State-space analysis of ocean and atmospheric data for use in forecasting ecological impacts of climate change

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Methodological Approach

- Compare climate patterns in North Pacific Large Marine Ecosystems using a variety of statistical methods
- Describe temporal co-variability on climate scales
- Propose mechanisms for co-variability
- Develop easy-to-use indices of climate-fisheries linkages
- Variety of analytical methods for identifying climate variability
  - Observations, anecdotal reports
  - Anomaly time series & fields
  - Indices & leading indicators
  - EOF analyses
  - Decomposition of PDO & other indices
  - State-space models of physical & biological series
  - Regional common trend analyses

What Do We Need from Statistical Methods?

- Distinguish low-frequency trends, AR, cyclic processes
- Avoid rigid assumptions (constant mean, variance)
- Time dependence in model
- Quantify non-stationary seasonality (phenology)
- Rigorous testing to determine best model
- Long history of time series methods, possibly new application to ocean science
- Available applications & toolboxes (Matlab, R)

‼ State-Space Time Series Decomposition

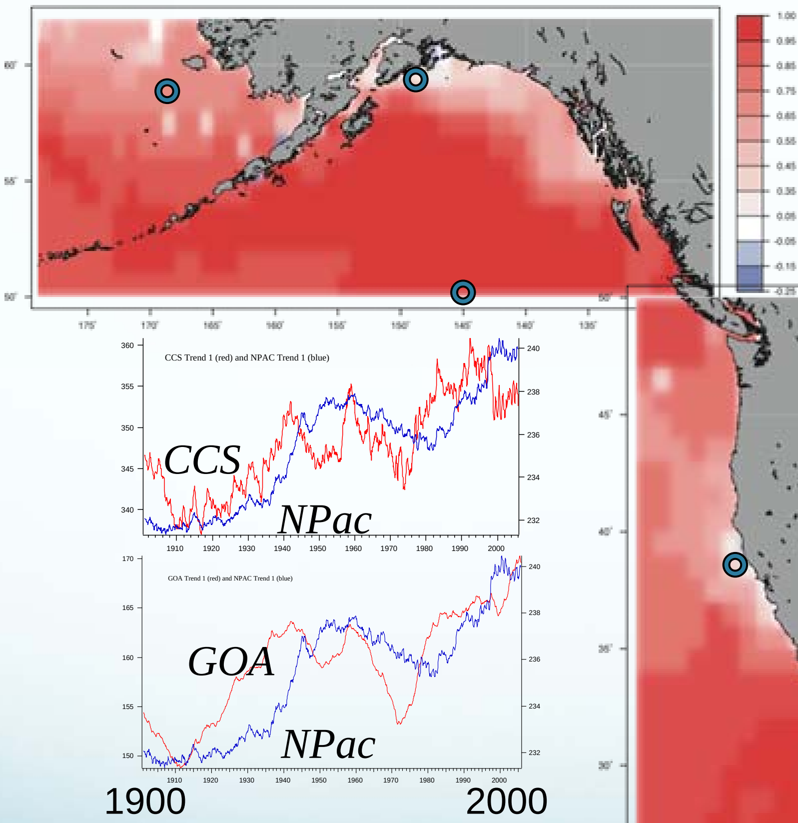
Data(t) = Trend(t) + Seasonal(t) + Irregular(t) + Error(t)

Trend - non-linear and non-parametric
Seasonal - non-stationary, changes in phase and amplitude
Irregular - can include AR or stochastic cyclic term
Error - allow for observational error

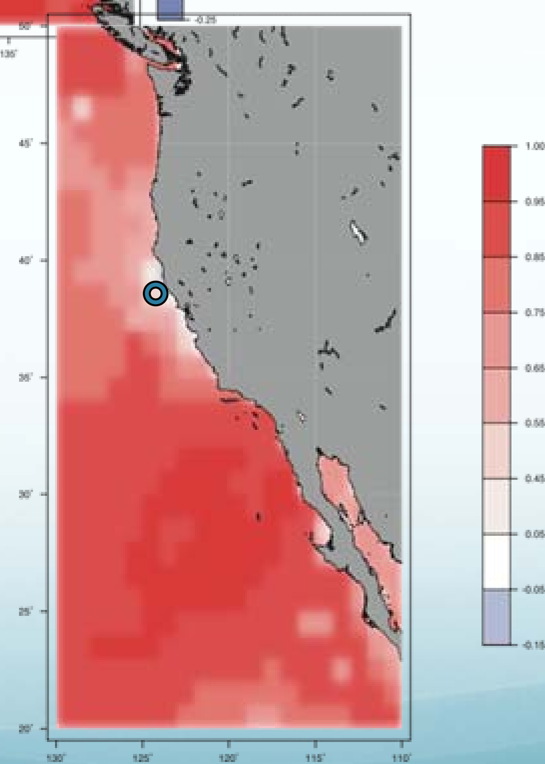
Dynamic factor analysis of trends

- UK Meteorological Office, Hadley Centre, SST Dataset (HadISST1.1), Reynolds OISST.v2
  - Global , 1-degree resolution, monthly, 1900-present
  - California Current, Gulf of Alaska, Oyashio, Kuroshio regions
- SODA assimilation model
  - Global, 5-degree, monthly, 1950-present

1st Common SST Trends in the Northeast Pacific (1900-2003)



- Positive correlations throughout domain
- Decadal fluctuations on overall warming trend
- Trend mitigated in coastal CCS, northern GOA



Mode 1:
"global SST mode"

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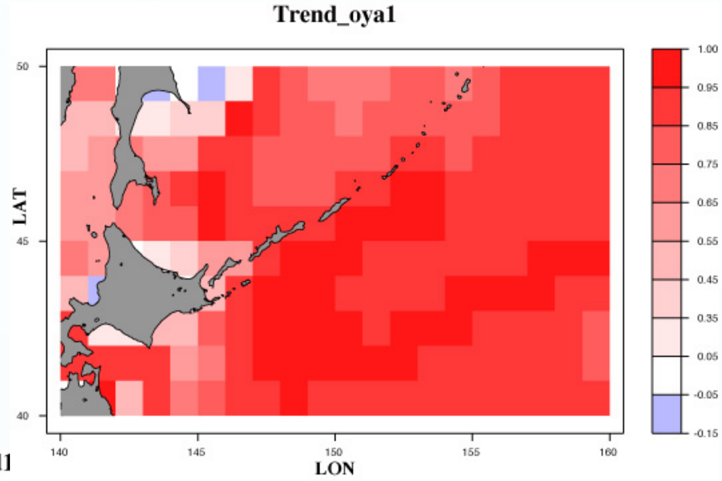

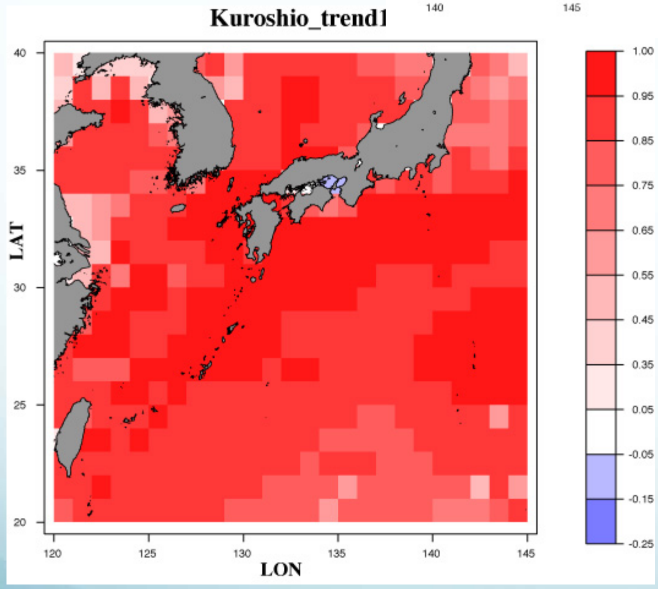

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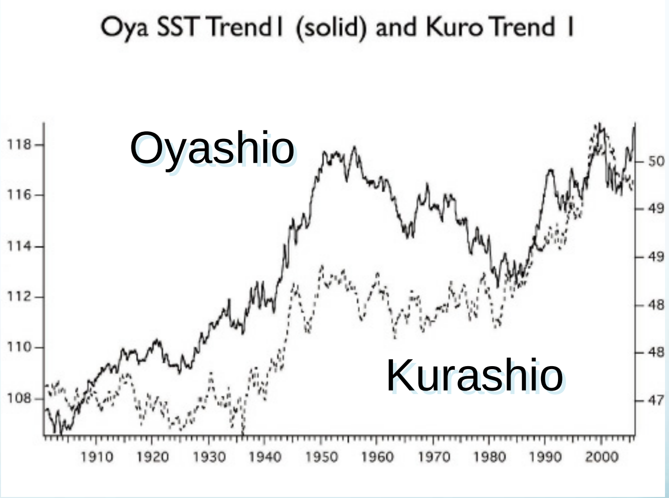
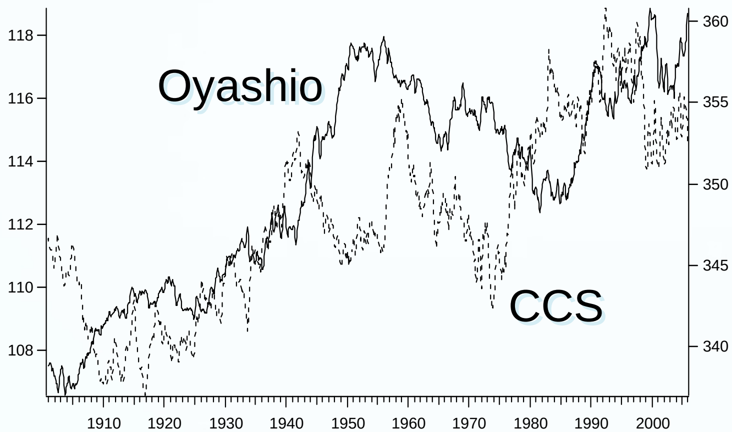
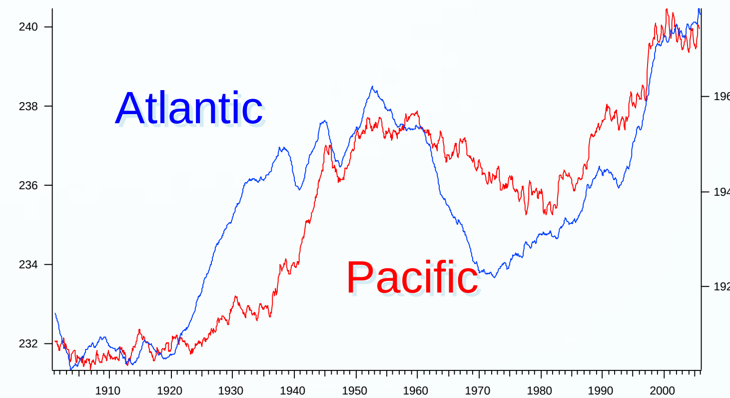
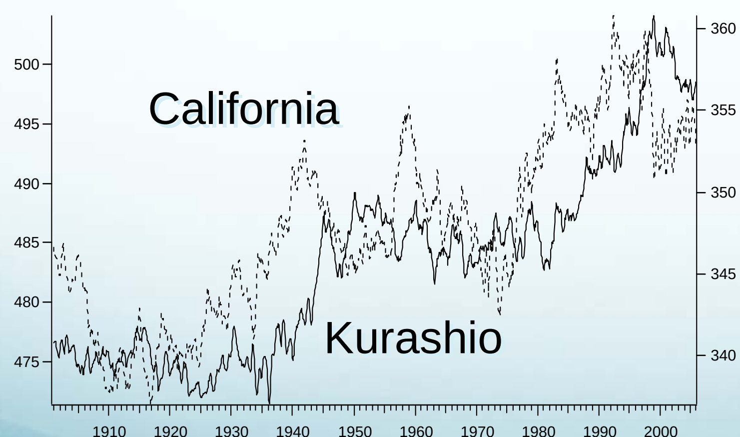


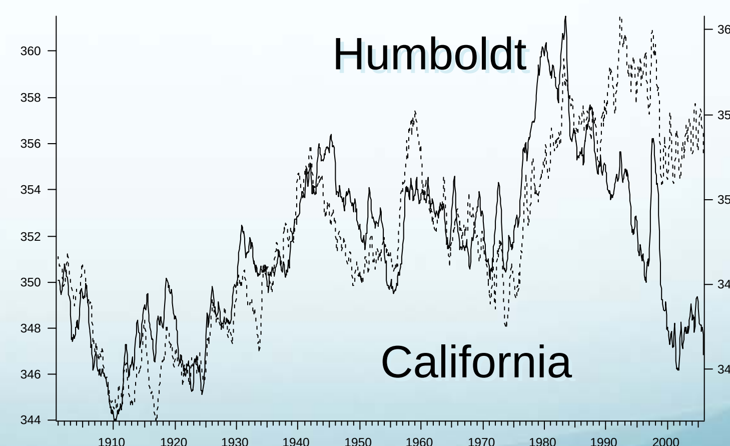
- Overall warming trend, accelerated in 1940s, 1980s
- Positive correlations throughout domain

1st Common SST Trends (1990-2003)



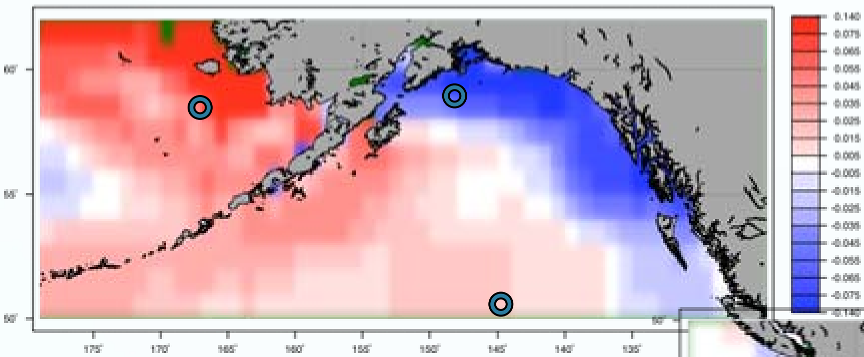




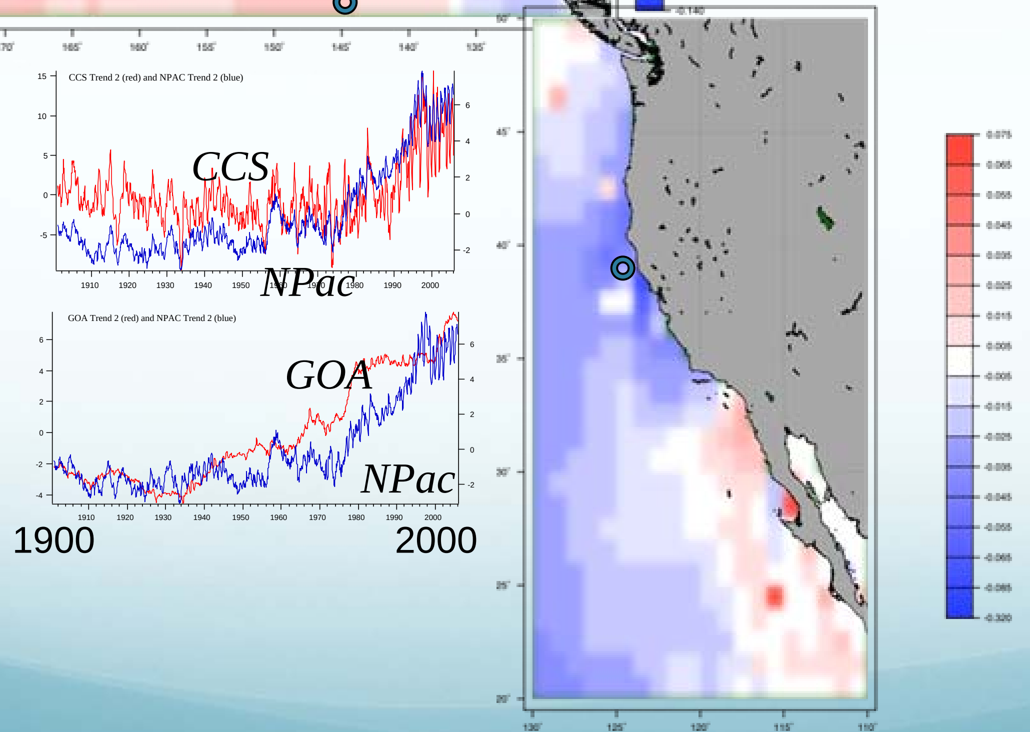


- Similar warming trend in Northeast & Northwest Pacific and Atlantic
- East to west "propagation"

2^{nd} Common SST Trends in the Northeast Pacific



- Accelerated T change since 1970s
- Positive loadings = enhanced warming
- Negative loadings = mitigated warming



Mode 2:

“global warming mode”

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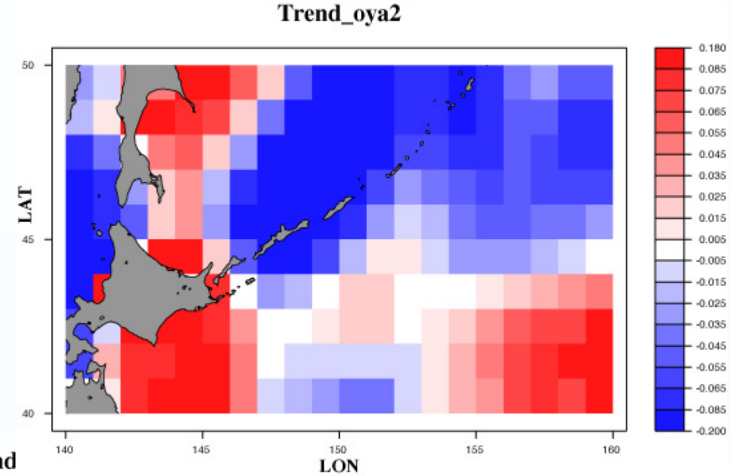

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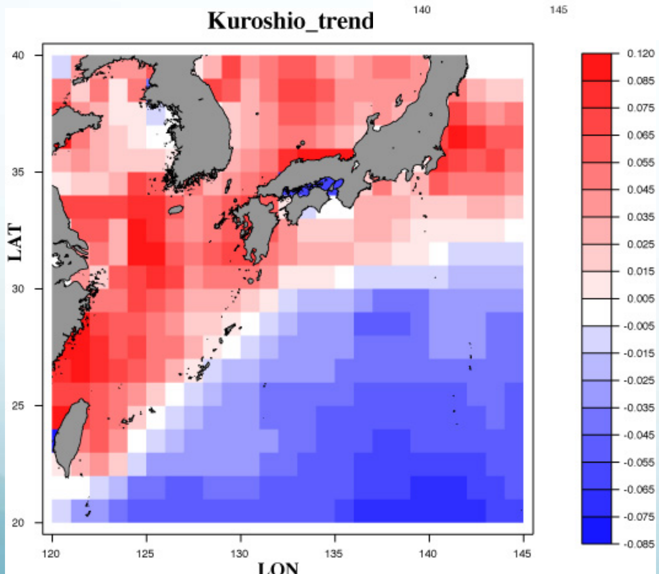
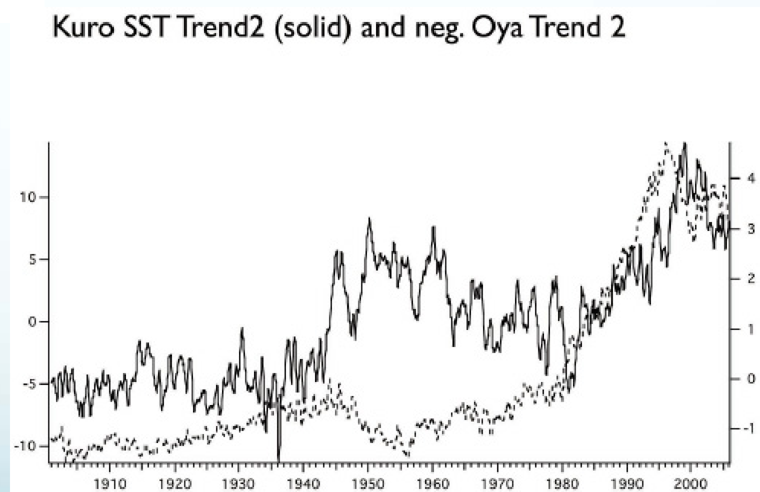
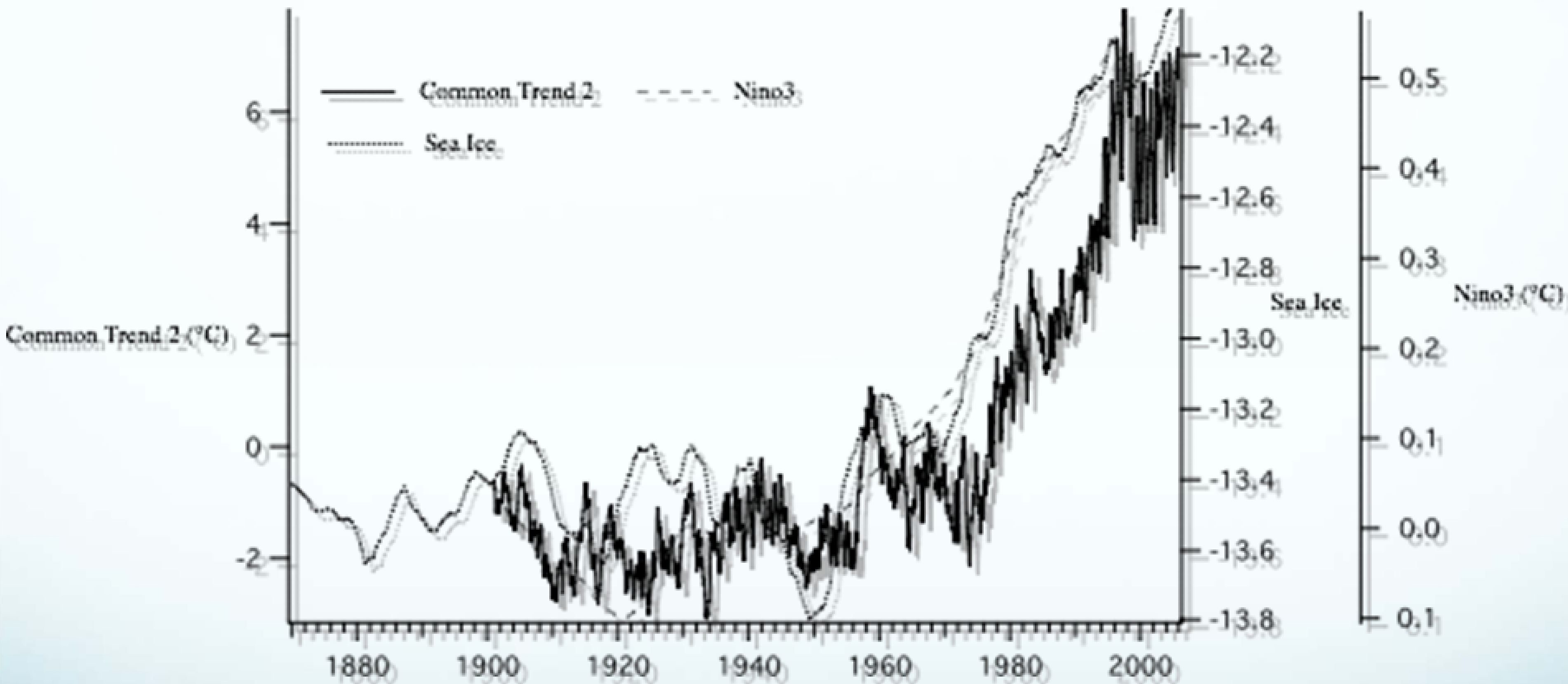




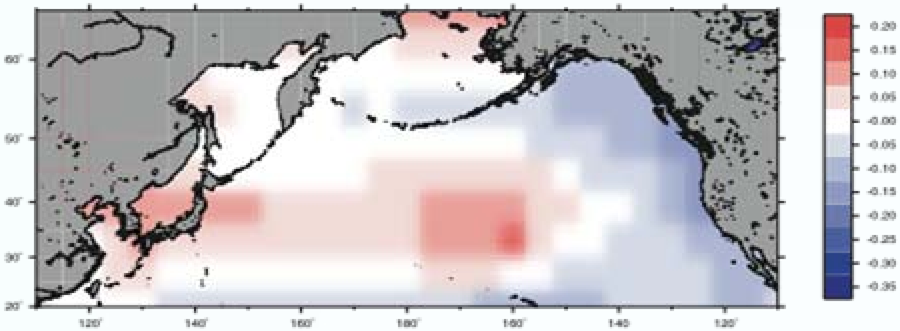
- Enhanced warming offshore northern Japan, East Asian Seas

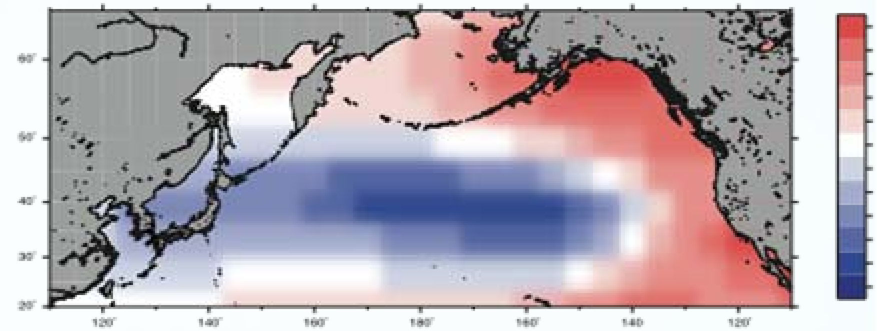


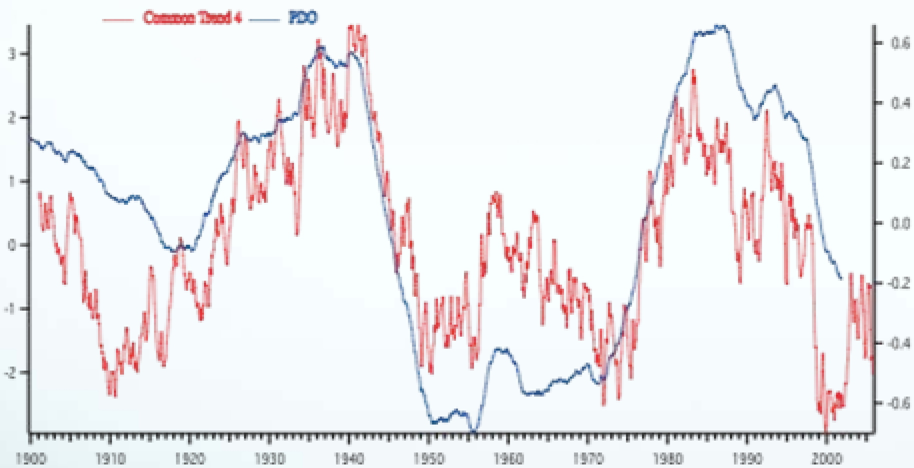
Comparison of Common Trend 2, N Pacific SST (5-degree) 1900-2003
NINO3 1900-2003
Negative of Arctic Sea Ice Extent 1880-2003

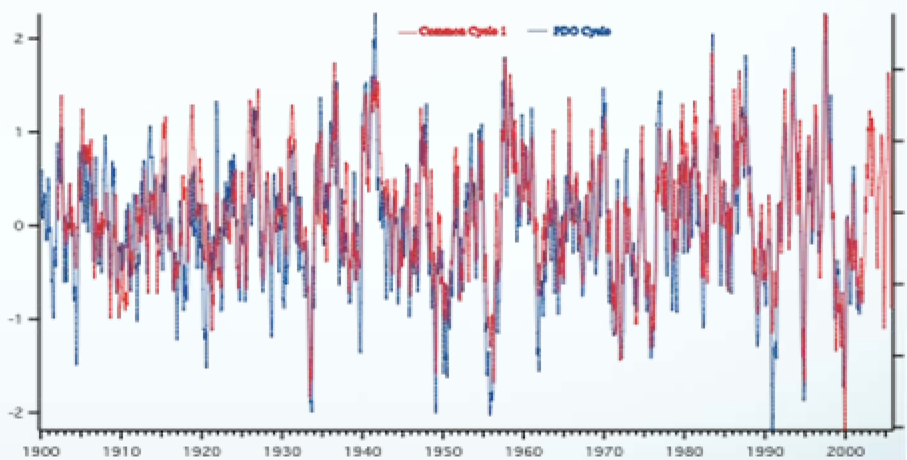
Trends

Stochastic Cycles



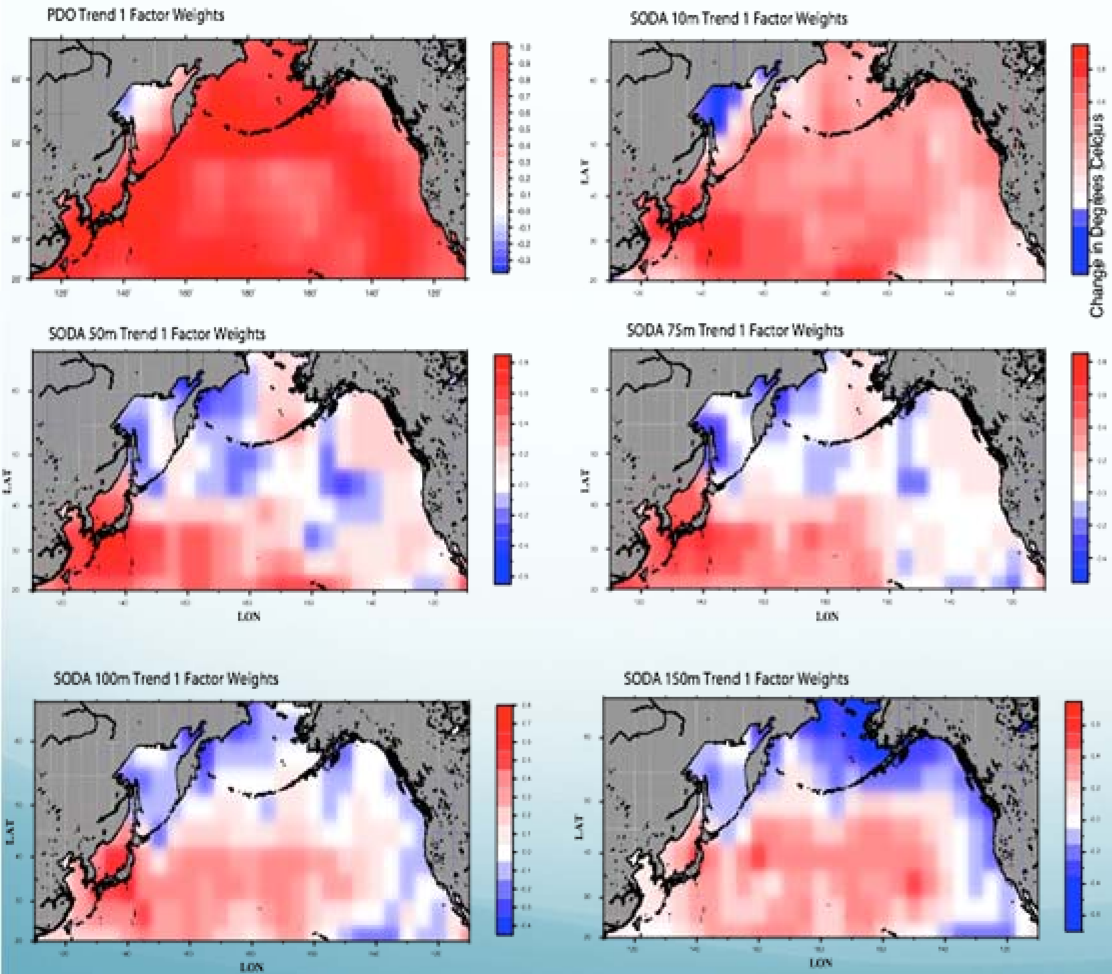


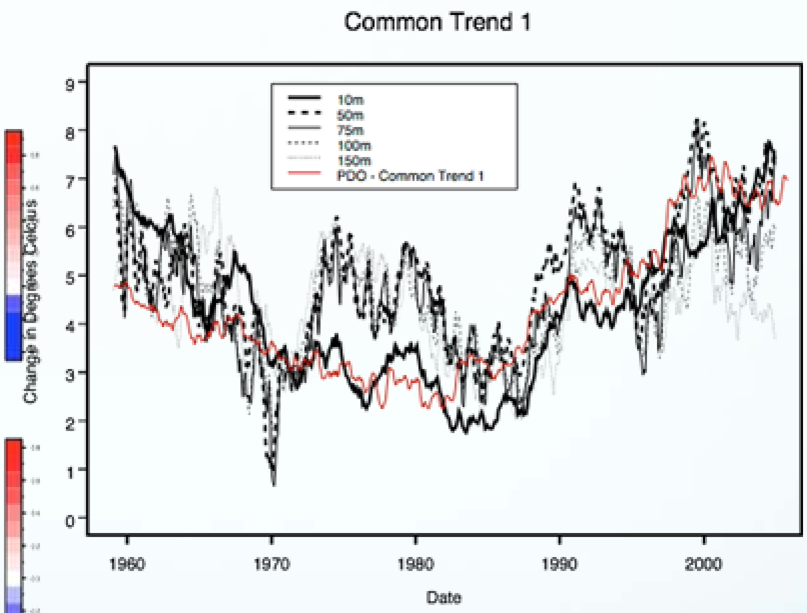




- Common trend 4 matches PDO trend
- Common cycle 1 matches PDO cycle
- PDO index combines HF cycle + non-seasonal trend
- Other SST non-seasonal variability not explained by PDO

1st Common Subsurface Temperature Trends (1950-2005)





Summary

- Global climate signals are modulated by regional processes e.g., upwelling strength & timing, FW input
- Indicators need to characterize dynamic climate processes
  - Need methods to decompose time/space structure
  - Different techniques provide unique insight
- Biology can respond to climate "noise"
  - Life history affects ecological response *(Think like a Fish!)*
- Need climate models, downscaling methods that can resolve regional processes *(Think global, act local)*

Compelling Questions

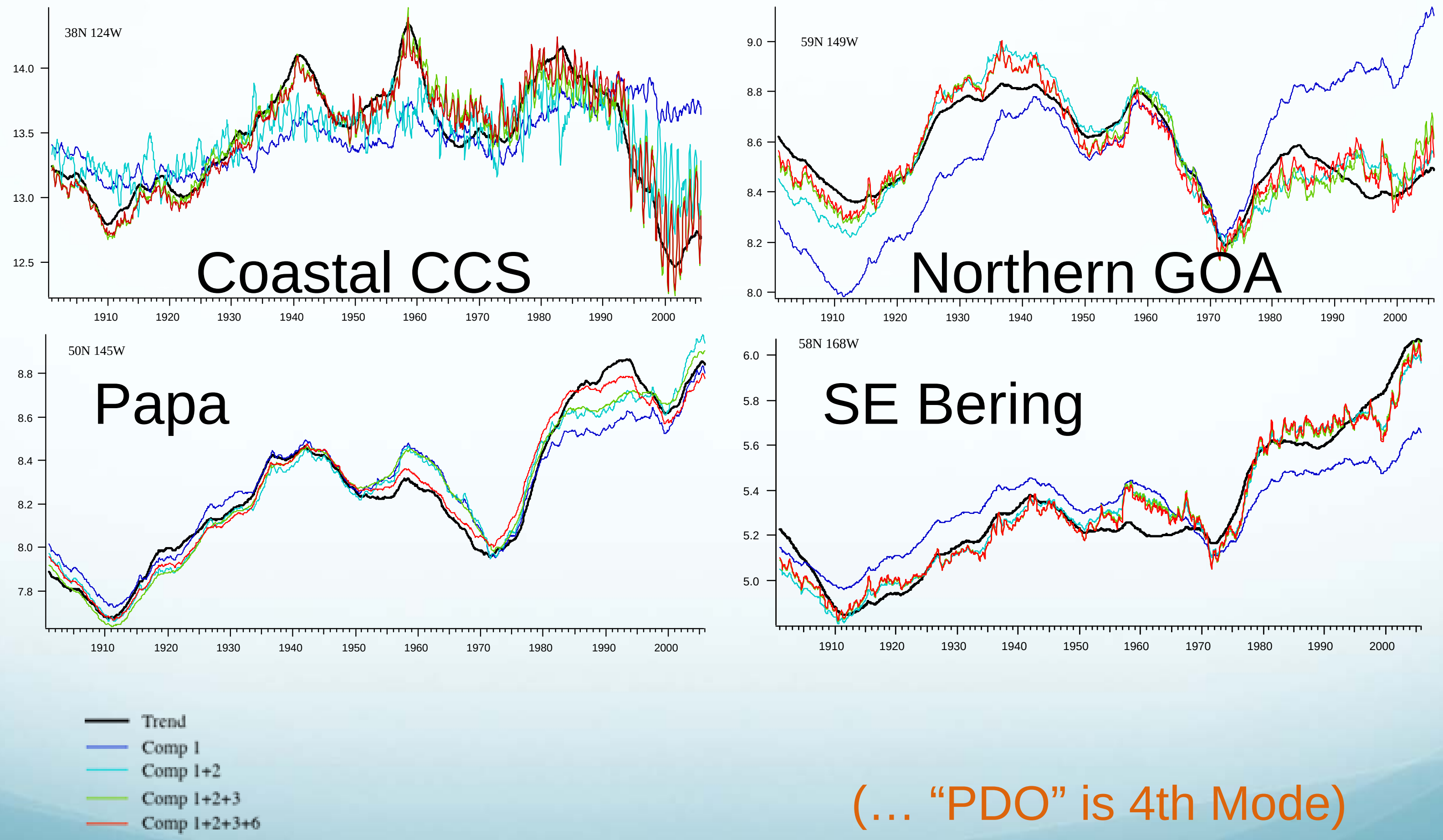
- How do we define & quantify climate variability?
- Are regime shifts real? If so …
  - What is the timing and morphology of climate regimes?
  - What is their 3-D spatial structure?
  - What are their causes & forcing mechanisms?
  - What are the biological responses & pathways?
  - How are regime impacts modulated by local processes?
  - Do North Pacific ecosystems vary in or out of phase?

Unanswered Questions

- Are regime shifts real and quantifiable?
- Are they a biological or physical phenomenon (or both)?
- How do we capture their ecological impacts with indices?
- How do local processes modulate large-scale climate forcing?
- What is the sensitivity of marine ecosystems to future climate change scenarios?

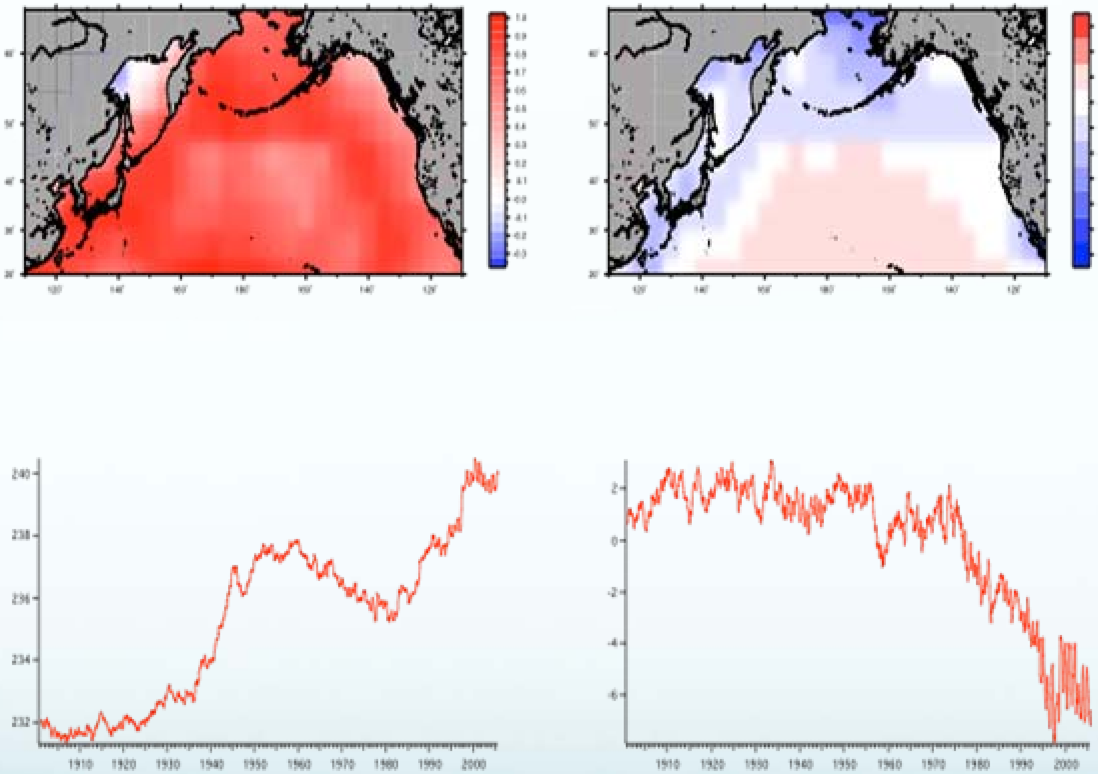
Thanks to U.S. GLOBEC, NOAA FATE program!

Common SST Trends in the Northeast Pacific



(… "PDO" is 4th Mode)

The PDO Revisited ...



Mendelssohn & Bessey, in prep.

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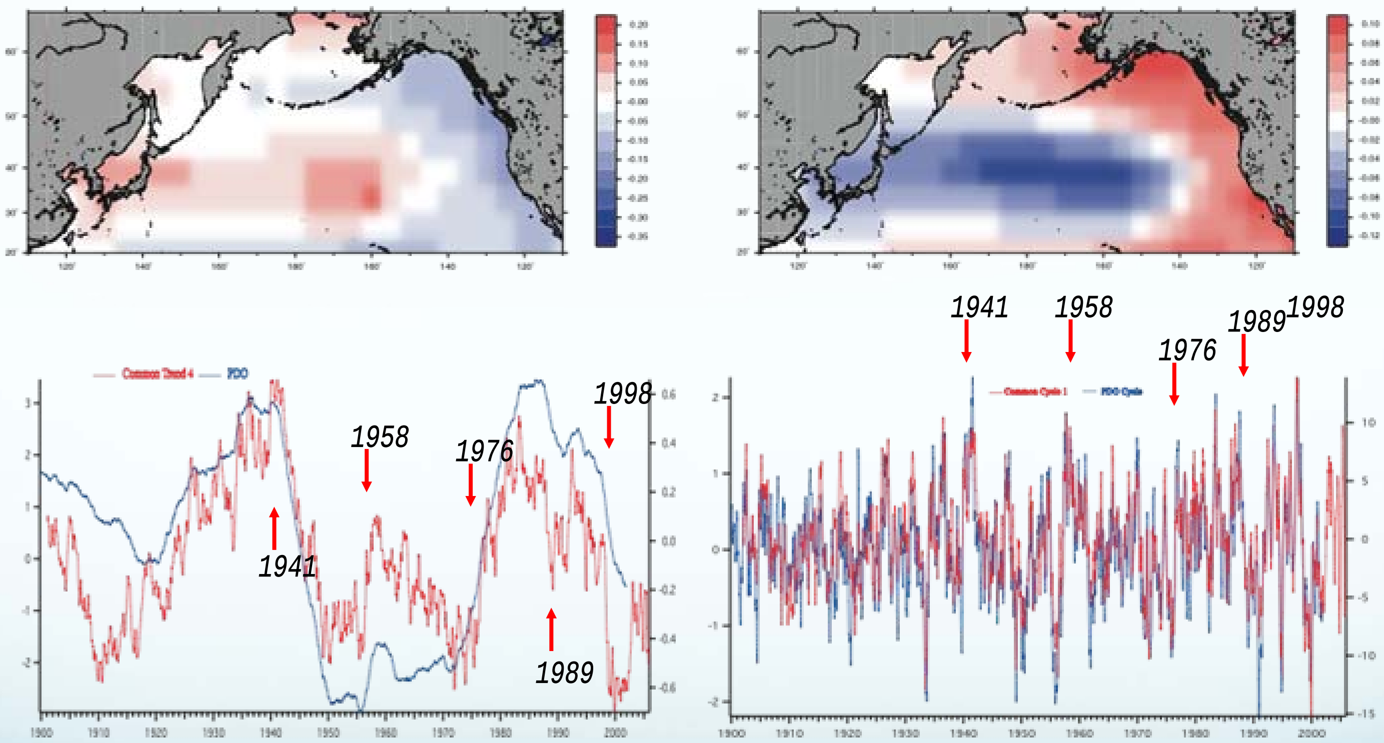

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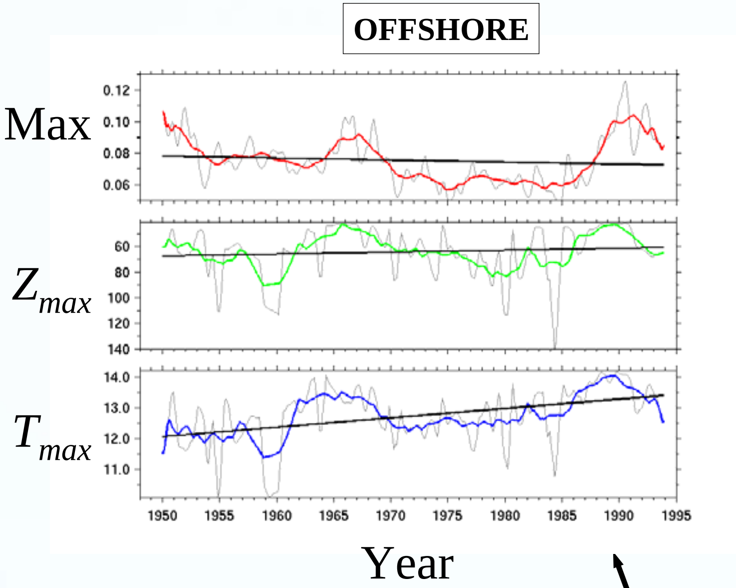
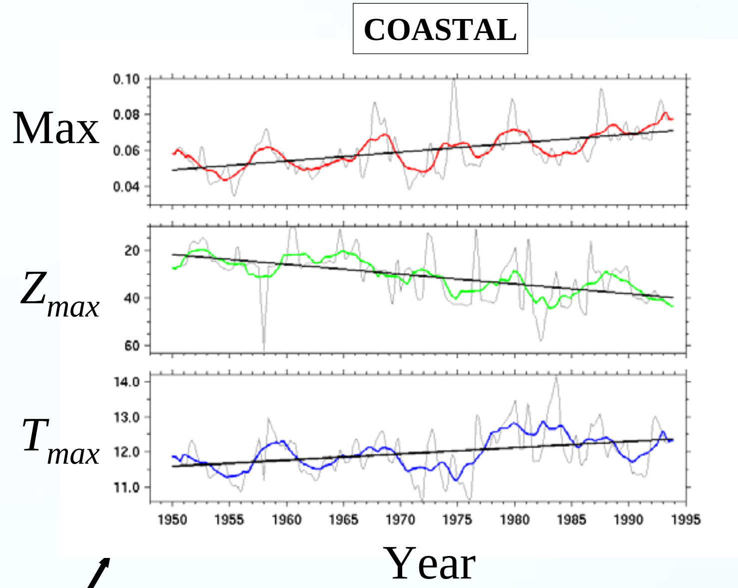
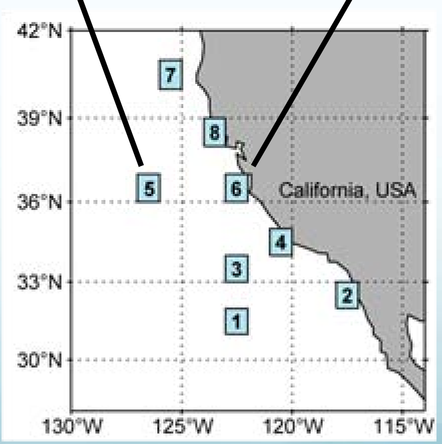
Coastal Ocean Stratification







Offshore

- strength: ↓ 7%
- depth: ↓ 10% (~7 m)
- temp: ↑ 1.3°C
- heat: ↑ 7%

Coast

- strength: ↑ 44%
- depth: ↑ 82% (~18 m)
- temp: ↑ 0.8°C
- heat: ↑ 7%

Palacios et al. (2004)

(1) State-space decomposition of time series

Data(t) = Trend(t) + Seasonal(t) + Irregular(t) + Error(t)

Trend - non-linear and non-parametric

Seasonal - non-stationary, changes in phase and amplitude

Irregular - can include AR or stationary, stochastic cyclic term

Error - allow for observational error

Statistical criteria for determining "best" model

(2) Stationary, stochastic cycle

$$\begin{bmatrix} \psi_t \\ \psi_t^* \end{bmatrix} = \rho \begin{bmatrix} \cos\lambda_c & \sin\lambda_c \\ -\sin\lambda_c & \cos\lambda_c \end{bmatrix} \begin{bmatrix} \psi_{t-1} \\ \psi_{t-1}^* \end{bmatrix} + \begin{bmatrix} \kappa_t \\ \kappa_t^* \end{bmatrix}, \qquad t = 1, \dots, T, \qquad (1)$$

where λ_c is the frequency, in radians, in the range $0 < \lambda_c \leq \pi$, κ_t and κ_t^* are two mutually uncorrelated white noise disturbances with zero means and common variance σ_κ^2, and ρ is a damping factor. A stochastic cycle becomes a first order autoregression if λ_c is 0 or π. Moreover, it can be shown that as $\rho \to 1$, then $\sigma_\kappa^2 \to 0$ and the stochastic cycle reduces to the stationary deterministic cycle:

$$\psi_t = \psi_0 \cos\lambda_c t + \psi_0^* \sin\lambda_c t, \qquad t = 1, \dots, T. \qquad (2)$$

State-Space Time Series Models

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Schwing & Mendelssohn (1997), Mendelssohn & Schwing (2002), Bograd et al. (2002), Mendelssohn et al. (2003,2004,2005), Palacios et al. (2004), Schwing et al. (2006)

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(2) Dynamic factor analysis of partial residuals
(trends, seasonals, ...)

Compare first two common SST trends in all regions

Schwing & Mendelssohn (1997), Mendelssohn & Schwing (2002), Bograd et al. (2002), Mendelssohn et al. (2003,2004,2005), Palacios et al. (2004), Schwing et al. (2006)