Fish diversity and corrosive water in the southern California Current System

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Effects of acidification on ichthyoplankton cannot be separated from the effects of temperature and oxygen because the variables are correlated (Alin et al. 2012).

The effects of acidification must be resolved as a multi-stressor effect of "corrosive" waters which can best be described by changes in water mass properties.

ALIN ET AL.: CCS PH AND CARBONATE SATURATION MODELS

Table 1. Best Empirical Models for pH, Aragonite Saturation, Calcite Saturation, Total Alkalinity, Dissolved Inorganic Carbon, and Carbonate Ion Concentration for the CalCOFI Sampling Region (27°N–37°N) Using Temperature, Oxygen, Salinity, and Sigma Theta as Proxy Variables[a]

Equation	Parameter[b]	VIF[c]	First Parameter Selected in Model	Variance Explained by First Parameter	Final r^2	RMSE	RMCVE	Coefficients ± SE
I	$pH^{est} = \alpha_0 + \alpha_1 (T - T_r) + \alpha_2 (O_2 - O_{2,r}) + \alpha_3 [(T - T_r) \times (O_2 - O_{2,r})]$	4.4, 3.8, 1.3	O_2	96%	0.980	0.024	0.024	$\alpha_0 = 7.758 \pm 0.001$ $\alpha_1 = 1.42 \times 10^{-2} \pm 7.4 \times 10^{-4}$ $\alpha_2 = 1.62 \times 10^{-3} \pm 2.2 \times 10^{-5}$ $\alpha_3 = 4.24 \times 10^{-5} \pm 5.2 \times 10^{-6}$

[a] Ω_{arag}, aragonite saturation; Ω_{calc}, calcite saturation; TA, total alkalinity; DIC, dissolved inorganic carbon; $[CO_3^{2-}]$, carbonate ion concentration; T, temperature; O_2, oxygen; S, salinity; σ_θ, sigma theta.
[b] $O_{2,r}$, T_r, S_r, and $\sigma_{\theta,r}$ for the calibration data set were 138.46 μmol kg^{-1}, 10.28°C, 33.889, and 26.01 kg m^{-3}, respectively.

There are two sources of corrosive water off southern and central California.

1) Seasonal upwelling

- during the spring and summer brings lower pH waters onto the shelf
- reaching depths of 40–120 m (Bograd et al. 2015)
- in some cases off Central California, reaching the surface (Feely et al. 2008).
- Coastal Upwelled Water originates from **a mixture of Pacific Subarctic and Pacific Equatorial Water.**

2) Advection

- brings **Pacific Equatorial Water** from the south
- primarily during the summer months (Meinvielle & Johnson 2013, Nam et al. 2015).

For the moment, I have ignored possible influence of Central Pacific Water.

Coastal Upwelled Water and Pacific Equatorial Water have distinct oceanographic signatures:

Upwelled waters are cool, saline, and oxygen poor, but relatively high in nutrients.

Pacific Equatorial Water is warm, saline, oxygen poor, and relatively lower in nutrients.

	Temperature	Salinity	Oxygen	Nutrients
Surface water masses (0–200 m)				
Pacific Subarctic	L	L	H	H
North Pacific Central	H	H	L	L
Coastal upwelled	L	H	L	H
Subsurface water masses (200–500)				
Equatorial Pacific	H	H	L	H

Table 2. Characteristics of the four principal water masses in the California Current System. L= low, H = high (from *Lynn and Simpson* [1987] & *Simpson* [1984]).

- The core CalCOFI sampling is mainly south of strong upwelling areas.
- Consequently we focus on Advection as the source of corrosive waters.
- We concentrated on the influence of Pacific Equatorial Water (PEW) advected from the south.

We hypothesize that:

Increasing presence of corrosive Pacific Equatorial Water affected ichthyoplankton diversity off southern California.

Our analyses used the California Cooperative Oceanic Fisheries Investigations (CalCOFI) hydrographic and ichthyoplankton data set collected since 1951, and a subset collected since 1985.

The CalCOFI data are ideal for testing this hypothesis because:

- ichthyoplankton data are collected at the same locations as physical profiles.
- methods are rigorously standardized and calibrated.
- larval fish are counted and consistently identified to species.
- effort is quantified.

Bograd et al. (2014) defined **two stations representative of core California Current (CC, 80 80) and core California Undercurrent (CU 93.3 30)**, based on properties on the 25.8 (CC) and 26.5 (CU) isopycnals.

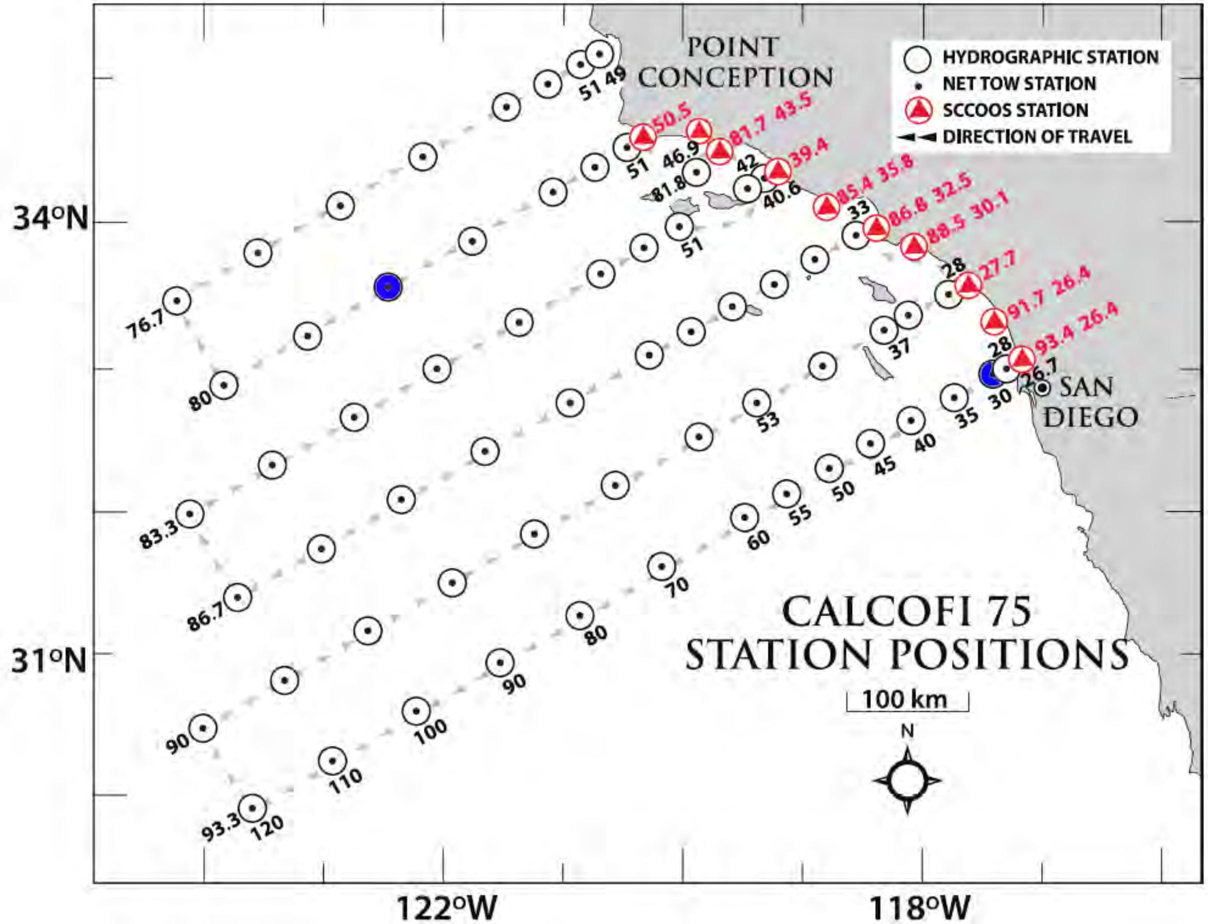


Figure 1. Map showing the "core" CalCOFI sampling domain comprising 6 lines or transects from San Diego to Avila Bay, now sampled quarterly. These stations have been sampled consistently since the beginning of the CalCOFI program except for the inshore stations (marked in red) that were added later as part of the Southern California Coastal Ocean Observing system (SCCOOS). Stations 93.3 30 and 80.0 80 used in this study are colored blue.

We pose five questions in this talk:

(1) Is there evidence of increased Pacific Equatorial Water (PEW) influence at CU (indicated by spiciness on the 26.5 isopycnal)?

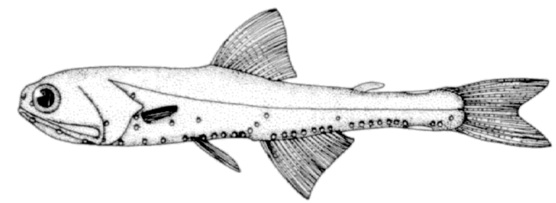
(2) Can diversity be described by the same models in periods with different PEW influence?

(3) Have species abundance patterns remained the same over time?

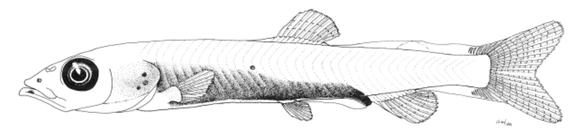
(4) How resistant to perturbations is the ichthyoplankton assemblage?

(5) How resilient is the assemblage following a major perturbation?

There are 4 numerically dominant mesopelagic fish in this study.

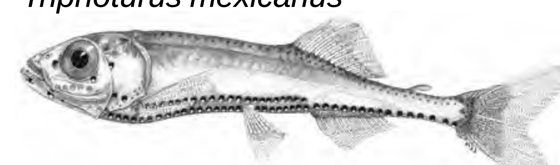


Stenobrachius leucopsaurus



Leuroglossus stilbius

Triphoturus mexicanus



Vinciguerria lucetia

Warm water associated and cool water associated mesopelagic fish species

Genus species	Common name	Subcategory
Bathylagus pacificus	slender blacksmelt	cool-water
Leuroglossus stilbius	California smoothtongue	cool-water
Lipolagus ochotensis	eared blacksmelt	cool-water
Protomyctophum crockeri	California flashlightfish	cool-water
Stenobrachius leucopsarus	northern lampfish	cool-water
Tarletonbeania crenularis	blue lanternfish	cool-water
Vinciguerria spp.	lightfishes	warm-water
Triphoturus mexicanus	Mexican lampfish	warm-water
Symbolophorus californiensis	bigfin lanternfish	warm-water
Bathylagoides wesethi	snubnose blacksmelt	warm-water
Ceratoscopelus townsendi	fangtooth lanternfish	warm-water
Diogenichthys laternatus	diogenes lanternfish	warm-water

Table 1. Mesopelagic species from CalCOFI surveys categorized as warm- or cool-water associated off southern California. *Vinciguerria* spp. includes *Vinciguerria lucetia* and *V. poweriae*

A little Methods

Larval fish time series (larvae 10 m^{-2}) obtained from counts of larvae in **oblique CalCOFI net tow samples.**

CalCOFI data are **consistent from 1951–1968, and from 1984 to the present.** However, the **intervening 14-year period (1969-1983) was only sampled triennially**, creating considerable data gaps.

Changes in **net tow depth** (140 to 210 m), **net mesh type** (silk to nylon) and **net type (**ring nets to bongo nets were made prior to 1978.

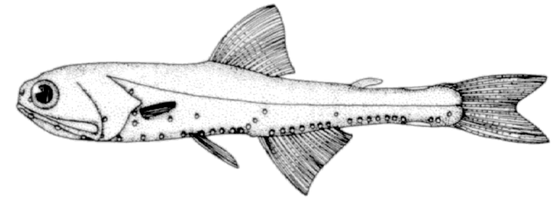
Taxonomic resolution for all species is currently consistent for all species back to 1965.

Considering the sampling changes, the taxonomic resolution, and the sampling frequency led us to focus on the 1985–2014 time interval for the full assemblage diversity analysis.

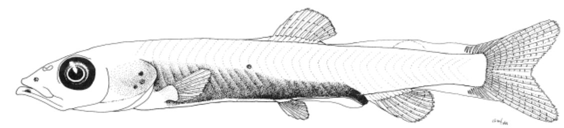
We could also do a **semi-quantitative evaluation of trends over the entire 1951–2014 time series.**

Question posed:

(1) Is there evidence of increased Pacific Equatorial Water (PEW) influence at CU (indicated by spiciness on the 26.5 isopycnal)?



Stenobrachius leucopsaurus



Leuroglossus stilbius

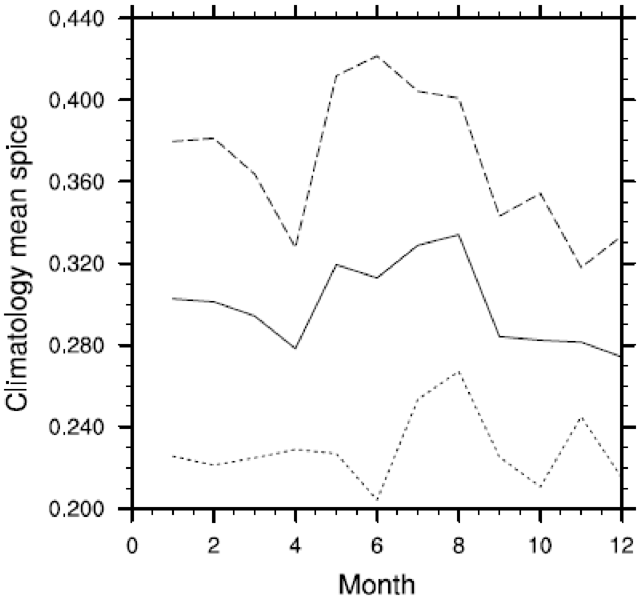
Triphoturus mexicanus

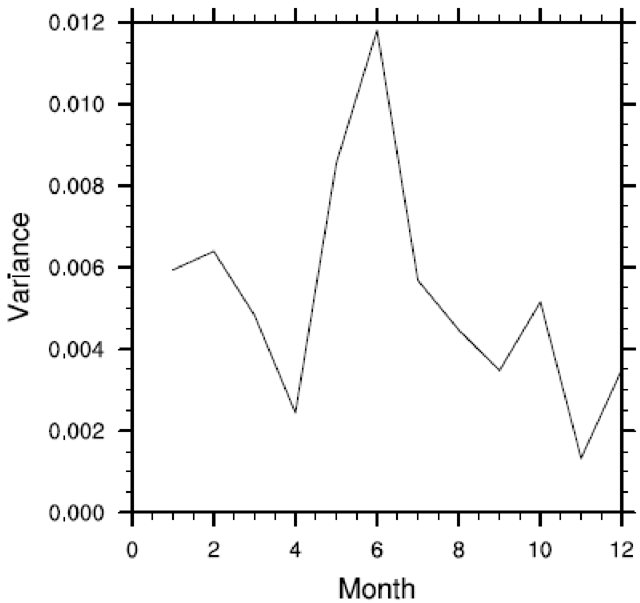
Vinciguerria lucetia

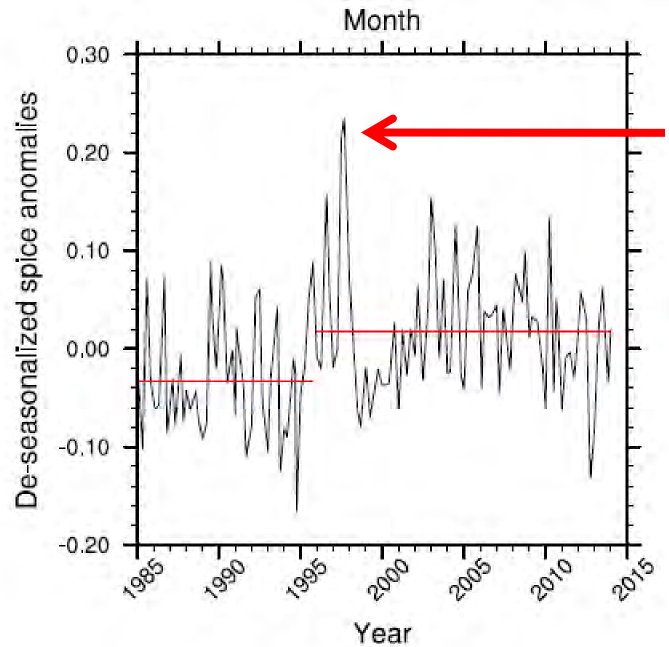
Spoiler:

2 published papers by Meinvielle and Johnson (2013) & Nam et al. (2015) already showed that the presence of Pacific Equatorial Water has increased.

Do we see any evidence of changes in the influence of Pacific Equatorial Water at the station representative of the core of the California Undercurrent (CU)?







Note highest spice during the 1997 El Niño

Evidence suggests increased mean spiciness at CU station after 1996.

Figure 2. (A) Monthly climatology of spiciness for the period 1985–2014 showing means ± one standard deviation. (B) Variance of the monthly climatology. (C) De-seasonalized anomalies of spice for 1985-2014. Red lines show average spice for two periods distinguished using Pettitt's test for change point detection ([*Pettitt*, 1979]). The break point is third quarter of 1995.

Changes in warm and cool water associated mesopelagic assemblages and their numerical dominants.

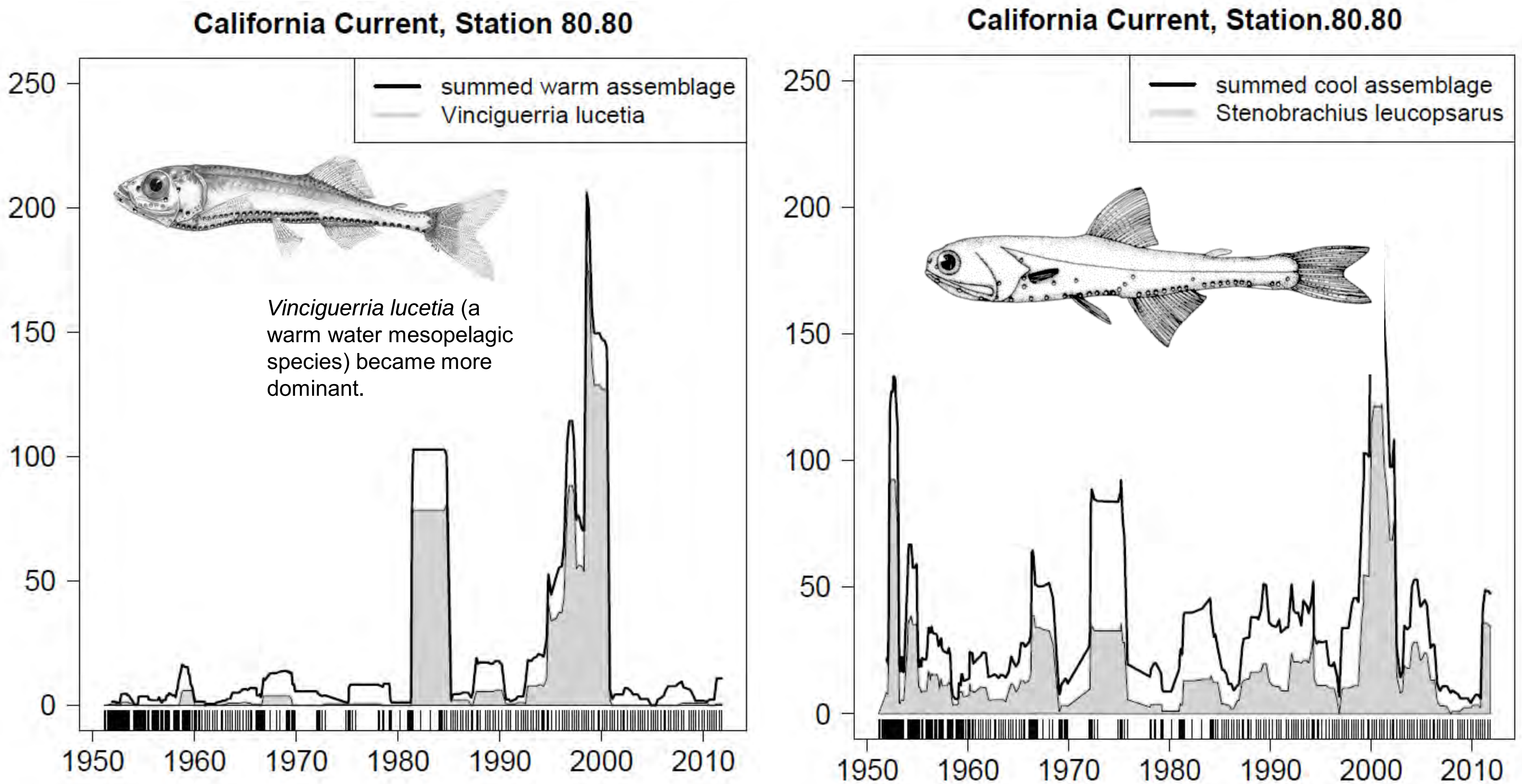
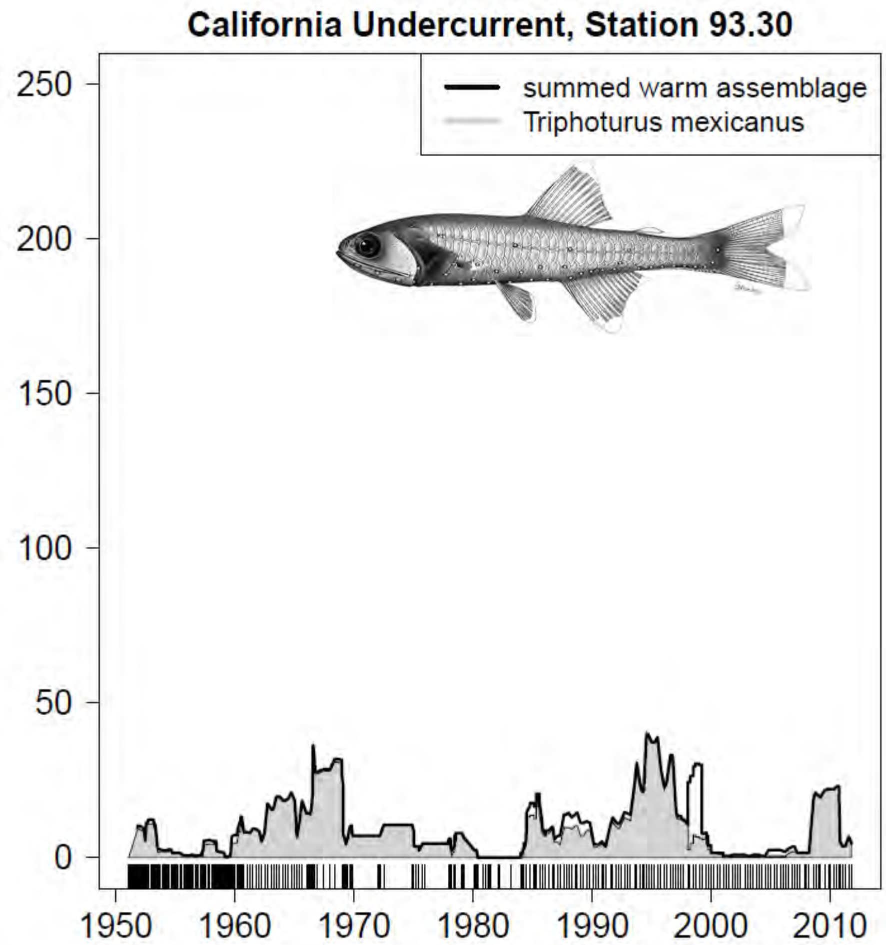


Figure 3. Time series of warm and cool water associated mesopelagic ichthyoplankton assemblage densities (larvae $10m^{-2}$) at CalCOFI station 80 80 representative of the core of the California Current. The numerically dominant species at each location (gray fill) is overlaid on total assemblage densities to illustrate differing species dominance in the assemblages.

Changes in warm and cool water associated mesopelagic assemblages and their numerical dominants.



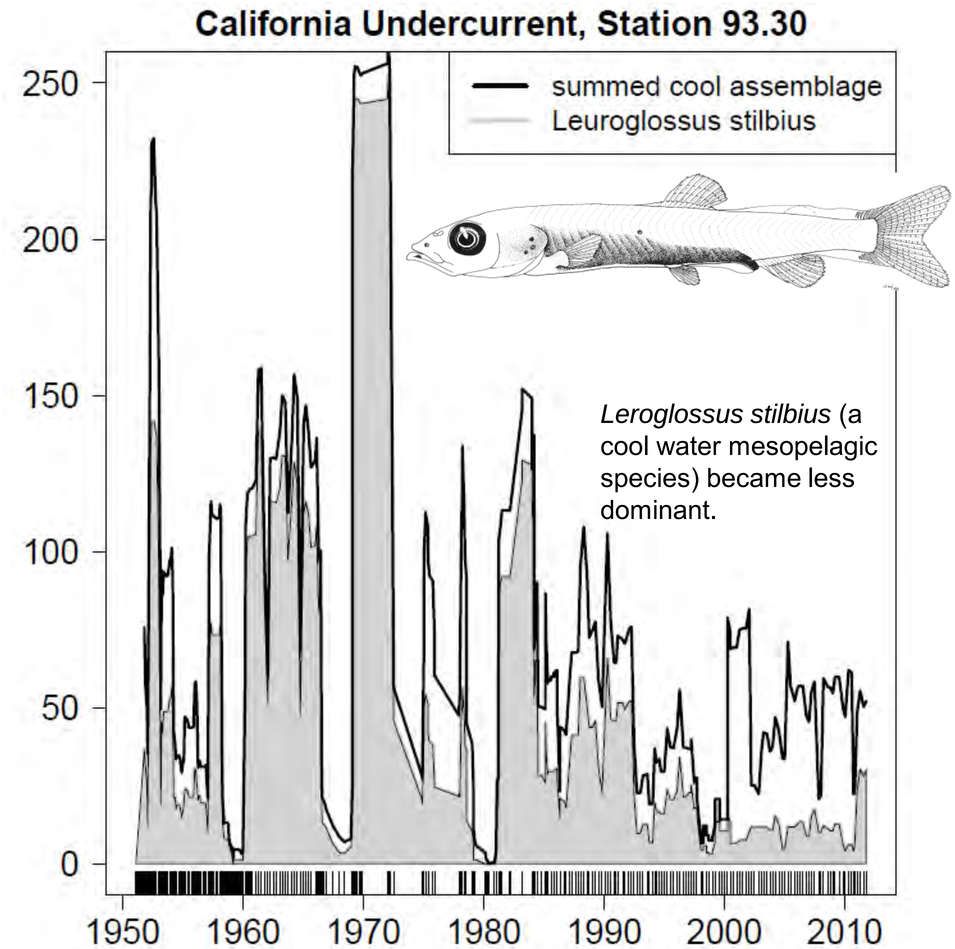


Figure 4. Time series of warm and cool water associated mesopelagic ichthyoplankton assemblage densities (larvae $10m^{-2}$) at CalCOFI station 93.3 30 representative of the core of the California Undercurrent. The numerically dominant species at each location (gray fill) is overlaid on total assemblage densities to illustrate differing species dominance in the assemblages.

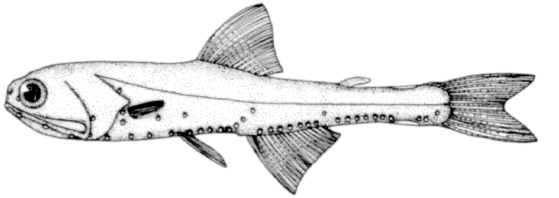
Question posed:

(2) Can species abundance be described by the same models in periods with different Pacific Equatorial Water influence?

Background:
The components of **Diversity** are:
- Species richness and
- Dominance or Evenness.

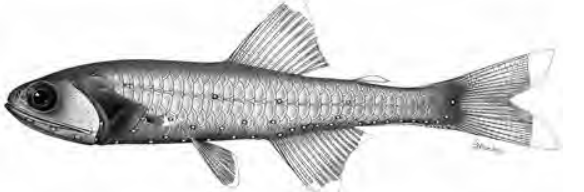
Ranked species abundance curves are a simple way to describe both these components.

In many cases a log or log normal model can be fit to these curves, but **various models**, with or without theoretical justification may provide a better fit to species abundance patterns.

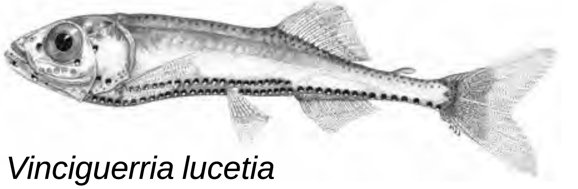


Stenobrachius leucopsaurus

Leuroglossus stilbius



Triphoturus mexicanus



Vinciguerria lucetia

Does the same model fit species abundance patterns in both time periods at CC and CU stations? (using all species, not just mesopelagics)

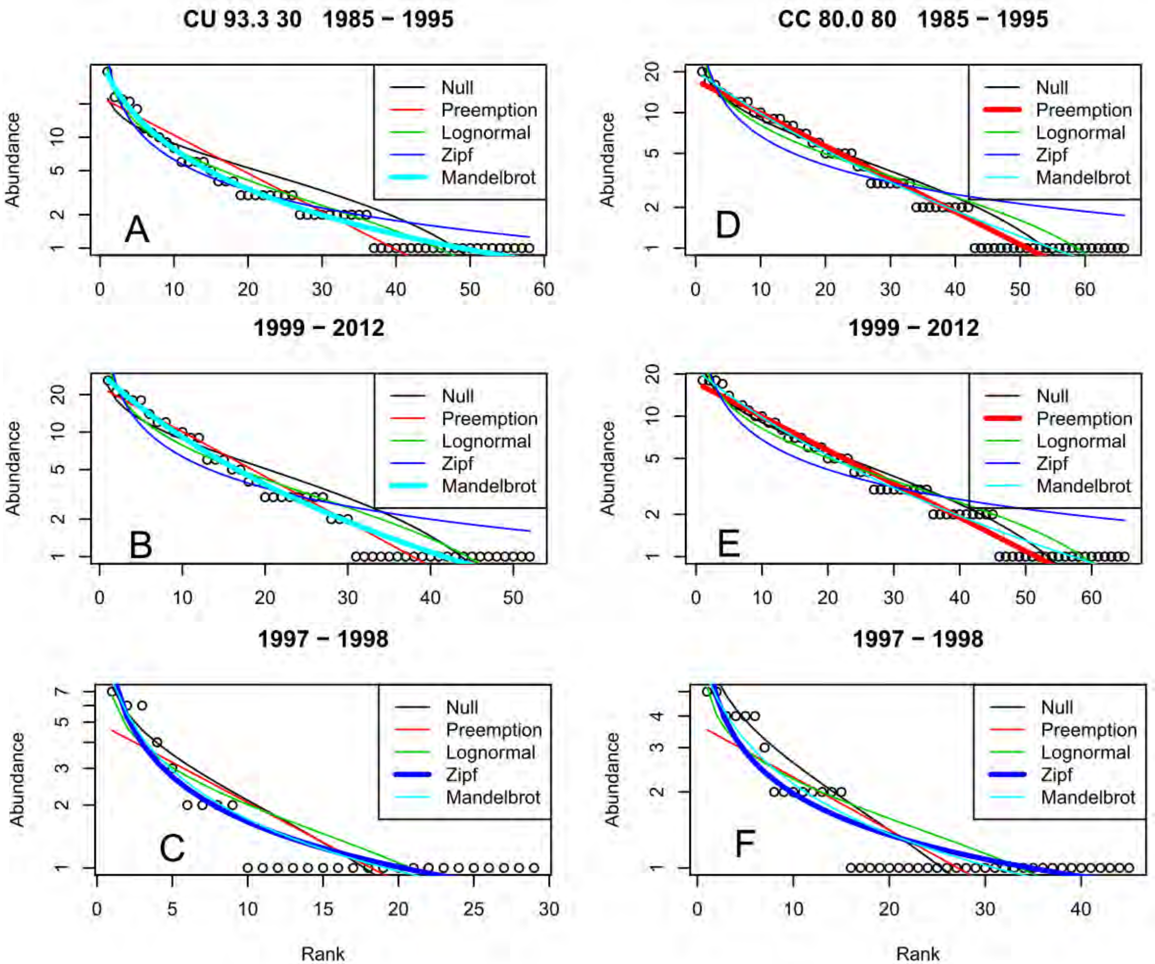


Figure 6. Species rank/ abundance plots for the ichthyoplankton assemblage in three time periods: (A & D) 1985–1995, (B & E) 1999–2012, and (C & F) 1997-1998 at CalCOFI station 93.3 30 representative of the California Undercurrent in the left column, and station 80.0 80 representative of the California Current in the right column. Lines show model fits to data.

Best fit to California Undercurrent (CU) data (A & B) was the Mandelbrot model:

$$\hat{a}_r = Nc(r + \beta)^\gamma$$

Best fit to California Current (CC) data (D & E) was the Preemption model:

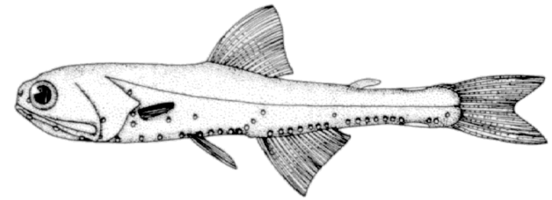
$$\hat{a}_r = N\alpha(1 - \alpha)^{r-1}$$

Best fit to 1997/98 El Niño data (D & E) at both the California Undercurrent and California Current stations was the Zipf model:

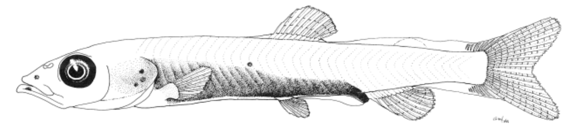
$$\hat{a}_r = N\hat{p}_1 r^\gamma$$

Question posed:

(3) Have species abundance patterns remained the same over time?



Stenobrachius leucopsaurus



Leuroglossus stilbius

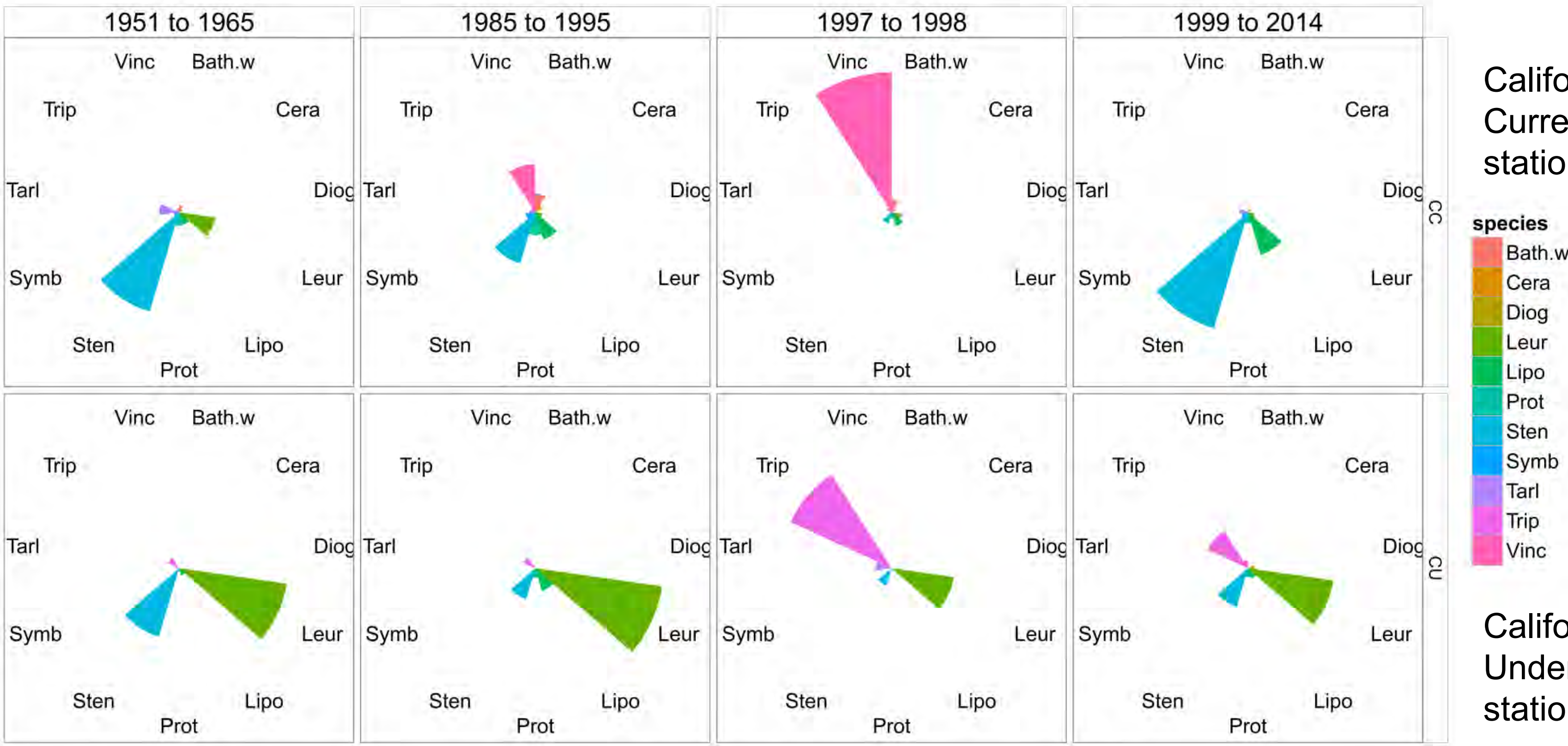
Triphoturus mexicanus

Vinciguerria lucetia

Used three types of multivariate tests: Redundancy Analysis, Constrained Correspondence Analysis, Adonis

Evaluated each season and station separately

Species dominance has changed over time on both the decadal scale and during the 1997/99 ENSO event (showing only warm and cool mesopelagics)



California Current station

California Undercurrent station

Which species are driving differences between decades? (using all species)

Example: **Station 80 80, spring**

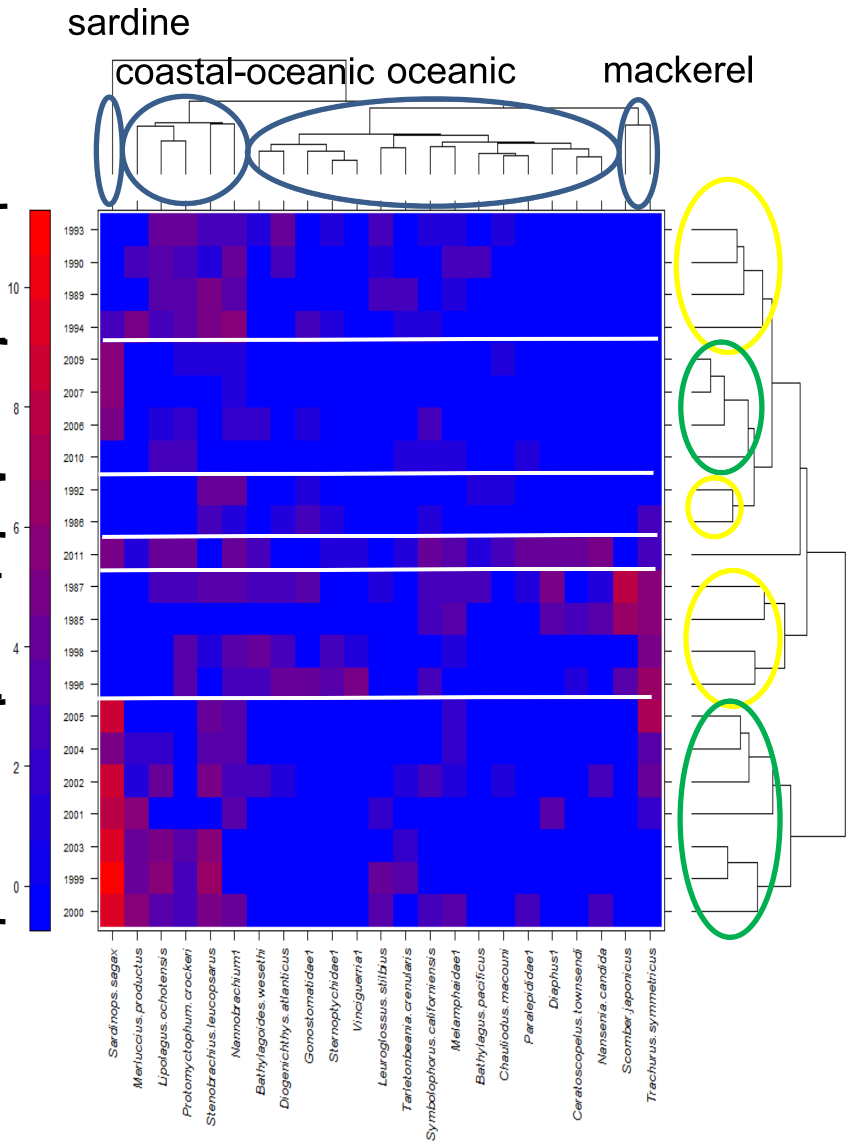
1989, 1990, 1993, 1994:
no sardine, coastal-oceanic, oceanic

2006, 2007, 2009, 2010:
sardine, coastal-oceanic

1986, 1992:
coastal-oceanic, oceanic

1985, 1987, 1996
no sardine, oceanic, mackerel

1999, 2000, 2001, 2002, 2003, 2004, 2005
sardine, coastal-oceanic



How do the species groups (e.g. oceanic, coastal-oceanic) and species change between decades at the California Current (st. 80 80) and California Undercurrent (st. 93.3 30) station? (using all species)

St. 80.0 80	p-value rda	p-value cca	p-value adonis	adj. R^2	If significant, which species are important drivers?	Does El Nino/La Nina stand out?
winter	0.15	0.21	0.63	0.02	NA	no
spring	0.005	0.005	0.001	0.27	more oceanic in early period, coastal-oceanic in late period	somewhat - more oceanic species in 1998
summer	0.02	0.06	0.02	0.10	more sardine in later period	somewhat - more *Vinciguerria* in 1998
fall	0.031	0.06	0.02	0.18	more oceanic species in early period	yes- more oceanic species such as *Idiacanthus, Bathylagoides wesethi*, and *Diogenichthys atlanticus* in both 1997 and 1998

St. 93.3 30	p-value rda	p-value cca	p-value adonis	adj. R^2	If significant, which species are important drivers?	Does El Nino/La Nina stand out?
winter	0.005	0.15	0.01	0.16	more anchovies in early period	yes - *Diogenichthys laternatus* and *Vinciguerria* abundant in winter 1998
spring	0.02	0.17	0.25	0.06	NA	somewhat - more *Triphoturus mexicanus* in 1998
summer	0.37	0.72	0.27	0.004	NA	no
fall	0.13	0.06	0.07	0.10	NA	no

Questions posed:

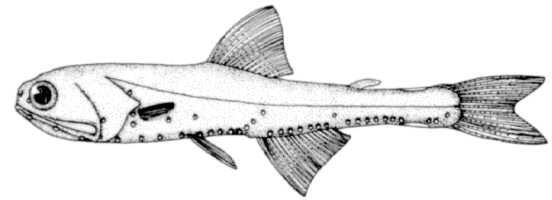
(4) How resistant to perturbations is the ichthyoplankton assemblage?

Where the perturbations are:

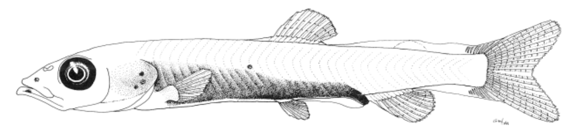
• increasing presence of Pacific Equatorial Waters (higher mean spiciness)

• the extreme 1997/99 ENSO event (highest peak in spiciness)

(5) How resilient is the assemblage following a major perturbation?



Stenobrachius leucopsaurus

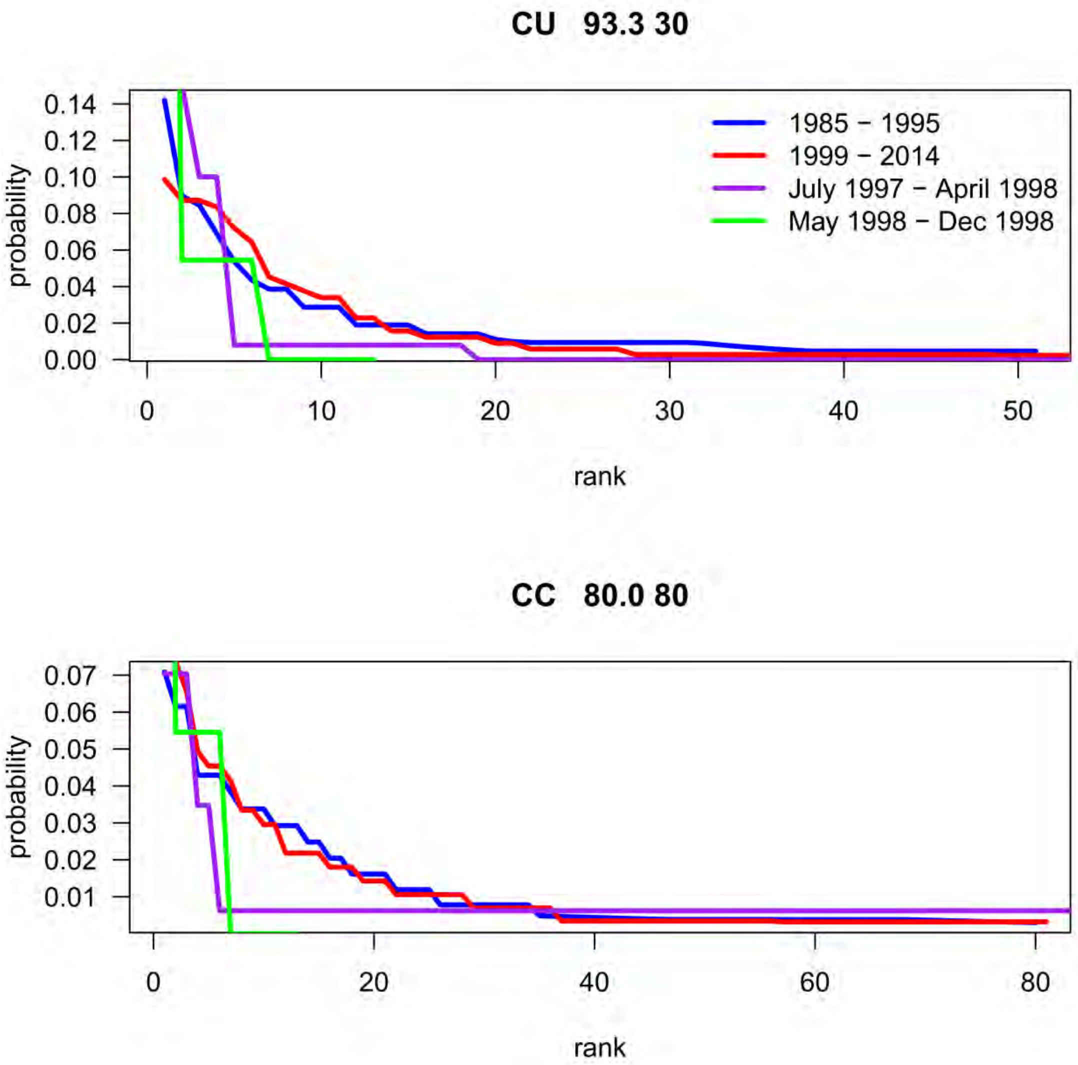


Leuroglossus stilbius

Triphoturus mexicanus

Vinciguerria lucetia

Are species abundance patterns the same over time? (using all species)



Kolmogorov-Smirnov test shows **no differences between 1985-1995 (blue) and 1999 – 2012 (red)** distributions at either the California Undercurrent (CU) or the California Current (CC) station.

K-S test shows **significant difference between 1985-1995 (blue) and both 1997/98 El Niño and 1998 La Niña** at both the California Undercurrent (CU) and the California Current (CC) station.

Figure 7. Species rank/ abundance plots for the ichthyoplankton assemblage in two time periods (1985–1995, and 1996–2012) at (A) CalCOFI station 93.3 30 representative of the California Undercurrent and (B) station 80.0 80 representative of the California Current. Lines show model best fits to data from Figure 6.

So **what is the prognosis for the coming El Niño** on the ichthyoplankton assemblage off Southern California?

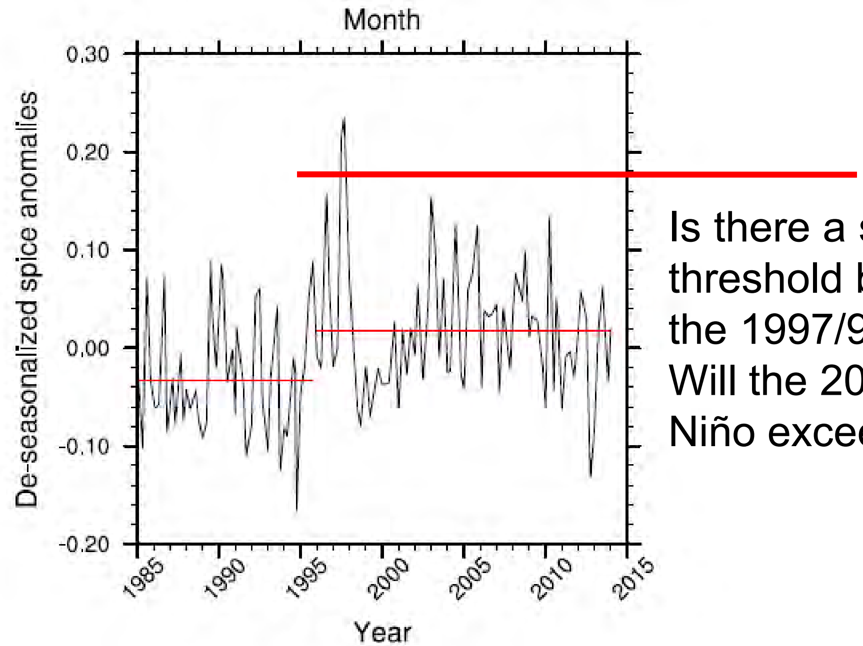
If the event is extreme like the Eastern Pacific El Niño of 1997/98 we can expect to see lower diversity, meaning:

- reduced species richness
- increased dominance (i.e. reduced evenness)

increased abundance of some species, like the warm water oceanic species *Vinciguerria lucetia.*

But

- the assemblage will likely exhibit resilience, reverting back to its former species abundance pattern.



Is there a spiciness threshold based on the 1997/98 El Niño? Will the 2015/2016 El Niño exceed it?

Conclusions:

1) Different models provided best fit to species abundance distributions at CC, CU and during an extreme ENSO event **indicating heterogeneous diversity in both space and time.**

2) Diversity did not change as the mean spiciness increased after 1996 at CU, suggesting that **assemblages are resistant to this much presence of "corrosive" Pacific Equatorial Water**.

3) The major perturbation of the ichthyoplankton assemblages was the extreme 1997/99 ENSO event associated with maximum spiciness. **This suggest a spiciness threshold for impact of "corrosive" Pacific Equatorial Water**.

4) While species abundance patterns shifted markedly during the 1997/99 ENSO event, they recovered to their original diversity, **indicating resilience following an extreme ENSO**.

5) **Despite evidence of resistance to corrosive waters except during an extreme ENSO and resilience following an extreme ENSO, species groups and species dominance have changed on decadal scales** in different ways, with different seasonality at the two locations, indicating the need for detailed spatial analyses.

Questions?