An Historical Analysis of the California Current using ROMS 4D-Var: 1980-2010

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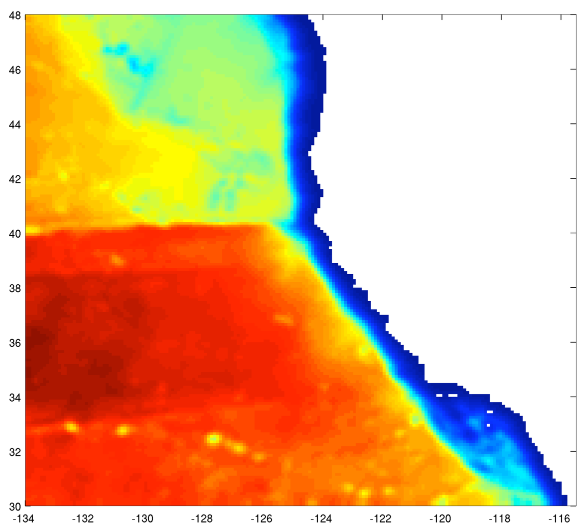
Model Set-up: ROMS CCS (California Current System)

Pronounced seasonal cycle of upwelling in Central California coast / Energetic mesoscale circulations

Bathymetry/Domain : Along the California Coast



Regional Ocean Modeling System

Hydrostatic primitive equations

$$\mathbf{x}(t_i)=M(t_i,t_{i-1})\left(\mathbf{x}(t_{i-1}),\mathbf{f}(t_i),\mathbf{b}(t_i)\right),\qquad \mathbf{x}=\left(\mathbf{T}^T,\mathbf{S}^T,\xi^T,\mathbf{u}^T,\mathbf{v}^T\right)^T$$

Surface forcing ($\mathbf{f}$), Open boundary conditions ($\mathbf{b}$), Temperature ($\mathbf{T}$), Salinity ($\mathbf{S}$), Water Height (ξ), Horizontal Velocities ($\mathbf{u},\mathbf{v}$)

- 1/10° horizontal resolution
- 42 s-levels following bathymetry : 0.3-8m over continental shelf ; 7-300m deep ocean
- Surface forcing and open boundaries compute daily and interpolated

Forcing $\mathbf{f}^b(t)$

- **atmospheric boundary layer fields, freshwater fluxes:** ERA 40 / 2.5° (1980- 2001), ERA interim Projects / 0.7° (2002-2010)
- **winds, 6h averaged from**: ERA 40 / 2.5° (1980- 2001), Cross Calibrated MultiPlatform (CCMP)/ 25km (1987-2010), ERA interim Projects / 0.7° (2002-2010)
- ocean surfaces fluxes : derived using **bulk formulation** of [Liu et al. (79)], [Fairfall et al. (96)]

Open boundary conditions $\mathbf{b}^b(t)$: North-South-West

- **tracer/velocity fields:** Simple Ocean Data Assimilation Product (SODA), Levitus seasonal climatology
- **free surface**: Chapman boundary condition, **vertically integrated flow**: Flather boundary condition
- **Sponge layer for viscosity** of 100 km, from 4 m².s⁻¹ to 400 m².s⁻¹

Observations

All data from in-situ and satellites available were used

- all observation of the same state were combined as super-observation over 6h- time window to reduce redundancy
- diagonal error covariance matrix: sum of measurement and representativeness errors

Summary of the different Observations Platforms

Observation Type	Observing Platform	Source	Combined Error	Period Covered
SSH	Altimeter	Aviso, 1 day average	0.04 m	1993-2010
SST	AVHRR/ Pathfinder	NOAA Coast Watch	0.6°C	1981-2011
SST	AMSR-E	NOAA Coast Watch	0.7°C	2002-2010
SST	GOES	NOAA Coast Watch	1°C	2001-2010*
SST	MODIS-Terra	NASA JPL	0.5°C	2000-2011
Hydrographic data	Various	UK Meteorological Office	0.5°C for T 0.1 for S	1950-2011

*The GOES SST are seriously biased during the period 2001-2002, so they are not used in ROMS 4D-VAR until 2003.

4D-Var Set-up

Cost function

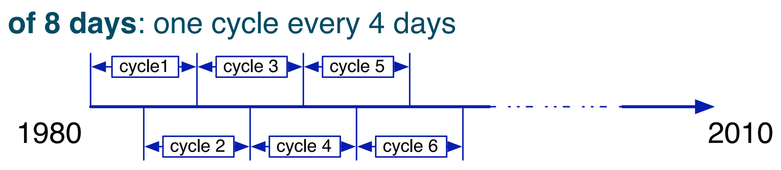
- Control vector $\mathbf{z}=\left(\mathbf{x}^T(t_0),\mathbf{f}^T,\mathbf{b}^T\right)^T$, no errors model
- Minimize non linear function:

$$J_{NL}=(\mathbf{z}-\mathbf{z}^b)^T\mathbf{D}^{-1}(\mathbf{z}-\mathbf{z}^b)+(\mathbf{y}^0-H(\mathbf{x}))^T\mathbf{R}^{-1}(\mathbf{y}^0-H(\mathbf{x}))$$

Prior information ($\mathbf{z}^b$), Observation ($\mathbf{y}^0$), Observation operator (H), Error covariance matrices ($\mathbf{D}$, $\mathbf{R}$)

Time assimilation windows:

- **31 years**, from January 1980 to December 2010
- **Overlapped cycles of 8 days**: one cycle every 4 days



- Prior state $\mathbf{x}^b$: state at the middle of the previous cycle, except the first cycle: long spin-up integration of the ROMS CCS

Error covariance matrix D uses diffusion operator approach

$$\mathbf{D}=\mathrm{diag}(\mathbf{B_x},\mathbf{B_f},\mathbf{B_b})$$

- Based on [Weaver et al. (2005)]
  - prior initial state composed on unbalanced components assumed to be uncorrelated:

$$\mathbf{B_x}=\Sigma\,\mathbf{C}\,\Sigma^T$$

  Diagonal matrix of standard deviations (Σ); Univariate correlation matrix, modeled as pseudo-diffusion ($\mathbf{C}$)
  - standard deviations computed from a long run without assimilation
- Decorrelation lengths:
  - $\mathbf{B_x}$: 50km horizontal, 30m vertical
  - $\mathbf{B_f}$: 300km (wind stress), 100km (heat/freshwater)
  - $\mathbf{B_b}$: 100km horizontal, 30m vertical
- Correlation lengths: semi-variogram method, [Bannerjee et.al, (04)] [Millif et al.(03)]

Incremental method, tangent linear hypothesis

- Control vector $\mathbf{z}=\mathbf{z}^b+\delta\mathbf{z}$

$$J=\delta\mathbf{z}^T\mathbf{D}^{-1}\delta\mathbf{z}+(\mathbf{d}-\mathbf{G}\delta\mathbf{z})^T\mathbf{R}^{-1}(\mathbf{d}-\mathbf{G}\delta\mathbf{z})$$

Tangent linear observation operator + Tangent linear model ($\mathbf{G}$); Innovation vector $\mathbf{d}=\mathbf{y}^o-H(\mathbf{x})$

- Assumed small non-linearities
- Cycles of 15 inner-loops: minimization of J , 1 outer-loop to update the innovation

For each cycle: B-preconditioned restricted Lanczos method

- Minimization of J using an adjoint model, searching for **δz** in the observation space
- Optimization method : Lanczos version of the Restricted Preconditioned Conjugate Gradient (RPCG) of [Gratton, Tshimanga, 2009], same rate of convergence as primal method.

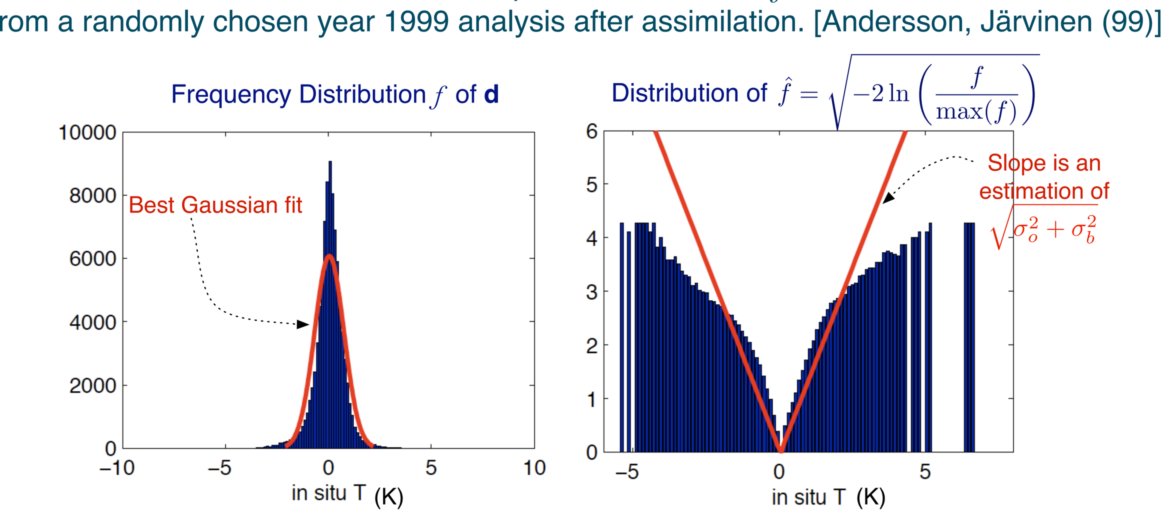
Background quality control

- Reject observation subject to gross errors or inconsistent with the model using the following criteria

$$\frac{(y_i^o-y_i^b)^2}{\sigma_o^2}<\alpha\left(1+\frac{\sigma_b^2}{\sigma_o^2}\right)$$

i_{th} observation (y_i^o); i_{th} element of $H(\mathbf{x}^b)$ (y_i^b); standard deviations of obs. and prior errors at obs. point (σ_o, σ_b)

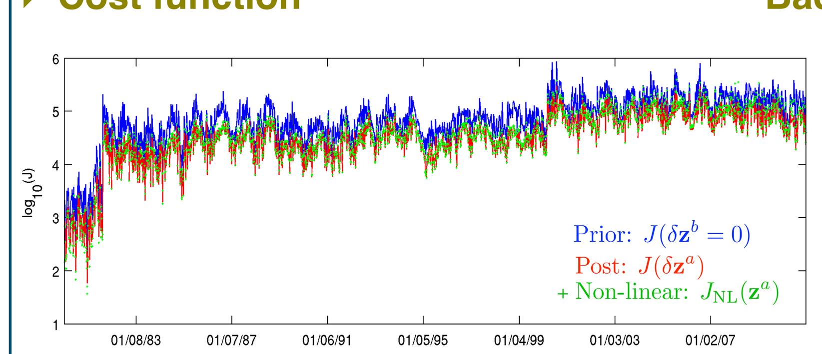
- Threshold values α estimated from frequential distribution f of innovation vectors **d** from a randomly chosen year 1999 analysis after assimilation. [Andersson, Järvinen (99)]



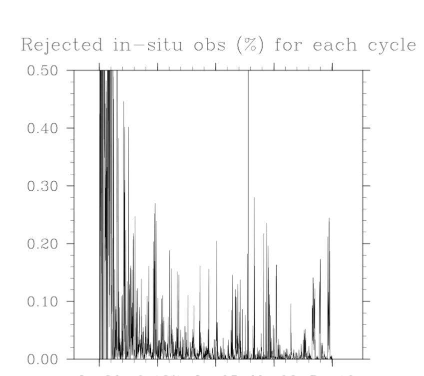
- 4 standard deviations seem to reflect a fair departure from the straight lines : α = 16
- Use of the same threshold for **all in situ data only**.

Monitoring

Cost function

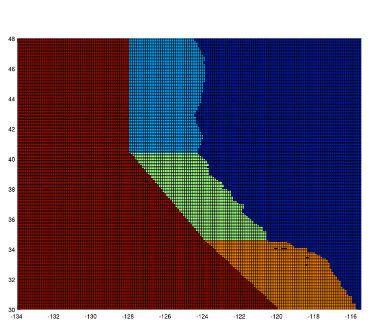


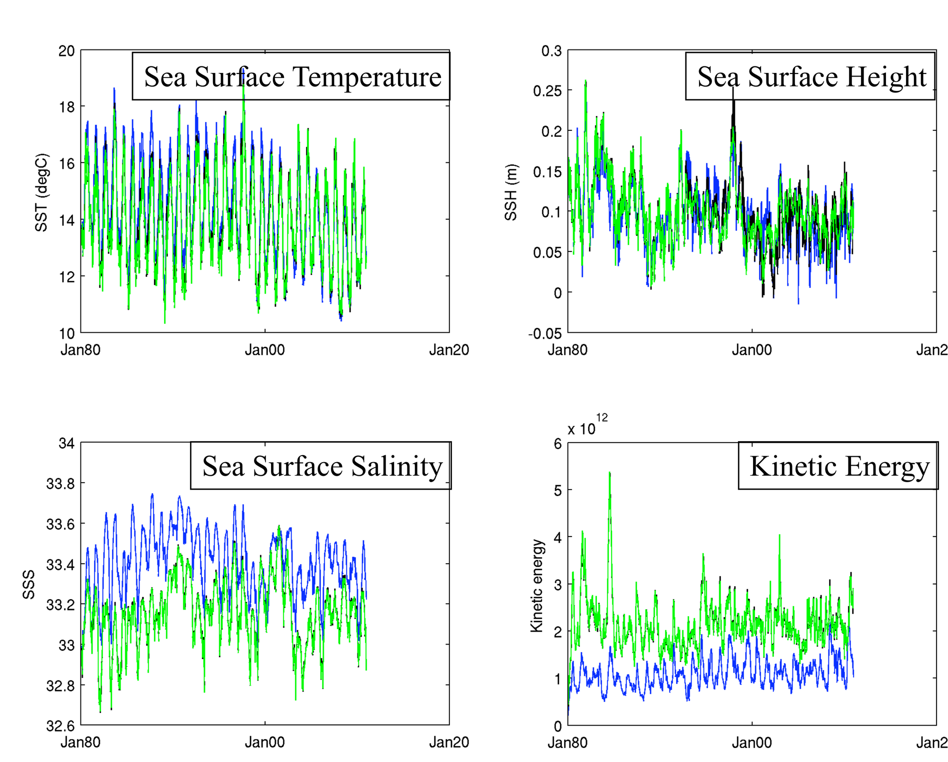
Background Quality Control



Time Series

- Divided in 4 regions - Spatially averaged only on **Center-East region**





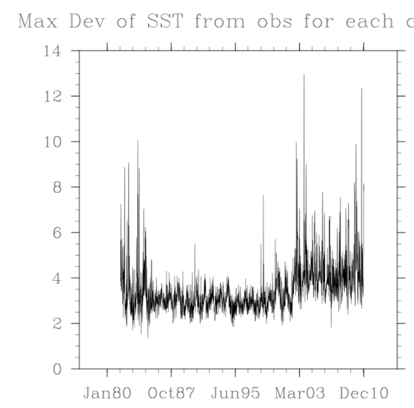
Prior (almost under the green curve)

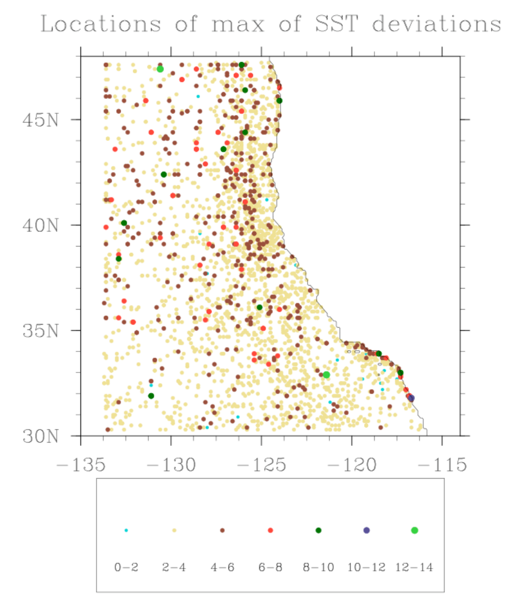
ROMS Forward

ROMS Analysis (after assimilation)

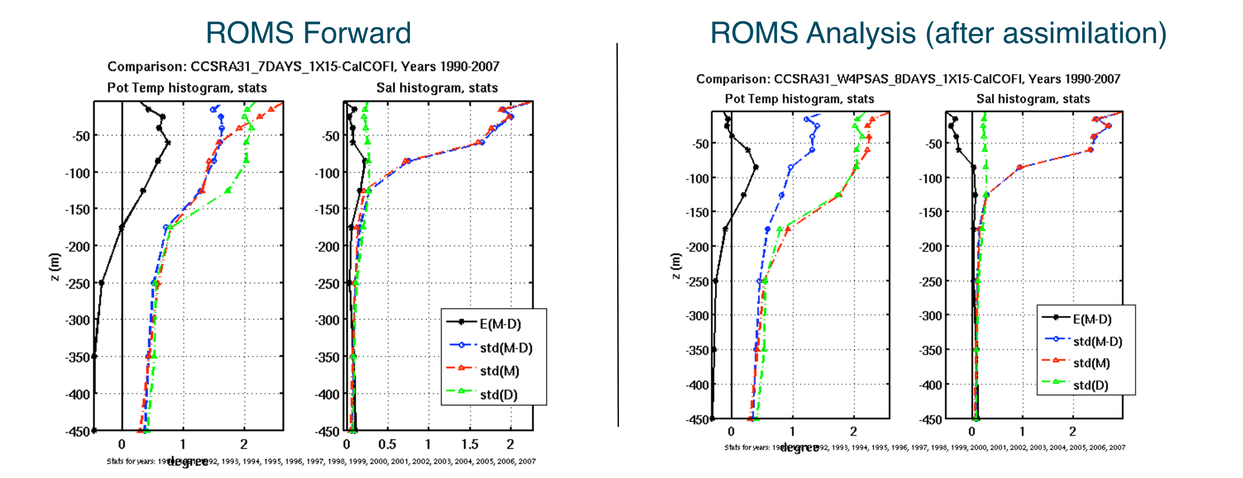
Departures from Observation

- Assimilated Sea Surface Temperature Observations





- California Cooperative Oceanic Fisheries Investigations- Calcofi Cruises (1990-2007)



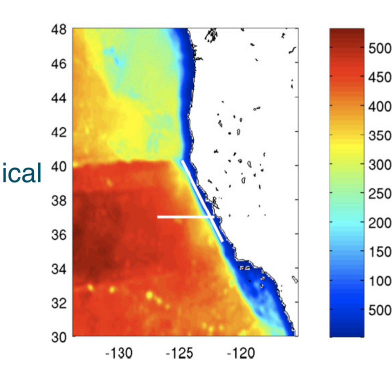
Variability

To understand seasonal to inter-annual and inter-decadal variability

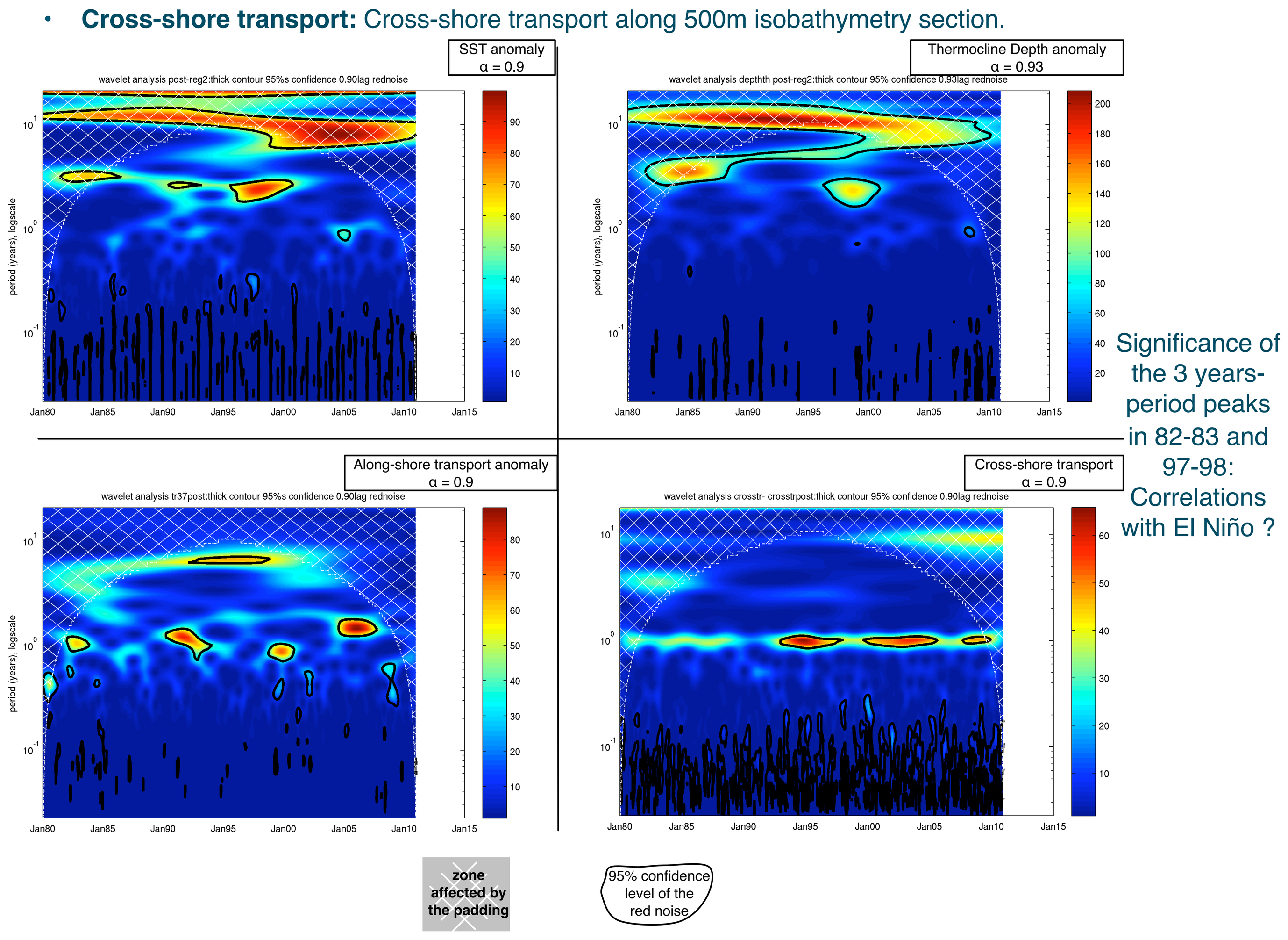
Time-frequency analysis based on wavelet decomposition

- Compute wavelet coefficients Wav(time,period) for time series of variables (spatially averaged for each cycle)
- Plot $|\mathrm{Wav}|^2$, the power wavelet; compare to the red-noise $\mathbf{r}(t_i)=\alpha\,\mathbf{r}(t_{i-1})+G(0,\sigma)$, with α chosen so that the Fourier transform of the red noise fits $\frac{1}{T}\sum_{time}|\mathrm{Wav}(time,period)|^2$; [Torrence, Compo (98)]
- Non-periodic signal padded with zeros to limit the boundaries reflection effect.
- Non-orthogonal Morlet wavelet : focus on the smooth/continuous variations of the timeseries

Wavelet analysis



- **Region Center-East**
- **SST anomaly**: Sea Surface Temperature minus climatological mean
- **Thermocline depth anomaly -** Depth of the thermocline minus climatological mean: Thermocline assumed to be the isotherm of 11°C. Based on vertical profiles of temperatures for the year 1995.
- **Along-shore anomaly:** Along-shore transport along 37°N section minus climatological mean.
- **Cross-shore transport:** Cross-shore transport along 500m isobathymetry section.

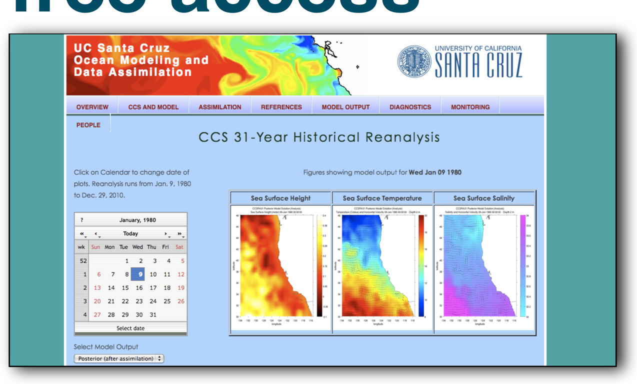


Significance of the 3 years-period peaks in 82-83 and 97-98: Correlations with El Niño ?

Community free access

Website/ OpenDAP

http://oceanmodeling.pmc.ucsc.edu/



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