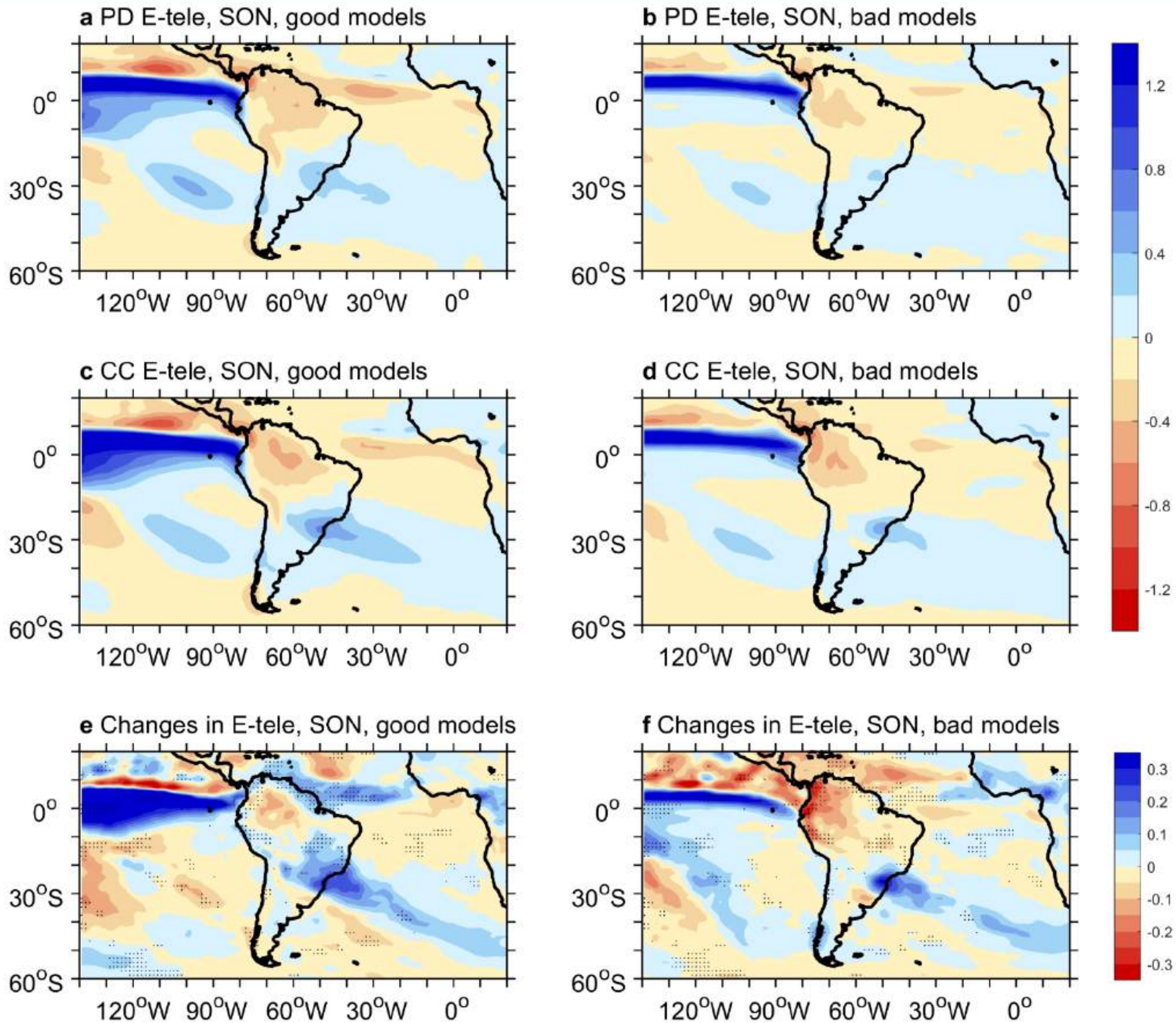


2. **Underestimate in Atlantic –Pacific interaction**




Difference in skewness bet. E and C vs alpha
Alpha
Skewness of E - skewness of C
Corre.Coeff.= -0.95
Slope= -0.17
p<0.001
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.5
0
0.5
1
1.5
2


e Changes, MAM, good models
f Changes, MAM, bad models
0°
30°S
60°S
120°W
90°W
60°W
30°W
0°


a PD E-tele, SON, good models
b PD E-tele, SON, bad models
c CC E-tele, SON, good models
d CC E-tele, SON, bad models
e Changes in E-tele, SON, good models
f Changes in E-tele, SON, bad models
0°
30°S
60°S
120°W 90°W 60°W 30°W 0°
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
0.3
0.2
0.1
0
-0.1
-0.2
-0.3

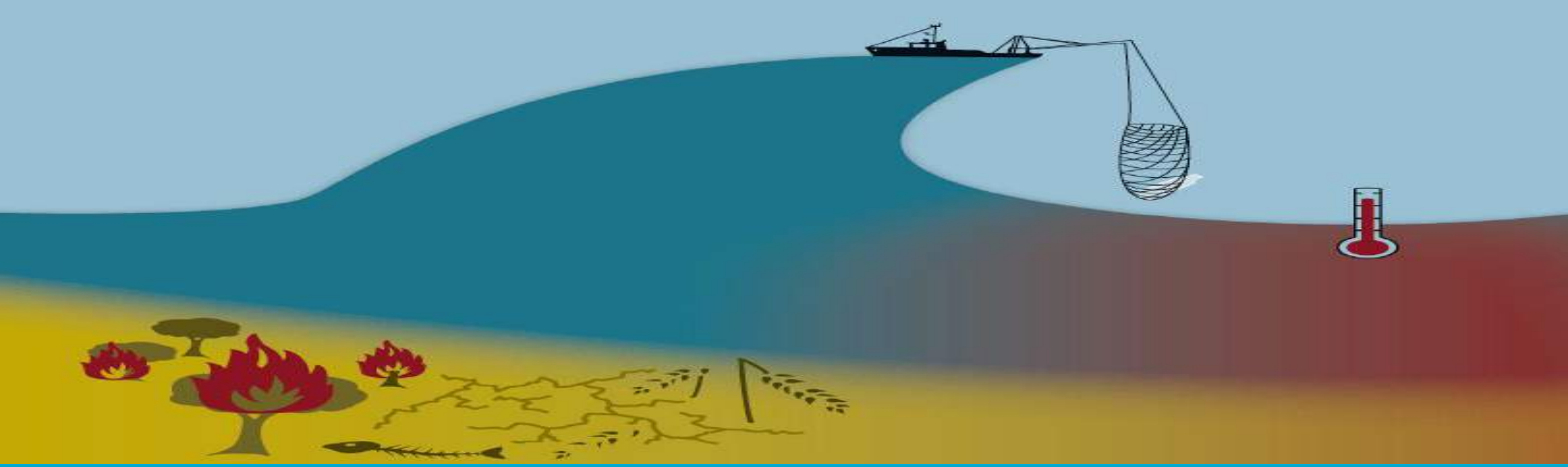
Summary

- Despite inter-model differences in details of El Niño/La Niña, a robust increase in its SST variability under greenhouse warming is projected across models.

- This increase in variability is largely due to greenhouse warming-induced intensification of upper-ocean stratification in the equatorial Pacific, which enhances ocean–atmosphere coupling.

- An increase in SST variance implies an increase in the number of extreme El Niño/La Niña events and associated extreme weather events

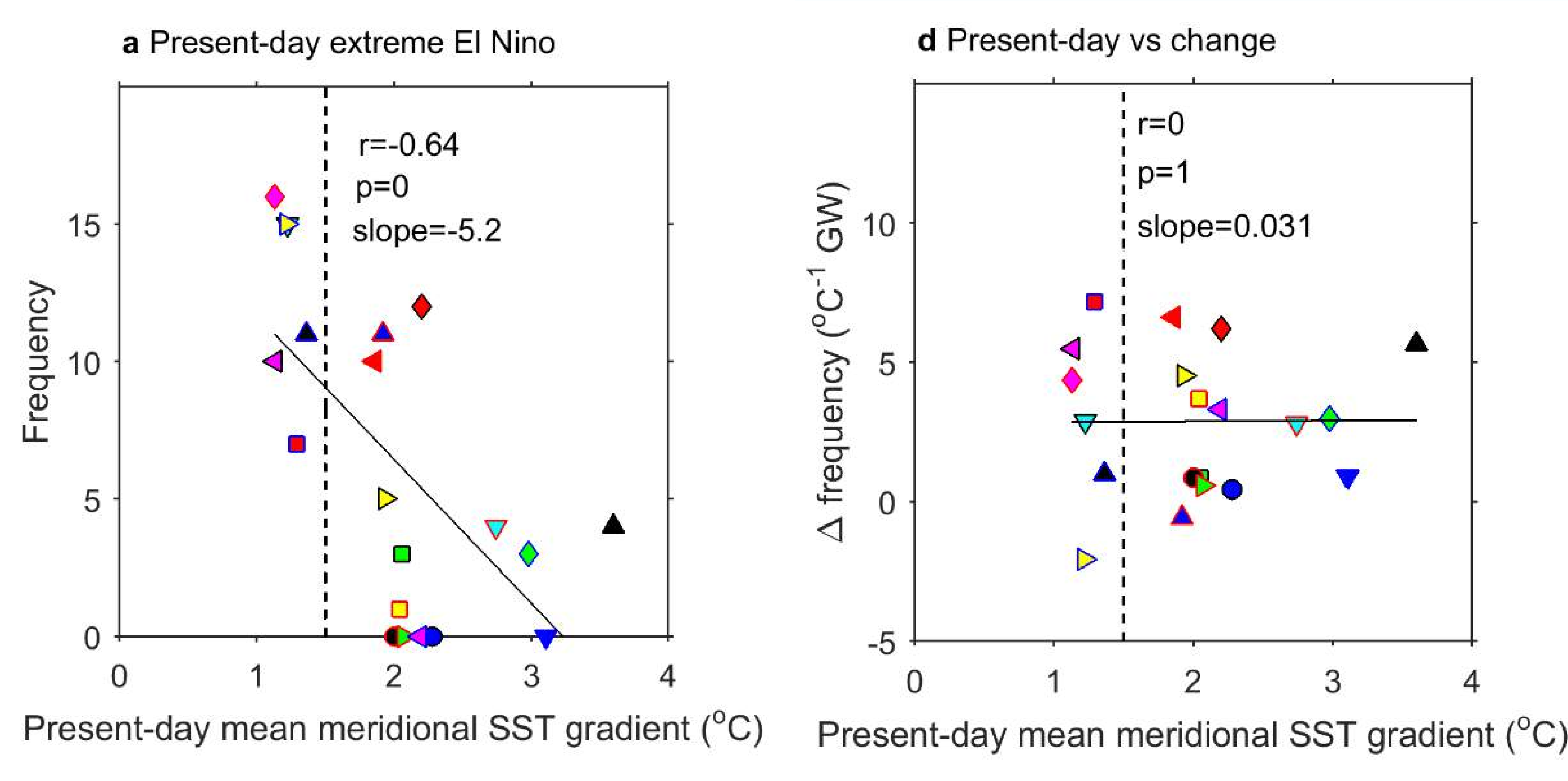
“To raise new questions, new possibilities, to regard old problems from a new angle”

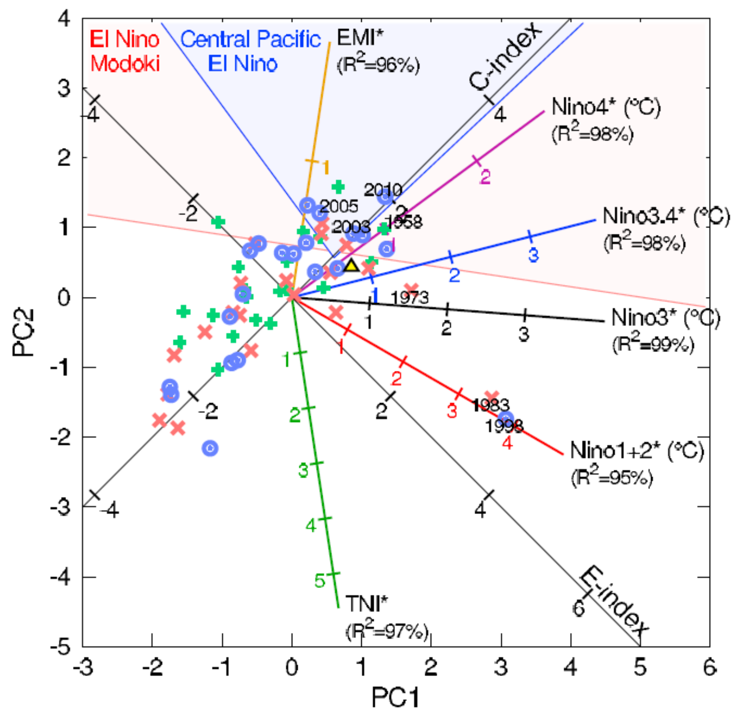


Thank you!

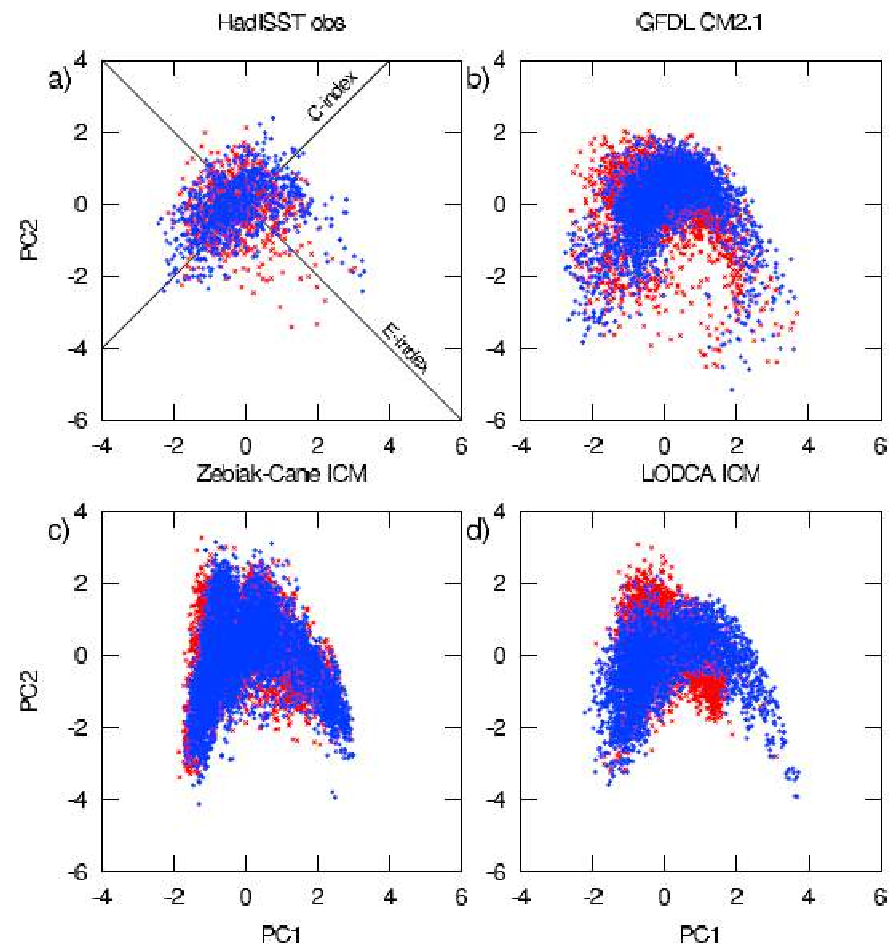
Uncertainties

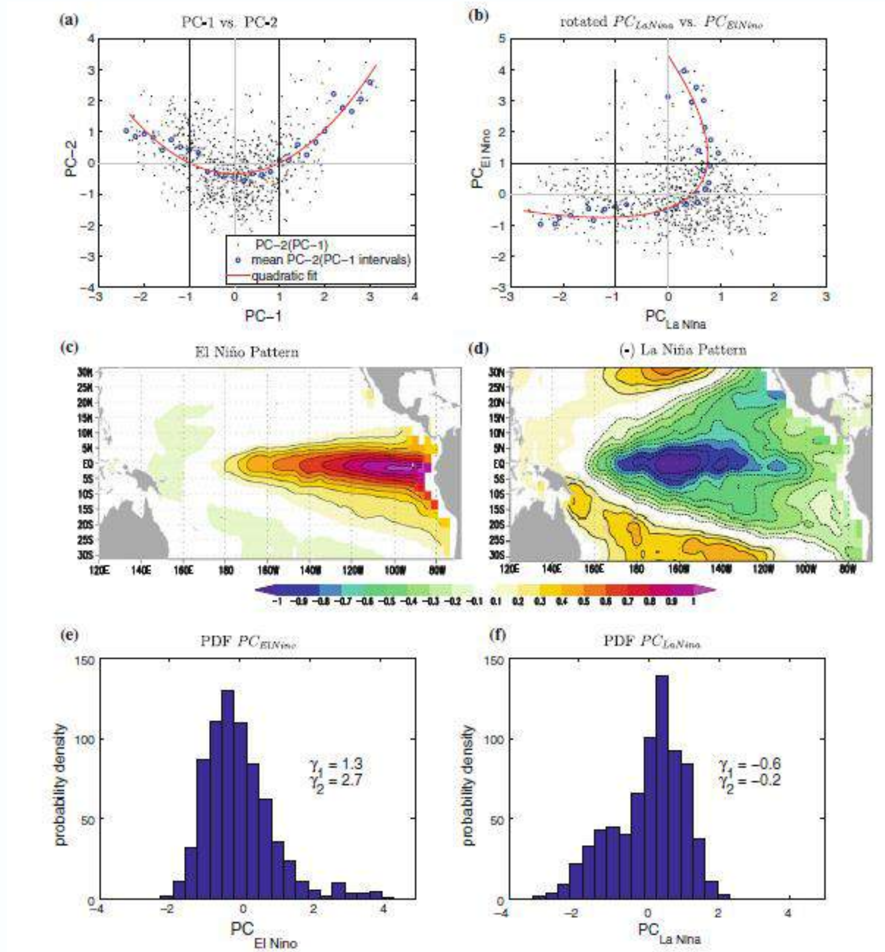
- **Model biases**



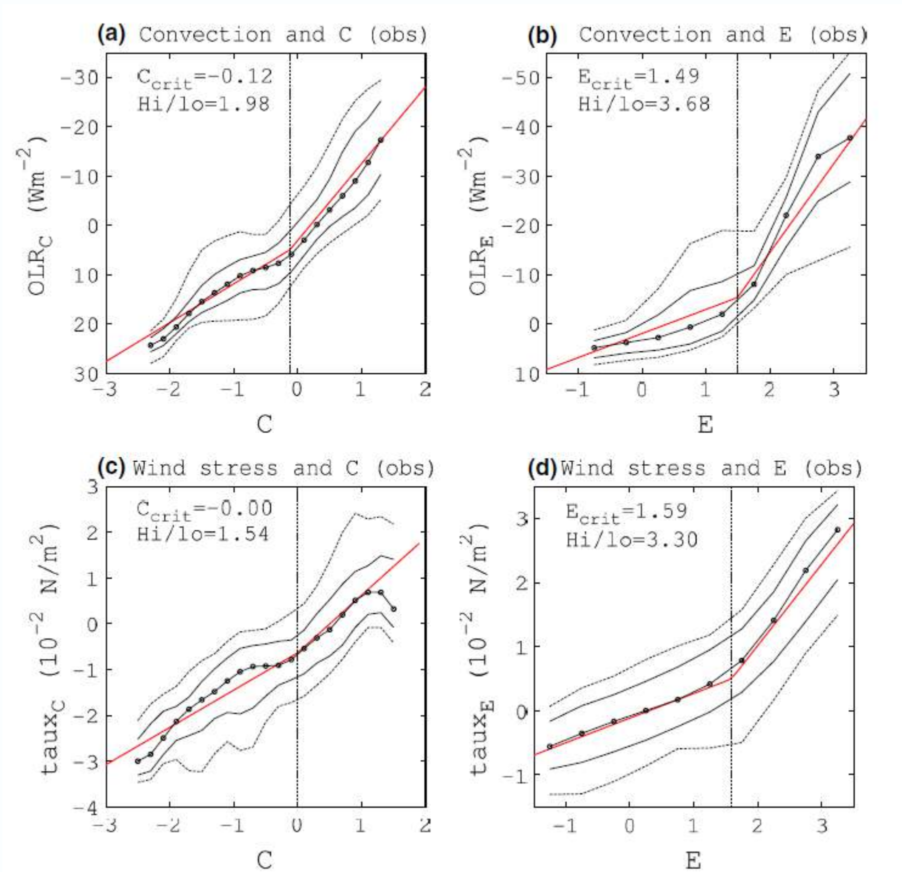


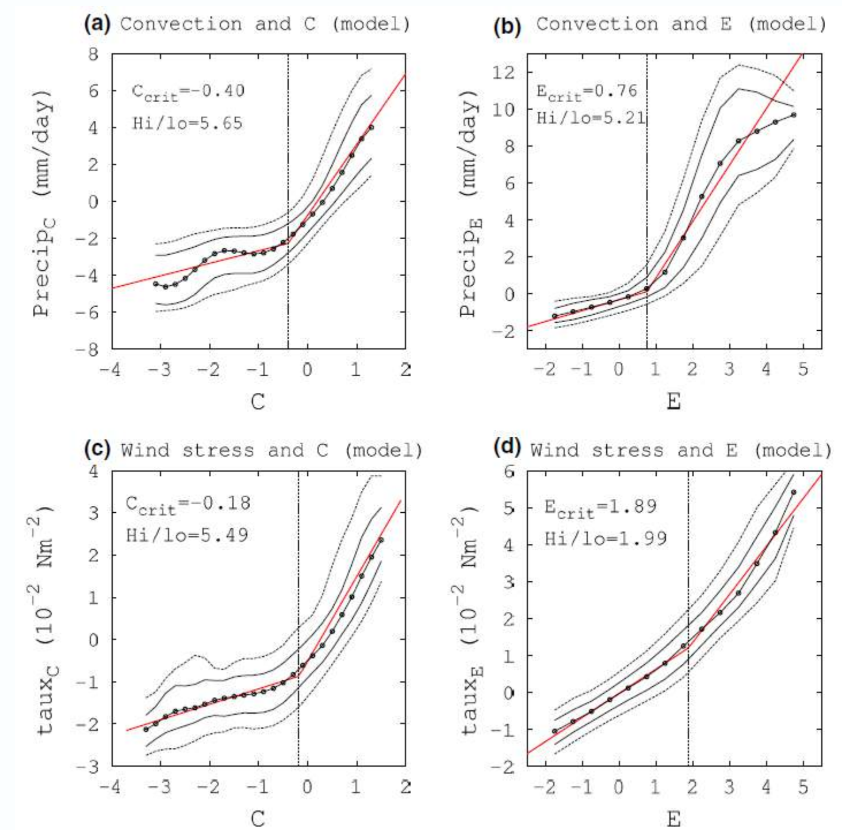
Takahashi et al. GRL 2011





Dpmmenget et al. Clim Dynamics 2013





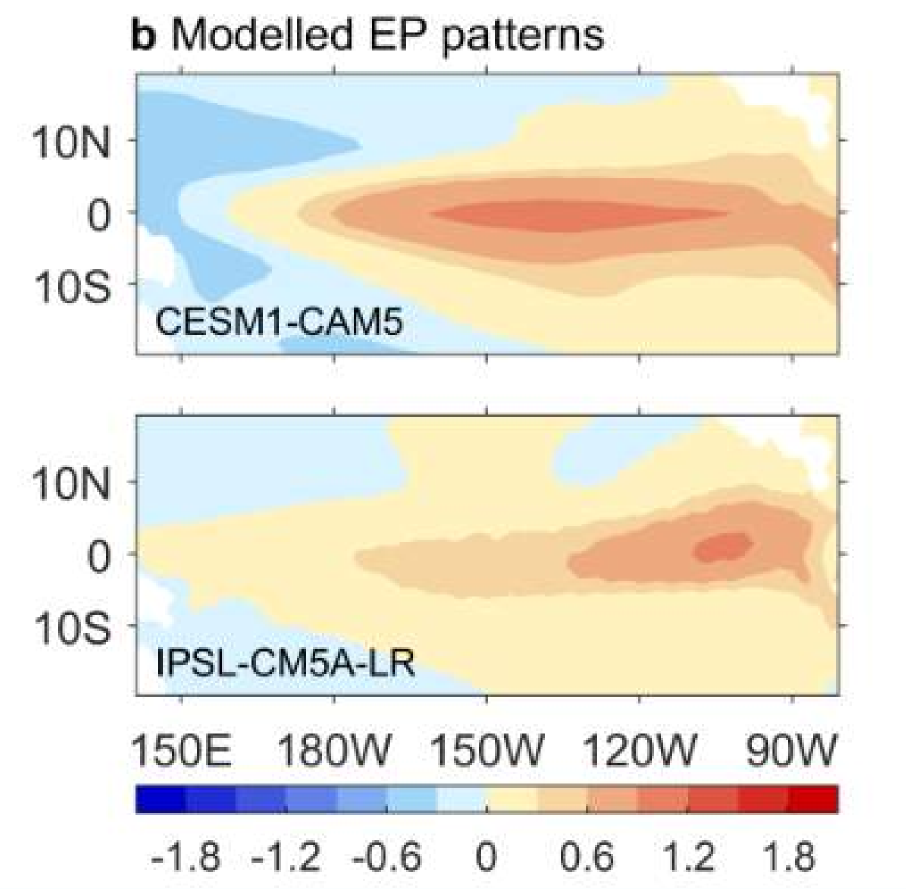
Models GFDL CM2.1

"To raise new questions, new possibilities, to regard old problems from a new angle"

Let's re-look at EP and CP patterns in observations.

Applying EOF onto monthly SST using 34 CMIP5 models

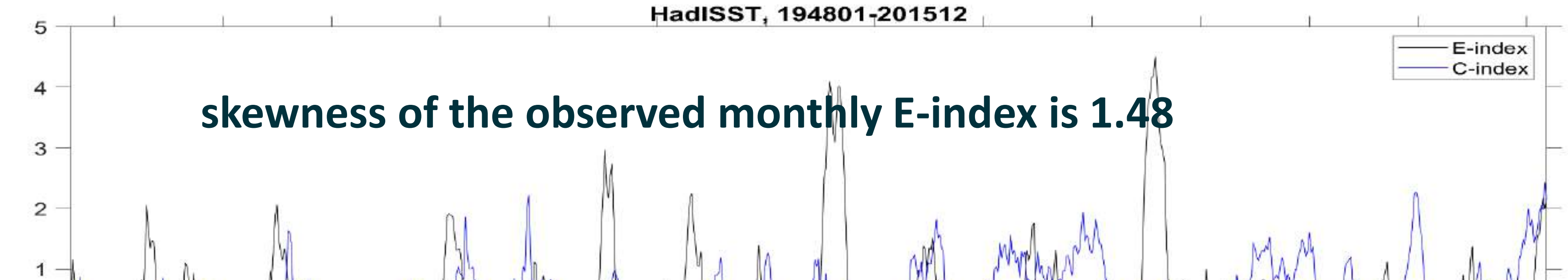
Historical+RCP8.5 (190001-209912)



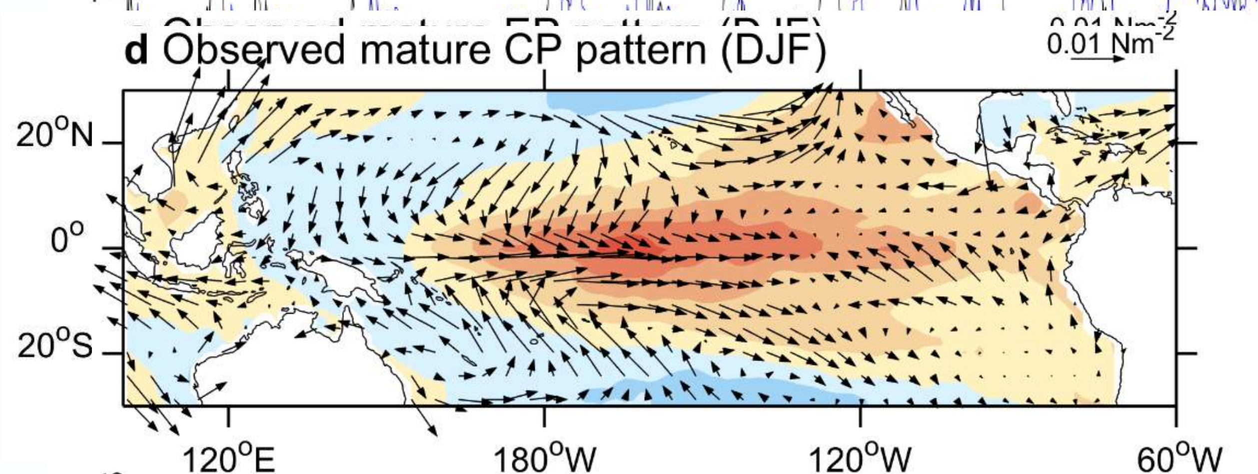
	Models	EP (SST)
1	FIO-ESM	250.75
2	GISS-E2-R	247.75
3	bcc-csm1-1-m	243.25
4	CCSM4	244.75
5	CESM1-BGC	241.75
6	CESM1-CAM5	223.75
7	CMCC-CESM	234.25
8	CMCC-CM	235.75
9	CMCC-CMS	241.75
10	CNRM-CM5	247.75
11	FGOALS-s2	231.25
12	GFDL-CM3	244.75
13	GFDL-ESM2M	246.25
14	GISS-E2-H	247.75
15	IPSL-CM5B-LR	252.25
16	MIROC5	237.25
17	MRI-CGCM3	240.25
18	MPI-ESM-LR	243.25
19	GFDL-ESM2G	252.25
20	NorESM1-M	252.25
21	ACCESS1-0	246.25
22	ACCESS1-3	253.75
23	CSIRO-Mk3-6-0	196.75
24	EC-EARTH	252.25
25	HadGEM2-AO	241.75
26	HadGEM2-CC	246.25
27	HadGEM2-ES	244.75
28	inmcm4	240.25
29	IPSL-CM5A-LR	258.25
30	IPSL-CM5A-MR	258.25
31	bcc-csm1-1	240.25
32	CanESM2	238.75
33	MPI-ESM-MR	238.75
34	NorESM1-ME	249.25

We can't use Nino3 region to represent EP-ENSO centre across models.

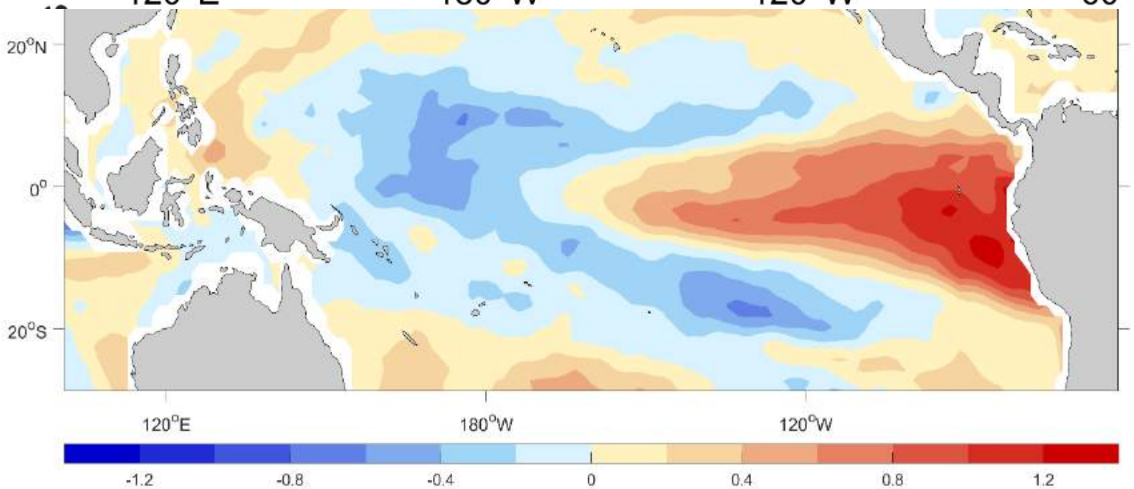
Can every model simulate well of EP-ENSO?



skewness of the observed monthly E-index is 1.48



.43



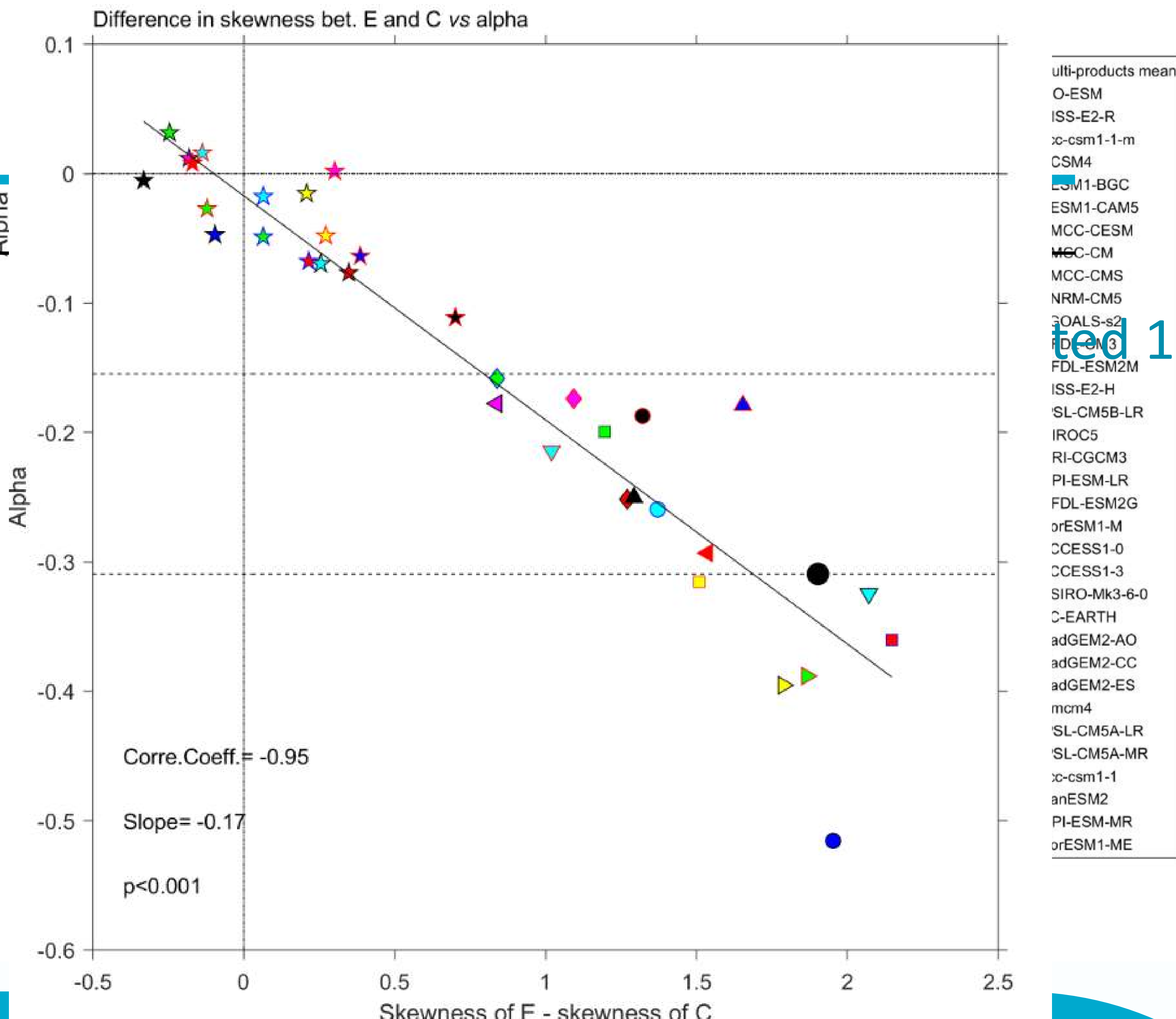
Centre of positive skewness is the centre for EP-ENSO; Centre of negative skewness is the centre for CP-ENSO

Model selection

Can models simulate a similar α and skewness of E- and C-index?

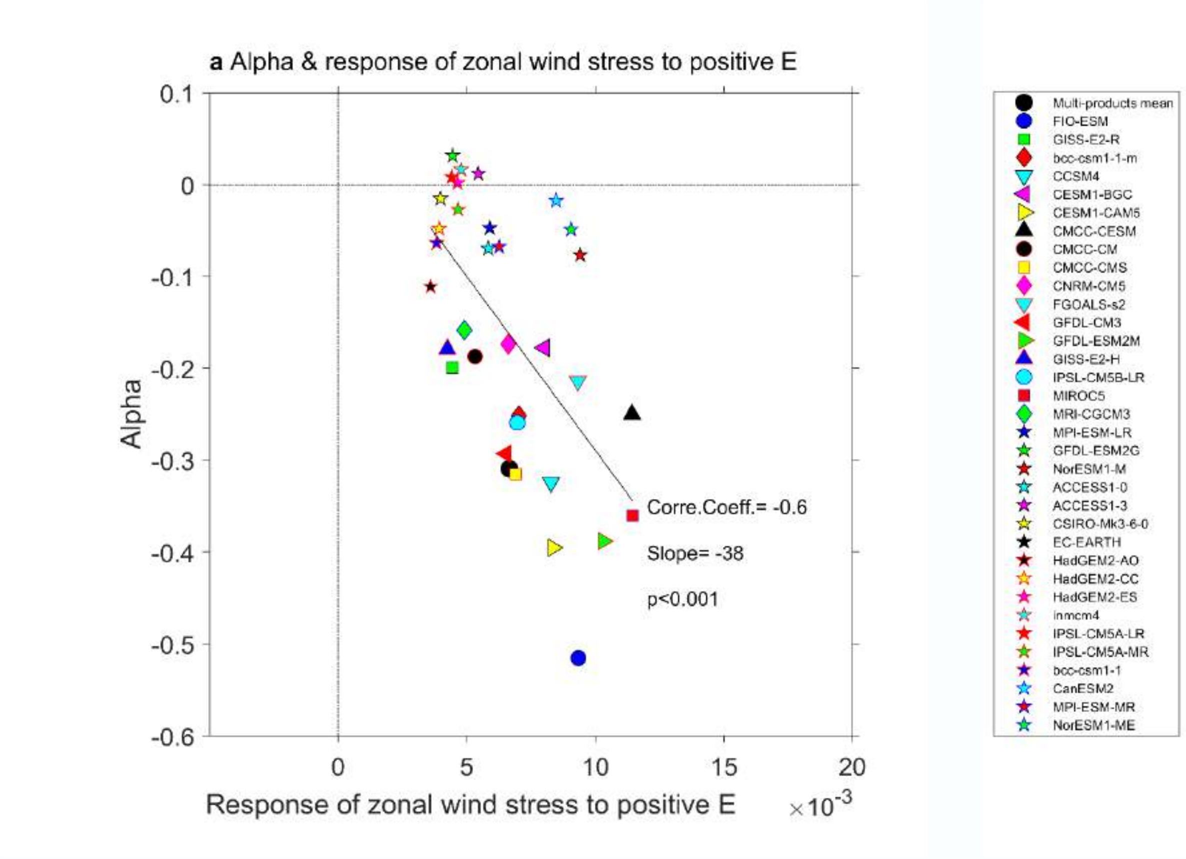
$\alpha_{obs}/2$

α_{obs}

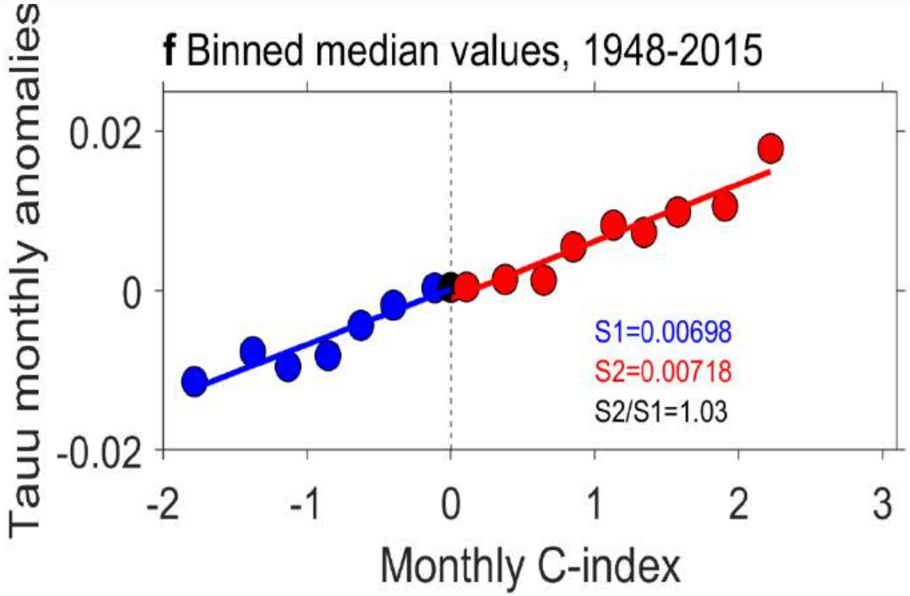


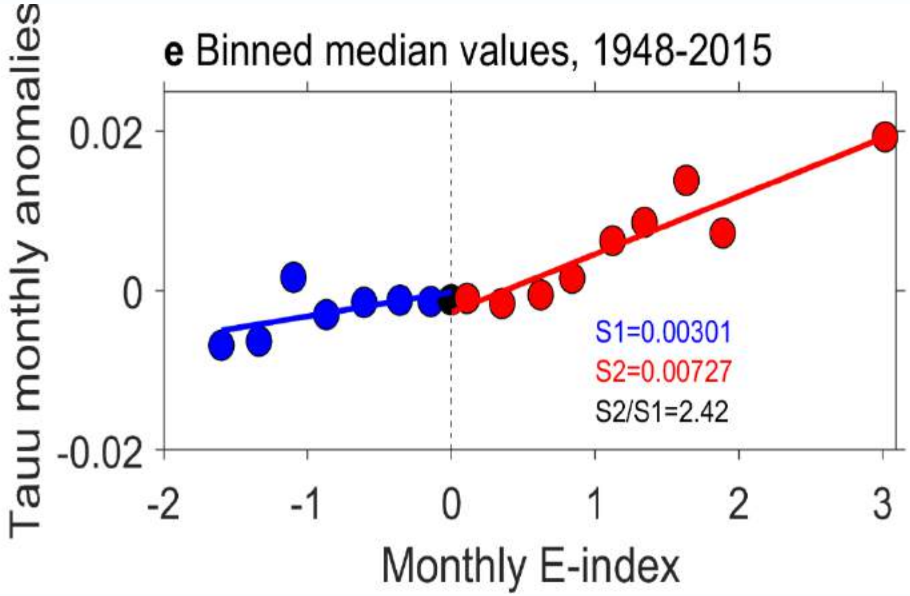
ted 17 models

Why models with a strong can simulate a better V-shape and strong skewness in E-index??



Nonlinear dynamics generate skewness

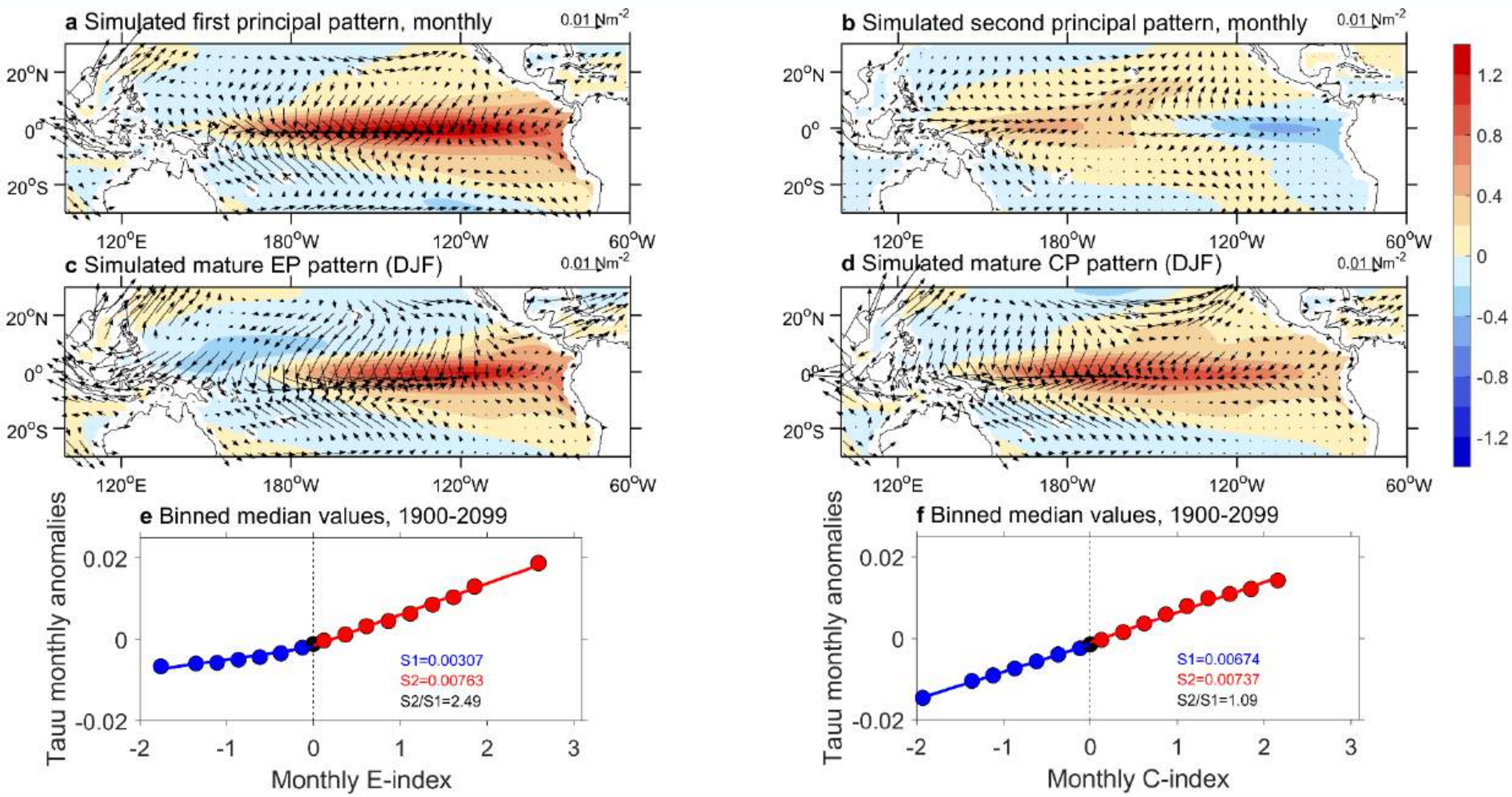




Wind stress anomalies respond linearly to concurrent monthly SST anomalies in the CP ENSO centre

However, the response is nonlinear for EP anomalies, stronger for warm anomalies than cold anomalies

For selected 17 models:



Wind projection coefficient

From linear theory, the total amount of momentum flux associated to equatorial wave dynamics can be estimated by the zonal wind stress along the equator multiplied by a coefficient, referred to as the ***wind projection coefficient***, , P_n, that depends on the ***vertical stratification*** of the ocean.

$$P = \sum_{n=1}^{n=3} P_n = \sum_{n=1}^{n=3} \left[\frac{150}{\int_{Z=5000m}^{Z=0} F_n 2\,(x_E, z)\,dz} \right]$$ Thual, et al. (2011; 2013)

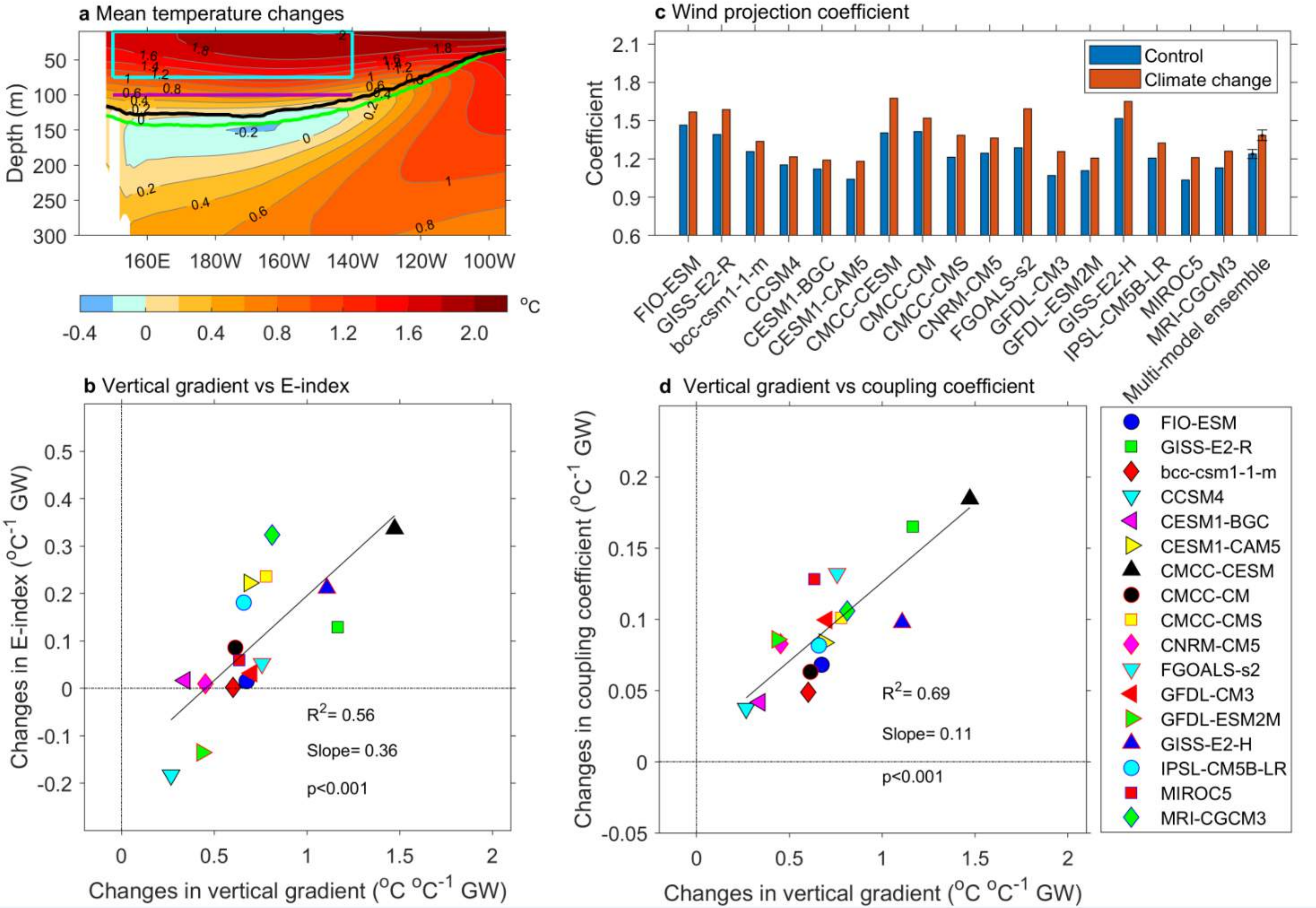
F_n corresponds to the vertical mode structure

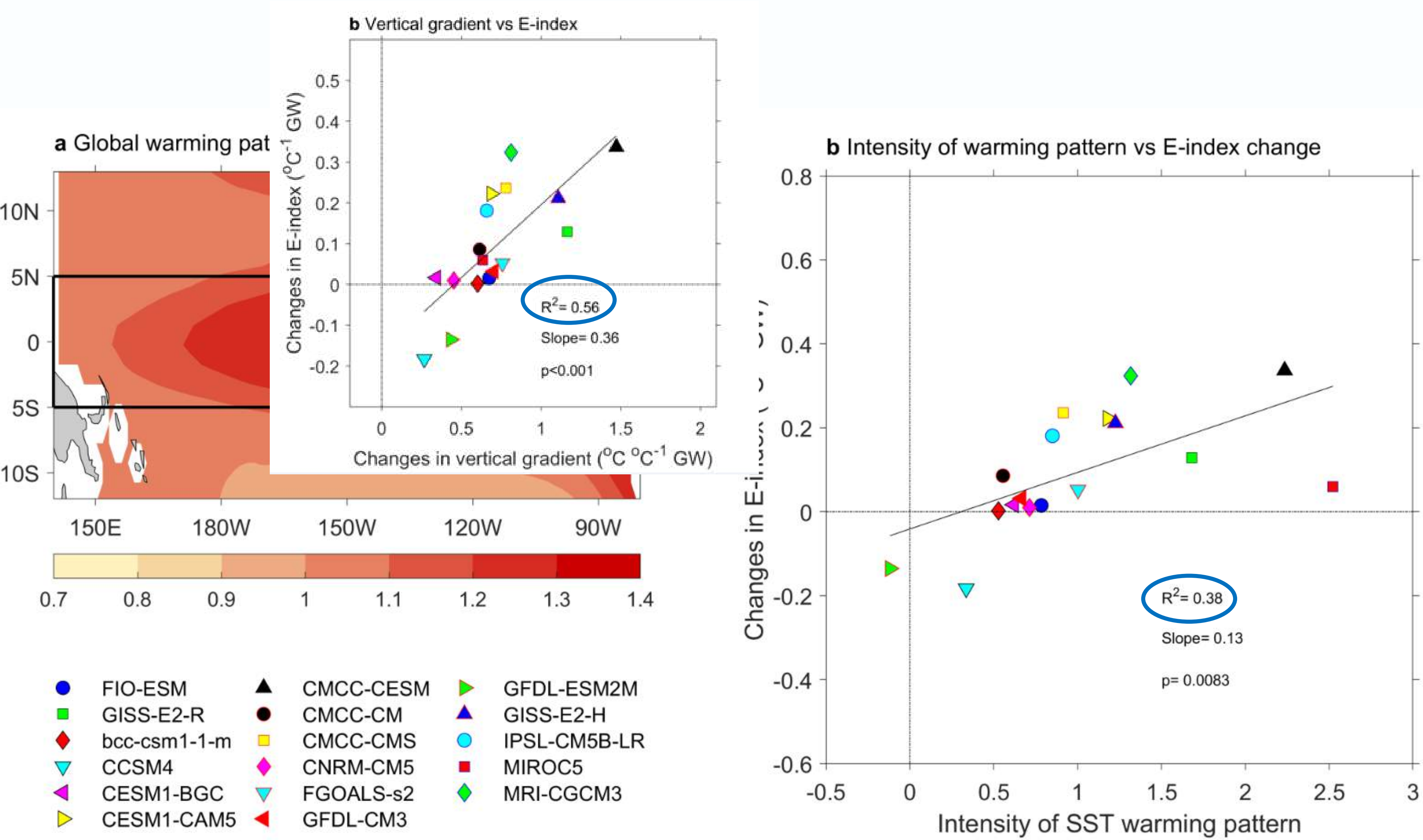
x_E the location along the equator, where the salinity and temperature profile are considered.

This location is taken as the centre of action of the zonal winds stress for the EP regime and corresponds to the maximum amplitude of the regressed patterns of the zonal wind stress associated with the EP regime.

The 150 constant is a normalizing coefficient (in metres) corresponding to the average thermocline depth in the central equatorial Pacific.

The larger the P coefficient, the sharper the mean thermocline and the larger the input of momentum flux into the baroclinic ocean response.


a Mean temperature changes
Depth (m)
50
100
150
200
250
300
160E
180W
160W
140W
120W
100W
°C
-0.4
0
0.4
0.8
1.2
1.6
2.0
c Wind projection coefficient
Coefficient
Control
Climate change
FIO-ESM
GISS-E2-R
bcc-csm1-1-m
CCSM4
CESM1-BGC
CESM1-CAM5
CMCC-CESM
CMCC-CM
CMCC-CMS
CNRM-CM5
FGOALS-s2
GFDL-CM3
GFDL-ESM2M
GISS-E2-H
IPSL-CM5B-LR
MIROC5
MRI-CGCM3
Multi-model ensemble
b Vertical gradient vs E-index
Changes in E-index (°C°C^-1 GW)
R^2= 0.56
Slope= 0.36
p<0.001
Changes in vertical gradient (°C °C^-1 GW)
d Vertical gradient vs coupling coefficient
Changes in coupling coefficient (°C°C^-1 GW)
R^2= 0.69
Slope= 0.11
p<0.001
Changes in vertical gradient (°C °C^-1 GW)



a Global warming pat
10N
5N
0
5S
10S
150E
180W
150W
120W
90W
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
b Vertical gradient vs E-index
Changes in E-index (°C⁻¹ GW)
Changes in vertical gradient (°C °C⁻¹ GW)
R²= 0.56
Slope= 0.36
p<0.001
b Intensity of warming pattern vs E-index change
Changes in E-index
Intensity of SST warming pattern
R²= 0.38
Slope= 0.13
p= 0.0083
FIO-ESM
GISS-E2-R
bcc-csm1-1-m
CCSM4
CESM1-BGC
CESM1-CAM5
CMCC-CESM
CMCC-CM
CMCC-CMS
CNRM-CM5
FGOALS-s2
GFDL-CM3
GFDL-ESM2M
GISS-E2-H
IPSL-CM5B-LR
MIROC5
MRI-CGCM3

Variability in E-index to RCP4.5