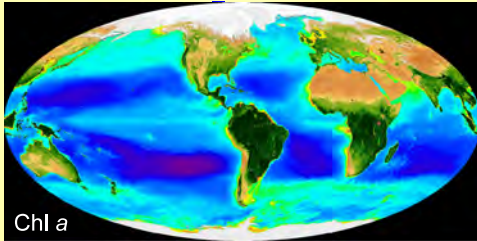


<div data-bbox="248 220 764 373" data-label="Text"> <p>1) Are gyres like chemostats? Yes: Slow, Stable, Steady-State or No: Fast, Unstable & Non-steady-state</p> <p>2) PDO, Domain Shift, and long-term patterns in gyre productivity</p> </div> <div data-bbox="349 384 667 411" data-label="Text"> <p>Class 26, Th 4 December 2008</p> </div> <div data-bbox="532 495 789 541" data-label="Image"> </div>	<div data-bbox="816 132 1333 172" data-label="Section-Header"> <p>Slide 1 1) Are gyres like chemostats?</p> </div> <div data-bbox="816 195 1268 231" data-label="Text"> <p>Yes: Slow, Stable, Steady-State or</p> </div> <div data-bbox="816 256 1323 294" data-label="Text"> <p>No: Fast, Unstable & Non-steady-state</p> </div> <div data-bbox="816 317 1312 392" data-label="Text"> <p>2) PDO, Domain Shift, and long-term patterns in gyre productivity</p> </div> <div data-bbox="816 476 940 512" data-label="Text"> <p>NOTES:</p> </div>
<div data-bbox="295 690 732 732" data-label="Section-Header"> <p>Remaining Lecture Schedule</p> </div> <div data-bbox="238 732 761 1054" data-label="List-Group"> <ul style="list-style-type: none"> • Class 26, Th 12/4/08 <ul style="list-style-type: none"> ▸ Gyre production and the solution to the great debate over gyre productivity ▸ Final exam questions posted in afternoon • Class 27, 12/9/08 <ul style="list-style-type: none"> ▸ Satellite Remote Sensing ▸ No bacterial processes in 2008 • Class 28, 12/11/08 <ul style="list-style-type: none"> ▸ Final Class, Vertical migration • 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 ▸ Jadyn starting at 10 am (do others want to start later too?) • Term papers (5-10 pages double spaced) due 12/22 by email (or earlier) </div>	<div data-bbox="816 657 1331 697" data-label="Section-Header"> <p>Slide 2 Remaining Lecture Schedule</p> </div> <div data-bbox="816 781 940 816" data-label="Text"> <p>NOTES:</p> </div>
<div data-bbox="306 1180 719 1220" data-label="Section-Header"> <p>Readings for these classes</p> </div> <div data-bbox="238 1255 761 1560" data-label="List-Group"> <ul style="list-style-type: none"> • Upwelling, PDO <ul style="list-style-type: none"> ▸ Chavez, F. P., J. Ryan, S. E. Lluch-Costa & C. Miguel Niquen. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299: 217-221. • Gyres <ul style="list-style-type: none"> ▸ Chapter 15 ▸ Platt et al. 1989. Biological production of the oceans: the case for a consensus. Mar. Ecol. Prog. Ser. 52: 77-88. ▸ Chavez et al. 2003. • Satellite Remote Sensing • Microbial Processes </div> <div data-bbox="532 1507 789 1554" data-label="Image"> </div>	<div data-bbox="816 1148 1287 1186" data-label="Section-Header"> <p>Slide 3 Readings for these classes</p> </div> <div data-bbox="816 1268 940 1304" data-label="Text"> <p>NOTES:</p> </div>

Oligotrophic gyres: Thesis, antithesis, synthesis (consensus)

http://seawifs.gsfc.nasa.gov/SEAWIFS/IMAGES/SEAWIFS_GALLERY.html



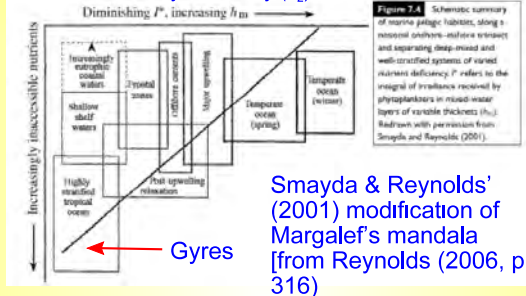
Chl a

Northern Hemisphere, Fall & Winter

Slide 4 Oligotrophic gyres: Thesis, antithesis, synthesis (consensus)

NOTES:

Vertical Eddy Diffusivity (k_z)



Sneyda & Reynolds' (2001) modification of Margalef's mandala [from Reynolds (2006, p 316)]

Slide 5

NOTES:

The f ratio

Ratio of new to total production

That fraction of production which can be coupled to nutrient inputs from outside the system of interest (Dugdale & Goering 1967). Operationally, new production is often regarded as the component of production coupled to nitrate uptake, since nitrate is the major form of nitrate below the nutricline. Occasionally, new production can include production coupled to reduced nitrogen compounds (e.g., urea) from sewage and riverine input (*cf.*, f -ratio, Regenerated Production).

Slide 6 The f ratio

NOTES:

Eppley et al. (1979)
See my chapter 13

New to total production measured by uptake (ρ) of ^{15}N nitrate and ^{15}N ammonium

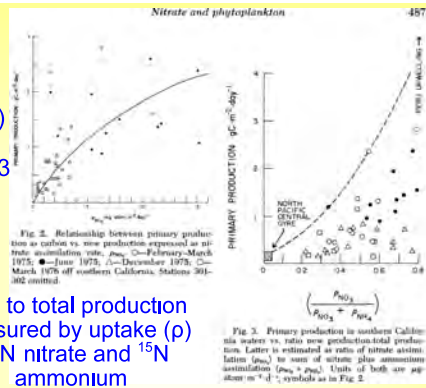


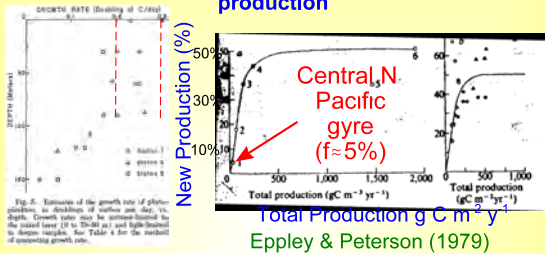
Fig. 3. Primary production in southern California waters vs. ratio new production/total production. Latter is estimated as ratio of nitrate assimilation (ρ_{NO_3}) to sum of nitrate plus ammonium assimilation ($\rho_{\text{NO}_3} + \rho_{\text{NH}_4}$). Units of both are $\mu\text{mole m}^{-2} \text{ day}^{-1}$; symbols as in Fig. 2.

Slide 7

NOTES:

1970s: Gyres as chemostat, low f ratio (5-10%), production & μ

3.5-5 day doubling time, f ratio \approx 5-10%, low production



Eppley et al. (1973)

Eppley & Peterson (1979)

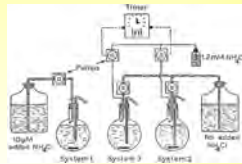
Slide 8 1970s: Gyres as chemostat, low f ratio (5-10%), production & μ

NOTES:

Are gyres like chemostats?

Old model: Slow, stable, steady state

- Old view
 - Steady state
 - Well mixed 2-layer systems
 - Constant supply of nutrients vertically through pycnocline
 - Constant nutrient concentrations
 - Constant standing stocks of phytoplankton and grazers
 - Dilution rate $-\mu = 0.14$ to 0.2 per day
 - The recycling ratio $= 1/f$ ratio ≈ 10 to 20
- Each of these chemostat analogies have been refuted or greatly modified!



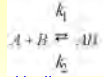
Slide 9 Are gyres like chemostats?

NOTES:

Steady State & Equilibrium

See Gallagher's Appendix of terms for full version

A system with properties that do not change with time is in **steady state**, which is not synonymous with **equilibrium**. In systems governed by chemical reactions or other rate equations, the equilibrium concentrations of substrates and products are governed by rate equations such as:



The chemical reaction described by the equation is in equilibrium if the concentrations of A, B, and AB are in the ratios governed by the reaction coefficients k_1 and k_2 . That is, the rate of the forward reaction equals the rate of the reverse reaction. A set of reversible processes that have reached equilibrium is often called a dynamic equilibrium. See Gallagher's Appendix on Vista4/Blackboard

Slide 10 Steady State & Equilibrium

NOTES:

Production in oligotrophic gyres

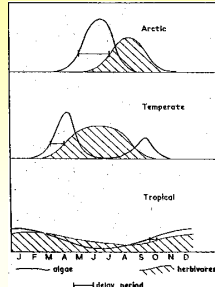
Figure from Cushing (1957)

• Old view of gyres

- ▶ Like a chemostat
 - Slow, steady, stable
 - Low f ratios
 - Low production
- ▶ 5-day doubling times
 - Low relative growth rates

• New view

- ▶ Not like a chemostat
 - Vertical structure
 - Episodic production
 - Long-term changes in production
 - Relatively high effective f ratios
- ▶ Fast and closely coupled primary and secondary production
 - Production relatively high
 - High relative growth rates



Slide 11 Production in oligotrophic gyres

NOTES:

The great productivity debate

Thesis, antithesis, synthesis

- See Peterson 1980 for review
 - ▶ Riley's O_2 -based Global production 126×10^9 tons
 - ▶ Steeman-Nielsen's: 15×10^9 tons
- Are gyres like slow chemostats?
 - ▶ Old view (Thesis): yes
 - Primary production: $100-200 \text{ mg C m}^{-2} \text{ d}^{-1}$
 - New: regenerated production, f ratio, < 0.1
 - 3- to 5-day doubling times for phytoplankton
 - ▶ Antithesis: Steady-state but with high productivity
 - Shulenberger & Reid, Gieskes & Kraay (1984)
 - ▶ Synthesis (Platt et al. 1989): Non steady-state systems



Slide 12 The great productivity debate

NOTES:

Eppley (1980): low gyre μ [$.15 \text{ d}^{-1}$]

But, primary production as high as $550 \text{ mg C m}^{-2} \text{ d}^{-1}$

• Estimated μ using

- ^{14}C production: $\mu = 0.15 \text{ d}^{-1}$ or 4.6 day doubling time
- Grazing rates in bottles $\mu = 0.09 \text{ d}^{-1}$ or 7.7-day doubling time
- Cell death (including grazing) $\mu = 0.19 \text{ d}^{-1}$ or 3.7 day doubling time

Table 1. Estimates of photosynthetic production as carbon in the central North Pacific gyre. Data units are day^{-1} , normalized to the phytoplankton standing stock as carbon (100 mg C m^{-2}). The depth of the euphotic zone is about 100 m.

	Range	Mean	Reference
Net increase in POC by ^{14}C method	0.02-0.34	0.15	Sharp et al. (10)
Grazing in bottles	0.09		Jackson (9)
Cell death	0.19 ^b		Venrick, Boers & Weinbock (10)
Extracellular release of organic ^{14}C		0.04 ^a	
Dark loss of ^{14}C from particles	0.01-0.17	0.06	Eppley & Sharp (44)
Total		0.35	
		$-5.5 \text{ mg C m}^{-2} \text{ d}^{-1}$	
		$-550 \text{ mg C m}^{-2} \text{ d}^{-1}$	

^aMay include grazing loss as well as spontaneous cell death.
^bAssumed to be 25% of net ^{14}C incorporation into particles. This rate may be larger if non-radioactive organic carbon is also released.

Slide 13 Eppley (1980): low gyre μ [$.15 \text{ d}^{-1}$]

NOTES:

Antithesis: The gyres have high production

- Methodological problems with measuring production
 - Differences between O_2 and ^{14}C method
 - Fitzwater *et al.* (1982): Metal contamination may have resulted in low gyre production estimates using both the O_2 and ^{14}C technique. Later work showed that the ^{14}C spike was particularly toxic
 - Filters:
 - Too big: Very small phytoplankton cells ($< 2 \mu\text{m}$) dominate gyre production and standing stock
 - Filtration pressure too strong for delicate picoplankton
 - Incubation bottles too small
 - Gieskes *et al.* (1979)
 - Incubation length too long or too short (Redalje's result)
 - Failure to account for microzooplankton grazing
 - Dark uptake of DIC in C-14 method: C-4 like metabolism
 - Light quality effects, see Laws *et al.*

Slide 14 Antithesis: The gyres have high production

NOTES:

The great productivity debate

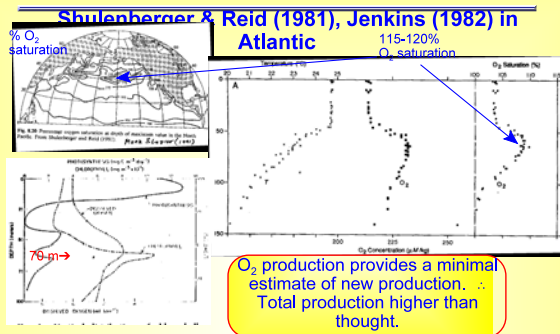
Thesis, antithesis, synthesis

- Thesis: Gyres are slow chemostats
- Revolutionary view (antithesis)
 - $1-3 \text{ g C m}^{-2} \text{ d}^{-1}$
 - New: regenerated production, f ratio, < 0.1
 - Relative growth, μ/μ_{max} close to 1
- Late 1990s Consensus view, summarized in Platt *et al.* 1989
 - Primary production: up to $500 \text{ mg C m}^{-2} \text{ d}^{-1}$
 - Metal contamination was a problem
 - Effective f ratio $< \text{annual}$ > 0.3 to 0.4
 - Relative growth, μ/μ_{max} close to 0.8 to ≈ 1
- Emerging view in 2001-2008: Pacific decadal oscillation & regime shift
 - Venrick & Hayward: interdecadal shifts in Chl a
 - Karl *et al.* (2001), Chavez *et al.* (2003) Pacific interdecadal oscillation & the regime-shift hypothesis: N to P limitation in the central North Pacific gyre

Slide 15 The great productivity debate

NOTES:

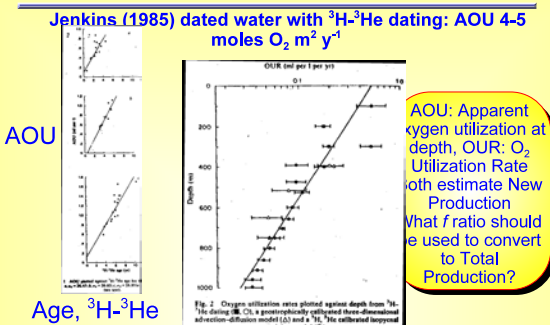
SSCM O₂: 120% saturation



Slide 16 SSCM O₂: 120% saturation

NOTES:

AOU in the Sargasso Sea



Slide 17 AOU in the Sargasso Sea

NOTES:

Indirect estimates of high gyre production

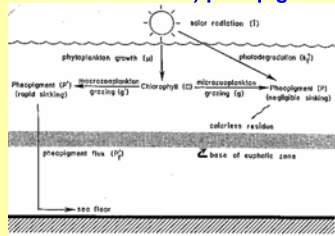
- Apparent oxygen utilization
 - Jenkins (1982): Estimated rate of consumption of organic matter at depth while following parcels of water in the North Atlantic
 - Used Helium-3 to date water masses to calibrate O₂ consumption rates
 - 4-5 mol O₂ m⁻² y⁻¹ new production based on oxygen utilization vs. age of deep water.
 - Or 36 g C m⁻² y⁻¹ **NEW PRODUCTION**
 - If *f* is 10%, then Total water column primary production would be 360 g C m⁻² y⁻¹, or roughly equivalent to coastal ecosystems
 - Jenkins confirmed estimates of **NEW PRODUCTION** by estimating NO₃⁻ flux to the euphotic zone and oxygen production in the surface ocean.

Slide 18 Indirect estimates of high gyre production

NOTES:

Sediment traps & gyre production

Macrozooplankton produce fast sinking fecal pellets: $100 \text{ mg C m}^{-2} \text{ d}^{-1}$, corresponds to new production; Welschmeyer & Lorenzen's (1985, L&O) pheopigment flux



Welschmeyer, N. A. and C. J. Lorenzen. 1985. Chlorophyll budgets: zooplankton grazing and phytoplankton growth in a temperate fjord and the Central Pacific gyres. *Limnol. Oceanogr.* 30: 1-21.

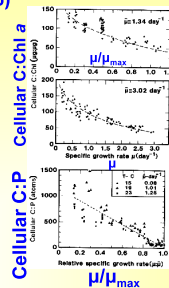
Slide 19 Sediment traps & gyre production

NOTES:

Relative growth rate μ/μ_{\max}

Goldman *et al.* (1979), Goldman (1980), replotted by Harris (1986)

- Redfield ratios of phytoplankton C:N:P only attained at $\mu/\mu_{\max} \approx 1$
- Gyre phytoplankton have Redfield ratios indicate growth near μ_{\max}
- Microscale nutrient patch hypothesis proposed by Goldman *et al.* (1979)
 - Phytoplankton taking up short-lived patches of macronutrients excreted by zooplankton
 - Possible but probably not the major mechanism



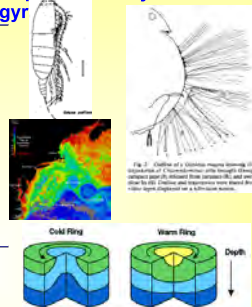
Slide 20 Relative growth rate μ/μ_{\max}

NOTES:

Excursis: Patches, Rings & Gyres

Cold core rings & storms can provide a major nutrient source to gyre

- Goldman *et al.* (1979) proposed that microscale nutrient patches (< 1 mm) fueled high gyre productivity
 - Lehman & Scavia (1982a&b, 1984) demonstrated with ^{32}P that phytoplankton could use patches
 - Sloppy feeding the likely source of patchy nutrients to phytoplankton
- Mesoscale eddies (500-1000 km scale) can provide a source of new nutrients to the gyres; Jenkins, McGillicuddy [WHOI]
- Hurricanes (cyclones) can provide nutrient input

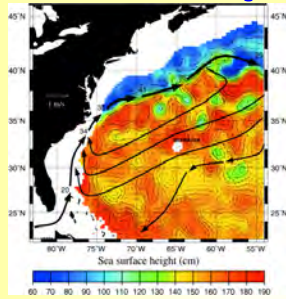


Slide 21 Excursis: Patches, Rings & Gyres

NOTES:

Bermuda (Sargasso) Time series

Steinberg et al. (2001)



Cold core rings enhance the vertical flux of NO_3^-



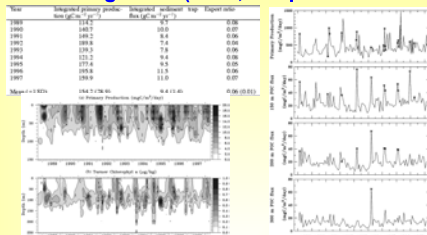
University of Massachusetts Dartmouth

Slide 22 Bermuda (Sargasso) Time series

NOTES:

Bermuda time series

Steinberg et al. (2001, Deep-Sea Research)



Non-Steady-state (but also low annual production [$154 \text{ gCm}^{-2}\text{y}^{-1}$ or $420 \text{ mg gCm}^{-2}\text{d}^{-1}$] & export flux ($9.4 \text{ gCm}^{-2}\text{y}^{-1}$ or 6%))

Slide 23 Bermuda time series

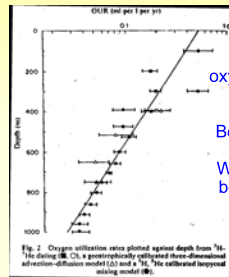
NOTES:

AOU in the Sargasso Sea

Jenkins (1985) dated water with ^3H - ^3He dating: AOU 4-5 moles $\text{O}_2 \text{ m}^{-2} \text{ y}^{-1}$

AOU

Age, ^3H - ^3He



AOU: Apparent oxygen utilization at depth, OUR: O_2 Utilization Rate
Both estimate New Production
What f ratio should be used to convert to Total Production?

Fig. 2 Oxygen utilization rates plotted against depth from ^3H - ^3He dating. CL is a geographically optimized three-dimensional advection-diffusion model (see text). The collected (open circles) and modeled (filled circles) AOU values are shown.

Slide 24 AOU in the Sargasso Sea

NOTES:

Are Steinberg's organic C fluxes consistent with Jenkins AOU of 4-5 mol O₂ m⁻²y⁻¹? NO

=Steinberg's Export flux 9.4 gCm⁻²y⁻¹ (export ratio about 6%)

Carbon export Flux is about 0.8 mol C m⁻² y⁻¹ year [9.4/12=.8]

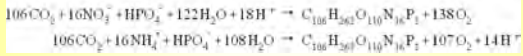
Moles O₂ export flux = moles C * Photosynthetic quotient (from Redfield ratio)

=0.8 * (107 moles O₂ / 106 moles C) ≈ 0.8 moles O₂

= Using Williams et al.'s (1983) estimate of the photosynthetic quotient (see Gallagher's appendix) for phytoplankton growth on NH₄⁺, 1.2, the O₂ export flux would be 0.96 mol O₂ m⁻²y⁻¹

This estimate is far below the Sargasso Sea seasonal average of 4-5 mol O₂ m⁻²y⁻¹ estimate by Jenkins

The BATS Sediment traps may be undersampling organic matter flux; See Rutman et al. 1986 on nitrates with sediment traps



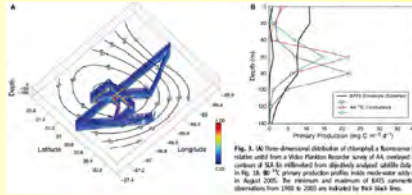
Slide 25 Are Steinberg's organic C fluxes consistent with Jenkins AOU of 4-5 mol O₂ m⁻²y⁻¹? NO

NOTES:

Eddy/Wind Interactions Stimulate Extraordinary Mid-Ocean Plankton Blooms

David J. McGillicuddy Jr.,^{1,2} Lawrence A. Anderson,³ Nicholas R. Bates,⁴ Thomas Bliley,^{1,2} Ann D. Burrows,¹ Craig A. Carlson,⁵ Robert S. Evans,⁶ Courtney Evers,⁷ Paul G. Falkowski,⁸ Sarah A. Goffman,⁹ Dennis A. Hare,¹⁰ William J. Jenkins,¹ Audrey Johnson,¹ Jeffrey A. Kirchner,¹ James K. Lueder,¹ Qing X. Li,¹ David A. Siegel,¹ Deborah S. Stoeckert¹

Episodic eddy-driven upwelling may supply a significant fraction of the nutrients required to sustain primary productivity of the subtropical ocean. New observations in the northeast Atlantic reveal that, although plankton blooms occur in both cyclonic and anticyclonic eddies, the biological responses differ. Eddy-driven upwelling can generate extraordinary diatom blooms and primary production at depth, relative to the time series near Bermuda. These blooms are sustained by enhanced interactions, which amplify the eddy-driven upwelling. In contrast, anticyclonic eddies sustain largest eddy-induced upwelling in cyclones. Carbon export inferred from oxygen isoclines in eddy cores is one to three times as much as annual net production for the region.

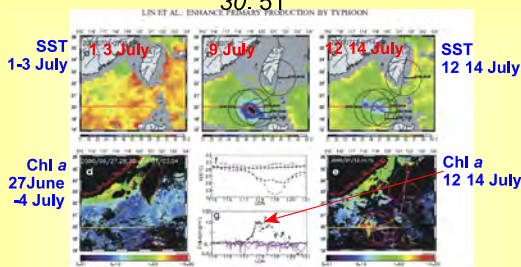


Sargasso Sea blooms caused by storms. Missed by routine BATS sampling

Slide 26

NOTES:

Pacific typhoons create blooms: Lin et al. 2003 Geophysical Research Letters 30: 51



1. TSM250 SST image on (a) 1-3 July 2000, before the arrival of typhoon Kai-Tak; (b) 9 July 2000, after Kai-Tak; (c) 12-14 July 2000, illustrating the match between cold SST pool (figure 1c) and the bloom patch (c). SeaWiFS surface Chl a image composite on (d) 27 June-4 July 2000, before Kai-Tak, and (e) 12-14 July 2000, after Kai-Tak. The circle denotes Kai-Tak's RMW (Radius of Maximum Wind). The location of the fastest 10% is shown in the bottom right panel.

Slide 27

NOTES:

Vertically migrating organisms

Can increase or decrease vertical DIN flux

- Vertically migrating organisms
- Villareal *et al.* (1993)
 - Very large diatoms (*Rhizosolenia*: several mm long)
 - take up nitrate beneath nutricline and vertically migrate to the surface
 - 2-27% of flux estimated by vertical diffusivity
 - Vertically migrate to high NO_3^- zone when nutrients are depleted
- Vertically migrating zooplankton can affect flux estimates for DIN [Longhurst *et al.* 1989]



Slide 28 Vertically migrating organisms

NOTES:

Synthesis: Higher productivity & the PDO

- Better estimates of productivity
 - New estimates of primary productivity with the ^{18}O method, measuring production of ^{18}O - O_2
 - Routine use of trace-metal free incubations
 - Importance first noted by Fitzwater *et al.* (1982)
 - Better control of light quality (blue light dominates gyre illumination)
 - Laws *et al.* (1984): Primary production in the deep-blue sea
- New methods of estimating production
 - Using changes in bulk properties of seawater
 - fast repetition rate fluorescence



Slide 29 Synthesis: Higher productivity & the PDO

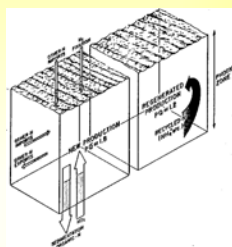
NOTES:

The **effective annual *f*-ratio** may be 0.3 to 0.4, not 0.05 to 0.1!

Platt *et al.* 1989 Figure 1

- In a steady-state system
 - Sinking rate of nitrogen is balanced by the vertical (and horizontal) flux of nitrogen
 - Oxygen utilization beneath the euphotic zone represents the horizontal sinking of primary production and should be equivalent to new production
 - New production could be measured by the vertical flux of NO_3^-
 - Total production = New production * $1/f$

- Problems with this 'chemostat' view
 - Gyres may not be 'steady-state,' with mini-blooms with high *f* ratios
 - There can be pronounced vertical structure



Slide 30 The effective annual *f*-ratio may be 0.3 to 0.4, not 0.05 to 0.1!

NOTES:

Platt et al.'s consensus

Reconciling high short-term rates with bulk properties

- Fallacy of the average and mismatched time scales
 - The f ratios in the gyre are much higher than 0.1; 30% to 40% would be more reasonable
 - $2 \text{ g C m}^{-2} \text{ d}^{-1}$ production with the low Chl a standing stocks in the gyres would violate the quantum requirements of photosynthesis
- Two-layered vertical structure
 - Low f ratios in surface
 - High f ratios at nutricline
 - Vertical nitrate flux trapped at the subsurface chlorophyll maximum
- Non-steady-state
 - Blooms due to rainfall events & mesoscale eddies, hurricanes, cyclones, typhoons
 - Pacific: Long-term increases in Chl a , species composition, and nutrient input due to PDO
 - Temporal decoupling of autotrophy & heterotrophy



Slide 31 Platt et al.'s consensus

NOTES:

The fallacy of averages

Estimating total production from indirect estimates

$$\begin{aligned}
 XT &= X \bar{Y} \quad (\text{unless } X \text{ and } Y \text{ are independent}) \\
 XT &= X \bar{Y} + \text{Covariance}_{X,Y} \\
 XT &= X \bar{Y} + r_{X,Y} \sqrt{S^2_X S^2_Y} \\
 \text{where } r_{X,Y} &= \text{correlation between } X \text{ and } Y \\
 S^2_X &= \text{Variance of } X \\
 \bar{X} &= \text{Mean of } X \\
 P_T &= P_{\text{est}} \frac{1}{f\text{-ratio}} \\
 P_T &= P_{\text{est}} \times \left(\frac{1}{f\text{-ratio}} + \text{Covariance}(P_{\text{est}}, f\text{-ratio}) \right) \\
 &= P_{\text{est}} \times \left(\frac{1}{f\text{-ratio}} + r_{P_{\text{est}}, f\text{-ratio}} \sqrt{\frac{1}{f\text{-ratio}^2} S^2_{P_{\text{est}}} S^2_{f\text{-ratio}}} \right)
 \end{aligned}$$

Welsh et al. 1988.
The fallacy of averages. Amer. Natur. 132: 277-288.

Slide 32 The fallacy of averages

NOTES:

Thermodynamic constraints

Effective f ratio can't be much lower than 0.4

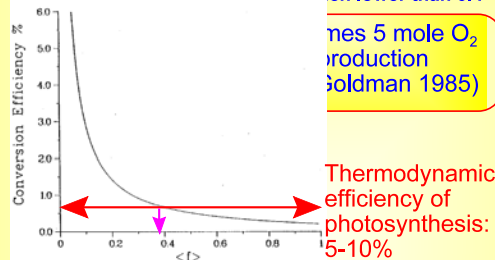


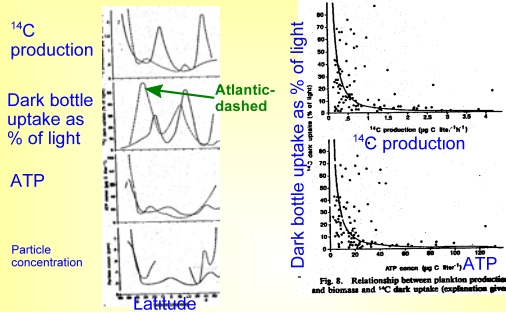
Fig. 2. Implied photosynthetic conversion efficiency as a function of annually averaged f -ratio at Station S in the Sargasso Sea, assuming that new production is $5 \text{ mol O}_2 \text{ m}^{-2} \text{ yr}^{-1}$

Slide 33 Thermodynamic constraints

NOTES:

Many gyre assimilation numbers used to estimate gyre productivity too high

Prakash *et al.* (1991)



Slide 34 Many gyre assimilation numbers used to estimate gyre productivity too high

NOTES:

Two-layered gyre model

King & Devol (1979), Altabet: High f ratios at SSCM.

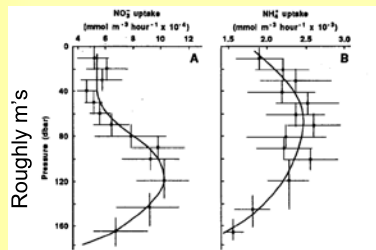


Fig. 2. Depth profiles of rate of uptake of nitrate and ammonium as ^{15}N . The vertical bars represent the range of the depth bin and the horizontal bars the standard error of the mean.

Most of the vertical NO_3 flux is trapped at the SSCM, where f ratios could be very high

Slide 35 Two-layered gyre model

NOTES:

Primary production in the deep-blue sea: Light quality effects in the N. Pacific gyre

Laws *et al.* (1984) Table 3: $\approx 400\text{-}500 \text{ mg C m}^{-2} \text{ d}^{-1}$

About 2x-4x earlier productivity estimates
High phytoplankton rates

Table 3. Autotrophic production from depth profile studies at about 28°N , 155°W . Incident irradiance (I_0) expressed as Einsteins $\text{m}^{-2} \text{ d}^{-1}$ of 400-700-nm light. Production expressed as $\text{mg C m}^{-2} \text{ d}^{-1}$ or $\text{mg N m}^{-2} \text{ d}^{-1}$.

1985	Location	I_0	Autotrophic assimilation based on ^{14}C uptake				Gross autotrophic assimilation	
			C	N*	C	N	C	N
21 Aug	$28^\circ 6.4'\text{N}$, $155^\circ 2.1'\text{W}$	49.1	Surface-1% I_0	268	48			
			1% I_0 -200 m	36	7			
			Total	304	55	435	72	
27 Aug	$28^\circ 28.7'\text{N}$, $154^\circ 34'\text{W}$	49.5	Surface-1% I_0	242	39			
			1% I_0 -200 m	54	10			
			Total	296	49	423	64	
2 Sep	$29^\circ 5.1'\text{N}$, $154^\circ 4.7'\text{W}$	48.5	Surface-1% I_0	308	53			
			1% I_0 -200 m	37	7			
			Total	345	60	493	78	

* Calculated with the methodology of DiTullio and Laws (1983).

Slide 36 Primary production in the deep-blue sea: Light quality effects in the N. Pacific gyre

NOTES:

Post Platt et al. (1989) Developments

- Karl's domain shift hypothesis
 - The Pacific gyre can switch from N to P limitation
 - The Pacific is more iron limited than the Atlantic and N fixation can be limited by Fe availability
- Pacific Decadal oscillation accounts for the nearly 2x increase in Chl *a* and production



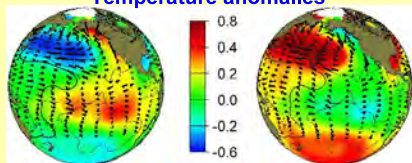
Slide 37 Post Platt et al. (1989) Developments

NOTES:

Pacific Decadal Oscillation (PDO)

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/>

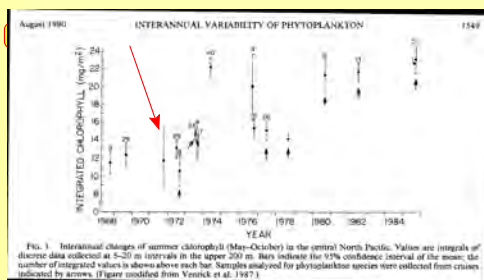
EEOS630

Slide 38 Pacific Decadal Oscillation (PDO)

NOTES:

Pacific decadal oscillation: 2x Chl *a* increase from '68 to '84, esp at SSCM

Venrick et al. (1987), Venrick(1990)

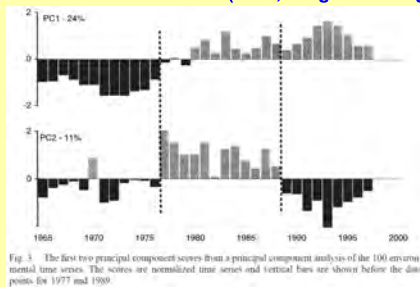


Slide 39 Pacific decadal oscillation: 2x Chl *a* increase from '68 to '84, esp at SSCM

NOTES:

Pacific Regime shifts (1977, 1989)

Hare & Mantua (2000, Prog. Oceanogr.)



Slide 40 Pacific Regime shifts (1977, 1989)

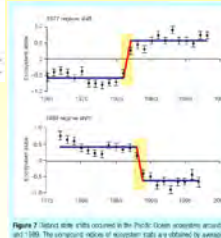
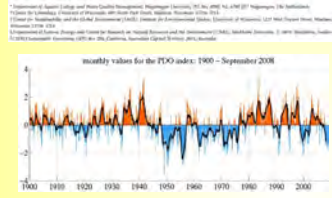
NOTES:

PDO Regime Change/Domain Shift

Scheffer et al. 2001 Nature 413: 591-596

Catastrophic shifts in ecosystems

review article 1977 & 1989 shifts

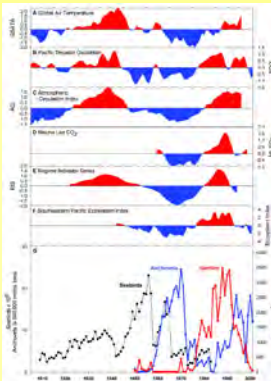
Markus Schaffer¹, Steve Carpenter¹, Jonathan A. Foley¹, Carl Folber¹, & Brian Walker²

Slide 41 PDO Regime Change/Domain Shift

NOTES:

Slide 42

NOTES:

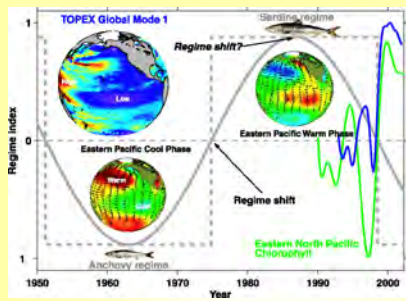


PDO Regime
Changes Sardines
off Peru with warm
phases, Anchoveta
with cold phases

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

Anchovy & Sardine Regimes

Chavez et al. 2003



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

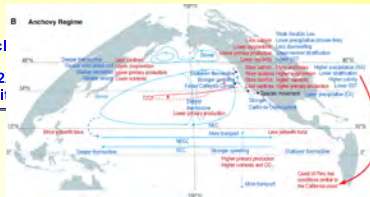
Slide 43 Anchovy & Sardine Regimes

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 2
 - lower gyre productivity



Slide 44 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

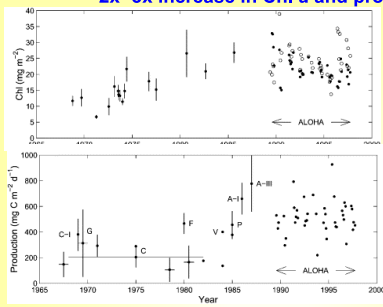


Slide 45 1930s & 1980s Sardine (Warm) Regime

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 46 The domain-shift hypothesis

NOTES:

Trichodesmium & gyre N₂ fixation

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

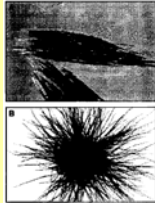
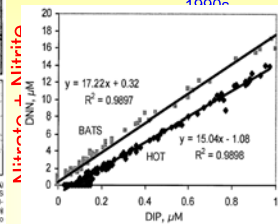


Fig. 1. Examples of Trichodesmium colonies. (A) Mat-forming colony of *T. thuyellum* (strain B-101). (B) Single cell or small colony of *T. thuyellum*. Colonies are typically 2 to 5 mm in length (Battisti) or diameter (Battisti) and are composed of tens to hundreds of aggregated filaments (trichomes). Each trichome consists of tens to hundreds of cells typically ~100; cells are generally 5 to 15 µm in diameter but can reach up to 100 µm in length (100 photos by H. Platt).



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

Karl: regime change with more Fe in Pacific in the 1990s

mail

Slide 47 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 f ratios, 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 1960s to the 1990s
 - 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 48 Conclusions on gyres

NOTES: