

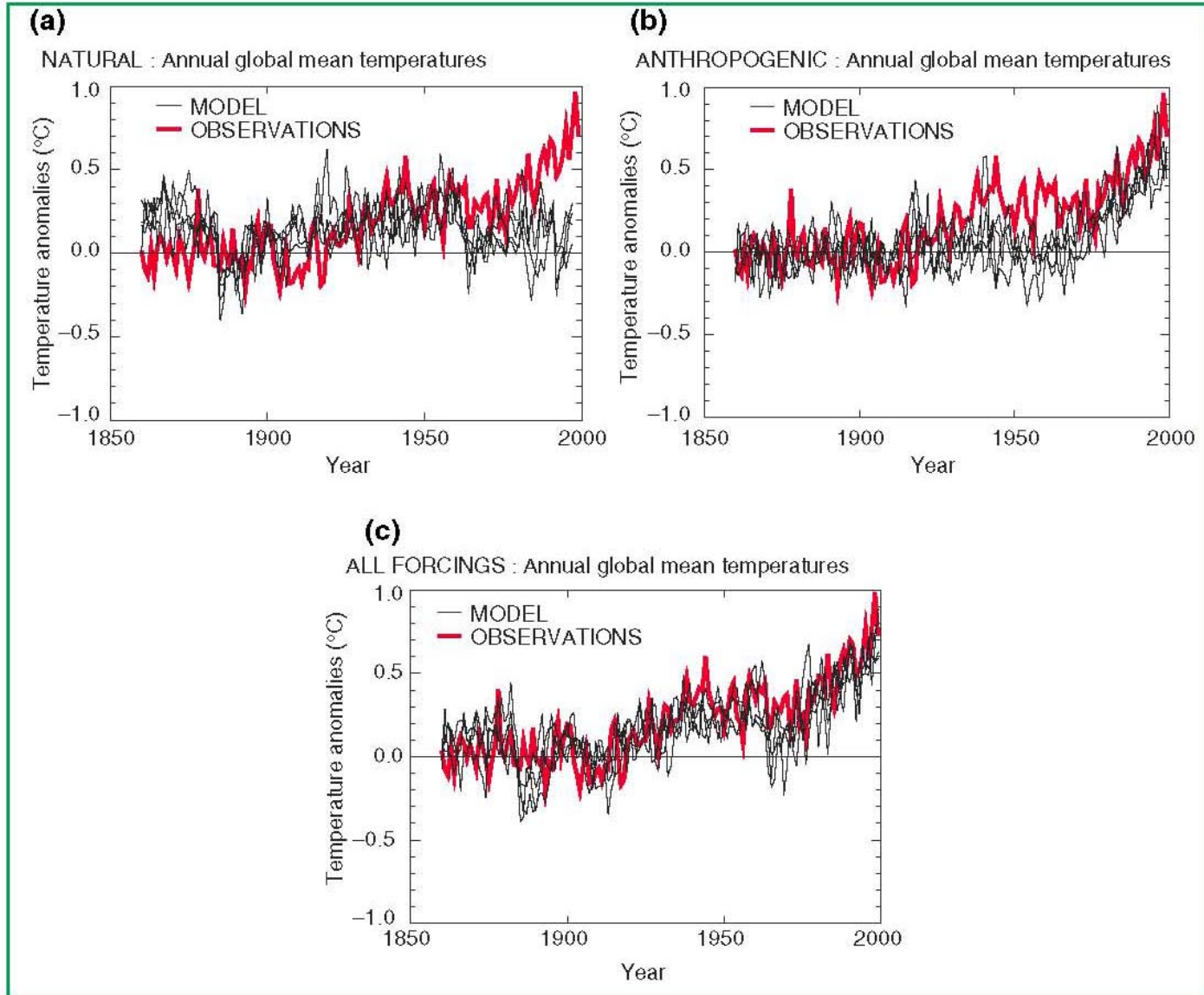
Error Estimates for Assimilation of Satellite Sea Surface Temperature Data in Ocean Climate Models

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Collaborators: Robert Miller and Yvette Spitz

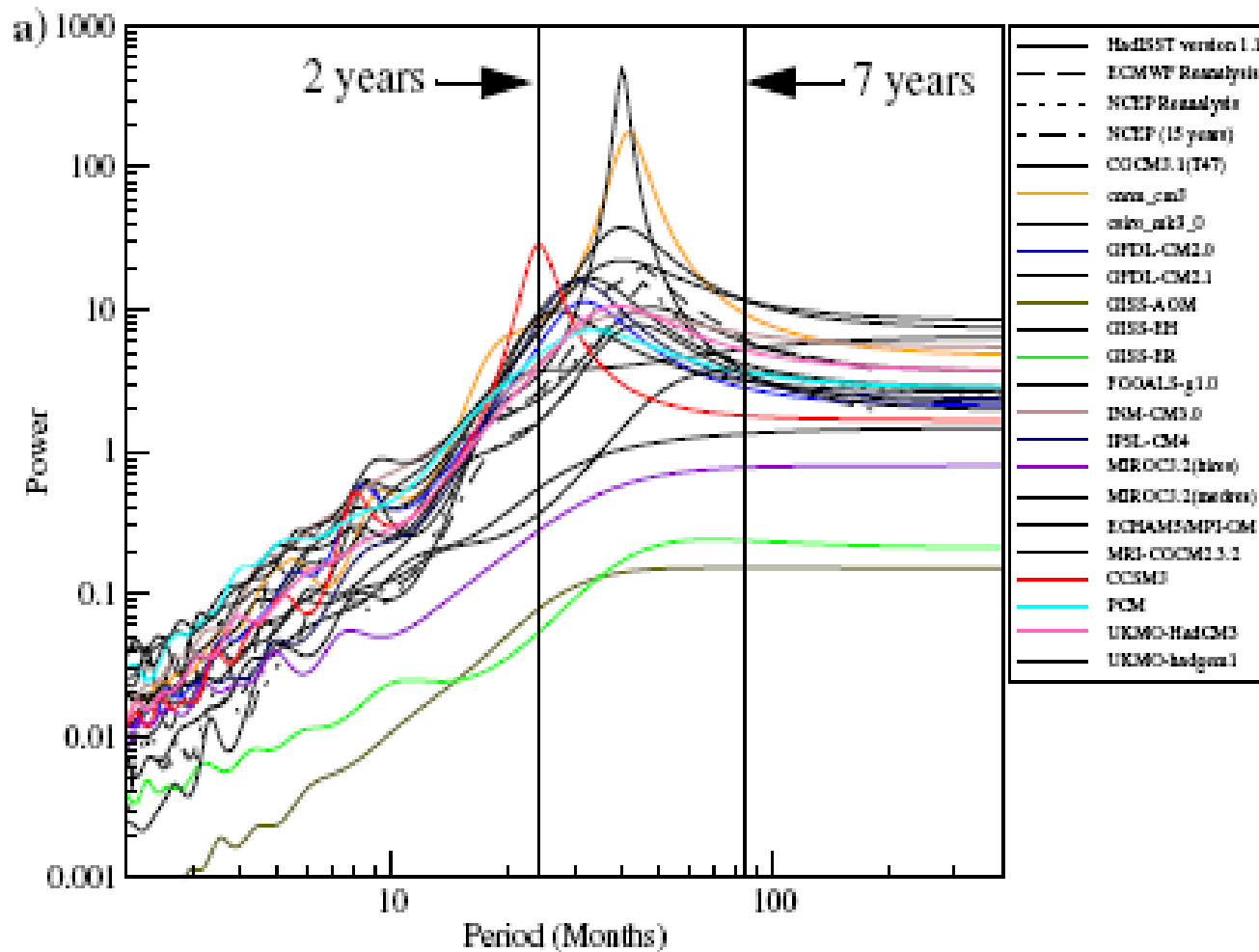


Evidence of climate change over the last century



greenhouse gases
sulphate aerosols

Power Spectra for NINO3 air temperature from the IPCC models



The models are improving but most tend to have a too regular and frequent El Nino cycle

BUT to understand and model the changes we need to know

- **What are the important aspects of that climate change?**
- **How do we “tune” our models?**
- **How sensitive these models are to the “tuning”?**
- **How do we characterize the errors in our models?**
- **What is the role of the ecosystem in modulating these changes?**
- **How much ecosystem complexity do we need to have?**

Outline

- Modeling of changes in the North Pacific basin and associated challenges
 - Discuss the ecosystem model and its parameter choice (application of variational adjoint method).
 - Impact of the choice of the model parameters and the atmospheric forcing on the coupled circulation/ecosystem results.
- Method under development used to estimate the error of representation of the circulation model.
- Climate change and its associated effect on the ecosystem.

Outline

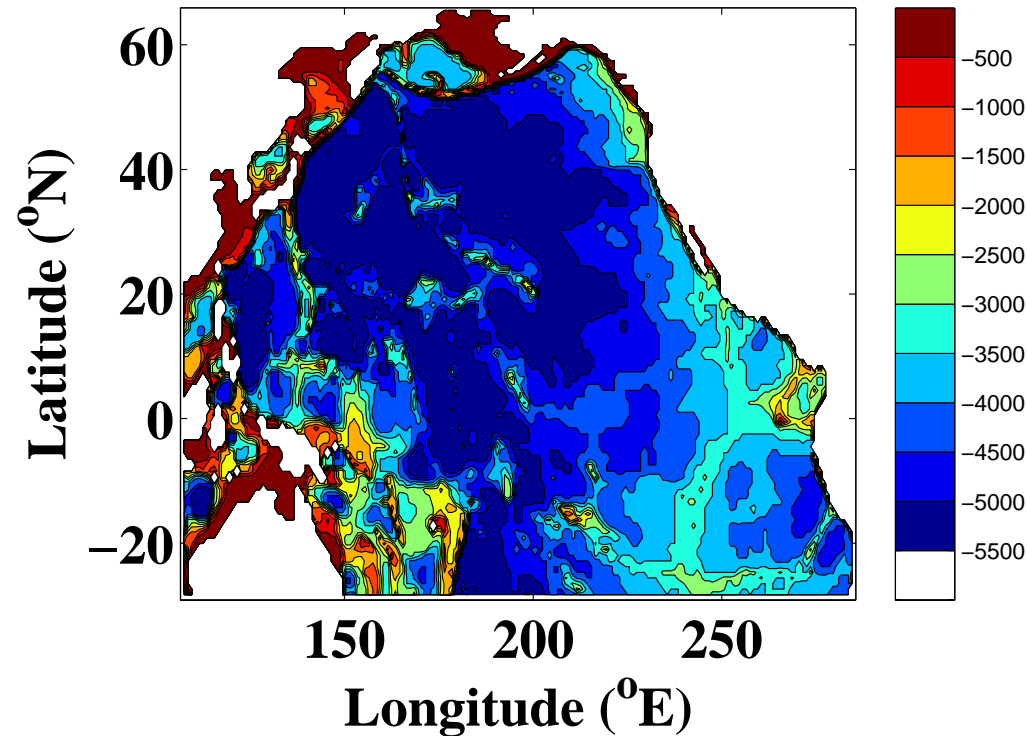
- We have coupled an oligotrophic ecosystem model into a coarse resolution ocean general circulation model of the North Pacific Ocean
- In this talk I will first present results from the physical circulation model
- Then I will describe an attempt to assimilate satellite SST into the model using a reduced state space filter and the model error estimates generated from this attempt
- If time allows I will describe the oligotrophic ecosystem model developed by Yvette Spitz
- Finally I will show results from a coupled model run and the impact of different forcing regimes



North Pacific Circulation Model

- Model:
Parallel Ocean Program (POP) model
- Domain:
105° E to 85° W
30° S to 64° N
- Resolution:
1° at Equator on mercator projection
0.5° average resolution
50 vertical levels with 25 in top 500 m

Bathymetry of North Pacific Model



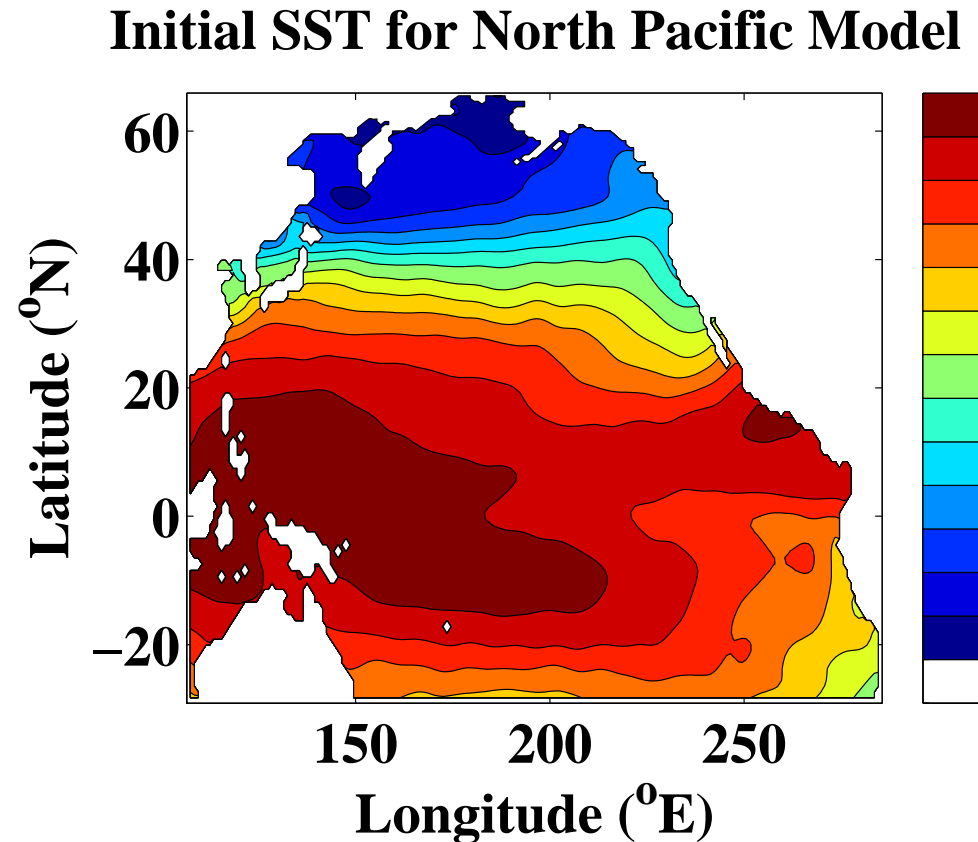
Model Forcing

- **25 years (1978 thru 2002) of NCEP/NCAR Reanalysis Fields are used to force the model**
- Wind Stress calculated from 10 m boundary layer winds using Smith et al
- Downwelling solar radiation flux reduced by a basin-wide cloud correction of 0.8765
- Longwave, Latent and Sensible Heat fluxes calculated from Model Sea Surface Temperature and 2 m boundary layer air temperature and humidity



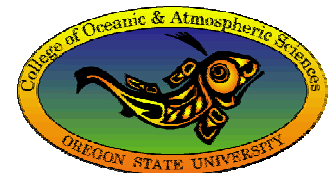
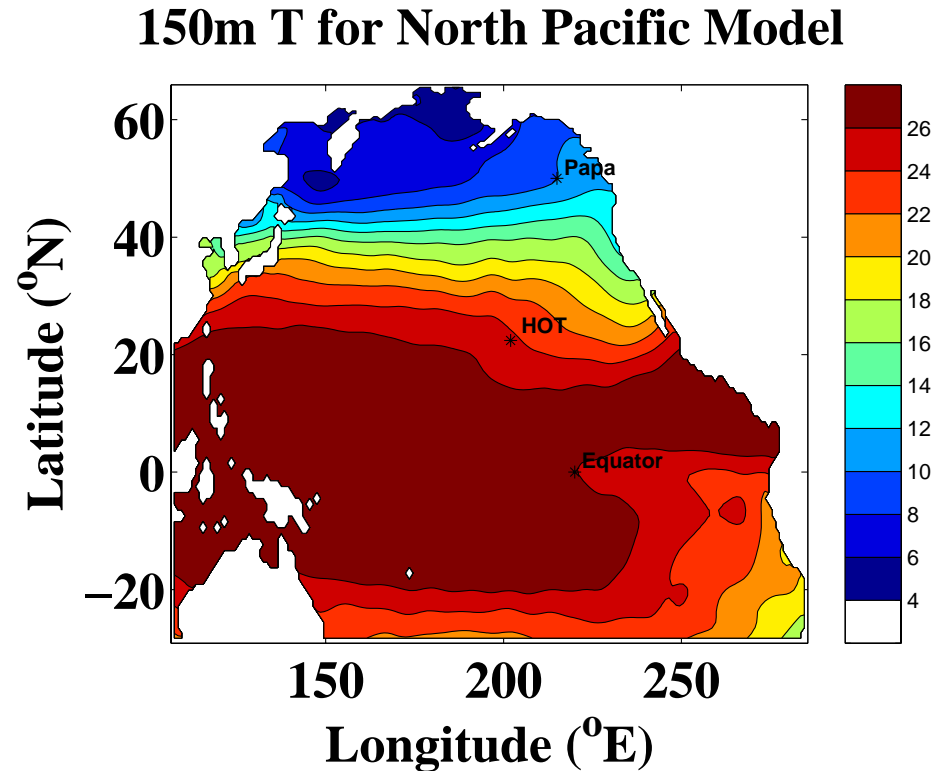
North Pacific Upper Ocean Model

- Model initialized from Levitus WOA98 temperature and salinity
- Model is restored to the initial surface salinity with 30 day restoration time
- Mixing is the upper ocean with the KPP mixed layer model of Large et al (1994)

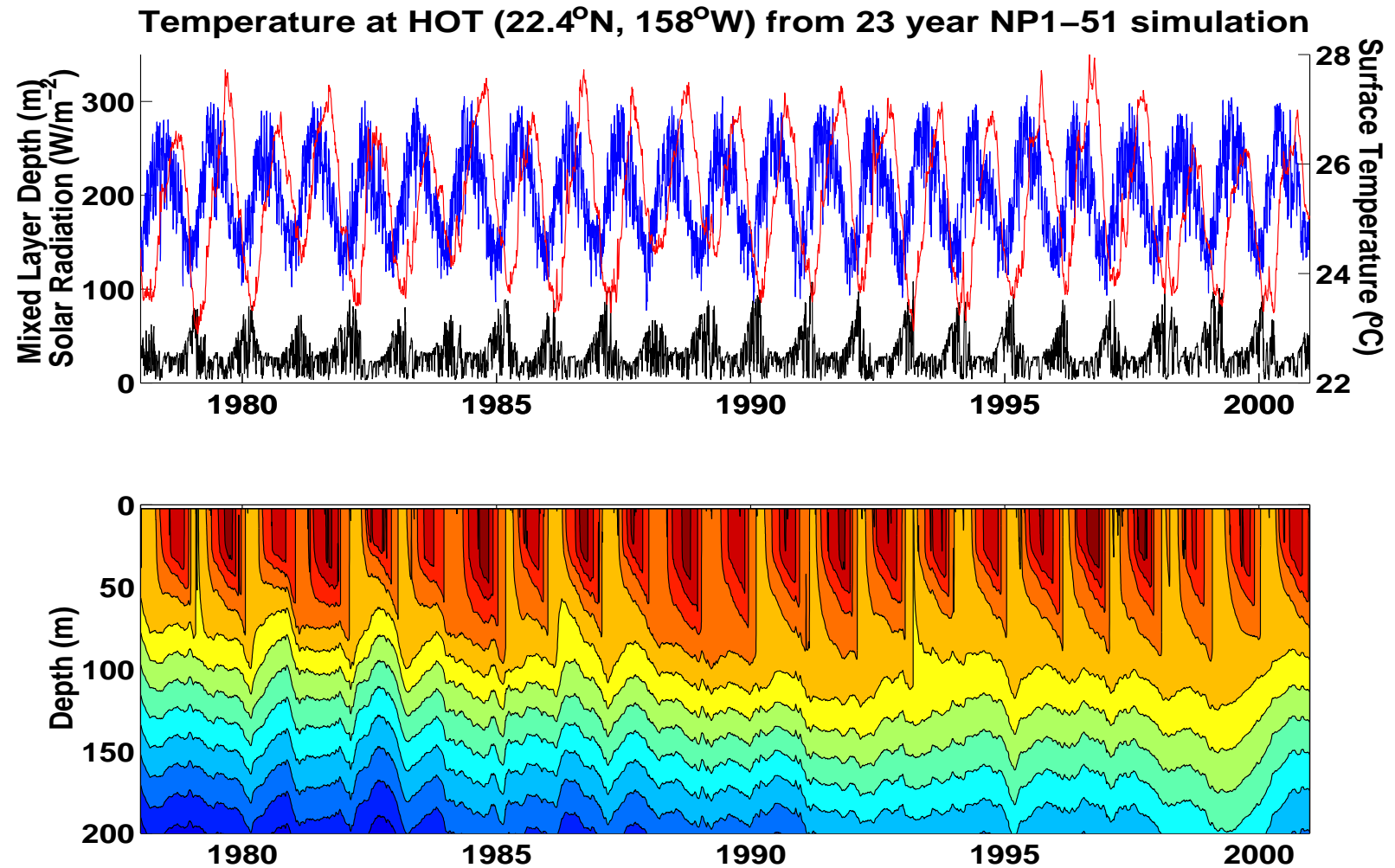


Results from 23 year Simulation

- The model is run for 23 years with surface forcing from NCEP Reanalysis bulk fluxes
- The model will be compared to time series observations at 3 locations
 - **HOT 22.4°N 158°W**
 - **Equator 0°N 140°W**
 - **Papa 50°N 145°W**

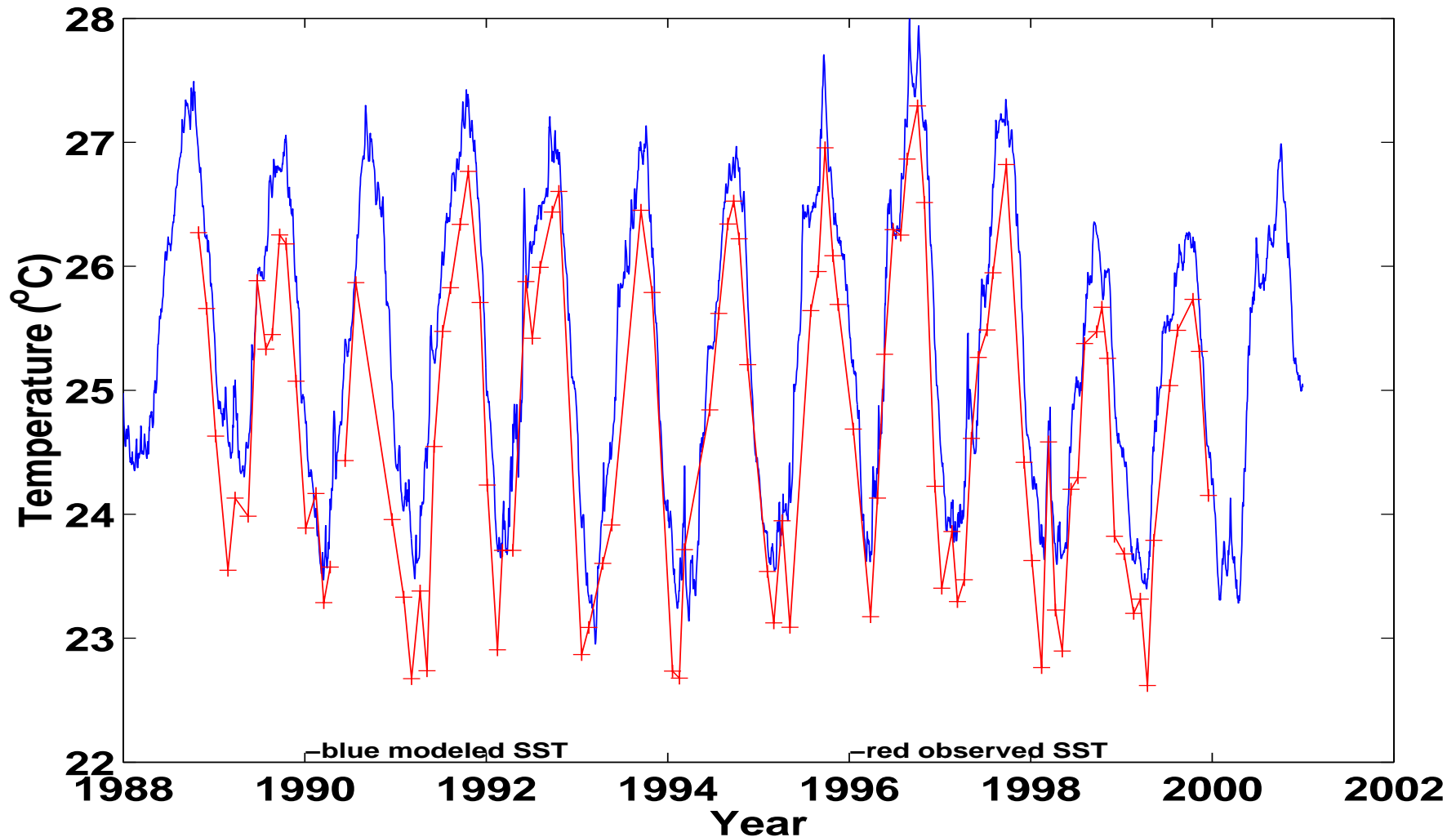


Model Results at Hawaiian Ocean Time-Series

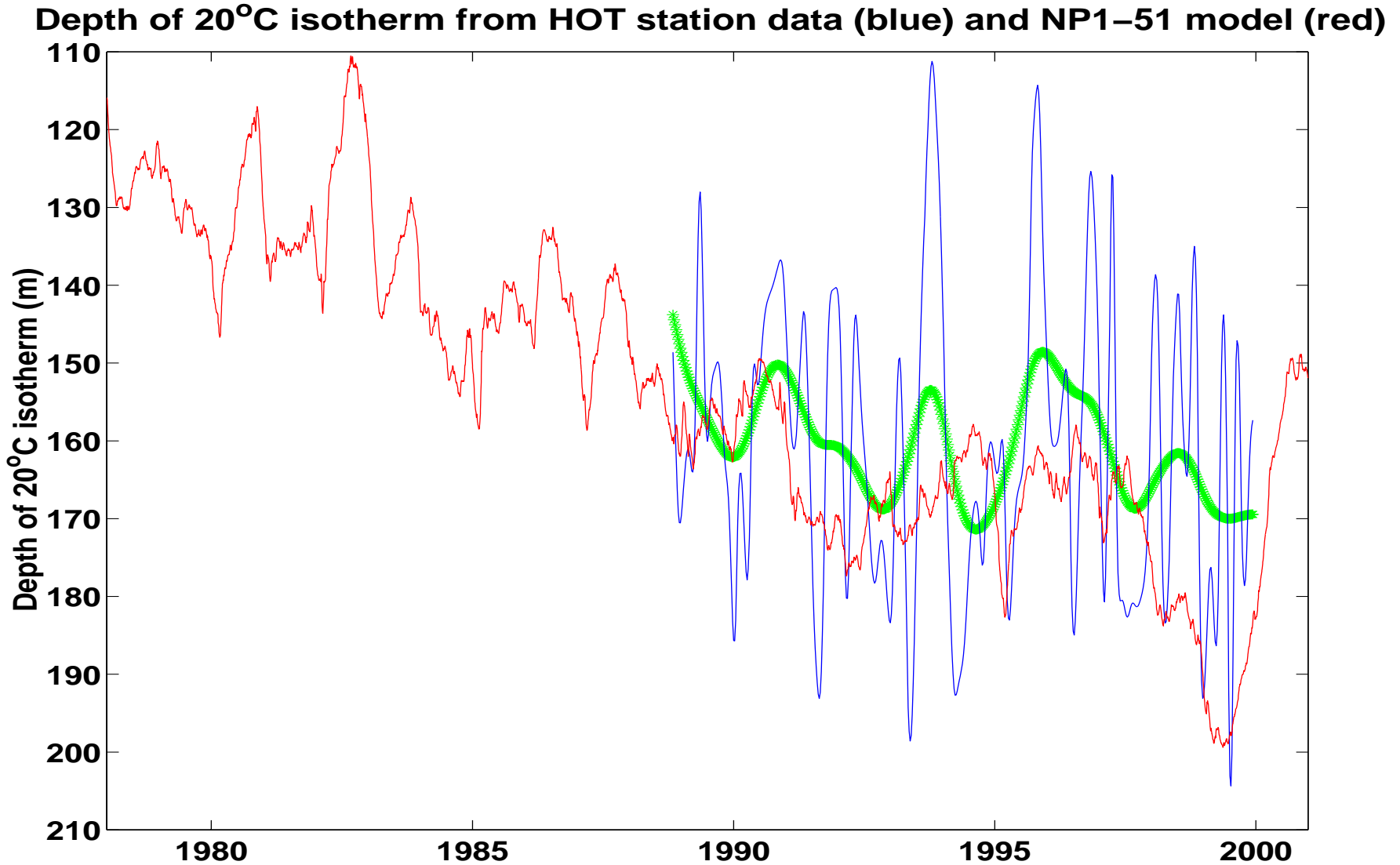


Sea Surface Temperature

Sea Surface Temperature at HOT (22.4°N, 158°W)

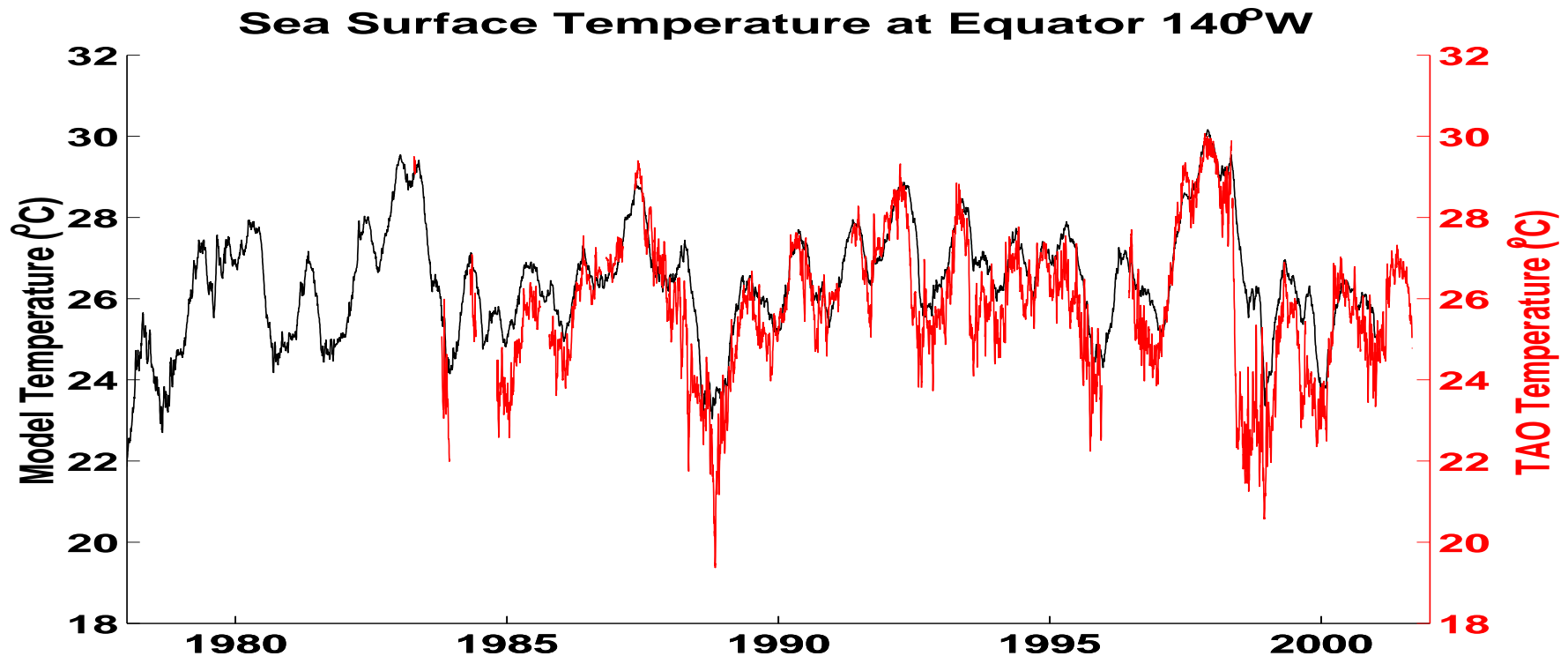


Depth of 20° C Isotherm

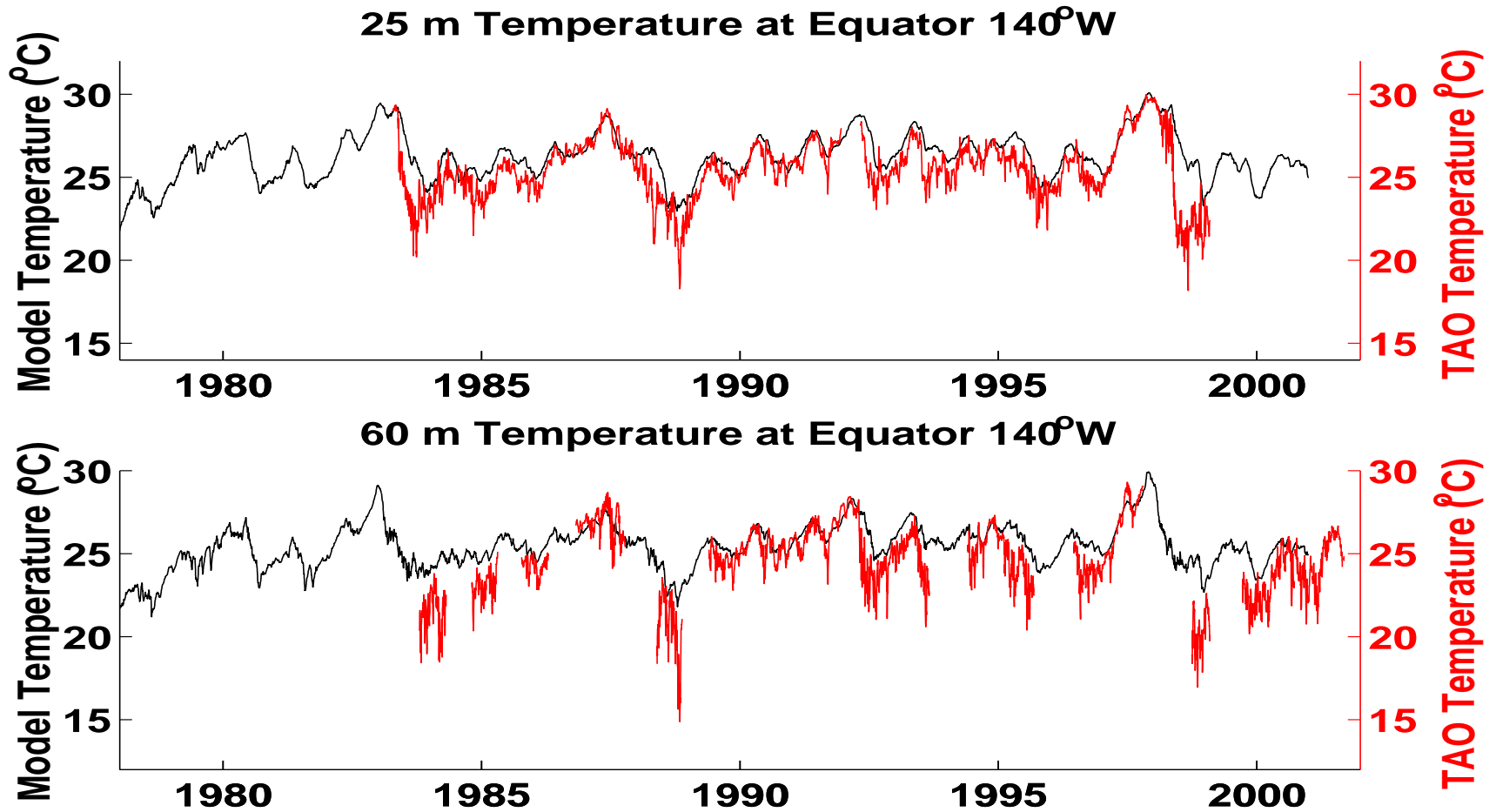


Sea Surface Temperature

- At the equator, the sea surface temperature is dominated by interannual variability and El Nino rather than seasonal variability

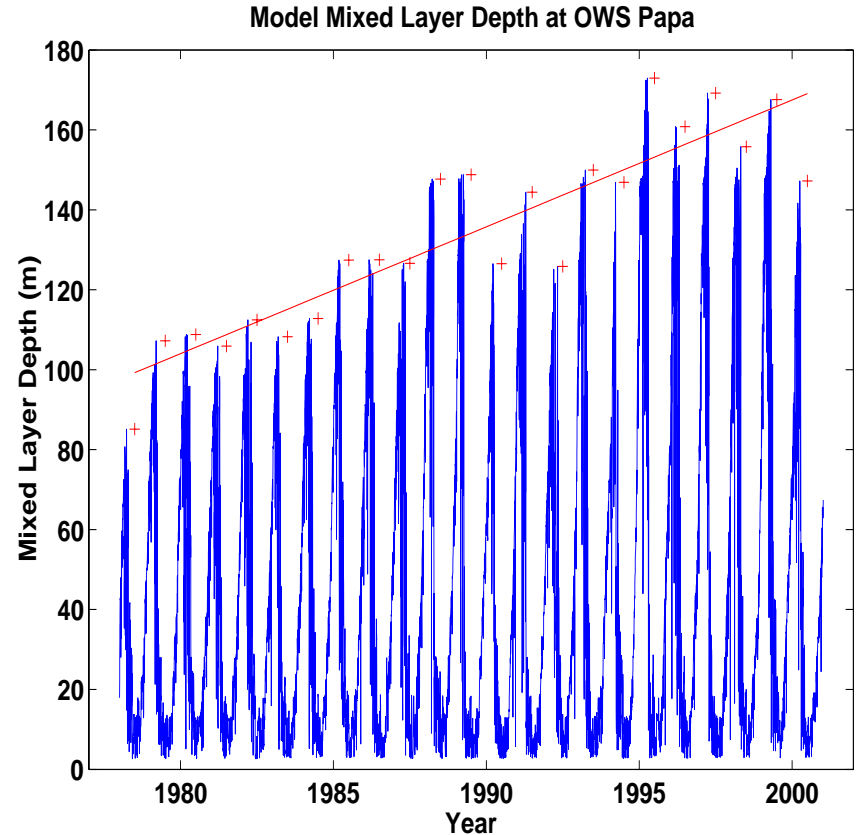


Subsurface Temperatures



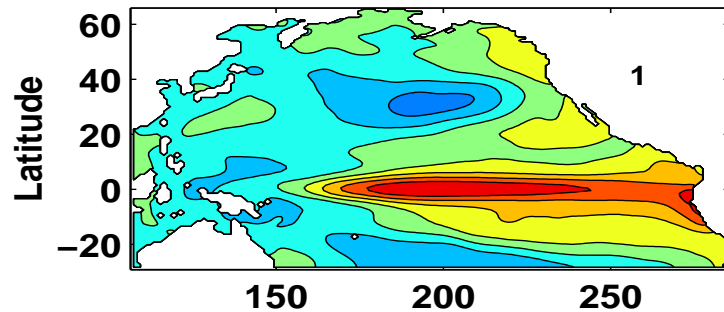
Model Mixed Layer at Papa

- The Sea Surface Temperature is dominated by the seasonal cycle with weak interannual variability
- The winter mixed layer depth increases at 3.2 m/yr in the model

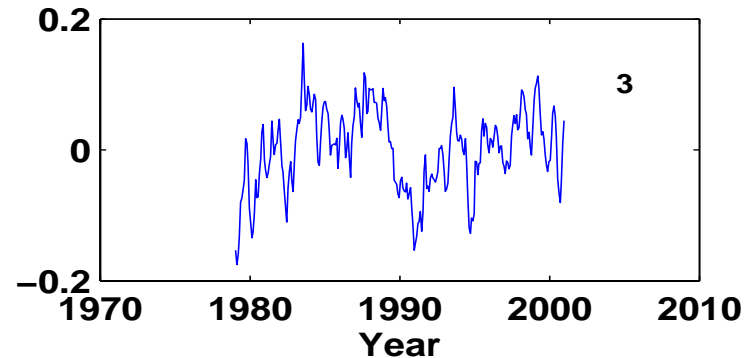
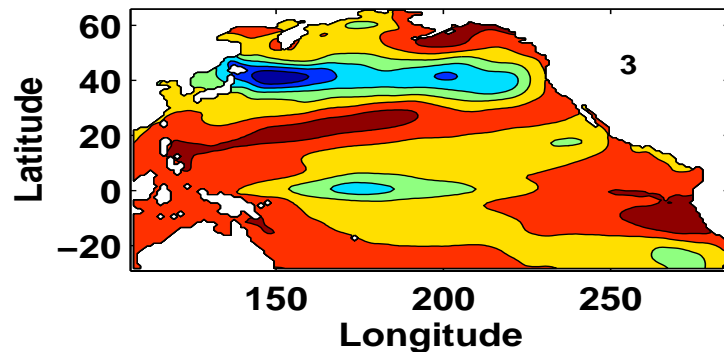
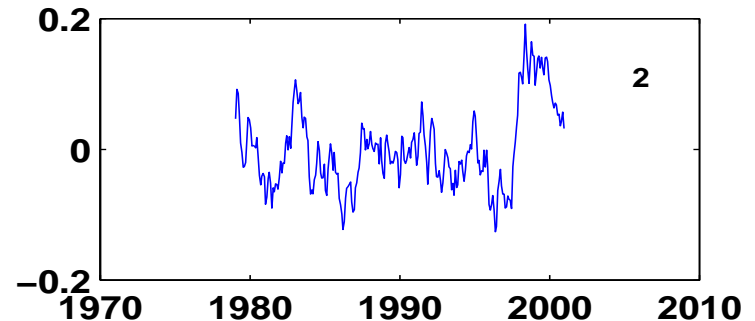
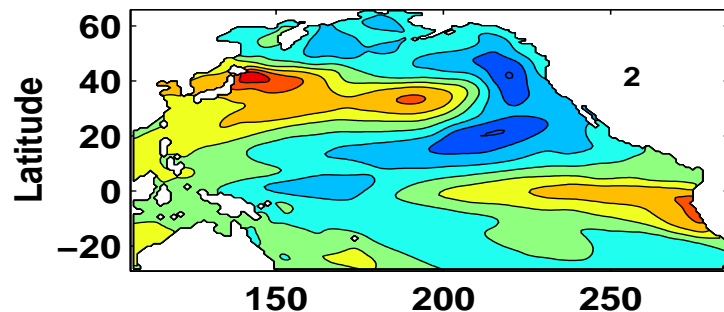
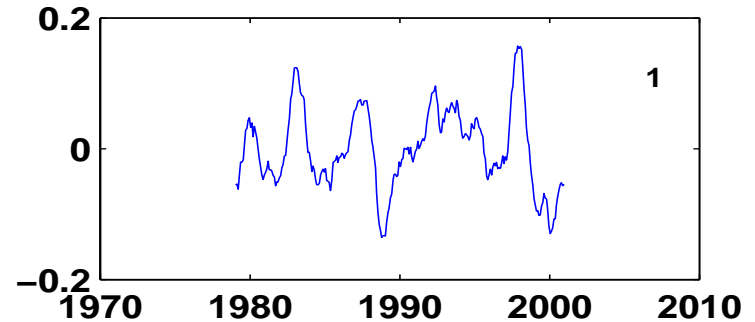


EOF Analysis of Sea Surface Temperature Anomalies

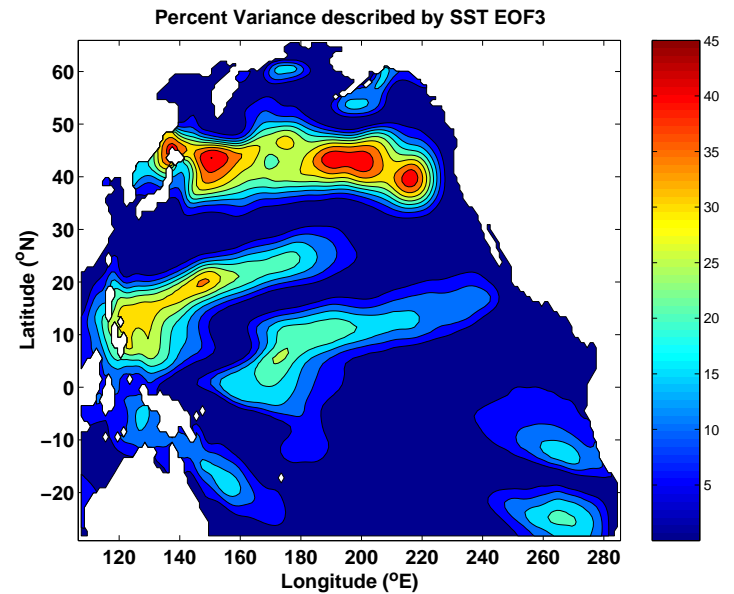
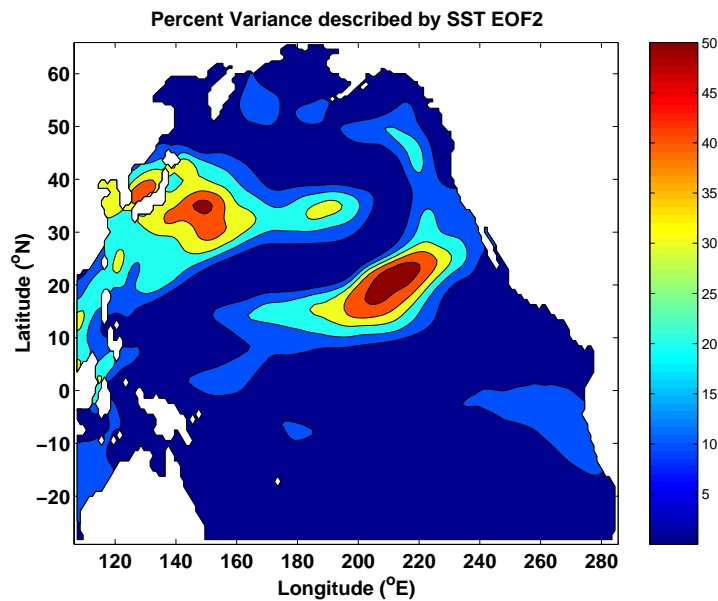
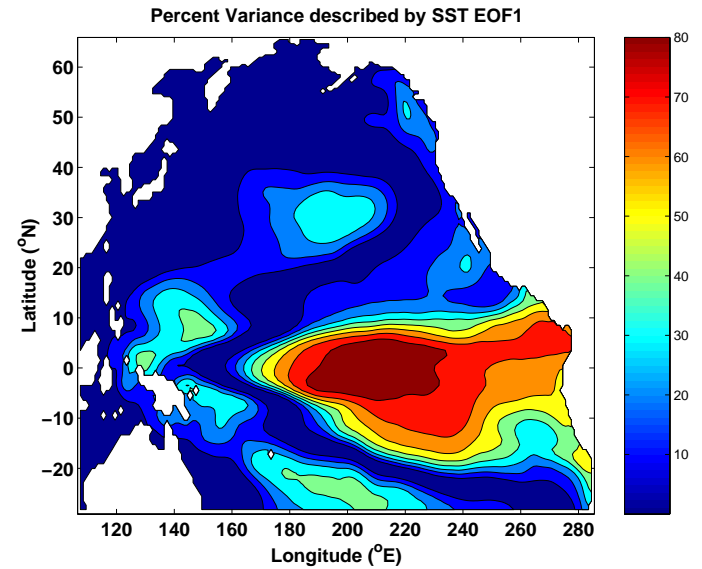
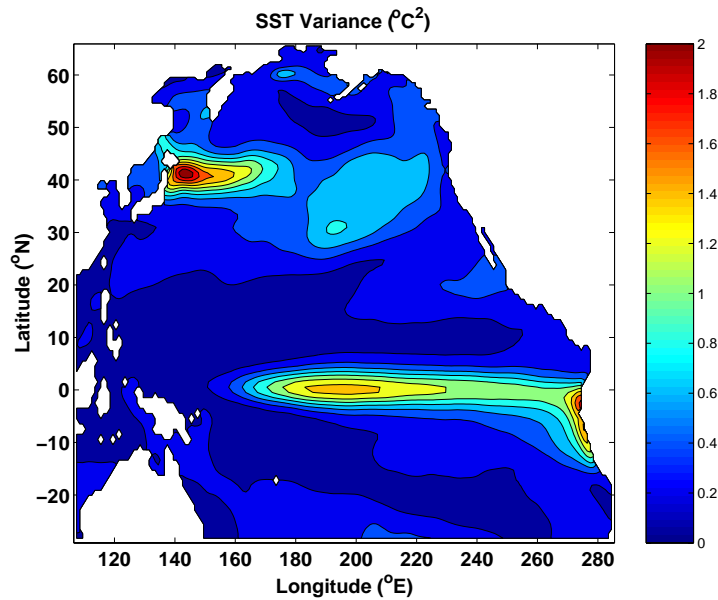
SST Anomaly EOF



Amplitude of SST Anomaly EOF

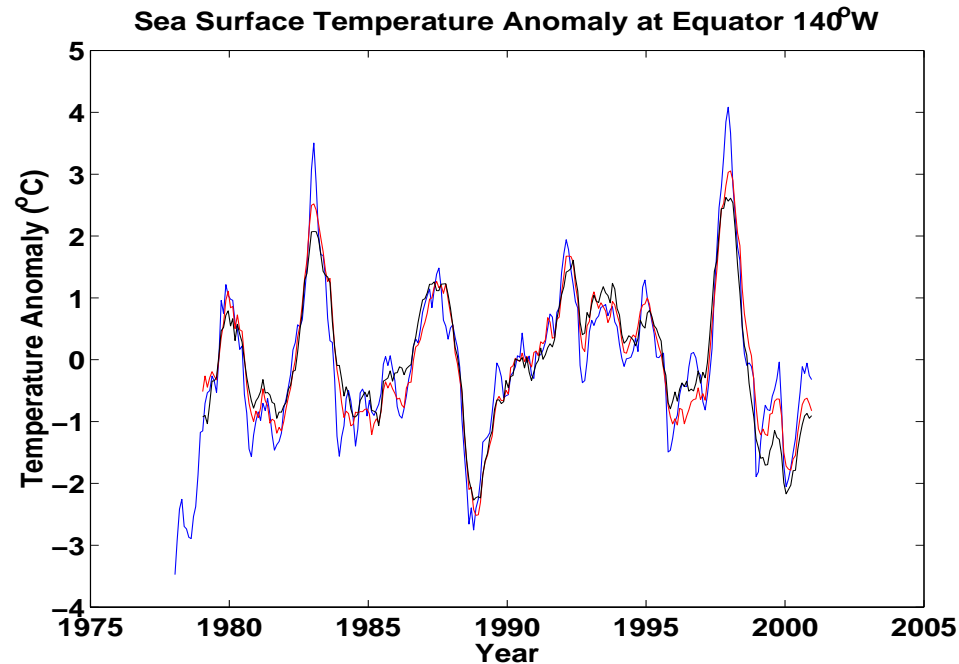


Variance described by SST EOFs



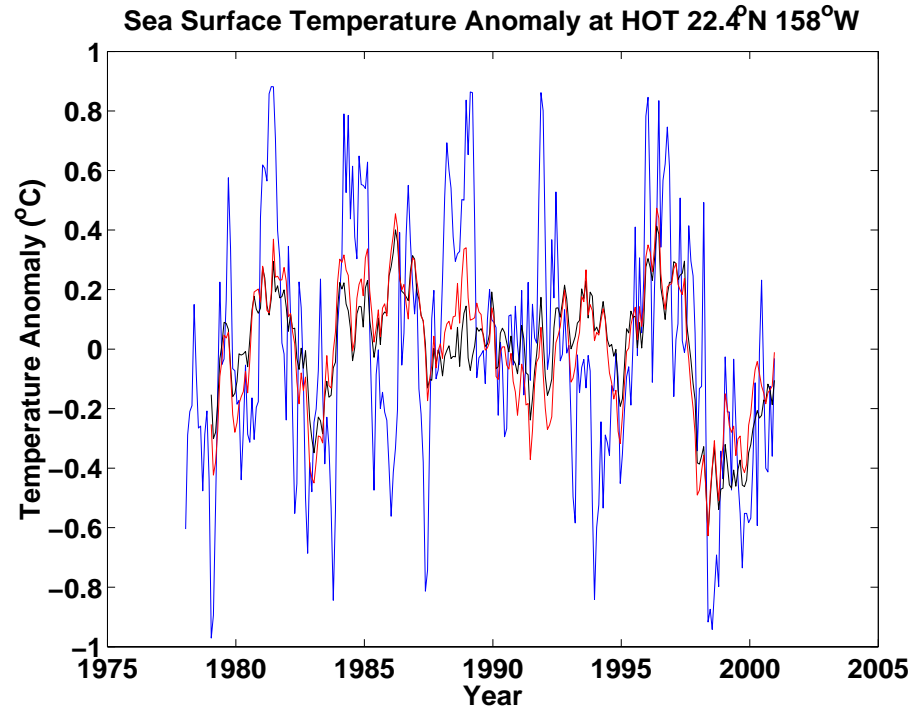
EOF Analysis of Sea Surface Temperature Anomalies

- The first EOF which describes 7% of the total variance is dominated by equatorial variability of the El Niño cycles. In the equatorial region, this mode describes 60-80% of the SST variance. The SST anomaly at 140W (blue) can be described by the first EOF (red) with the next two EOFs (black) making an insignificant contribution to the temperature.



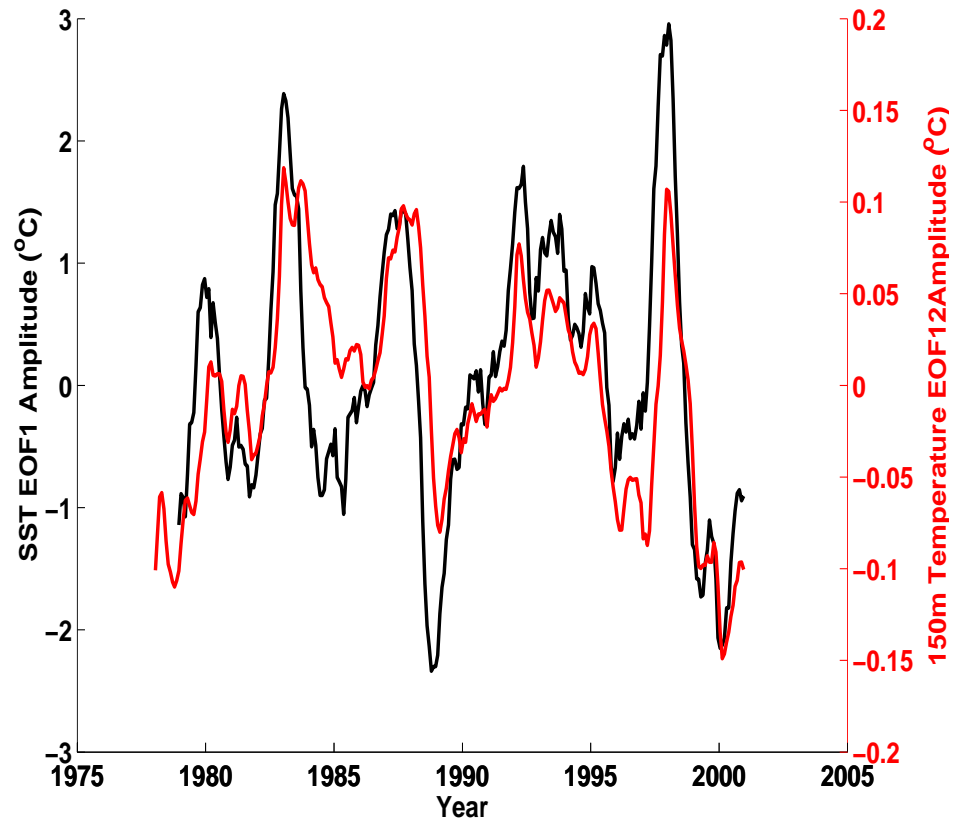
EOF Analysis of Sea Surface Temperature Anomalies

- The second EOF of the SST with 4% of the total variance described is dominated by variability in the strength of the subtropical gyre. In the subtropical gyre, this mode describes 30-50% of the SST variance. The SST anomaly at HOT (blue) is dominated by the second mode (red) with little contribution by the other two modes (black)



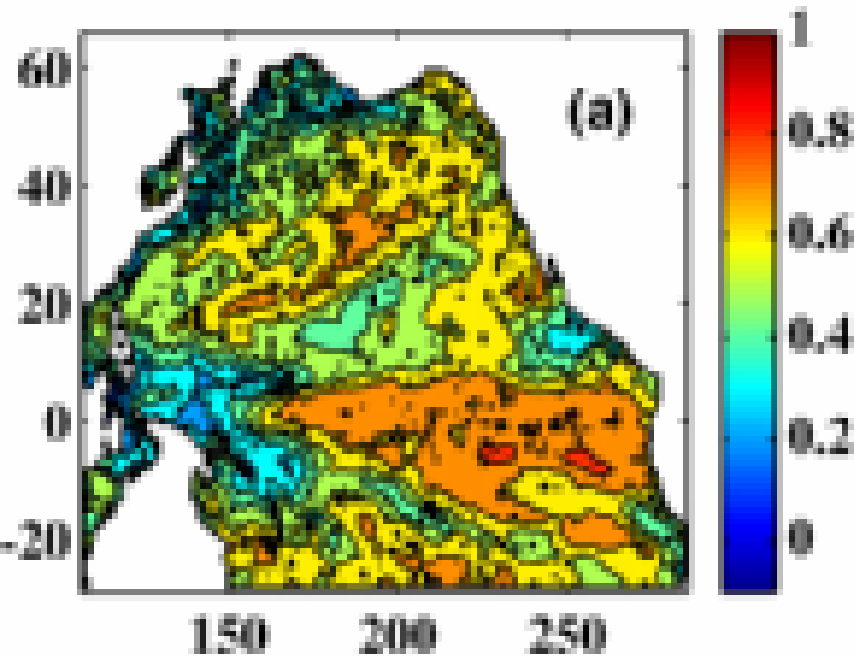
EOF Analysis of 150 m Temperature

- The first EOF of the 150 m temperature is dominated by the equatorial variance in the western tropical Pacific. The amplitude of this mode is correlated with the first mode of the SST anomaly with correlation coefficient of 0.71

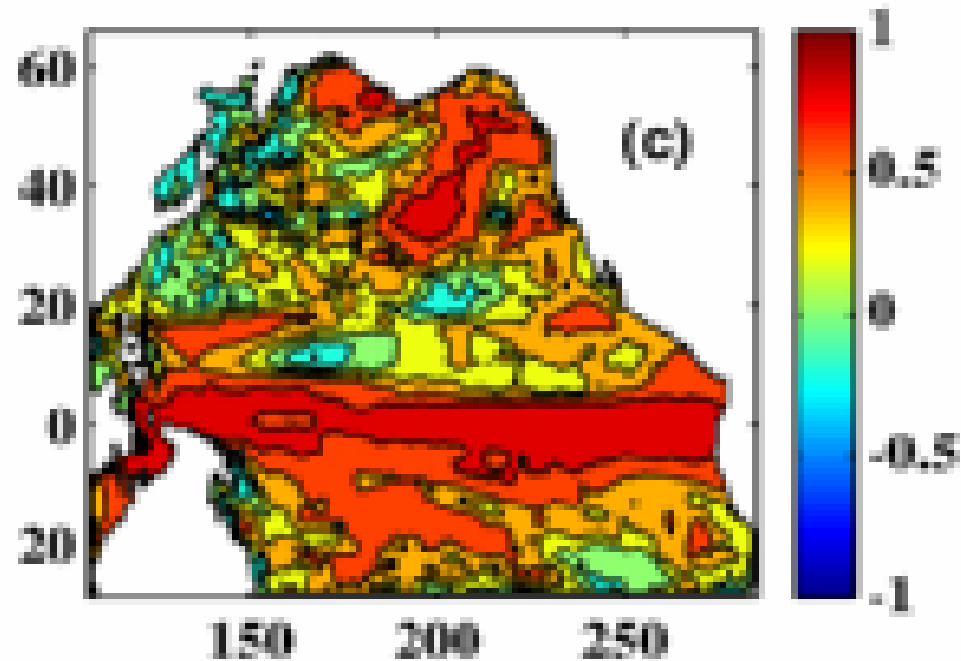


Correlation between model forecast and the remotely sensed SST and Sea Level Observations

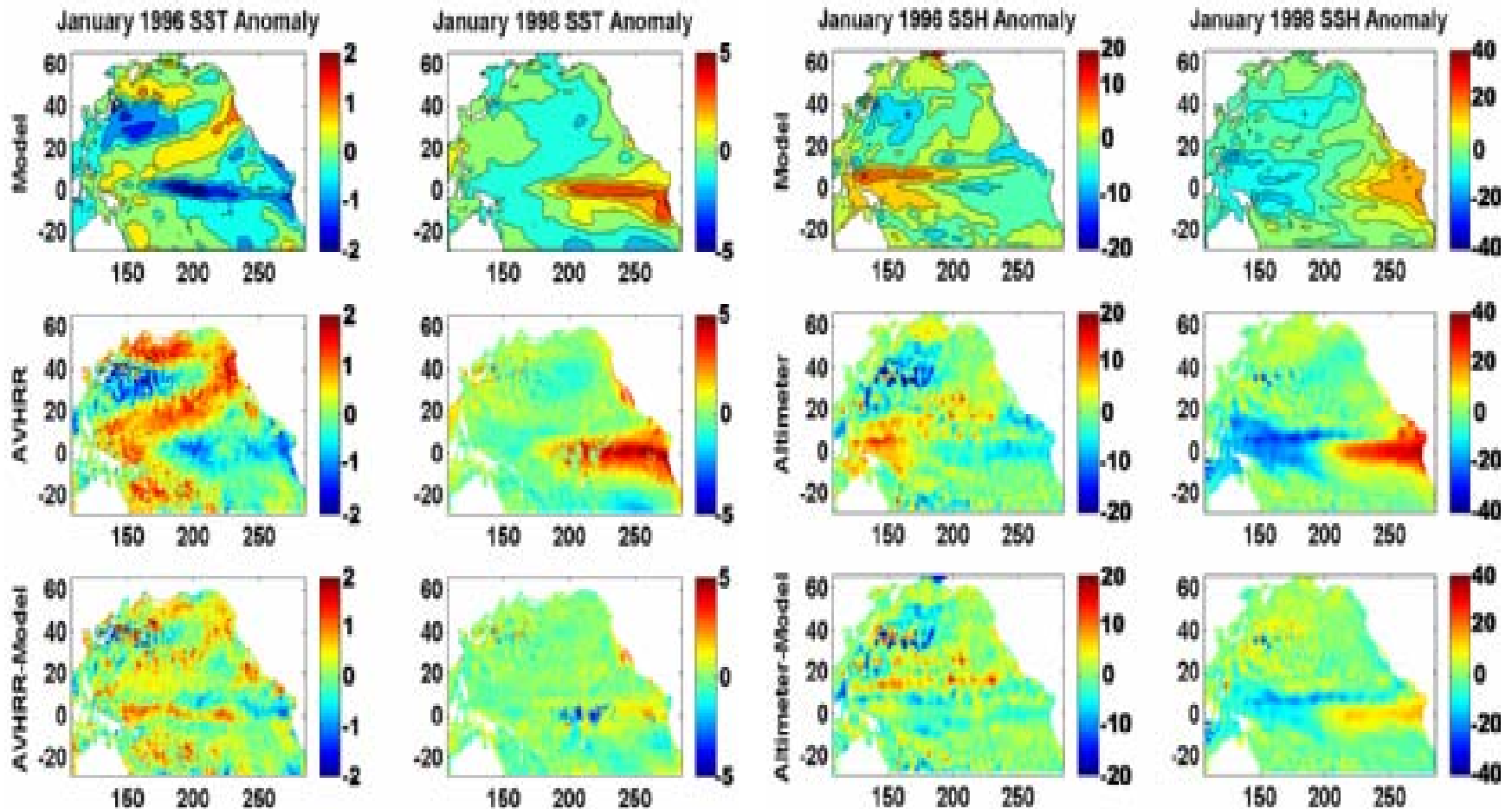
Model and AVHRR SST



Model and TOPEX SSH



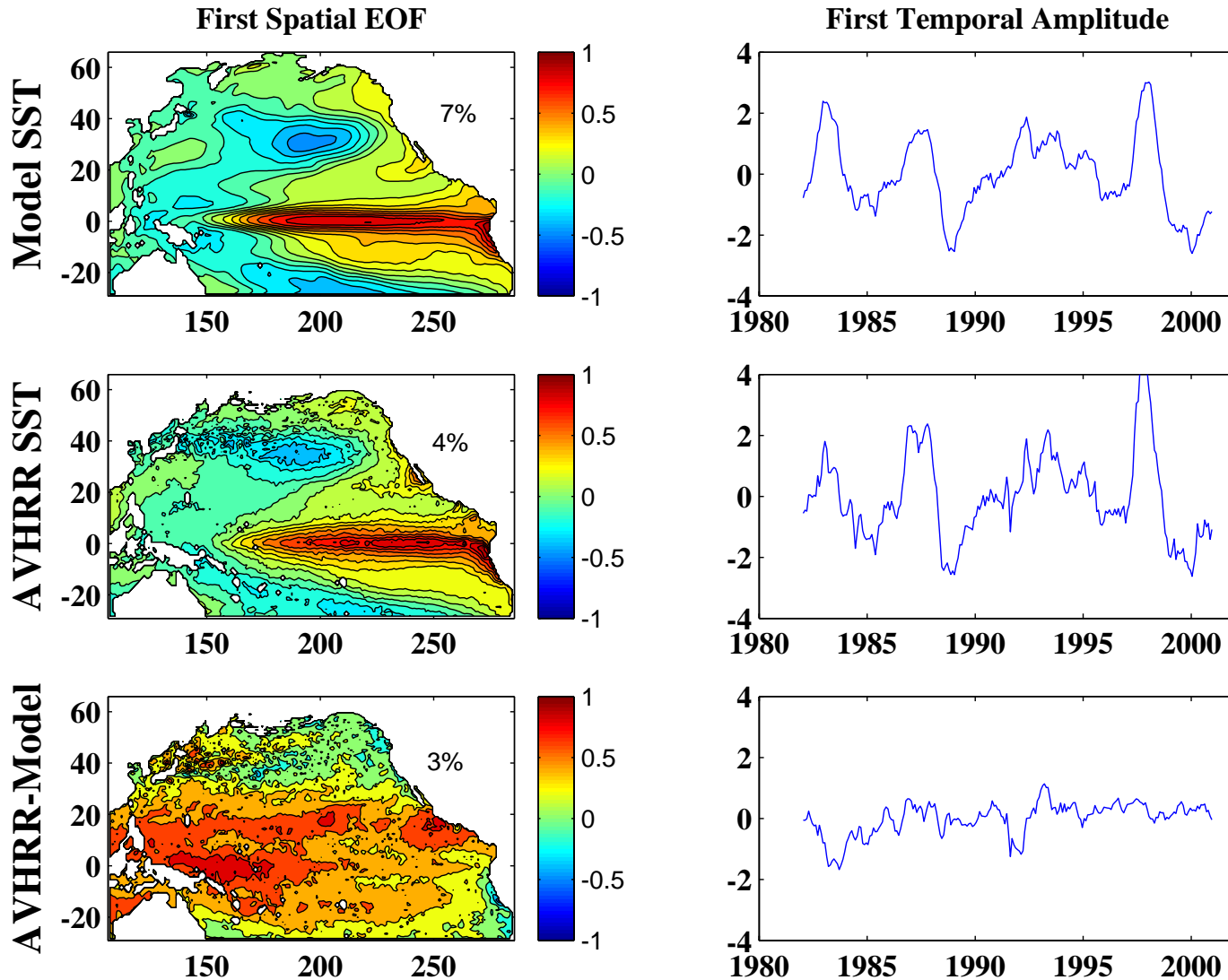
Model and Data Comparison for a non-El Nino year (Jan 1996) and an El Nino year (Jan 1998)



SST

SSH

Model and AVHRR-Seasonal Anomaly of SST First EOF



Combining data and models

If \mathbf{w}^f is the forecast model state at time t (horizontal velocity, temperature, salinity and free surface elevation)

If \mathbf{z} is the vector of observations at time t , the matrix H defines the mapping from the state space to the observation space, so $H\mathbf{w}^f$ contains the predicted values of the observations.

The corrected state vector \mathbf{w}^a at time t is given by

$$\mathbf{w}^a = \mathbf{w}^f + \mathbf{P}^f H^T (H\mathbf{P}^f H^T + \mathbf{R})^{-1} (\mathbf{z} - H\mathbf{w}^f)$$

where \mathbf{P}^f is the error covariance matrix of forecast state vector \mathbf{w}^f and \mathbf{R} is the observation error covariance (includes that part of the signal that cannot be represented in terms of the model state),

The matrix:

$$\mathbf{K} = \mathbf{P}^f H^T (H\mathbf{P}^f H^T + \mathbf{R})^{-1}$$

is known as the *Kalman* gain matrix. In a Kalman filter, \mathbf{P}^f evolves by the model dynamics. In an optimal interpolation (OI) scheme, the matrix \mathbf{P}^f is static, independent of time.

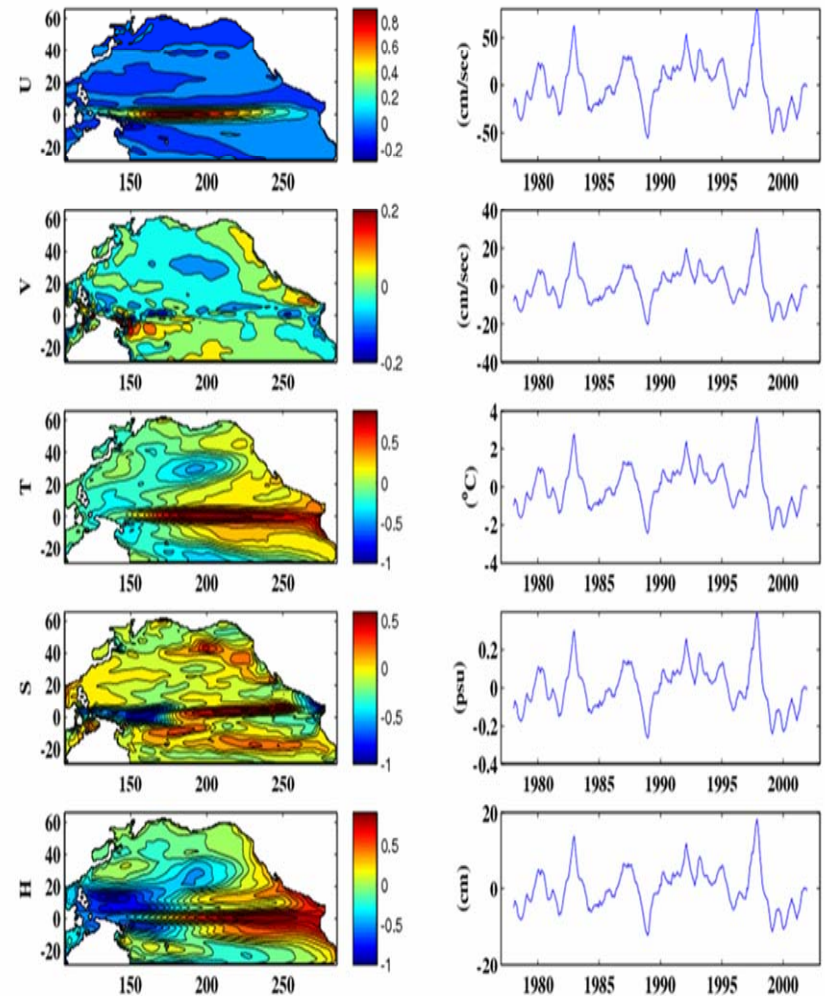
Large number of state variables prohibits solving the full system

—————→ ***Reduced State Space Kalman Filter***

- 1) Compute the **multivariate empirical orthogonal functions** (EOF's) of our 23 year time series of deviations from the seasonal cycle,
- 2) **A statistical test is performed in order to estimate the number of significant degrees of freedom.** (Preisendorfer (1988)) (35 modes accounting for 59% of the total variance)
- 3) Recast the Kalman filter problem in terms of a Reduced State Space of approximately 35 EOFs instead of 10^5 discrete points
- 4) We estimate the **multivariate model error covariance P^f** by **performing linear regressions to fit the EOF's of the SST model data misfits with the temperature component of the model multivariate EOF's.**
- 5) Using the estimated model covariance, we calculate the Kalman gain and the update the model to combine with the observations.

Model Multivariate EOF

- The first EOF of the surface velocity, temperature, salinity and sea level
- The first EOF is dominated by ENSO



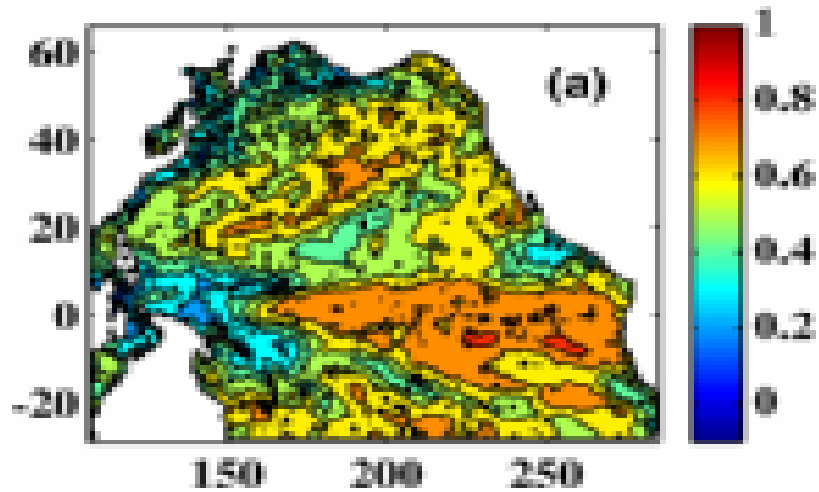
Large number of state variables prohibits solving the full system

—————→ ***Reduced State Space Kalman Filter***

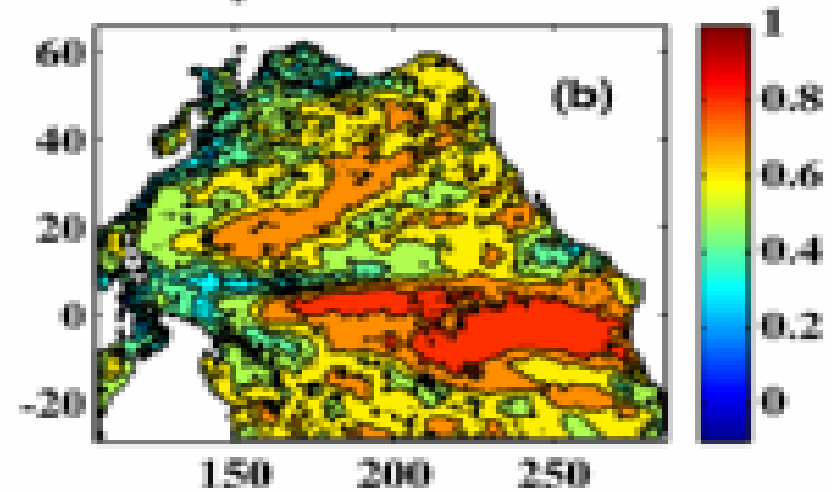
- 1) Compute the **multivariate empirical orthogonal functions** (EOF's) of our 23 year time series of deviations from the seasonal cycle,
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Model and Data Correlations before and after Reduced State Space OI

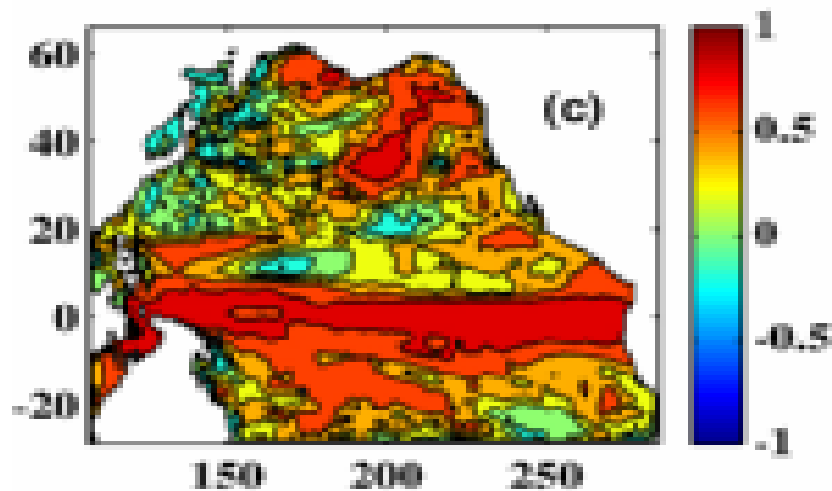
Model and AVHRR SST



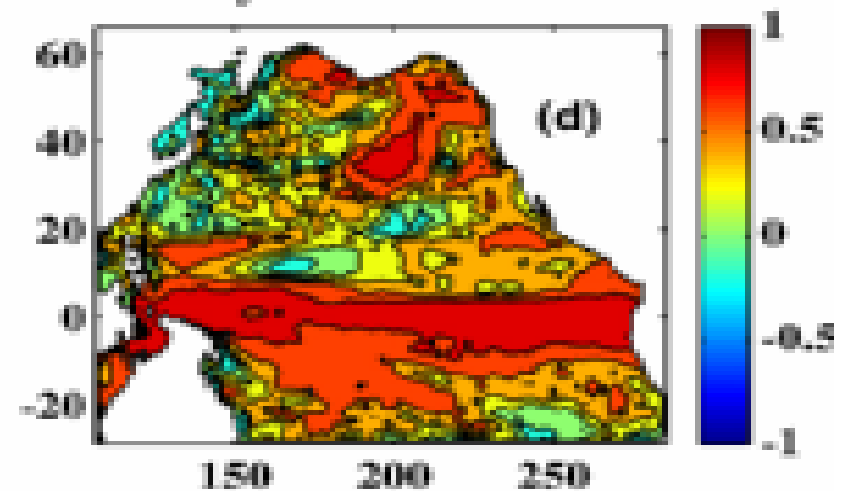
Analysis and AVHRR SST



Model and TOPEX SSH



Analysis and TOPEX SSH



Representation error

The Kalman filter blending of the model and the observations made a modest improvement of the model outputs

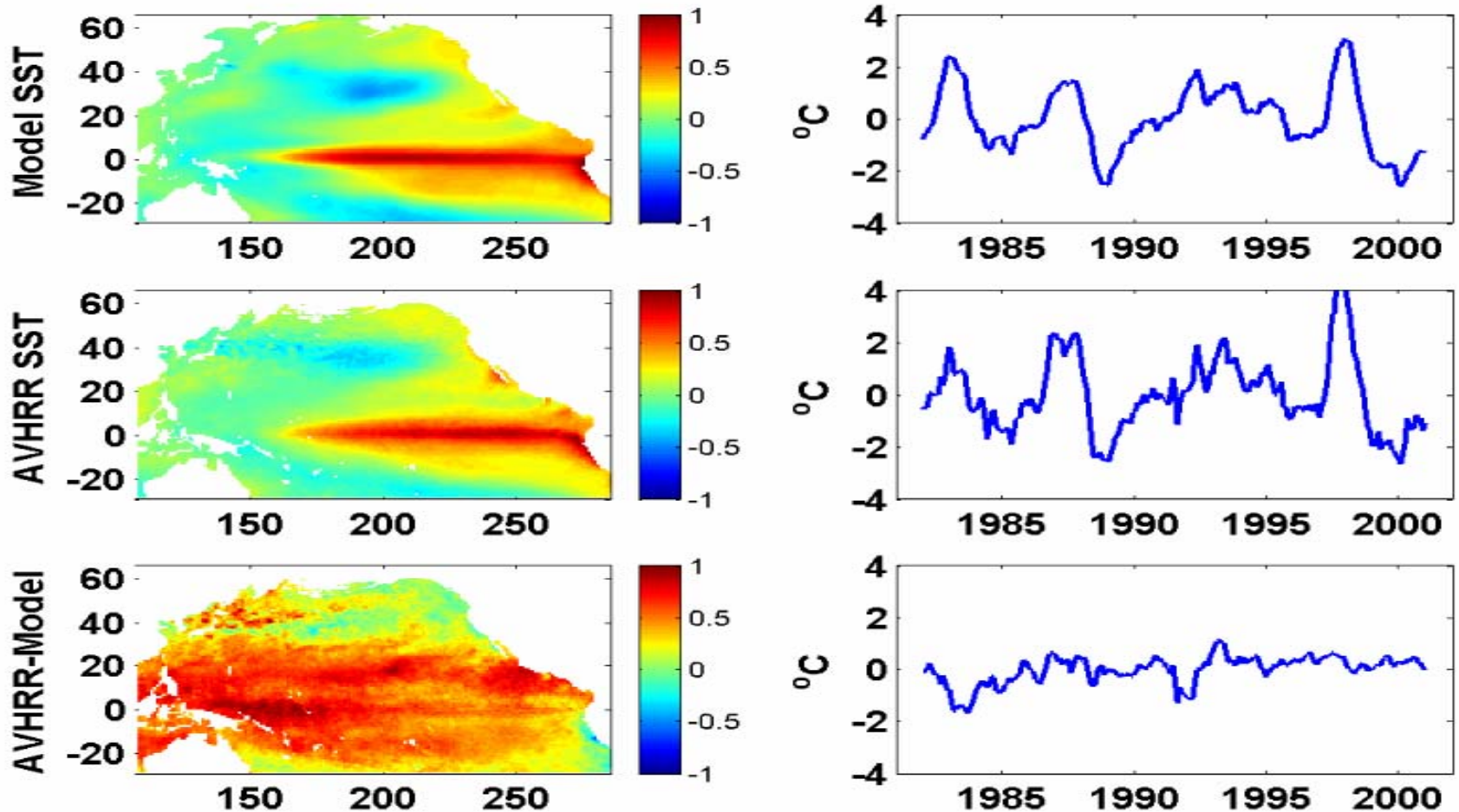
Why was not there a bigger impact?

The model cannot represent all of the variability observed in the data.

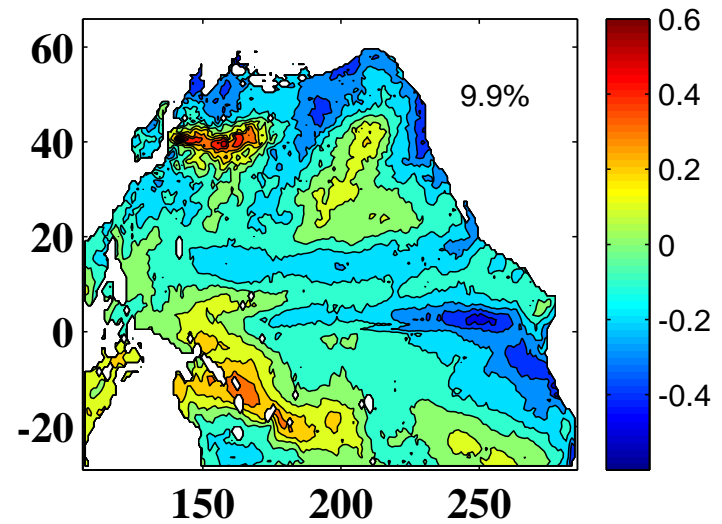
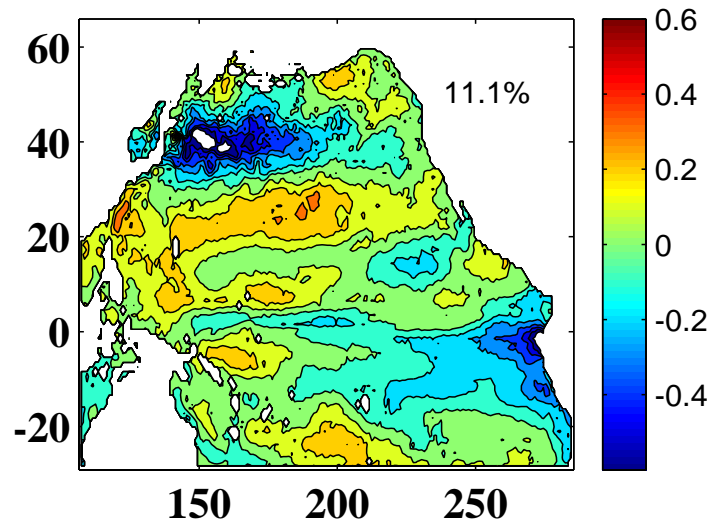
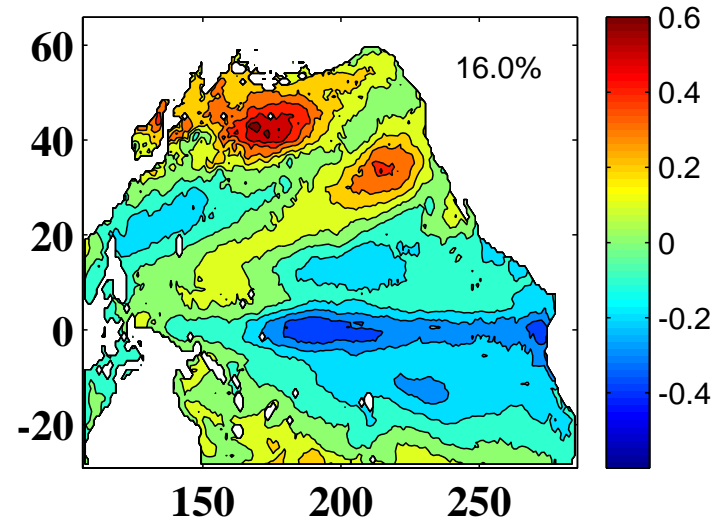
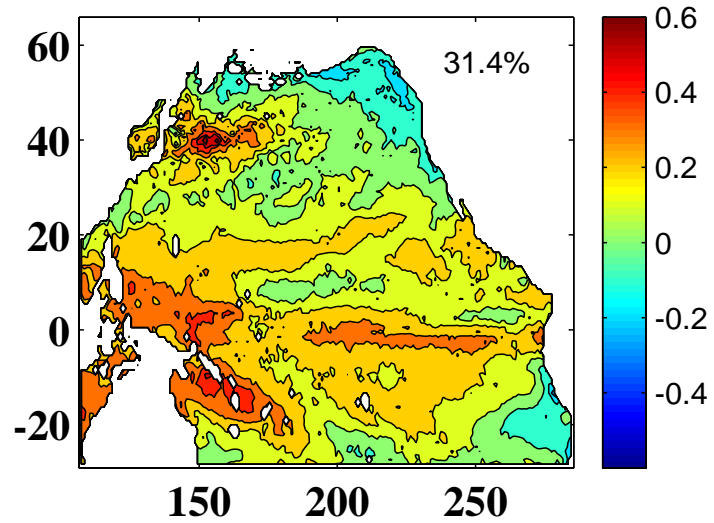
Using the Reduced State Space, we can estimate this error of representation

The difference between the model data misfit and the EOF representation of this misfit (error of representation) gives us information on where improvement is needed.

Model and AVHRR-Seasonal Anomaly of SST First EOF

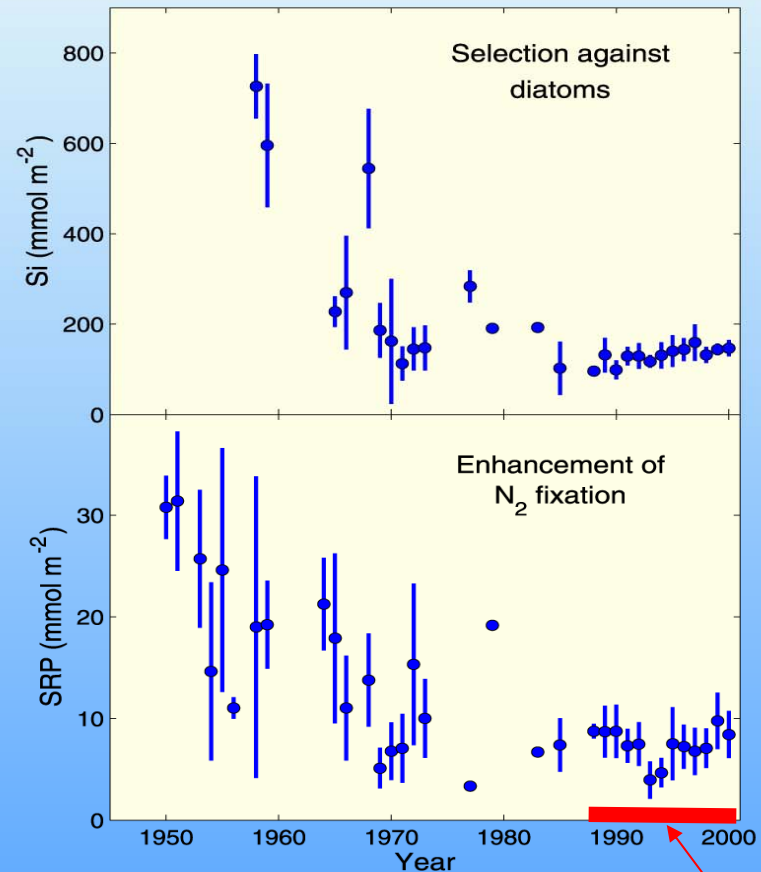
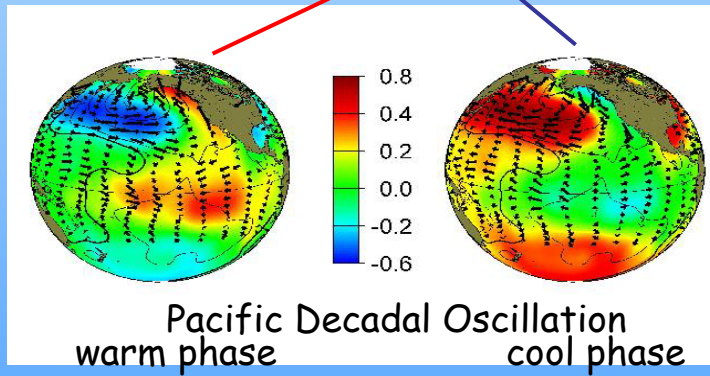
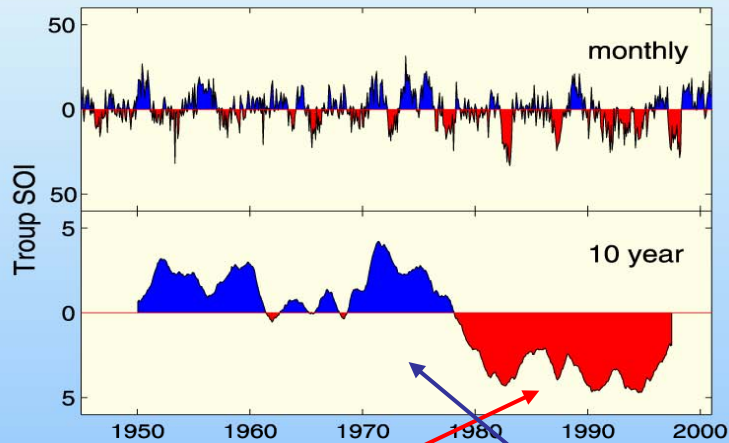


EOFs of the model temperature error of representation.



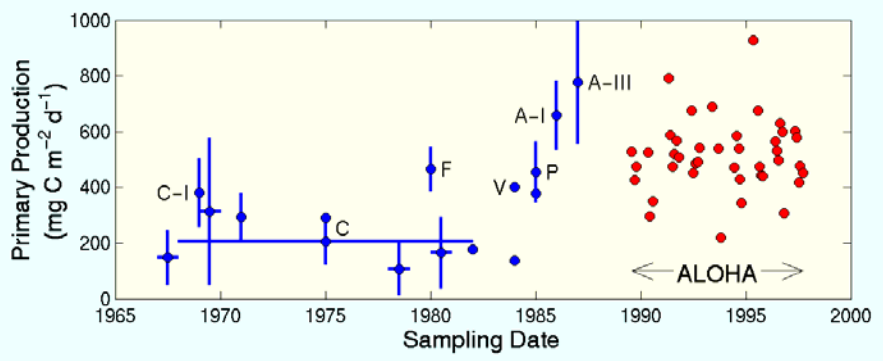
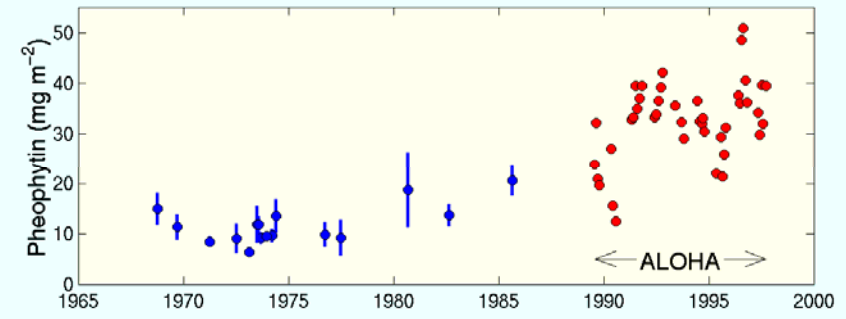
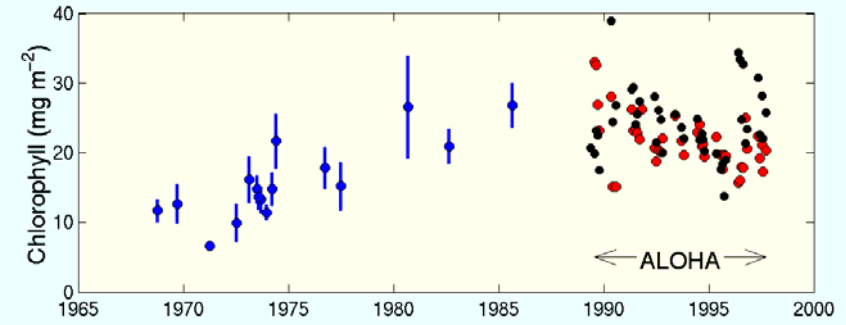
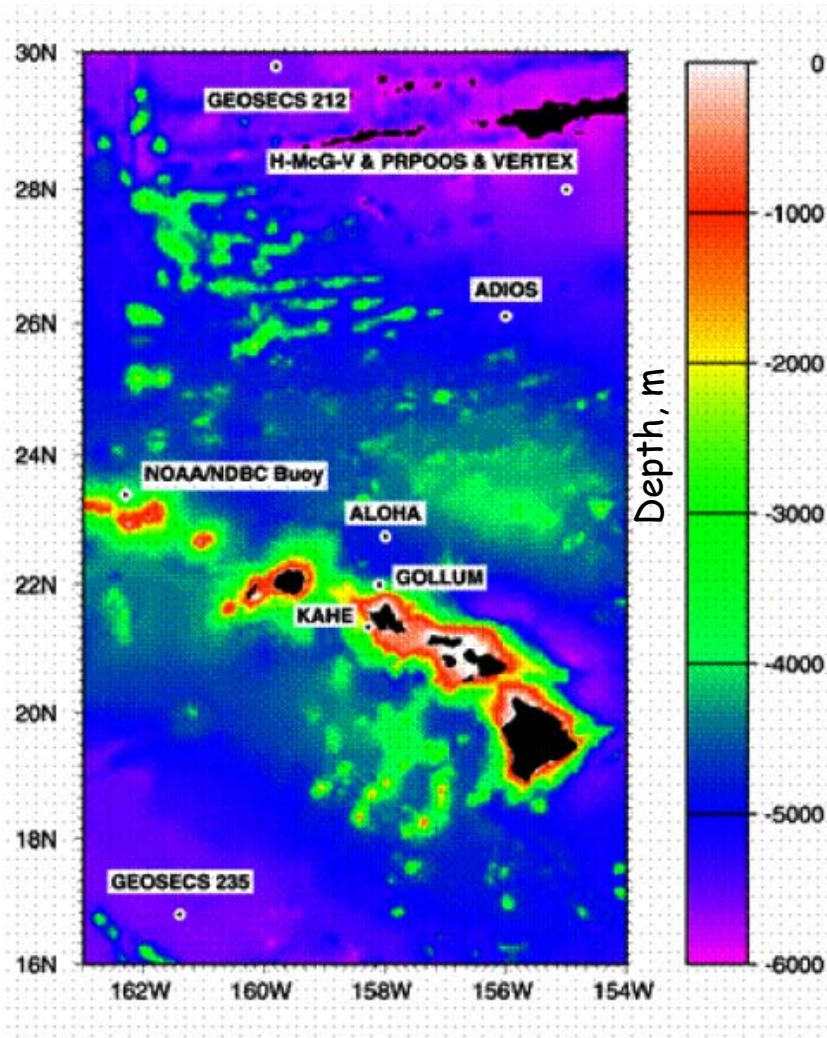
Numbers in upper right corners of panels are percent of total variance.

Climate Change in the North Pacific Ecosystem



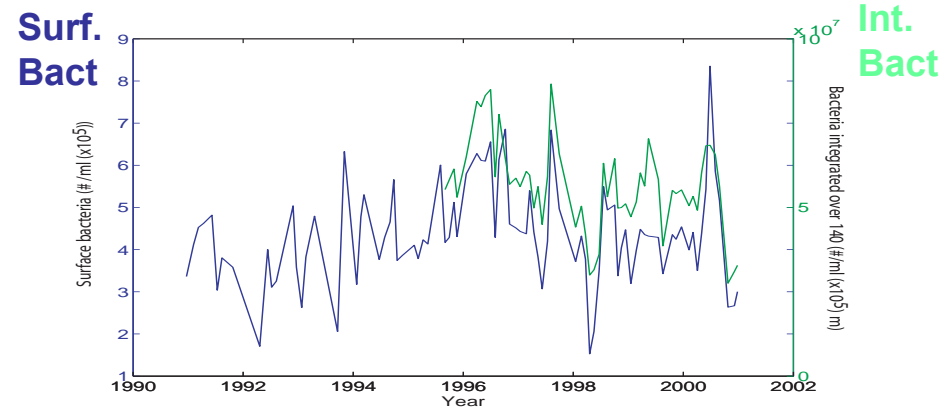
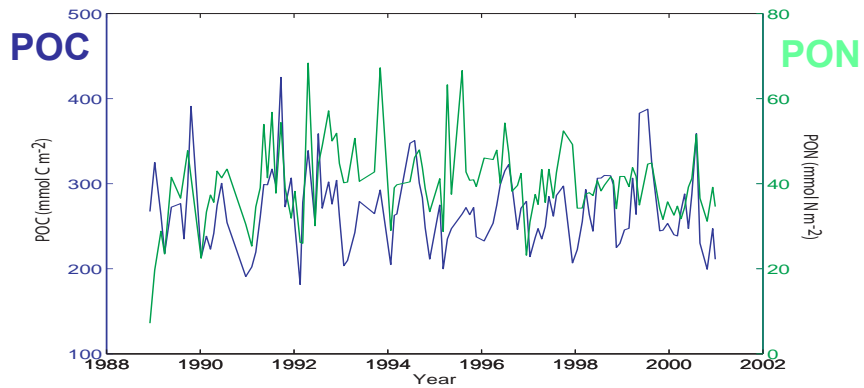
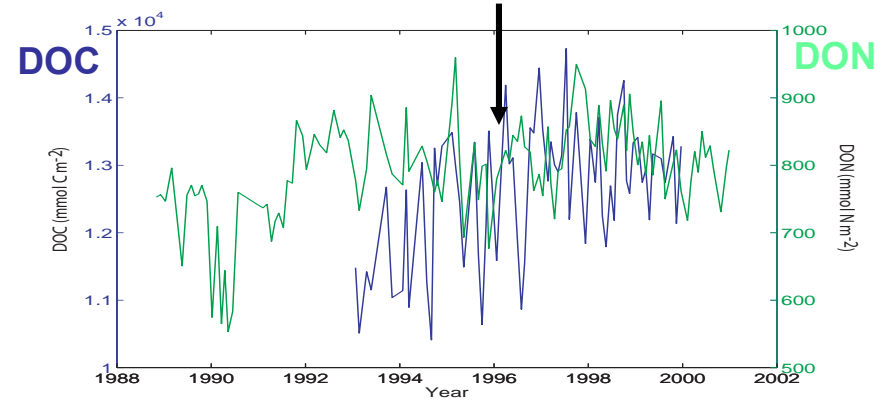
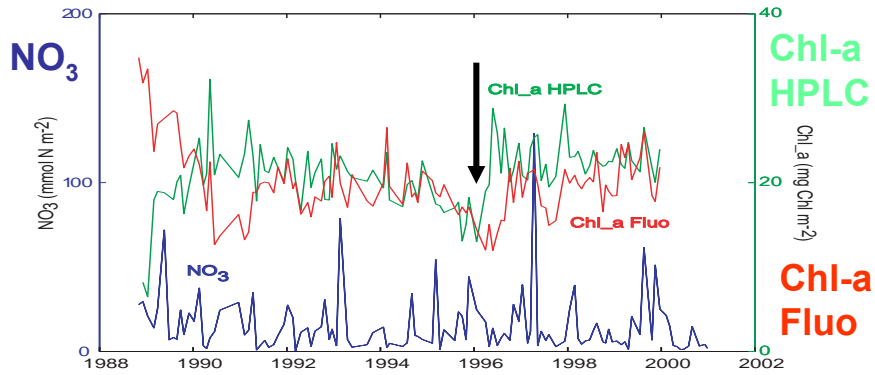
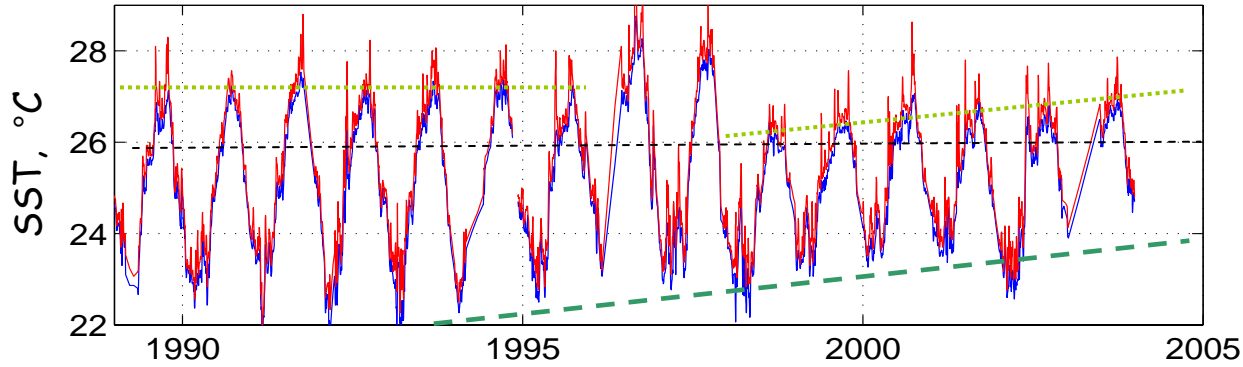
Karl et al. (2001)

A long-term record in the NPSG suggests a significant and persistent increase in chlorophyll concentrations in the late 1970's.



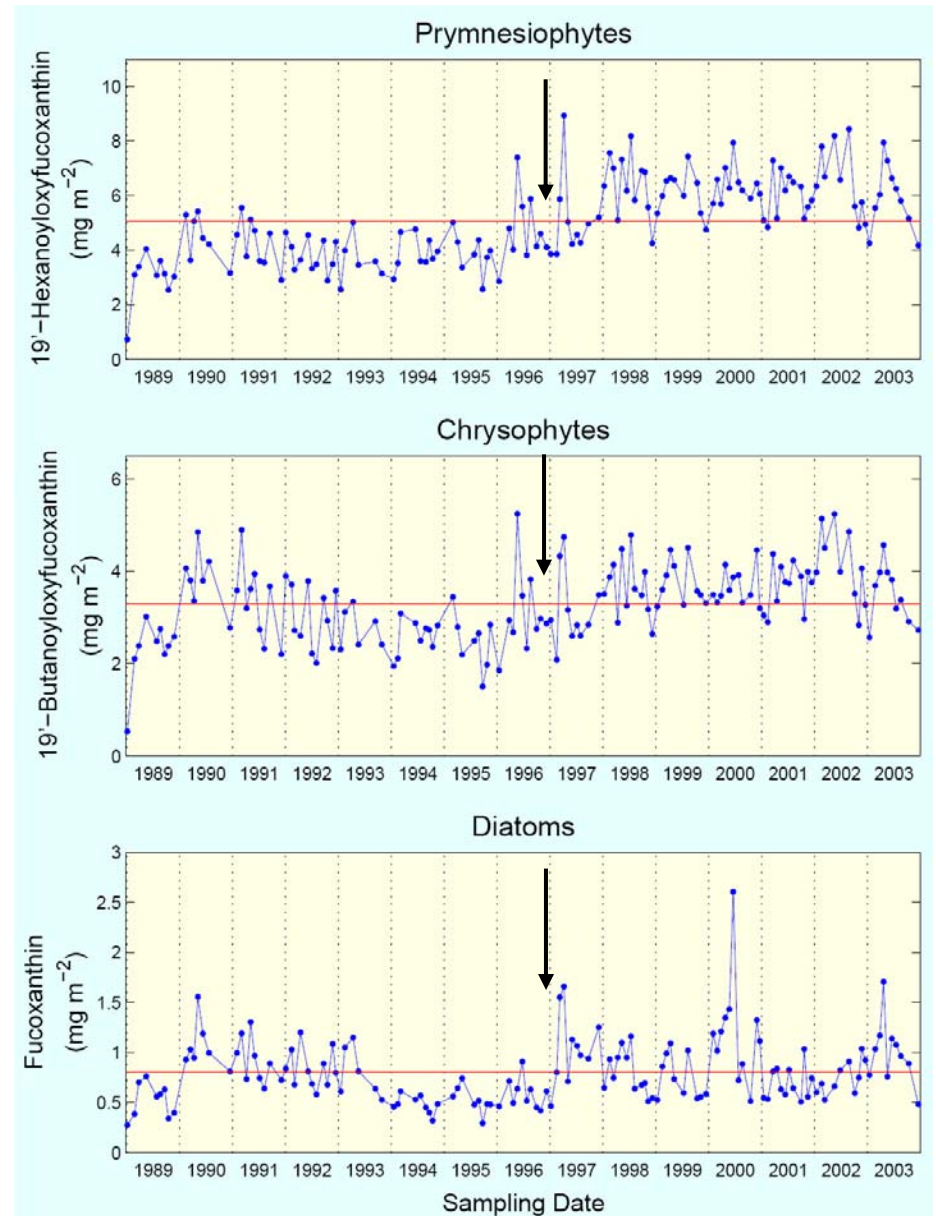
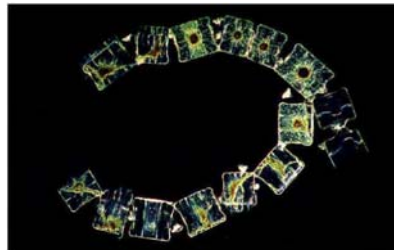
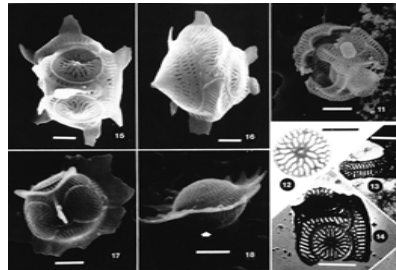
Karl et al. (2001)

Interannual changes and trends at the Hawaii Ocean Time Series Station





Phytoplankton taxa display distinct long term patterns of variability



Can we model to the changes observed in the ecosystem in the late 90s?

AND

What are the challenges to build such a model?

- ***Circulation Model:***

Ocean component of the Community Climate System Model (CCSM): Parallel Ocean Program (POP) model

Domain: 105° E to 85° W - 30° S to 64° N

Resolution: 1° at Equator on Mercator projection

0.5° average resolution

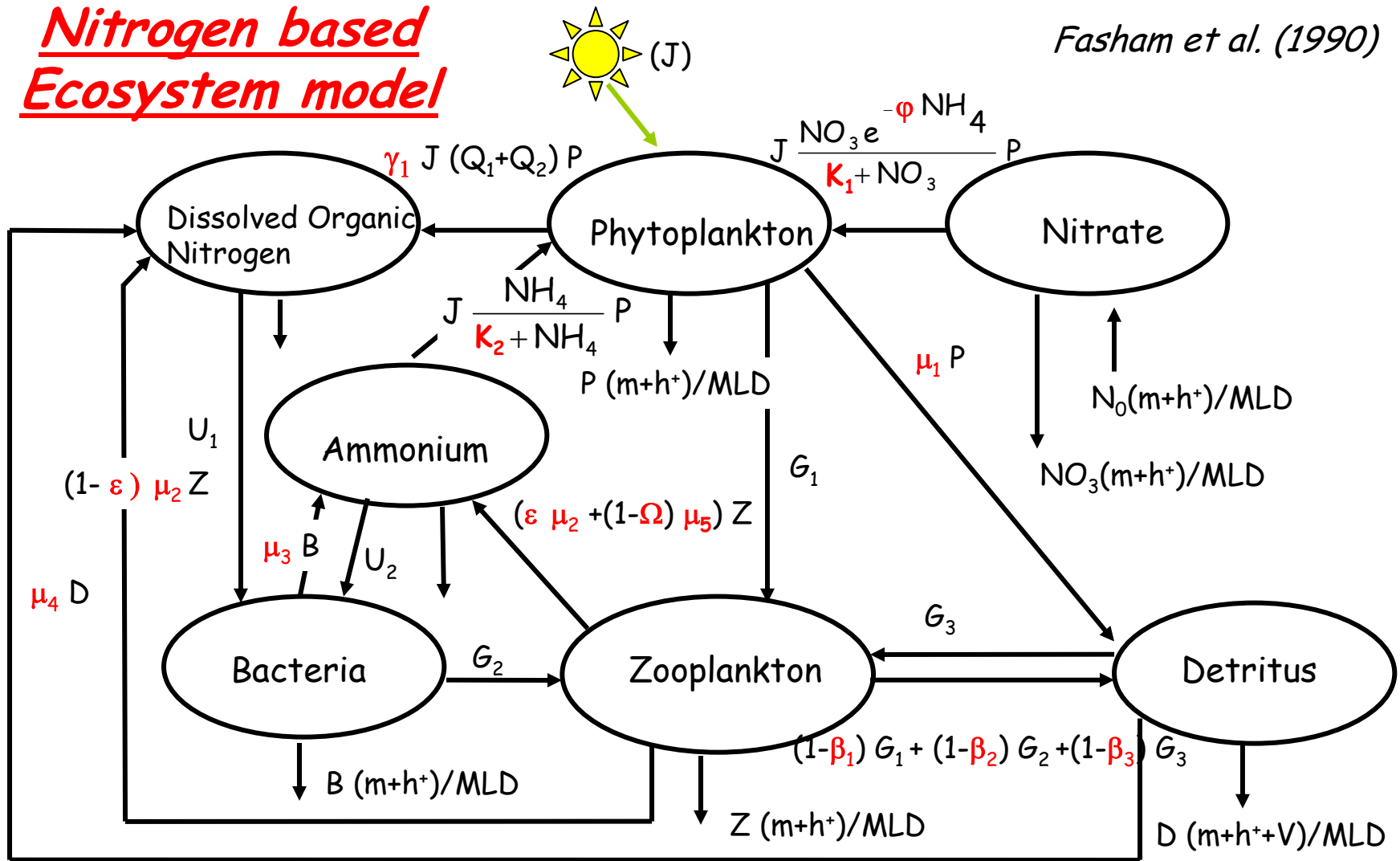
50 vertical levels with 25 in top 500 m

- ***Ecosystem Model:***

From Fasham et al. (1990) to Spitz et al. (2001): nitrate, ammonium, phytoplankton, chl-a, two zooplankton, Bacteria, detritus (N and C), DOM (N and C)

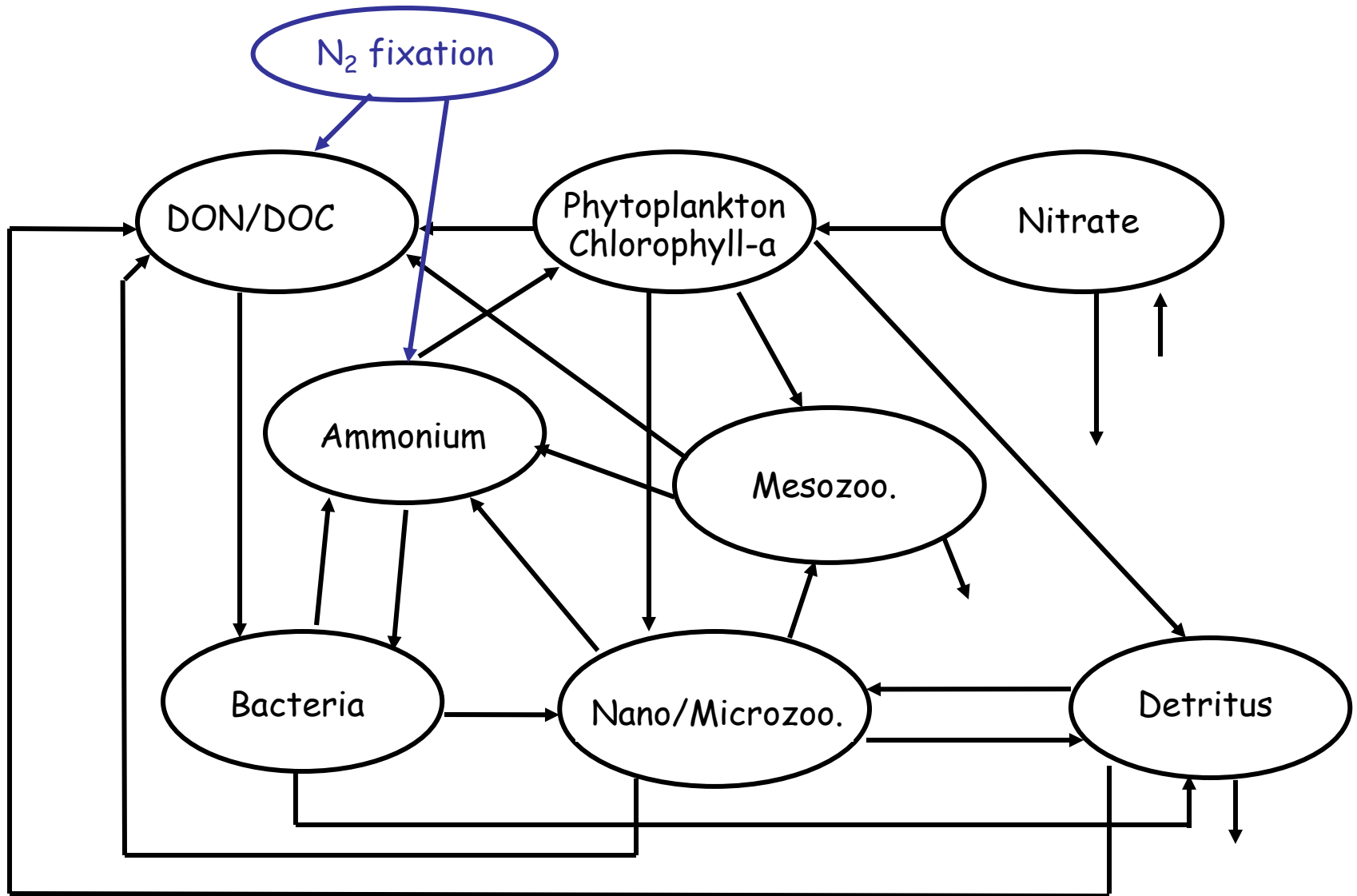
Nitrogen based Ecosystem model

Fasham et al. (1990)

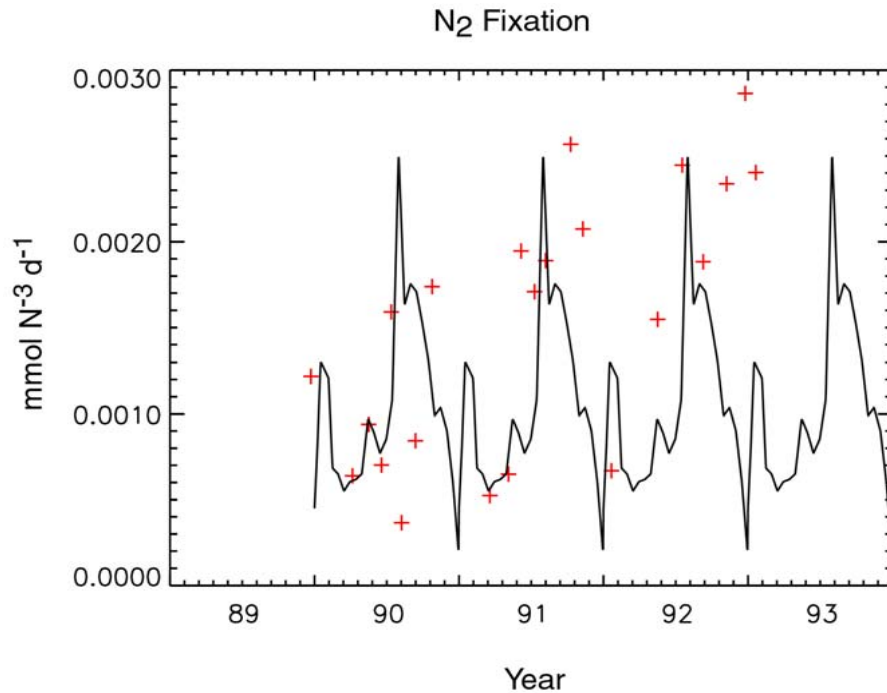


e.g.
$$\frac{\partial P}{\partial t} = J(Q_1 + Q_2)P - \gamma_1 J(Q_1 + Q_2)P - \mu_1 P - G_1 - P(m+h^+)/MLD$$

Ecosystem model for HOT



Dinitrogen fixation at HOT

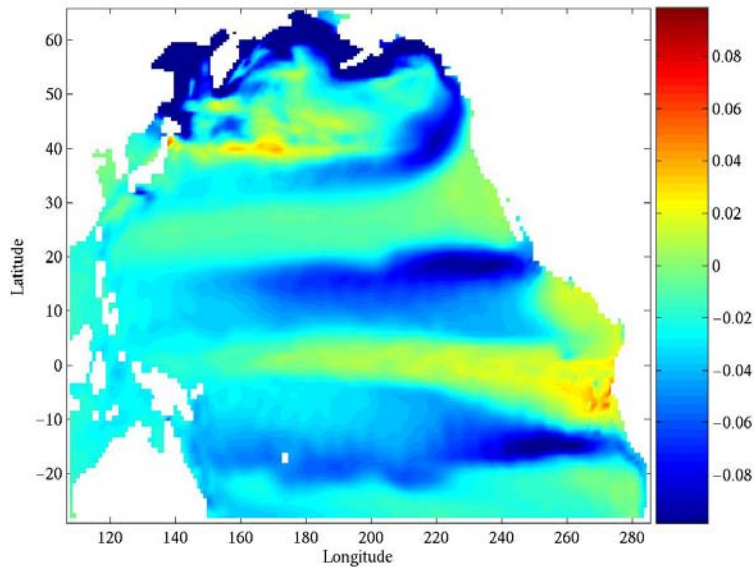


+ HOT observations (Karl et al., 1997)
— Model estimates

- Using observed trichome abundances: 21.90 ± 10.95 mmol N m⁻² yr⁻¹
- From the model results: 25.81 ± 15.32 mmol N m⁻² yr⁻¹

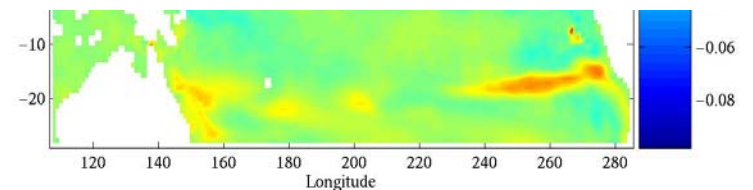
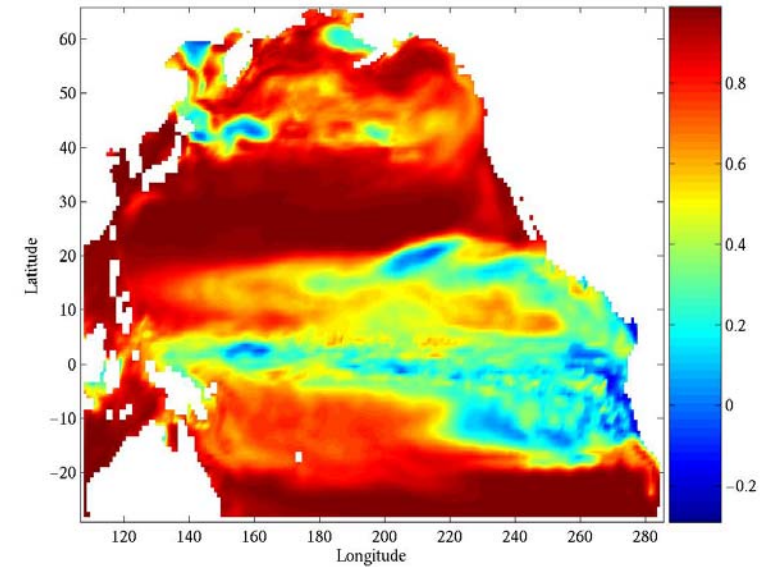
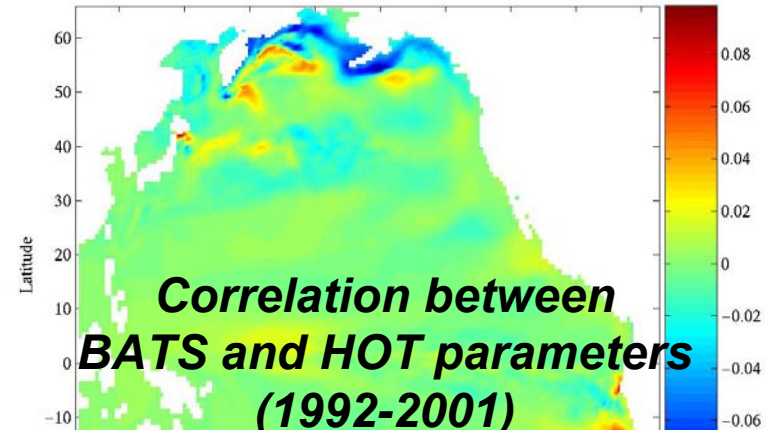
Surface Chlorophyll-a (mg Chl m⁻³)

Mean Difference between BATS and HOT simulation (1992-2001)



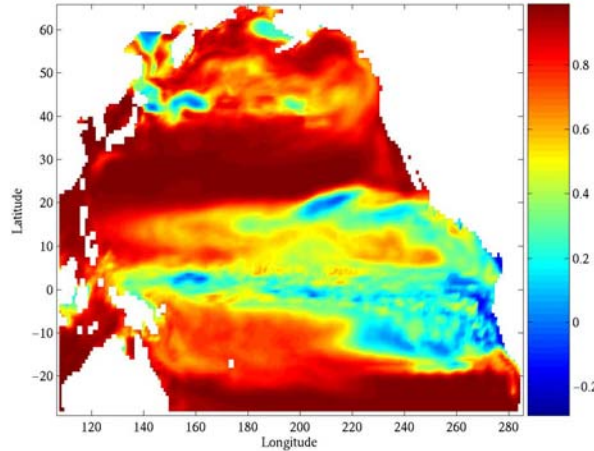
The mean varies between 0.05 and 0.25 mg Chl m⁻³

BATS parameters: (97-01)-(92-96)



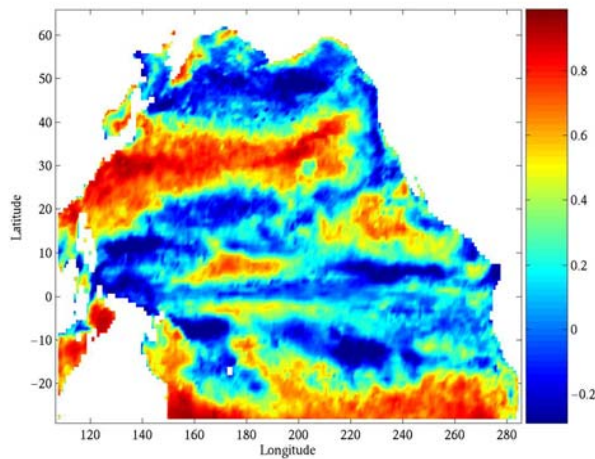
Correlation between model simulations

Correlation between BATS and HOT parameters

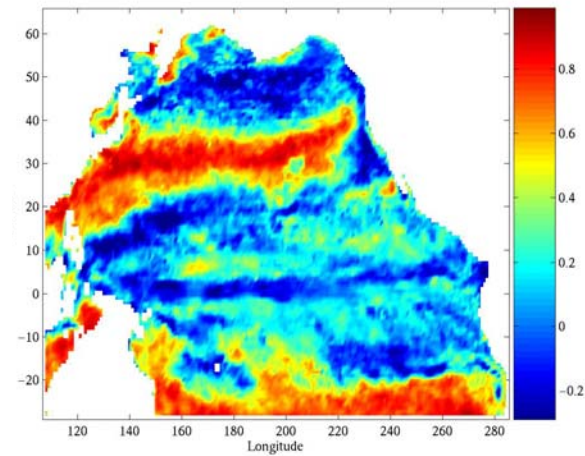


Correlation with SeaWiFS surface chlorophyll-a (98-01)

BATS parameters



HOT parameters

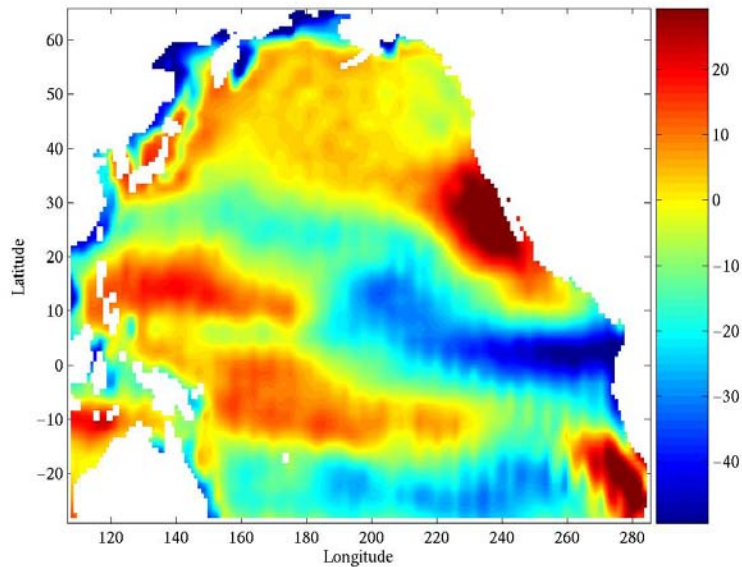


Potential source of error - Atmospheric forcing

- Wind stress and non solar radiation affect directly the circulation and indirectly the ecosystem
- Solar radiation affects directly the ocean circulation and ecosystem (i.e. photosynthesis)

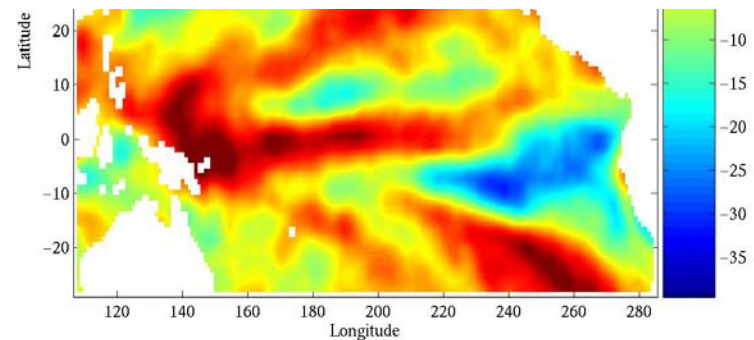
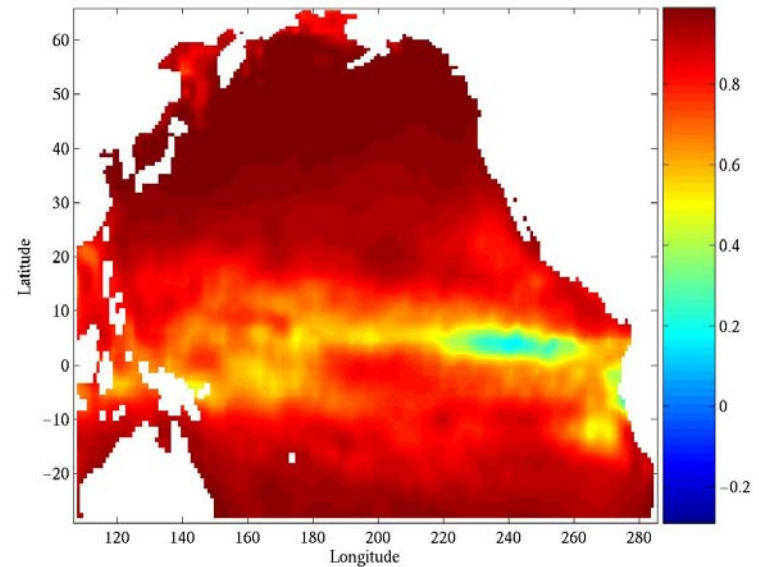
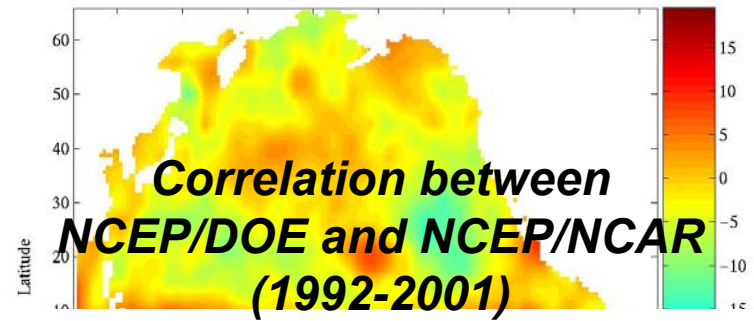
Downward Short Wave Radiation ($W m^{-2}$)

Mean Difference between
NCEP/DOE and NCEP/NCAR
(1992-2001)



The mean varies between 100 and 220 $W m^{-2}$

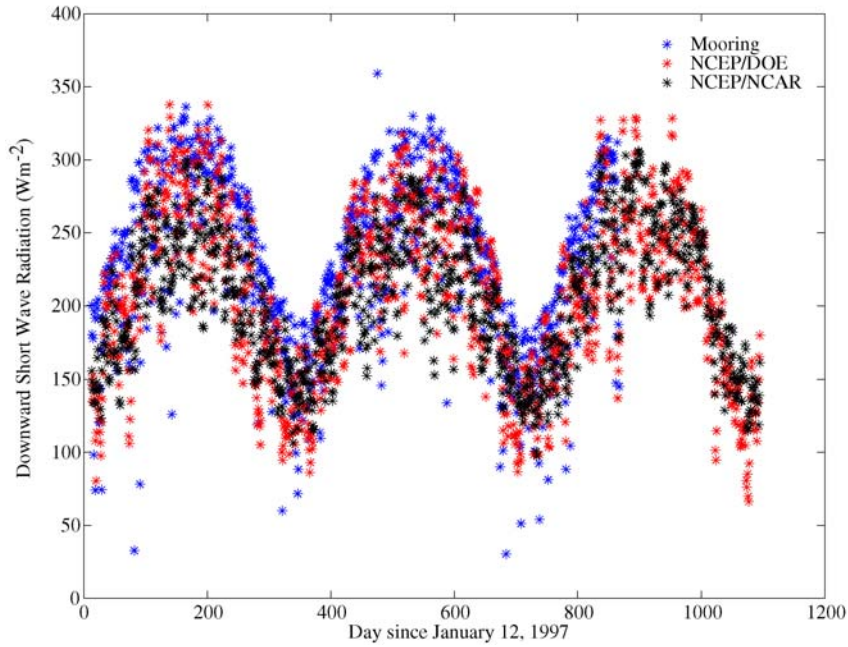
NCEP/NCAR : (97-01)-(92-96)



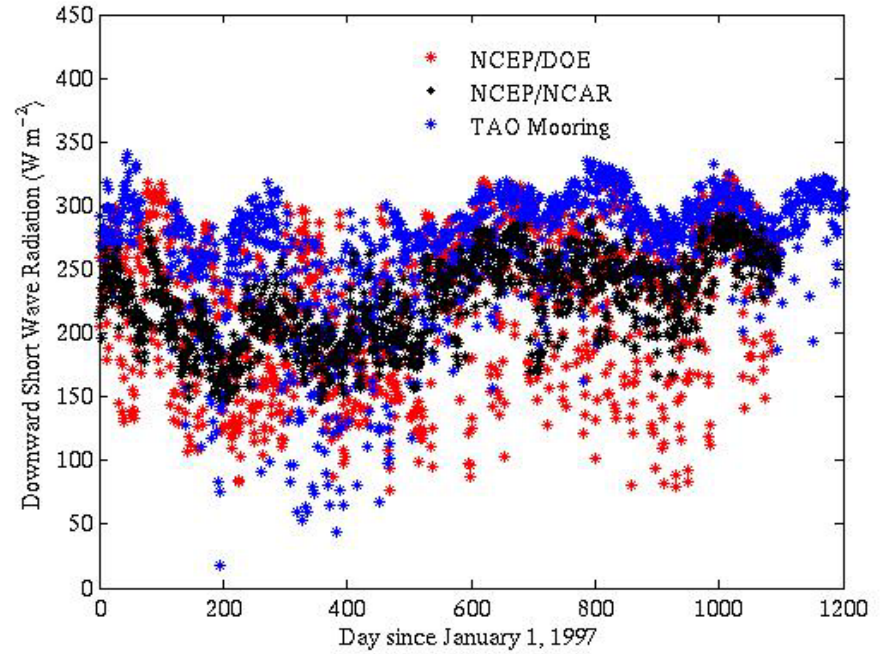
Note change of scale

Downward Short Wave Radiation ($W m^{-2}$)

Hale-Aloha Mooring

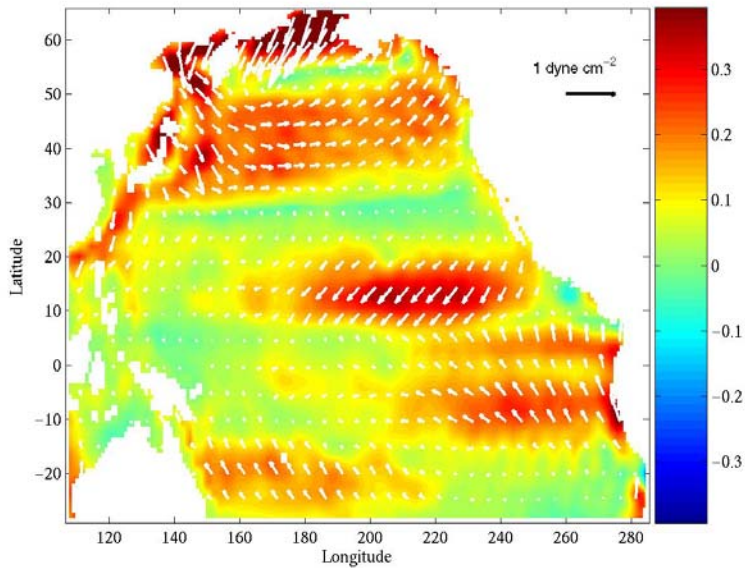


Equator $0^{\circ}N$ - $140^{\circ}W$

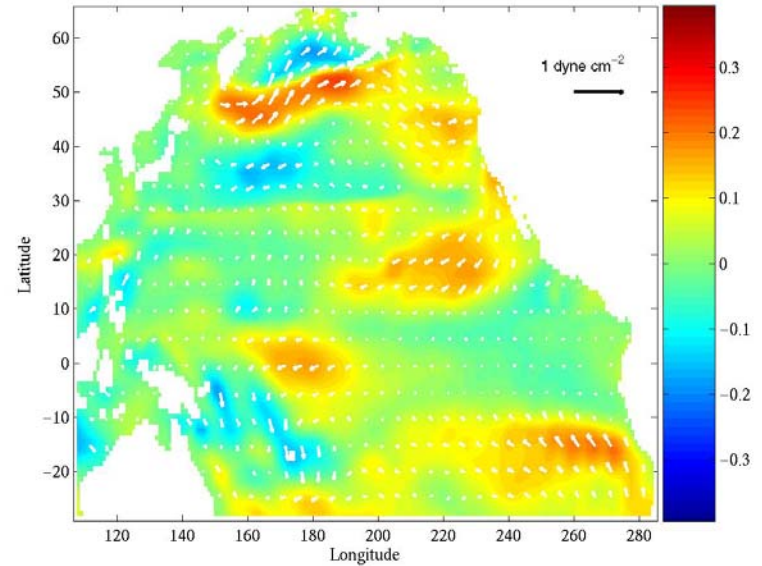


Wind Stress (dyne cm⁻²)

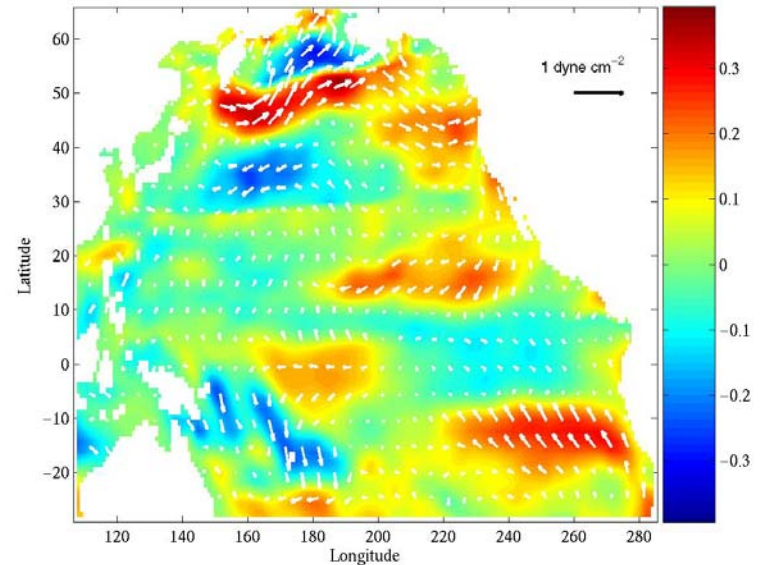
Mean Difference between NCEP/DOE and NCEP/NCAR (1992-2001)



NCEP/NCAR : (97-01)-(92-96)

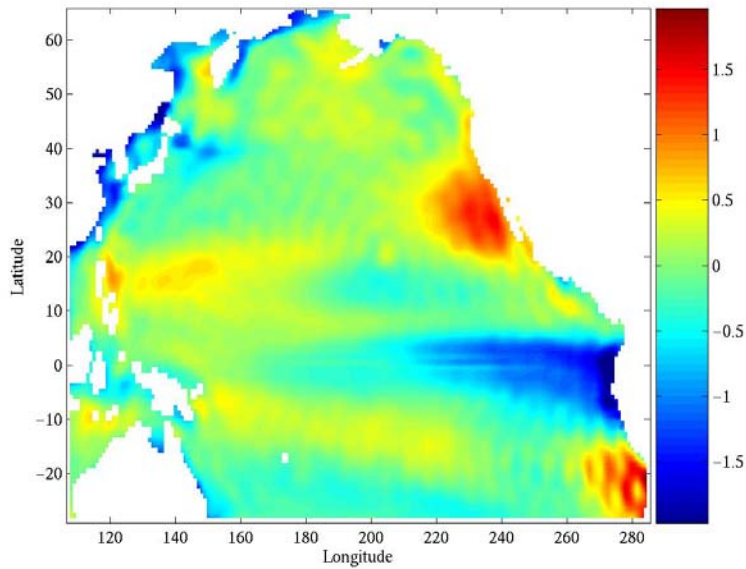


NCEP/DOE : (97-01)-(92-96)



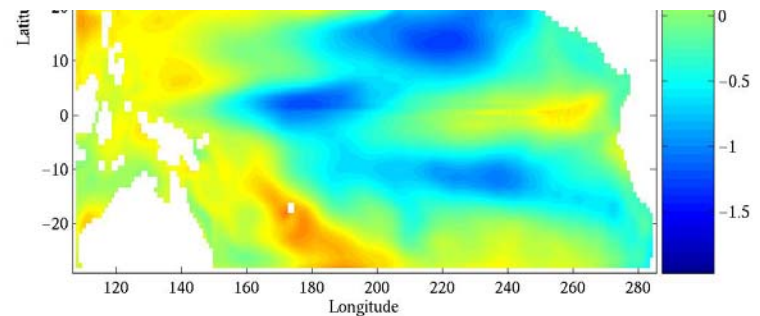
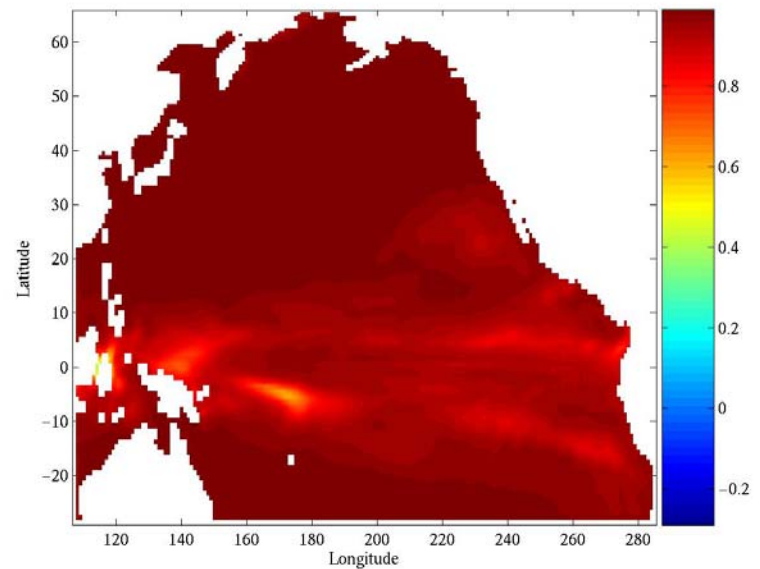
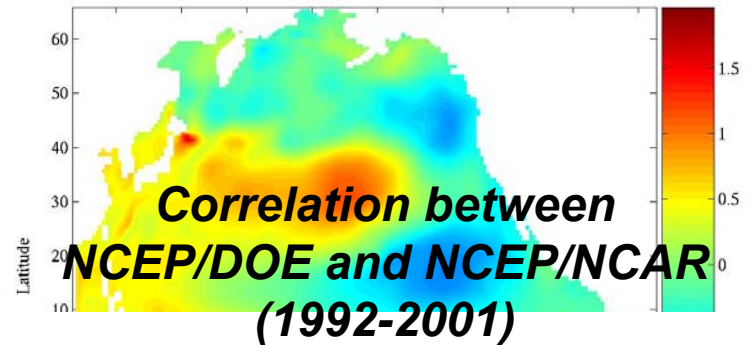
Surface Temperature (°C)

**Mean Difference between
NCEP/DOE and NCEP/NCAR
(1992-2001)**



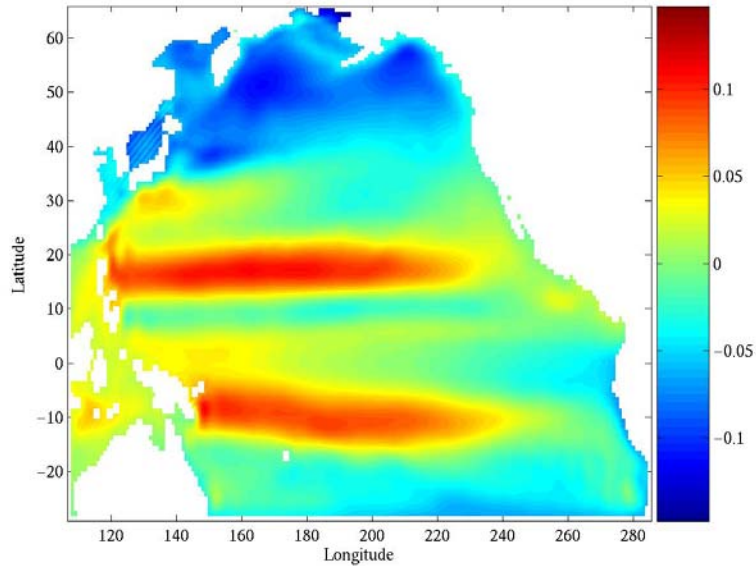
The mean varies between 5 and 25 °C

NCEP/NCAR : (97-01)-(92-96)



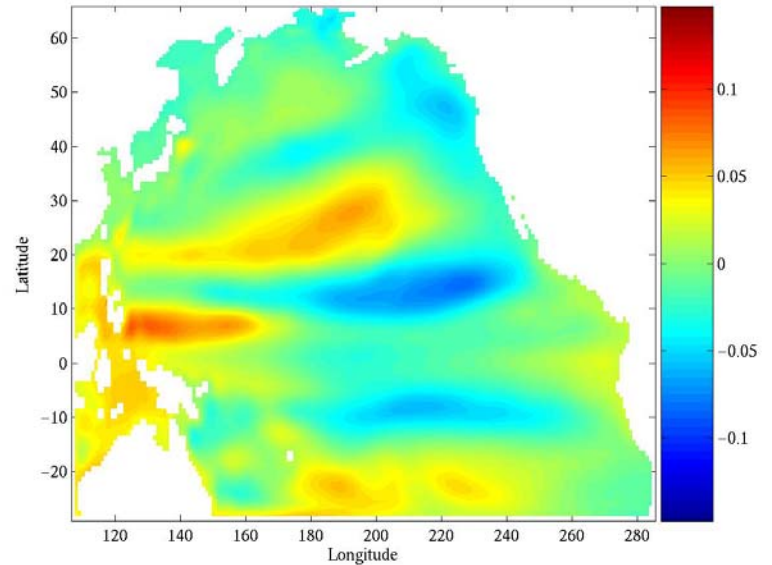
Sea Surface Height (m)

**Mean Difference between
NCEP/DOE and NCEP/NCAR
(1992-2001)**

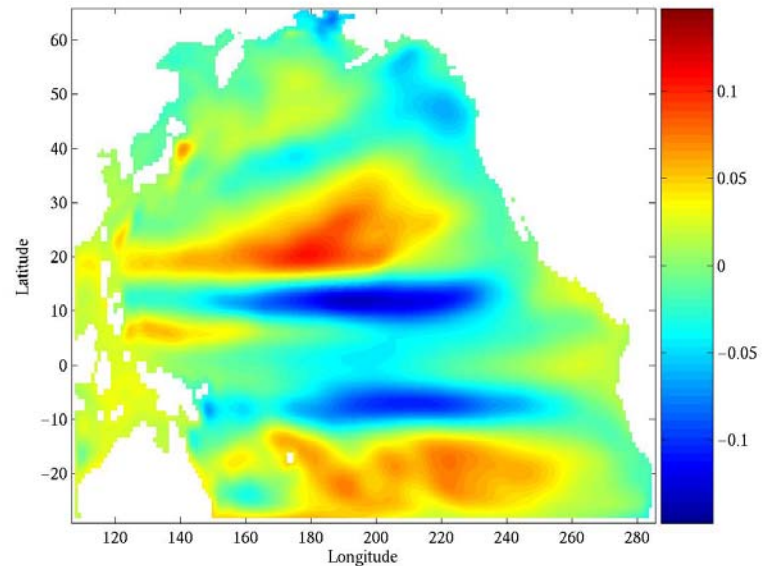


The mean varies between -0.8 and 0.5 m

NCEP/NCAR : (97-01)-(92-96)

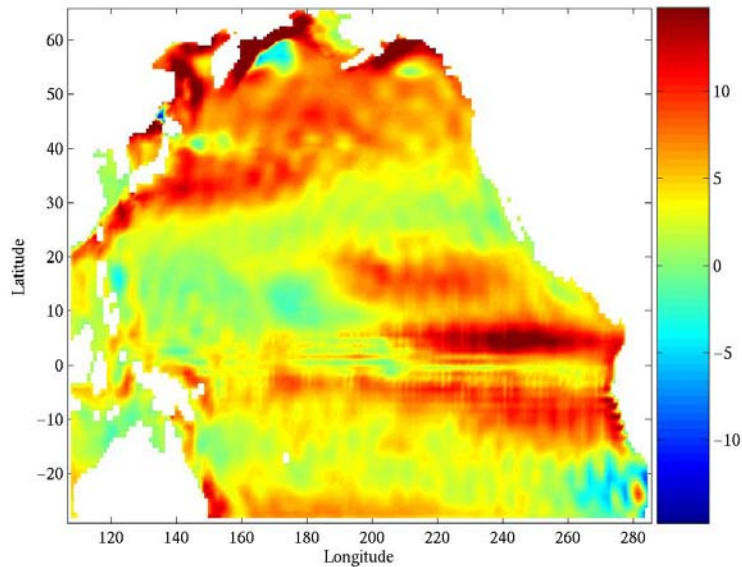


NCEP/DOE : (97-01)-(92-96)

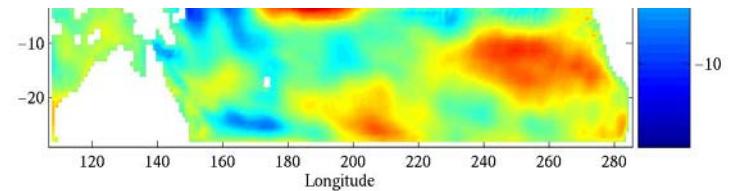
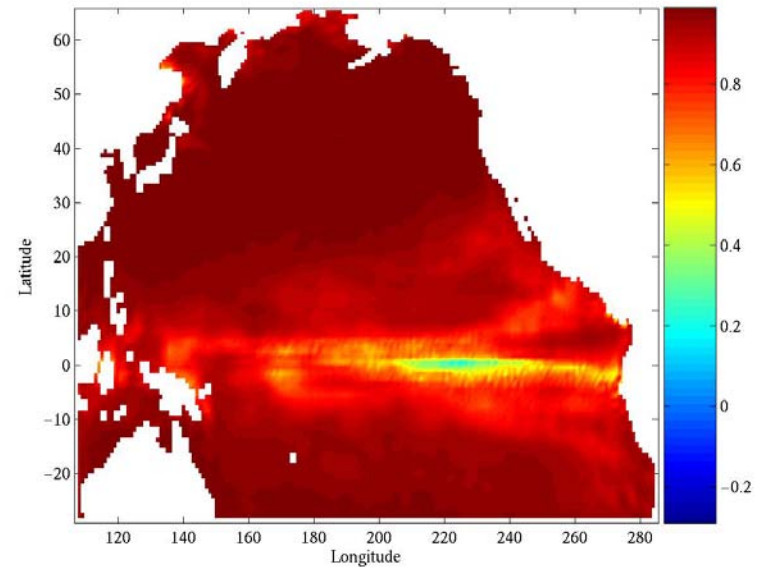
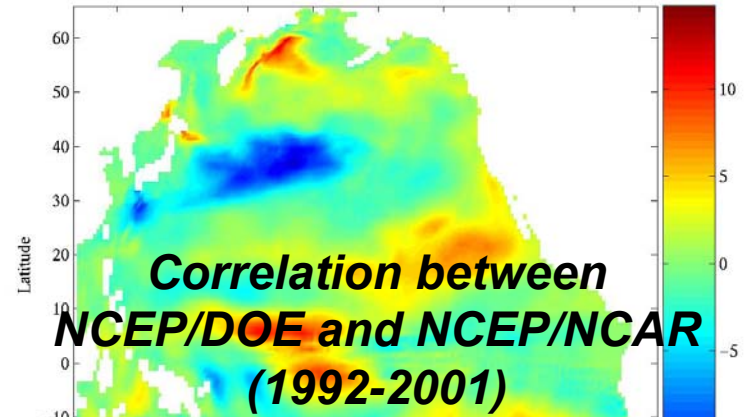


Mixed Layer Depth (m)

Mean Difference between
NCEP/DOE and NCEP/NCAR
(1992-2001)

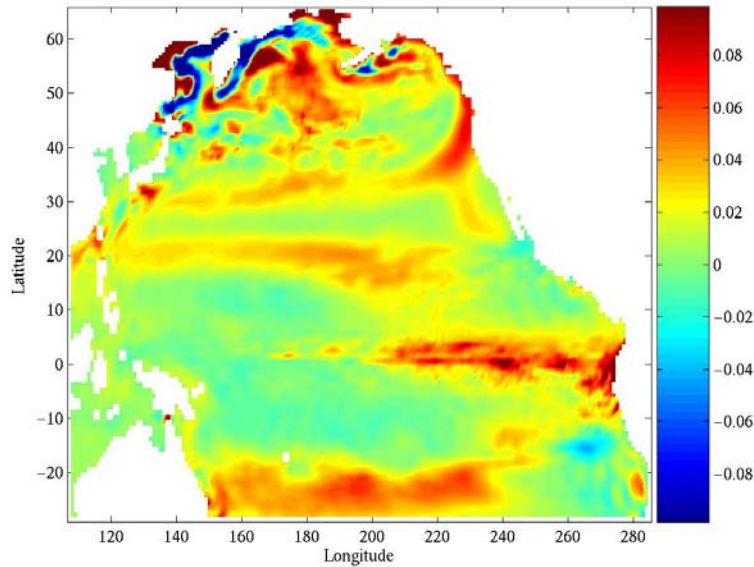


NCEP/NCAR : (97-01)-(92-96)



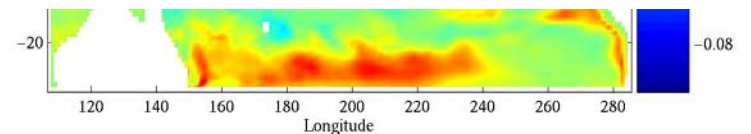
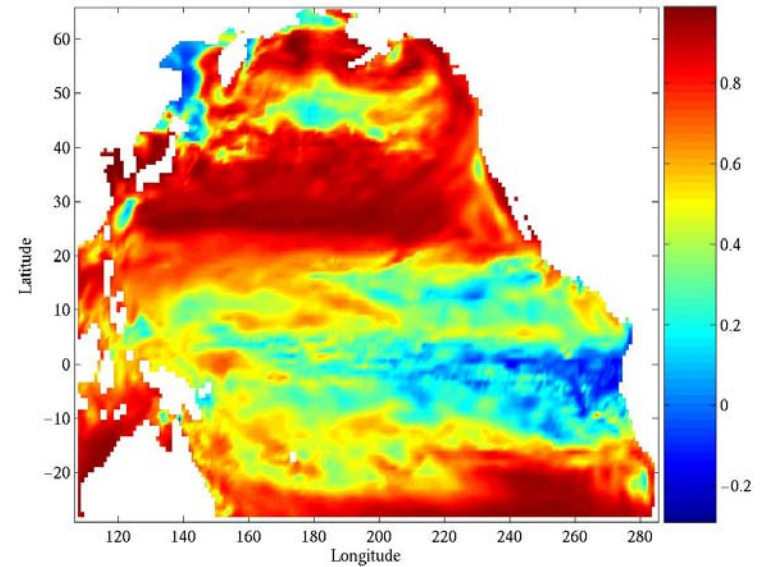
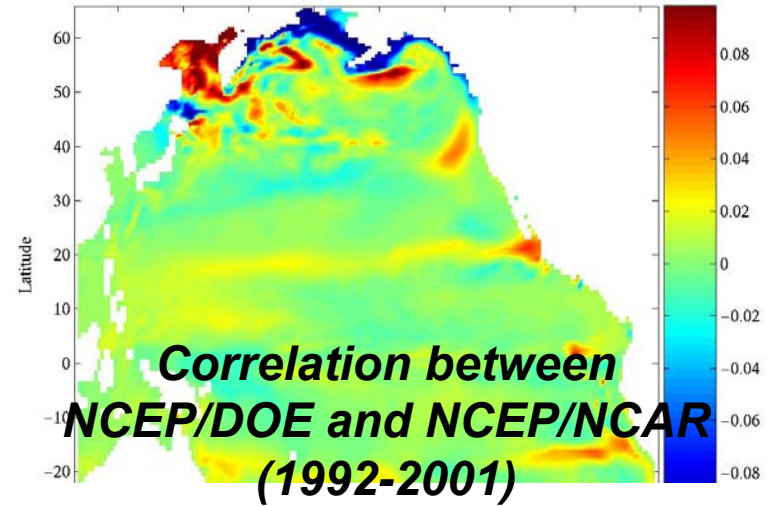
Surface Chlorophyll-a (mg Chl m⁻³)

Mean Difference between NCEP/DOE and NCEP/NCAR (1992-2001)

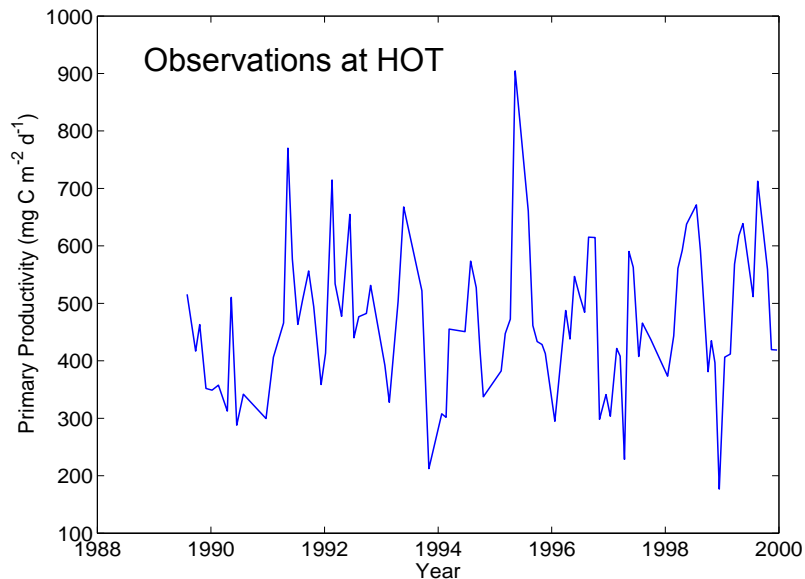


The mean varies between 0.05 and 0.25 mg Chl m⁻³

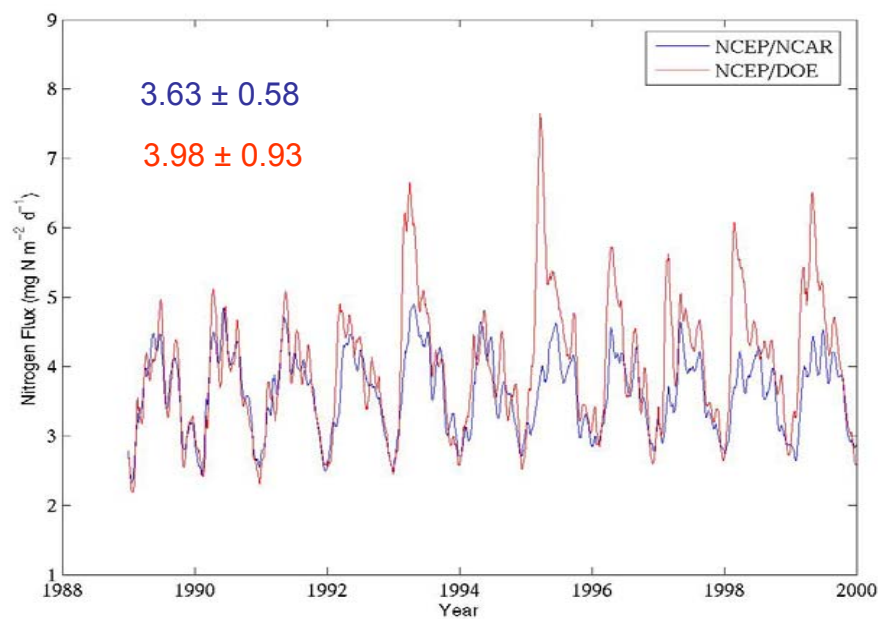
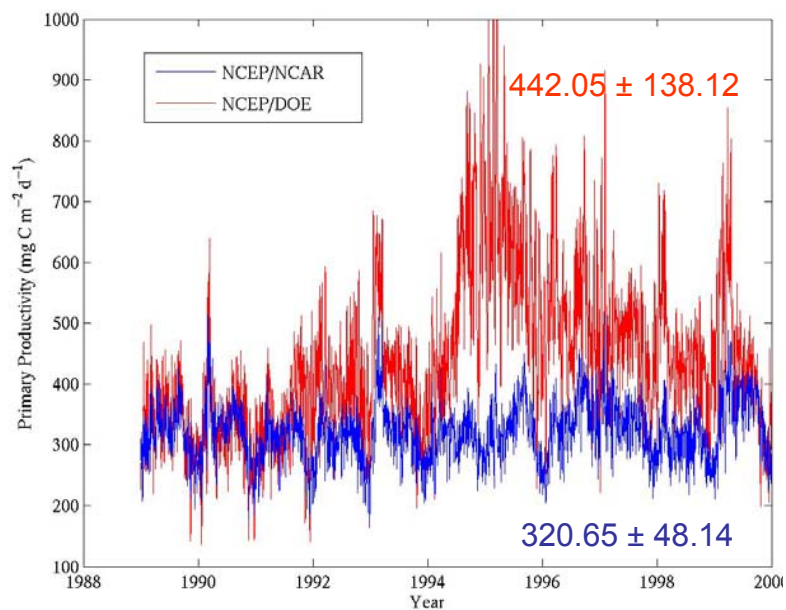
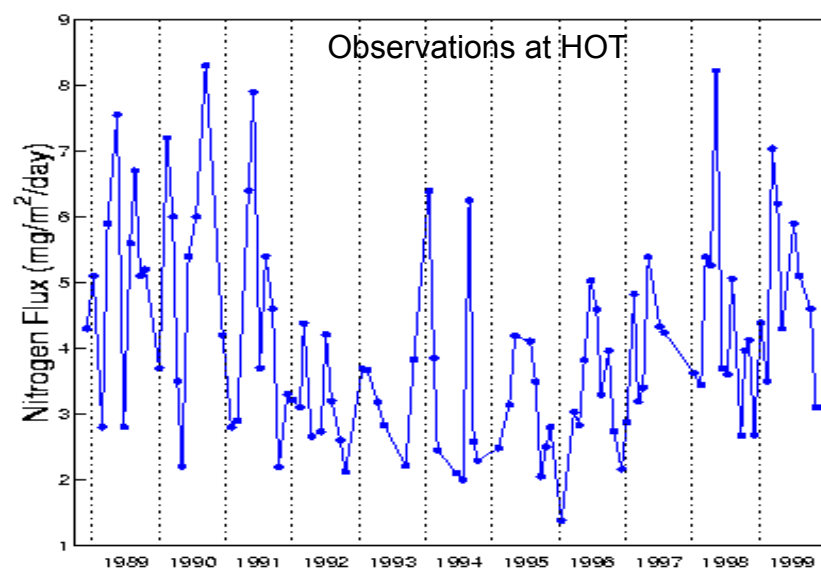
NCEP/NCAR : (97-01)-(92-96)



Primary Productivity

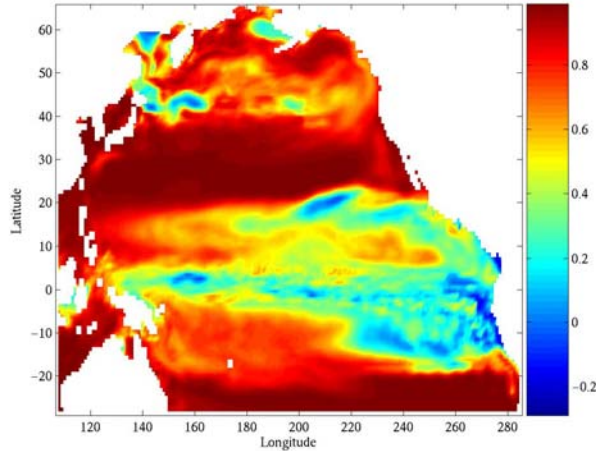


Nitrogen Flux at 150m

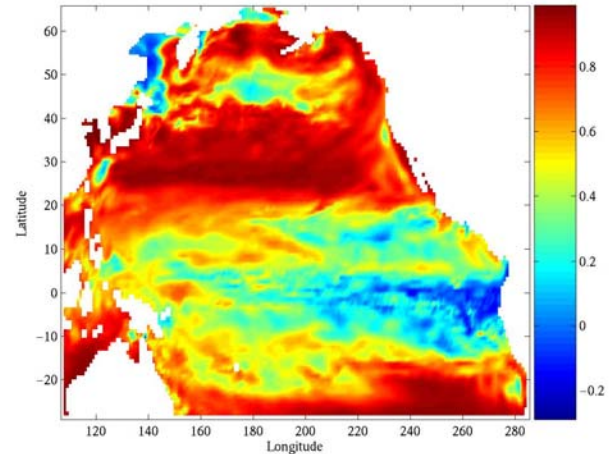


Correlation between model chlorophyll-a simulations

**Correlation between
BATS and HOT parameters**

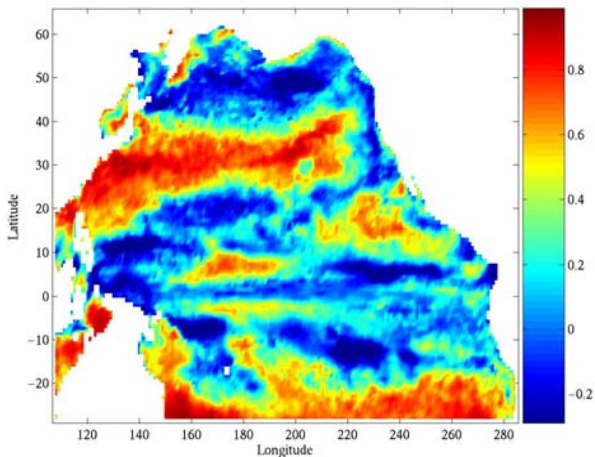


**Correlation between
NCEP/DOE and NCEP/NCAR**

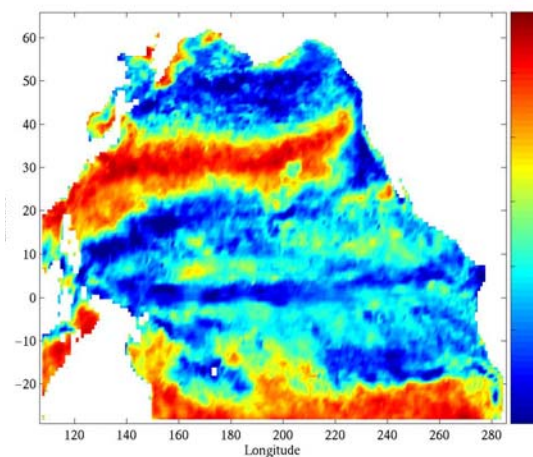


Correlation with SeaWiFS surface chlorophyll-a (98-01)

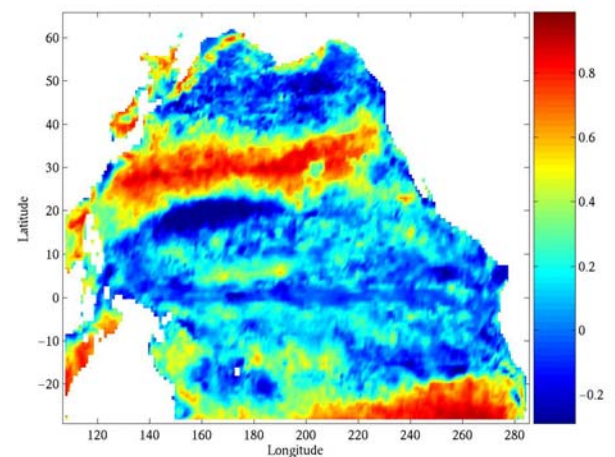
**NCEP/NCAR
BATS parameters**



**NCEP/NCAR
HOT parameters**



**NCEP/DOE
HOT parameters**



Conclusions

- **Errors induced by unknown model parameters and errors in the atmospheric forcing are of the same magnitude (if not larger) than the variations due to climatic changes**
- **Larger impact of errors in the downward solar radiation on the modeled circulation as well as on the ecosystem than the wind stress.**

Conclusions and future work

- Ecosystem model parameter choice still remains an issue and can lead to errors of the same order of magnitude than the signal we are trying to reproduce and analyze
- Atmospheric forcing choice can impact the estimate of the interannual to decadal variability. This impact is larger for the ecosystem than for the circulation.
- Data assimilation, such as Kalman filter (Reduced State Space) can help us to estimate the error of representation of the circulation model. This technique will be applied to estimate these errors in the ecosystem model and the coupled circulation/ecosystem model.
- Observations on longer times and of new kinds will help improve model and reduce the errors. Climatic change assessment will also be improved.

Issues with ecosystem modeling -> data assimilation

- The number of ecosystem components needed to represent a given ecosystem is undetermined (NPZ, NPZD, NNPZD, ...)
- The parameterization of the various links in the ecosystem is not well defined (e.g. grazing -> Ivlev versus Michaelis-Menten)
- Most of the model parameters are little known and some of them not measurable (e.g. plankton mortality)