Non- steady state dynamics: Upwelling, Coastal hypoxia, Red Tides, ENSO & PDO

Class 24, Tu 25 November 2008

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Slide 1 Non- steady state dynamics: Upwelling, Coastal hypoxia, Red Tides, ENSO & PDO

NOTES:

Final exam & upcoming classes

- Final exam will be 3-h closed book, but with essay questions provided in advance
  - **There is no set date for the final, so I'll have Angeliki send you emails to fix a time for the 3-h in class final. Copies of old final exams will be on Vista/Blackboard**
  - **Arnab at Lowell and Christina at Amherst: when date is set, arrange for your advisor or other faculty member to proctor the exam**
- **Outer continental shelf oil effects papers will be due at the time of the final. I'll be uploading a set of papers on the Gulf of Mexico drilling program after class**
  - **My Matlab program stopped working, but it should be remedied by the weekend**
- Next class: Production in gyres & satellite remote sensing, zooplankton vertical migration

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Slide 2 Final exam & upcoming classes

NOTES:

Upwelling, El Niño & Red Tides

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Slide 3 Upwelling, El Niño & Red Tides

NOTES:

Upwelling topics

- Background lecture on upwelling at the coast and at the Pacific equatorial divergence
- Upwelling off the New Jersey coast, hypoxia, and upwelling in MA Bay
- El Niño, La Niña and ENSO
- Analysis of Ryther et al. (1971)

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Slide 4 Upwelling topics

NOTES:

Upwelling Web Resources

See Gallagher's Upwelling Chapter 12 for new links

- Rich Signell's MA Bay upwelling
- U Washington Atmospheric Sciences report on El Niño and climate prediction
- NOAA PMEL El Niño Theme page
  - Dynamic height & upwelling movie
- Rutgers COOL
- SeaWiFS images of global Chl *a*
- California upwelling indices

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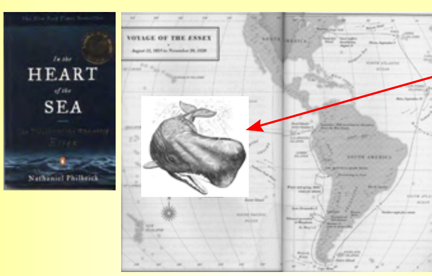
Slide 5 Upwelling Web Resources

NOTES:

Upwelling and whales

Voyage of Essex: Aug 12, 1819 → Nov. 20, 1820



Essex rammed & sunk

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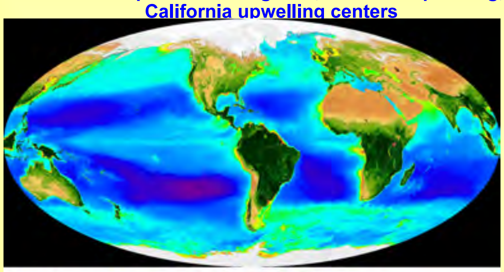
Slide 6 Upwelling and whales

NOTES:

SeaWiFS image of Chl *a*

Note Equatorial divergence, Peruvian upwelling, California upwelling centers



Northern Hemisphere, Fall & Winter

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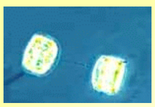
Slide 7 SeaWiFS image of Chl a

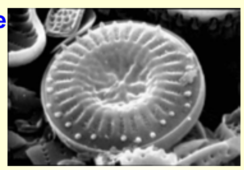
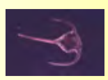
NOTES:

Upwelling & diatoms

(Dinoflagellates can also be important)



Diatoms have silica tests, often form chains, usually large

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Slide 8 Upwelling & diatoms

NOTES:

Why is production so high & the phytoplankton cells so large?

High nutrients & turbulence, low grazing, or all three?

- High DIN
  - Large cells may have an advantage with high NO_3^- concentrations
    - Diatoms have a relatively high specific growth rate (μ)
    - Diatoms have a V_{max} for taking up & storing nitrate
- High turbulence (Ramon Margalef's explanation)
- Non-steady state dynamics & large cell size reduces grazer control
  - Evans & Parslow (1985): Blooms occur when grazers can't control phytoplankton
  - Geider, Platt & Raven: Diatoms have few physiological advantages leading to high μ, but they do have reduced grazing rates

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Slide 9 Why is production so high & the phytoplankton cells so large?

NOTES:

Why are fisheries yields high?

High DIN and high turbulence lead to large phytoplankton cell sizes.

- High primary production
- Anchoveta & sardines can filter phytoplankton directly with their gill rakers
- Typical Tropical Structure Food chain
  - nanophytoplankton ➔ heterotrophic nanoflagellates ➔ ciliates ➔ copepods ➔ fish
- Upwelling Food chain
  - diatoms & large dinoflagellates ➔ fish
  - The ecological efficiency for each link is at best 40% and probably closer to 10%
  - More links produces lower fish yields

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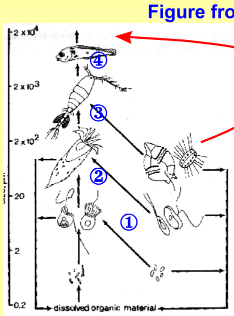
Slide 10 Why are fisheries yields high?

NOTES:

Upwelling & Fish production

Figure from Fenchel (1988)



① NO_3^- ➔ diatoms & dinoflagellates➔fish (gill rakers)
Adult fish eat zooplankton
Open-ocean food chain: 2-4 trophic links
Ecological efficiency is 10% to 40% at each link: $0.4^4=0.0256\approx3\%$
$0.1^4=0.0001\approx0.01\%$

Slide 11 Upwelling & Fish production

NOTES:

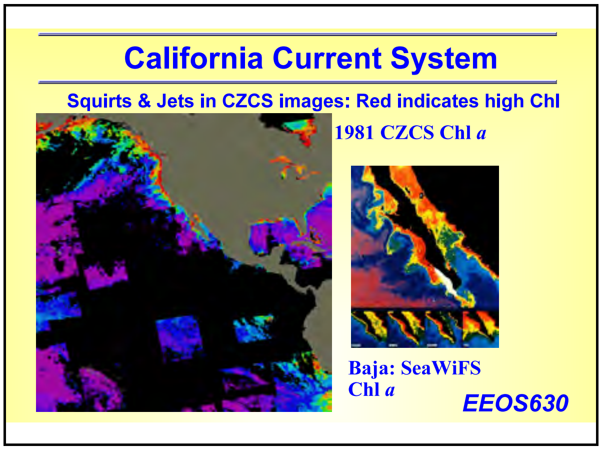
Efficiencies

Summarized in Gallagher's Appendix of terms

- **Assimilation efficiency** = assimilation/**ingestion**=(growth + respiration)/**ingestion**
  - Fenchel (1982): 60% **assimilation efficiency** for protozoa.
- **Net growth efficiency** = Growth/(growth+respiration)
  - Annual net growth efficiency = $Production_{annual}/(Production_a + Respiration_a)$
  - Banse (1979): 13% to 55%, no clear dependence of NGE on animal weight
- **Gross growth efficiency (GGE)** = growth/ingestion
  - **GGE** = **Assimilation efficiency** * **Net growth efficiency** = (G+R)/**I** * G/(G+R)
  - Fenchel (1988) estimates the GGE of phagotrophic microbes at ≈30%. Rivkin & Legendre (2001): bacterial GE is about 50% near 0º C declining to about 10% at 30ºC.
- **Ecological Efficiency** = The amount of energy extracted from a trophic level/amount of energy supplied to that trophic level (Slobodkin 1961).
  - **Ecological efficiency** of a population is the **gross growth efficiency** averaged over a sufficiently long interval that steady state is achieved. An ecological efficiency of 10% is often assumed, but may be much higher.

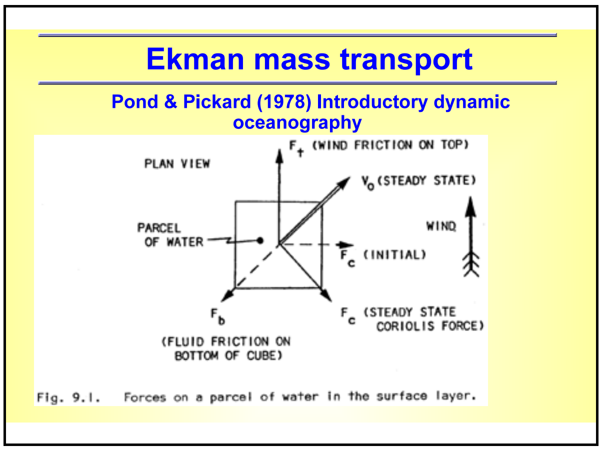
Slide 12 Efficiencies

NOTES:



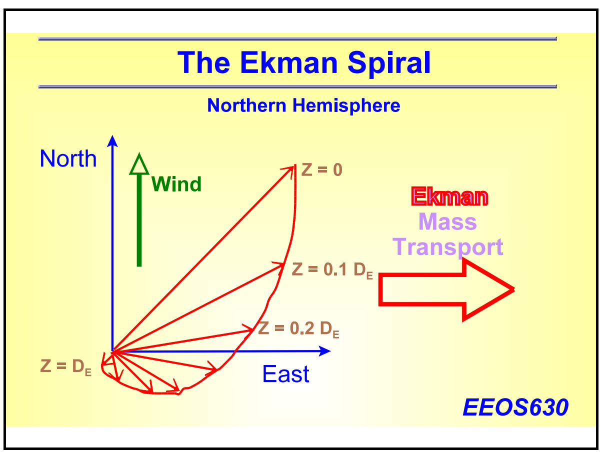
Slide 13 California Current System

NOTES:



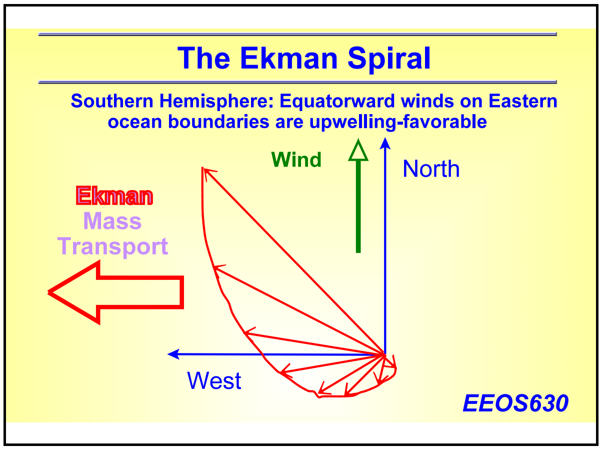
Slide 14 Ekman mass transport

NOTES:



Slide 15 The Ekman Spiral

NOTES:



Slide 16 The Ekman Spiral

NOTES:

Depth of the Ekman Layer

Upwelling affects the the thin surface of the ocean

Table 1. Depth of the Ekman layer as a function of Wind speed and latitude. The following approximation can be used to predict the depth of frictional influence as ƒ(W, wind speed & θ, latitude):

$$D_E \cong \frac{4.3\,W}{\sqrt{\sin\theta}}$$

		Latitude		
		10°	45°	80°
V_o/W		0.030	0.015	0.013
Wind Speed	10 m/sec D_E =	100m	50 m	45 m
	20 m/sec D_E =	200m	100 m	90 m

W= wind velocity
V= the velocity of the sea surface
D_E =Ekman Depth

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Slide 17 Depth of the Ekman Layer

NOTES:

Ekman's Equations

$$u = \pm V_o \cos\left(\frac{\pi}{4} + \left[\frac{\pi z}{D_E}\right]\right) \exp\left[\frac{-\pi z}{D_E}\right]. \left[\begin{matrix} + \text{for } N \\ - \text{for } S\end{matrix}\right]$$

$$v = V_o \sin\left(\frac{\pi}{4} + \left[\frac{\pi z}{D_E}\right]\right) \exp\left[\frac{-\pi z}{D_E}\right]$$

where, $V_o = \frac{\sqrt{2}\,\pi\,\tau_{yw}}{D_E\,\rho\,|f|}$
= the total surface current.
τ_{yw} = magnitude of the wind stress ≈ prop. (wind speed)^2.
$|f|$ = absolute value of the Coriolis parameter.
$= |2\,\omega \sin\theta|$.

D_E = Ekman depth $= \pi\sqrt{\left(\frac{2A_z}{|f|}\right)}$
A_z = Vertical kinematic eddy viscosity.

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Slide 18 Ekman's Equations

NOTES:

Causes of coastal upwelling

With the Oregon-California coast as an example

- Wind stress creates Ekman mass transport and a barotropic pressure gradient (tilt in sea-surface slope)
  - Wind blows equatorward on eastern boundaries
  - Mass transport offshore (90 degrees to the right of the wind direction)
  - Divergence develops at the coast
  - An eastward sea-surface slope develops setting up a barotropic pressure gradient. The pressure gradient points to the coast (eastward).
- The barotropic pressure gradient force drives a surface geostrophic current to the south (the Coriolis force is directed westward to the right of the current direction)

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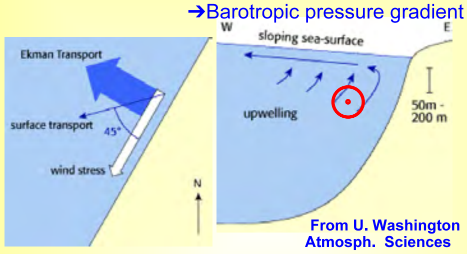
Slide 19 Causes of coastal upwelling

NOTES:

Coastal Upwelling (off CA, looking North)

Ekman Mass Transport creates a barotropic pressure gradient

➔Barotropic pressure gradient



From U. Washington Atmosph. Sciences

Slide 20 Coastal Upwelling (off CA, looking North)

NOTES:

Causes of coastal upwelling

Upwelling due to the divergence at coast

- Offshore transport at the coastal divergence causes upwelling of cold, often nutrient-rich, water from 50-100 m (can be deeper)
  - Isopycnal surfaces (surfaces of the same density) are tilted upward towards shore due mainly to temperature differences.
  - The offshore gradient in water-column density structure sets up a baroclinic pressure gradient to the west (offshore)
  - At depth (>100-200 m) the offshore baroclinic component>>>barotropic component, producing northward geostrophic flow at depth.
    - Because of continuity, net mass transport must be Eastward (onshore in the bottom layer).

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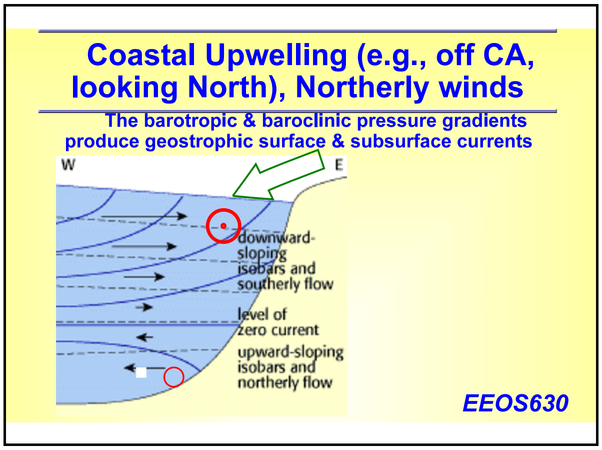
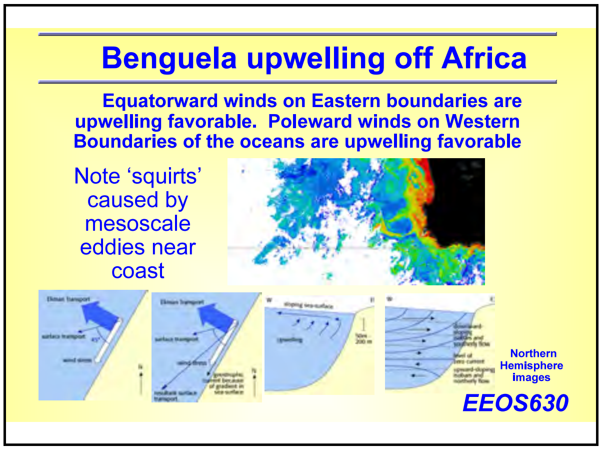
Slide 21 Causes of coastal upwelling

NOTES:



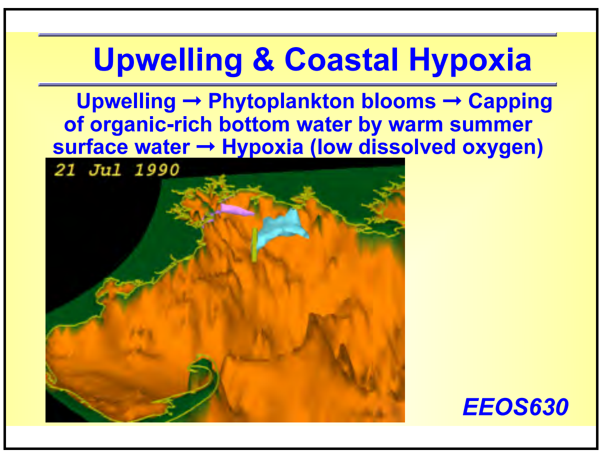
Slide 22 Coastal Upwelling (e.g., off CA, looking North), Northerly winds

NOTES:



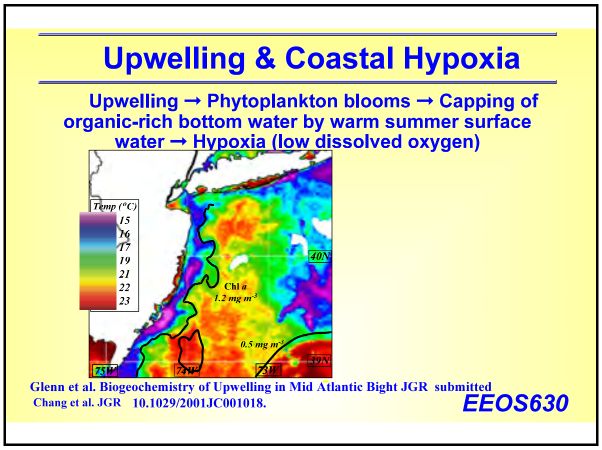
Slide 23 Benguela upwelling off Africa

NOTES:



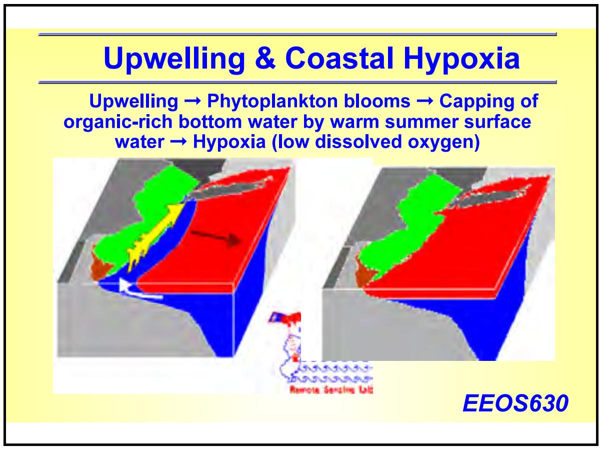
Slide 24 Upwelling & Coastal Hypoxia

NOTES:



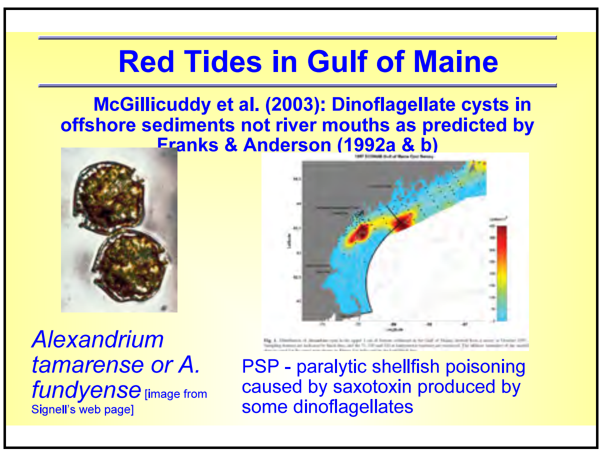
Slide 25 Upwelling & Coastal Hypoxia

NOTES:



Slide 26 Upwelling & Coastal Hypoxia

NOTES:

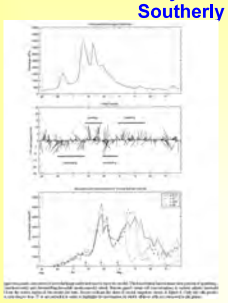


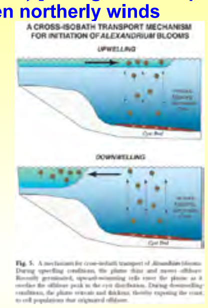
Slide 27 Red Tides in Gulf of Maine

NOTES:

Red Tides in MA Bay

McGillicuddy *et al.* (2003) [Gallagher's Chapter 14]: Southerly then northerly winds





Slide 28 Red Tides in MA Bay

NOTES:

Conclusions: NJ & New England

Upwelling occurs with poleward (Northerward) winds.

- MA Bay: Upwelling is a major source of nutrient-rich water to inner MA Bay (probably exceeding riverine & anthropogenic input)
- Off the coast of New Jersey, upwelling causes summer hypoxia in bottom waters
  - Upwelling-favorable (Southerly) winds create a coastal divergence
  - Nutrient-rich water is upwelled near the coast, producing a bloom (diatoms & dinoflagellates)
  - The POC from the bloom settles to bottom waters
  - As upwelling favorable winds decline and downwelling favorable winds increase, the bottom waters are capped, reducing O_2 flux
  - Microbial respiration of labilie (fresh) phytodetritus results in hypoxia (dissolved O_2 < 5 mg/l)
- Red tides in MA Bay caused by coupled upwelling & downwelling favorable winds

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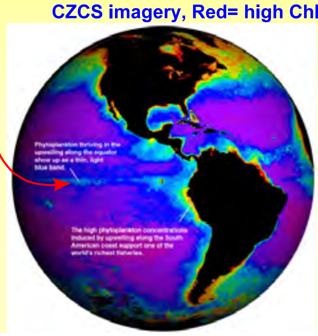
Slide 29 Conclusions: NJ & New England

NOTES:

The Equatorial Divergence

CZCS imagery, Red= high Chl *a*



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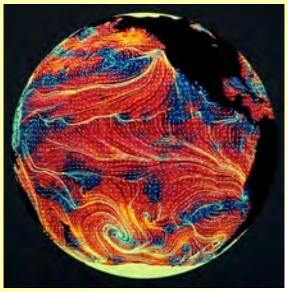
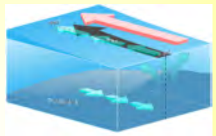
Slide 30 The Equatorial Divergence

NOTES:

Easterly equatorial winds





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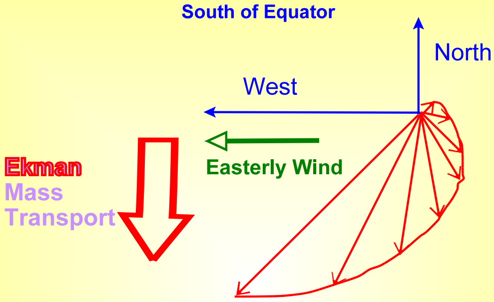
Slide 31 Easterly equatorial winds

NOTES:

The Ekman Spiral

South of Equator



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Slide 32 The Ekman Spiral

NOTES:

Ryther *et al.* (1971)

Followed water advecting from upwelling zone

- Measured production on changes in water mass bulk chemical properties, assuming
  - Redfield ratio
  - C:Chl *a* ratio=35
  - Max: 10 g C m^{-2} d^{-1} production (Chavez & Barber (1987): Avg: 2.3 g C m^{-2} d^{-1})
  - phytoplankton standing stock peaked at 3 days returned to low levels after 5 days
- All measures of production close, but ^{14}C low
- Phytoplankton population ultimately controlled by grazing.

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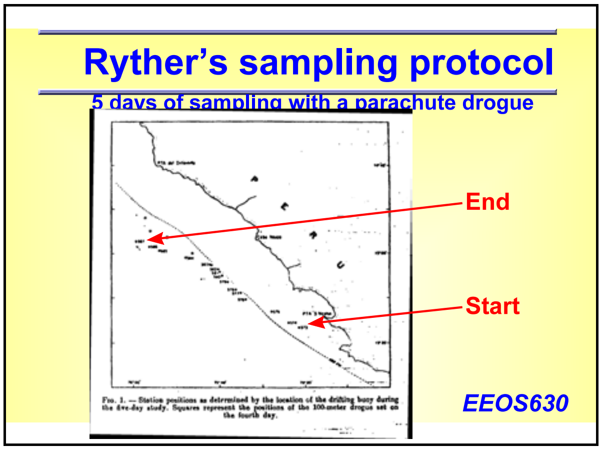
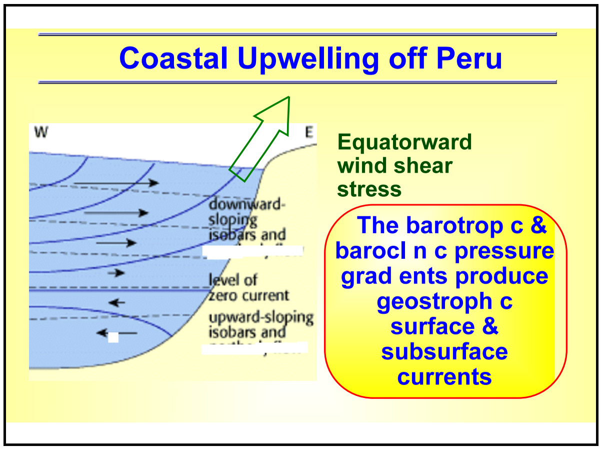
Slide 33 Ryther et al. (1971)

NOTES:



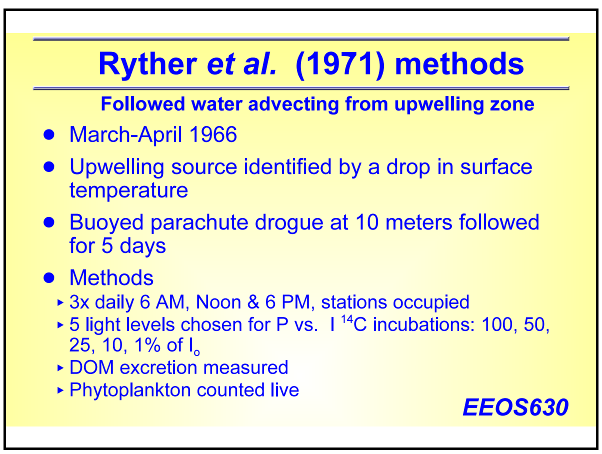
Slide 34 Ryther's sampling protocol

NOTES:



Slide 35 Coastal Upwelling off Peru

NOTES:



Slide 36 Ryther et al. (1971) methods

NOTES:

Ryther *et al.* (1971) productivity

Primary production estimates

- Measured production on changes in water mass bulk chemical properties, assuming
  - Redfield ratio: O:C:N:P=276:106:16:1
    - RKR ratios maintained for 5 days: no nutrient limitation evident
  - C:Chl *a* ratio=35 assumed
    - Best estimate of C:Chl *a* ratio was 50
- ^{14}C estimates using 6 AM, noon and 6 pm incubations over 24 hours
  - compared to changes in particulate organic carbon standing stock from noon to noon and 6 PM to 6 PM

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Slide 37 Ryther et al. (1971) productivity

NOTES:

Ryther *et al.* (1971) results

Comparison of productivity estimates

- Estimates using the ^{14}C method were lower than estimates of nutrient uptake and oxygen production, but comparable to POC production
  - Loss of DOM during growth (Fogg: 1/3 of gross production lost as DOM)
  - Constant DOM production in this study
  - Loss of POM to the system
- Even though POC declined from day 3 to 5, removal of nutrients and O_2 production indicates high productivity

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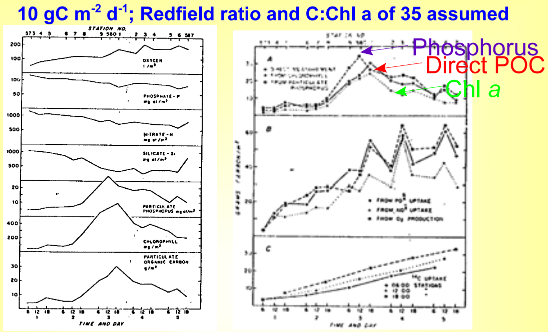
Slide 38 Ryther et al. (1971) results

NOTES:

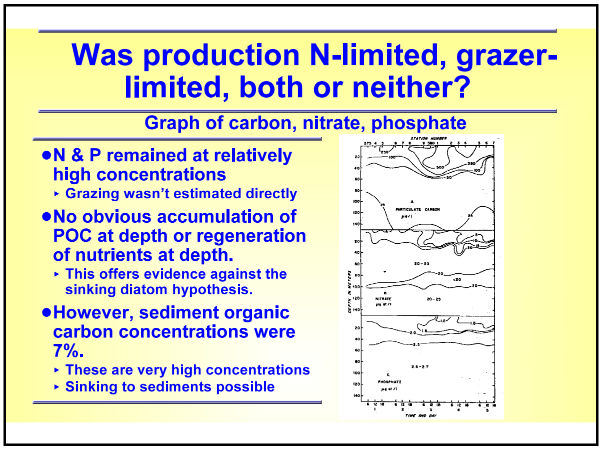
Production very high

10 gC m^{-2} d^{-1}; Redfield ratio and C:Chl a of 35 assumed



Slide 39 Production very high

NOTES:



Slide 40 Was production N-limited, grazer-limited, both or neither?

NOTES:

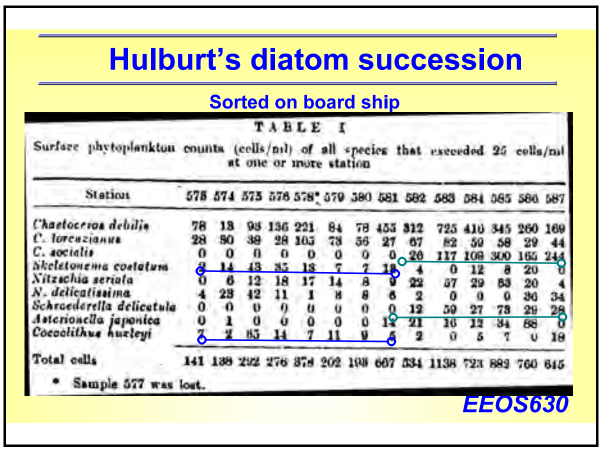


TABLE I

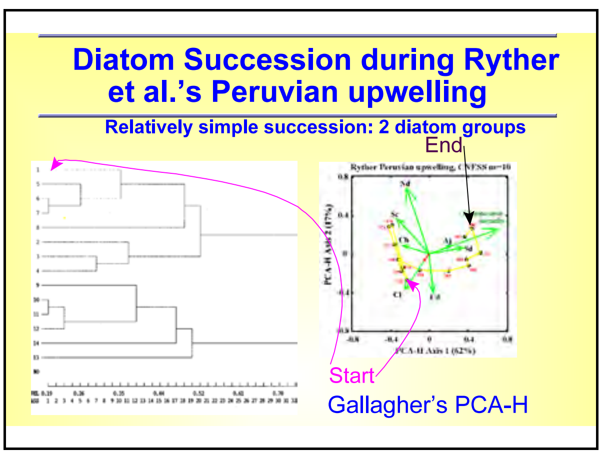
Surface phytoplankton counts (cells/ml) of all species that exceeded 25 cells/ml at one or more station

Station	573	574	575	576	578*	579	580	581	582	583	584	585	586	587
Chaetoceros debilis	78	13	93	136	221	84	78	453	312	725	410	345	260	169
C. lorenzianus	28	30	39	28	103	73	56	27	67	82	59	58	29	44
C. socialis	0	0	0	0	0	0	0	0	26	117	109	300	165	244
Skeletonema costatum	3	14	43	35	13	7	7	19	4	0	12	8	20	0
Nitzschia seriata	0	6	12	18	17	14	8	9	22	57	29	63	20	4
N. delicatissima	4	23	42	11	1	8	8	6	2	0	0	0	36	34
Schroederella delicatula	0	0	0	0	0	0	0	0	12	59	27	73	29	28
Asterionella japonica	0	1	0	0	0	0	0	14	21	16	12	34	88	0
Coccolithus huxleyi	7	2	85	14	7	11	9	5	2	0	5	7	0	19
Total cells	141	138	292	276	378	202	199	667	534	1138	723	882	760	645

* Sample 577 was lost.

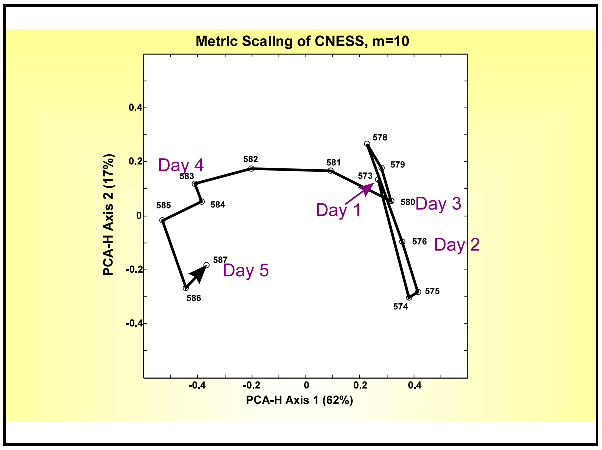
Slide 41 Hulburt's diatom succession

NOTES:



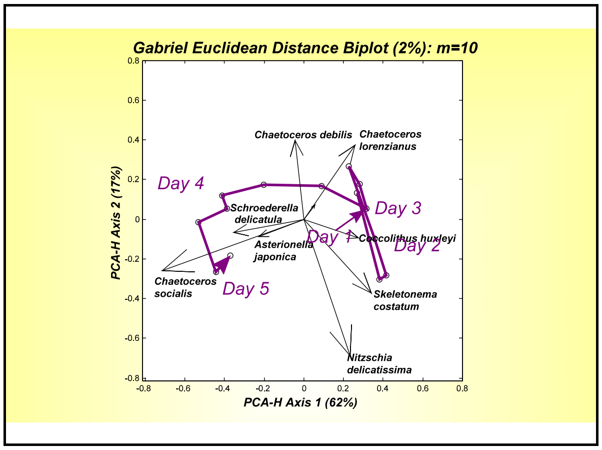
Slide 42 Diatom Succession during Ryther et al.'s Peruvian upwelling

NOTES:



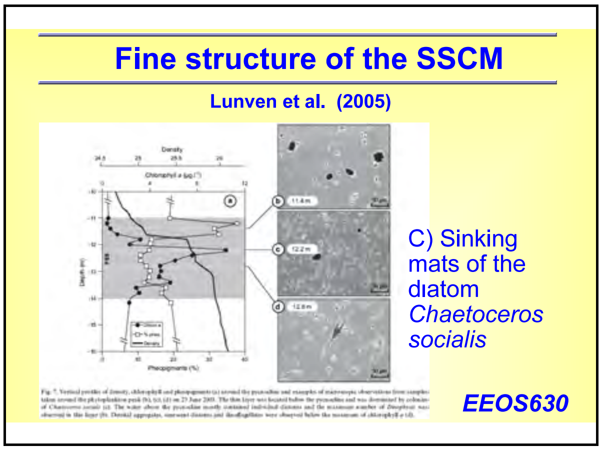
Slide 43

NOTES:



Slide 44

NOTES:

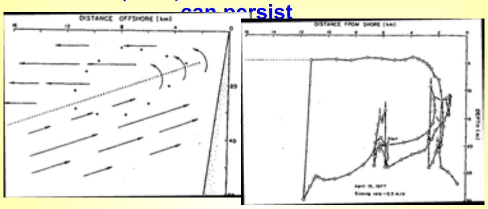


Slide 45 Fine structure of the SSCM

NOTES:

How do diatoms maintain themselves in upwelling systems?

Smetacek: rapid sinking an adaptation to maintain cells in upwelling systems; modeled by Smith *et al.* (1983). Diatoms that sink 0.5 m d^{-1} can persist



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Slide 46 How do diatoms maintain themselves in upwelling systems?

NOTES:

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
  - 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)

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Slide 47 Conclusions: Ryther et al. (1971)

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 parameters may be associated phytoplankton succession

Slide 48 Production at upwelling centers

NOTES:

Critical depth and upwelling:

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

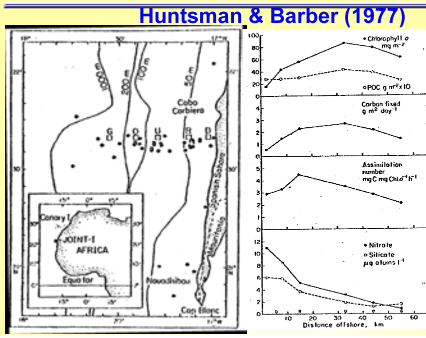
- Northwest African Upwelling
- High production is inversely correlated with upwelling favorable winds!
- Sverdrup's critical depth is key.
- Phytoplankton light-limited under high winds and vertical mixing regimes (wind speed>10 m s^{-1}).
  - Phytoplankton adjust the assimilation number in response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

Slide 49 Critical depth and upwelling:

NOTES:

NW African Upwelling

Huntsman & Barber (1977)



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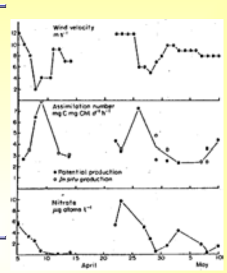
Slide 50 NW African Upwelling

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**
- **When upwelling-favorable winds die down**
  - **Water column warms & stratifies**
  - **Assimilation number increases**
  - **Nitrate uptake at high rate**
- **Sverdrup's critical depth concept applies**



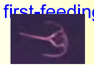
Slide 51 NW African Upwelling

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
  - Hunstman & 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



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Slide 52 Lasker's stable-ocean hypothesis
NOTES: