ENSO Diversity and its Precursors

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Part 1: ENSO diversity characteristics and dynamics
Part 2: Precursors of ENSO diversity

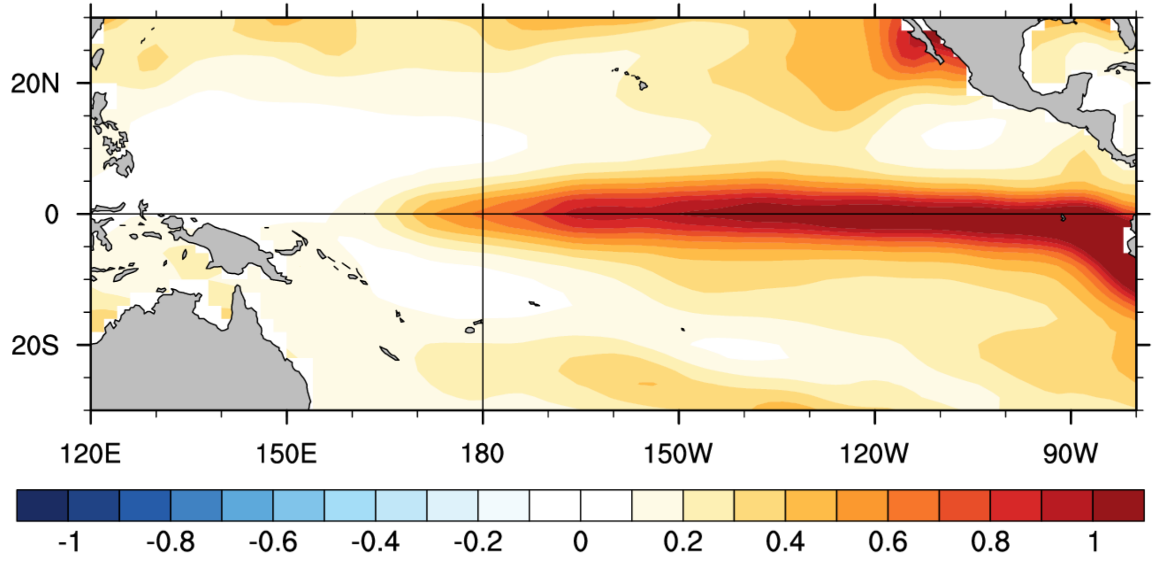
Part 1: ENSO Diversity Characteristics and Dynamics

- What is ENSO diversity and why does it matter?
- Indices of ENSO diversity and classification of events
- Characteristics of EP vs. CP events
- Dominant dynamical processes underpinning SST along the equatorial Pacific

"Canonical" ENSO pattern

The simplest way to characterize the ENSO pattern is through interannual SST variance

ERSSTv5 1950-2020



Large variability is found from the coast of South America to the dateline.

“Canonical ENSO pattern”

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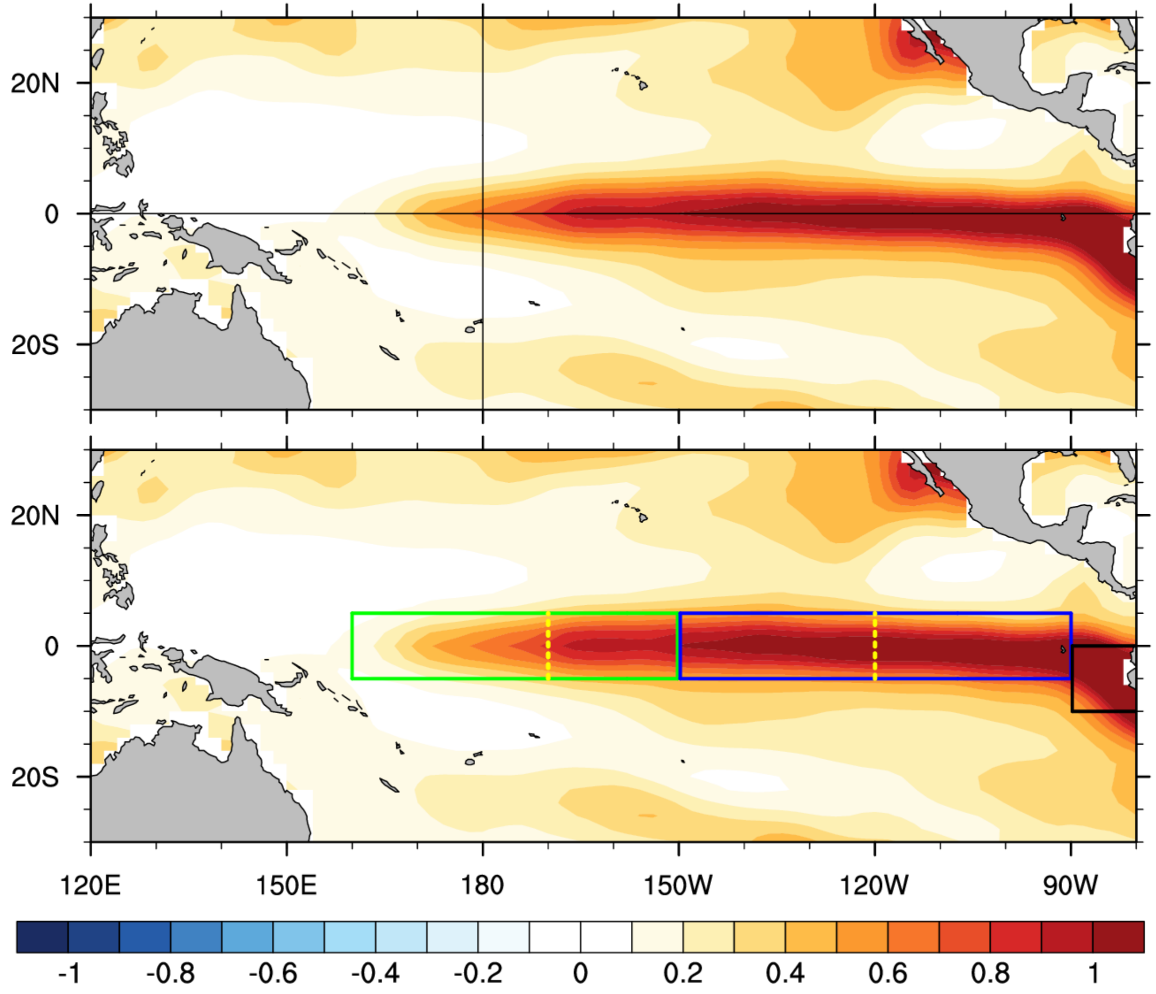


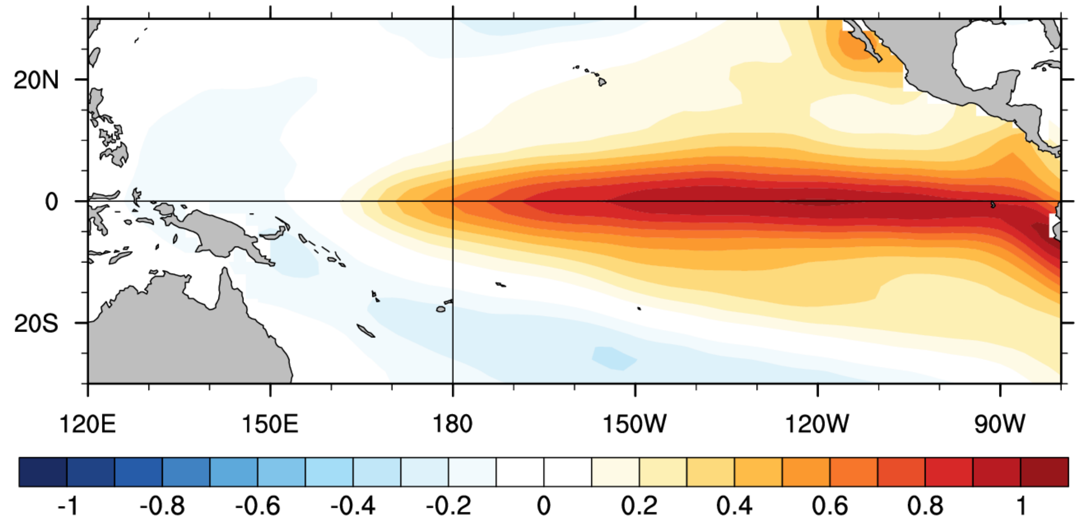
Large variability is found from the coast of South America to the dateline.

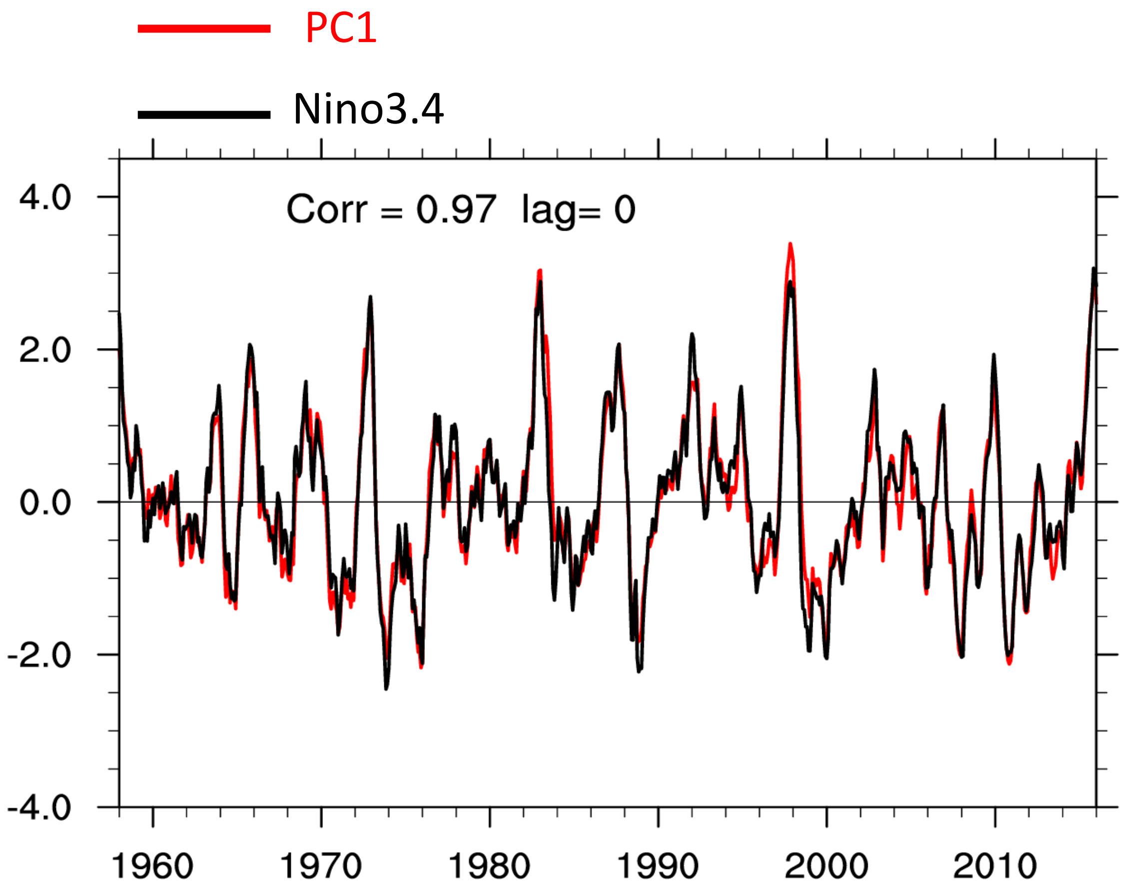
Largest variance is seen in the eastern equatorial Pacific, especially in the Niño-3 and Niño-1+2

What is ENSO Diversity?

The ”canonical” pattern of ENSO can also be described by the leading Empirical Orthogonal Function (EOF) of SST over the tropical Pacific.

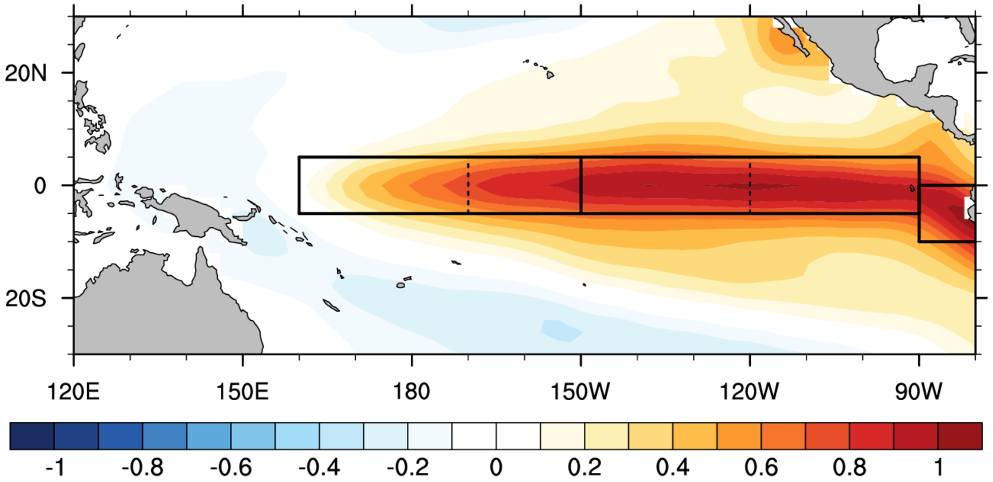
ERSSTv5 1950-2020

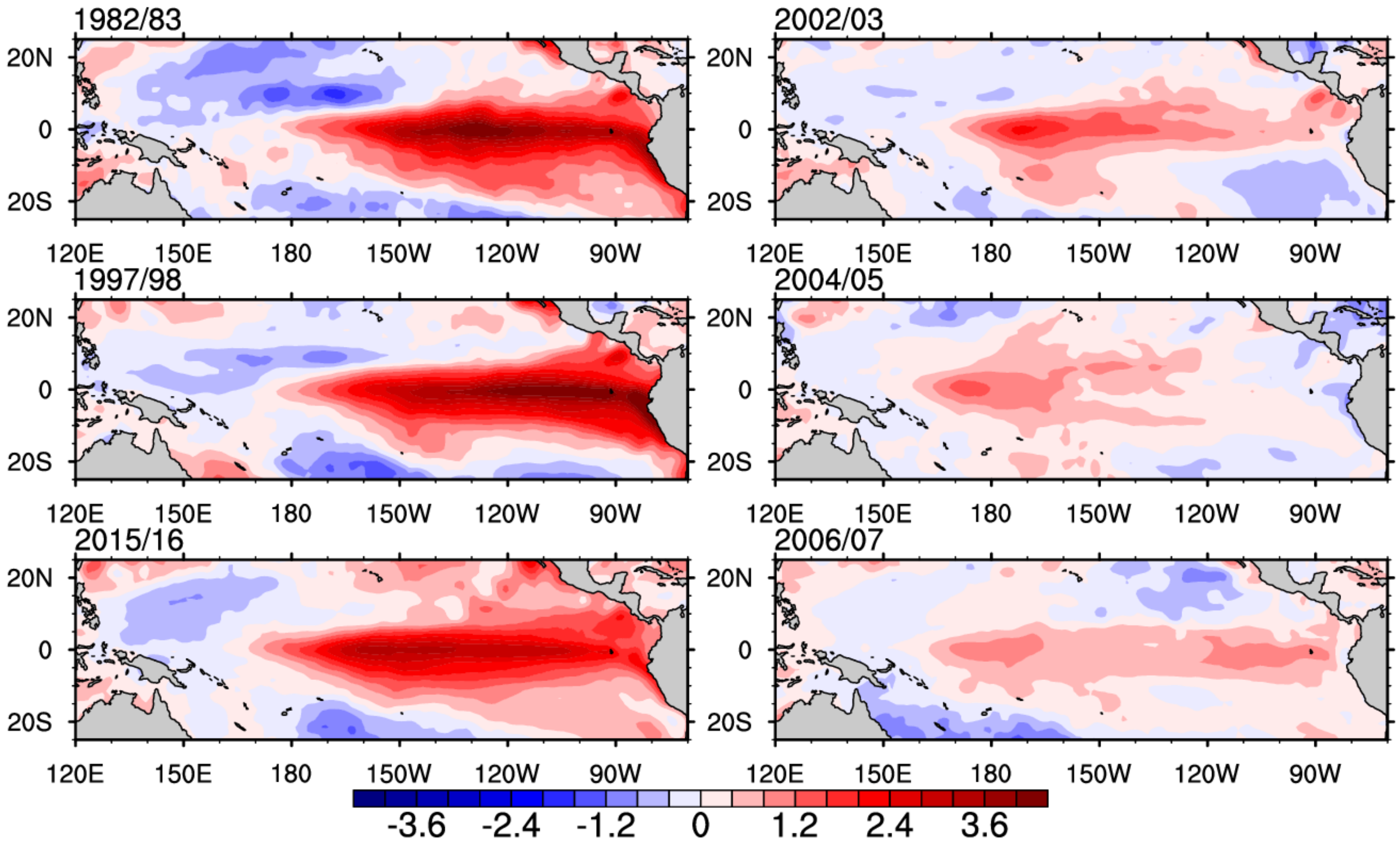




"No two El Niño events are quite alike" (Wyrtki, 1975)

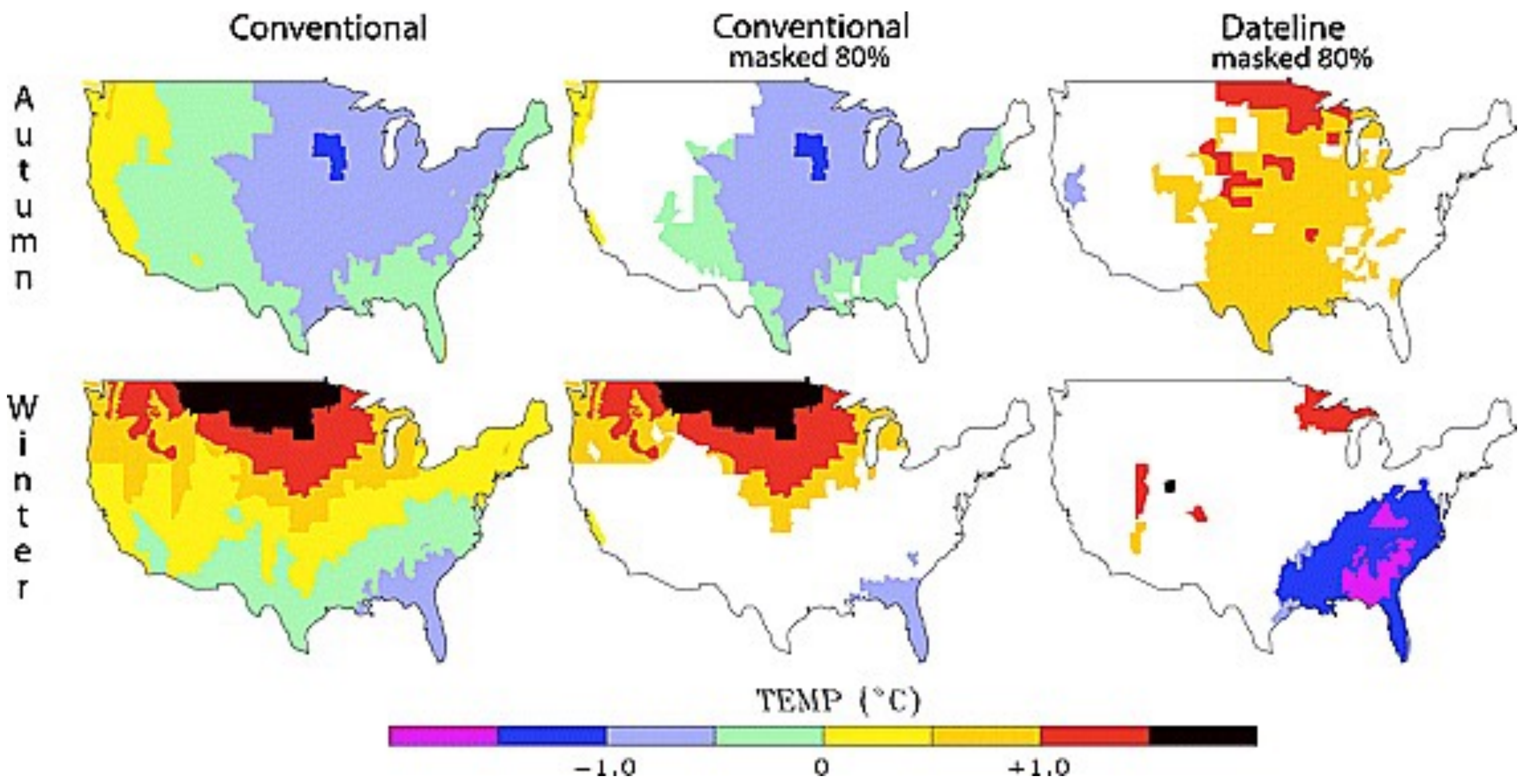
"Canonical" El Nino





ENSO diversity refers to these differences in spatial patterns. Pattern diversity is associated with differences in event intensity and temporal evolution.

Why does ENSO Diversity matter?



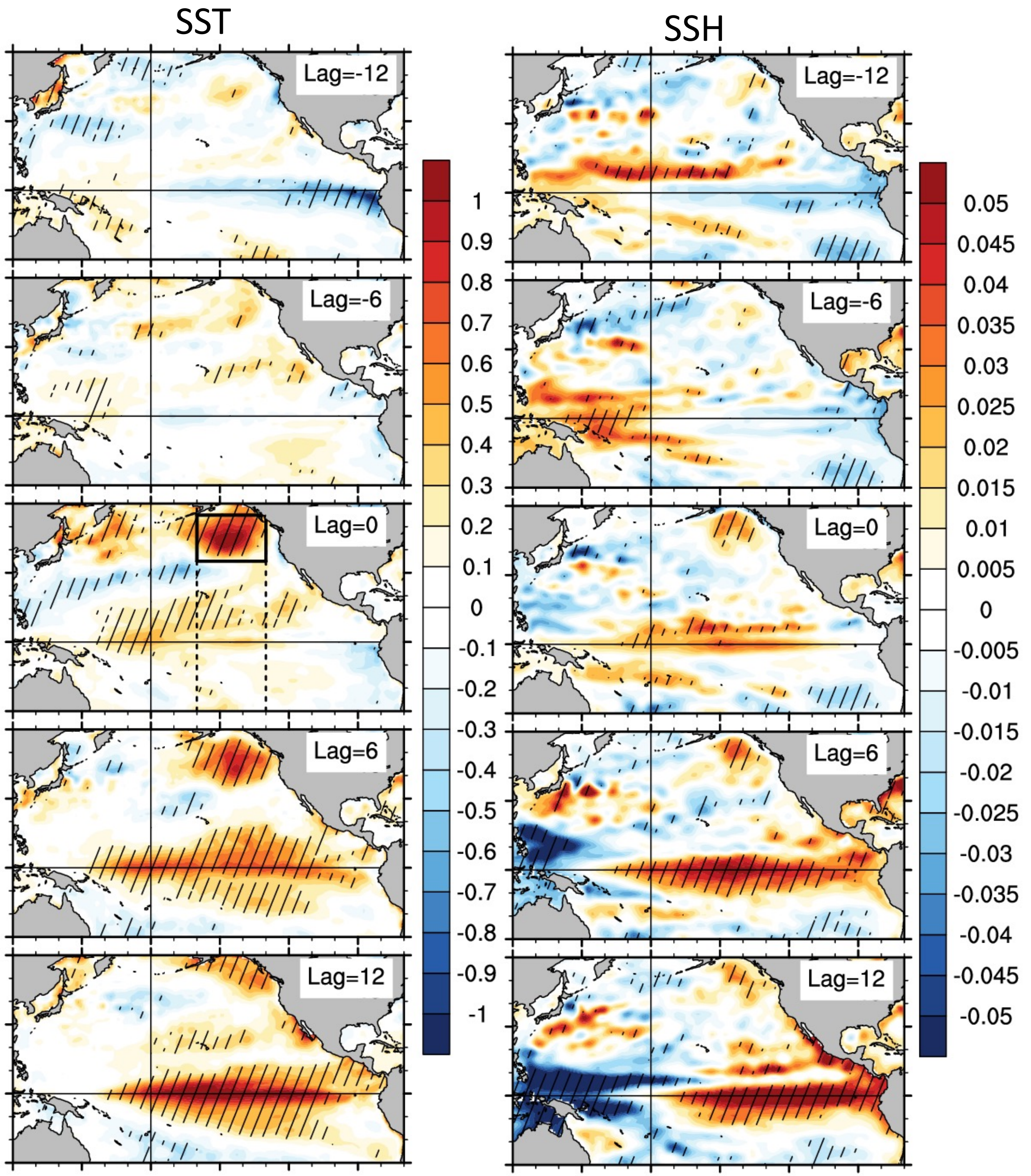
Patterns and even sign of surface air temperature anomalies over the US differ greatly for "conventional" and "dateline" El Nino events.

Larkin & Harrison, 2005

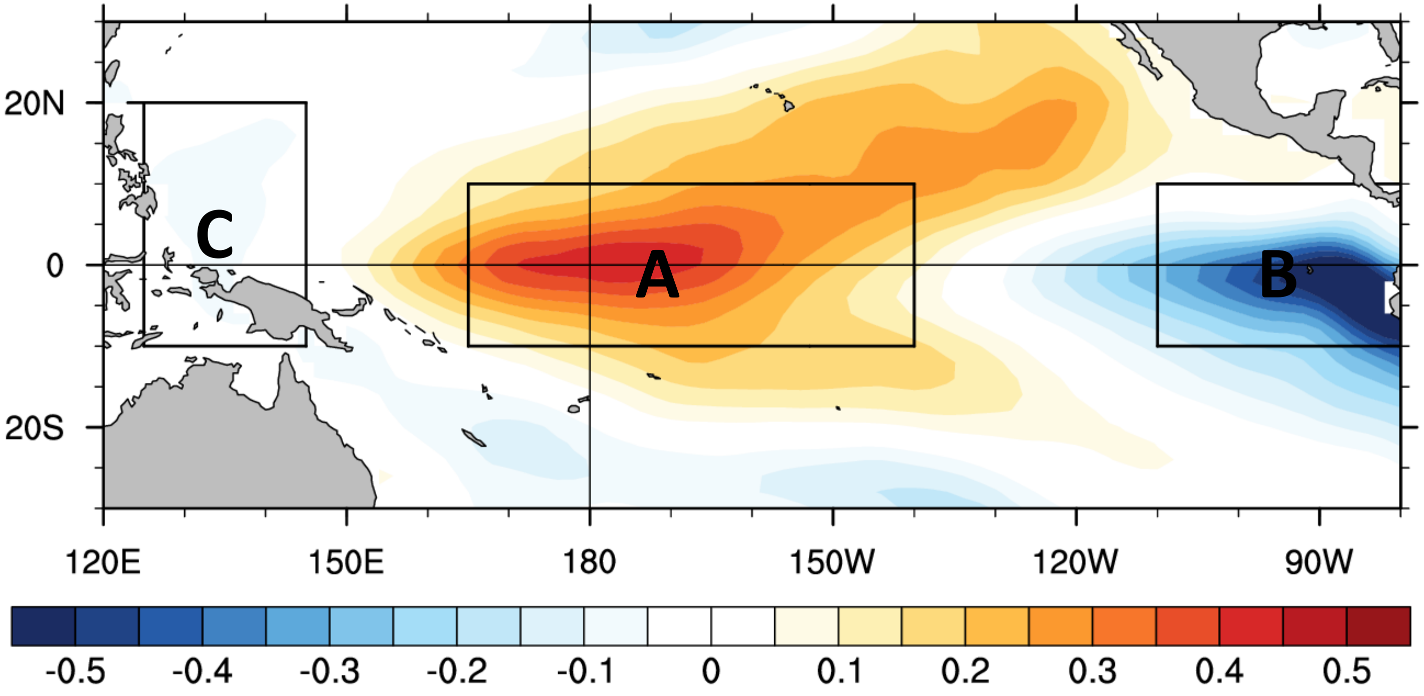
Central Pacific El Niño related to the development of Northeast Pacific marine heatwaves

Composites of intense warm events (marine heatwaves) in the northeast Pacific during 1958-2015. Events develop in conjunction with central Pacific El Niño events, which appear to increase their persistence.

Capotondi et al., 2022



El Niño Modoki ("El Niño with a difference")
Ashok et al. (2007)



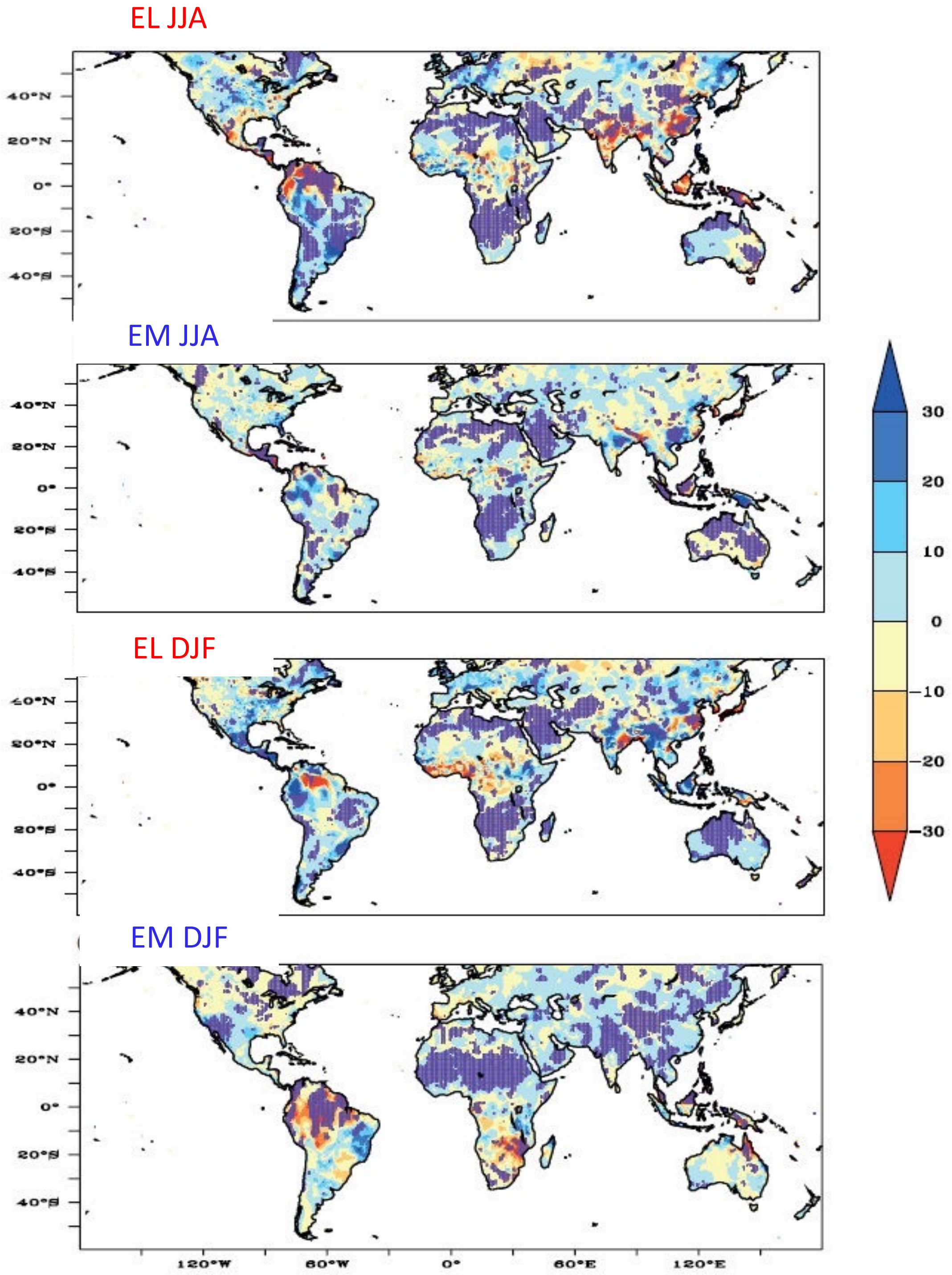
<u>El Niño Modoki Index (EMI)</u>

EMI = SSTA (A) - 0.5 * SSTA (B) – 0.5* SSTA (C)

An El Niño Modoki occurs when EMI exceeds 0.5 sigma for at least three seasons, from boreal Summer to boreal Winter.

Ashok et al. (2007)

Canonical (EL) and Modoki (EM) El Nino teleconnections



Composite precipitation from Climate Research Unit (CRU) rainfall during EL and EM events.

EL: 1957/58, 1965/66, 1972/73

EM: 1967/68, 1977/78, 1991/92, 1994/95, 2002/03, 2004/05

Marathe and Ashok, 2021

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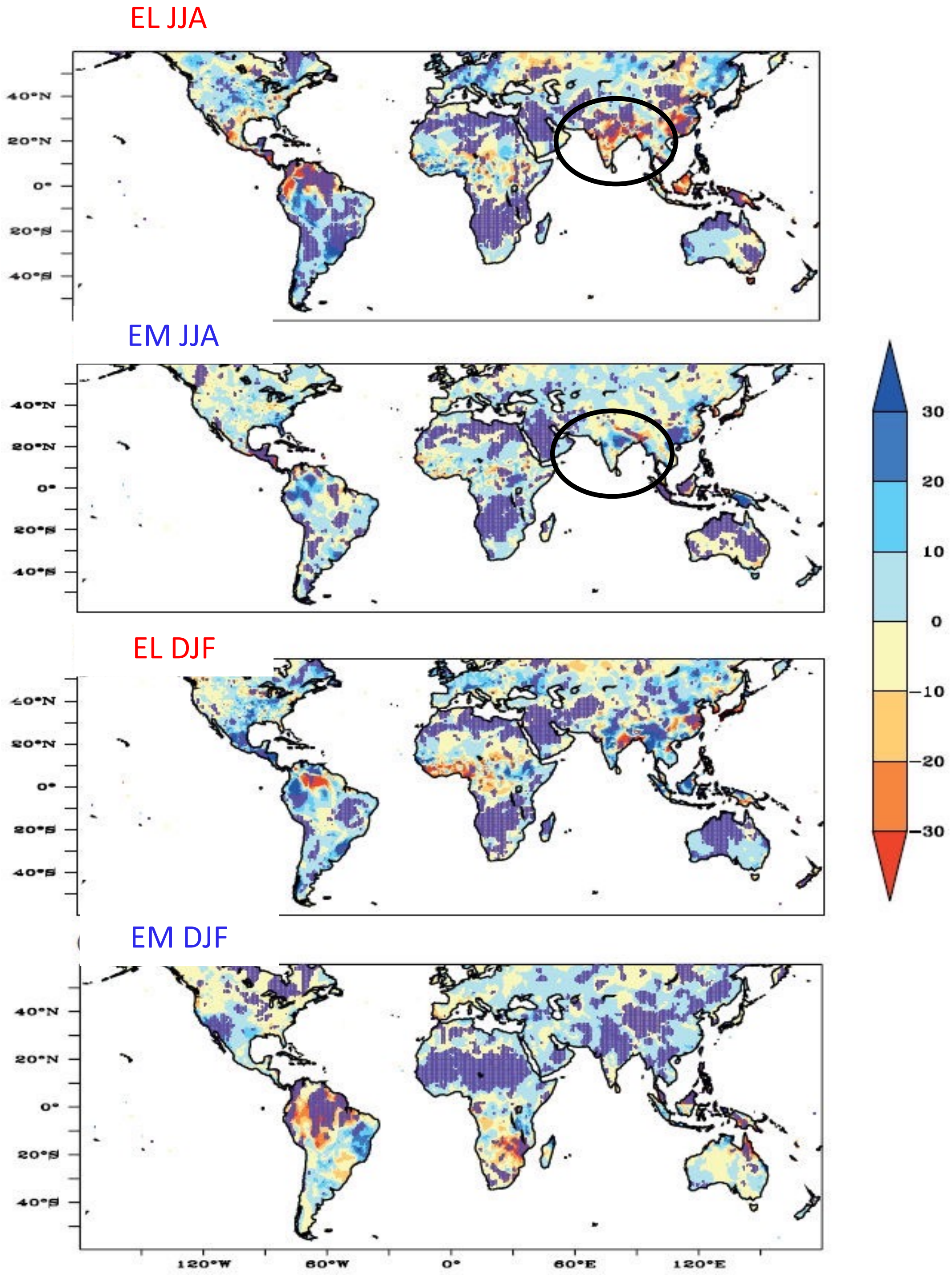

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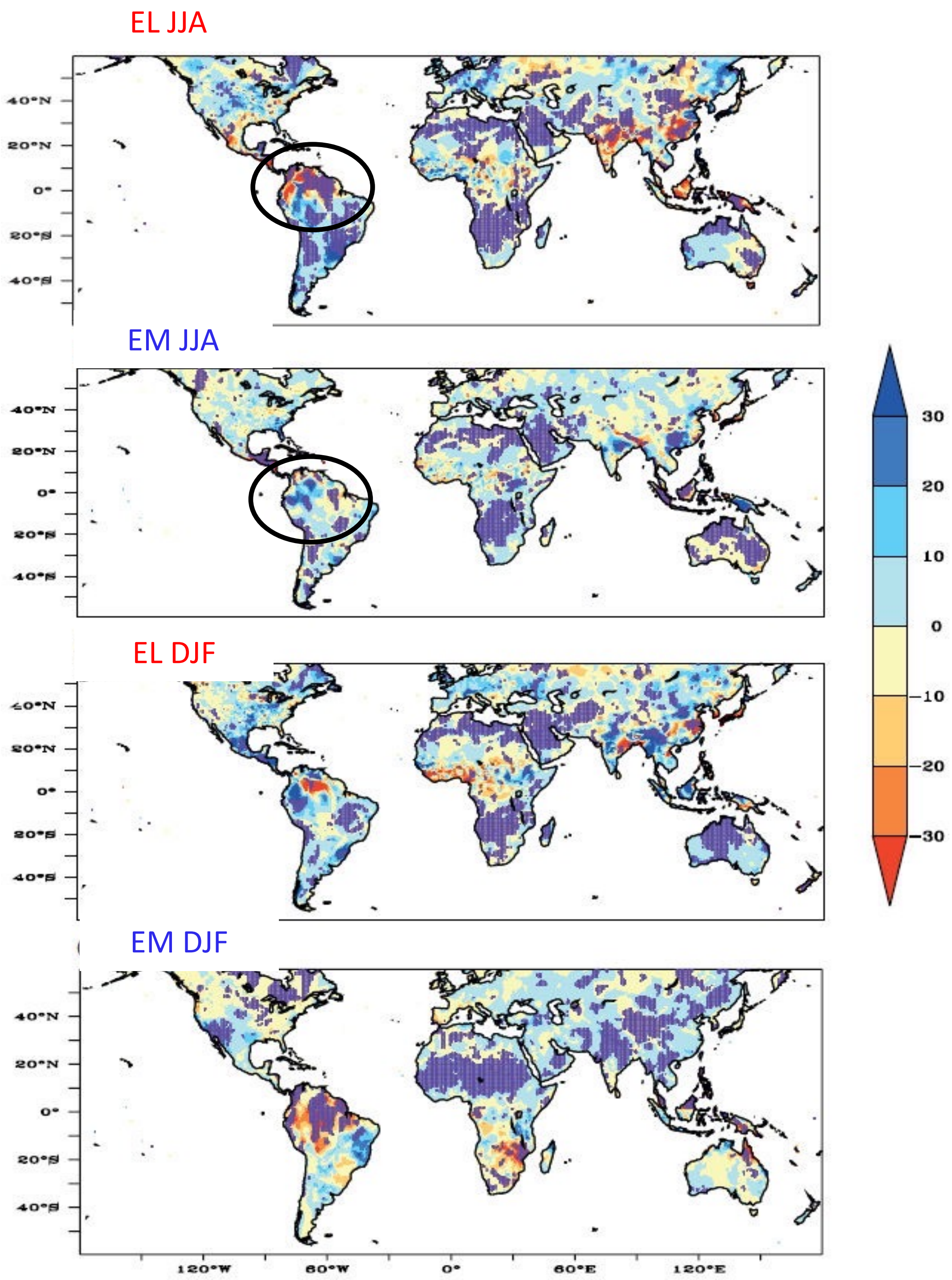

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Marathe and Ashok, 2021

Is ENSO diversity due to distinct "modes" or "phenomena" or just different expressions of the ENSO phenomenon?

Ashok et al. (2007):

"*We believe that identifying a unique phenomenon with the most appropriate definition, just as new species in biology, is important to promote further research.* "

Some researchers believe in the existence of **distinct** types of events with possibly different dynamics, evolutions, and teleconnections. While El Niño Modoki itself may be associated with a different large-scale dynamics, evidence supports the concept of a broad range of event types.

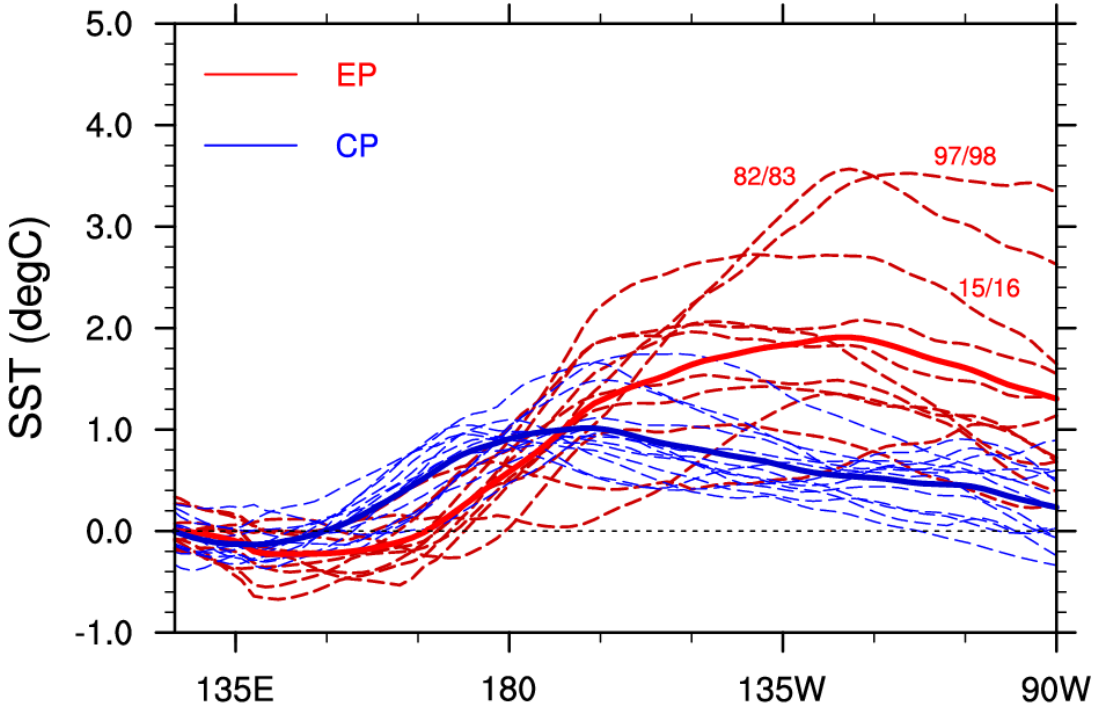
Indices of ENSO diversity: *Niño-3 - Niño-4*

Niño-3 – Niño-4 approach
(Kug et al. 2009; Yeh et al. 2009)

EP events (Cold Tongue): Winter Niño-3 index is larger than one standard deviation (or larger than 0.5°C, depending on the application) and larger than Niño-4

CP events (Warm Pool): Winter Niño-4 index exceeding one standard deviation (or 0.5°C) and exceeding the Niño-3 index.

Equatorial profiles of anomalous SST for EP and CP El Niño events.



Capotondi et al., 2021

Indices of ENSO diversity: *EPnew – CPnew*

EPnew – CPnew indices Linear combination of standardized Niño-3 and Niño-4 indices:

EP-new=Niño-3 - αNiño-4

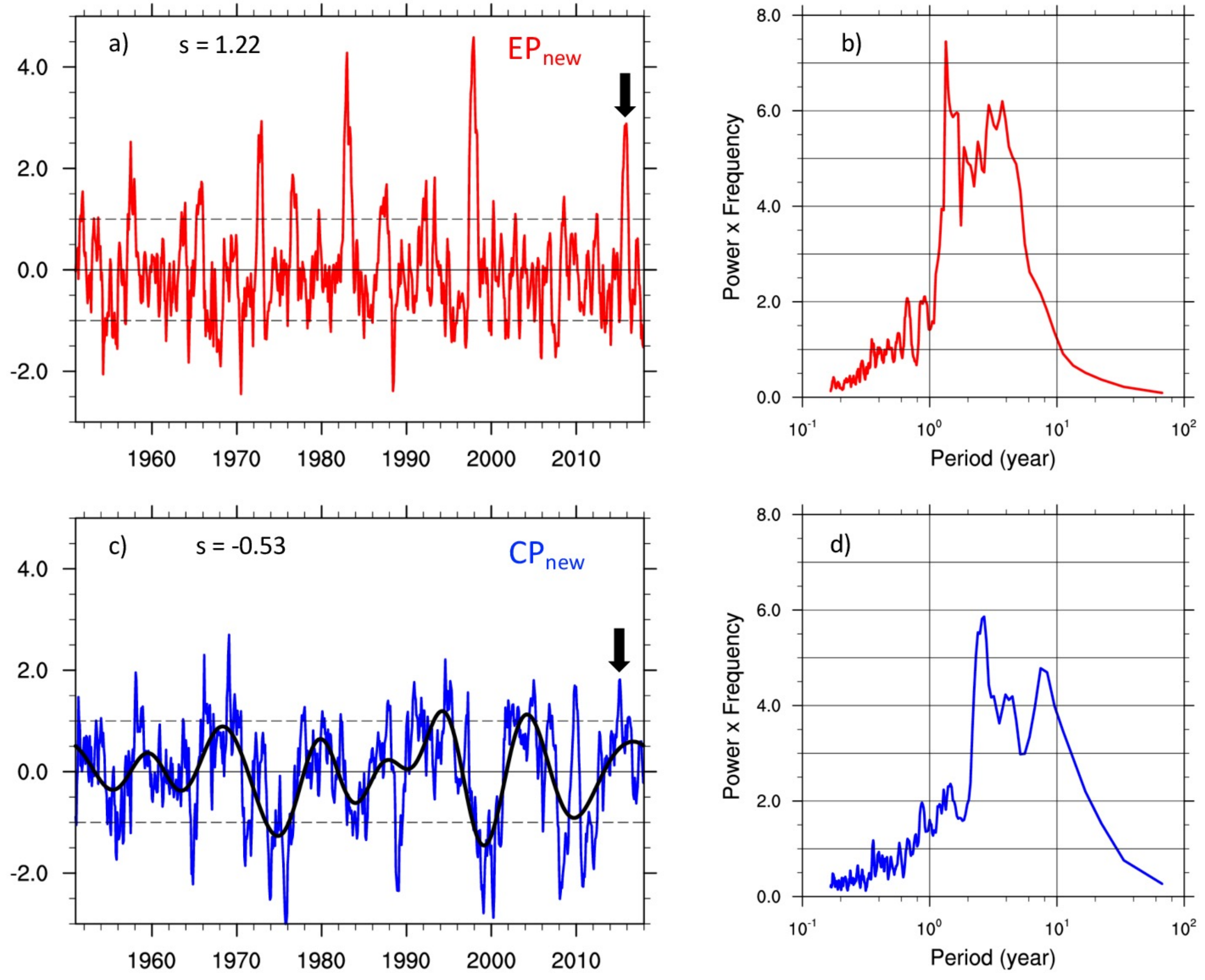
CP-new=Niño-4 - αNiño-3, with α=0.5

Motivated by the need of indices for CP and EP El Niño types that were uncorrelated, unlike the Niño3 and Niño4 indices.

Ren and Jin, 2011
Sullivan et al. 2016

EP events are positively skewed,
CP events are negatively skewed

CP events have power at decadal timescales



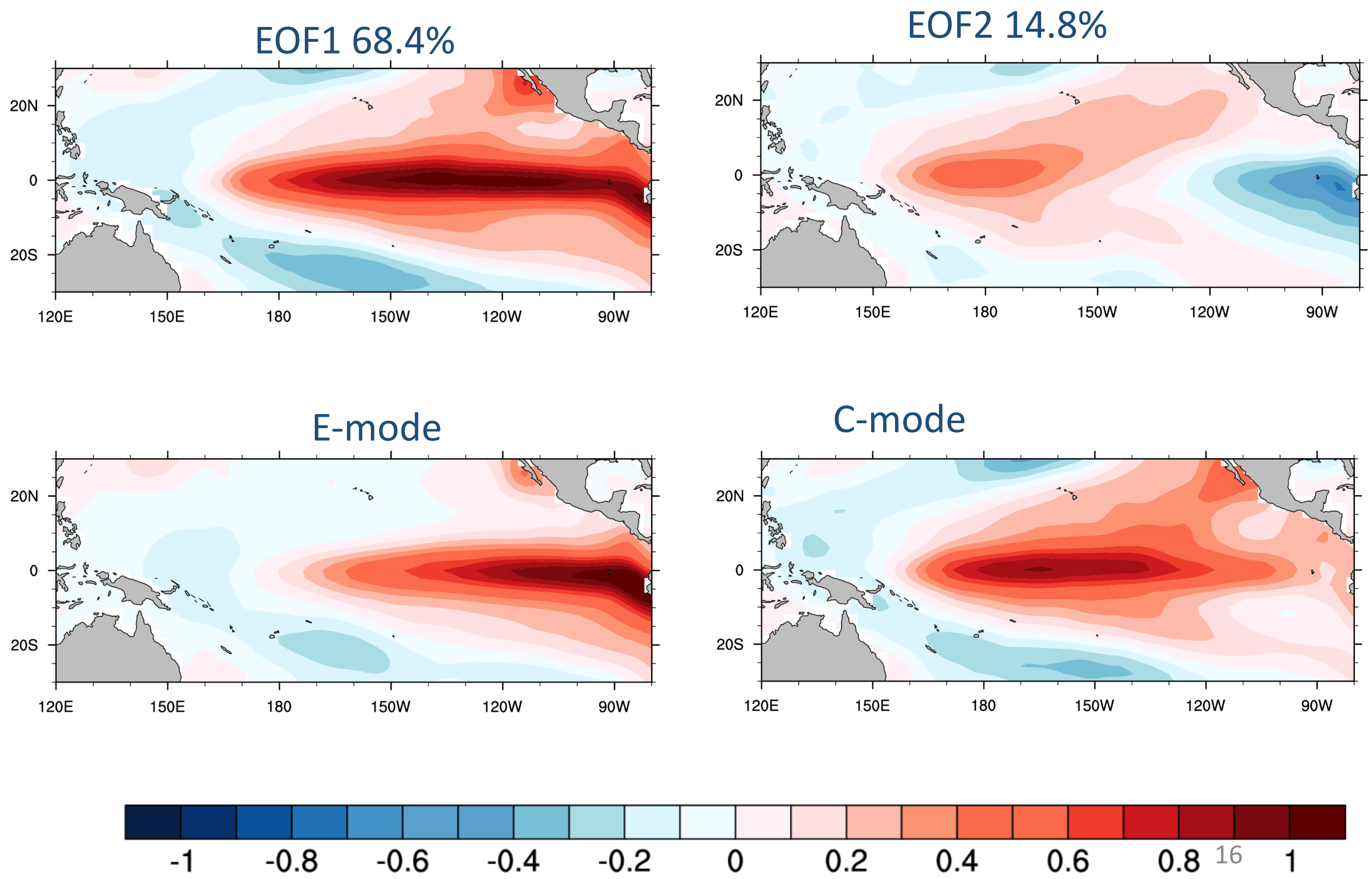
Indices of ENSO diversity: *E – C* indices

<u>Definition</u> (Takahashi et al., 2011):

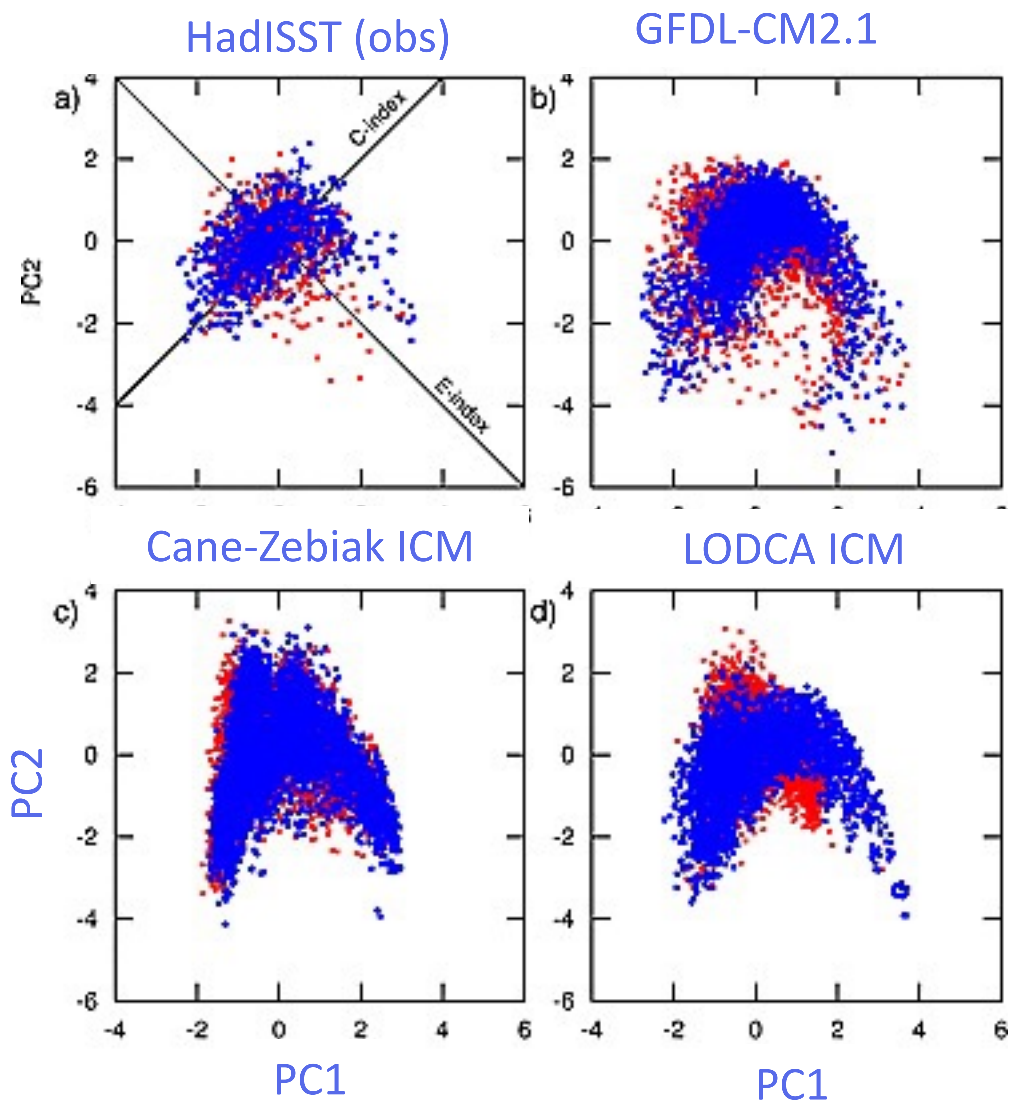
E-mode index: (PC1-PC2)/$\sqrt{2}$

C-mode index: (PC1+PC2)/$\sqrt{2}$

They are independent by construction, and identify moderately warm events, primarily in the central equatorial Pacific, and extreme events in the eastern Pacific, respectively.



How important are nonlinearities for ENSO diversity?



Takahashi et al. (2011)

Blue: October –March
Red: April-September

Since EP and CP events can be determined from EOFs, and there is a nonlinear relationship between PC1 and PC2, this seems to imply that nonlinearities may be important for diversity, consistent with the skewness of ENSO indices.

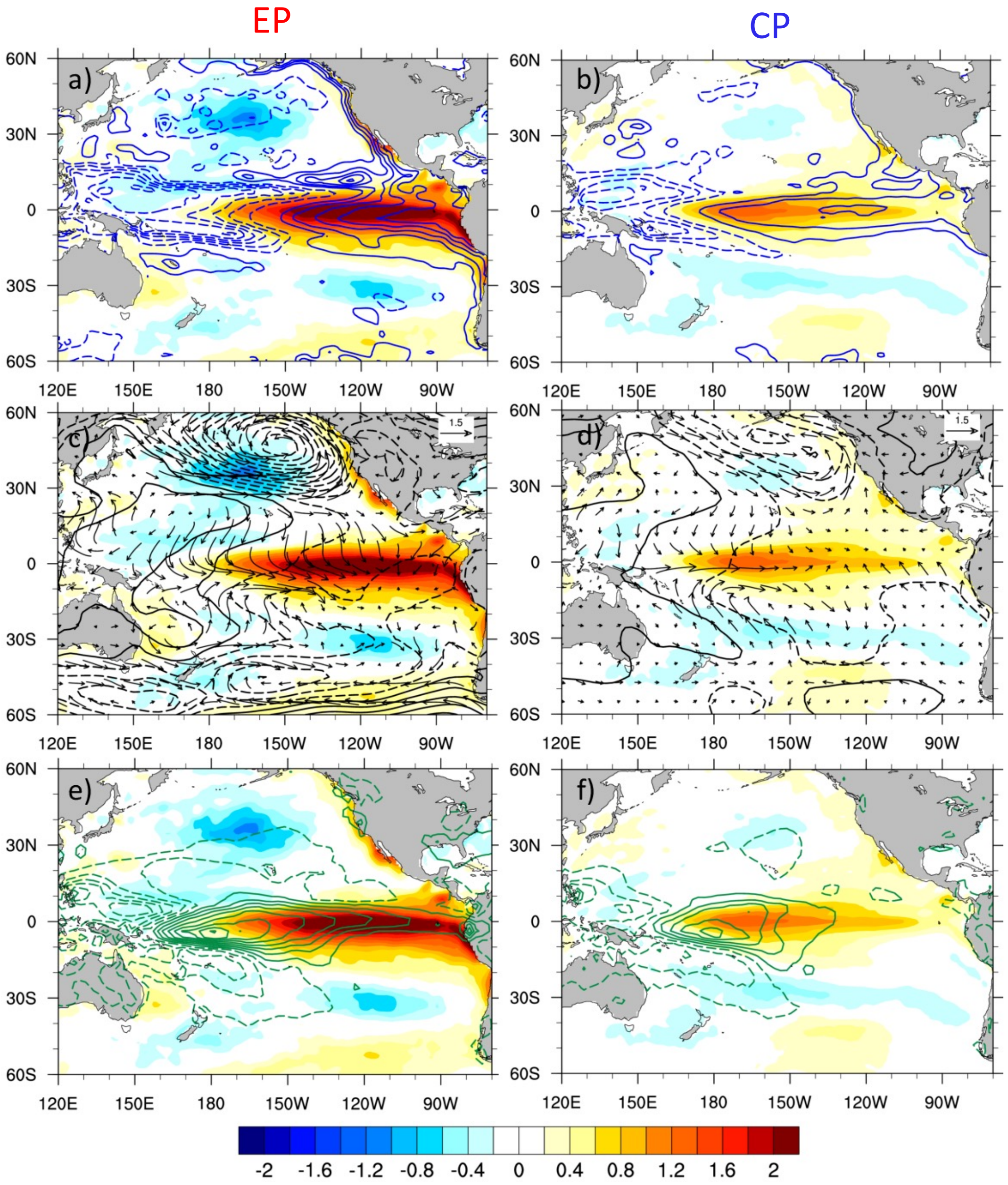
To be discussed more in Part 2

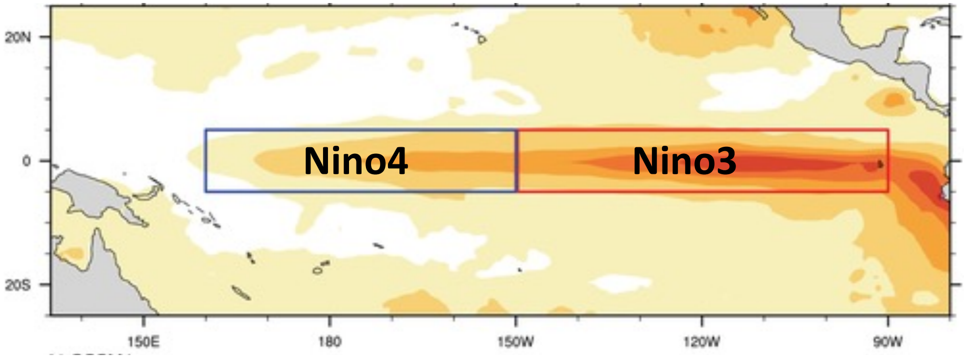
Composite characteristics of EP/CP events

Shading: SST
Contours: SSH

Shading: SST
Contours: SLP

Shading: SST
Contours: PR





ECMWF ORAS4 ocean reanalysis (1958-2015)

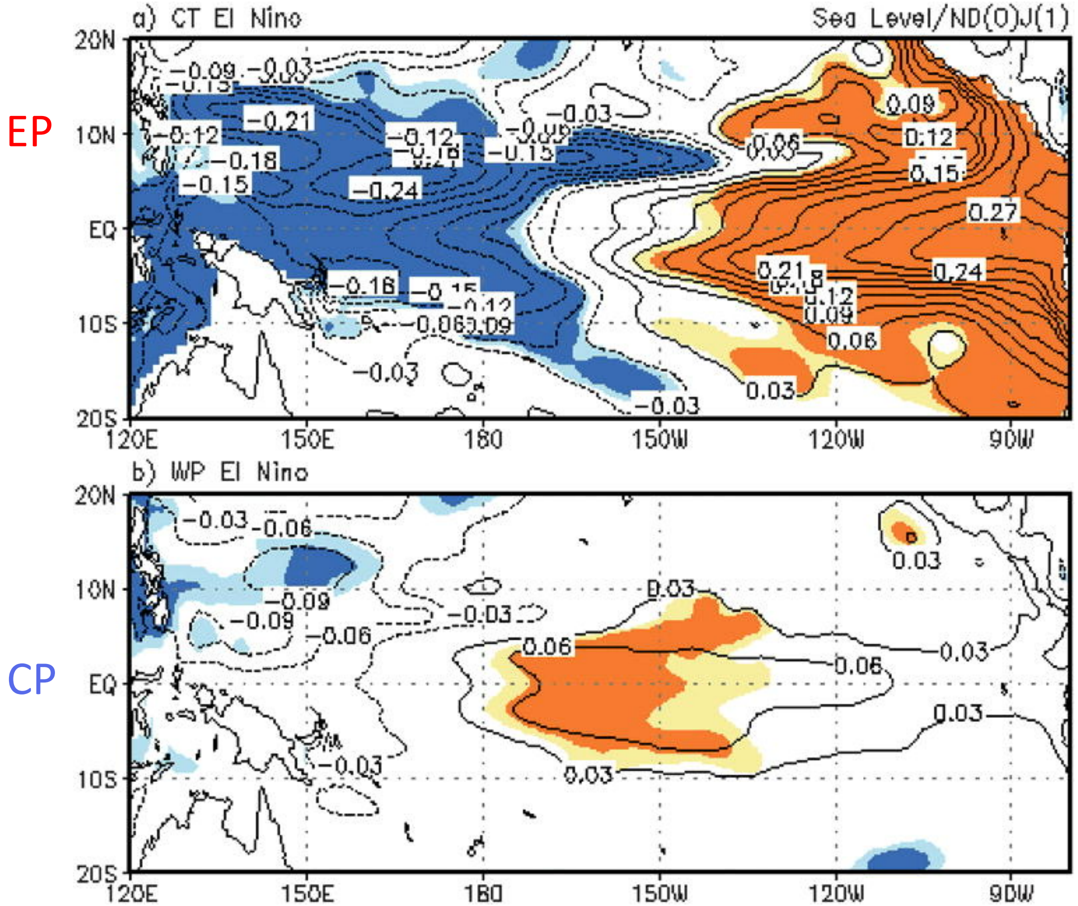
CP events are generally weaker than EP events, and have maximum anomalies around the dateline.

SSH, SLP and precipitation anomalies are confined further to the west during CP events relative to EP events

Capotondi et al., 2021, ENSO Monograph

Dynamical Processes
Recharge/Discharge processes differ in EP/CP events

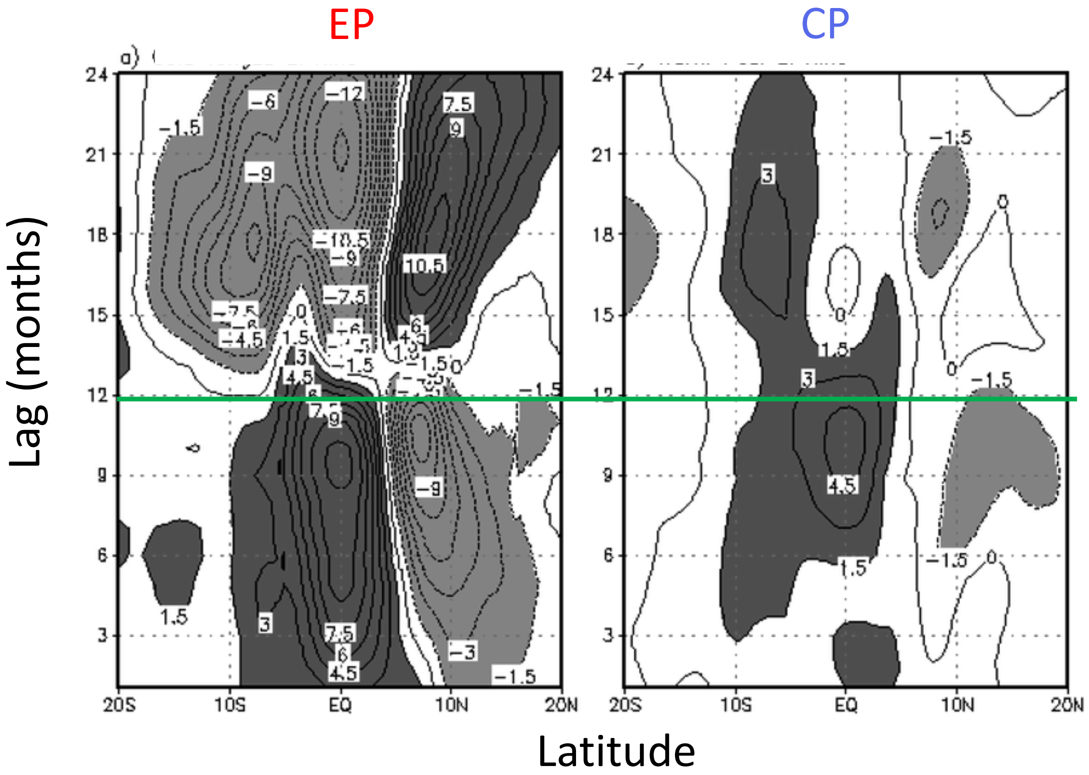
Composite Sea Level during NDJ



Sea Level data from GODAS ocean reanalysis over **1980-2005**

Kug et al., 2009

Time evolution of zonal average of sea level for composite EP and CP events



EP events transition rapidly from a recharge to a discharge state, while CP events have no real discharge

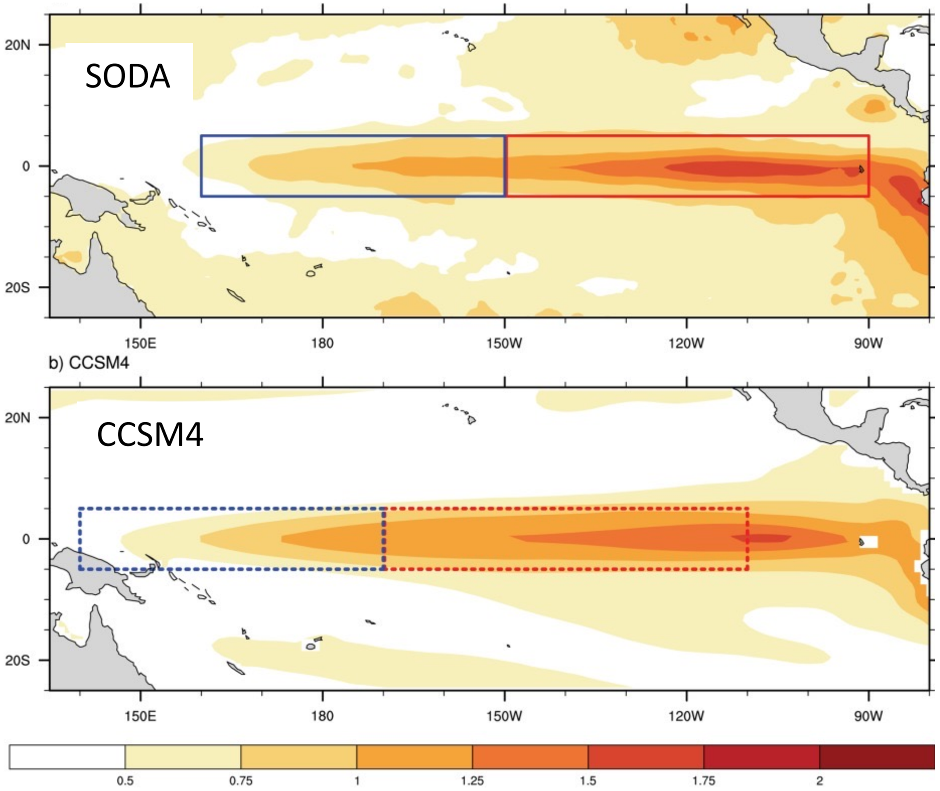
So far, we have considered composite characteristics of a small sample of events based on ocean reanalysis. We can use similar diagnostics in the long records of climate models.

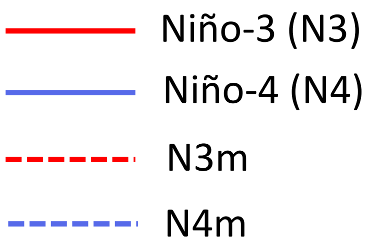
ENSO diversity in the NCAR-CCSM4 climate model

The Community Climate System Model version 4 (CCSM4) has a “relative good” representation of ENSO in terms of spatial pattern, amplitude and spectral characteristics (Deser et al., 2012).

Here, we use years 800-1299 of the 1300 years **pre-industrial control simulation**
CCSM4 is compared with Simple Ocean Data Assimilation version 2.0.2/3 (1958-2007)

SST standard deviation

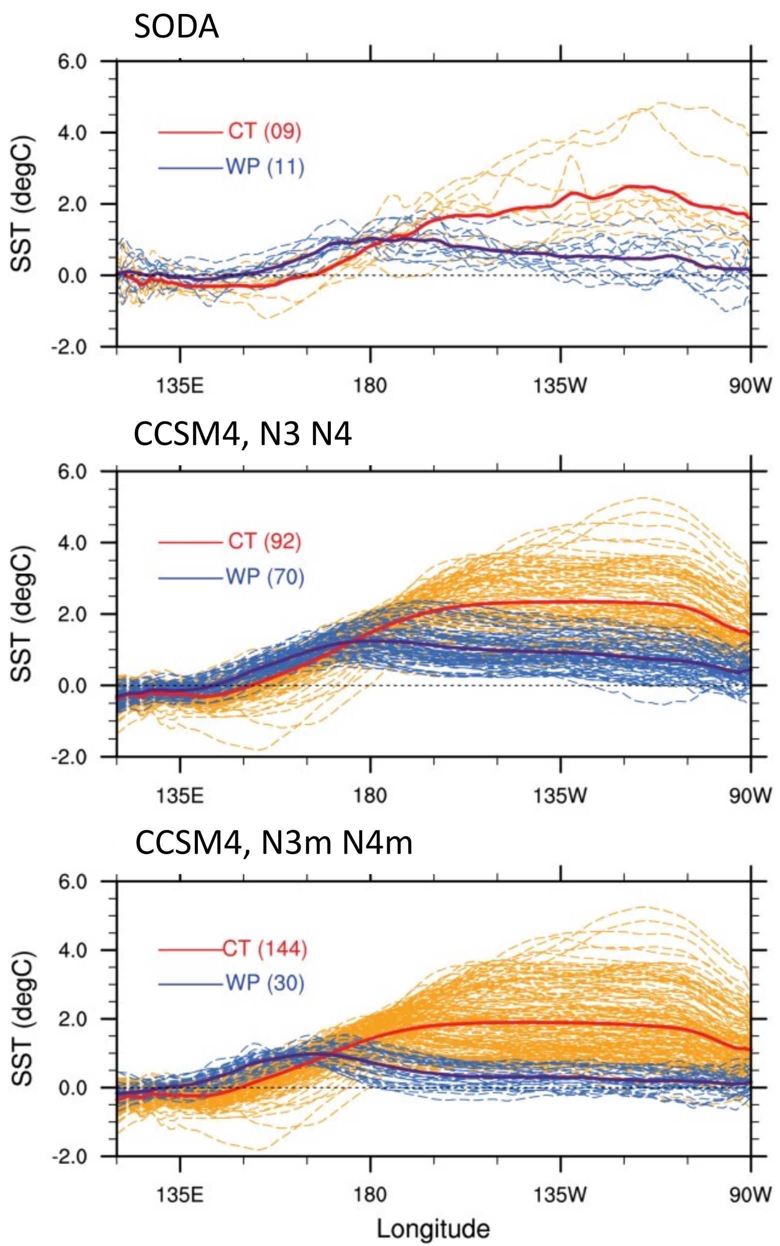




N3m and N4m regions are displaced 20^o west of the N3 and N4 regions to account for the westward displacement of the model’s SST anomalies

Capotondi, 2013, J. Geophys. Res.

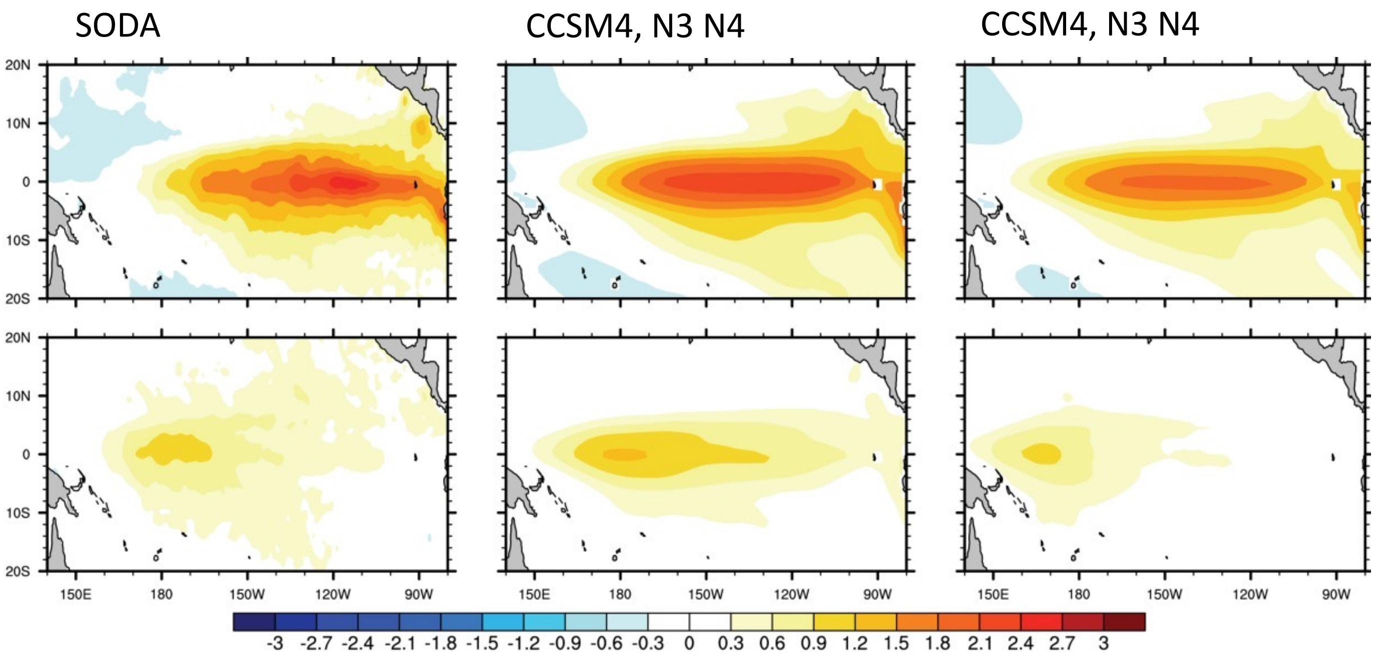
ENSO diversity in the NCAR-CCSM4 climate model



Longitudinal profiles of SST for events with the largest anomalies in the Eastern or Western regions

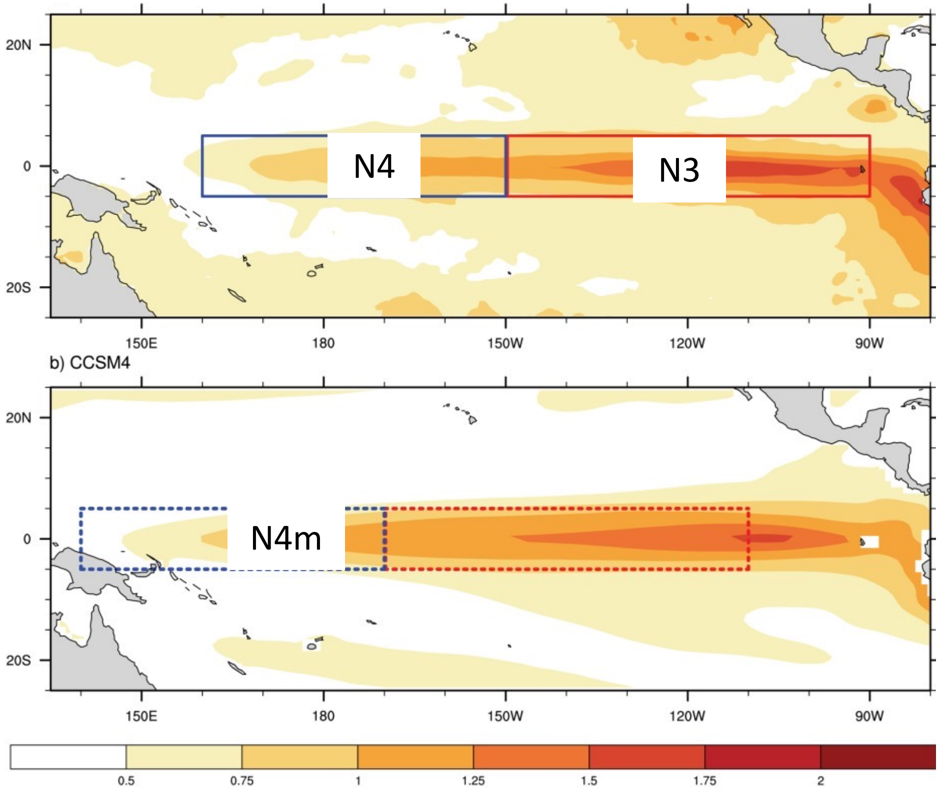
Unlike other models, CCSM4 is able to separate EP and CP clusters, although there is an overlap

SST composites

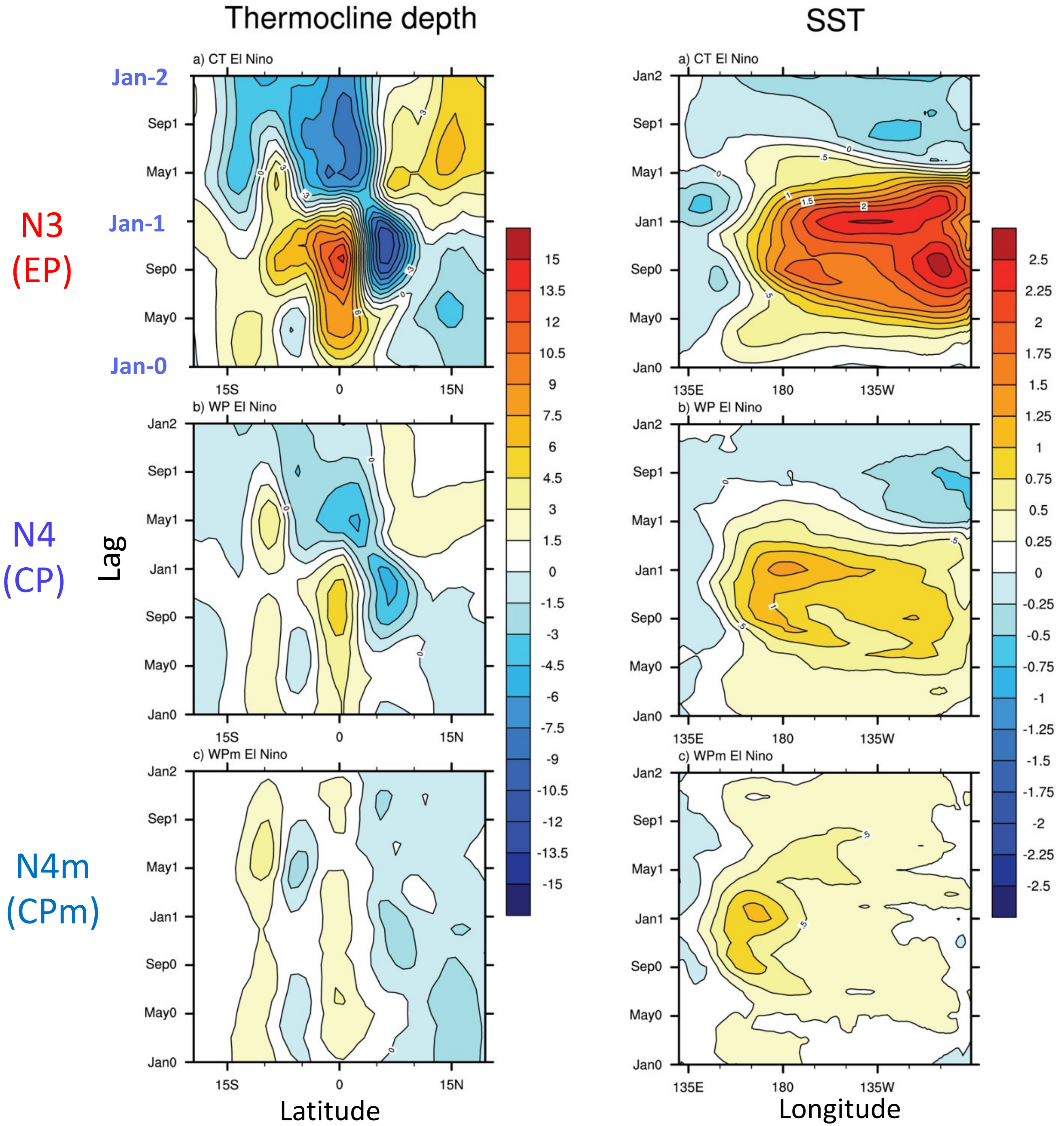


Recharge/Discharge processes in CCSM4

Composite evolution of zonally averaged thermocline depth and SST as a function of lag from the Jan-0 (developing year) to Jan-1 (event peak) to Jan-2 (year following the peak)



Capotondi, 2013



Dynamical processes of ENSO diversity in CCSM4: A heat budget analysis

$$\rho c_p H \frac{\partial T}{\partial t} = Q_{ocn} + Q_F$$

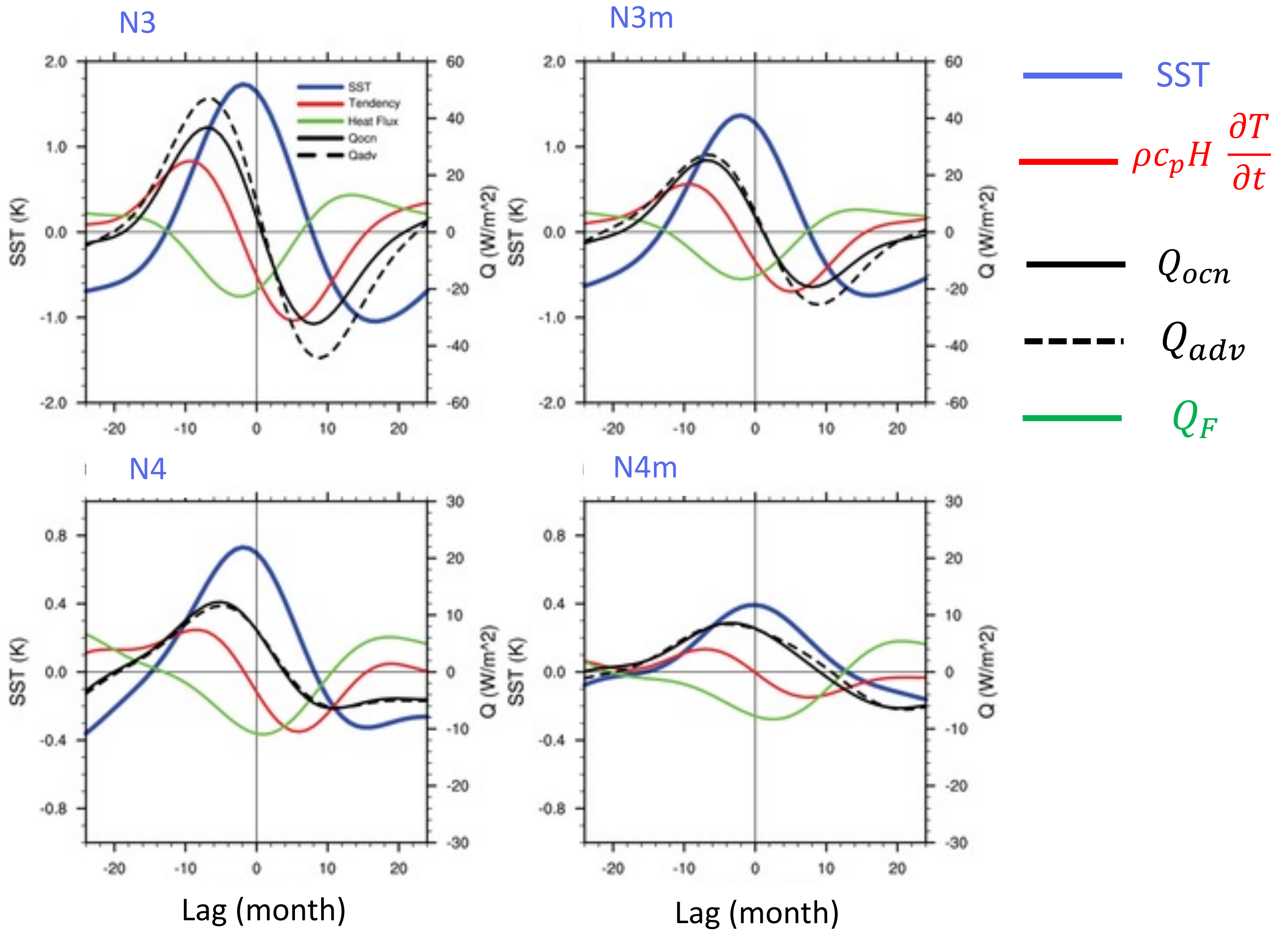
ρ= density of sea water
c_p= ocean heat capacity
H= upper-ocean depth (chosen as 65 m)

T = Temperature averaged over depth H

Q_{ocn}= Ocean heat flux convergence due to advective processes

Q_F= Surface heat flux

For each region, all terms are averaged between 2.5^{o}S-2.5^{o}N and to depth H, and composited for different event types



Lag 0 is January of the event peak. Events are identified based on DJF values

Ocean advective processes

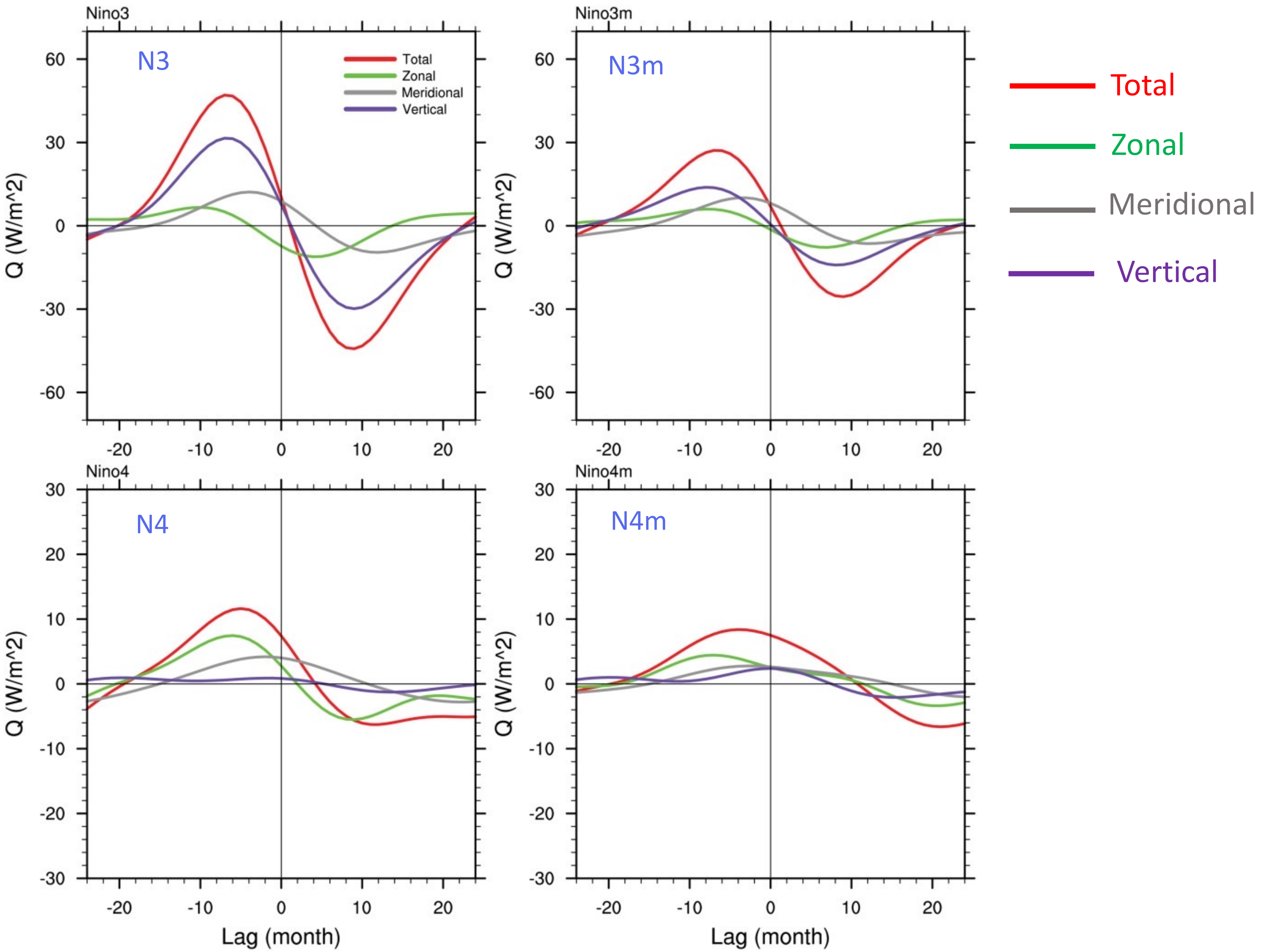
$$Q_{adv} = Q_z + Q_m + Q_v$$

Q_z = Zonal
Q_m = Meridional
Q_v = Vertical

$$Q_z = \int_{-H}^{0} u \frac{\partial T}{\partial x} dz$$

$$Q_m = \int_{-H}^{0} v \frac{\partial T}{\partial y} dz$$

$$Q_v = \int_{-H}^{0} w \frac{\partial T}{\partial z} dz$$



Vertical advection dominates in the **N3** and **N3m** regions, while zonal advection dominates in the **N4** and **N4m** regions

The magnitude of the zonal advection term is comparable in all regions

Ocean advective processes

Ocean variables can be divided into mean and anomaly components: e.g., $u = \bar{u} + u'$

$$u\frac{\partial T}{\partial x} = \bar{u}\frac{\partial T'}{\partial x} + \boxed{u'\frac{\partial \bar{T}}{\partial x}} + u'\frac{\partial T'}{\partial x}$$

Zonal advection of mean zonal temperature gradient, known as "Zonal Advective feedback" is the dominant zonal advection term in most regions

$$w\frac{\partial T}{\partial z} = \boxed{\bar{w}\frac{\partial T'}{\partial z}} + \boxed{w'\frac{\partial \bar{T}}{\partial z}} + w'\frac{\partial T'}{\partial z}$$

Thermocline feedback

Upwelling feedback

Thermocline feedback is dominant in the Eastern Pacific, while upwelling feedback is more prevalent in the Central Pacific

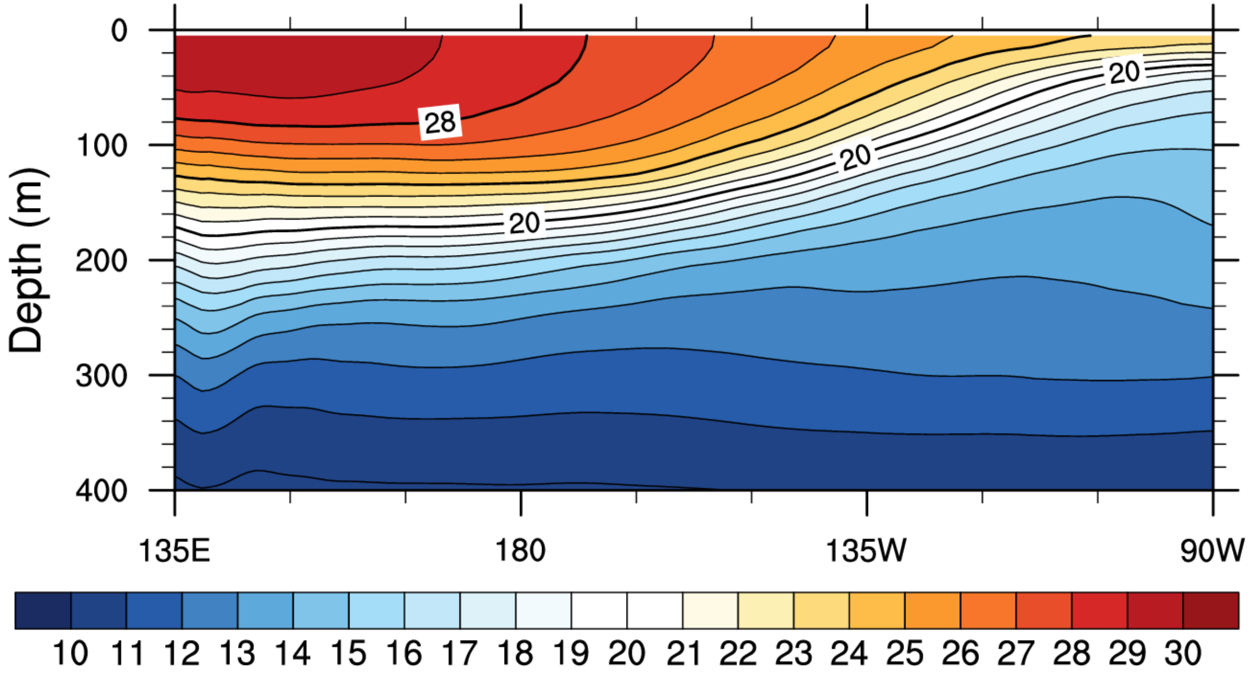
ENSO diversity: Bimodal or ”Continuum”?

ENSO characteristics vary smoothly as we consider events peaking at different longitudes

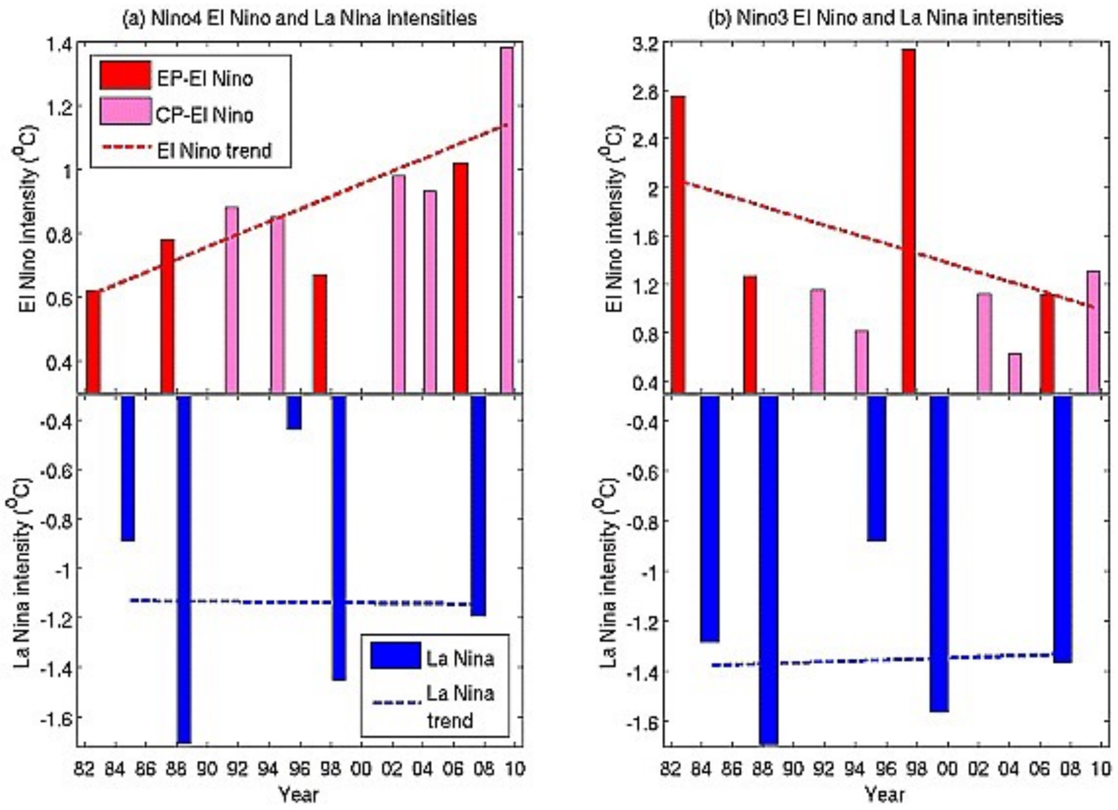
Heat budget analysis indicates that the dynamical processes are the same in different regions, although their relative importance may vary from region to region due to the zonal asymmetry of the equatorial mean state.

In the eastern Pacific, where the thermocline is shallower, vertical advection is the dominant term, while in the central/western Pacific, with larger zonal temperature gradients, and enhanced zonal current variability due to the anomalous winds, makes zonal advection more relevant.

Mean temperature along the equator
GODAS (1980-2020)



ENSO diversity and climate change

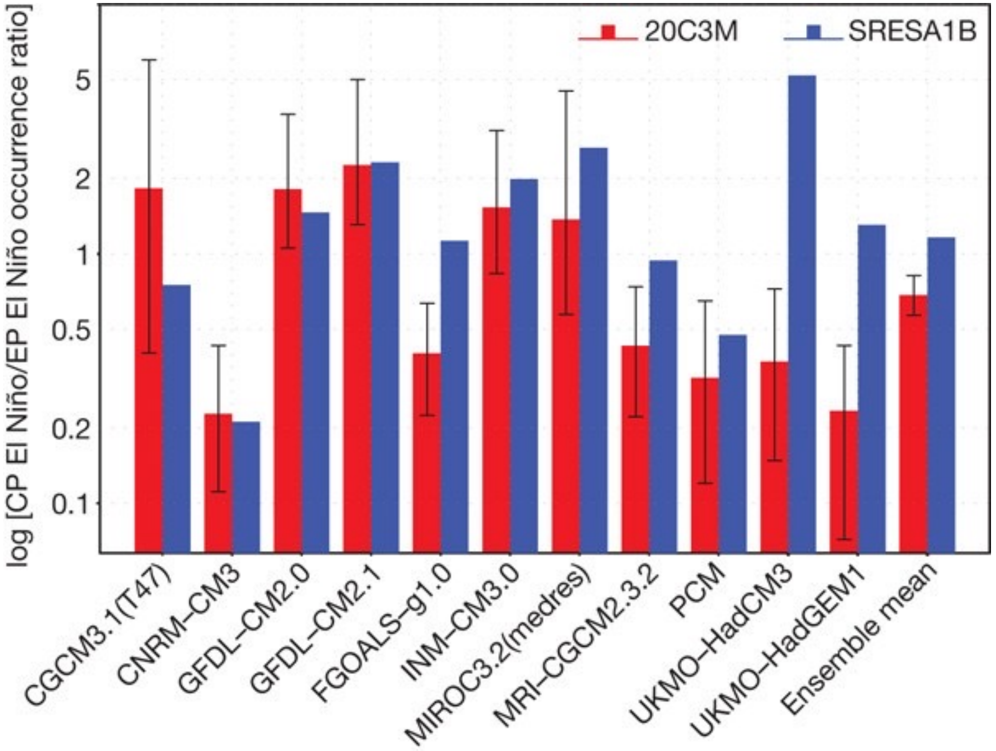


Intensity of El Niño and La Niña events over the Central Equatorial Pacific (Niño-4 region) and the Eastern Pacific (Niño-3 region)

Amplitude of El Niño event increases in the CP, and decreases in the EP, suggesting a possible trend towards more El Niño activity in the CP region.

Lee and McPhaden, 2010

ENSO diversity and climate change



Ratio of CP and EP occurrences in models participating in the CMIP3 project.

Red bars are for historical simulations ending in year 2000 (20C3M) and blue bars are for Special Report for Emission Scenario A1B (SRESA1B) climate projections. Results indicate An increase in the frequency of CP events in most models considered in this study.

Yeh et al., 2009

BUT

Other studies have shown decadal modulations in the frequency of CP vs. EP events in long control simulations (Kug et al., 2010) and also over multiple SST dataset over the last century (Dieppois et al., 2021). Additional studies using Large Ensembles are underway to address this question. Results to-date indicate inter-model differences in ENSO diversity projections.

Key Points

- There are different ways to classify ENSO events in two broad categories, although there are smooth transitions between different spatial patterns
- EP events are positively skewed, while CP events are negatively skewed, raising the question about the role of nonlinearities in ENSO diversity
- Winds, zonal thermocline gradients and precipitation tend to be confined in the western Pacific, while they extend further east for EP events. Precipitation anomalies can extend all the way to the eastern ocean boundary
- Recharge/discharge processes are less pronounced during CP events
- The same key dynamical processes are active at different longitudes along the equatorial Pacific, but their relative importance is zonally asymmetric
- El Niño Modoki has a different structure and is orthogonal to the canonical, but it may be seen as a part of the ENSO evolution

ENSO Diversity and its Precursors
Part II

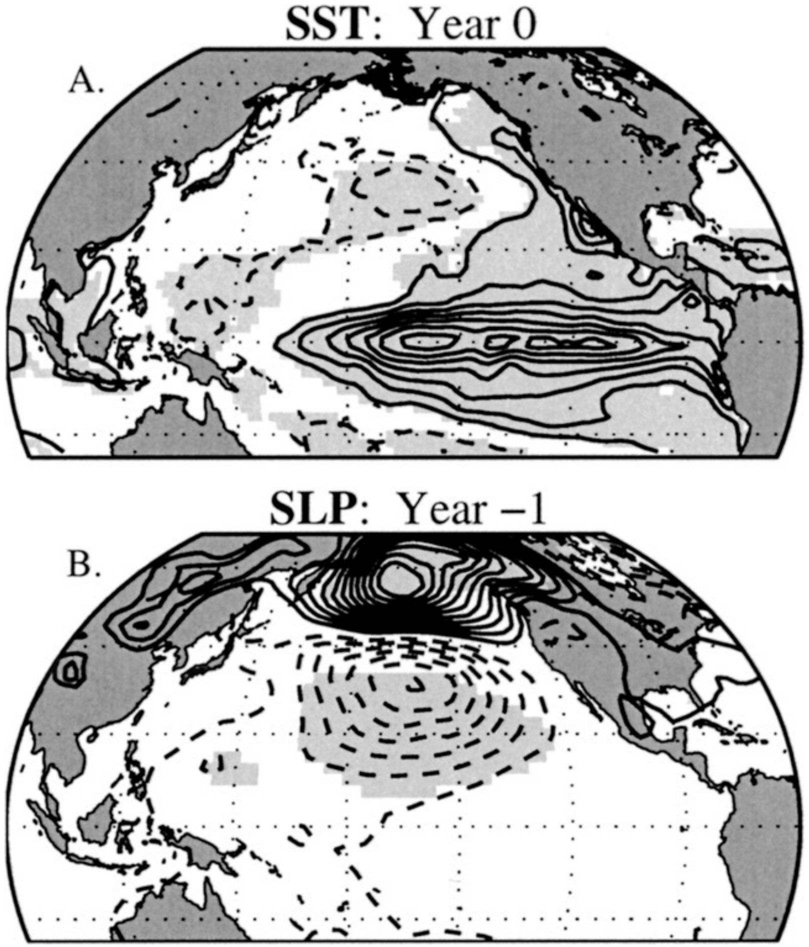
- ENSO precursors. ”Precursors” are patterns of variability that can help us anticipate ENSO events and provide indications of their predictability.

- Review proposed precursors

- Show that they are captured by a Linear Inverse Model (LIM)

- Use LIM to identify precursors of different ENSO types.

Extra-tropical Precursors
Seasonal Footprinting Mechanism (SFM)



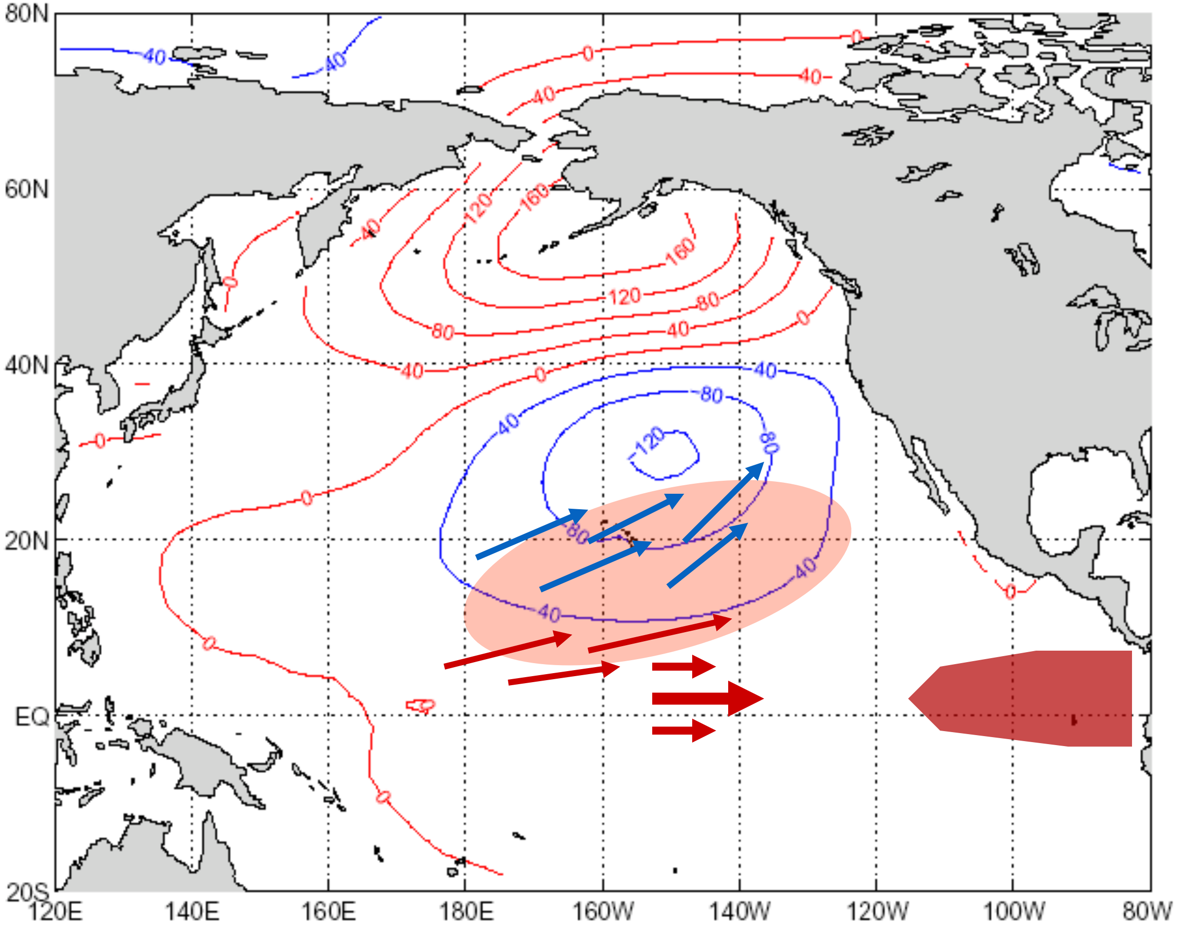
Composites of SST anomalies during El Niño events based on the ONI index (averaged SST anomaly in 6^{o}S-6^{o}N, 180^o-90^{o}W) in NDJFMA (NCEP reanalysis)

Composites of associated SLP anomalies one year earlier: the "North Pacific Oscillation"

Vimont et al., 2003

Precursors

Seasonal Foot Printing Mechanism (SFM)



- *NPO in NDJ (-1)*

  ⇓

- *Winds & Heat Flux*

  ⇓

- *SST in FMA (0)*

  ⇓

- *Tropical Winds*

- *Feedback (e.g. WES)*
  JJAS(0)

  ⇓

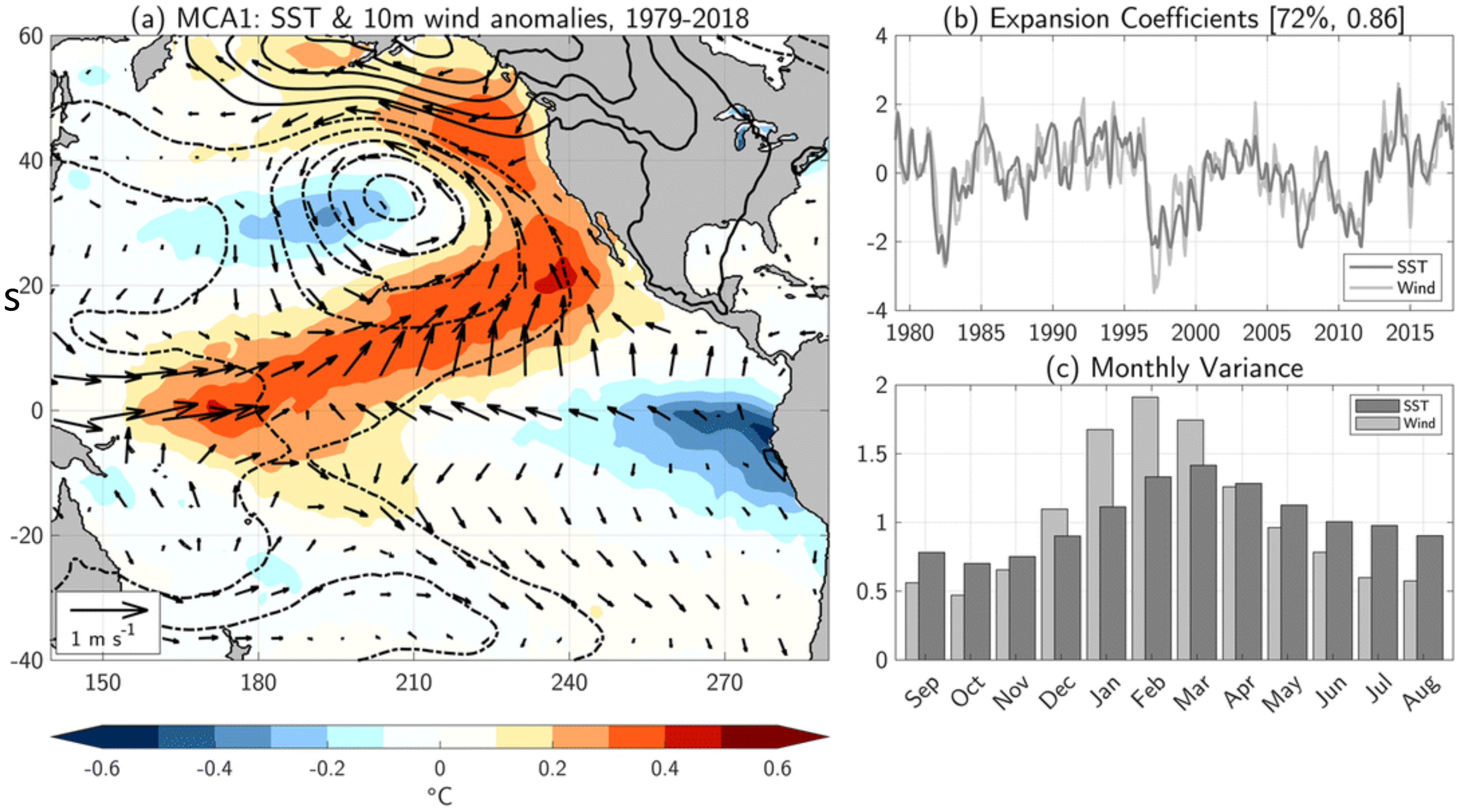
- *El Nino in NDJ(0)*

Vimont et al. 2001, GRL; 2003a&b, J. Climate

The North Pacific Meridional Mode (NPMM)

Obtained through Maximum Covariance Analysis (MCA) of SST and 10 m wind anomalies

SST (shading), SLP (contours), and vector winds (arrows)

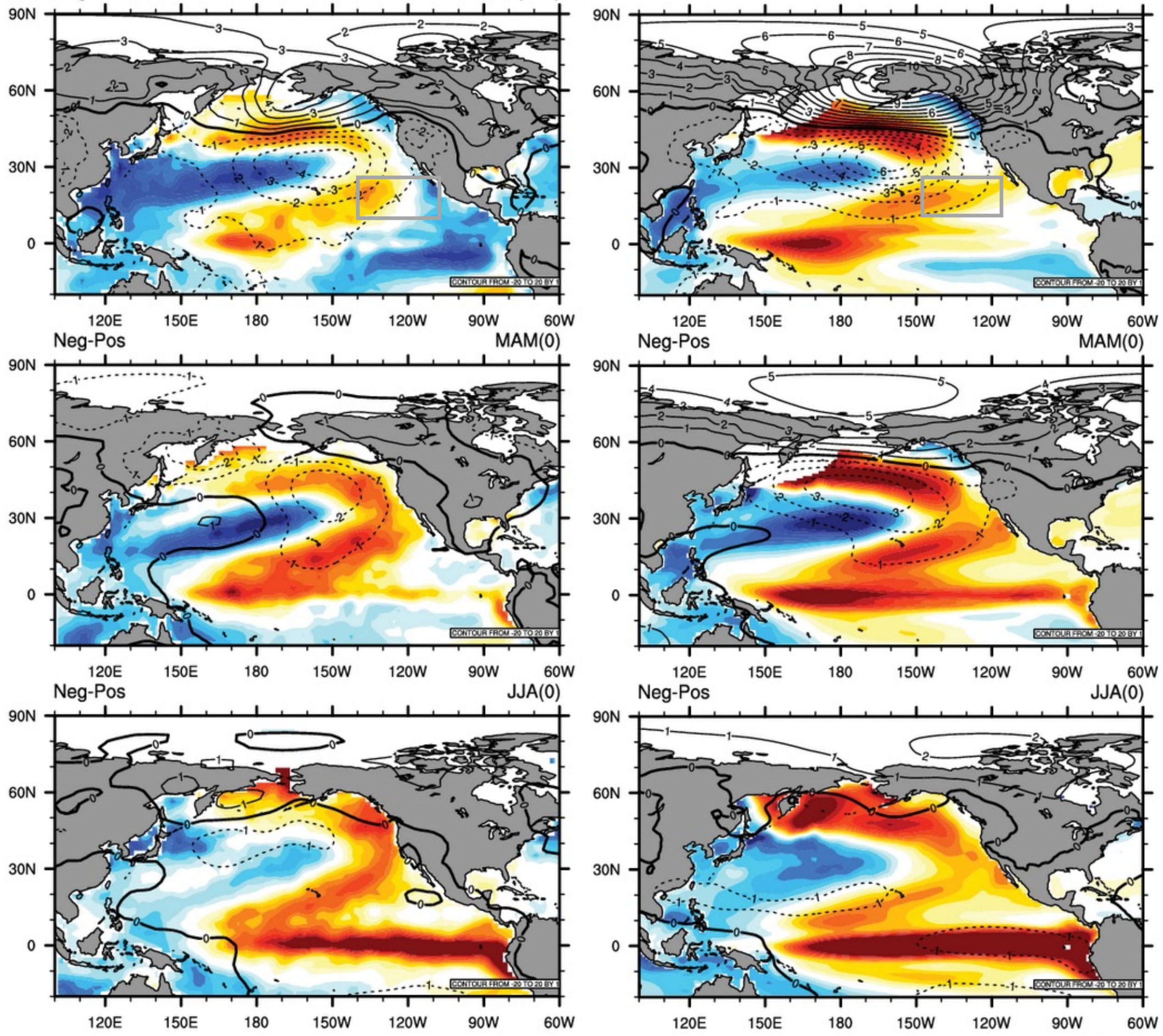


Expansion coefficients of SST (dark grey) and winds (light gray)

Monthly variance of SST (dark grey) and winds (light gray)

Amaya, 2019

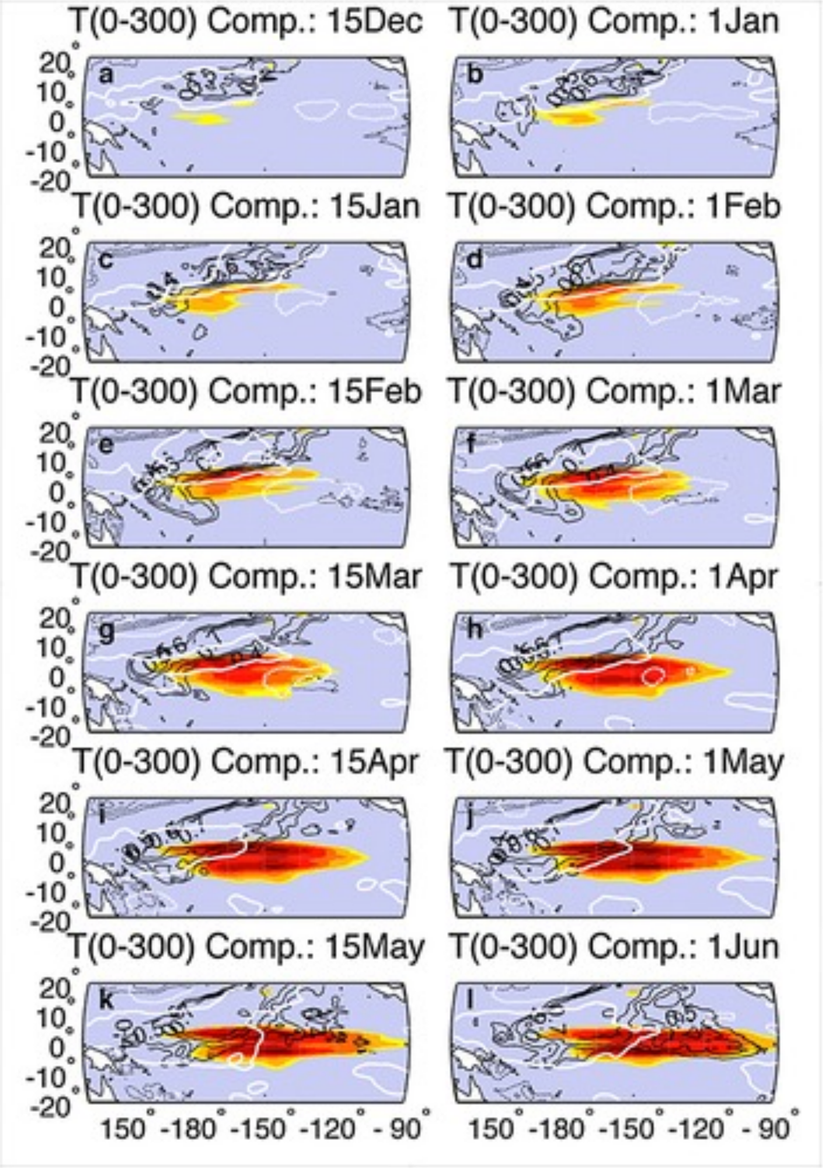
Composite evolution of SST and SLP composites during ENSO development



Composites of SST and SLP based on a SLP sub-tropical index (average SLP in 175°-140°W, 10°-25°N). Composites are computed by averaging the fields when SLP Index is (< -1σ) minus (>1σ).

Deser et al., 2012

NPMM can contribute to the recharge of the equatorial ocean



Off-equatorial wind anomalies can force oceanic Rossby waves, which alter the zonal slope of the thermocline, and modify the equatorward thermocline transport:

"**Trade Wind Charging**" mechanism

Fields concurrent or following negative boreal winter SLP Index values

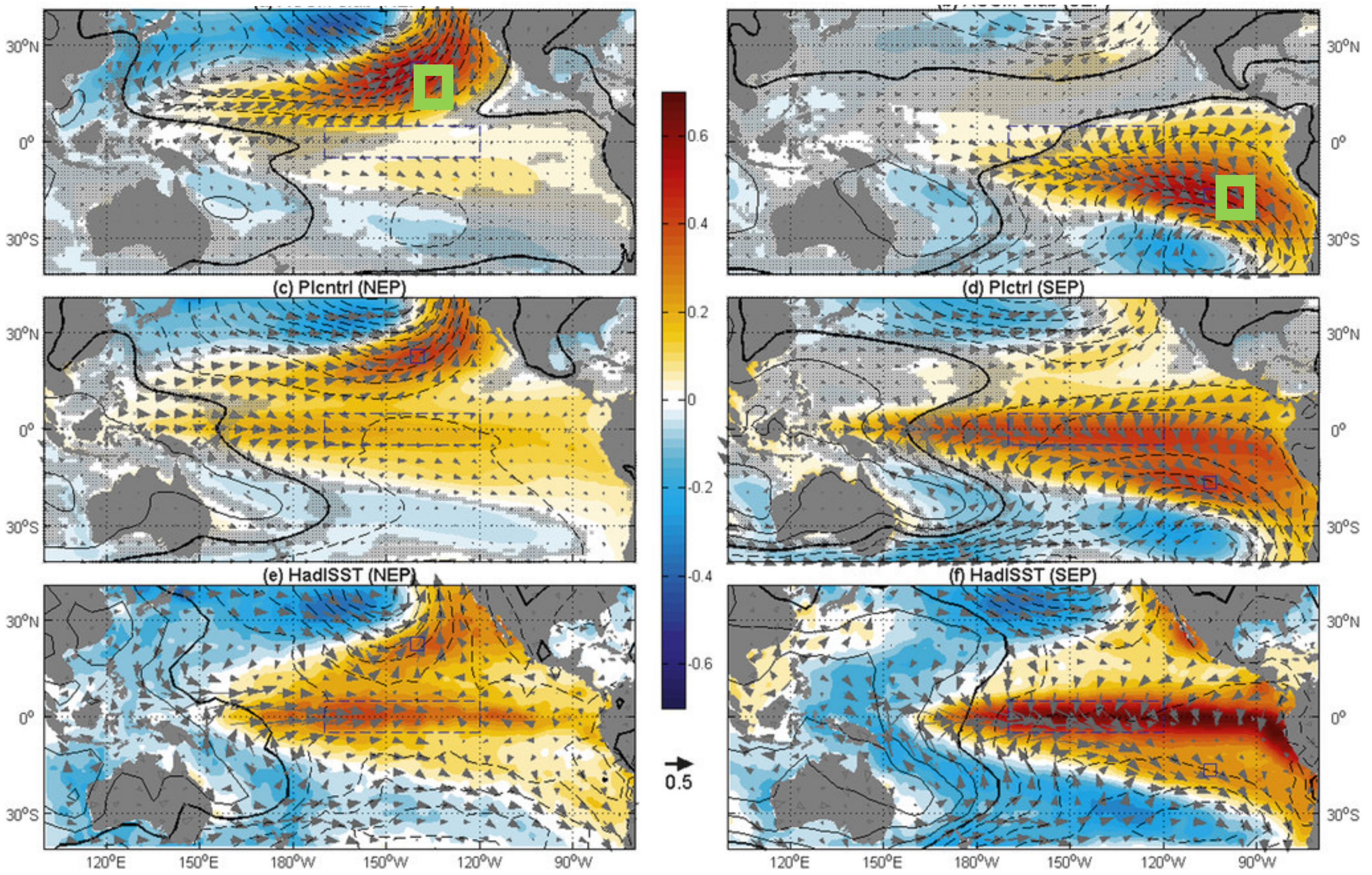
Shading: 0-300 m heat content
Black contours : SST
White contours: Zonal wind stress anomalies

Anderson et al. (2013)

South Pacific Meridional Mode (SPMM)

NPMM

SPMM



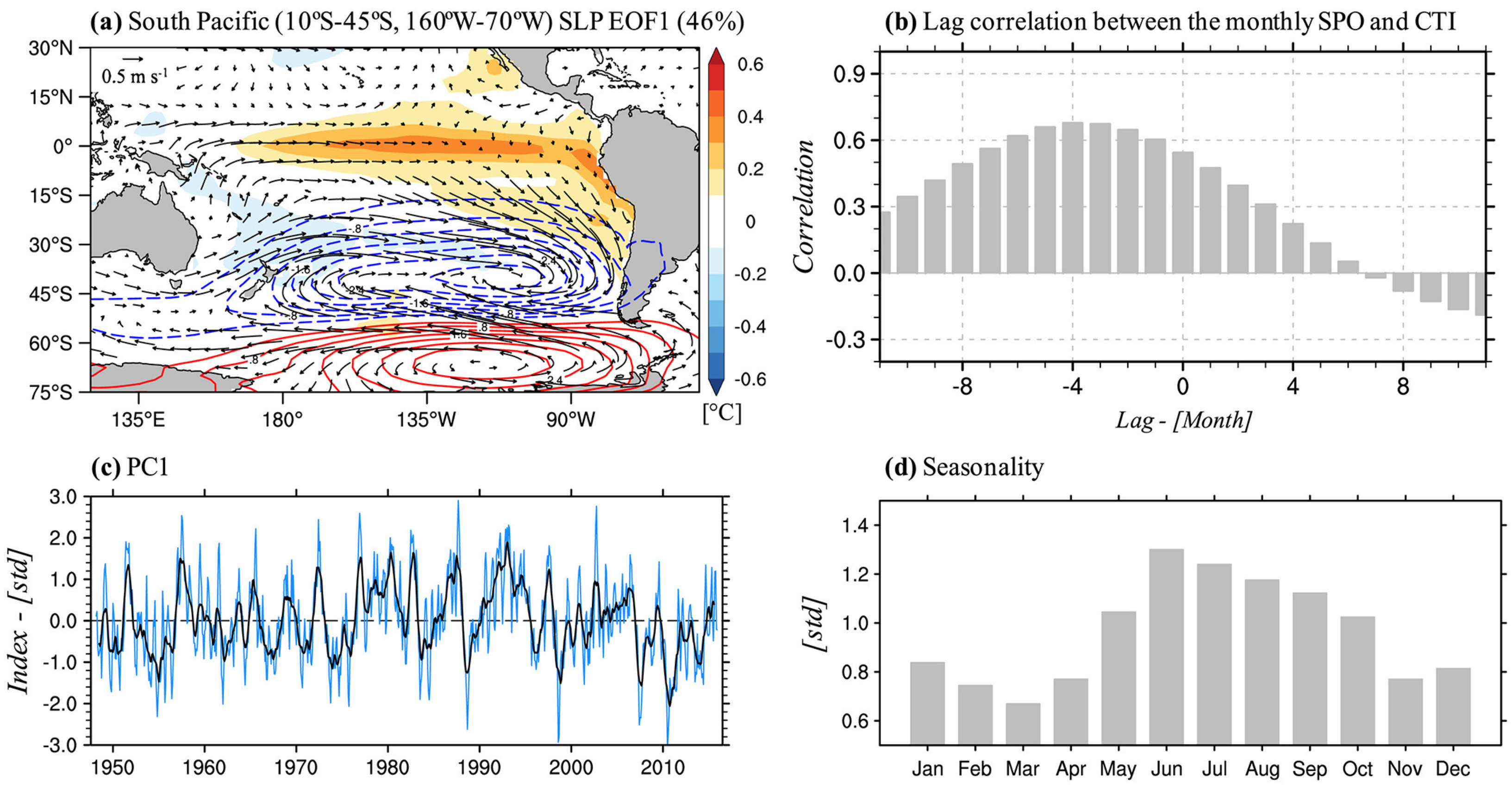
Multi-model mean of 11 AGCM-slab models

Pre-industrial control simulations of 10 coupled models (CMIP3)

HadISST + SLP (UK Met Office) + Surface winds from NCEP-NCAR reanalysis.

Zhang et al., 2014

Forcing of South Pacific Meridional Model



"**South Pacific Oscillation**" (SPO) is defined as the leading PC of SLP in 10ºS-45ºS, 160ºW-70ºW.

It peaks in boreal Summer, and has a significant correlation with CTI at a lead time of 3-4 months.

You and Furtado (2017)

NPMM and SPMM are the leading extra-tropical precursors for ENSO. We will now see that we can obtain such precursors as part of optimal initial conditions for ENSO in the context of a Linear Inverse Model (LIM).

Precursors in a Linear Inverse Modeling (LIM) framework

$$d\boldsymbol{x}/dt = \boldsymbol{L}\boldsymbol{x} + \boldsymbol{\xi}$$

$\boldsymbol{x}$ state vector including SST and SSH EOFs
$\boldsymbol{L}$ Dynamical Operator
$\boldsymbol{\xi}$ Stochastic forcing, which is white in time, but spatially coherent

$$\boldsymbol{x}(\tau) = \boldsymbol{G}(\tau)\boldsymbol{x}(0) = \exp(\boldsymbol{L}\tau)\,\boldsymbol{x}(0)$$

$$\boldsymbol{G}(\tau) = \boldsymbol{C}(\tau)/\boldsymbol{C}(0)$$

$\boldsymbol{C}(\tau)$ covariance matrix at lag τ
$\boldsymbol{C}(0)$ Instantaneous covariance matrix

To reduce the number of degrees of freedom, the system variables are usually projected on their leading EOFs, retaining about 80% of each field's variance

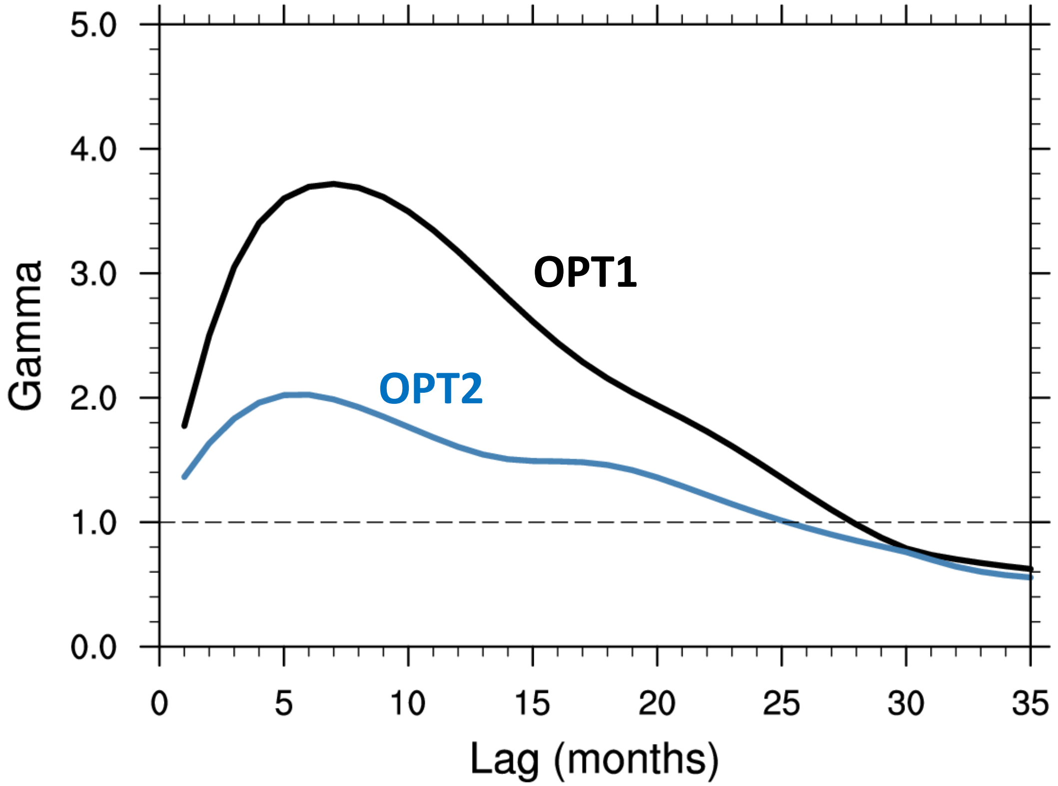
Modal Growth in the LIM

$$dx/dt = Lx + \xi$$

The dynamical operator L is not symmetric, so the eigenvectors are not orthogonal. Transient growth is possible through constructive interference of some of the eigenvectors.

$$x(\tau) = G(\tau)x(0)$$

$$\gamma^2(\tau) = \frac{x(\tau)^T x(\tau)}{x(0)^T x(0)} = \frac{x(0)^T G(\tau)^T G(\tau) x(0)}{x(0)^T x(0)}$$



Modal Growth in the LIM

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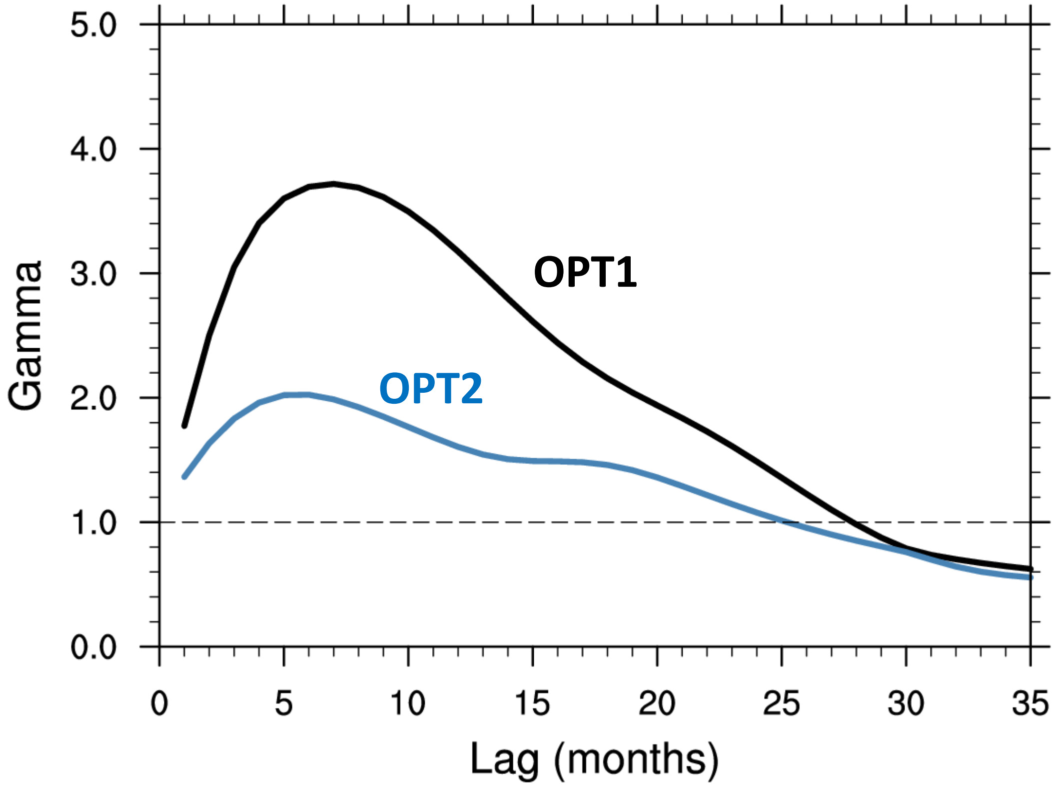
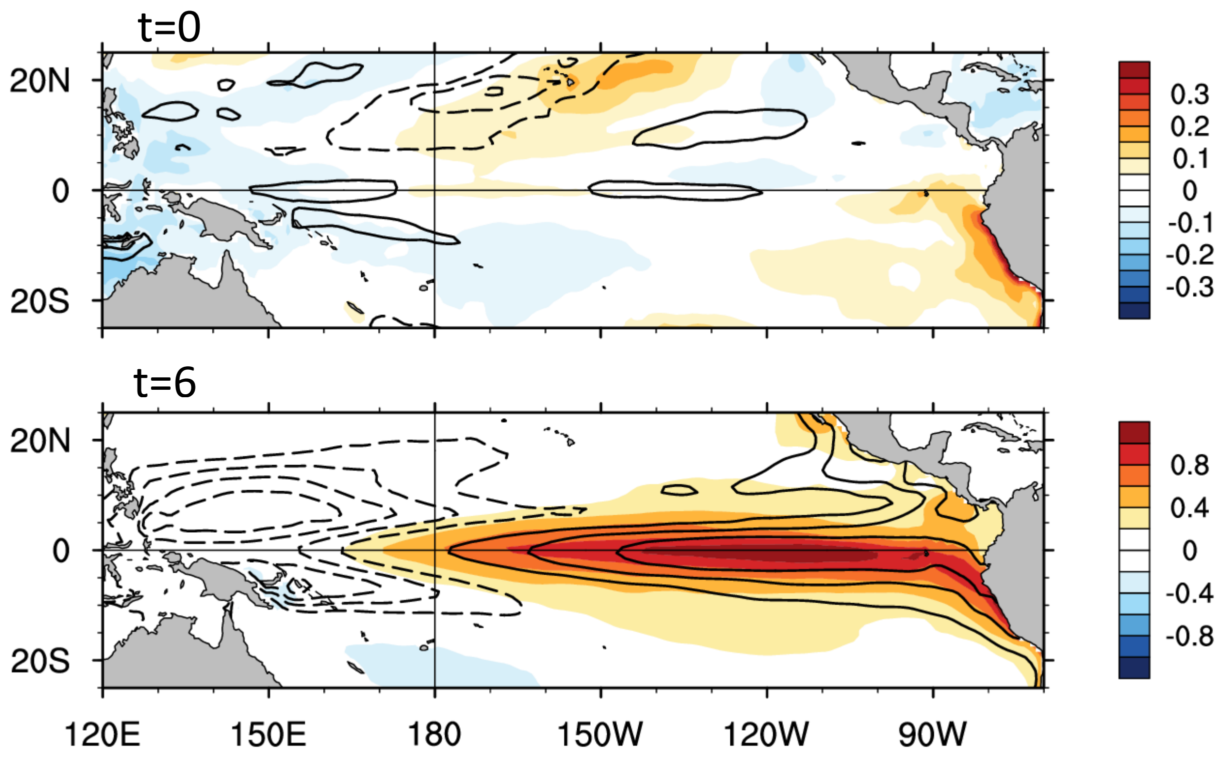
$$\gamma^2(\tau) = \frac{\boldsymbol{x}(\tau)^T\boldsymbol{N}\boldsymbol{x}(\tau)}{\boldsymbol{x}(0)^T\boldsymbol{x}(0)} = \frac{\boldsymbol{x}(0)^T\boldsymbol{G}(\tau)^T\boldsymbol{N}\boldsymbol{G}(\tau)\boldsymbol{x}(0)}{\boldsymbol{x}(0)^T\boldsymbol{x}(0)}$$



N = ***I*** Euclidean norm (L2 norm)

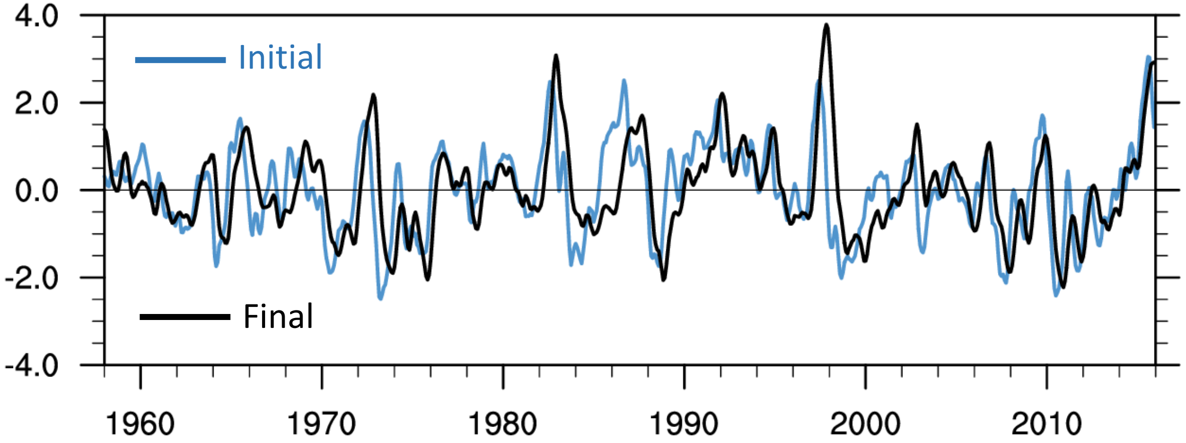
N can be chosen to find optimal growth in a specified "direction"

Leading Optimal Structure (L2-norm)



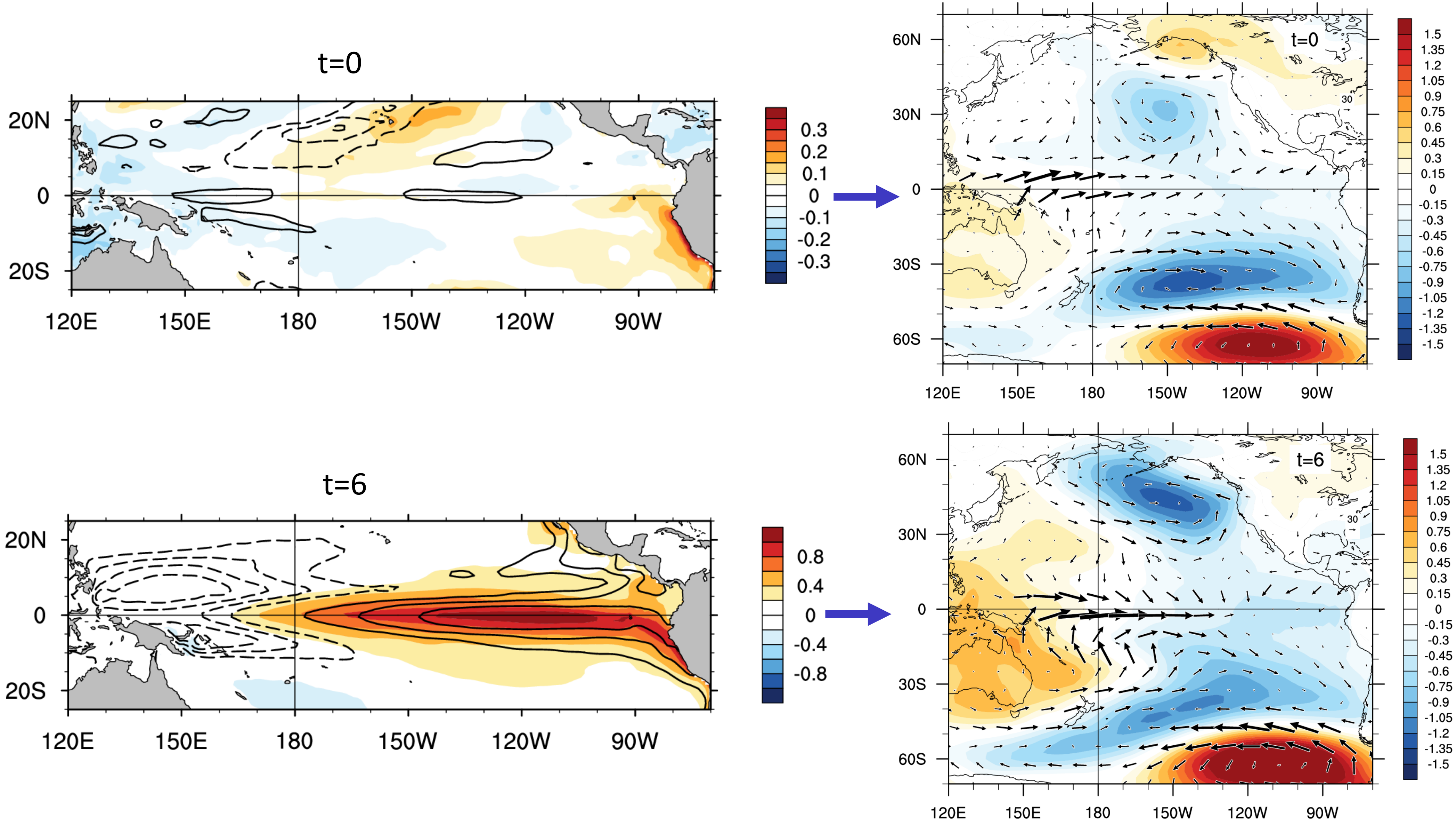
Initial conditions (t=0) show SST structures similar to the North and South Pacific Meridional Modes (PMM and SPMM) with positive SSH anomalies (deeper thermocline) in the central and western equatorial Pacific.

Final state (t=6 months) corresponds to a mature El Niño conditions with the largest SST anomalies in the central/eastern Pacific, and SSH anomalies indicating a reduced zonal thermocline slope.



Correlation coefficient is 0.83 when Initial time series leads Final time series by 4 months, and 0.75 at a lead time of 6 months. Ocean conditions with a large projection on the initial state can be expected to be conducive to an El Niño event.

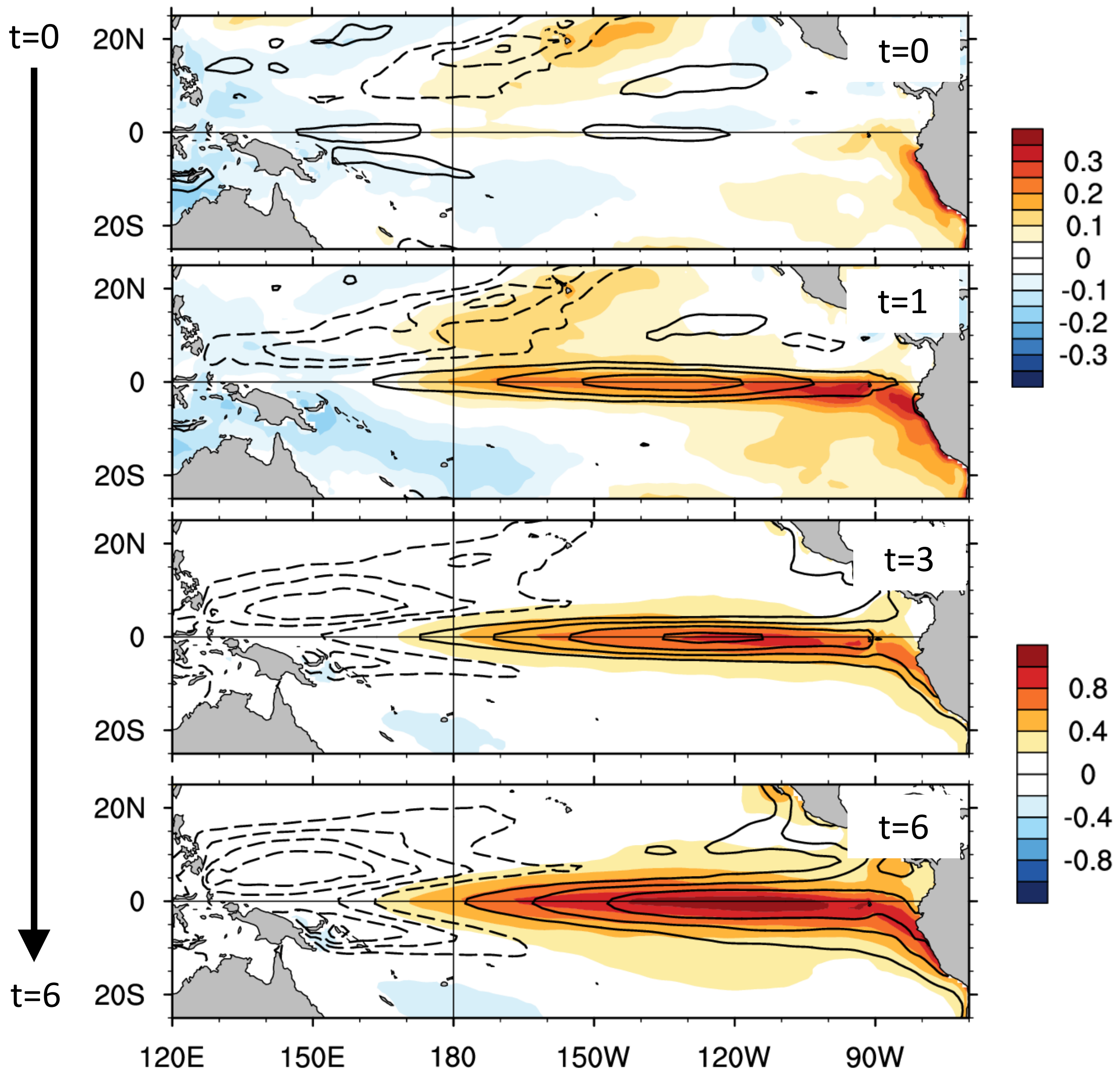
Associated SLP and vector winds fields



SLP (shading) includes NPO and SPO

SLP includes a deepened Aleutial Low in the Northern Hemisphere,

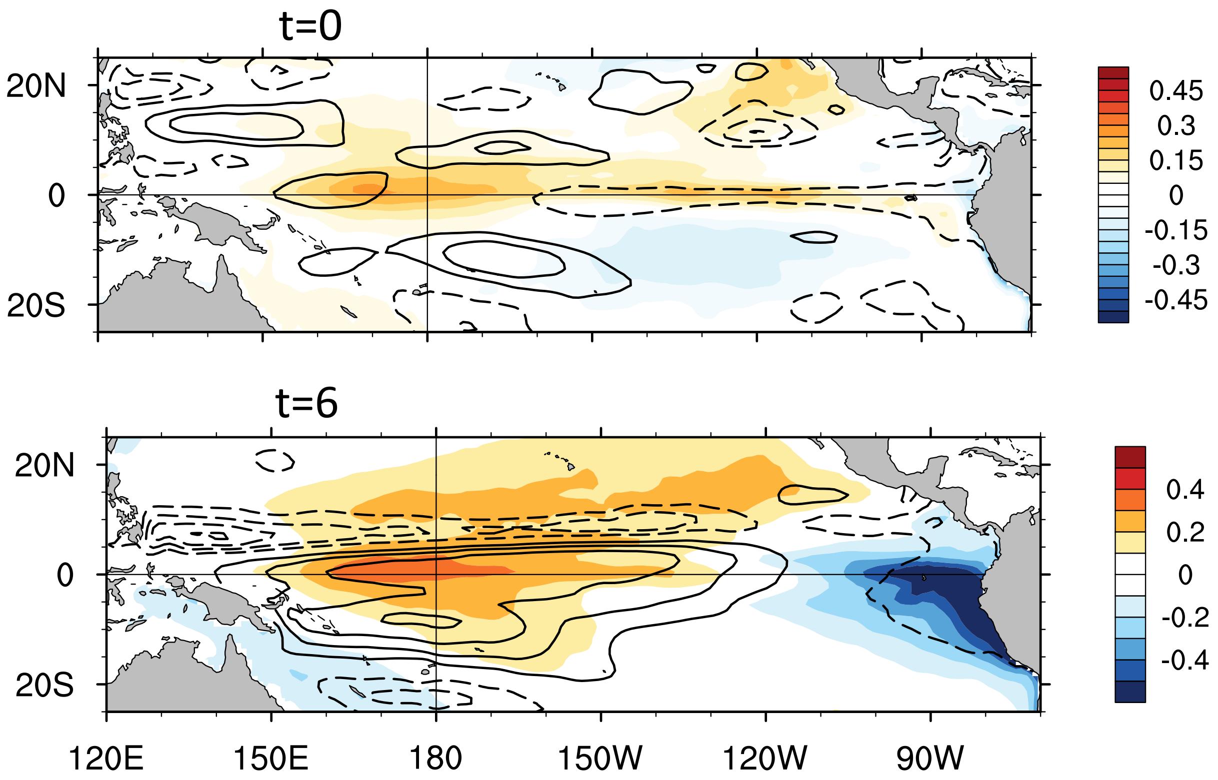
Time evolution of leading optimal mode



From t=0 to t=1, SST anomalies of the PMM propagates toward the central equatorial Pacific, and SST anomalies of the SPMM extend westward along the equator. Heat content increases rapidly along the equator, maybe associated with the “Trade Wind Charging” mechanism.

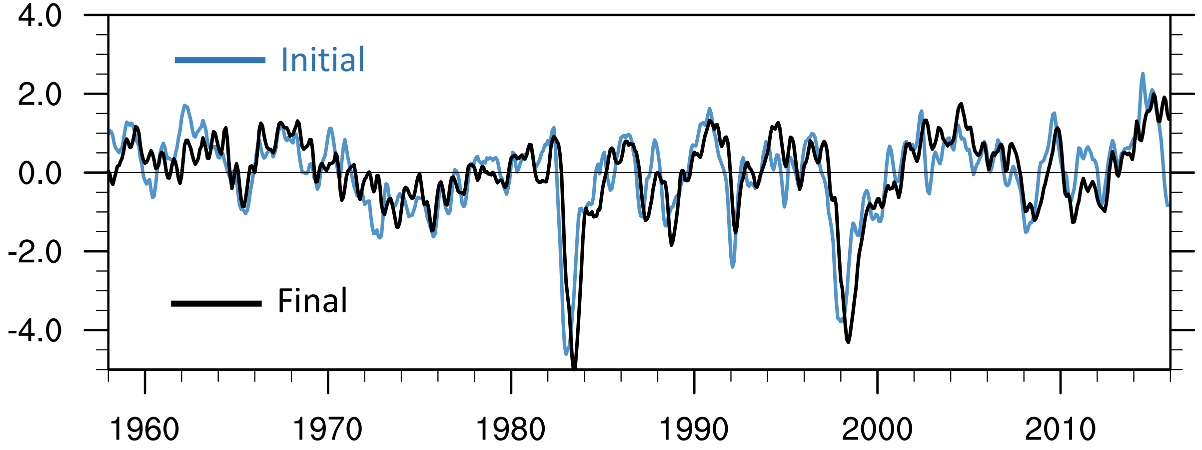
As positive heat content anomalies grow along the equator, negative SSH anomalies, likely associated with upwelling oceanic Rossby waves, propagates from the off-equatorial regions to the western equatorial Pacific to produce the thermocline shoaling of the mature ENSO state.

Second Optimal Structure



Second optimal structure develops from an initial state with weak positive anomalies along the equator, especially in the eastern Pacific, and negative SSH anomalies in the eastern Pacific.

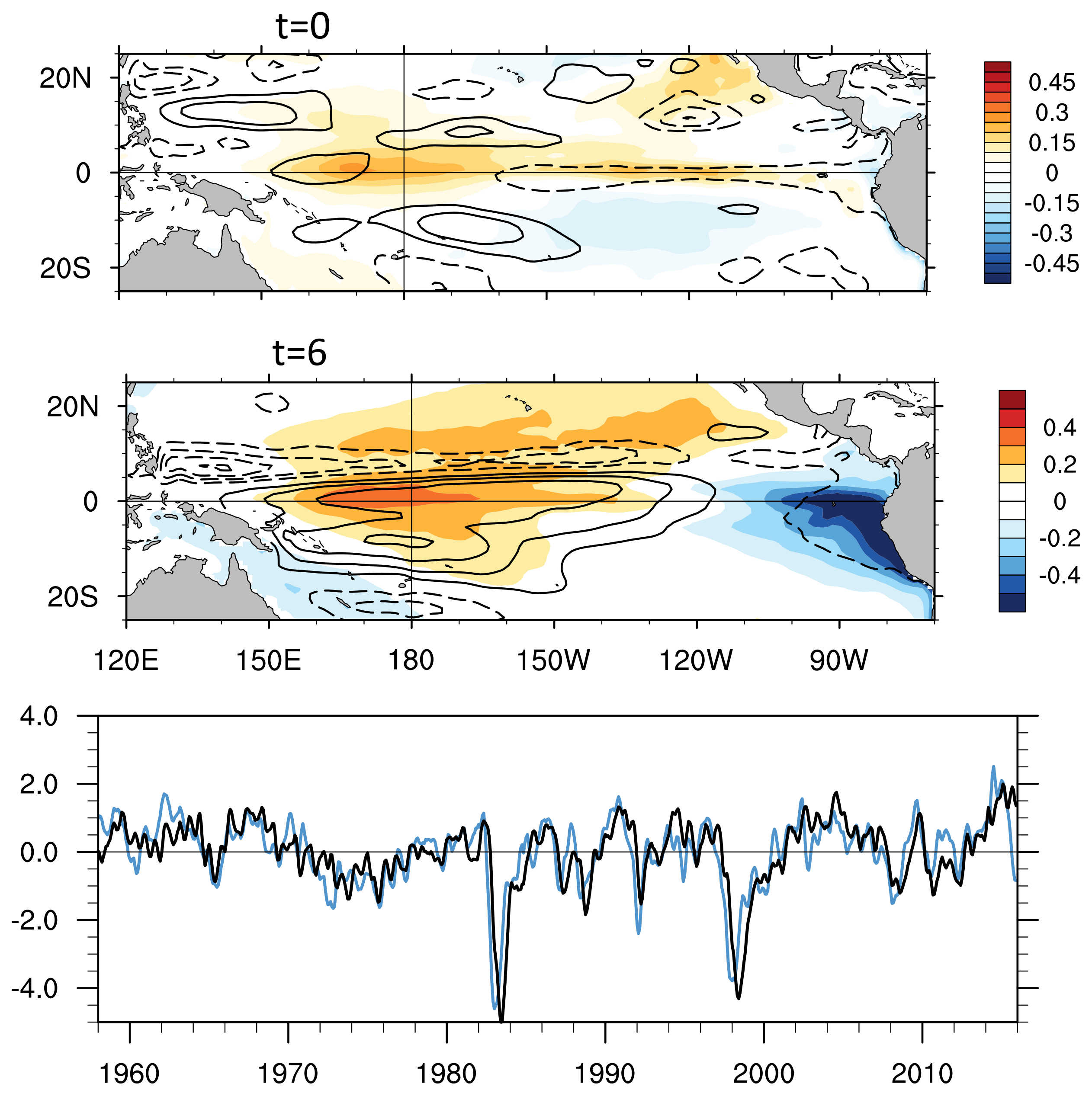
Final state resembles a Modoki pattern.

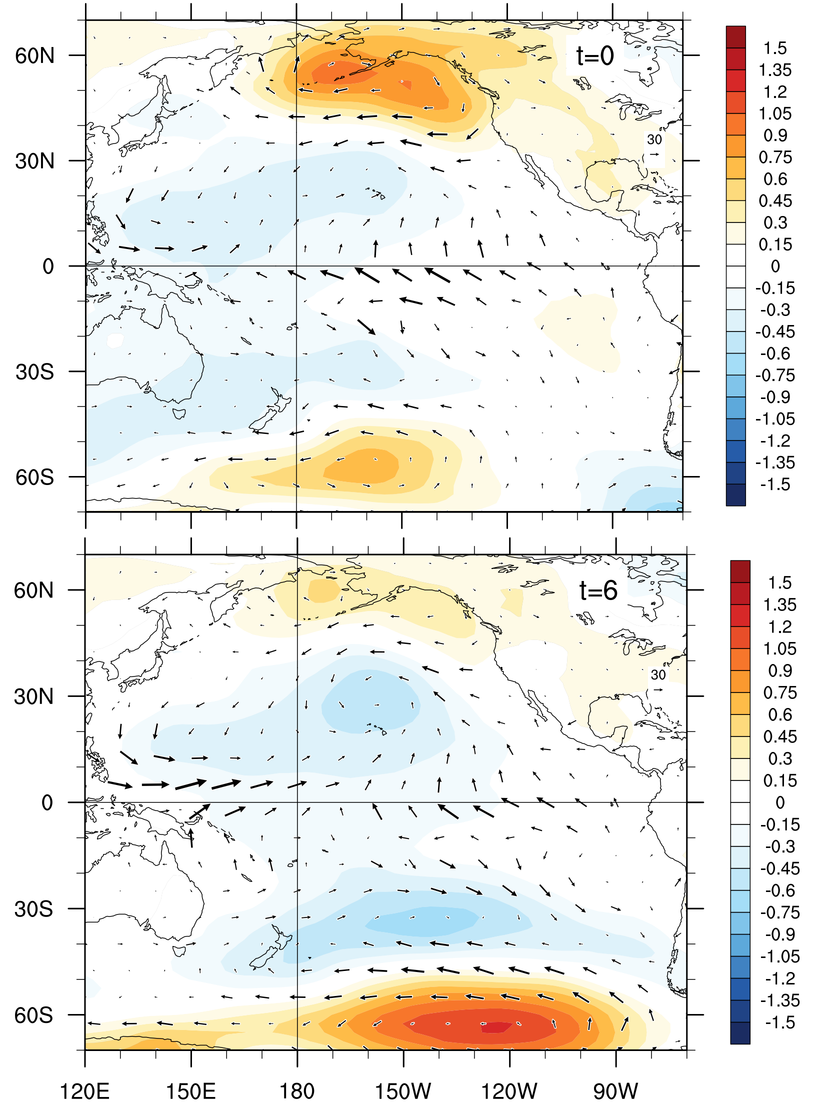


Correlation coefficient is 0.86 when Initial time series leads Final time series by 3-4 months, and **0.79** at a lead time of 6 months.

This empirical mode captures the La Niña conditions and exhibits a negative skewness.

Second Optimal Structure





ENSO diversity from a LIM perspective

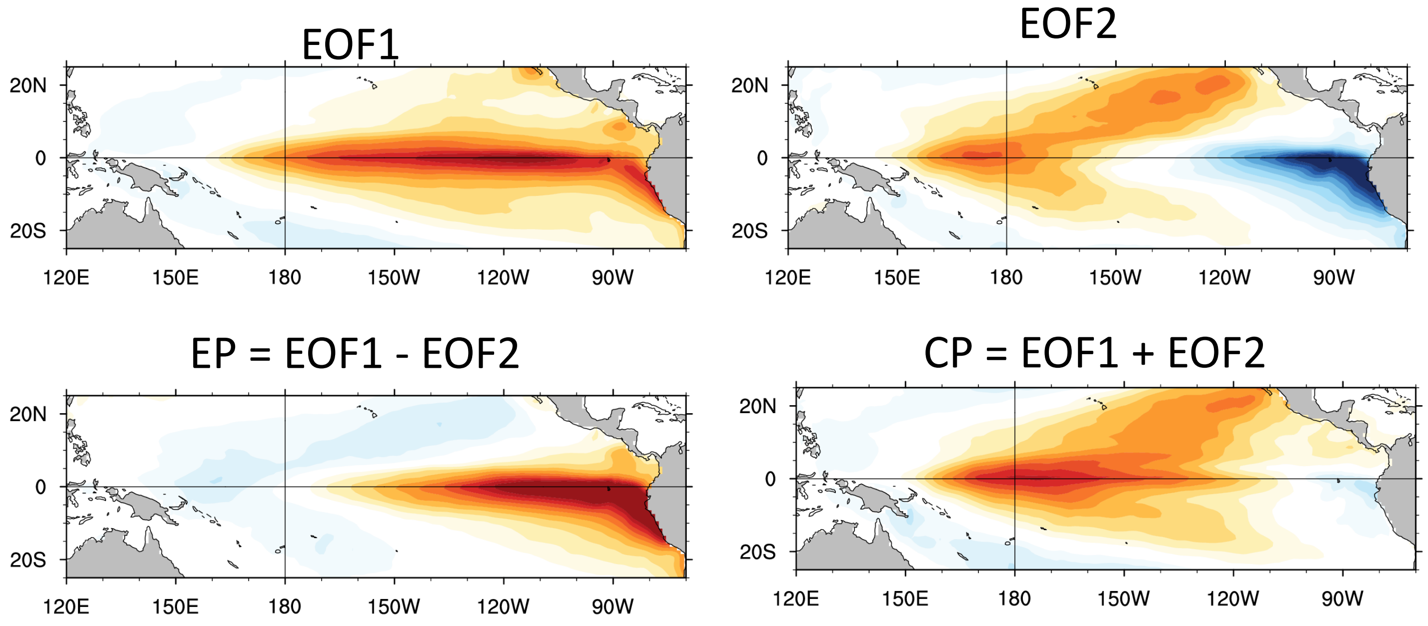
- Although linear, the LIM supports different flavors of ENSO. Thus, ENSO diversity can arise without deterministic dynamical nonlinearities.

- Since initial state vectors can contain different combinations of our two initial growing structures, different flavors of ENSO can be generated in a quasi-continuum fashion.

Second growing structure is a specific expression of CP El Nino, resembling El Nino Modoki.

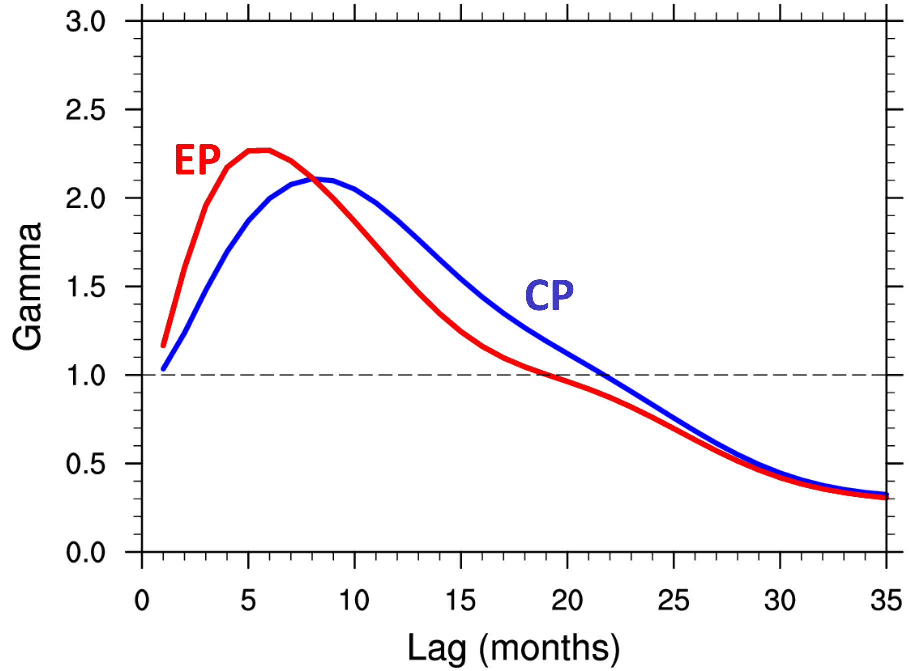
What are the initial conditions for EP and CP events obtained with different definitions?

EP and CP events from definition of Takahashi et al. (2011)



$$\gamma^2(\tau) = \frac{\boldsymbol{x}(\tau)^T \boldsymbol{N} \boldsymbol{x}(\tau)}{\boldsymbol{x}(0)^T \boldsymbol{x}(0)} = \frac{\boldsymbol{x}(0)^T \boldsymbol{G}(\tau)^T \boldsymbol{N} \boldsymbol{G}(\tau) \boldsymbol{x}(0)}{\boldsymbol{x}(0)^T \boldsymbol{x}(0)}$$

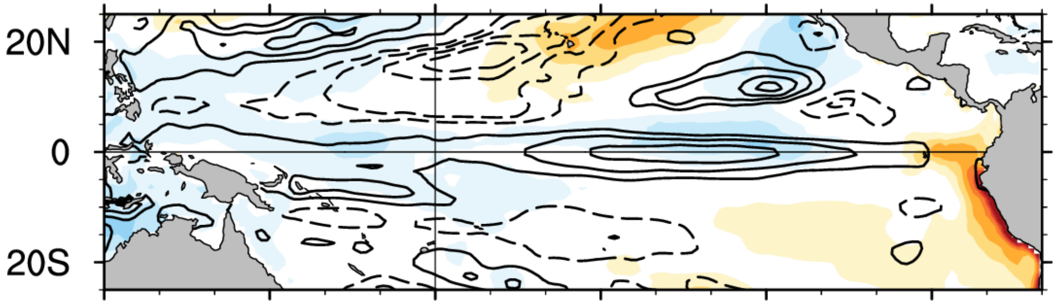
Maximum Amplification curves for EP and CP El Niño events



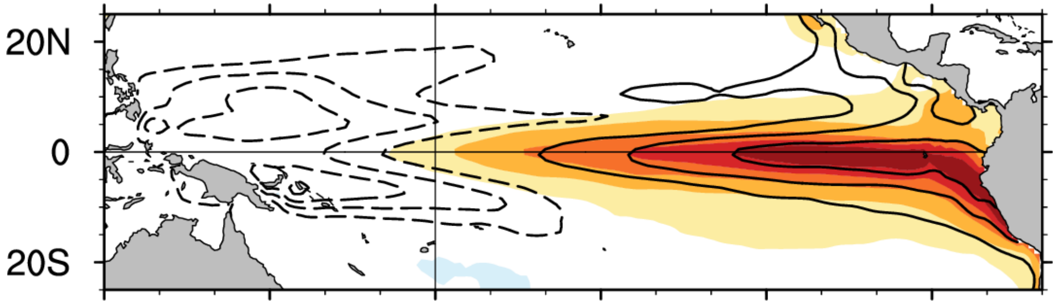
Precursors of ENSO diversity (SST, SSH)

EP events

$$x_E(0) = \begin{bmatrix} SST_{E0} \\ SSH_{E0} \end{bmatrix}$$

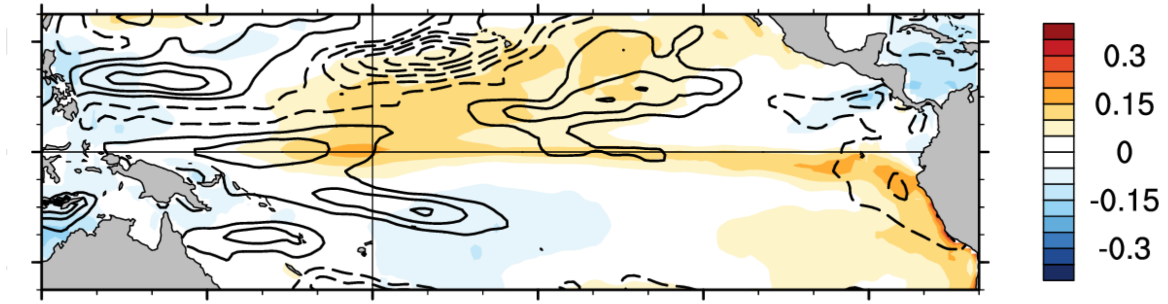


$$x_E(6) = G(6)\, x_E(0)$$

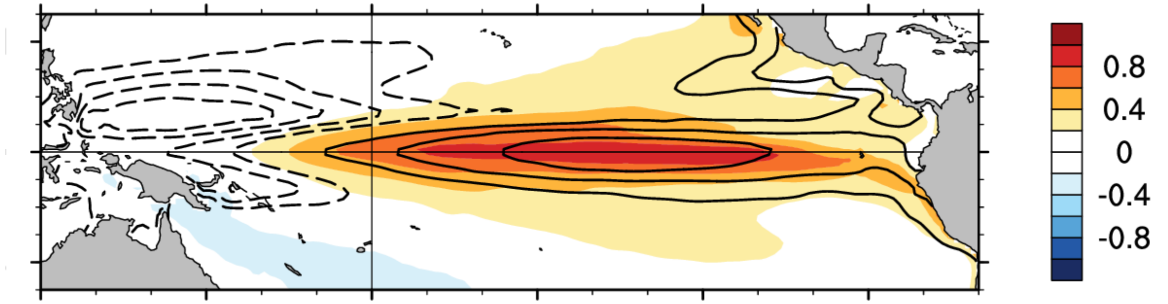


CP events

$$x_C(0) = \begin{bmatrix} SST_{C0} \\ SSH_{C0} \end{bmatrix}$$



$$x_C(6) = G(6) x_C(0)$$

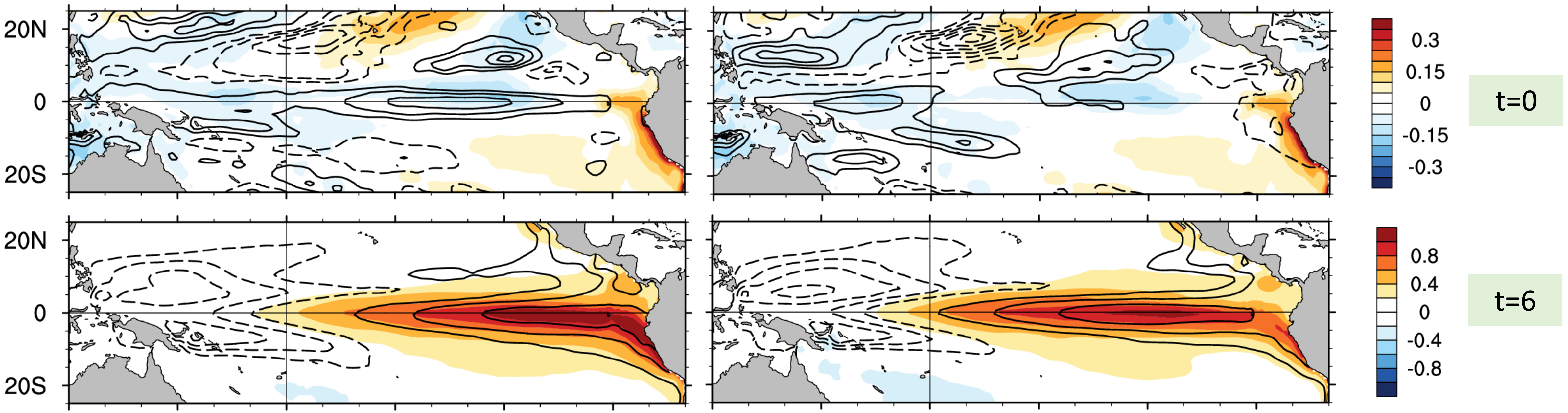


Influence of subsurface initial/background conditions

EP events

$x_E(0) = \begin{bmatrix} SST_{E0} \\ SSH_{E0} \end{bmatrix}$

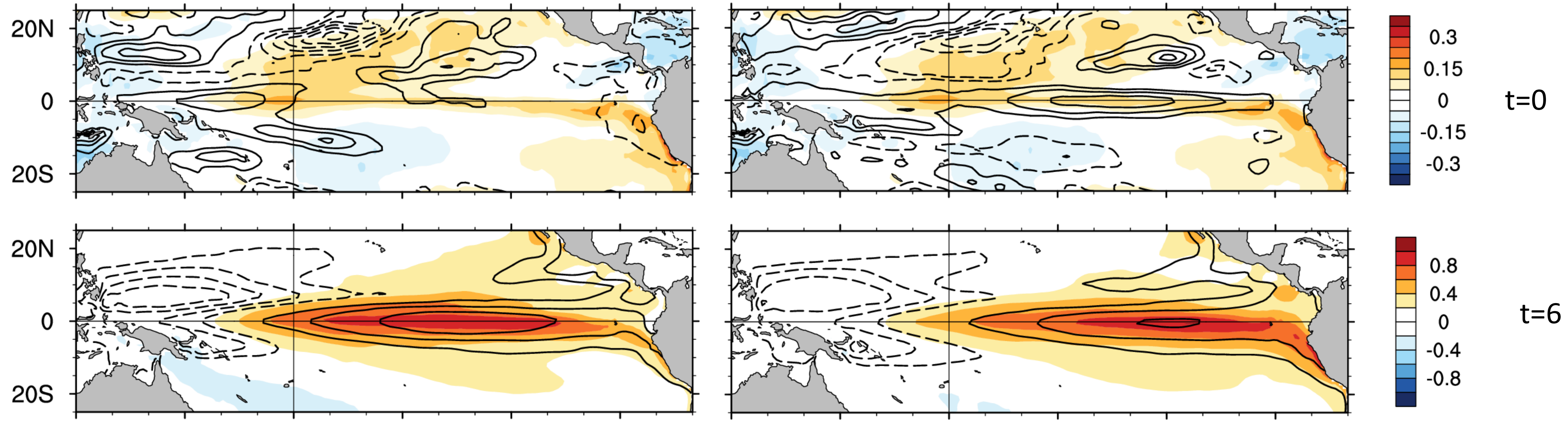
$\tilde{x}_E(0) = \begin{bmatrix} SST_{E0} \\ SSH_{C0} \end{bmatrix}$



Influence of subsurface initial/background conditions

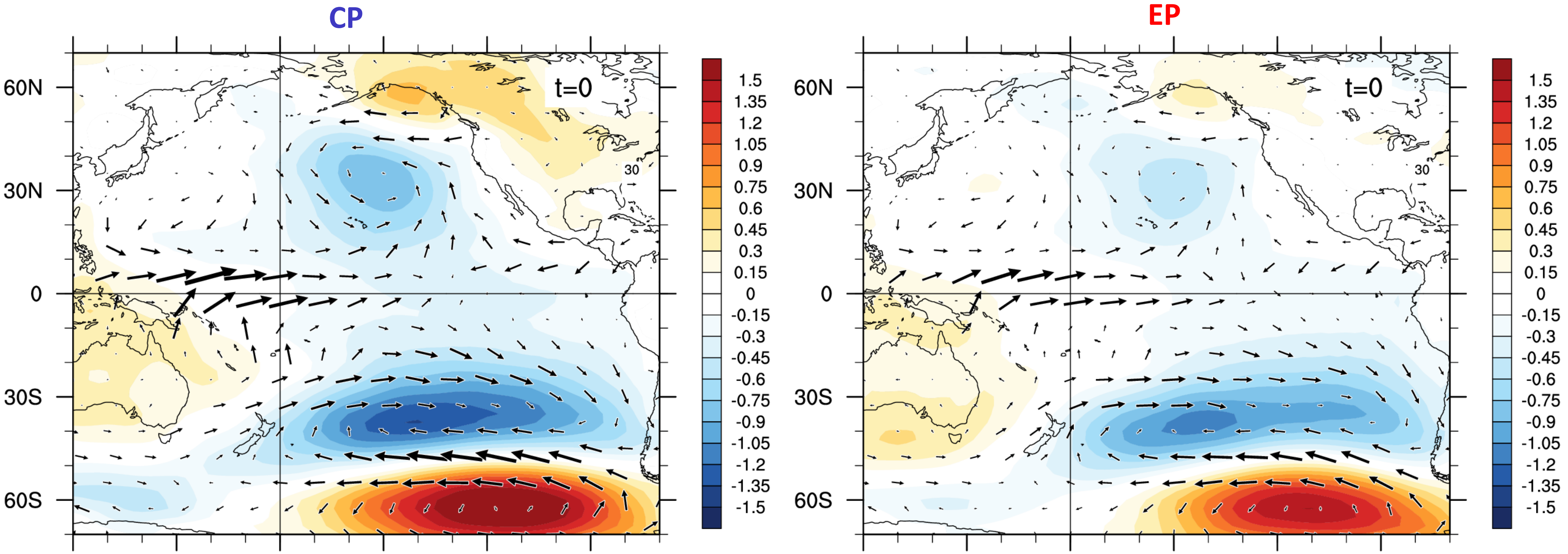
CP events

$$x_C(0) = \begin{bmatrix} SST_{C0} \\ SSH_{C0} \end{bmatrix} \qquad \tilde{x}_C(0) = \begin{bmatrix} SST_{C0} \\ SSH_{E0} \end{bmatrix}$$



Initial subsurface conditions, as well slowly varying background conditions can partly control the development of different types of ENSO events, and need to be captured to predict them, at least as a necessary condition

Precursors of ENSO diversity (SLP, Winds)



SLP and winds precursors are very similar to those seen for “canonical” events, but they are much weaker for EP events.

We can examine dominant patterns of wind variability and their relationship with ENSO diversity

Data

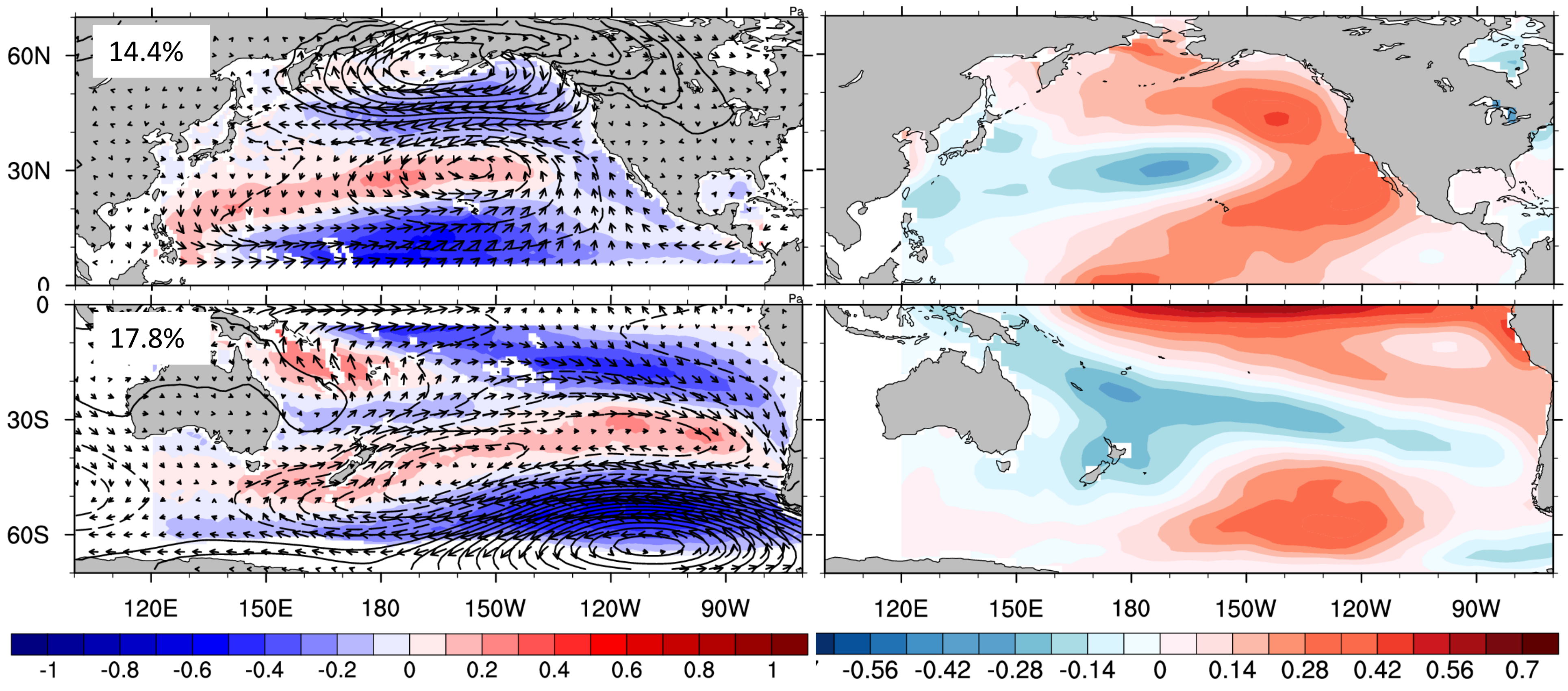
10m Wind Speed data from 3 different state-of-the-art products:

- Merged satellite ocean surface winds (“SAT”, 1988 – present)
- ECMWF-ERA5 Atmospheric Reanalysis (1979 – present)
- 20CRv3 Atmospheric Reanalysis (1836 – 2015)

Hemispheric EOFs of wind speed captures Northern and Southern Hemisphere ENSO precursors

SAT Hemispheric EOFs (shading) with SLP (contour) and vector wind (arrow) regressions

SST regressions on PC1 of wind speed



SLP shows dipoles typical of the North Pacific Oscillation (NPO) in the Northern Hemisphere, and South Pacific Oscillation (SPO) in the Southern Hemisphere

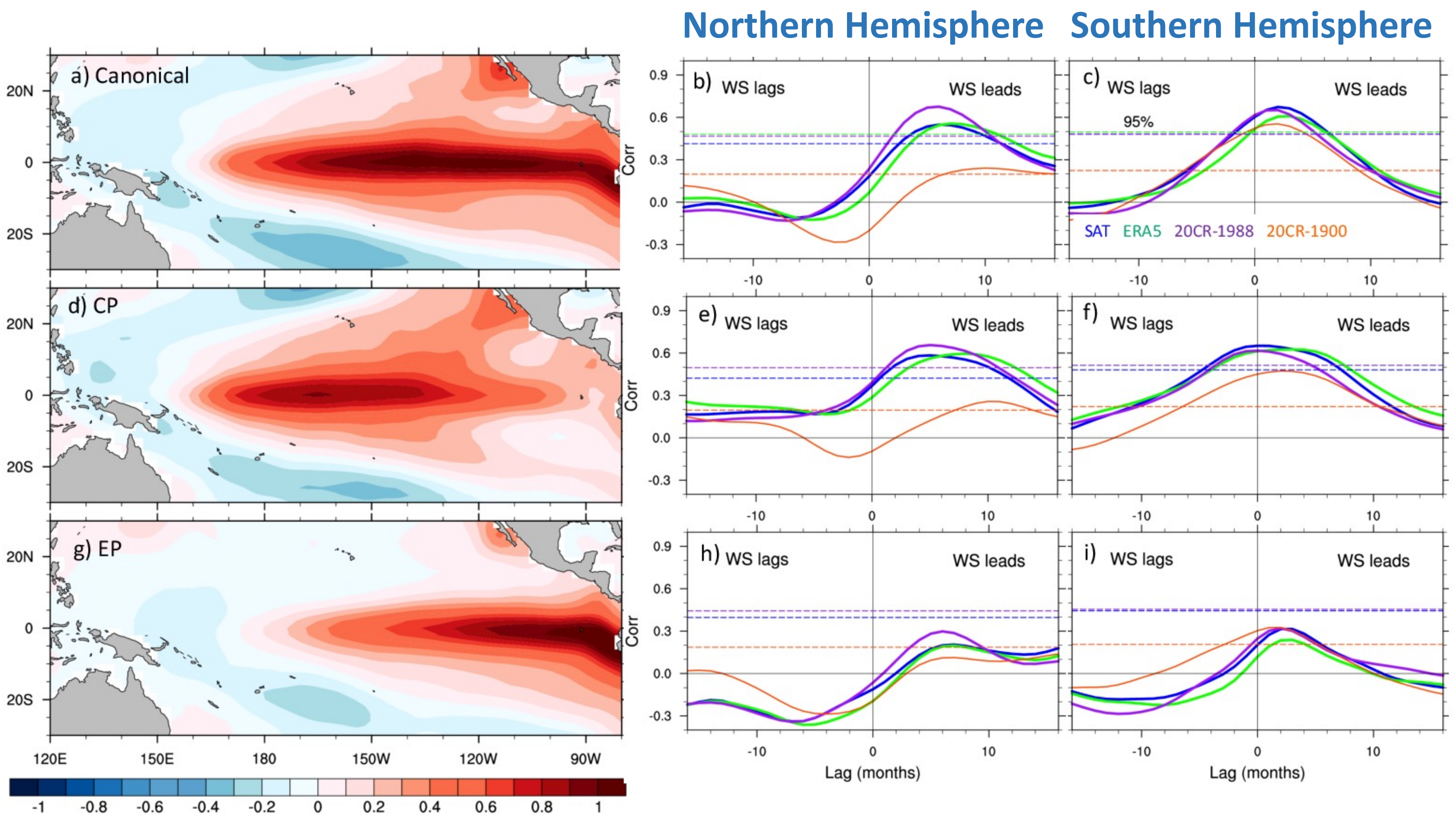
SST regressions show structures consistent with the PMM in the NH, anomalies of the opposite sign in the WNP, and anomalies consistent with the SPMM in SH.

What is the relationship of the wind speed patterns with different ENSO types?
Is there a preferred relationship with E- or C-type events?

SST EOF1

C-mode

E-mode



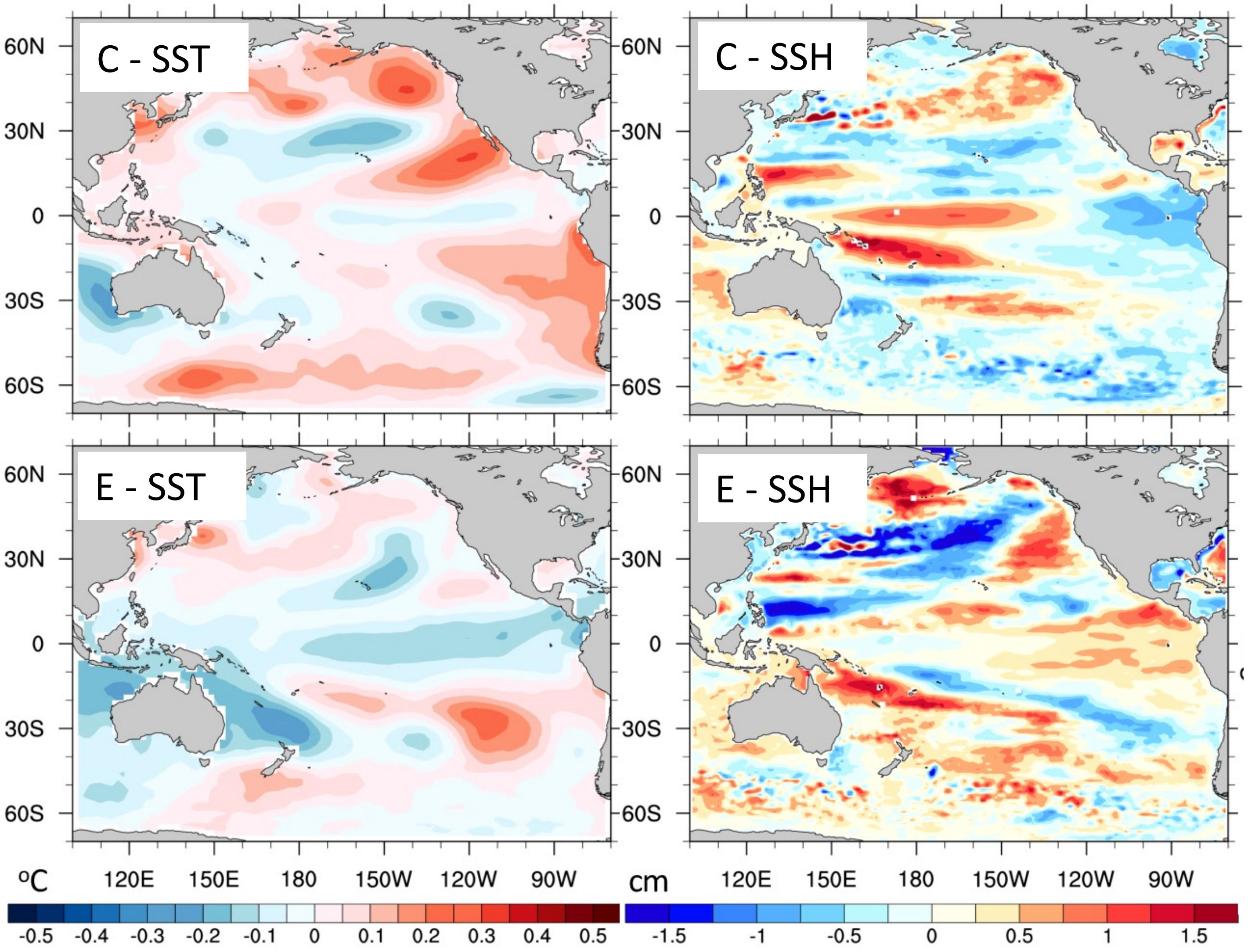
Correlations since 1900 are larger in the SH than in the NH

Correlations with E-index are not statistically significant

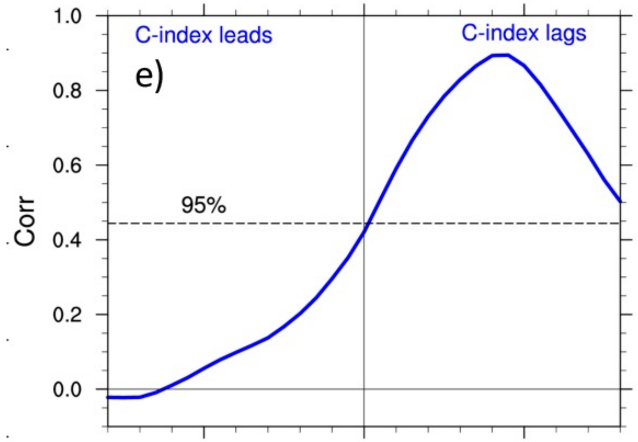
Extra-tropical precursors captured by the leading pattern of wind speed are not effective triggers of Eastern Pacific events.

What are the precursors of E-type events?

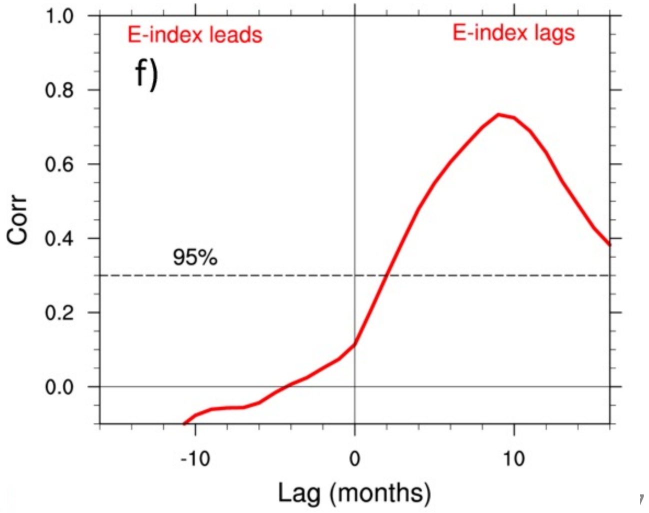
$E(t) = \boldsymbol{H}_E(t)\,\boldsymbol{x}_E(0)$ $C(t) = \boldsymbol{H}_C(t)\,\boldsymbol{x}_C(0)$ $t = 9$ months, $\boldsymbol{x}$=(SST, SSH)



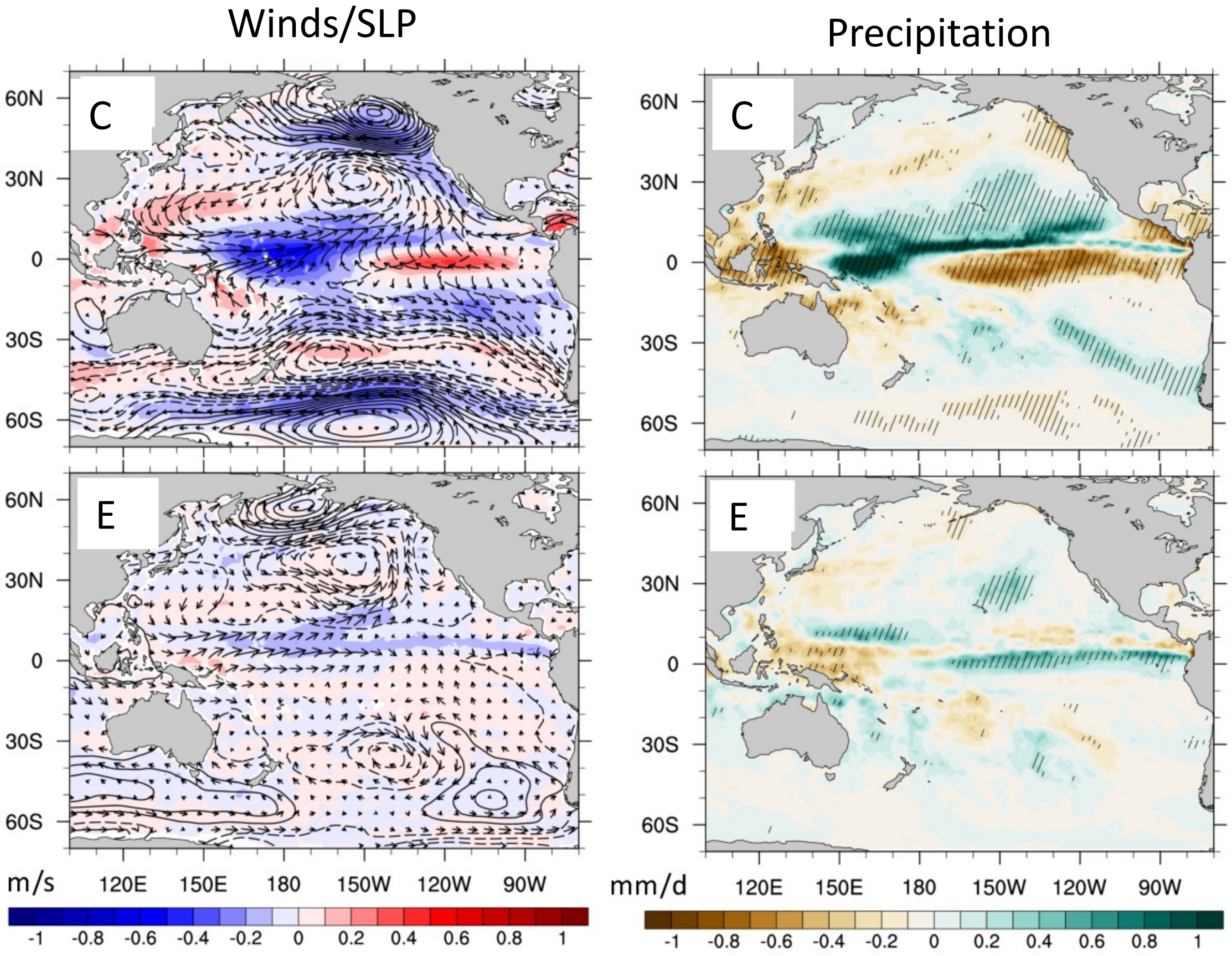
Optimal index for C-mode vs C-index



Optimal index for E-mode vs E-index



Wind and precipitation signatures of C and E precursors



C-events appears to be associated to the leading patterns of wind variability and are characterized by reduced precipitation in the eastern equatorial Pacific

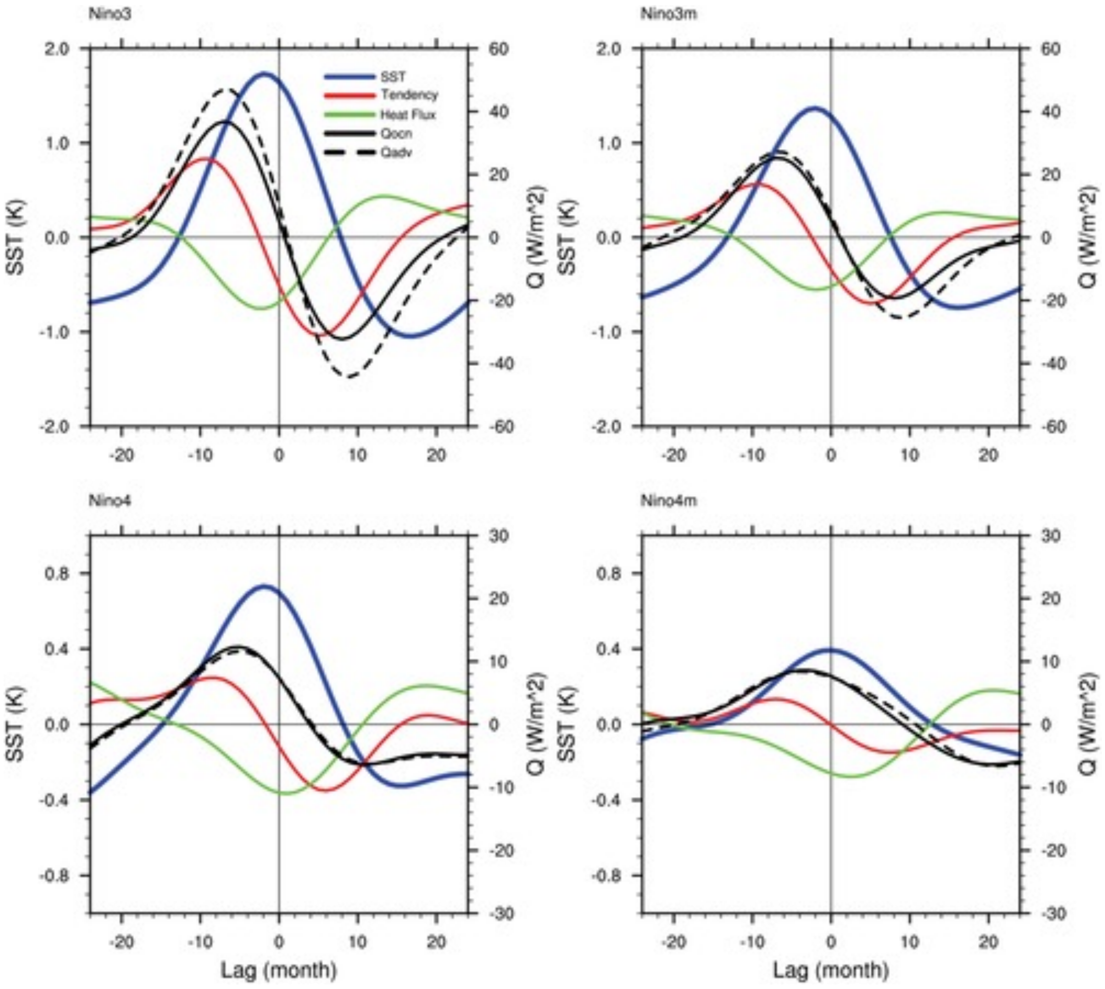
E-events have the largest wind signature along the equator with westerly extending to the eastern part of the basin, as well as precipitation.

Concluding Points

- The NPMM and SPMM are robust precursors of ENSO events, and are captured by a LIM.
- Growing modes of the LIM include canonical and “Modoki” patterns. These patterns are captured in spite of the model linearity. Other flavors of ENSO can be obtained as superpositions of the initial conditions of these structures.
- The LIM framework also allows to assess that initial heat content conditions play a key role in the development of different ENSO types, with a recharged equatorial thermocline being more conducive to EP events, and an enhanced zonal thermocline slope favoring CP events.
- Extra-tropical precursors appear to be more influential on CP than EP events. EP events may be more controlled by the equatorial heat content.

Are different events characterized by different dynamical processes?

Show heat budget analysis conducted on CCSM4



$$\rho c_p H \frac{\partial T}{\partial t} = Q_{ocn} + Q_F$$

E and C indices; Show how they are constructed

Use these indices to discuss skewness. Show the boomerang shape between PC1 and PC2

Do their spectra show a decadal component in the E-index?

Does ENSO diversity mean two different ENSO types or a “continuum” of events?

A linear inverse modeling perspective

What is a linear Inverse model (define the equations, discuss non-orthogonality of L’s eigenvectors, discuss growth as a superposition of eigenvectors)

An SST-only model, MA curve(s), initial optimal, final condition (this also has a second growing mode, which looks like EOF2; Difficult to explain the difference; Just use SST and SSH to construct the LIM)

An SST+SSH LIM; What do we gain? Are we gaining the second mode?

Mention Matt’s paper on the fact that different events can be viewed as the superposition of the two leading optimals

A linear system can produce diversity, implying that Nonlinearities are not a fundamental component of diversity