Decadal-scale Variability in Upwelling Processes in the California Current Ecosystem and Potential Biological Responses

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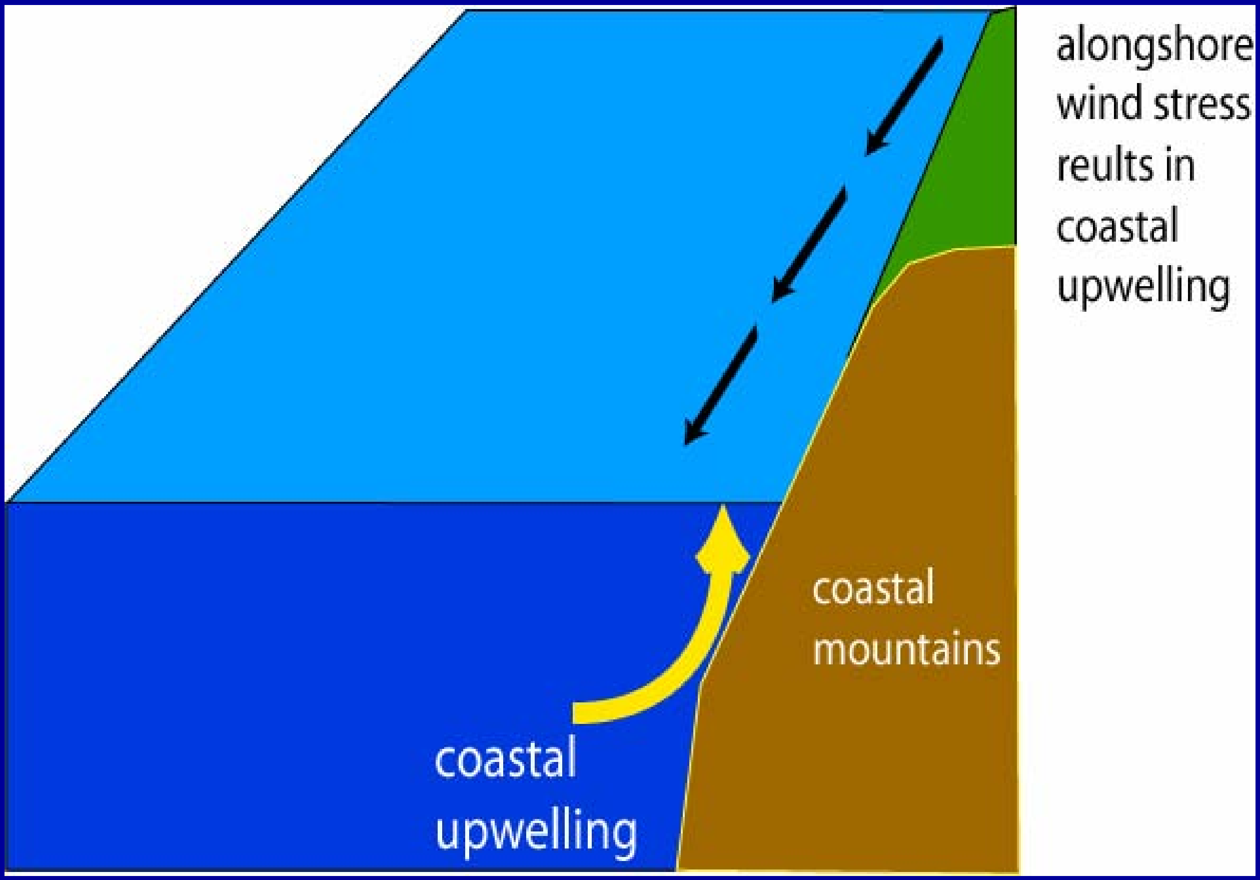
Production in the California Current Ecosystem

Primary production is dependent on nutrients supplied by upwelling.

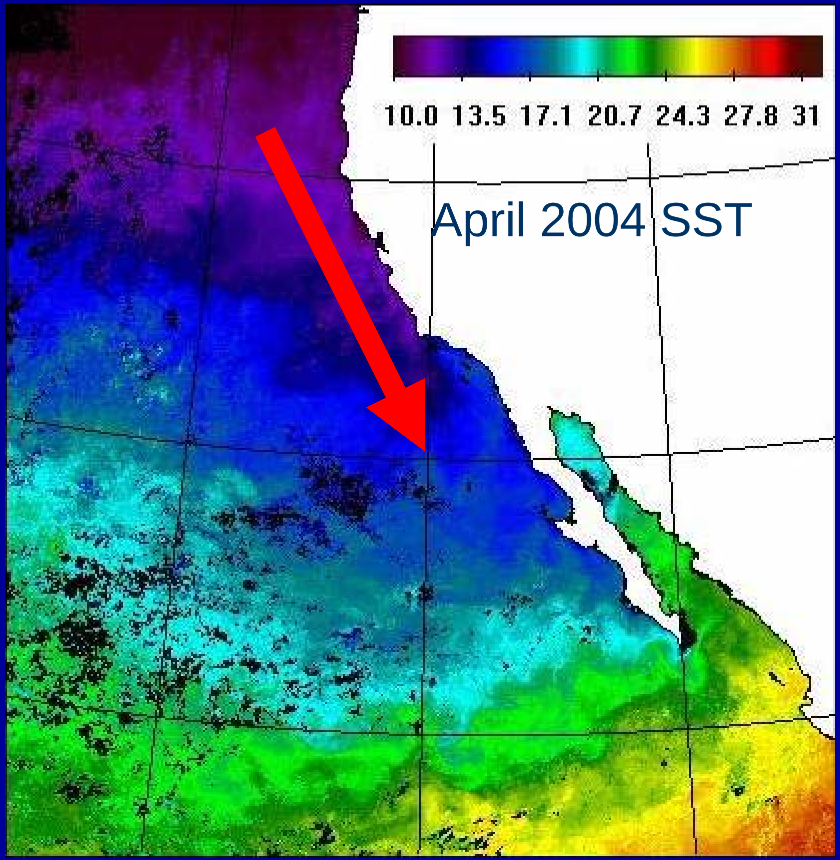
$$W_{coastal} = \frac{\tau}{R_d \rho_w f}$$

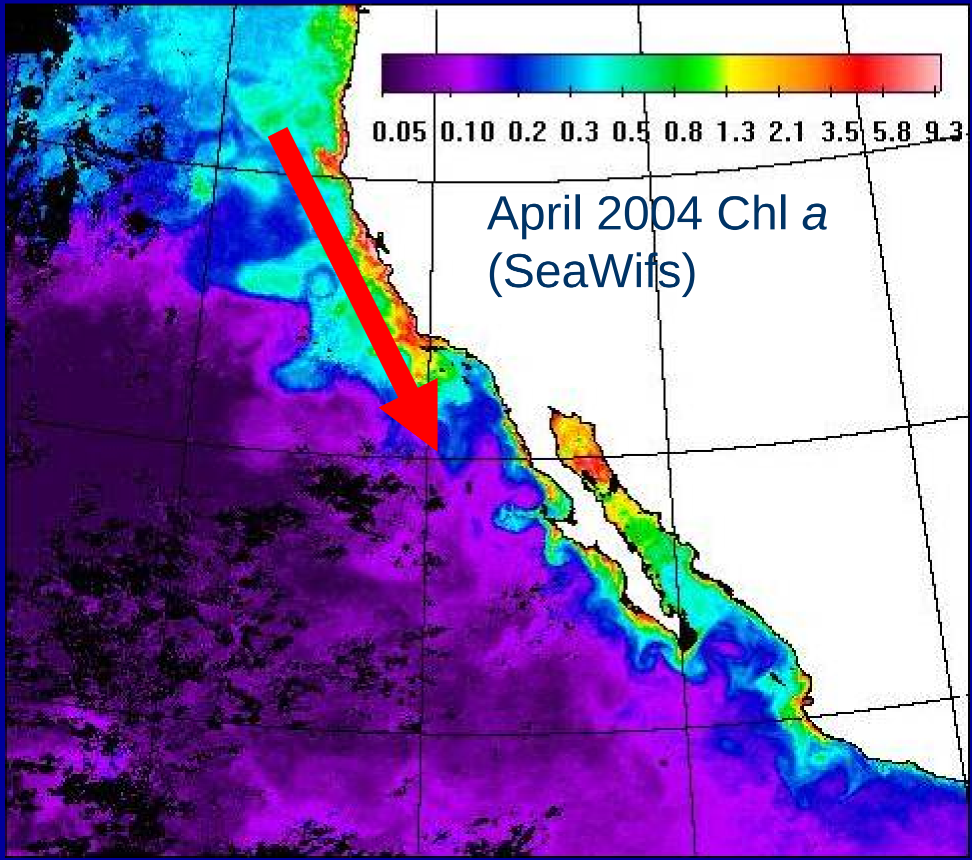


w:	vertical velocity
τ:	wind stress
R_d:	Rossby radius
f:	Coriolis parameter
ρ_w:	water density

Production in the California Current Ecosystem

Alongshore, equatorward winds force cold, high-nutrient waters to the surface.





Production in the California Current Ecosystem

Primary production dependent on nutrients supplied by upwelling.

$$W_{coastal} = \frac{\tau}{R_d \rho_w f}$$

$$W_{oceanic} = \frac{\nabla \times \tau}{\rho_w f}$$

w:	vertical velocity
τ:	wind stress
R_d:	Rossby radius
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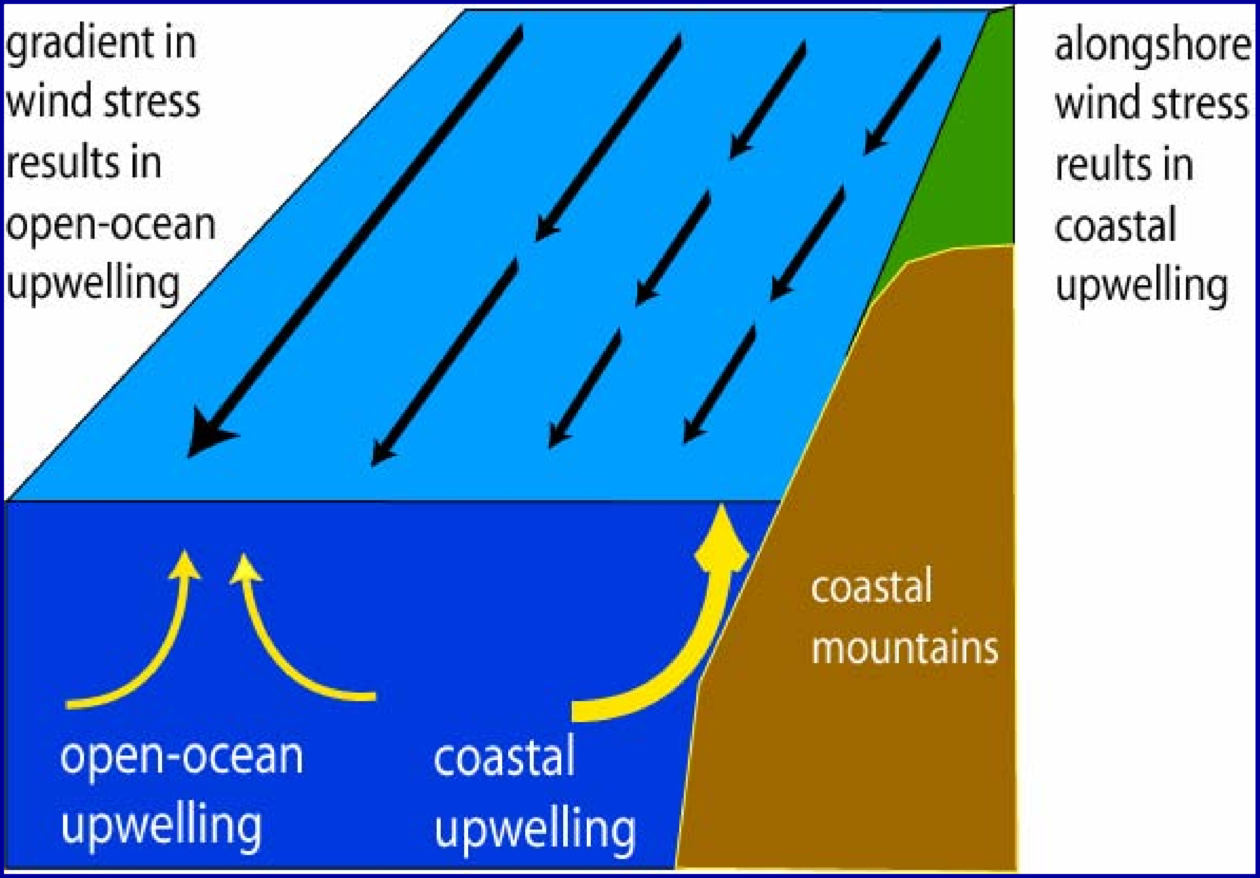


Curl Review

$$\nabla \times \tau = \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}$$

Wind-stress curl is related to the sum of:

the alongshore gradient in zonal winds

and

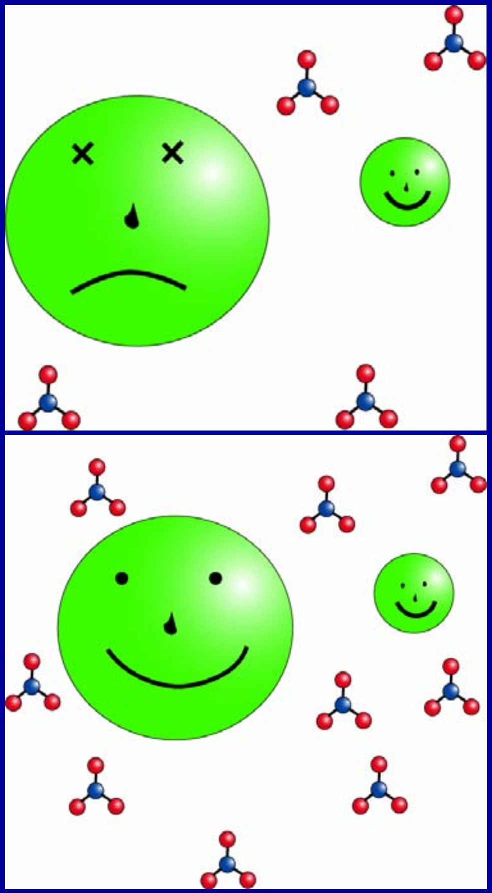
the across-shore gradient in meridional winds.

Production in the California Current Ecosystem

- Coastal upwelling delivers nutrients at a rate much higher than open-ocean upwelling (Pickett and Paduan, 2003; Pickett and Schwing, 2006).
- However, open-ocean upwelling acts over a much larger ocean surface area and may supply a major portion of nutrients to the ecosystem. This transport of nutrients may have a significant (and perhaps dominant) effect on the productivity of the California Current (Yoshida and Mao, 1957; Chelton, 1982; Pickett and Paduan, 2003; Pickett and Schwing, 2006).
- We hypothesize that different ecosystem types result from the two upwelling processes. An ecosystem with large primary and secondary producers results from fast upwelling and high supply of nutrients. Small plankton result from slow upwelling and low supply of nutrients. These ecosystem differences also influence populations of grazers.

Changing nutrient supply → Shifting community structure

oligotrophic conditions, small sizes may bloom



eutrophic conditions, all sizes may bloom

- When production is nutrient-limited under slower rates of nutrient supply, smaller phytoplankton (with a large surface-area-to-volume ratio) are able to out compete larger phytoplankton.
- When nutrient supply is high and production is not nutrient limited, the advantage for small cells is lost. Large phytoplankton may bloom as well.

The size structure of the community is maintained through each trophic step. Larger phytoplankton feed larger zooplankton—smaller phytoplankton feed smaller zooplankton.

Approach

Three steps have been taken to investigate the influence of coastal upwelling and open-ocean upwelling on the CCE:

1) relationships between upwelling rate and plankton size
2) historic variability in upwelling processes
3) relationships between upwelling rate and fish productivity

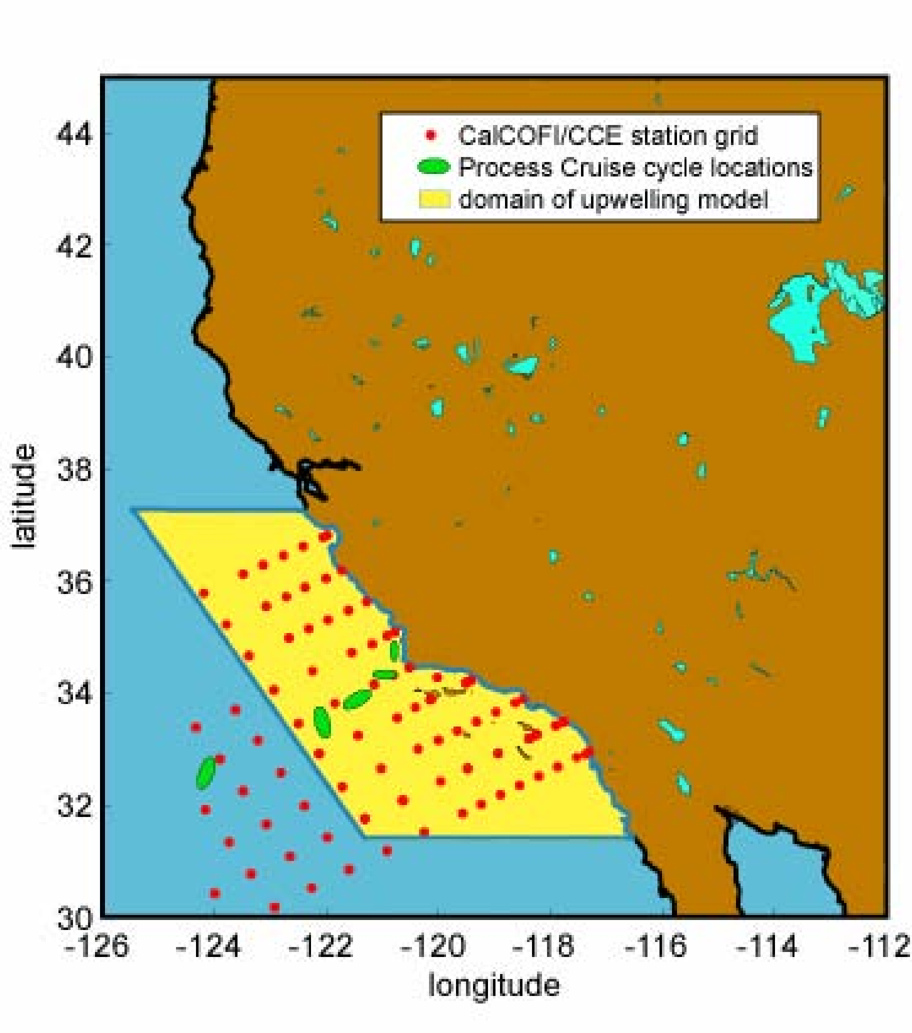
Upwelling Rate and Plankton Size

Size-fractionated plankton assessments in May 2006:

Phytoplankton		Zooplankton	
<1	µm	200-500	µm
1-3	µm	500-1000	µm
3-8	µm	1000-2000	µm
8-20	µm	2000-5000	µm
>20	µm	>5000	µm

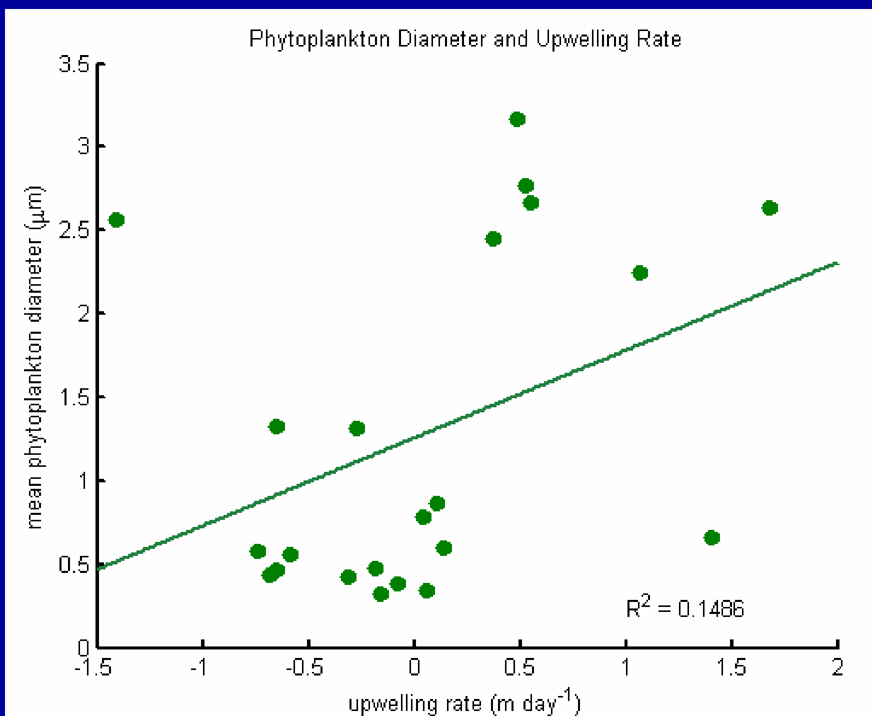
These classes were weighted by their contribution to total fluorescence or dry mass to determine "mean size" of plankto in each cast.

Upwelling rate was inferred from wind stress and wind-stress curl data sampled by the NASA/JPL Scatterometer and shipboard anemometer.

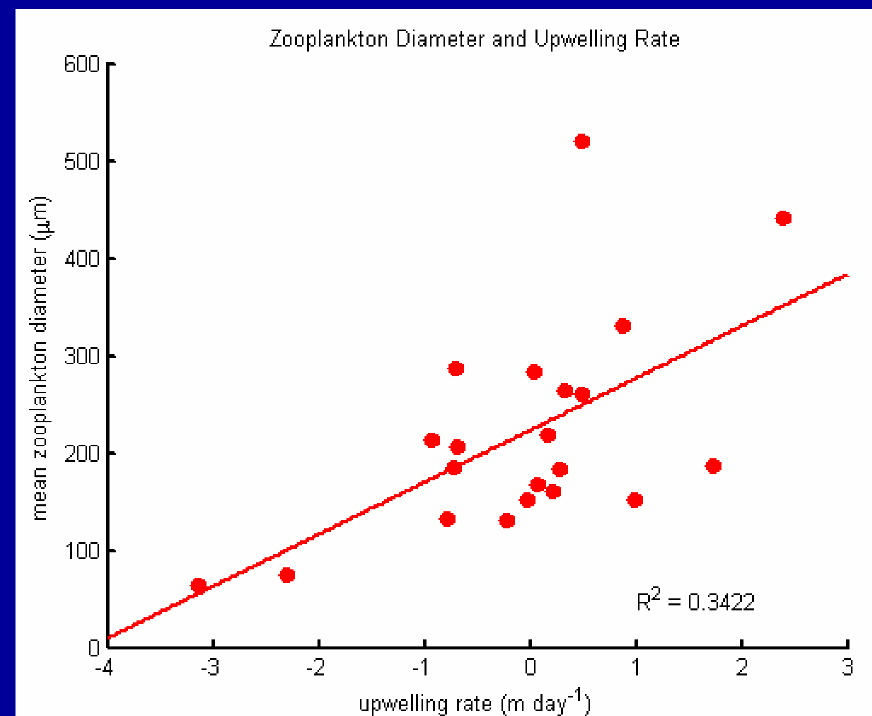


Upwelling Rate and Plankton Size – Preliminary Results

Phytoplankton and zooplankton sizes increased with upwelling rate.



1-day mean upwelling rate



3-day mean upwelling rate

Approach

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3) relationships between upwelling rate and fish productivity

Historic Upwelling Variability

- NCEP reanalysis winds were downscaled to estimate historic wind stress since (1948 – 2004).
- Coastal (<10 km offshore) and open-ocean upwelling rates were estimated using these wind stresses.

$$w_{coastal} = \frac{\tau}{R_d \rho_w f}$$

$$w_{oceanic} = \frac{\nabla \times \tau}{\rho_w f}$$

w: vertical velocity
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R_d: Rossby radius
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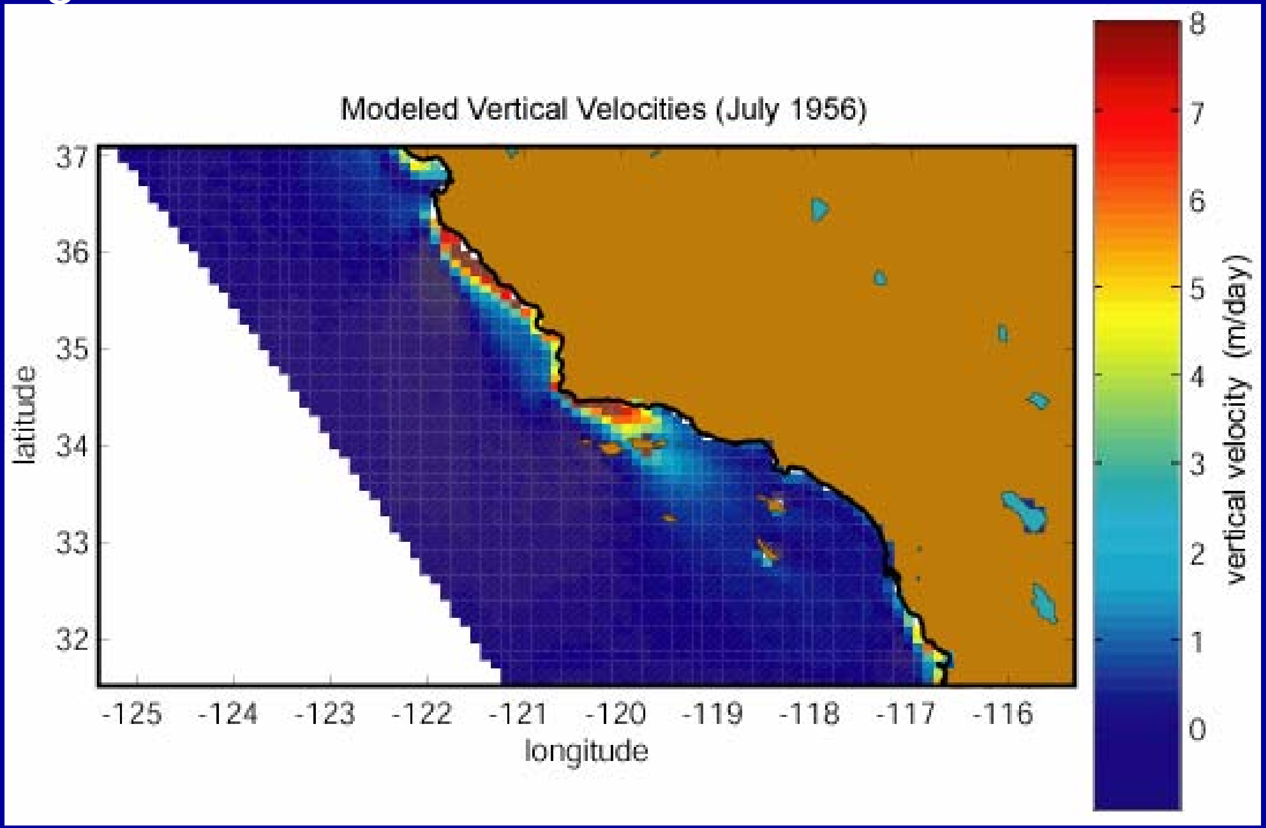
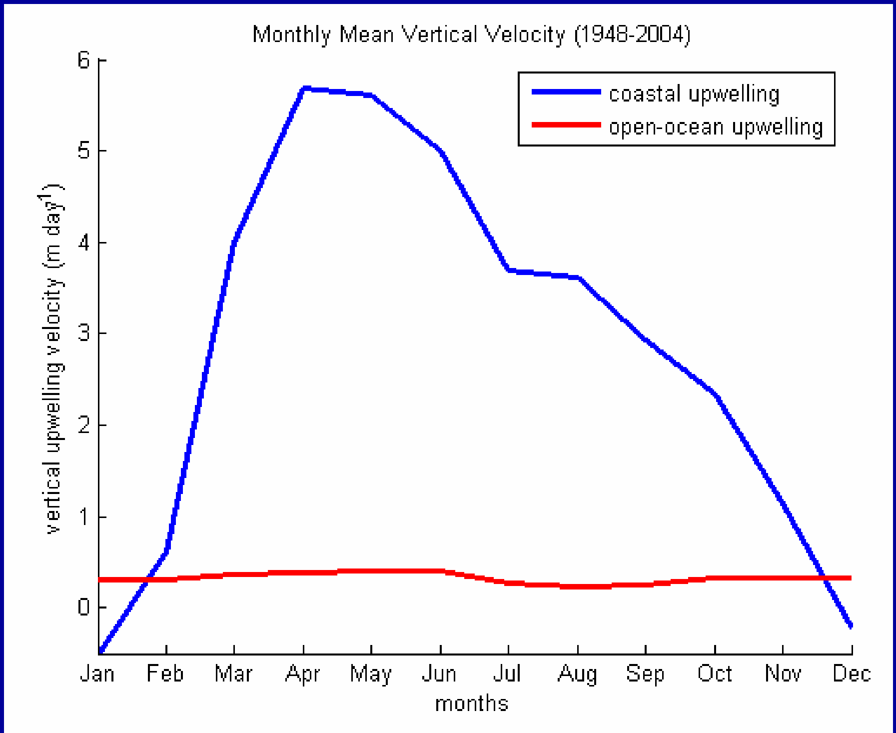
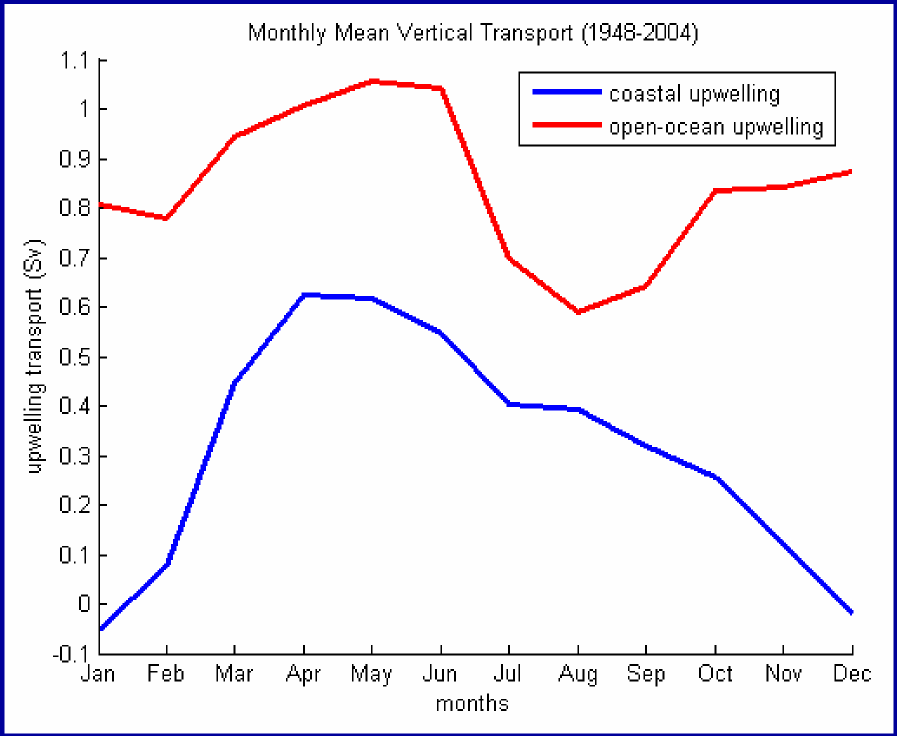


Historic Upwelling Variability – Seasonal Cycle

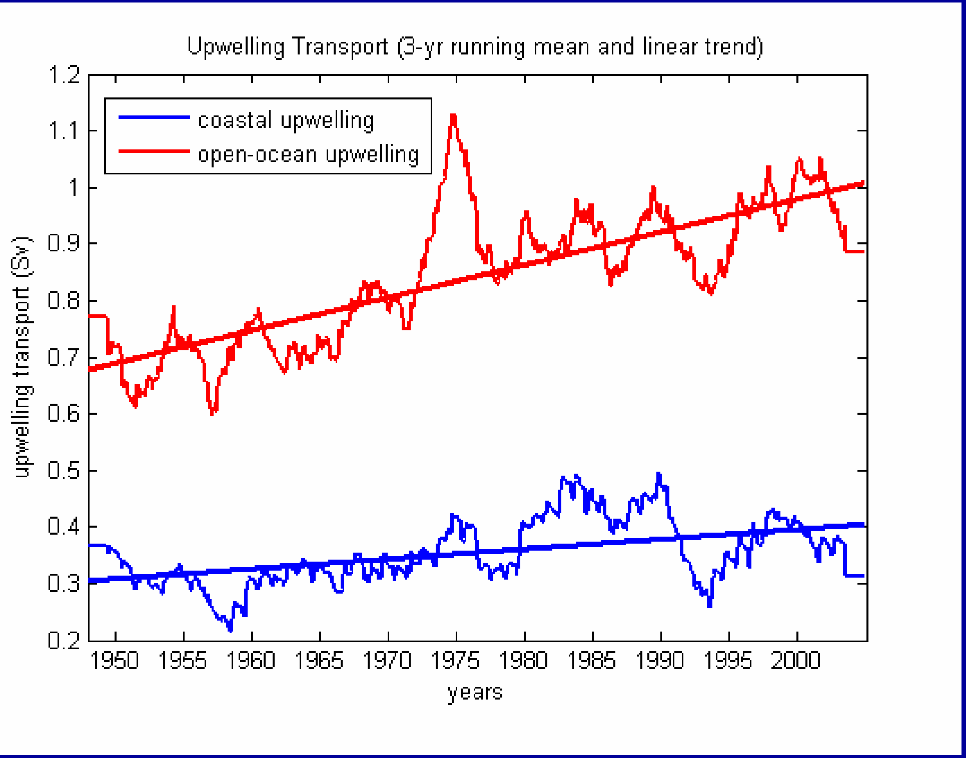
- There were strong seasonal cycles with upwelling peaks in spring and early summer.
- Coastal upwelling had higher vertical velocities.
- Volume transport was dominated by open-ocean upwelling.





Historic Upwelling Variability (1948-2004)

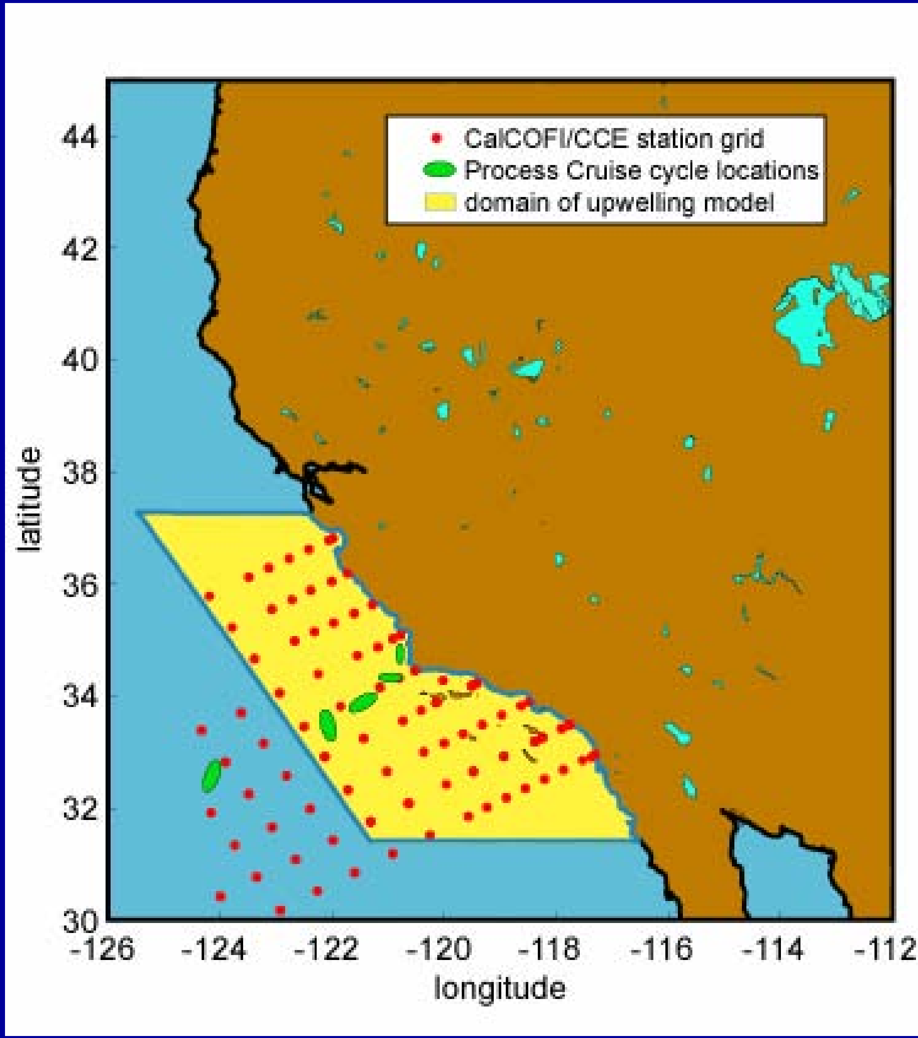
- There have been increases in both coastal and open-ocean upwelling.
- There was strong decadal variability in both upwelling mechanisms.
- Transport due to coastal and open-ocean upwelling appear vary independently.
- There was a peak in open-ocean upwelling in the mid-1970s.



Historic Upwelling Variability (1984-2004)

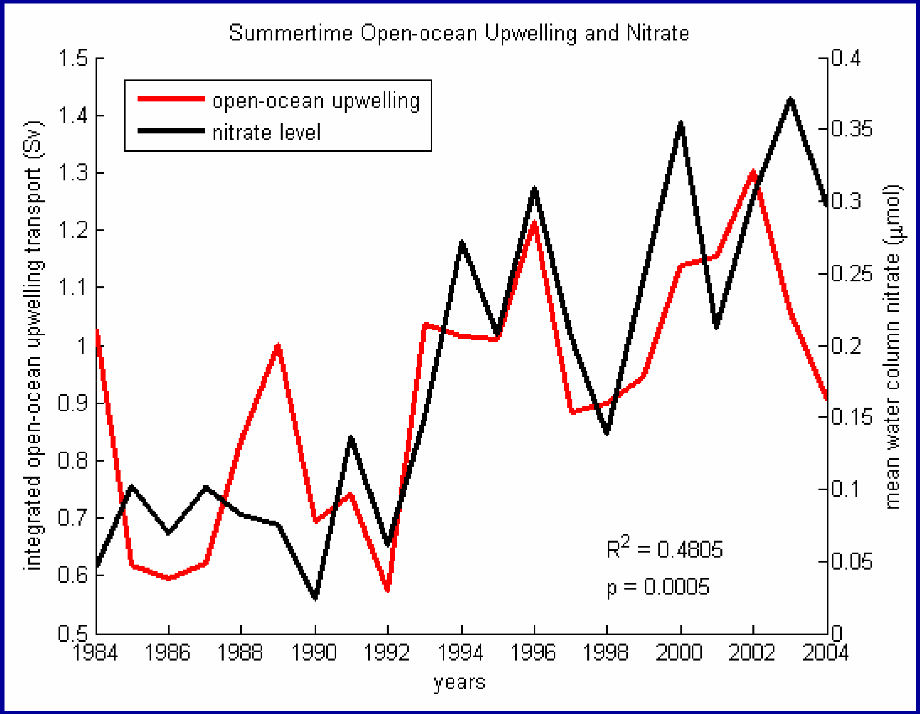
CalCOFI Nutrient and Chlorophyll Sampling (summers, 1984-2004):

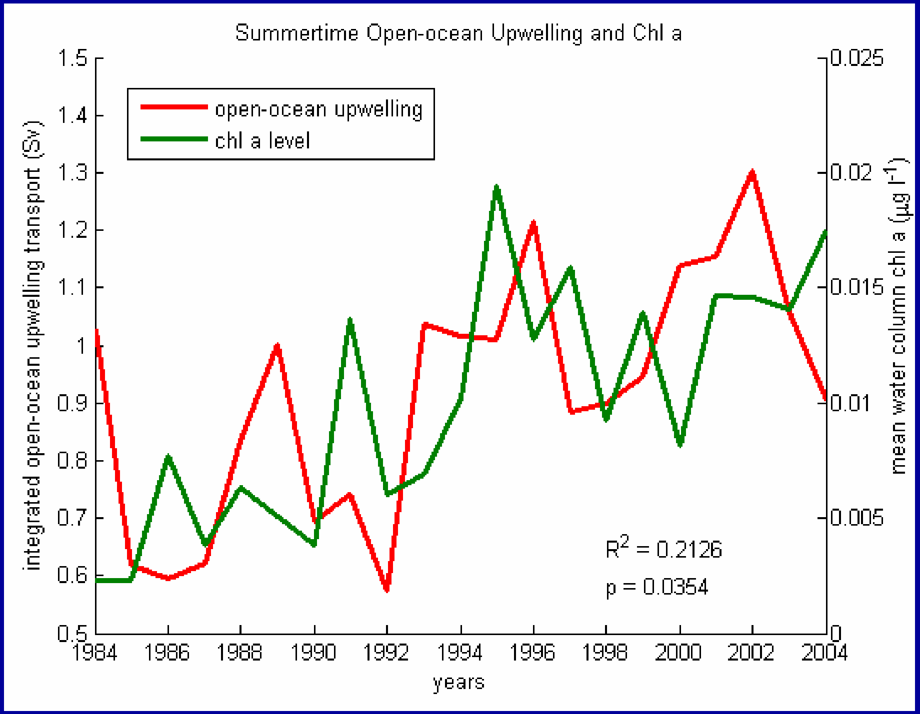
- Nitrate measurements were integrated from 50 m to 150 m
- Chl a measurements were integrated from 5 m to 150 m.



Historic Upwelling Variability (1984-2004)

- Nitrate, chl a, and open-ocean upwelling showed similar trends.
- Positive nitrate correlation was significant, even when detrended.
- Coastal upwelling was not correlated with nitrate or chl a.





when detrended: still significant no longer significant

Approach

Three steps have been taken to investigate the influence of coastal upwelling and open-ocean upwelling on the CCE:

1) relationships between upwelling rate and plankton size
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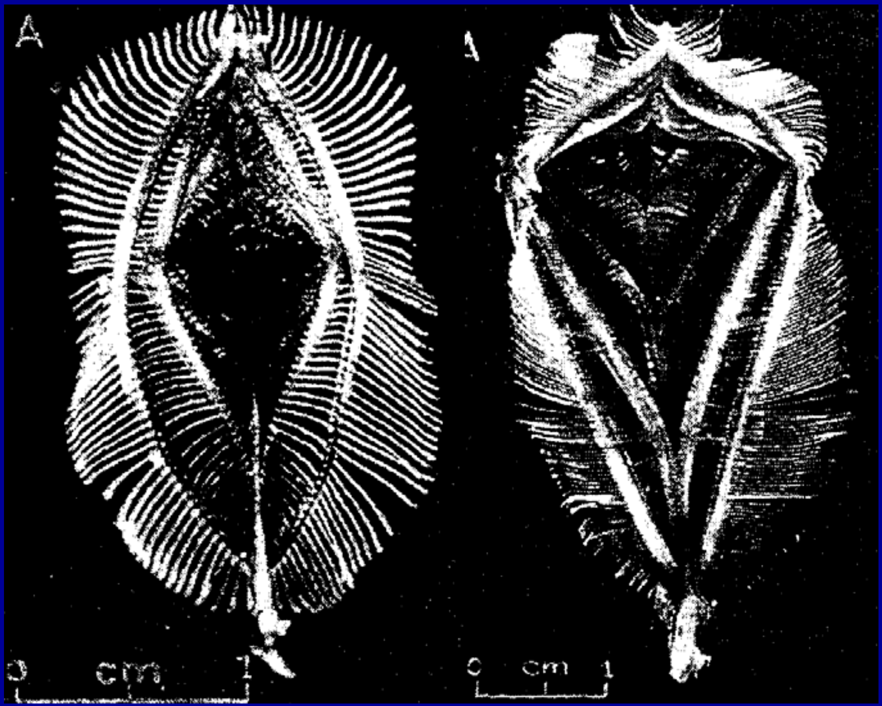
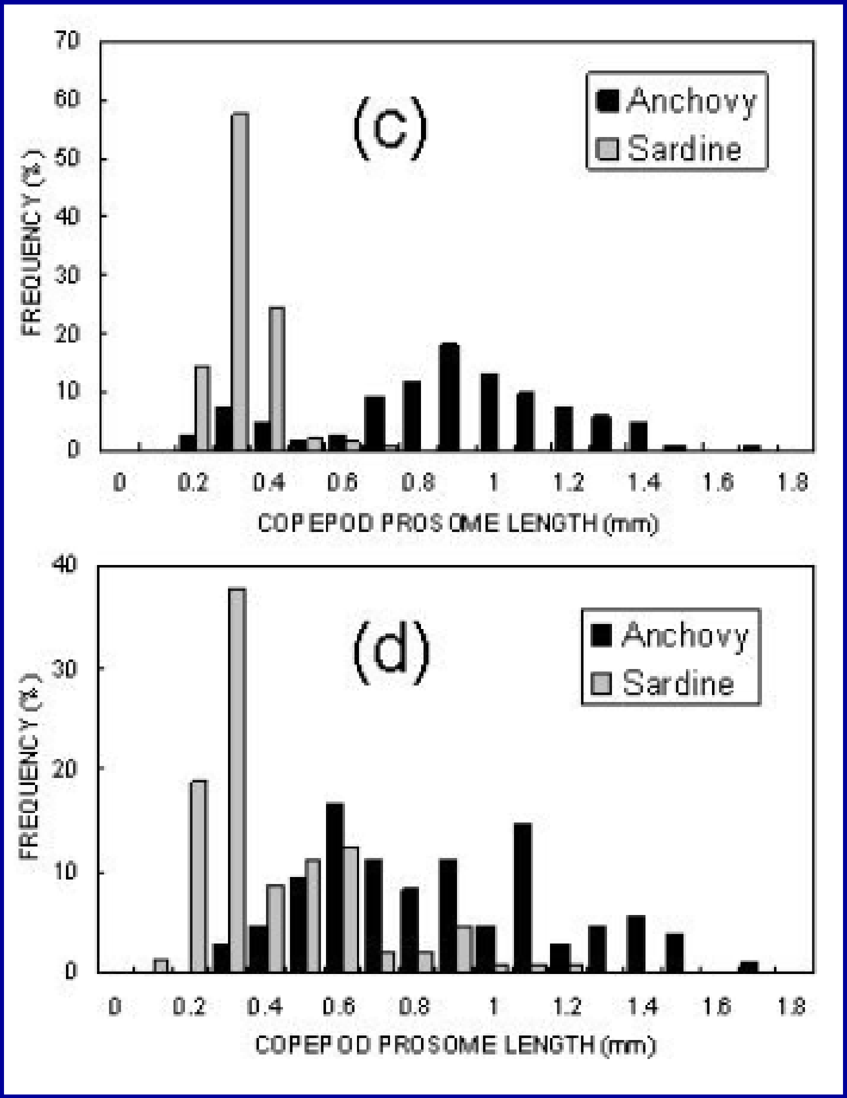
Differences between species

- Evidence (morphological and dietary) suggests that sardine prey upon small plankton and anchovy on large plankton.



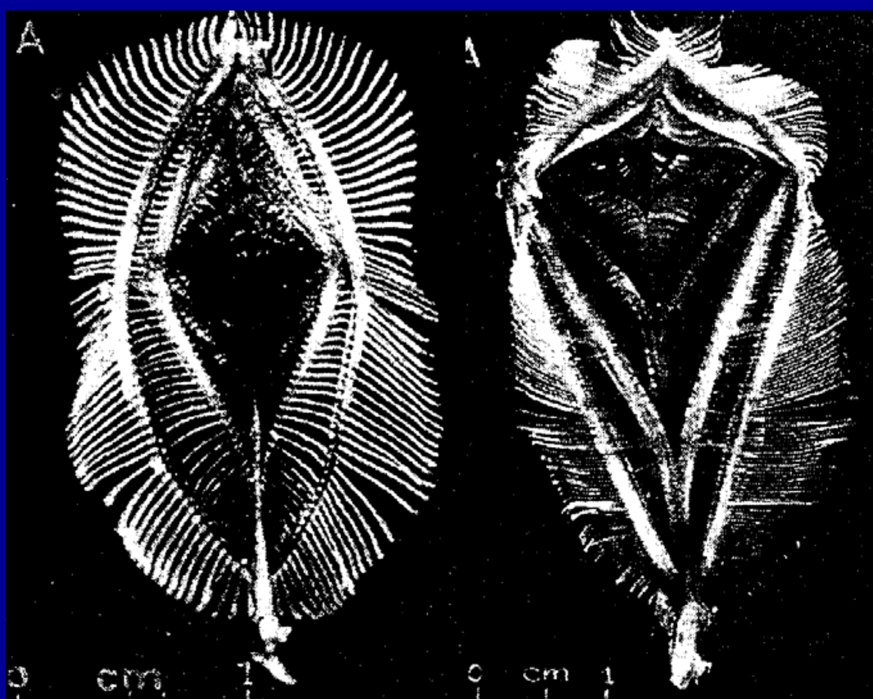
Engraulis sp. *Sardinops* sp.



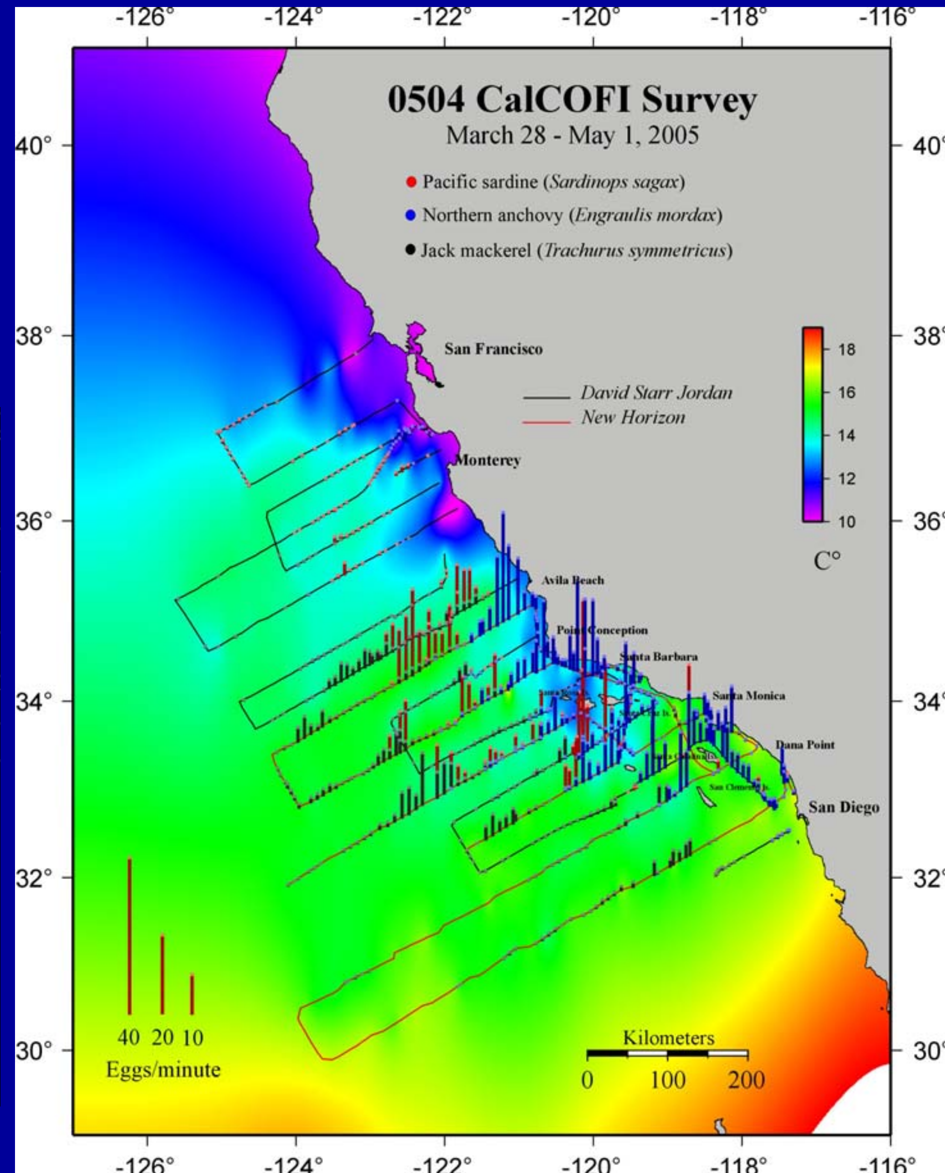
Louw et al., 1998

Differences between species

- Current evident suggests anchovy are coastal and sardine more oceanic.

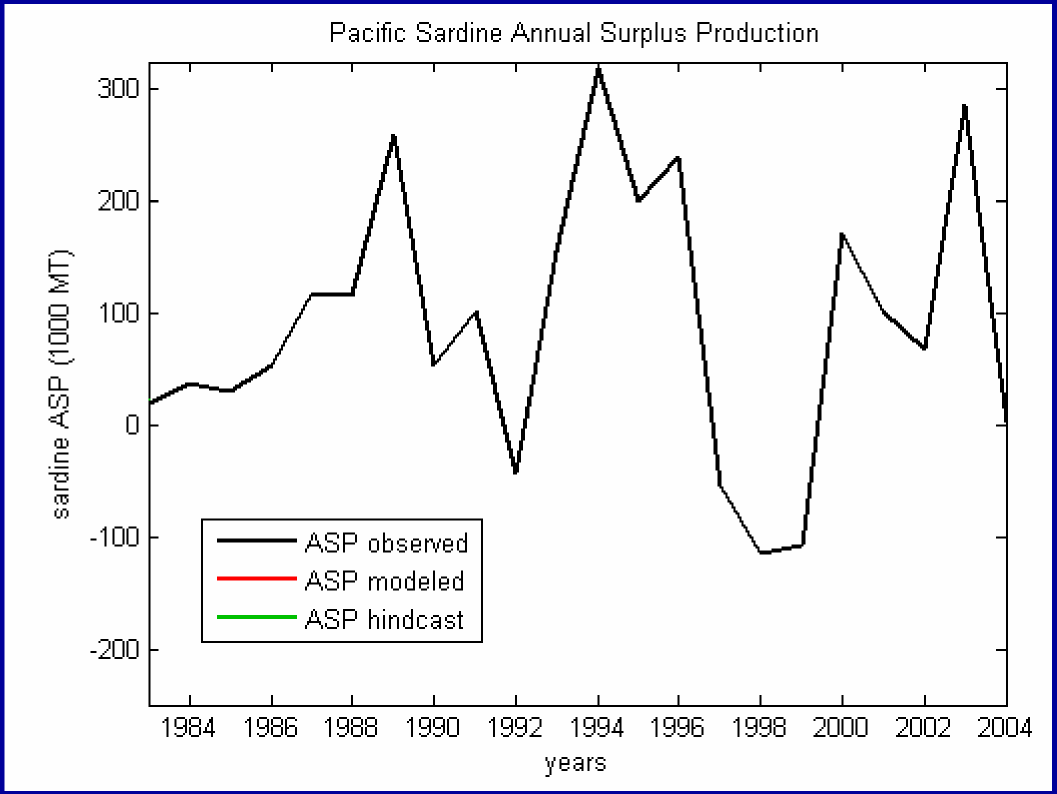


Engraulis sp. *Sardinops* sp.



Sardinops sagax stock assessment

- ASP, or annual surplus production, is the change in stock biomass from one year to the next (corrected for catch). This is chiefly a function of recruitment.
- Age-structured sardine stock assessments have been performed by NOAA (SWFSC) since 1983. Different methods were used in prior assessments (1935-1963).



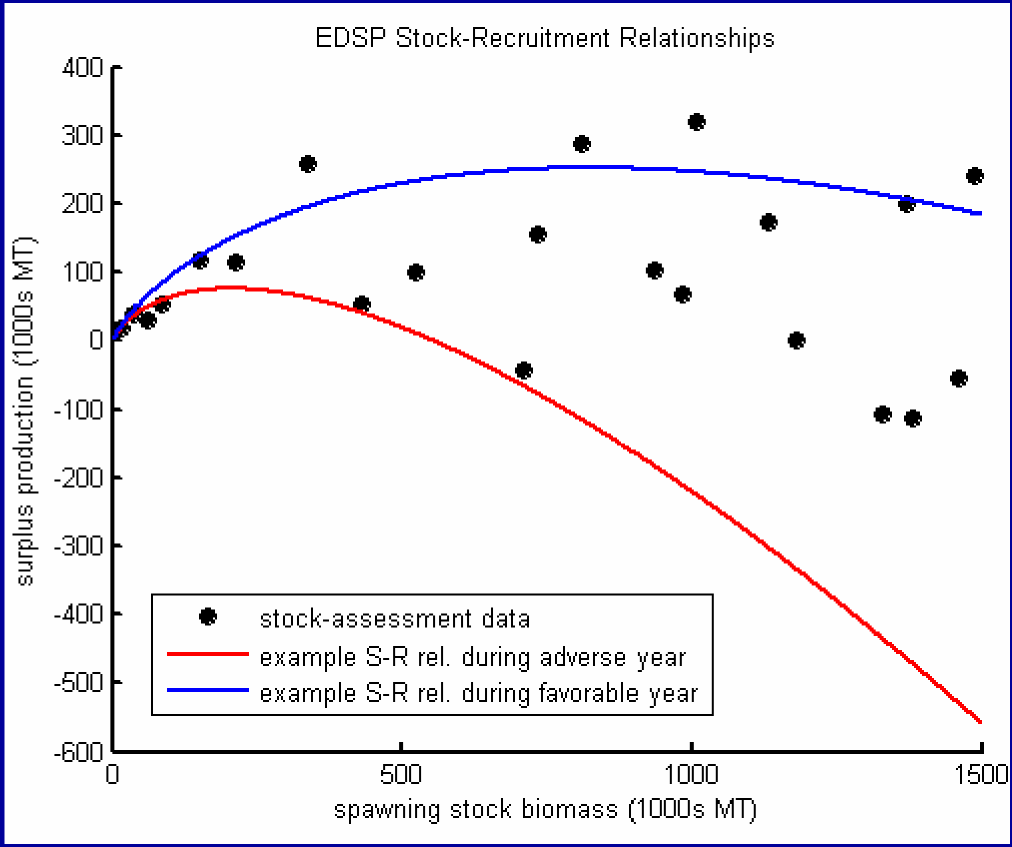
Environmentally-Dependent Surplus Production Model

An environmental factor (density-independent regulation) is included in a standard logistic stock-recruitment model (density-dependent regulation):

$$ASP_t = rB_t\left(1 - \frac{ln[B_t]}{ln[K]}\right)$$

$$K = B_{max}(E_t + \alpha)$$

r: population growth rate
B_t: stock biomass (ages 1+)
B_{max}: population carrying capacity (estimated)
K: environmental carrying capacity
E_t: environmental parameter
α: constant scaler (estimated)



Testing Performances of Simple Environmental Parameters

Environmental Index	Range	Interval	Number of Indices
upwelling block counts	-6 to 20 m day^{-1}	2 m day^{-1} increments	13 × 12 = 156
coastal upwelling transport	n/a	n/a	1 × 12 = 12
open-ocean upwelling transport	n/a	n/a	1 × 12 = 12
SST block counts	10 to 20 ºC	2 ºC increments	5 × 12 = 60
mean SST	n/a	n/a	1 × 12 = 12
			TOTAL = 252 indices

Upwelling transport by both mechanisms, area counts of upwelling ranges, mean SST (COADS), and area counts of SST ranges were tested.

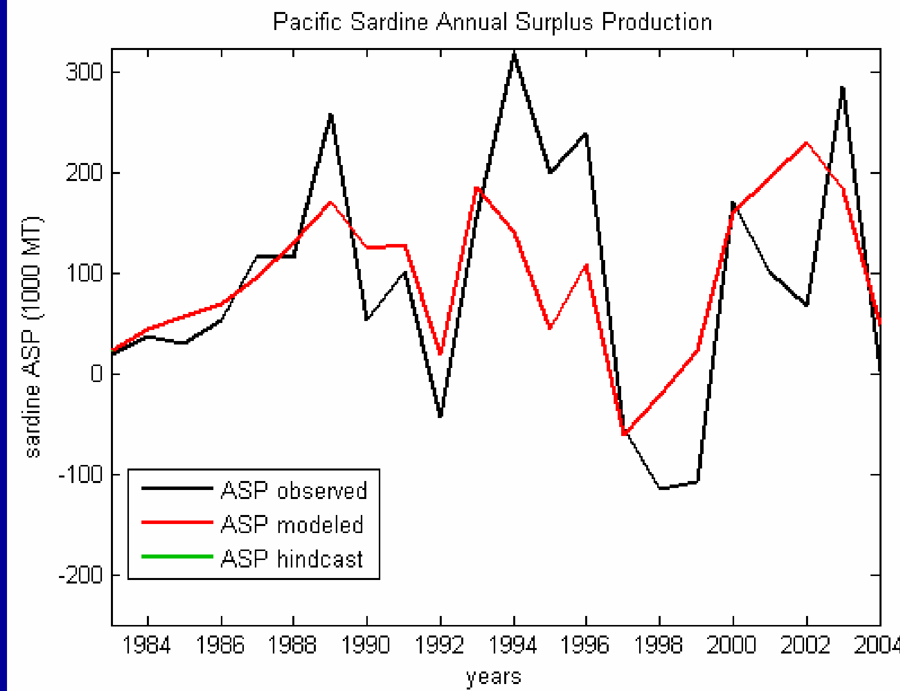
Three-month means were generated to create annual indices. Means were centered on each month of the year.

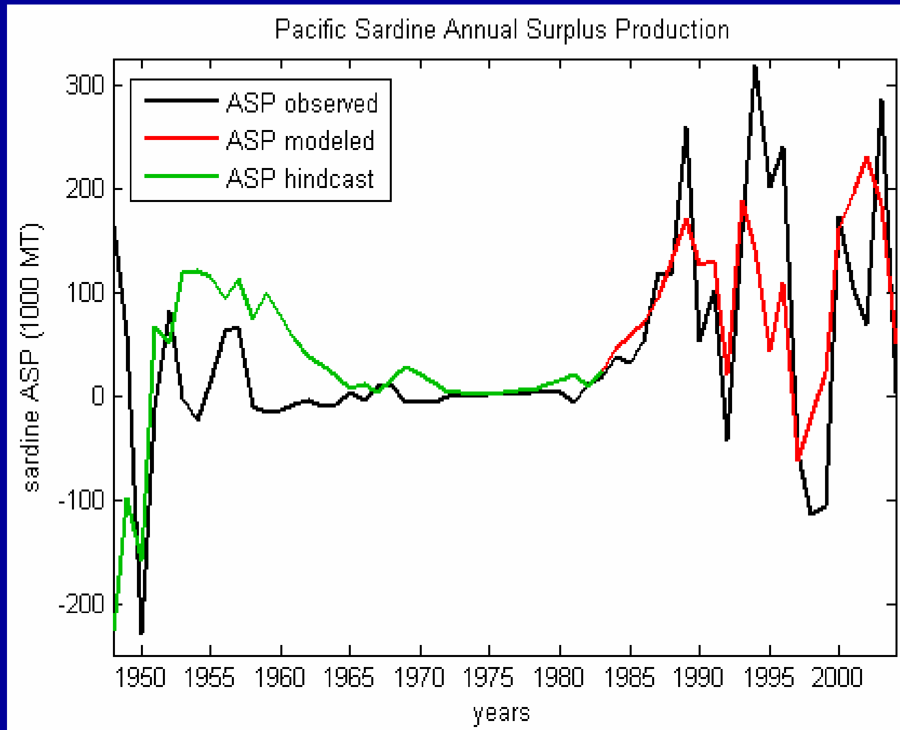
Which E_t performs best?

Tests by cross validation (1983-2004) and long-term prediction (hindcast) produced the same results:

1) open-ocean upwelling transport (June through August)
2) upwelling areas in the range of 4 to 6 m day^{-1} (June through August)

were the best performing E_t.





Summary

- Upwelling rate appears to influence the size of phytoplankton and zooplankton.
- In the CCE, the upwelling transports attributed to coastal and open-ocean upwelling appear to have varied independently, have increased since the late 1940s, and show decadal-scale variation. Open-ocean upwelling is the dominant source of nutrients to the CCE.
- Summertime nitrate measurements are positively correlated with summertime open-ocean upwelling.
- Surplus production in the *Sardinops sagax* stock may be explained by open-ocean upwelling combined in a stock-recruitment equation.

Future

- Consider what large scale climate changes influence coastal wind stress and wind-stress curl.

- Exploration in other systems. (*e.g.*, What is the importance of wind-stress curl to upwelling in the northwest and southeast Pacific?)

- Application of these biological mechanisms to future atmospheric conditions (*e.g.*, Auad et al. 2006).

- Examine higher resolution data (*e.g.,* winds, LOPC).

- Measure community structure and sizes of individual zooplankton collected from areas with different upwelling rates.

Acknowledgements

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Masao Kanamitsu supplied the downscaled NCEP atmospheric data and Ralf Goericke provided size-fractionated chl *a* data.

Thanks!