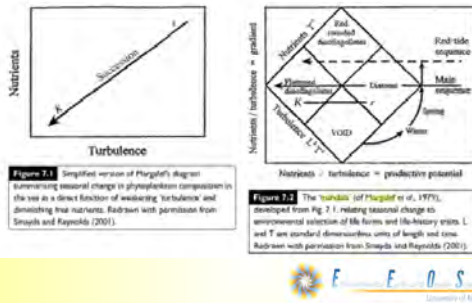


<div data-bbox="250 249 764 430" data-label="Section-Header"> <p>1) The role of turbulence & Nutrients in controlling phytoplankton production along an inshore-offshore gradient: Lasker's Stable-Ocean Hypothesis</p> <p>2) El Niño & PDO</p> </div> <div data-bbox="341 436 660 466" data-label="Text"> <p>Class 25, Tu 2 December 2008</p> </div> <div data-bbox="531 497 786 541" data-label="Image"> </div>	<div data-bbox="815 132 1362 323" data-label="Section-Header"> <p>Slide 1 1) The role of turbulence & Nutrients in controlling phytoplankton production along an inshore-offshore gradient: Lasker's Stable-Ocean Hypothesis</p> </div> <div data-bbox="815 344 1066 382" data-label="Text"> <p>2) El Niño & PDO</p> </div> <div data-bbox="815 466 940 501" data-label="Text"> <p>NOTES:</p> </div>
<div data-bbox="293 806 734 844" data-label="Section-Header"> <p>Remaining Lecture Schedule</p> </div> <div data-bbox="233 869 764 1150" data-label="List-Group"> <ul style="list-style-type: none"> • Class 25, 12/2/08 Tu <ul style="list-style-type: none"> • El Niño, La Niña, PDO • Gyre production and the solution to the great debate over gyre productivity • Topics for study questions emailed to class • Class 26, 12/4/08 <ul style="list-style-type: none"> • Final exam questions handed out • Satellite Remote Sensing • Class 27, 12/9/08 <ul style="list-style-type: none"> • Microbial processes • Class 28, 12/11/08 <ul style="list-style-type: none"> • Final Class, Zooplankton Vertical migration game • Final Exam, 9 am - Noon 12/15 Monday <ul style="list-style-type: none"> • 3 hour closed book • UMB in classroom, Amherst & Lowell: pdf will be mailed to proctors • Term papers (5-10 pages double spaced) due 12/22 by email (or earlier) </div>	<div data-bbox="815 770 1333 810" data-label="Section-Header"> <p>Slide 2 Remaining Lecture Schedule</p> </div> <div data-bbox="815 892 940 928" data-label="Text"> <p>NOTES:</p> </div>
<div data-bbox="336 1291 686 1331" data-label="Section-Header"> <p>Study Question Topics</p> </div> <div data-bbox="233 1358 764 1610" data-label="List-Group"> <ul style="list-style-type: none"> • Benthic Community Structure & OCS oil exploration <ul style="list-style-type: none"> • Describe the patterns of benthic community structure on the outer continental shelf of your choice (North Sea, Gulf of Mexico, California, Georges Bank). Either describe the observed effects of outer continental shelf oil exploration on these ecosystems or methods that could be used to assess the effects of OCS oil exploration. • Matlab option: Analysis of patterns of Georges Bank community structure (would have to be done over January break) using Matlab. • Updated pollution handout coming with references on each OCS area • 2) Primary production <ul style="list-style-type: none"> • What is the geritol solution to global warming and might it work? • 3) Upwelling & Zooplankton <ul style="list-style-type: none"> • How do ENSO, NAO and PDO affect patterns of primary and secondary production? Choose either ONE NAO effects in the Gulf of Maine or PDO effects off the West Coast and central Gyre </div> <div data-bbox="531 1621 786 1665" data-label="Image"> </div>	<div data-bbox="815 1260 1245 1297" data-label="Section-Header"> <p>Slide 3 Study Question Topics</p> </div> <div data-bbox="815 1379 940 1415" data-label="Text"> <p>NOTES:</p> </div>

Margalef's Mandala & Turbulence

Margalef (1979) modified by Smauda & Reynolds (2001)



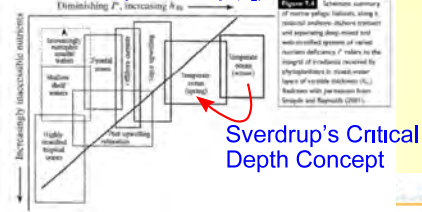
Slide 4 Margalef's Mandala & Turbulence

NOTES:

Phytoplankton habitats along an inshore-offshore mixing & nutrient gradient

From Reynolds (2006), Smayda & Reynolds (2001)

Vertical Eddy Diffusivity (k_z)

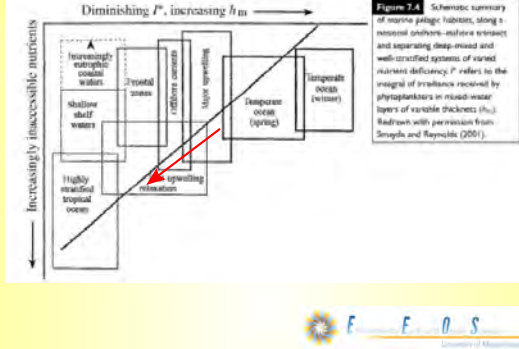


Slide 5 Phytoplankton habitats along an inshore-offshore mixing & nutrient gradient

NOTES:

Vertical Eddy Diffusivity (k_z)

Diminishing P^* , increasing $h_m \longrightarrow$

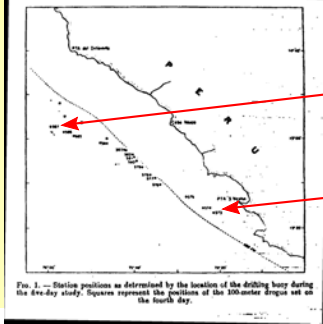


Slide 6

NOTES:

Ryther's sampling protocol

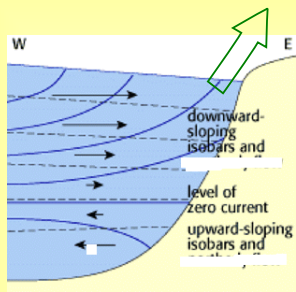
5 days of sampling with a parachute drogue



Slide 7 Ryther's sampling protocol

NOTES:

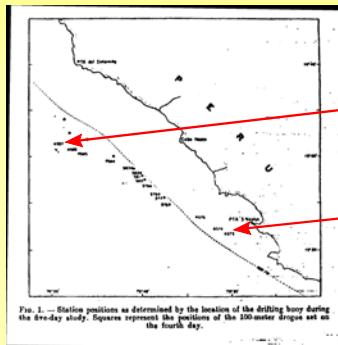
Coastal Upwelling off Peru



The barotropic & baroclinic pressure gradients produce geostrophic surface & subsurface currents

Slide 8 Coastal Upwelling off Peru

NOTES:



End, Day 5

Start

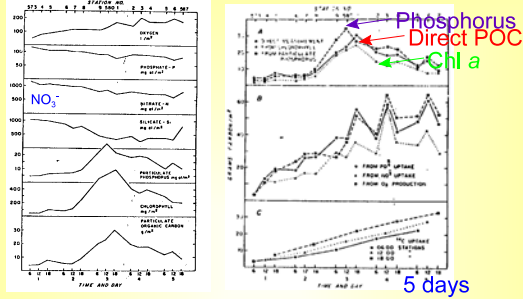
Slide 9

NOTES:

Slide 10 Production very high

Production very high

10 gC m⁻² d⁻¹; Redfield ratio and C:Chl a of 35 assumed



NOTES:

Slide 11 Conclusions: Ryther et al. (1971)

Conclusions: Ryther et al. (1971)

Grazing implicated to account for decrease in biomass after day 3 – Could it be sinking?

- Phytoplankton species succession
 - *Chaetoceros debilis*, a diatom, most abundant species
 - Rapid replacement by *Chaetoceros socialis*
 - 9 species described
- Phytoplankton standing stock peaked at 3 days returned to low levels after 5 days
- Highest production measured in the ocean at that time
 - 3-11 g C m⁻² d⁻¹ production (Avg=10 g C m⁻² d⁻¹)
- Phytoplankton population ultimately controlled by grazing (or sinking)

NOTES:

Production at upwelling centers

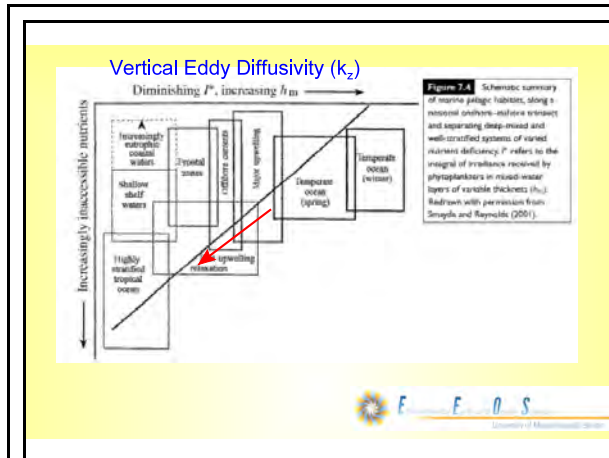
MacIsaac et al.'s 4-stage succession (8-10 d period, 30-60 km advection from upwelling center)

- Stage I: Seeding the water mass
 - High DIN, low temperature
 - High mixing (low average light intensity)
 - Seeding of the water mass stochastic
- Stage II: Shift up
 - P vs. I parameters (α and assimilation no.) adjust to new light regime
 - High nutrient uptake
- Stage III: Zone of peak growth, day 3 in Ryther et al. 1971
 - Zone of rapid successional change
- Stage IV: Shift down, Day 5 in Ryther
 - Nutrient depletion OR grazing

Note: Many of these changes in P vs. I and nutrient uptake characteristics may be associated phytoplankton succession

Slide 12 Production at upwelling centers

NOTES:



Slide 13

NOTES:

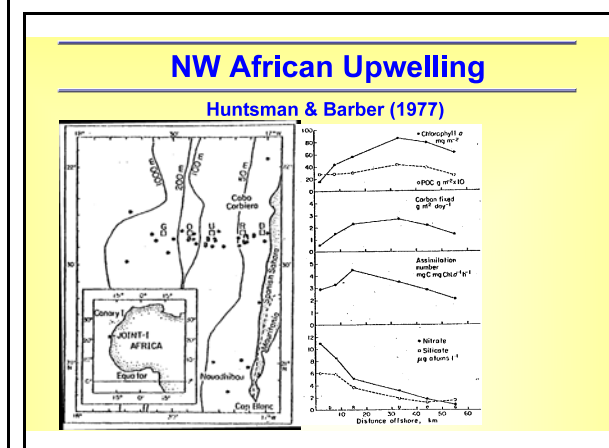
Critical depth and upwelling:

Huntsman & Barber (1977), discussed in Mann & Lazler

- Northwest African Upwelling
- High production is inversely correlated with upwelling favorable winds!
- Sverdrup's critical depth is key.
- Phytoplankton light-limited under high winds and vertical mixing regimes (wind speed $> 10 \text{ m s}^{-1}$).
 - Phytoplankton adjust the assimilation number in response to higher average light intensities
 - With mixing, no shade acclimation observed between shallow & deep phytoplankton samples
- Blooms occur after stratification events

Slide 14 Critical depth and upwelling:

NOTES:



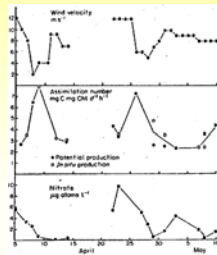
Slide 15 NW African Upwelling

NOTES:

NW African Upwelling

Primary productivity **inversely** correlated with upwelling-favorable winds Huntsman & Barber (1977)

- With wind velocities over 10 m s^{-1} , phytoplankton are mixed so deep that they are light-limited
 - The mixed layer depth exceeds the critical depth
- When upwelling-favorable winds die down
 - Water column warms & stratifies
 - Assimilation number increases
 - Nitrate uptake at high rate
- Sverdrup's critical depth concept applies



Slide 16 NW African Upwelling

NOTES:

Lasker's stable-ocean hypothesis

Species composition & non-steady state conditions key

- Why is there large year-to-year variability in Northern anchovy standing stocks off California?
- Are the 1st feeding larvae food limited?
 - Lasker took first-feeding larvae on-board ship
 - They starved except in water from the subsurface Chl a maximum (SSCM)
 - The SSCM dominated by 40- μm *Gymnodinium splendens*
- A period of stable water required after intense upwelling
 - Huntsman & Barber (1977) found that Chl a concentrations and production were inversely related to upwelling winds.
- During El Niño years, the water column is stable, but production is drastically reduced and first-feeding larvae starve

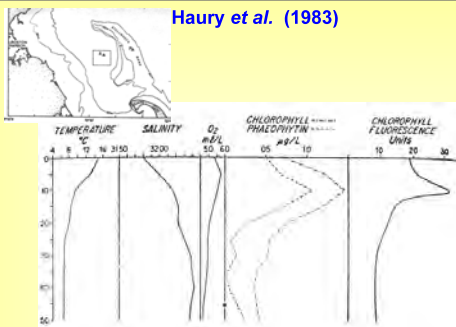


Slide 17 Lasker's stable-ocean hypothesis

NOTES:

MA Bay subsurface Chl a maxima

Haury *et al.* (1983)



Slide 18 MA Bay subsurface Chl a maxima

NOTES:

El Niño, La Niña & PDO

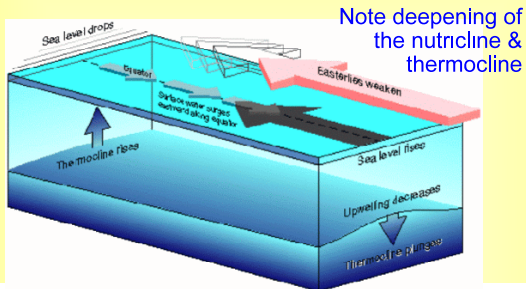


Slide 19 El Niño, La Niña & PDO

NOTES:

El Niño: warmer water than usual near Peruvian coast

Weakened easterly winds, and reduced SST gradient.

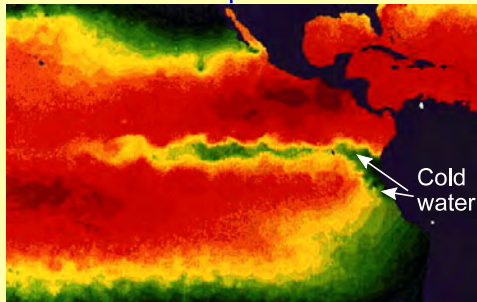


Slide 20 El Niño: warmer water than usual near Peruvian coast

NOTES:

The Equatorial Divergence (CZCS)

Sea-surface Temperature: Non-El Niño Year

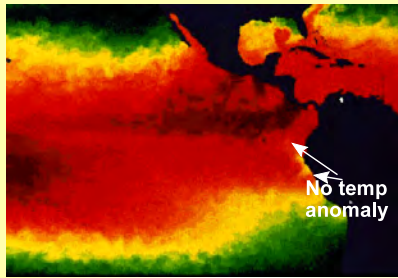


Slide 21 The Equatorial Divergence (CZCS)

NOTES:

The Equatorial Divergence (CZCS)

Sea-surface Temperature: El Niño Year

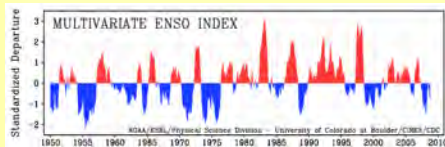


Slide 22 The Equatorial Divergence (CZCS)

NOTES:

El Niños: '83, '97-99, '06; La Niña in '07; ENSO neutral in 2008

<http://www.cdc.noaa.gov/people/klaus.wolter/MEI/>



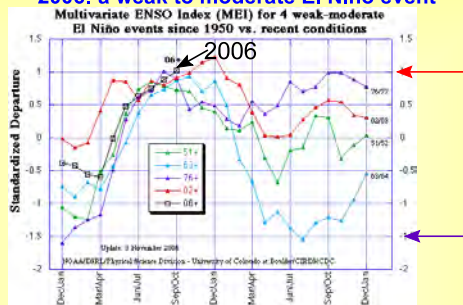
2006 was a mild El Niño year (red), 2007 La Niña (blue), with cooler than average Eastern equatorial waters. 2008 is ENSO neutral. There is also a long term climate pattern in the Pacific called the Pacific decadal oscillation.

Slide 23 El Niños: '83, '97-99, '06; La Niña in '07; ENSO neutral in 2008

NOTES:

Multivariate ENSO Index

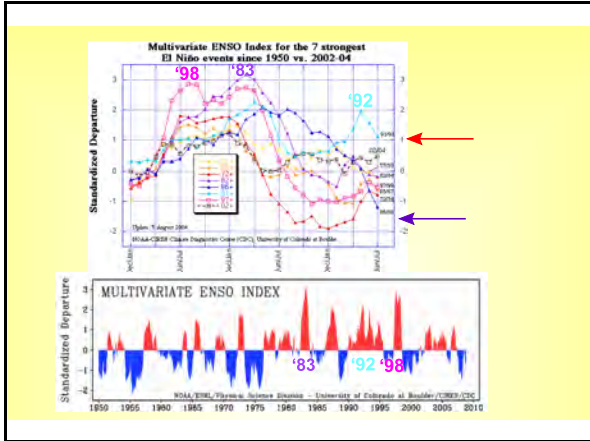
2006: a weak to moderate El Niño event



Slide 24 Multivariate ENSO Index

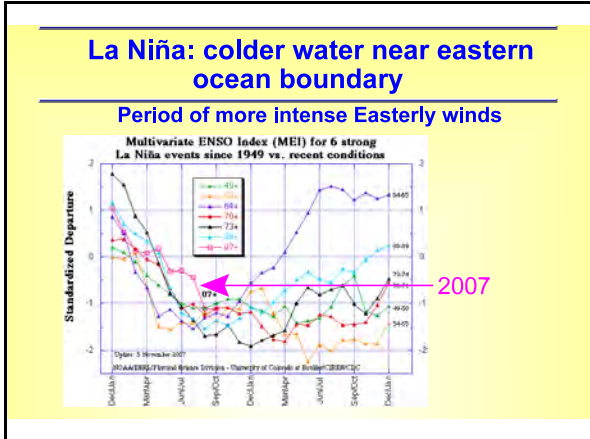
NOTES:

Slide 25



NOTES:

Slide 26 La Niña: colder water near eastern ocean boundary



NOTES:

Ecological effects of El Niño

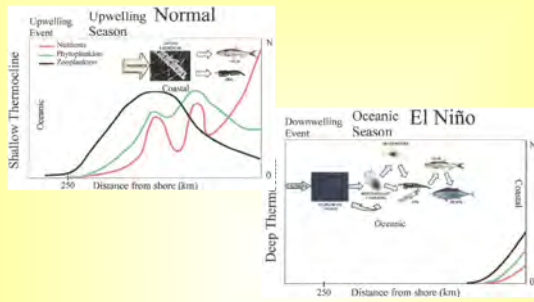
- Barber & Chavez (1986) for ecological effects of '83 El Niño
- Reduced production near the coast and equator
 - In 1982-1983, production at the Peruvian upwelling center reduced despite "normal" equatorward winds
 - CO₂ flux to the atmosphere decreases: Why?
 - Reduced abundance of microphytoplankton, macrozooplankton and fish
 - Birds along the equator abandon their nests, Schreiber & Schreiber (1984) Central Pacific seabirds and the El Niño Southern oscillation: 1982-1983 perspectives. Science 225: 713.
 - Fish populations are reduced or migrate

Slide 27 Ecological effects of El Niño

NOTES:

El Niño effects off California

Chavez et al. 2002 Prog. Oceanogr. 54: 205-232.

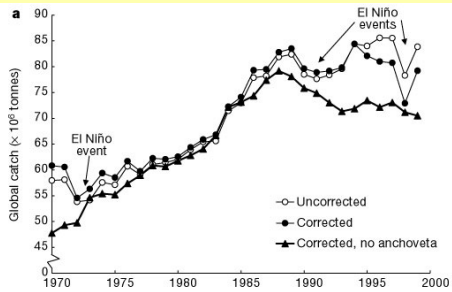


Slide 28 El Niño effects off California

NOTES:

Global Fisheries & El Niño

Watson & Pauly (2001) Nature 414: 534-536.

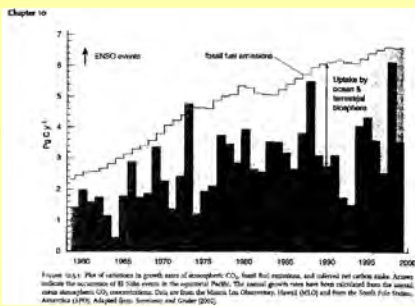


Slide 29 Global Fisheries & El Niño

NOTES:

El Niño reduces oceanic flux of CO₂ to atmosphere; forest fires caused by El Niño drying can increase CO₂

Sarmiento & Gruber 2006



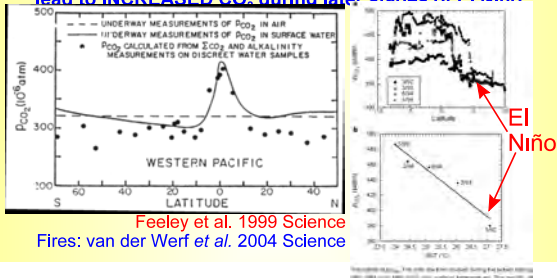
During El Niño there is much lower equatorial production BUT the most important effect is reduced upwelling of CO₂ rich water which normally outgasses at equator

Slide 30 El Niño reduces oceanic flux of CO₂ to atmosphere; forest fires caused by El Niño drying can increase CO₂

NOTES:

El Niño & equatorial outgassing

From Broecker & Peng, Tracers in the Sea; During El Niño, oceanic CO₂ outgassing reduced (30-80%), but terrestrial production also reduced: increased fires lead to INCREASED CO₂ during later stages of El Niño



Feeley et al. 1999 Science

Fires: van der Werf et al. 2004 Science

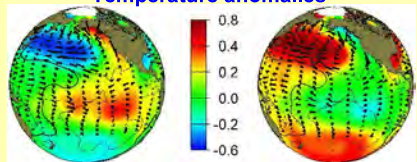
Slide 31 El Niño & equatorial outgassing

NOTES:

Pacific Decadal Oscillation (PDO)

Strongly related to long-term ENSO patterns

Temperature anomalies



Warm phase on CA coast; cool in gyre

Cold phase on CA coast; warm in gyre

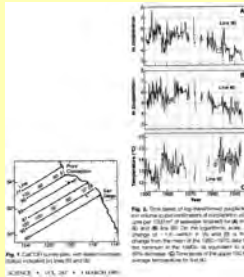
<http://tao.atmos.washington.edu/pdo/>

Slide 32 Pacific Decadal Oscillation (PDO)

NOTES:

McGowan's CALCOFI data Zooplankton '58-'59 El Niño & PDO

Roemmich & McGowan 1995 Science 267: 1324-1326



80% decline in zooplankton biomass over 43 years in the California Current Ecosystem



Slide 33 McGowan's CALCOFI data Zooplankton '58-'59 El Niño & PDO

NOTES:

<div data-bbox="357 168 659 205" data-label="Section-Header"> <h3>Pacific regime shifts</h3> </div> <div data-bbox="251 214 756 243" data-label="Text"> <p>Hare & Mantua (2000) Prog. Oceanography 47: 103-145</p> </div> <div data-bbox="243 256 557 489" data-label="Figure"> </div> <div data-bbox="560 285 721 417" data-label="Text"> <p>PCA of 100 environmental time series: 31 climatic & 69 biological</p> </div> <div data-bbox="243 487 557 537" data-label="Caption"> <p>Fig. 4. Loadings on the first principal component (PC1) from a principal component analysis of the 100 environmental time series. The loadings are correlation coefficients between each time series and the first PC score (Fig. 3). Positive correlations are shaded blue, negative correlations are shaded red. Shaded regions correspond to definitions in Table 1 and Fig. 1. Locations of some of the southern limit were plotted (black dots) (see Fig. 1) to enhance clarity.</p> </div>	<div data-bbox="816 132 1227 172" data-label="Section-Header"> <h3>Slide 34 Pacific regime shifts</h3> </div> <div data-bbox="816 256 940 291" data-label="Text"> <p>NOTES:</p> </div>
<div data-bbox="256 653 761 693" data-label="Section-Header"> <h3>Pacific Regime shifts: 1977 & 1989</h3> </div> <div data-bbox="319 701 683 730" data-label="Text"> <p>Hare & Mantua (2000, Prog. Oceanogr.)</p> </div> <div data-bbox="243 726 680 982" data-label="Figure"> </div> <div data-bbox="243 982 683 1026" data-label="Caption"> <p>Fig. 3. The first two principal component scores from a principal component analysis of the 100 environmental time series. The scores are normalized time series and vertical bars are shown before the data points for 1977 and 1989.</p> </div>	<div data-bbox="816 621 1354 693" data-label="Section-Header"> <h3>Slide 35 Pacific Regime shifts: 1977 & 1989</h3> </div> <div data-bbox="816 779 940 816" data-label="Text"> <p>NOTES:</p> </div>
<div data-bbox="263 1176 747 1213" data-label="Section-Header"> <h3>PDO, ENSO & CALCOFI zooplankton</h3> </div> <div data-bbox="311 1220 698 1249" data-label="Text"> <p>Hare & Mantua 2000 Figures A5 & A9</p> </div> <div data-bbox="237 1245 735 1486" data-label="Figure"> </div> <div data-bbox="237 1495 505 1547" data-label="Text"> <p>Regime shifts indicated by vertical dotted lines</p> </div>	<div data-bbox="816 1146 1312 1222" data-label="Section-Header"> <h3>Slide 36 PDO, ENSO & CALCOFI zooplankton</h3> </div> <div data-bbox="816 1306 940 1344" data-label="Text"> <p>NOTES:</p> </div>

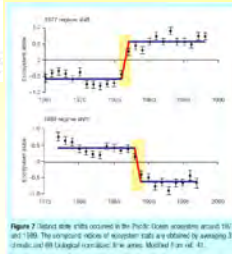
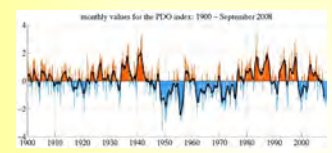
PDO Regime Change/Domain Shift

Scheffer et al. 2001 Nature 413: 591-596

Catastrophic shifts in ecosystems

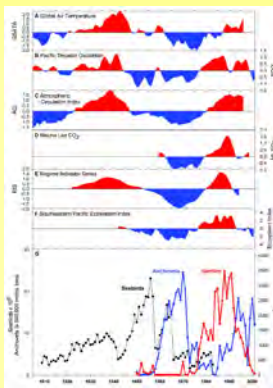
Marine Institute, Stoneham, Massachusetts, USA; and the University of California, San Diego, La Jolla, California, USA

Figure 7: Distinct shifts in the Pacific Ocean ecosystem around 1977 and 1989. The abrupt shifts in ecosystem state are obtained by averaging 31 months and 60 10-day temporal composites of the same. Modified from ref. 45.



Slide 37 PDO Regime Change/Domain Shift

NOTES:



PDO Regime Changes Sardines off Peru with warm phases, Anchoveta with cold phases

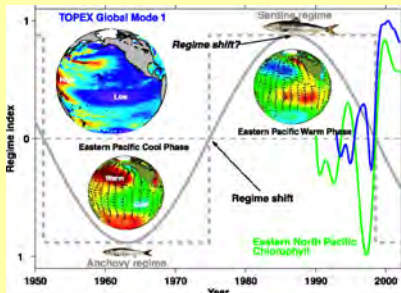
Chavez et al. (2003) Fig. 1; Peruvian fish landings

Slide 38

NOTES:

Anchovy & Sardine Regimes

Chavez et al. 2003



This has a much bigger effect on Northern Anchovy than Lasker's stable ocean hypothesis

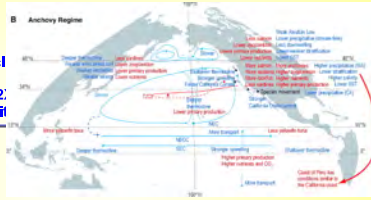
Slide 39 Anchovy & Sardine Regimes

NOTES:

1960s -> 1978 Anchovy (Cold) Regime

Chavez et al. (2003) Science

- California current
 - Higher nutrients
 - High macrozooplankton (*Calanus pacificus*) off California
 - More seabirds
 - More salmon
- Gyre
 - Deeper gyre thermocline
 - Chl a concentration 2x
 - lower gyre productivity



Slide 40 1960s -> 1978 Anchovy (Cold) Regime

NOTES:

1930s & 1980s Sardine (Warm) Regime

Chavez et al. (2003)

- California & Peru in 1930s & 1980s: Sardine Regime
 - Low macrozooplankton off CA
 - Deeper thermocline
 - Less salmon
 - Off Alaska & British Columbia
 - More salmon
 - Higher production
- Gyres
 - Shallower thermocline
 - Much higher production in gyres

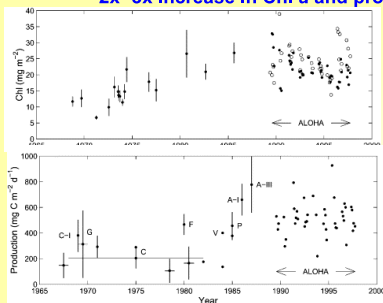


Slide 41 1930s & 1980s Sardine (Warm) Regime

NOTES:

The domain-shift hypothesis

2x -3x increase in Chl a and production



Karl et al. (2001): No strong evidence for trace metal effects on production

Slide 42 The domain-shift hypothesis

NOTES:

Trichodesmium & gyre N₂ fixation

Mat-forming N₂-fixing cyanobacterium, Capone et al. (1997)

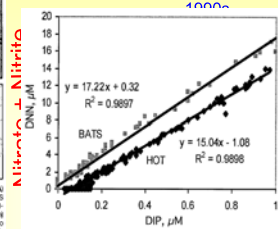
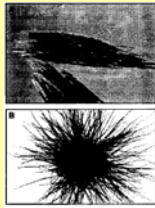


Fig. 1. Examples of Trichodesmium colonies. (A) Mat-forming colony of Trichodesmium culture B-101. (B) Single colony of Trichodesmium. Colonies are typically 2 to 5 mm in length (parallel to filament) and are composed of filaments of aggregated filaments (spherules). Each spherule consists of filaments of hundreds of cells (typically ~100); cells are generally 5 to 15 μm in diameter but can range up to 50 μm in length (100 μm scale bar).

More Fe-rich dust & N fixation in Atlantic (Wu et al. 2000)

Slide 43 Trichodesmium & gyre N₂ fixation

NOTES:

Conclusions on gyres

From stable deserts to non-steady-state systems

- Thesis
 - Gyres as chemostat: slow (desert-like, 5-d doubling time), slow production (slow) stable, steady-state
- Antithesis: high μ , high productivity ($>> 1 \text{ g C m}^{-2} \text{ d}^{-1}$)
- Synthesis: high μ , moderate production, non steady-state on short & long time scales
- Mesoscale eddies, storms that produce short-term blooms important in controlling DIN flux: episodic
- Effective frations, over the monthly time scale, are high, roughly 30-40%
- Long-term decadal scale changes in nutrient input to the gyres, due to the Pacific decadal oscillation (PDO)
 - Doubling of chl a from the 1950s to the 1980s
 - Regime change due to
 - change in depth to the nutricline
 - enhanced Fe input. Increased frequency of N₂ fixing Trichodesmium in the Pacific in the 1990s

Slide 44 Conclusions on gyres

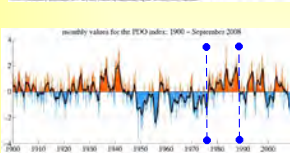
NOTES:

PDO Regime Change/Domain Shift

Scheffer et al. 2001 Nature 413: 591-596

Catastrophic shifts in ecosystems

Review article
1977 & 1989 shifts



Gradual changes in PDO results in large shifts in ecosystem structure throughout the Pacific

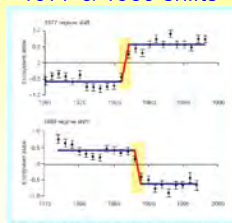


Figure 7. Distinct shifts in the Pacific Ocean ecosystem around 1977 and 1989. The corresponding shifts in ecosystem state are obtained by averaging 37 (1977) and 69 (1989) biological variables. See text for details. Modified from ref. 40.

Slide 45 PDO Regime Change/Domain Shift

NOTES:

<div data-bbox="235 157 511 546"> </div> <div data-bbox="519 199 779 346" style="border: 1px solid red; border-radius: 15px; padding: 5px; color: red;"> <p>PDO Regime Changes: Sardines off Peru with warm phases, Anchoveta with cold phases</p> </div> <div data-bbox="519 409 779 525"> <p>Chavez et al. (2003) Fig. 1; Peruvian fish landings</p> </div>	<div data-bbox="824 136 933 168" style="background-color: #cccccc;"> <p>Slide 46</p> </div> <div data-bbox="824 262 933 294" style="background-color: #cccccc;"> <p>NOTES:</p> </div>
<div data-bbox="235 651 779 1060"> <h3 style="text-align: center;">Conclusions on upwelling</h3> <p style="text-align: center;">Upwelling possible on all coasts & the equator</p> <ul style="list-style-type: none"> Upwelling occurs along coasts and at the equator when winds are upwelling favorable Ekman mass transport, associated with the Ekman spiral, creates a divergence at the coast and at the equator <ul style="list-style-type: none"> Ekman spiral due to the balance of drag & Coriolis forces Surface current is 45° to the right of the wind in the surface. Velocity declines with depth, spiralling clockwise in the N, counterclockwise in the S. At the Ekman depth, or depth of frictional influence, the currents are oriented opposite to the surface current Net Ekman mass transport is 90° to the right of wind in the Northern hemisphere (left in Southern hemisphere) Ekman transport creates a sea-surface tilt and upwelling producing windward surface and opposite geostrophic counter currents. <div data-bbox="527 976 787 1039" style="text-align: right;"> </div> </div>	<div data-bbox="824 619 1299 661" style="background-color: #cccccc;"> <p>Slide 47 Conclusions on upwelling</p> </div> <div data-bbox="824 745 933 777" style="background-color: #cccccc;"> <p>NOTES:</p> </div>
<div data-bbox="235 1134 779 1543"> <h3 style="text-align: center;">Conclusions: El Niño</h3> <ul style="list-style-type: none"> During El Niño years, easterly winds weaken, the pycnocline on the Eastern boundary deepens, and the pycnocline on the Western boundary deepens Despite upwelling favorable winds, upwelled water is warmer and contains lower nutrient concentrations. La Niña is a period of intensive Easterly winds, shallow pycnoclines and nutraclines on Eastern boundaries <div data-bbox="527 1459 787 1522" style="text-align: right;"> </div> </div>	<div data-bbox="824 1102 1234 1144" style="background-color: #cccccc;"> <p>Slide 48 Conclusions: El Niño</p> </div> <div data-bbox="824 1228 933 1260" style="background-color: #cccccc;"> <p>NOTES:</p> </div>