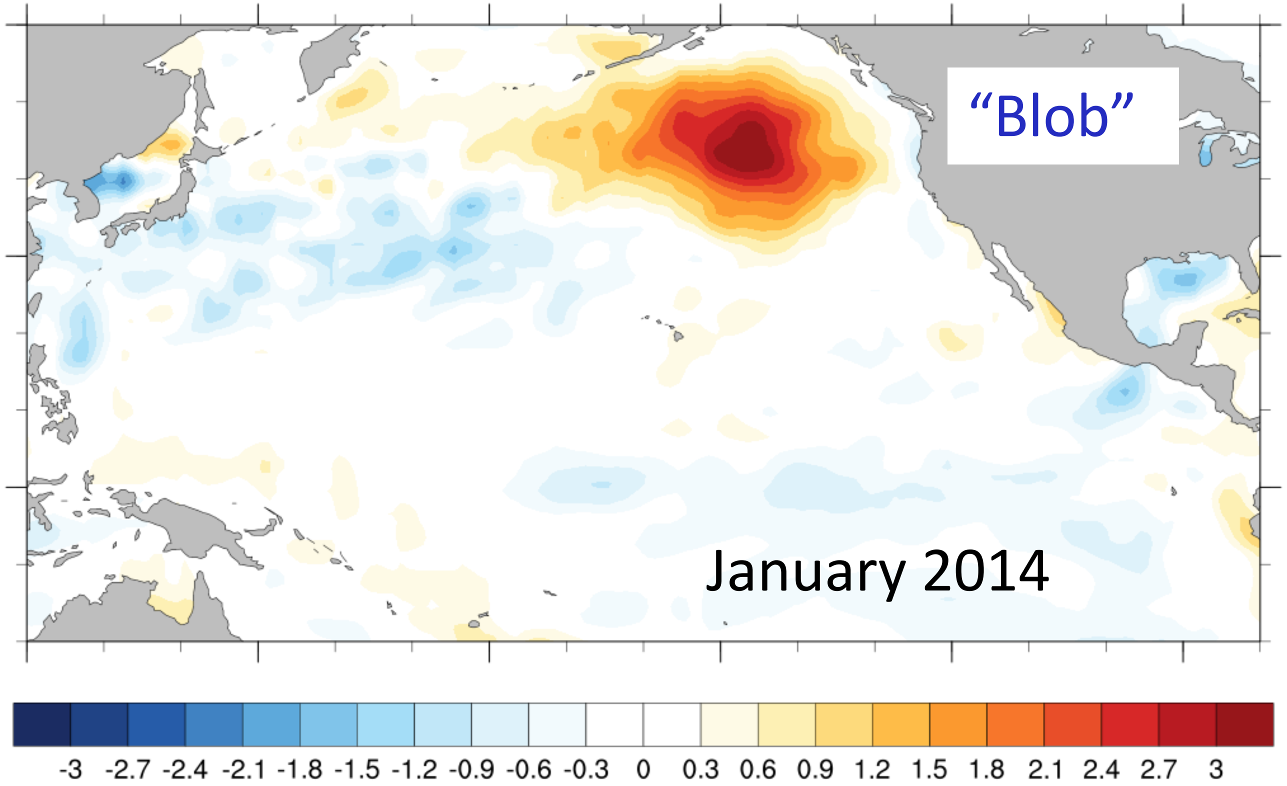
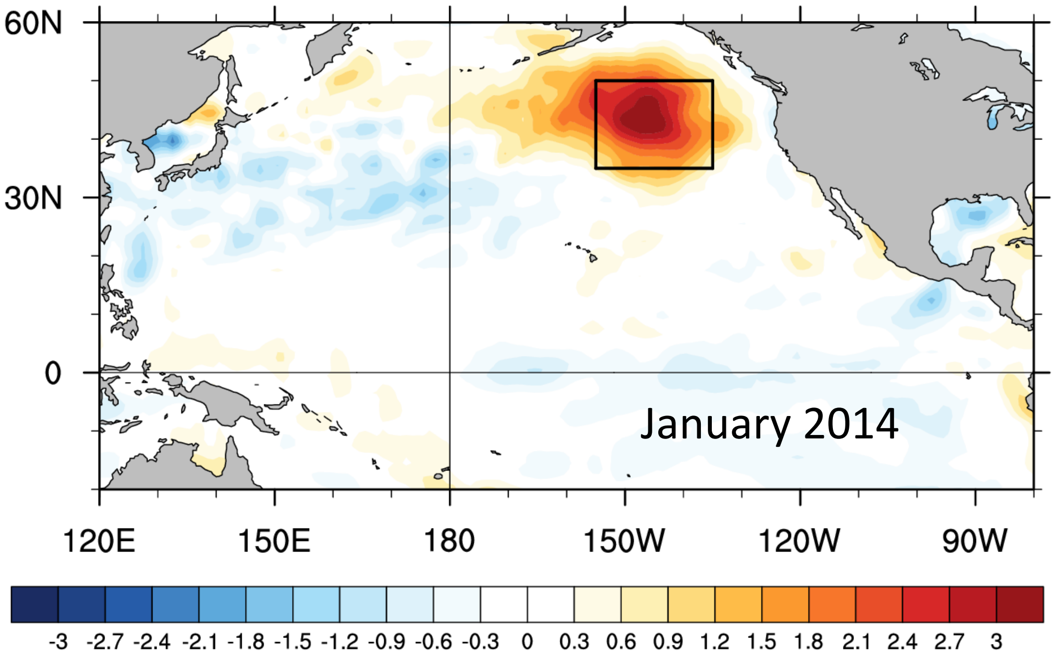
Local and Remote Drivers of Northeast Pacific Marine Heatwaves

Antonietta Capotondi@noaa.gov
University of Colorado, CIRES and NOAA/PSL, Boulder, CO, USA



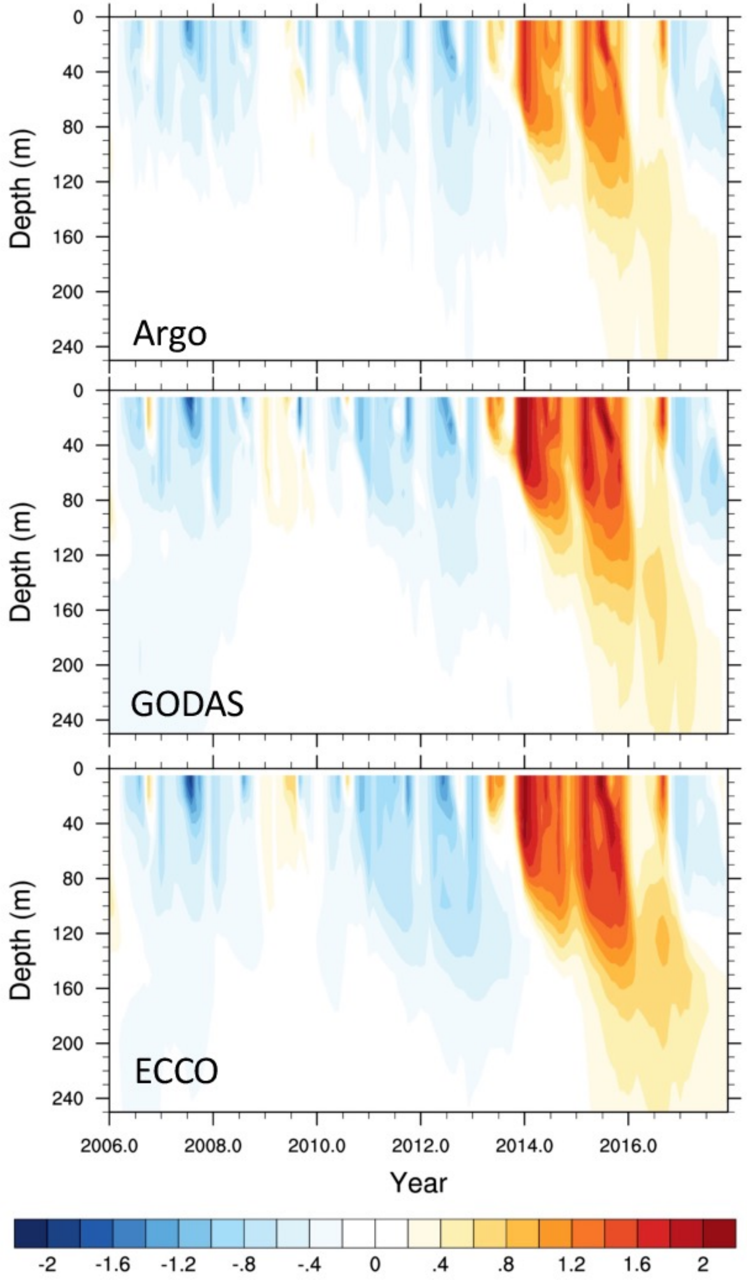
- Examine mechanisms of MHWs unique to this scientifically interesting and economically-important region
- Explore methodologies to identify large-scale drivers of MHWs

The “Blob”

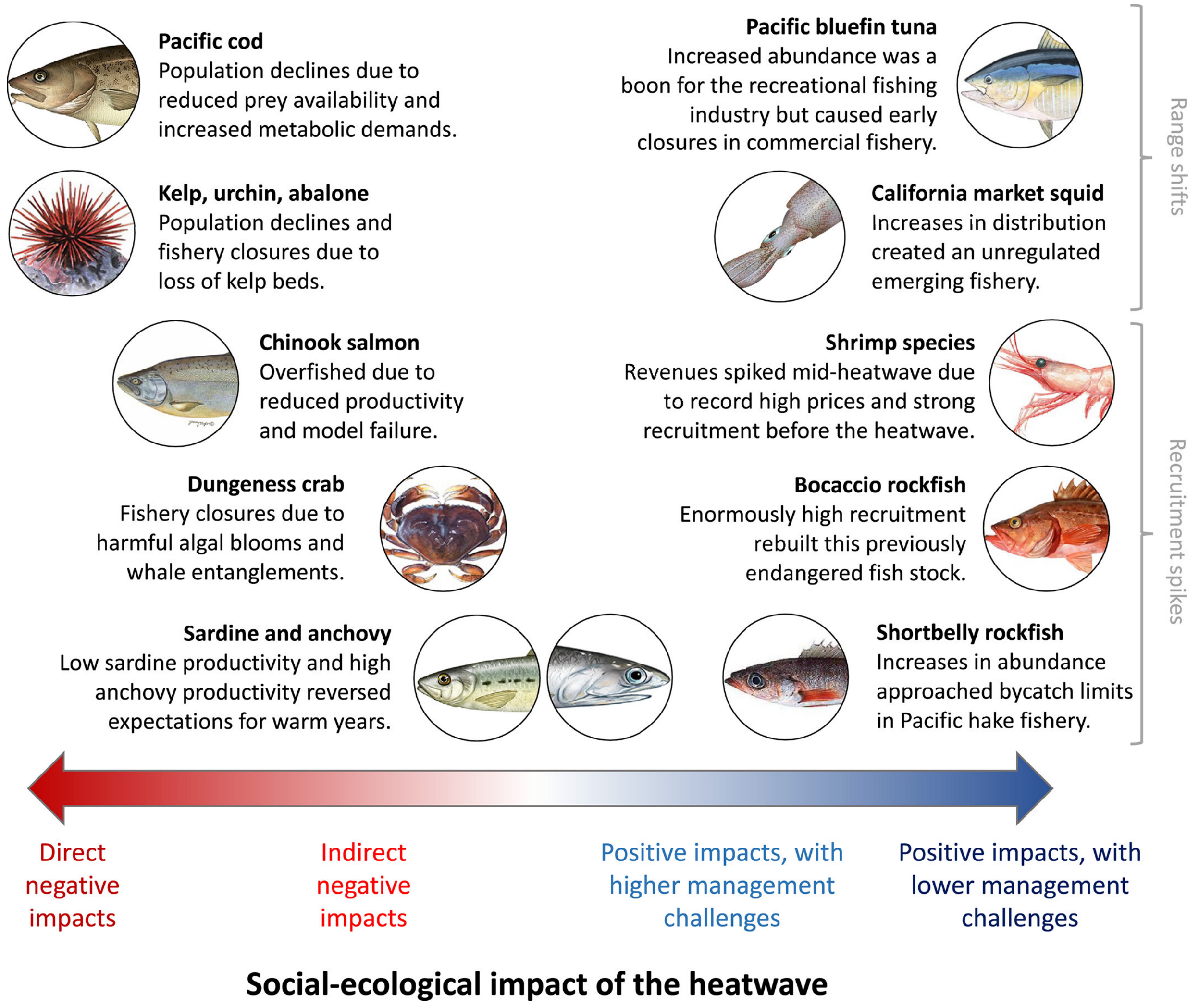


Surface anomalies were associated with large subsurface signals, with significant amplitudes reaching to about 150 m.

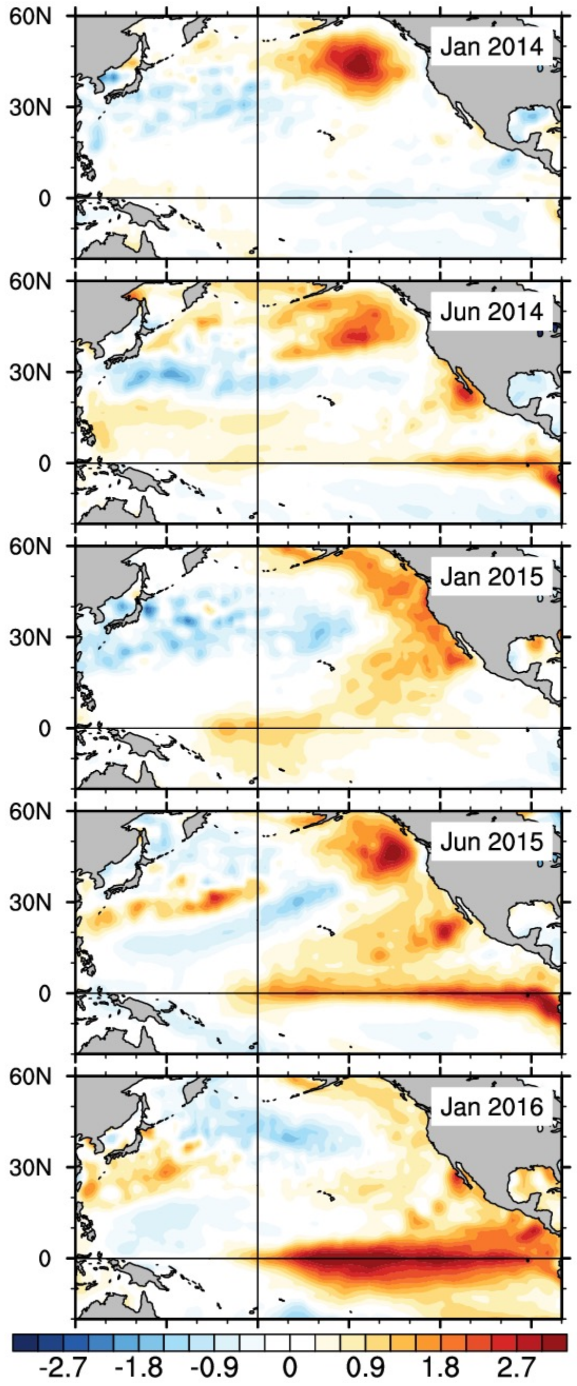
Evolution of Blob anomalies at depth



Consequences for Fisheries



Free et al. 2023, *Fish & Fisheries*



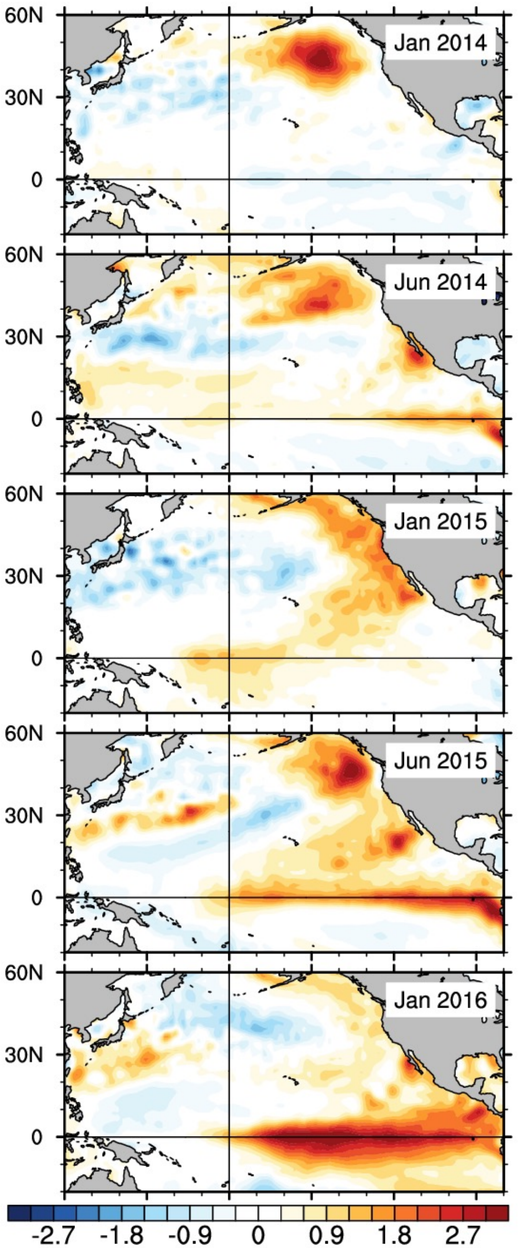
Evolution of the 2014-2016 MHW

The Blob persisted for about 2 years.
No ENSO anomalies were present at the peak of initial anomalies of the Blob.

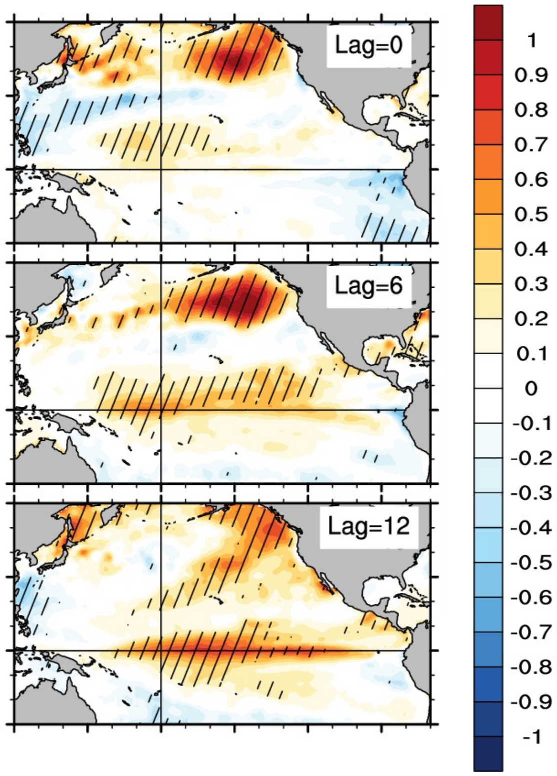
From the offshore region of the Gulf of Alaska, anomalies extended toward the coast of North America as the weak 2014 El Nino and then the extreme 2015-16 El Nino developed in the equatorial Pacific

Evolution typical of intense NE Pacific SST anomalies starting in the Blob region

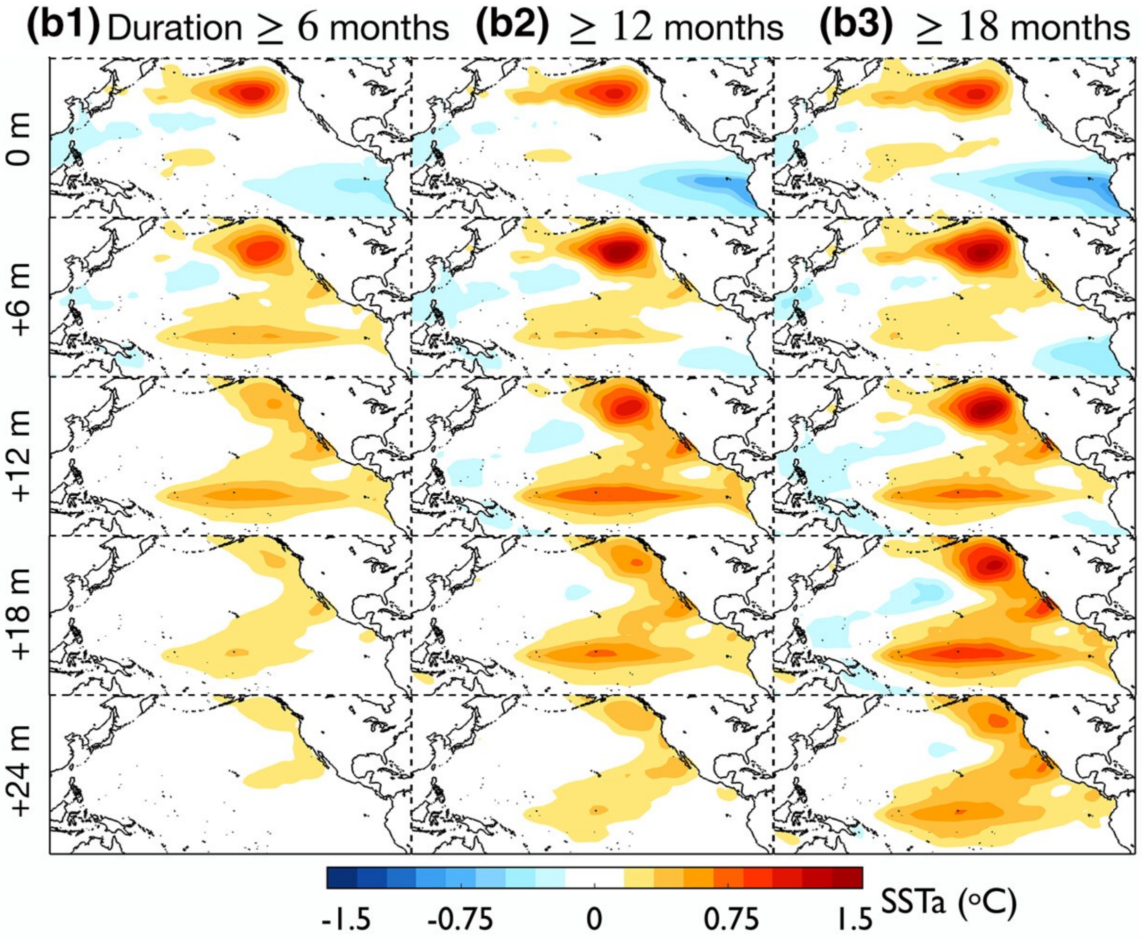
OISST Blob 1.0



ORAS4 composite (1958-2015)



Capotondi et al., *GRL*, 2022



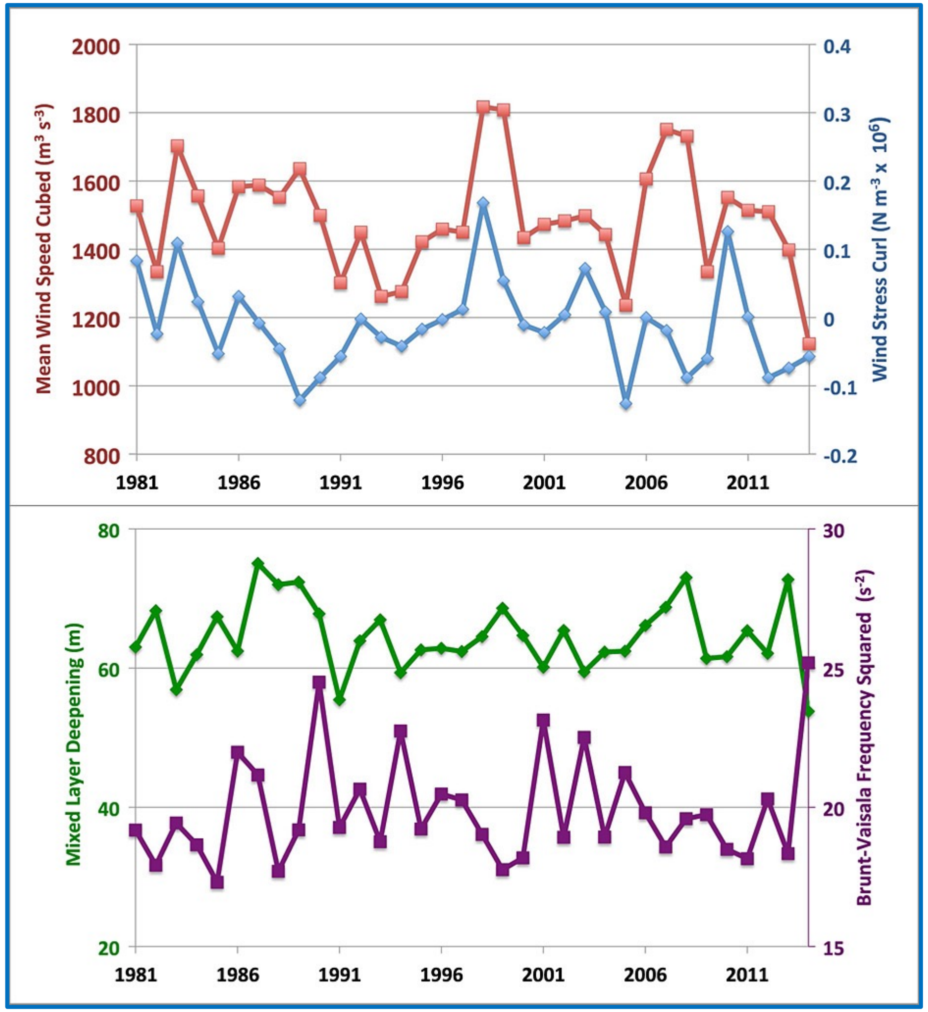
Composites based on 2000 70-year segments from a LIM simulation

Xu et al., *GRL*, 2021

This evolution is related to the large-scale drivers of these events as shown shortly

Local forcing of the “Blob”

Seasonal means (October to January)



Bond et al., 2015, *GRL*

The extreme intensity of the SST anomalies in the area of the “Blob” was related to local conditions:

1. Wind speed cubed (atmospheric driver of turbulent ocean mixing) was at a **minimum** in 2014 relative to the entire 1981-2014 period.
2. Wind stress curl (linked to dynamical changes in pycnocline depth) did not exhibit an ”extreme” value -> dynamical processes may not be critical.
3. Mixed Layer Depth Deepening (change in MLD from September to February) was **particularly low** in 2014
4. Stratification at the base of the mixed layer (Brunt Vaisala frequency squared) was **particularly high** in 2014.

Heat Budget Equation

$$\frac{\partial T}{\partial t} = -\frac{1}{H}\int_{-H}^{0}(\boldsymbol{u}\cdot\nabla_h T)dz + \frac{Q}{\rho C_p H} + Residual$$

T Mixed Layer Temperature

H Mixed Layer Depth

$\boldsymbol{u}$ Horizontal velocity vector

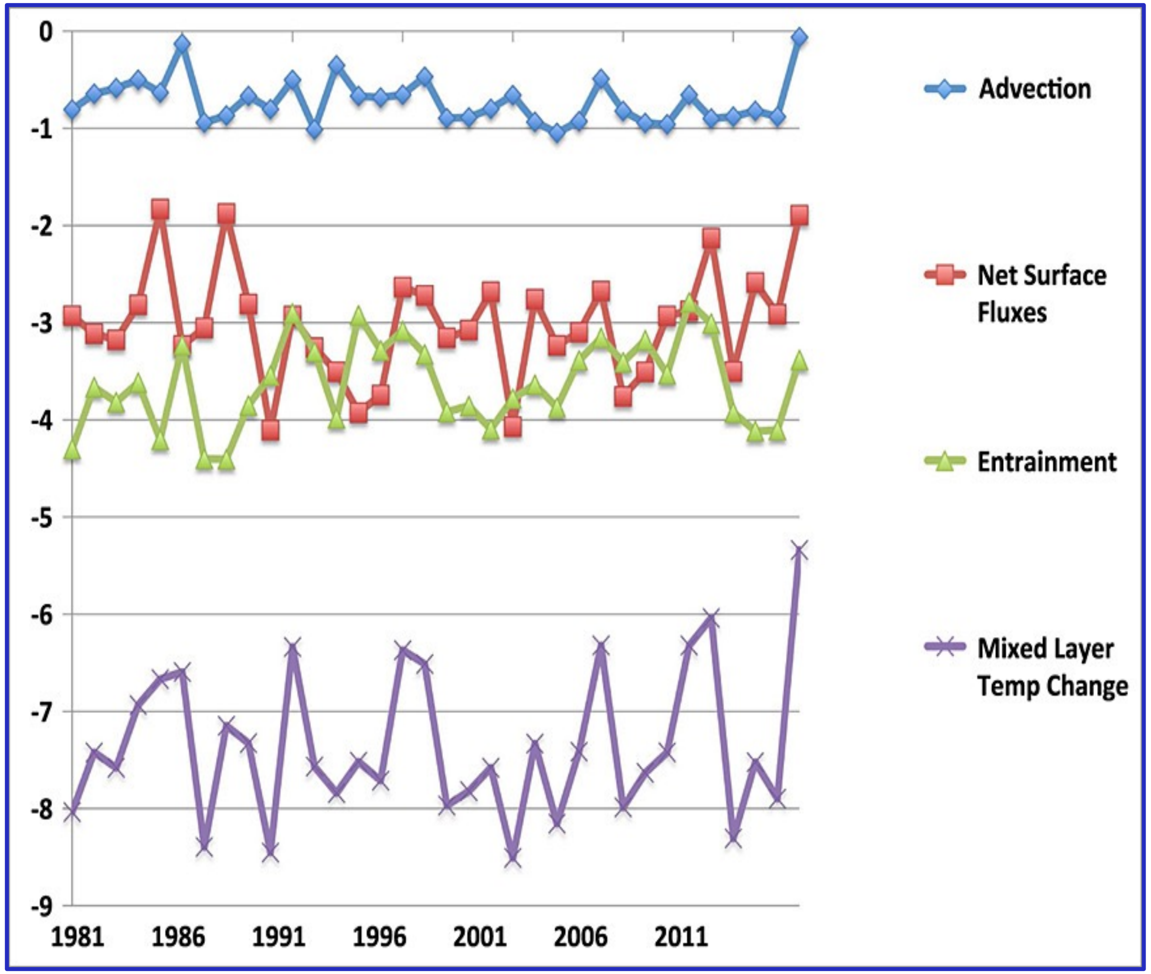
Q Net surface heat flux

ρ Average ocean density

C_p Specific heat capacity of seawater

Residual = Horizontal eddy heat fluxes, radiative heat loss, entrainment and vertical advection at the base of the mixed layer

Heat Budget analysis



Bond et al., 2015, *GRL*

October-January heat loss by zonal advection was close to zero in 2013-14

October-January Net Surface heat Flux loss was lower than average in 2013-14

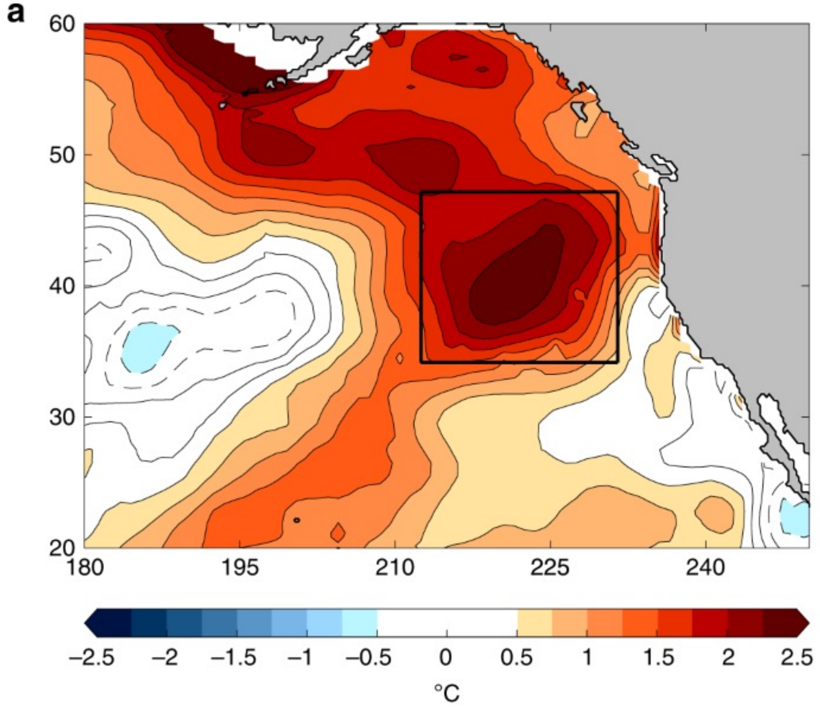
October-January Entrainment (residual) was close to average in 2013-14

Seasonal values of the Mixed Layer temperature change from September to February (based on GODAS ocean reanalysis). MLD computed based on a density criterion.

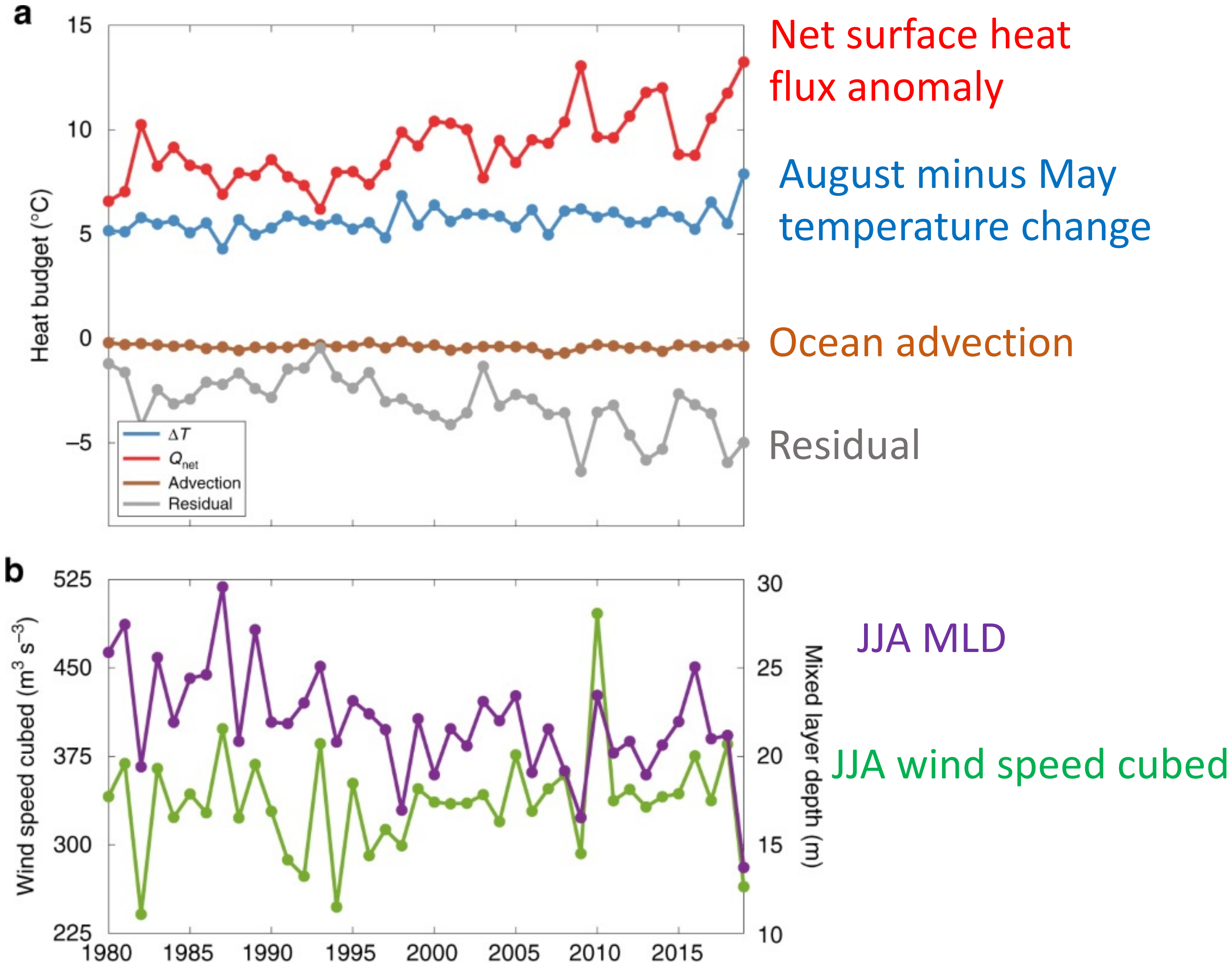
Reduced heat losses by surface fluxes and horizontal advection (mainly associated to Ekman currents) were the dominant contributors to the positive temperature anomalies.

Local Drivers of Blob 2.0

5-m temperature anomaly during JJA 2019 (GODAS ocean reanalysis)



Amaya et al. (2020)



Local forcing of the "Blob"

Current evidence of local drivers of Northeast Pacific MHWs indicate that anomalous surface heat fluxes played a key role in the development of these MHWs, with a more modest role for ocean advection.

These heat budgets used ocean reanalyses that may not conserve quantities.
A heat budget based on a conservative reanalysis (JPL-ECCO) is currently underway (Sala et al. in preparation). Preliminary results to-date support the key role of the heat fluxes near the surface with a relatively larger contribution from advection at depth.

Is local atmospheric forcing influenced by Large-Scale Climate drivers?

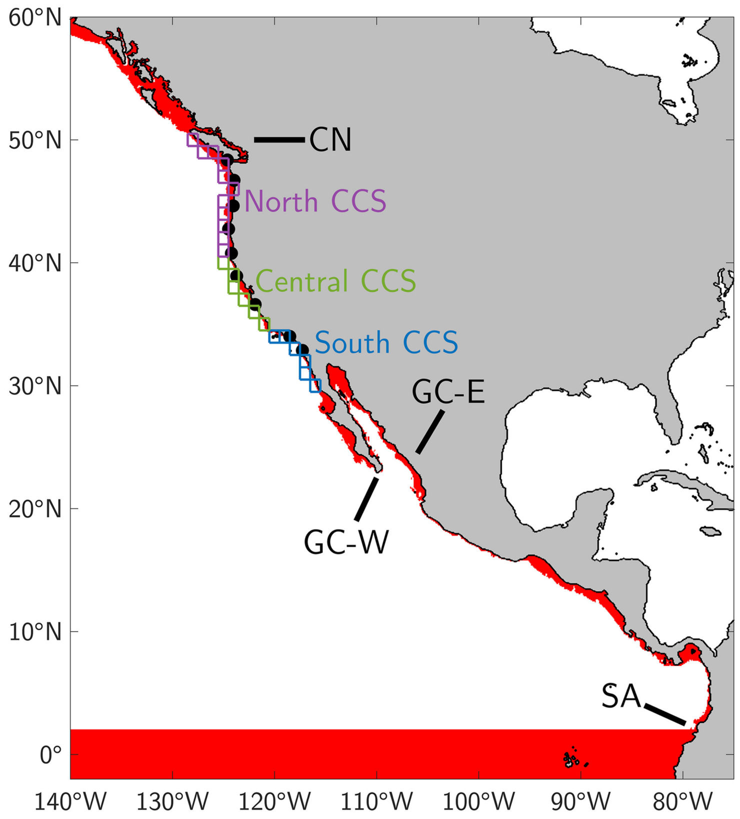
Holbrook et al. (2019) showed that ENSO and the PDO are important drivers of Northeast Pacific MHWs

How and to what degree do ENSO and PDO affect MHWs?

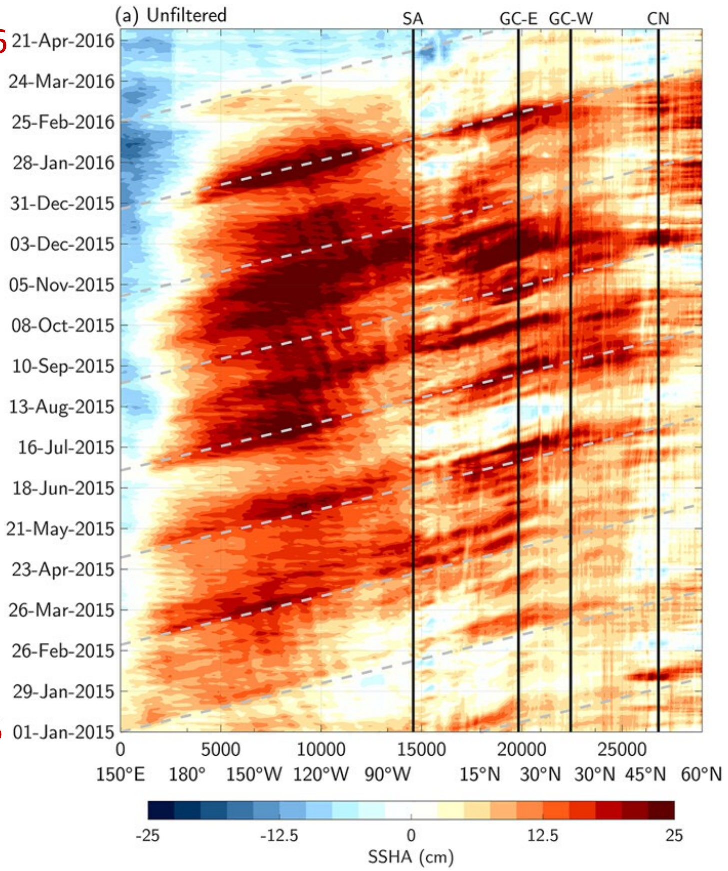
ENSO affects SSTs in the Northeast Pacific, especially along the west coast of the US, through oceanic and atmospheric pathways

How does ENSO Influence the Northeast Pacific?

Oceanic pathway



21 April 2016



1 Jan 2015

2015-16 El Nino

Equatorial Kelvin waves are observed to propagate along the equator and northward along the west coast of North America in spite of the complexity of the coast.

Amplitudes decrease with increasing latitude, and offshore scale of waves decreases with latitude. Oceanic pathway more important at southern latitudes.

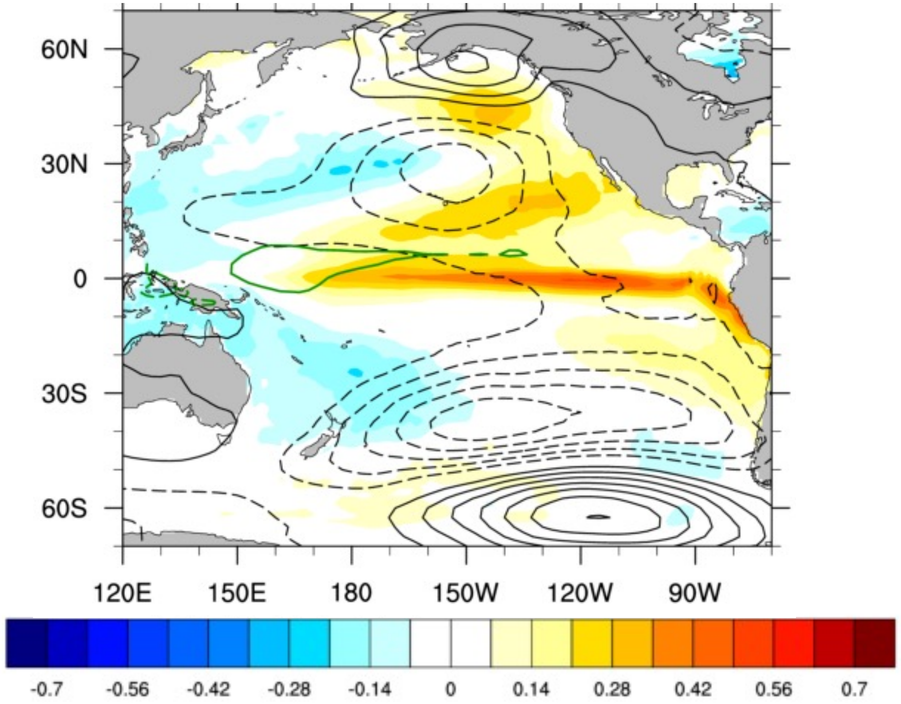
Amaya et al., *JGR-Oceans*, 2021

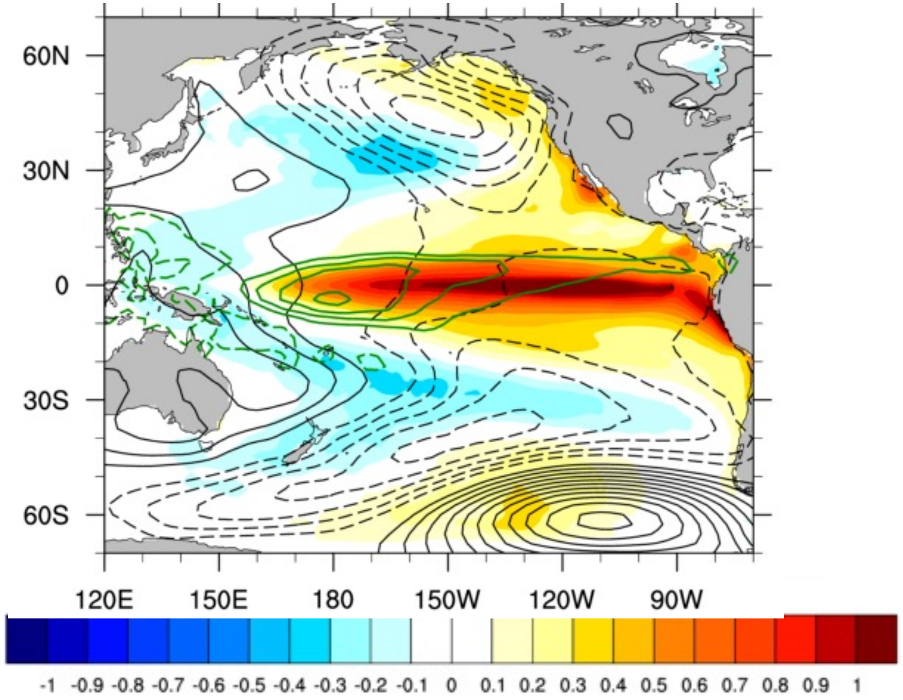
How does ENSO Influence the Northeast Pacific?

Atmospheric pathway

Extra-tropical atmospheric variability, e.g., North Pacific Oscillation (NPO) and South Pacific Oscillation (SPO) influence ENSO development -> two-way interaction between tropics and extra-tropics.

The mature phase of ENSO is associated with deeper and eastward displaced Aleutian Low (anomalous low pressure center) with southerly winds and warm SSTAs along the coast.

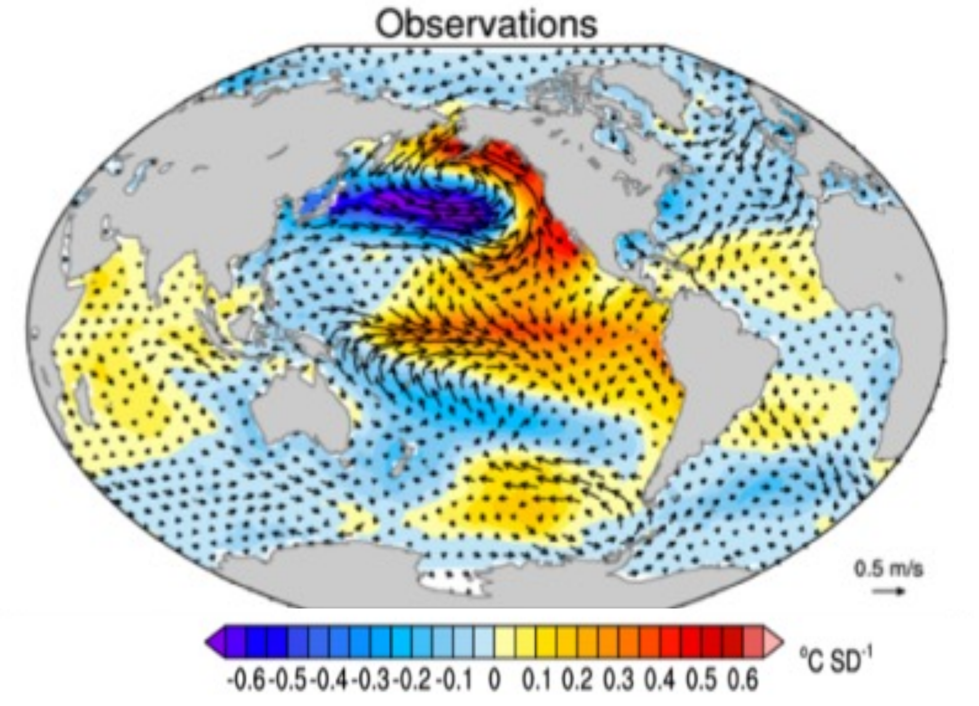




ENSO events can have different spatial patterns and different teleconnections within a large level of atmospheric noise

The Pacific Decadal Oscillation (PDO)

PDO is defined as the leading empirical orthogonal function of monthly SST anomalies over the North Pacific (20–60°N)

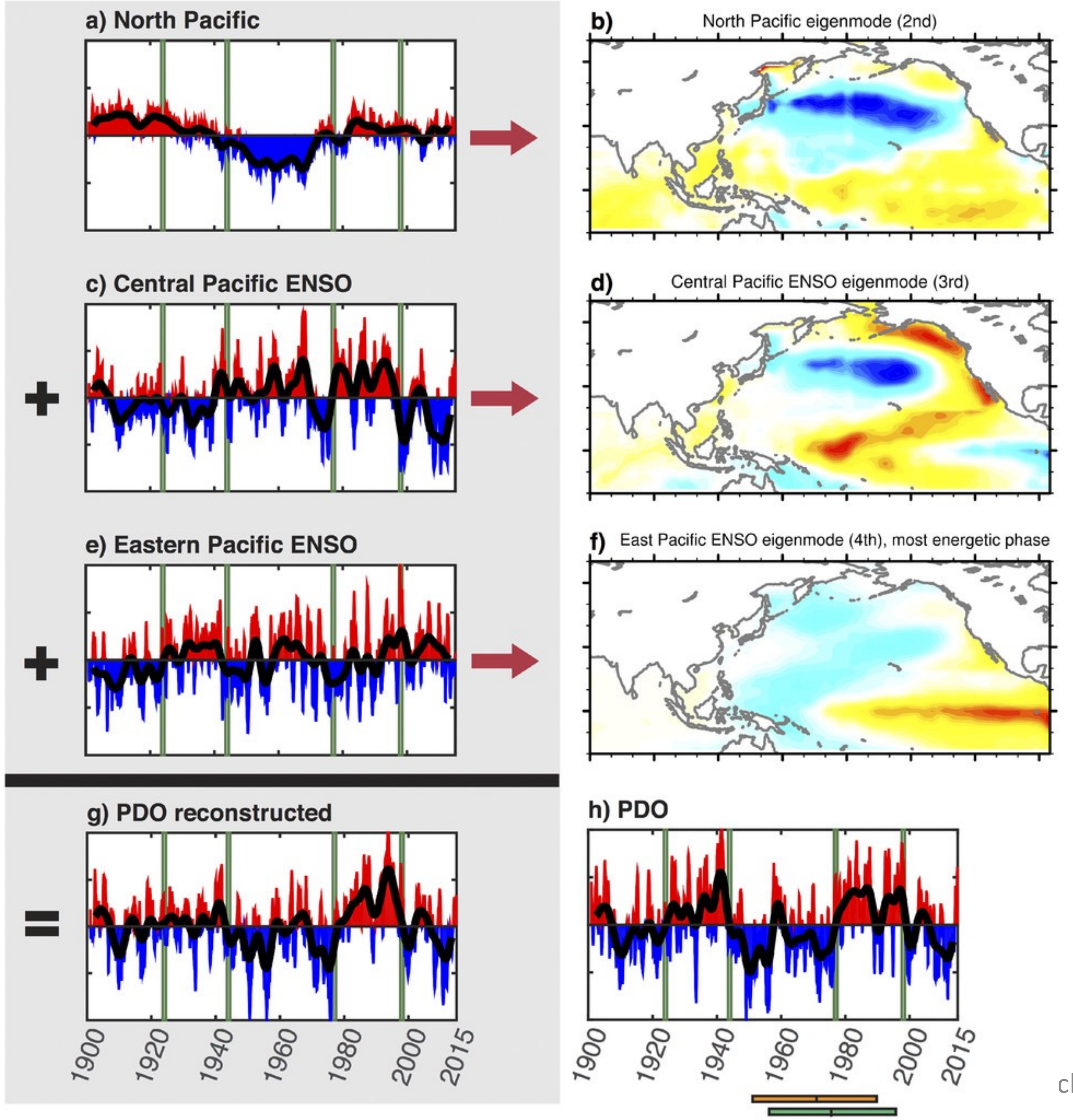


Regression of SST (ERSSTv5) and surface winds (ERA5) on the PDO index.

A deepened Aleutian Low results in a counterclockwise circulation, with enhanced winds in the central North Pacific (colder SSTs) and southerly wind anomalies along the coast on North America (warmer SSTs).

Capotondi et al. *JAMES*, 2020

The PDO arises as the superposition of different *dynamical* modes



Center of action in the North Pacific
Multi-decadal timescale

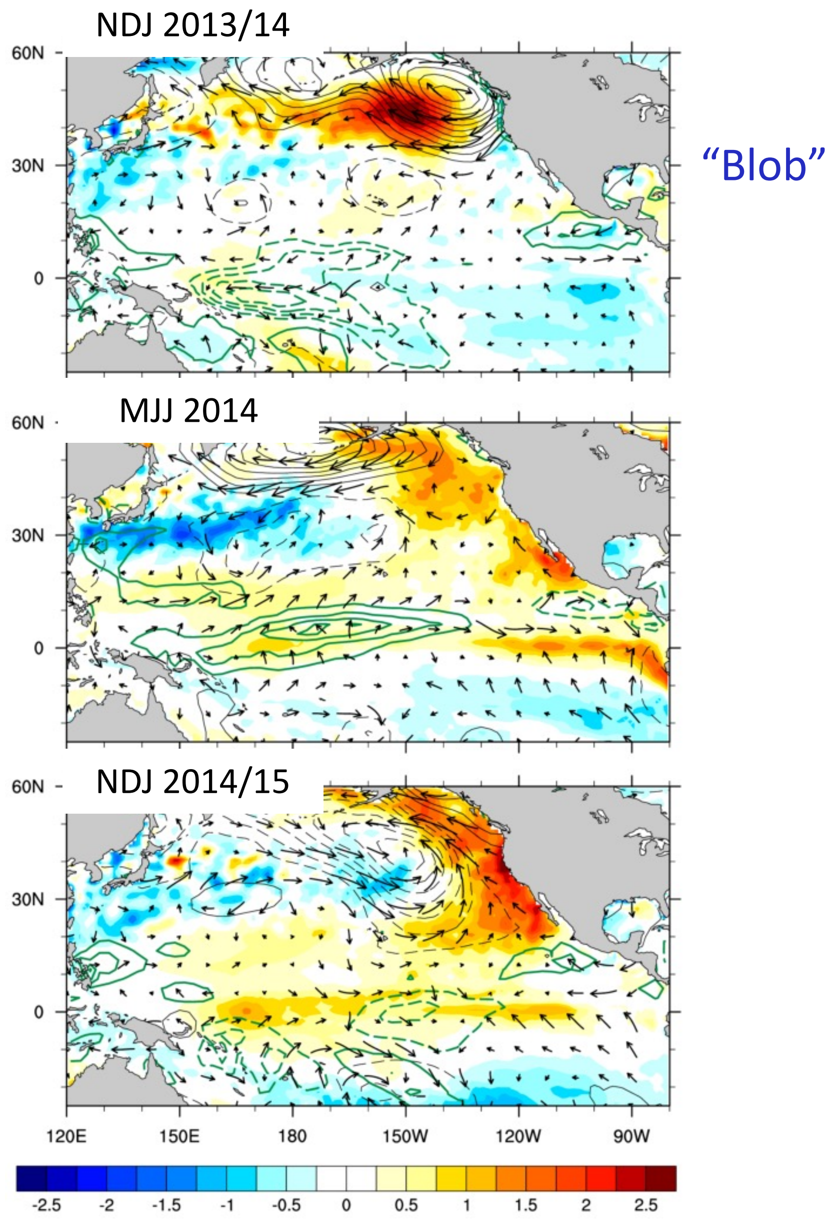
Anomalies span the North Pacific and the central equatorial Center Pacific
Quasi-Decadal timescale

Anomalies centered on the equator as in Eastern Pacific ENSO events
Interannual timescale

It is important to isolate the specific processes that can favor the development of MHWs

Newman et al. 2016, *J. Climate*

What were the atmospheric conditions during Blob 1.0



A sea level pressure dipole was present during the initial phase of the Blob 1.0. Anomalous winds weakened the climatological winds and resulted in reduced ocean heat loss through turbulent heat fluxes. Cyclonic circulation on lower lobe of dipole favors the development of weak positive SSTAs.

As the weak 2014 El Nino developed in the equatorial Pacific, anomalous SLP in the North Pacific shifted to a deepened Aleutian Low, as typical for mature El Nino events

Di Lorenzo & Mantua, 2016, *Nat. Clim. Change*
Capotondi et al., 2019, *Sci. Rep.*

How can we objectively determine the Large-Scale drivers of Northeast Pacific MHWs?

Climate modes may not be independent, have different expressions, evolve in time, and may result from the superposition of different processes.

Instead of using specific indices, we are going to adopt a multivariate approach and identify climate states that are most conducive to MHW conditions in the Northeast Pacific.

Using a Linear Inverse Modeling (LIM) framework

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

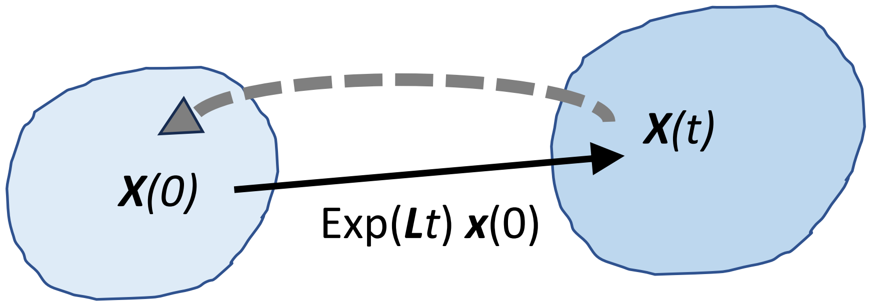
x state vector including SST and SSH EOFs over 30°S-60°N (data from ECMWF-ORAS4, 1958-2015)

L Dynamical Operator

ξ Stochastic forcing, white in time, but spatially coherent

$$\boldsymbol{x}(t+\tau) = \mathbf{G}(\tau)\, \boldsymbol{x}(t) + \varepsilon$$

$$\mathbf{G}(\tau) = \exp(\mathbf{L}\,\tau) = \mathbf{C}(\tau)\,\mathbf{C}(0)^{-1}$$

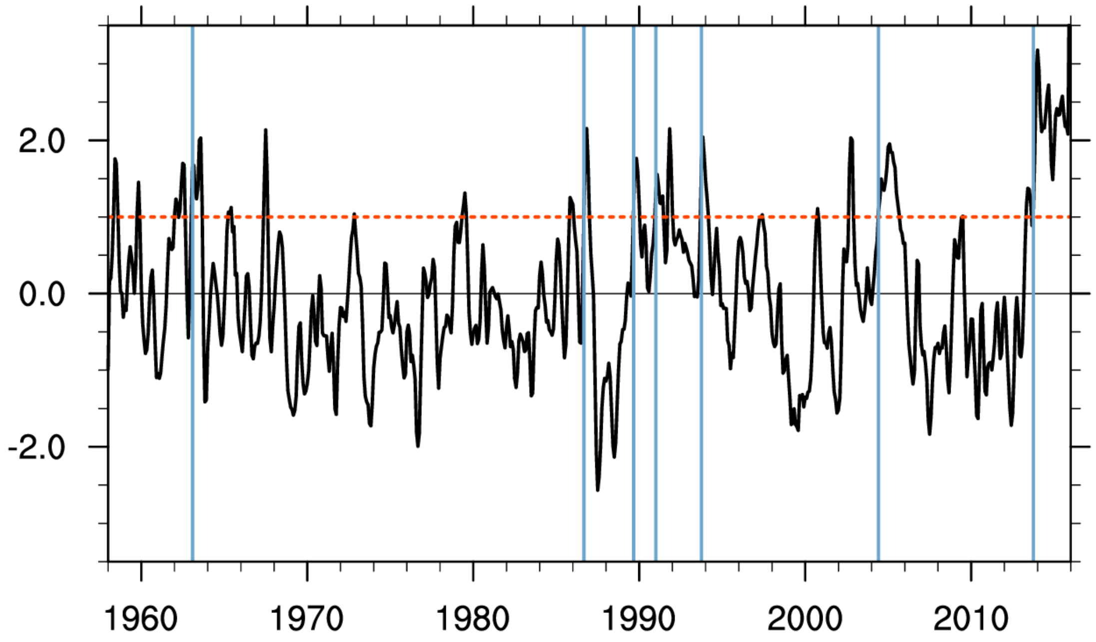


LIM can be used for:

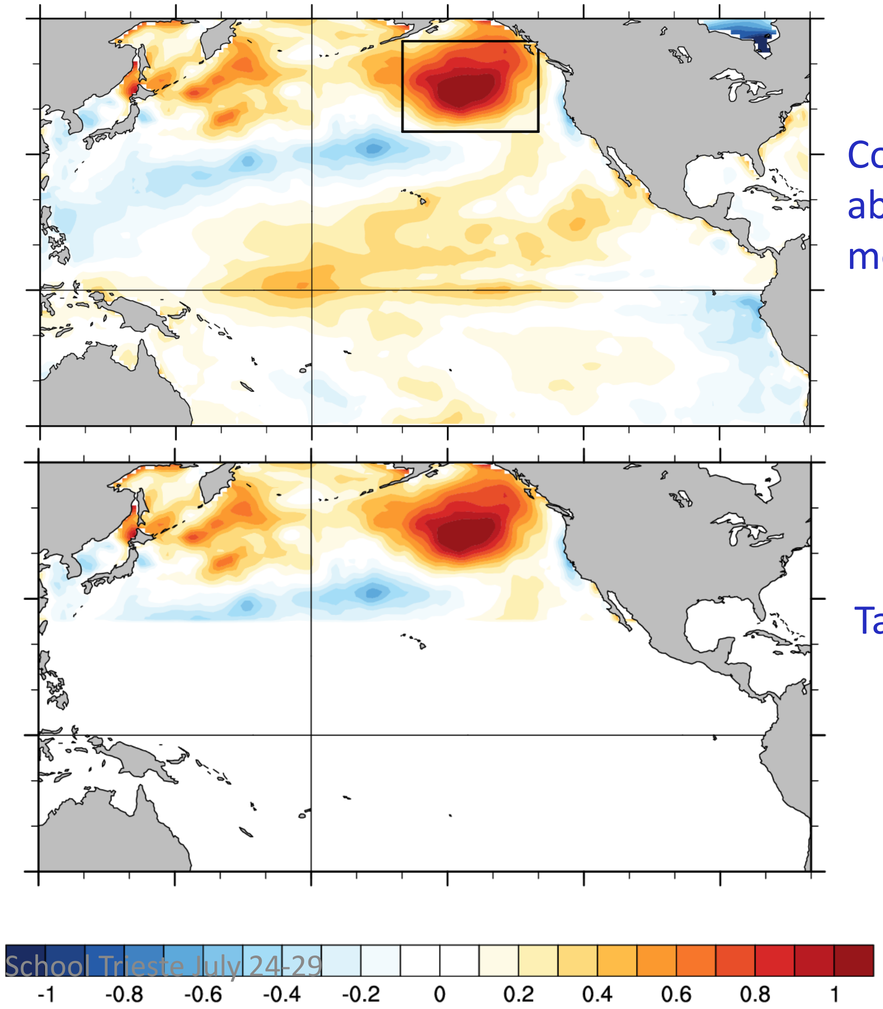
- Create very long (millennial) synthetic time series consistent with the statistics of the training data
- Prediction
- **Determine optimal precursors**

Determining the optimal initial conditions

NEPacific Index



Event composites at t=0

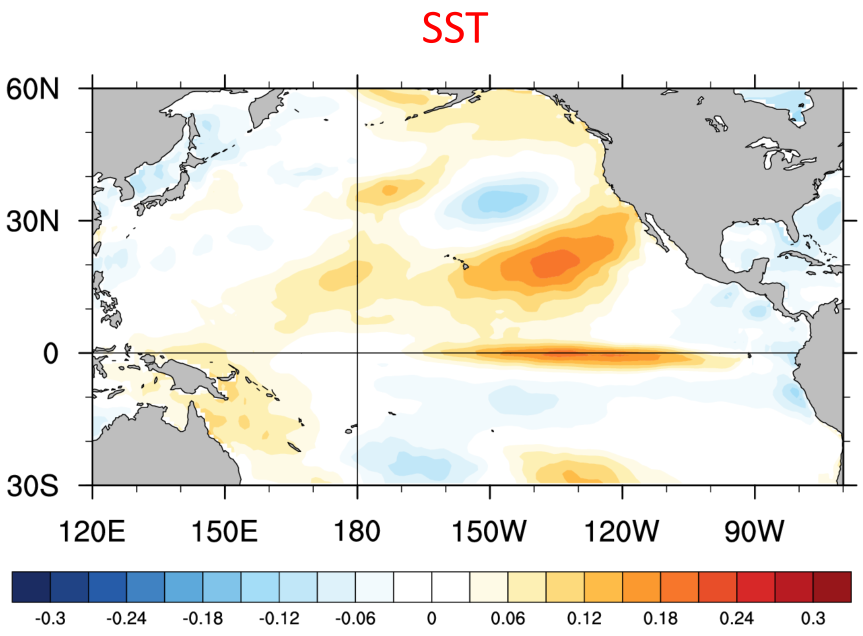


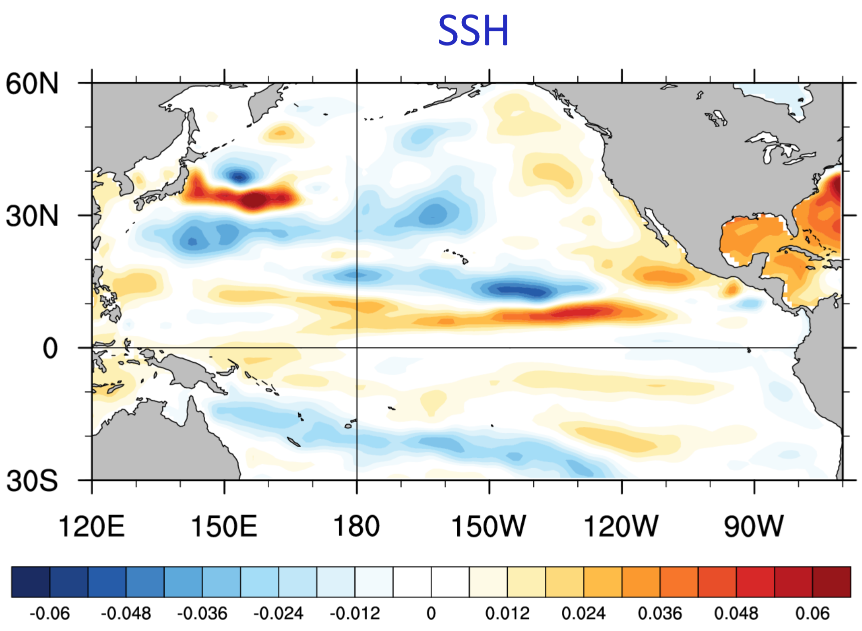
Composite of events above 1 std, lasting more than 5 months

Target state

We search for initial conditions that optimally grow toward the composite conditions north of 25°N.

Optimal initial conditions (τ=9 months)

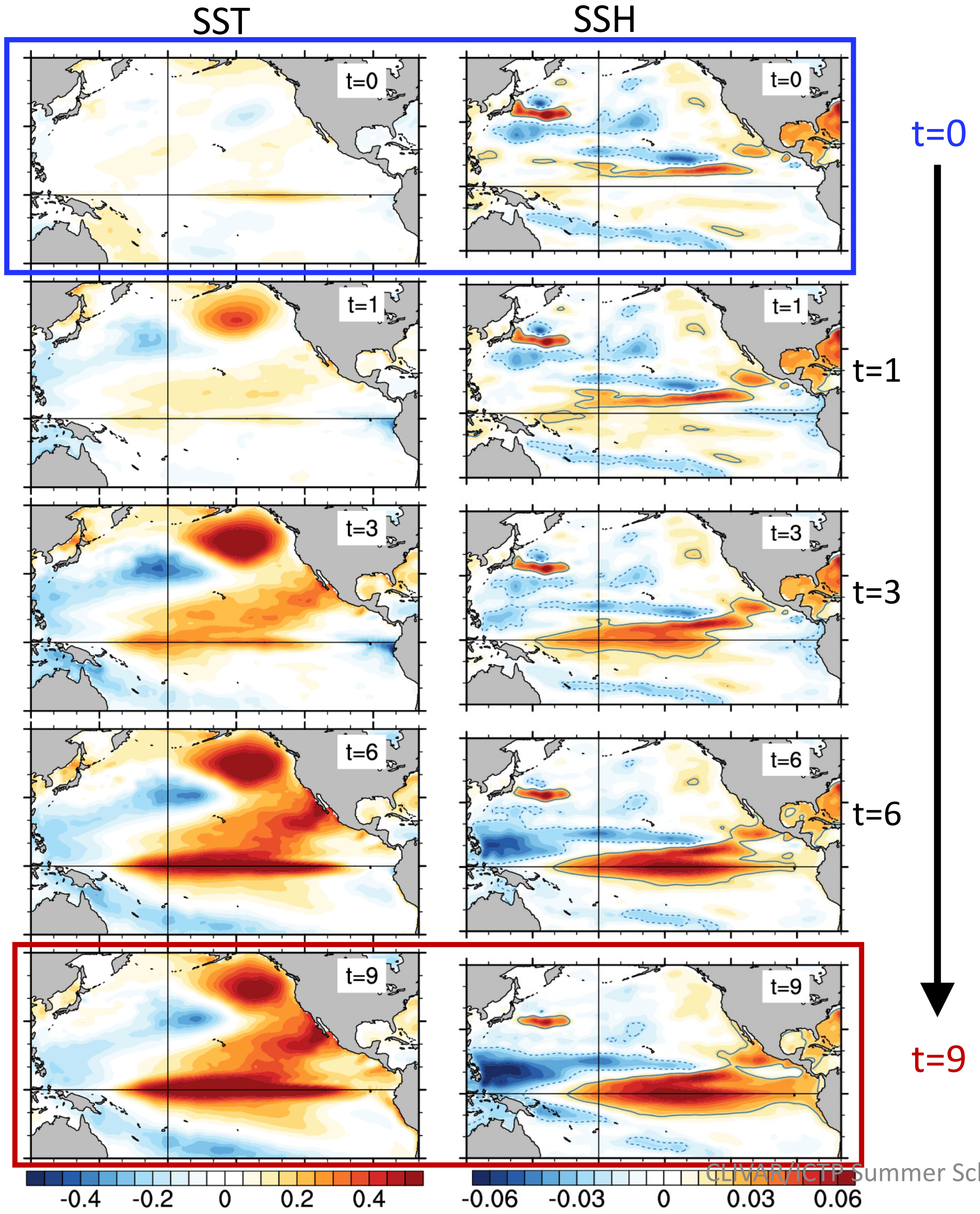


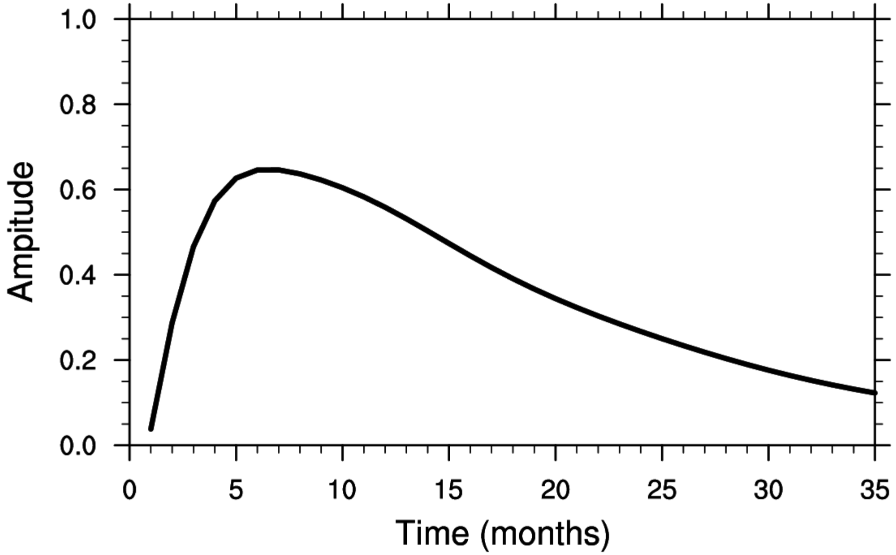


Initial SST anomalies have the largest anomalies in the subtropics (NPMM) and along the equator

Largest SSH anomalies are seen in the tropics, where they underscore changes in heat content associated with ENSO dynamics. Positive anomalies (enhanced heat content) are also present in the Northeast Pacific.

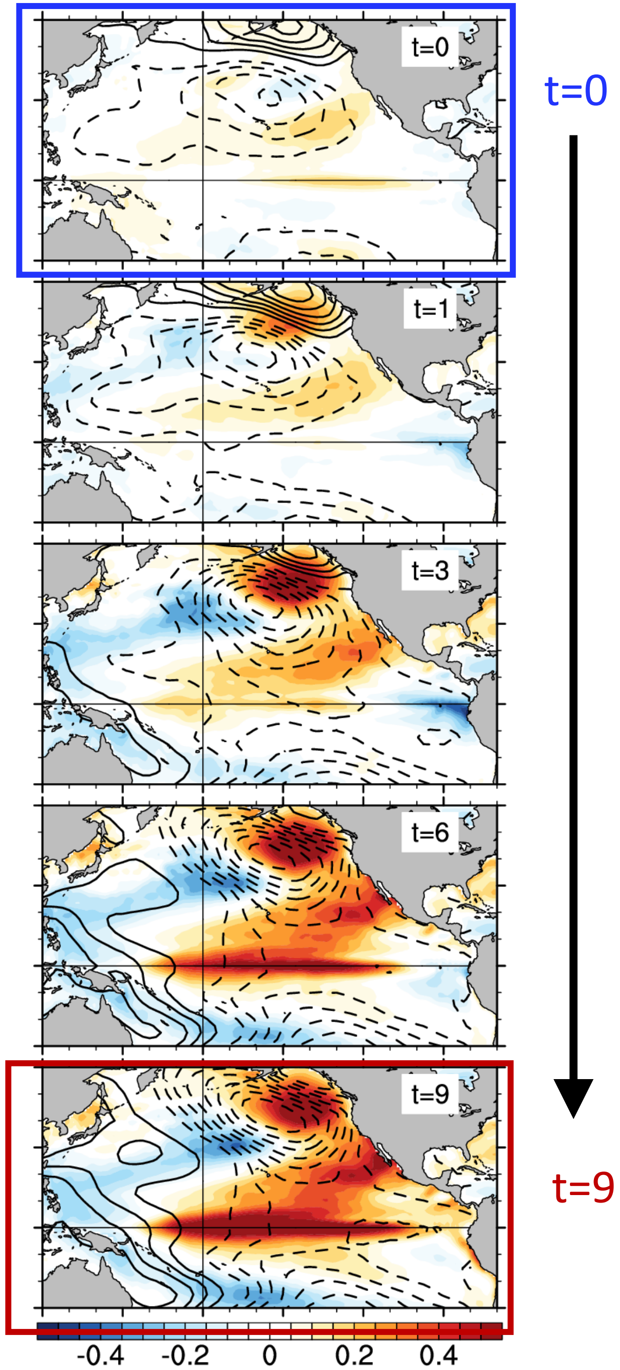
MHW evolution (τ =9 months)





Projection of the evolving optimal on the "Target-state" shows growth until ~6-9 months, then a slow decay.

SST/SLP

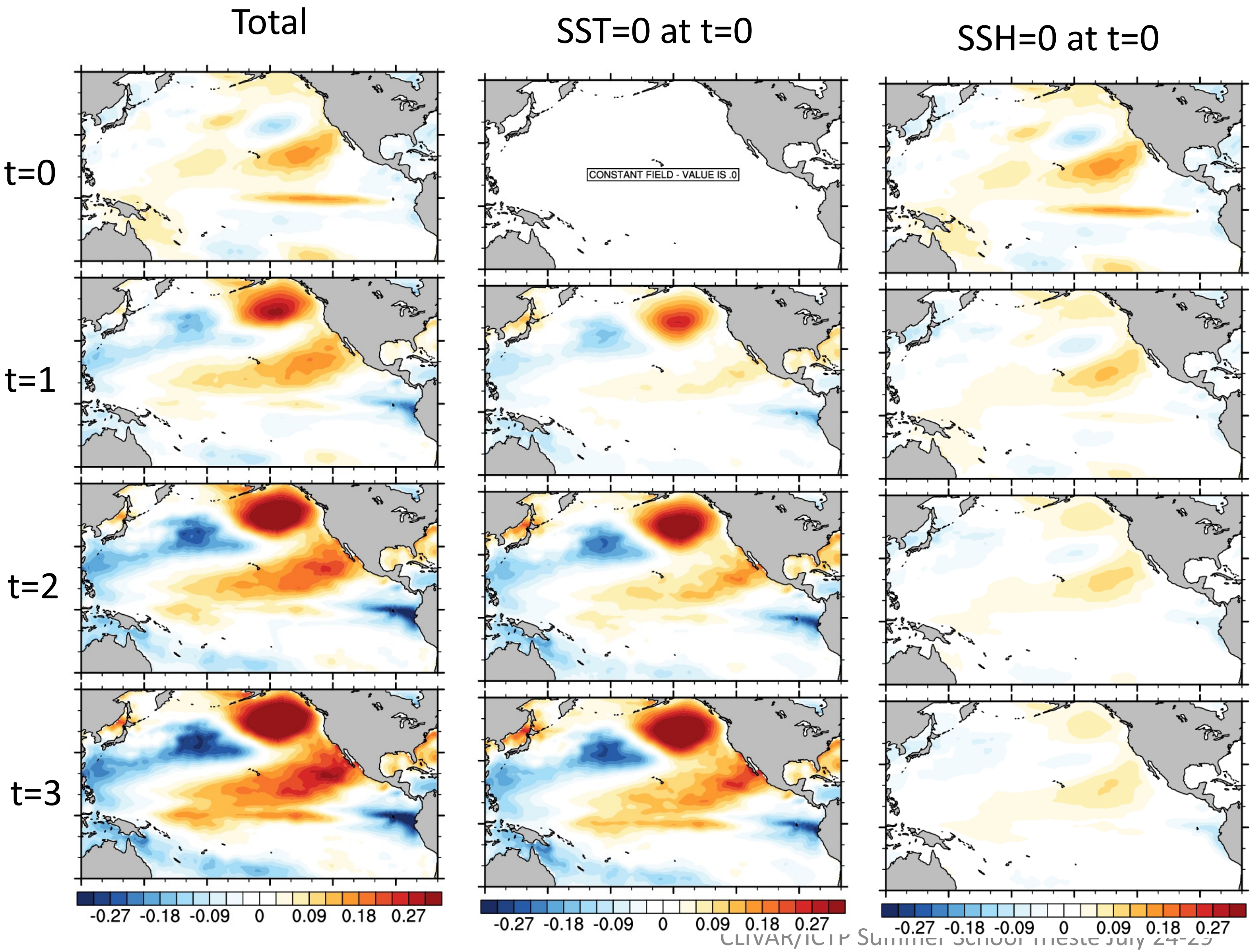


SLP anomalies during MHW

The optimal initial condition is characterized by NPO-like SLP anomalies, associated with the development of the North Pacific Meridional Mode.

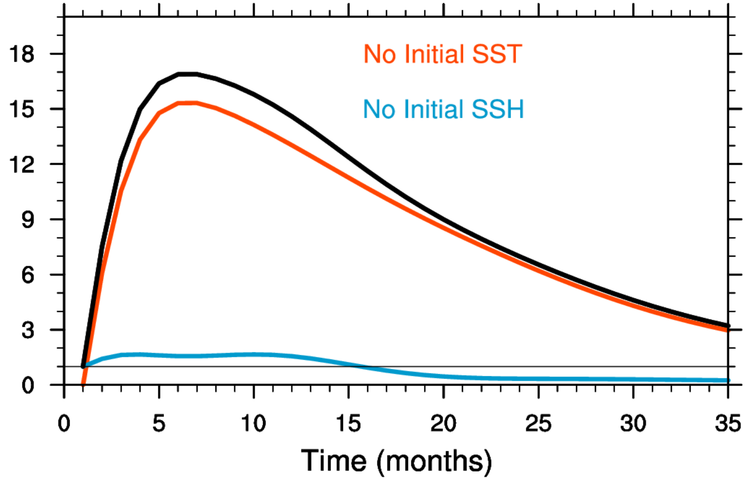
As ENSO develops in central equatorial Pacific atmospheric conditions in the northeast Pacific exhibit a deepened Aleutian Low resulting in warm conditions along the coast.

Relative importance of initial SST and SSH anomalies on MHW evolution

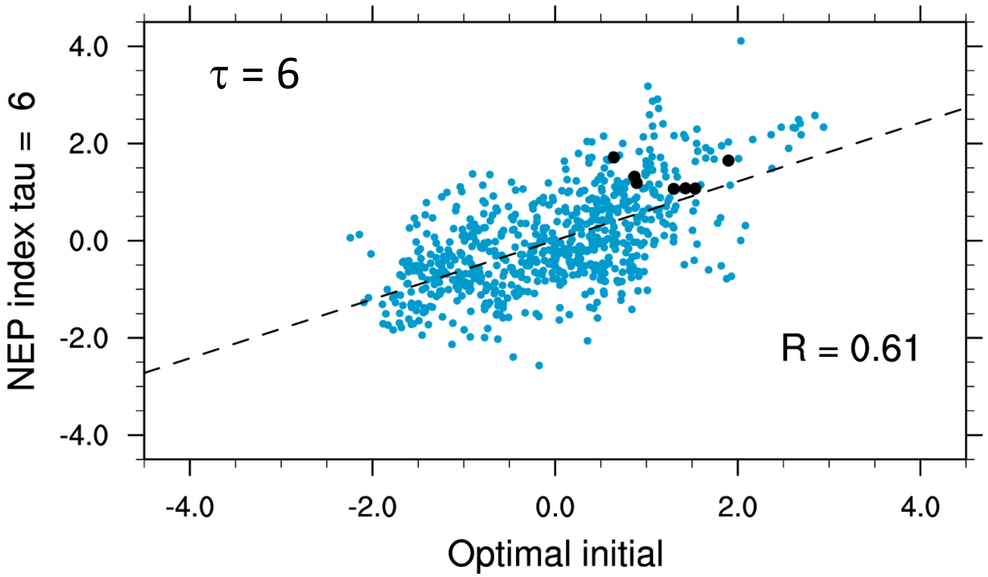


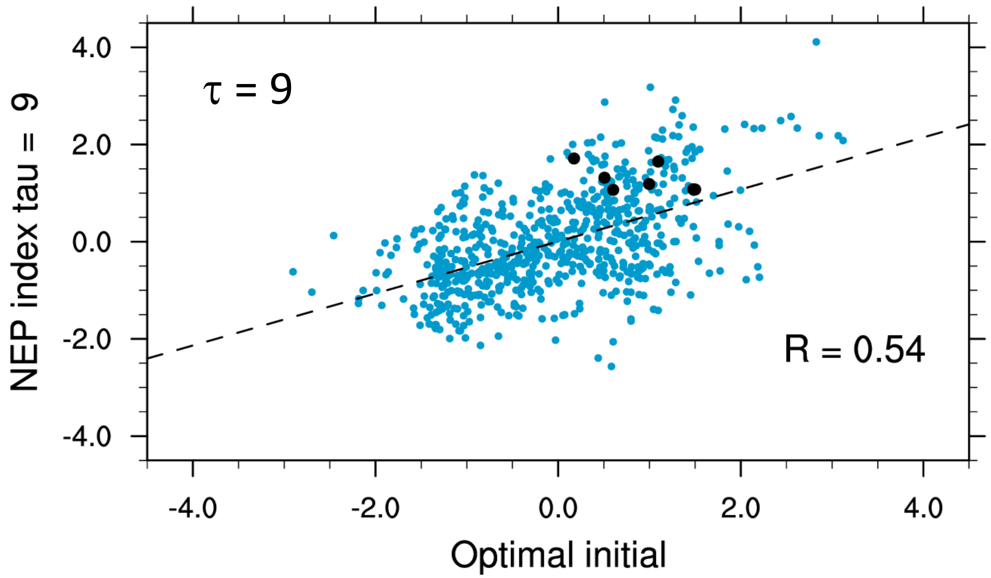
The initial SST anomalies are not critical for the development of the MHW.

MHWs do not develop in the absence of initial SSH anomalies, but it is unclear which aspects of the initial SSHAs are most important.



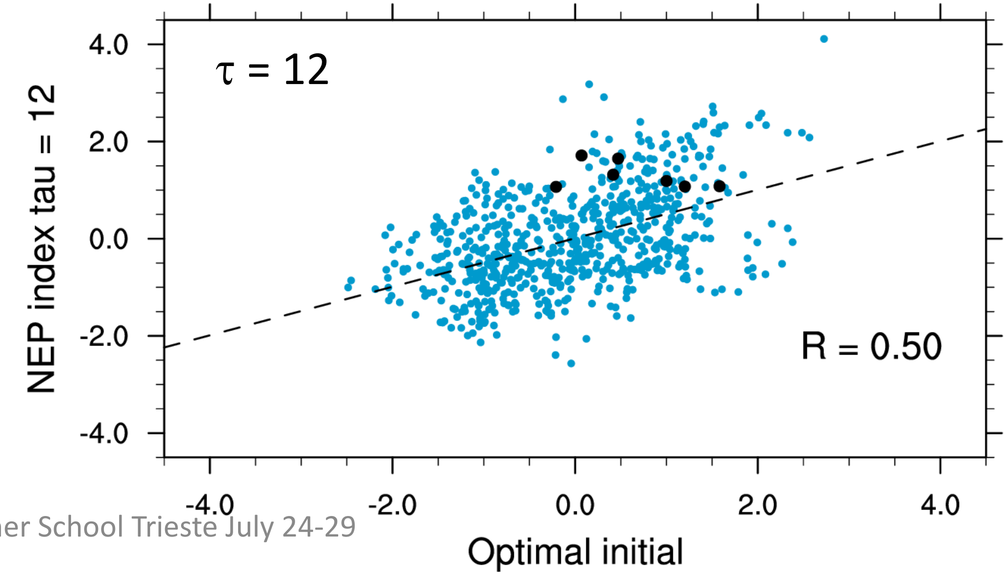
Can the optimal initial conditions help anticipate MHW occurrence?



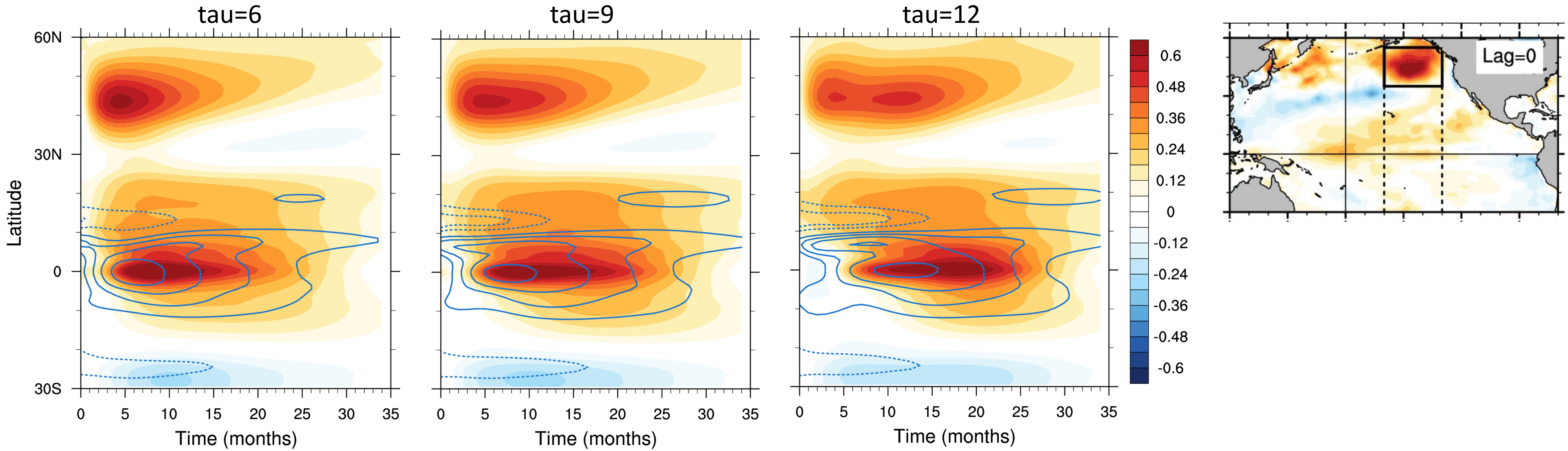


Index of optimal initial conditions at time *t* vs. the NEPac index at time *t*+τ shows a quasi-linear relationship with correlations significant at the 99% level.

Scatter indicative of atmospheric noise



Relationship with ENSO development



Northeast Pacific MHWs grow concurrently with tropical Pacific anomalies and precede El Nino events.

Longer persistence of Northeast Pacific anomalies is associated with a slower onset and longer duration of central equatorial Pacific anomalies, as found by Xu et al. (2021)

Are the optimal initial conditions related to known modes of variability?

What is the role of the tropics vs. extra-tropics?

Are the optimal initial conditions related to known modes of variability?

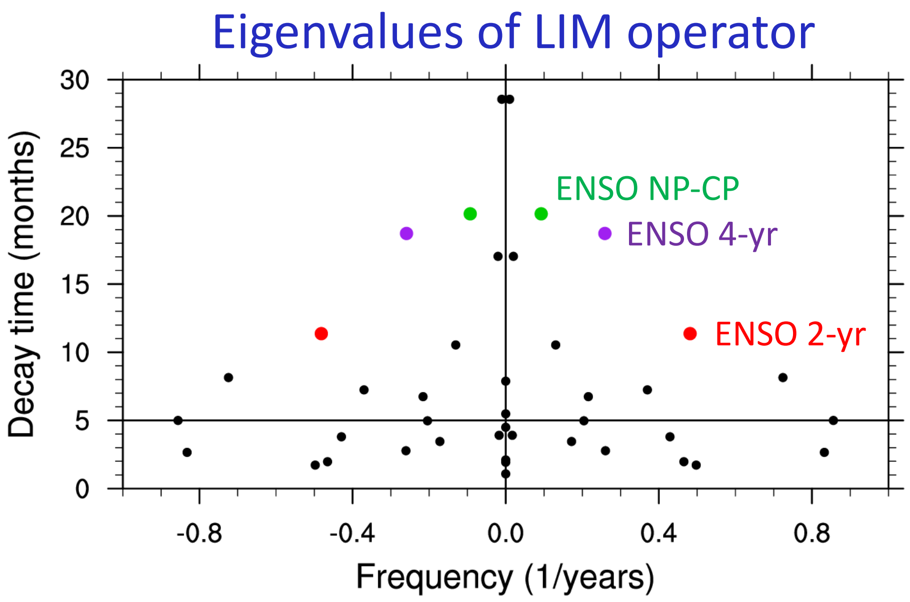
We decompose our initial MHW optimal $x_{\text{MHW}}(0)$ in terms of the eigenvectors of the LIM dynamical operator u_i and examine which eigenvectors are most important for the MHW growth.

This approach can be used to attribute the origin of forecast skill.

The LIM is a dissipative system sustained by noise, so the ***L*** eigenvectors are all decaying, but they can be oscillatory.

$$\boldsymbol{x}_{\boldsymbol{MHW}}(0) = \sum_{\boldsymbol{i}=1}^{\boldsymbol{i}=\boldsymbol{N}} \alpha_i \, \boldsymbol{u}_{\boldsymbol{i}}$$

Which dynamical modes are more important?

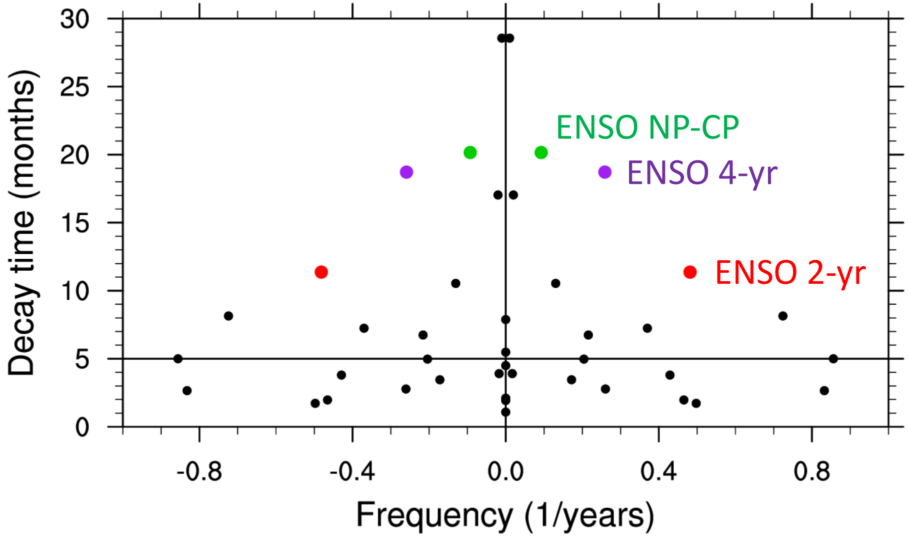


The eigenvectors of ***L*** include 3 ENSO flavors: The NP-CP mode encompasses the tropical and North Pacific, the 4-yr and 2-yr mode are primarily tropical.

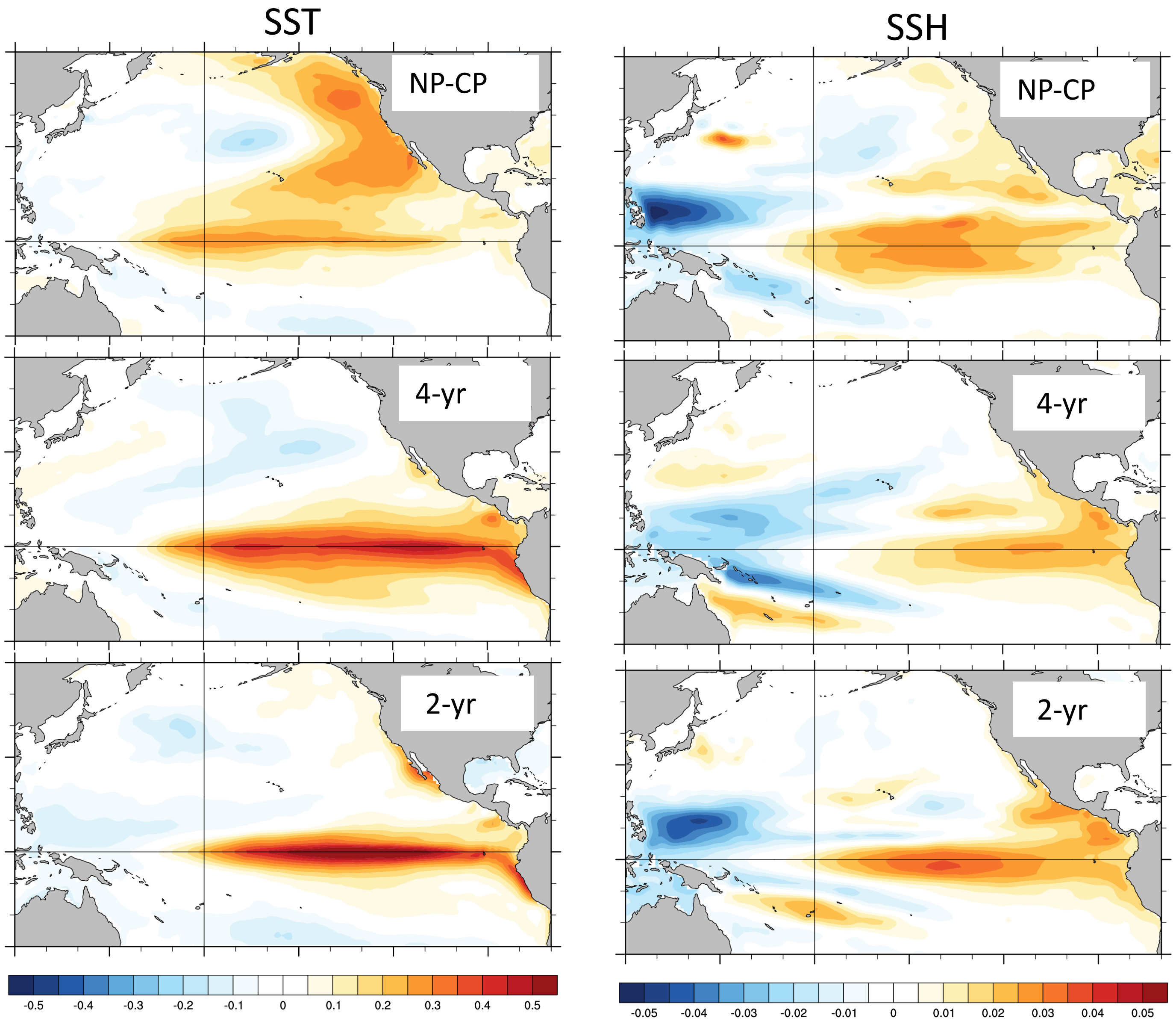
The NP-CP mode appears to play a key role in the growth of the MHW. **Is this dynamics responsible for MHW development?**

Is the North Pacific leading the tropics or *vice versa*?

Eigenvalues of LIM operator



Selected Eigenvectors of *L* (phase of maximum amplitude)



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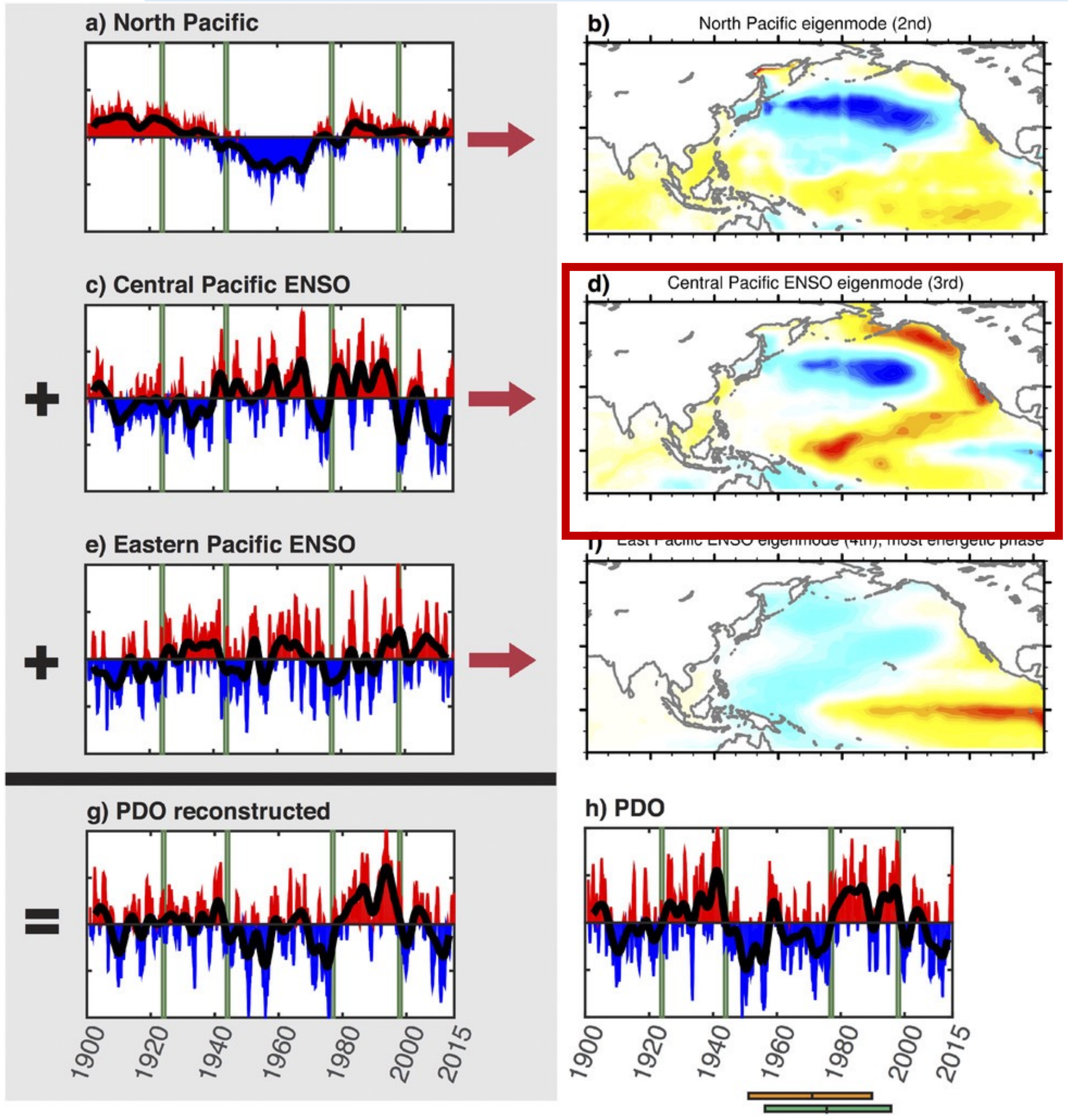
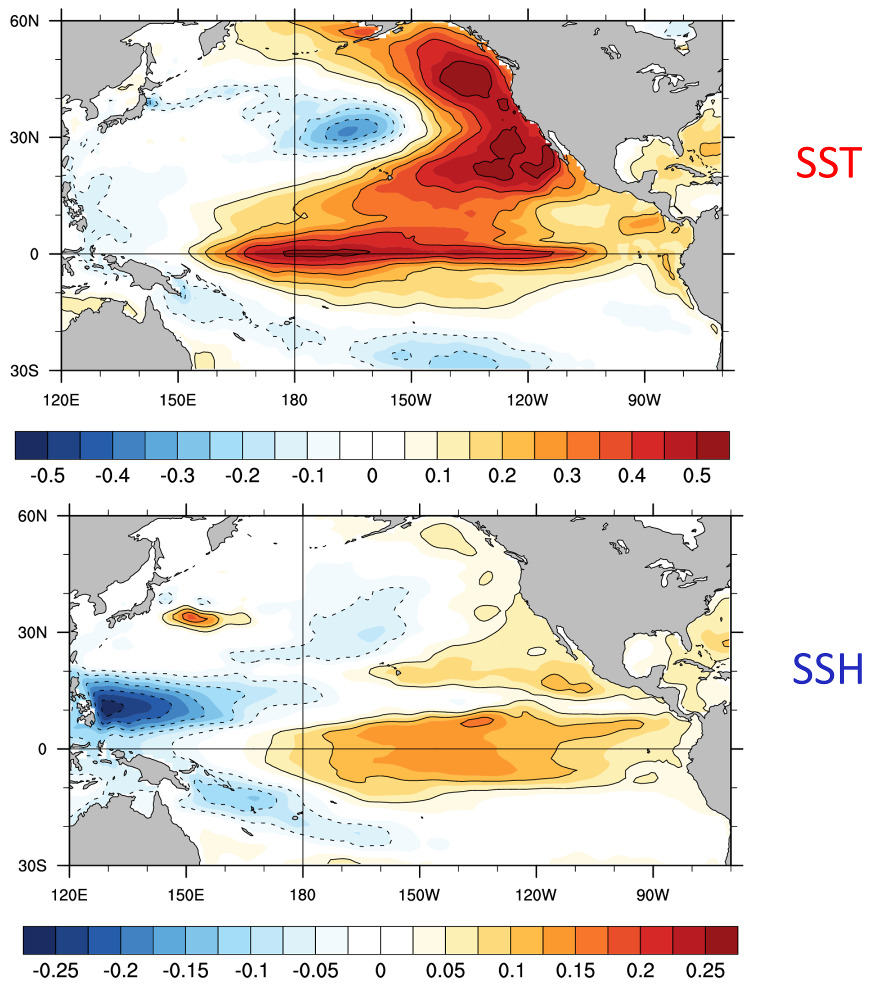
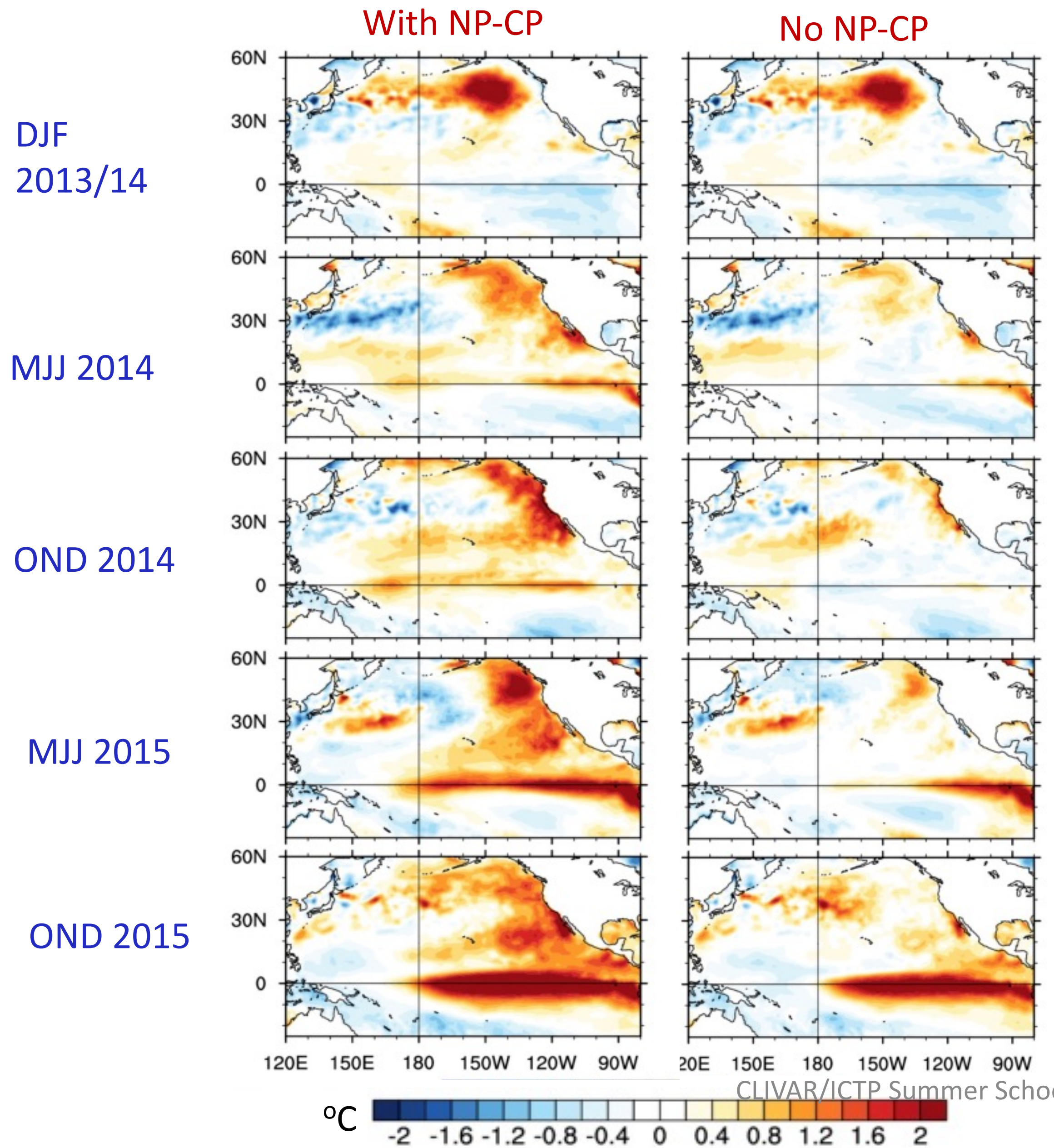
Eigenvector of the dynamical LIM operator: “NP-CP”





How would the Northeast Pacific have evolved without the NP-CP eigenmode?



A Blob-type anomaly is present in the Winter of 2013-2014, but anomalies do not grow in the Northeast Pacific during the following seasons.

No warming develops in the central equatorial Pacific. The 2015/16 El Niño initiates from the eastern equatorial Pacific.

No intense warming in the Northeast Pacific is seen even during this El Niño event

Main Final Points

- The Northeast Pacific has experienced intense and persistent MHWs over the last 60 years, with a characteristic evolution that appears related to large-scale modes of climate variability.
- We have identified an optimal precursor of Northeast Pacific MHWs, which can provide some skill in anticipating the occurrence of these MHWs (within a large level of atmospheric noise).
- The development of this MHW is related to a decadal dynamical mode of variability (“NP-CP”), which links MHW growth to the development of CP El Nino events in the equatorial Pacific. This decadal mode is one component of the PDO.
- ENSO develops in the equatorial Pacific concurrently with the development of the NE Pacific MHW, so it cannot be seen as the “forcing”, but can sustain MHW persistence.
- Results highlight the importance of considering different ENSO types and different components of the PDO, rather than using standard indices, to maximize the predictive skill that may be provided by these modes of variability.