Response of El Niño/La Niña to greenhouse warming

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

Ash Wednesday 1983
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

Monsoons

Indian Ocean Dipole

Typhoons, Cyclones & Hurricanes

El Niño Conditions

Mechanisms of Tropical Atlantic Variability

 Courtesy of Mike McPhaden
How ENSO will respond to greenhouse warming has challenged scientists for many years.
The impact of global warming on the tropical Pacific Ocean and El Niño

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The El Niño–Southern Oscillation (ENSO) is a climatic phenomenon that involves the decadal-to-centennial variability in the tropical Pacific region and affects ecosystems around the world. The impact of global warming on ENSO is expected to change, with a potential for a more slowly farther away from the observed climate. Therefore, the question arises: how will ENSO variability change in the future? The research suggests that processes that are related to ENSO will change, despite consideration of the role of events in the future.

Anthropogenic global warming has increased the average temperature of the Earth's surface and oceans. This has resulted in a more rapid rate of climate change and pronounced seasonal variability. The average distribution of precipitation shifts to higher latitudes, with an increase in rainfall and an increase in the number of droughts. 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 temperature and precipitation affect global weather patterns and have economic impacts on agriculture, fisheries, and tourism. More recently, researchers have developed and used mathematical models to simulate the dynamics, energetics, linear stability and nonlinearity of ENSO. Complex coupled global circulation models (CGCMs) have become powerful tools for examining ENSO dynamics and the interactions between global warming and ENSO. ENSO is now an emergent property of many CGCMs, that is, it is generated spontaneously as a result of the complex interplay of processes within the atmosphere and ocean.
ENS0 and greenhouse warming

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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 planet1, 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 in the eastern Pacific carries up off the eastern coast of South America.

During the 1982/1983 and 1997/1998 extreme El Niño events6,8, surface warming anomalies propagated eastward in an uncharacteristic fashion13,14, 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 Peru6,8. 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 SPCZ10), spurring floods and damage, owing to Pacific proteins and shifting rain.
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.

In terms of rainfall variability ......
Frequency of swings doubles

Characteristics of extreme El Niños: DJF rainfall and SST

Green 5 mm per day
Purple 28°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
Characteristics of extreme El Niños

Rainfall in the eastern Equatorial Pacific reaches > 5 mm per day, which we define as an extreme El Niño
There is a doubling of extreme El Niño events 17/20 showing an increase.
Increasing frequency of extreme El Niño events due to greenhouse warming

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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

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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 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—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.

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

Agus Santoso¹, Shayne McGregor², Fei-Fei Jin³, Wenju Cai³, Matthew H. England¹, Soon-II An¹, Michael J. McPhaden⁵ & Eric Gillyard⁶,⁷
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.

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

Yeh et al. Nature 2009
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.

Increased frequency of extreme La Niña events under greenhouse warming

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Observed relationship, 1979-2010

Niño4 < -1.75 std  Niño4 SST index

1982 1997
1988 1998
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?
Increased variability of eastern Pacific El Niño under greenhouse warming

Wenju Cai¹,²*, Guojian Wang¹,², Boris Dewitte³,⁴,⁵,⁶, Lixin Wu¹*, Agus Santoso²,⁷, Ken Takahashi⁸, Yun Yang⁹, Aude Carreric⁶ & Michael J. McPhaden¹⁰

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
\[ E = \frac{PC_1 - PC_2}{\sqrt{2}} \]

\[ C = \frac{PC_1 + PC_2}{\sqrt{2}} \]

Niño3 may represent Eastern Pacific El Niño
Using five (5) reanalysis products

The nonlinearity can be measured by a quadratic relationship

\[ PC2(t) = \alpha |PC1(t)|^2 + \beta PC1(t) + \gamma \]

\[ \alpha = -0.31 \]
skewness of the monthly C-index is -0.43

skewness of observed monthly E-index is 1.48

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
Dommenger 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

a) Projected changes in variability of monthly E-index

b) Projected changes in variability of monthly Niño3 index
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.

(Ham and Kug, Climate Dynamics, 2012)
For obs the link between ... is not clear, but...

- $\alpha = -0.31$
- E-index skewness $+1.4$
- C-index skewness $-0.41$
\( \alpha \) links the two skewness
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.
**Vertical gradient vs E-index**

![Graph showing the relationship between changes in vertical gradient and changes in E-index. The graph includes data points for various models such as 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. The correlation coefficient $R^2 = 0.56$, the slope is 0.36, and the p-value is $p < 0.001$.](image)
CP-index

(a) Projected changes in variability of CP index, monthly

(b) Projected changes in occurrences of events with CP>=1 s.d., DJF

(c) Projected changes in occurrences of events with CP<=-1.75 s.d., DJF

Legend:
- Control
- Climate change
Uncertainties

1. Cold tongue bias leads to higher
2. Underestimate in Atlantic–Pacific interaction

A. Projected equatorial surface warming

B. Difference in projected surface warming due to Atlantic decadal influence
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
“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)

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

Can every model simulate well of EP-ENSO?
The skewness of the monthly C-index is -0.43.

The skewness of the observed monthly E-index is 1.48.

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 $\alpha$ and skewness of $E$- and $C$-index?
\[ \alpha_{\text{obs}} / 2 \]

![Graph showing difference in skewness between E and C vs alpha](image)

**Selected 17 models**

- ESM1-BGC
- ESM1-CAM5
- MCC-CESM
- C-CM
- MCC-CMS
- NRM-CM5
- RIAS-ao2
- FDL-ESM2
- FDL-ESM2M
- ISS-E2-H
- SL-CM5B-LR
- IROC5
- R1-CGCM3
- PI-ESM-LR
- FDL-ESM2G
- eofEsm1-M
- CESM1-0
- CESM1-3
- SIRO-MK3-B6-0
- C-EARTH
- adGEM2-AO
- adGEM2-CC
- adGEM2-ES
- mcm4
- SL-CM5A-LR
- SL-CM5A-MR
- csm1-1
- anESM2
- PI-ESM-MR
- eofEsm1-ME

**Correlation Coefficient:** 0.95

**Slope:** -0.17

**p-value:** <0.001
Why models with a strong can simulate a better V-shape and strong skewness in E-index??

![Graph showing relationship between Alpha and response of zonal wind stress to positive E.](image)

- Alpha & response of zonal wind stress to positive E
- Corr. Coeff. = -0.6
- Slope = -38
- p < 0.001
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.

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

\( F_n \) 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**

Graph showing the mean temperature changes across different depth levels with depth in meters on the y-axis and temperature in °C on the x-axis.

**b Vertical gradient vs E-index**

Scatter plot showing the relationship between changes in E-index and changes in vertical gradient with a linear regression line, indicating a correlation.

**c Wind projection coefficient**

Bar chart illustrating the wind projection coefficient with different models and climate change scenarios.

**d Vertical gradient vs coupling coefficient**

Scatter plot demonstrating the relationship between changes in vertical gradient and coupling coefficient, with a linear regression line and statistical significance indicated.
Variability in E-index to RCP4.5

a) Projected changes in variability of EP index, monthly

b) Projected changes in occurrences of events with EP >= 1.5 s.d., monthly -> DJF