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### UPWELLING, EKMAN MASS TRANSPORT, AND EL NIÑO, ENSO & PDO

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### Assignment

### Τορις

"Describe the changes in a parcel of water as it is advected offshore from an upwelling center. Answer the following questions: What is meant by 'upwelling', an Ekman spiral, and Ekman transport?"





### **REQUIRED READINGS**

- Chavez, F. P., J. Ryan, S. E. Lluch-Costa & C. Miguel Ñiquen. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299: 217-221. [Describes the warm and cold phases of the Pacific Decadal Oscillation (PDO) and effects on coastal and gyre ecosystems]
- Mann, K. H. and J. R. N. Lazier. 1996. Dynamics of marine ecosystems: biological-physical interactions in the oceans, 2nd Edition. Blackwell Scientific Publications. [Read Chapter 5: Vertical structure in coastal waters: coastal upwelling regions (pp. 139-179). Skim or skip 5.2.3 on Rossby deformation. Also skim or skip 5.6-5.8]
- Ryther, J. H., D. W. Menzel, E. M. Hulburt, C. J. Lorenzen and N. Corwin. 1971. The production and utilization of organic matter in the Peru Coastal current. Inv. Pesq. 35: 43-59. [*This paper describes one of the classic field studies in biological oceanography. A parcel of water was tracked as it was advected from an upwelling system.*]

### SUPPLEMENTAL

- Barber, R. T. and F. P. Chavez. 1986. Ocean variability in relation to living resources during the 1982-83 El Niño. Nature 319: 279-285. [Summarizes one of the most severe recent El Niño events.]
- Chavez, F. P., J. T. Pennington, C. G. Castro, J. P. Ryan, R. P. Michasaki, B. Schlining, P. Walz, K. R. Buck, A. McFadyen, and C. A. Collins. 2002. Biological and chemical consequences of the 1997–1998 El Niño in central California waters. Prog. Oceanogr. 54: 205-232.[Contains an historical review of the CA upwelling ecosystem, and the effects of El Niño]
- Huntsman, S. A. and R. T. Barber. 1977. Primary production off northwest Africa: the relationship to wind and nutrient conditions. Deep-Sea Research 24: 25-34. [Production inversely correlated with upwelling intensity! This surprising result is a consequence of the operation of Sverdrup's (1953) critical depth concept.] {5, 12}
- MacIsaac, J. J., R. C. Dugdale, R. T. Barber, D. Blasco, and T. T. Packard. 1985. Primary production cycle in an upwelling center. Deep-Sea Research 32: 503-529. [A 4 Zone classification of phytoplankton in upwelling systems is described: Zone 1: low Chl a concentrations, low nutrient uptake, Zone II: rapid nutrient uptake (shift up), Zone III: maximum nutrient uptake and production & onset of nutrient limitation, and Zone IV: High Chl <u>a</u>, lowered nutrient uptake (shift down), and significant nutrient limitation. The path through these 4 states takes 8-10 days.]
- McGillicuddy, D. J, R. P. Signell, C. A. Stock. B. A. Keafer, M. D. Keller, R. D. Hetland and D. M. Anderson. 2003. A mechanism for offshore initiation of harmful algal blooms in the coastal Gulf of Maine. J. Plankton Research 25: 1131-1138.[This paper is outlined in Gallagher's Chapter 14. A model in which red tide blooms are seeded from offshore sediments, with blooms resulting from upwelling followed by downwelling winds] {?}
- Pickard, G. L. and W. J. Emery. 1982. Descriptive physical oceanography, 4th edition. Pergamon Press, New York. [Read pages 215-218 on coastal upwelling. See figures on handout on the sea-surface temperature in summer and winter.]
- Pond, S. and G. L. Pickard. 1978. Introductory dynamic oceanography. Pergamon Press, New York. [Skim pages 81-96 on Ekman transport and upwelling.]

### **Comments on upwelling & El Niño**

Upwelling centers constitute less than 1% of the world's oceanic surface area but account for over 50% of the protein catch from the ocean. There are two reasons for this finding. The first is that upwelling centers are zones of high primary production. Ryther *et al.* (1971) document production of up to 10 g C m<sup>-2</sup> d<sup>-1</sup>. Minas *et al.* (1986) describe more typical





primary production rates of roughly 0.6 g C m<sup>-2</sup> d<sup>-1</sup> in the Peruvian upwelling system with higher rates off California and Northwest Africa. **Chavez & Barber (1987)** reviewed previous estimates of production and estimated a mean production of 2.3 g C m<sup>-2</sup> d<sup>-1</sup> for the Peruvian upwelling system. Peruvian upwelling system is the World's richest fishery area because of its large areal extent. The southwest African upwelling center (adjacent to the Benguela Current) has the largest production, and is greater than NW Africa (the Canary Current), which is greater than the Peruvian upwelling center. The Peruvian upwelling center occurs along a longer coastline and has more total production.

**Margalef (1978)** proposed a second explanation for the high production of upwelling systems: turbulence. Upwelling centers are characterized by high rates of vertical turbulence and advection. This energy is sufficient to keep large-celled diatoms (>10  $\mu$ m diameter) within the euphotic zone, and a high proportion of primary production is made up of large-celled phytoplankton. There is an alternate explanation for the dominance of large phytoplankton at upwelling centers based on their being better competitors under conditions of high nutrients (*e.g.*, High  $V_{max}$  for NO<sub>3</sub><sup>-</sup> uptake), but there is only weak evidence for this.

The large individual size of the phytoplankton population allows fish (*e.g.*, Anchoveta, and Sardines) to graze directly on phytoplankton, eliminating the intermediate macrozooplankton link. In other marine ecosystems, the nanophytoplankton are grazed by heterotrophic nanoflagellates and other microzooplankton (*e.g.*, ciliates and copepod nauplii); net zooplankton (*e.g.*, calanoid copepods) graze the microphytoplankton (>2  $\mu$ m). Assuming an optimistic ecological transfer efficiency of 40%, one intermediate grazing link would produce fisheries yields 40% of that obtainable in an upwelling system and two grazer links (*e.g.*, calanoid copepods grazing ciliates which graze nanophytoplankton) would produce fisheries yields that were 16% of that obtainable in an upwelling system. The enhanced vertical advection (modeled by **Smith** *et al.* (1983)) and vertical eddy diffusion rates of nutrients facilitate the growth of large, normally fast-sinking diatoms. The large relative size of the dominant phytoplankton, combined with overall high production rates are the reasons that such increased ecological efficiencies from primary producers to fish are obtainable.

The succession sequence observed in a water mass as it is advected offshore is not all that predictable. Estrada & Blasco (1979) argue that the history of seeding of an upwelling center can have major effects on the history of production and the species composition in that water mass. Smith et al. (1983) describe an unsuccessful model of phytoplankton seeding of the Peruvian upwelling system. With their innovative model of phytoplankton growth and phytoplankton sinking as the cells are advected away from the upwelling center, they'd hoped to explain how diatoms maintain themselves in upwelling centers. Their model didn't fit the observed patterns in phytoplankton community structure. MacIsaac et al. (1985) and Brown & Field (1986) describe recently upwelled water as being Stage I and Zone I respectively. This is water with high nutrient concentrations, but with low Chl a concentrations and low Chl-specific production (i.e., assimilation numbers). MacIsaac et al. (1985) describe the process of adaptation of the recently seeded phytoplankton to the high NO<sub>3</sub> and high turbulent regime as "shift-up"; this occurs in their Zone II. Undoubtedly some of this shift up is successional as well as physiological. Older reviews stressed the importance of conditioning of the water mass (e.g., release of dissolved organic matter (DOM) to chelate free-ion metal activity and the release of organic compounds required by auxotrophs [e.g., B-complex vitamins]), but there isn't much strong evidence for this. Stage II in the **Brown** & Field (1986) scheme and Zone III in the MacIsaac et al. (1985) scheme is the zone of high Chl a, high specific primary production, and reduced nutrients concentrations. The mature water mass offshore or downstream from an upwelling center is classified as Stage III and Zone IV, in which nutrient limitation sets in. This succession sequence takes 8-10 days. Ryther et al. (1971) describe the 1st 5 days of a succession sequence as a parcel of water is advected from a Peruvian upwelling system. They argue that nutrients were not limiting, and that the phytoplankton population was controlled by grazing.

### **UPWELLING AND FISH: LASKER'S STABLE-OCEAN HYPOTHESIS**

Ruben Lasker (1975, 1978, 1988) proposed an innovative hypothesis to explain the large interannual variability in northern anchovy in the California upwelling system. Lasker took hundreds of first-feeding anchovy larvae to sea and added them to natural phytoplankton assemblages collected at different locations in upwelling systems. Surprisingly, the anchovy larvae starved on the chain-forming diatoms that dominated in the well-mixed water columns typical of strong upwelling. These larvae could only feed on the high concentrations of the relatively large, naked dinoflagellate *Gymnodinium splendens* which are found at subsurface Chl *a* maxima. Lasker (1975) proposed that a period of low winds after an upwelling event was required for the development of these subsurface Chl *a* maxima — hence, the stable ocean hypothesis.





Huntsman & Barber (1977) found a similar pattern in the Northwest African upwelling system. During periods of strong, upwelling favorable (equator-ward) winds, the mixing depths were sufficiently deep that the phytoplankton were light-limited. Huntsman & Barber (1977) applied Sverdrup's (1953) critical-depth concept to argue that the highest productivity in this upwelling system is found shortly after a period of upwelling favorable winds. It is during this period of low wind stress that the surface layer warms and stratifies, producing a shallower mixed layer that can result in high production.

Both Lasker (1975) and Huntsman & Barber (1977) that it is the episodic, non steady-state nature of upwelling systems that produces high production and high fisheries yields. Upwelling provides high concentrations of nitrogen and silicate-rich water. Periods of low wind stress allow the surface layers to warm sufficiently for stratification to limit the vertical mixing of phytoplankton cells. With increased vertical stability comes high phytoplankton production and standing stocks. Moreover, Lasker (1975) showed that diatoms are not always the base of the fish food web; dinoflagellates are often the required food source for the key juvenile stages of commercial fish species.

In recent years, the Pacific interdecadal oscillation (PDO) has been discovered and used to explain long-term patterns in abundance of anchoveta and sardines. Curt Ebbesmeyer, a physical oceanographer at the University of Washington, had noted that there were long-term patterns in the physical oceanography of the subarctic Pacific that were coupled to long-term changes in fishery yields. **McGowan et al. (1998)** documented tremendous decadal changes in the abundance of the large macrozooplanker *Calanus pacificus* in the California current system. In the early 1970s, Eppley and co-workers documented very low Chl *a* and production in the central N. Pacific gyre. In the mid 1980s Laws and coworkers found not only higher production, which could have been due to changes in methods, but 2 to 3 times more Chl *a*, which could not be due to differences in methods. It is now known that many of these differences are associated with long-term, decadal-scale, changes in the climate of the Pacific. These long-term changes are called the Parcific decadal oscillation (PDO).

The PDO describes a climate pattern which affects the central Pacific gyres as well as upwelling centers. As shown in Figure 1, there are periods during which production along the California current upwelling centers are reduced and macrozooplankton and fish standing stocks are low (red in Figure 1).



# **Figure 1**. The Pacific decadal oscillation. During positive (red phases), the temperatures are warmer than usual in the California current and productivity is lower. Simultaneously, production is higher in the gyres. http://www.jisao.washington.edu/pdo/

There are phases of the PDO, which **Chavez et al. (2003)** describe as anchovy and sardine phases. In the anchovy phase, water temperature is lower on the California coast, nutrient input and productivity higher and Anchovies dominate. In the Central North Pacific gyre, nutrient input and productivity are lower during the cold phase. These phases, shown in







**Figure 2**. Environmental variables apparently coupled to the Pacific decadal oscillation, Fig. 1 from **Chavez et al. (2003)** 

Figure 2, mark periods when productivity & macrozooplankton abundance is reduced on the California shelf (the Sardine phases) and periods when productivity is high on the California shelf and *Calanus pacificus* abundances are high, the Anchoveta phases.

## PHYSICAL OCEANOGRAPHY OF THE WASHINGTON-OREGON COASTAL UPWELLING

The following description, drawn from the work of Dr. Barbara Hickey (U. Washington), describes the dynamics of upwelling on the Washington-Oregon shelf:

- 1. Wind blows from the North [due to an annually recurring high pressure center off California]
- 2. Ekman Mass transport offshore (90 degrees to the right of the wind direction)
- 3. Divergence develops at the coast
- 4. An eastward sea-surface slope develops setting up a barotropic pressure gradient. The pressure gradient points to the coast (eastward).

![](_page_5_Picture_10.jpeg)

![](_page_5_Picture_11.jpeg)

Drawing (looking South):

![](_page_6_Figure_2.jpeg)

- 5. The barotropic pressure gradient force drives a geostrophic current to the south (the Coriolis force is directed westward to the right of the current direction)
- 6. Offshore transport at the coastal divergence causes upwelling of water from 50-100 m (can be deeper)
- 7. Isopycnal surfaces are tilted upward towards shore (due to temperature mainly).
- The offshore gradient in water-column density structure sets up a baroclinic pressure component to the west (offshore) [The length of the arrows indicates the relative magnitudes of the baroclinic pressure gradient force which increases with depth]
   Baroclinic: =>

==> ===> (Coast) ====> =====>

- 9. At depth (>100-200 m) the offshore baroclinic component>>>barotropic component, producing northward geostrophic flow at depth.
- 10. Because of continuity, net mass transport must be Eastward (onshore in the bottom layer).

### MA BAY UPWELLING

The world's major coastal upwelling centers are located on the Eastern margins of the oceans. Why? Upwelling favorable winds occur on both the eastern and western margins of the ocean. However, the western margins of the ocean basins have strong and deep coastal currents, like the Gulf Stream in the North Atlantic, the Brazil current in the South Atlantic, and the Kuroshio/Oyoshio current system in the Pacific. **Stommel (1948)** was the first to describe why the Western margins of ocean basins are associated with these energetic western boundary currents. It is only on the Eastern margins of ocean basins that one can find a large-scale sea surface density structure in which cold nutrient-rich deep waters are within 100 m of the surface. However, on a smaller scale, colder more nutrient-enriched waters can be found within a few 10s of meters of the surface. On a small scale, upwelling can occur on any coast if the winds are favorable.

Rocky Geyer at WHOI was the first in this region to document the importance of coastal upwelling in MA Bay. Upwelling occurs whenever the winds blow for a period of a few days from the South or Southwest. Rich Signell has modeled this process with a three-dimensional numerical simulation model. His movies are available on his web page (http://crusty.er.usgs.gov/rsignell.html). During periods of upwelling favorable winds, *i.e.*, poleward and parallel to the coast, surface waters are advected offshore by Ekman mass transport to be replaced by cooler, more nutrient-rich deeper waters.

### UPWELLING AND LOW DISSOLVED OXYGEN

Scott Glenn at Rutgers University has used his three-dimensional simulation model of the New Jersey Coast to predict the timing and location of low-dissolved oxygen events on the New Jersey coasts. **Glenn et al. (1996)** and **Glenn's web page** includes a brief description of upwelling and hypoxia on the New Jersey coast. During the summer months, a warm layer of surface water is found close to the coast and extends offshore. After a few days of upwelling-favorable (i.e., southerly or from the south) winds, cool, DIN-rich water upwells near the coast, causing a small phytoplankton bloom. A considerable amount of labile particulate organic matter can sink to the bottom. As the winds die down after a few days, the warm surface water caps the deep water. The strong thermocline limits vertical oxygen diffusion, and hypoxia develops. Because the organic matter gets focused at three 'cusps' along on the coast, the low dissolved oxygen is focused in these areas.

![](_page_6_Picture_16.jpeg)

### **ENSO** EVENTS

Upwelling is a phenomenon that affects only the skin of the ocean (*i.e.*, the upper 100-300 m of the ocean). Slight changes in sea-surface slope and distribution of isopycnal surfaces during an El Niño Southern Oscillation (ENSO) event can have disastrous consequences on the productivity of upwelling systems. During ENSO events, the Easterly winds near the equator weaken, the sea-surface slope along the Pacific tilts towards the east, and the Eastern edge of the Pacific experiences warmer sea-surface temperatures and deepened isopycnal surfaces. Upwelling-favorable winds may be present during ENSO events, but the water from the upper 100-m is no longer as nutrient-rich.

ENSO events are episodic, occurring roughly every 4-5 years. **Barber & Chavez** (1986) document the following ENSO years: 1965, 1969, 1972, 1976, 1982-1983. Mann & Lazier (1996) cite the 1982-1983 ENSO event as the type that occurs only once every one hundred years. The 1997 ENSO event was less

![](_page_7_Figure_4.jpeg)

Figure 3. The multivariate ENSO index, updated weekly at: hundred years. The 1997 http://www.cdc.noaa.gov/ENSO/enso.mei\_index.html

severe than the 1982-1983 event. The multivariate ENSO index is calculated as the 1<sup>st</sup> principal component of a PCA of Pacific-wide gradients in sea surface temperature and pressure. It shows the magnitude of the ENSO events during the last 50 years (Figure 3). The major signals from the 1983 and 1997 ENSO events were a weakening of the NE Trade winds and a warming of the Eastern Pacific sea surface by approximately 4°C from non-ENSO years. More important than the warmer sea surface temperature, which you can recall from **Eppley (1972)** has little effect on production, is the deepening of the nutricline at coastal upwelling centers and at the equatorial divergence.

### **CURRENT STATUS OF ENSO**

The following NOAA site gives the latest ENSO advisory: http://www.cpc.ncep.noaa.gov/products/analysis\_monitoring/enso\_advisory/index.shtml

![](_page_7_Picture_10.jpeg)

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In Fall 2008, oceanic conditions along the equatorial Pacific Pacific equator were near the long-term mean, but in 2004 the temperature anomaly, relative to the long-term mean temperature, was sufficiently positive, warmer than usual, that NOAA declared an El Niño. Figure 4 shows the sea-surface temperatures and sea-surface temperature anomalies in the Pacific on November 26, 2008. NOAA has declared late 2008 to be an ENSO neutral period: neither El Niño nor La Niña.

### **BIOLOGICAL EFFECTS OF EL NIÑO**

The decrease in production at the equatorial divergence during El Niño years has pronounced effects on marine biogeochemical cycles and marine communities. Upwelling favorable (*i.e.*, Westerly along the equator or equator-ward along eastern ocean margins) winds continue unabated during ENSO years, and upwelling intensity remains high. However, during El Niño years, the upwelled water at the coast and at the equator is usually warmer and contains far fewer nutrients.

Barber & Chavez (1983, 1986) and Schreiber & Schreiber (1984) document the biological consequences of the 1982-1983 El Niño. Barber & Chavez studied patterns of primary production at the Peruvian upwelling center, and Schreiber & Schreiber (1984) documented the failure of bird hatcheries on islands located near the equatorial divergence. During ENSO events, birds either do not nest, or they abandon their nests.

The primary production rate drops precipitously at upwelling centers and at the equatorial divergence during ENSO years. With a drop in production, it might be expected that atmospheric  $CO_2$  levels should increase — after all, decreased phytoplankton produced air-sea flux of  $CO_2$ .

enhanced primary production, driven by upwelled nitrogen.

However, during ENSO years, atmospheric  $CO_2$  concentrations decline **C.glf**. (relative to the long-term increase). The reason is that the equatorial divergences are major sites of  $CO_2$  outgassing. During non-ENSO years, upwelling increases the flux of  $CO_2$  from the ocean surface to the atmosphere by transporting  $CO_2$ -rich deep water to the surface. This effect more than offsets the increase in atmosphere to sea flux of  $CO_2$  from

### **UPWELLING ON THE WEB**

There is a tremendous amount of material on upwelling and El Niño on the web. Table 1 shows a brief description of material on upwelling and El Niño on the web.

Table 1. Upwelling and ENSO resources on the web			
Location	Description	URL	
California Current	Upwelling indices from British Columbia through Baja California	http://www.pfeg.noaa.gov/products/PFEL/mo deled/indices/upwelling/NA/upwell_menu_NA. html	
	NOAA office of global programs ENSO page	http://www.ogp.noaa.gov/enso/	
El Niño	NOAA's PMEL El Niño theme page	http://www.pmel.noaa.gov/tao/elnino/nino-ho me.html	

Observed Sea Surface Temperature (\*C)

![](_page_8_Figure_11.jpeg)

**Figure 4**. Sea-surface temperature anomalies for 26 November 2008, indicating a slight cooling relative to the long-term average but not enough to be declared a La Niña.

http://www.cpc.ncep.noaa.gov/products/a nalysis\_monitoring/enso\_update/sstweek\_ c.gif.

![](_page_8_Picture_15.jpeg)

Table 1. Upwelling and ENSO resources on the web			
Location	Description	URL	
	NOAA PMEL: What is an El Niño?	http://www.pmel.noaa.gov/toga-tao/el-Niño-st ory.html	
	NOAA PMEL: Links to 3-d computer animations	http://www.pmel.noaa.gov/tao/vis/tao-vis.html	
	NOAA PMEL: El Niño dynamic height movies	http://www.pmel.noaa.gov/tao/vis/explorer/t-d yn-med.html	
	Scripps Institute of Oceanography El Niño predictions. Using an experimental model, this site predicts mild El Niño conditions for late 2004.	http://meteora.ucsd.edu/~pierce/elnino/elnino. html	
	FSU Ocean-Atmosphere El Niño links	http://www.coaps.fsu.edu/lib/elninolinks/	
MA Bay	Movies of upwelling from MA Bay by Rich Signell	http://crusty.er.usgs.gov/index.html#upwell	
New Jersey	A reprint of a 3-page article by Dr. S. Glenn at Rutgers describing upwelling and low dissolved oxygen off the New Jersey Coast.	http://www.agu.org/sci_soc/eisglenn.html#real -time	
New Jersey	Coastal Ocean Observing Laboratory		
Upwelling & El Niño	A Report to the nation, posted on the U. Washington Atmospheric Sciences department web page. This includes several of the colorful graphics used in the slide show.	http://www.atmos.washington.edu/gcg/RTN/rt nt.html	
Pacific Decadal Oscillation	University of Washington Atmospheric Sciences: an overview of the PDO with graphics & texts	http://tao.atmos.washington.edu/pdo/	

### **Terms and concepts**

CUEA	Coastal u major up	pwelling ecosystem analysis. An international NSF-funded program to analyze the World's welling centers.
Ekman spiral	see Appe	ndix 1-def on WebCT/Vista 4
Ekman mass trans	sport	see Appendix 1-def on WebCT/Vista 4
ENSO		El Niño Southern Oscillation
Geostrophic curre	nts:	Currents modeled by balancing the Coriolis and pressure gradient force (the latter determined
		by sea-surface slope [barotropic component] and seawater density structure [baroclinic component]).
PDO	Pacific D	Decadal oscillation, or Pacific interdecadal oscillation

### **Outline of readings**

![](_page_9_Picture_6.jpeg)

### REQUIRED

Chavez, F. P., J. Ryan, S. E. Lluch-Costa & C. Miguel Ñiquen. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299: 217-221. [Describes the warm and cold phases of the Pacific Decadal Oscillation (PDO) and effects on coastal and gyre ecosystems]

![](_page_10_Figure_3.jpeg)

![](_page_10_Figure_4.jpeg)

Chavez et al. 2003. Fig 3.

### Chavez et al. 2003. Fig 1.

- Mann, K. H. and J. R. N. Lazier. 1996. Dynamics of marine ecosystems: biological-physical interactions in the oceans. Blackwell Scientific Publications. [Read Chapter 5: Vertical structure in coastal waters: coastal upwelling regions (pp. 139-171)]
- 5. Vertical structure in Coastal waters: coastal upwelling regions.
  - 5.1. Introduction
    - 5.1.1. Cushing (1971): 26 million tons of fish, sardines mainly, in the Benguela current region off SW Africa & Canary current off NW Africa, 12 million tons of Peruvian Anchovy, 5 million tons of anchovy & hake in the California current system
    - 5.1.2. "... the key to high biological productivity is the upwelling of 'new' nutrients from deep waters into the euphotic zone and the retention of phytoplankton in well-lighted waters by stratification of the water column."
    - 5.1.3. A few upwelling centers constitute about half of the world's fish catch, but most of these fish are used as fish meal.
    - 5.1.4. Ekman transport
    - 5.1.5. Ocean basins have fast, deep western boundary currents, upwelling of nutrient rich deep water more prevalent on eastern basins
    - 5.1.6. 5 Currents associated with upwelling areas (Fig. 5.01)
      - 5.1.6.1. The California current
      - 5.1.6.2. The Peru current
      - 5.1.6.3. The Canary current off NW Africa
      - 5.1.6.4. The Benguela current
      - 5.1.6.5. The Somali current in the Western Indian Ocean
  - 5.2. The physics of coastal upwelling
  - 5.2.1. The Ekman spiral
- Fig. 5.02. Forces in the Ekman spiral
- Box 5.01 Mathematical derivation of the Ekman spiral
- Fig. 5.03. Horizontal projection of Ekman spiral
  - 5.2.2. Ekman drift and coastal upwelling
    - 5.2.2.1. Ekman mass transport, the net movement of the wind-driven flow, is 90° to the right of the wind (in the Northern Hemisphere, to the left in the Southern hemisphere):

Eugene Gallagher © 2010

![](_page_10_Picture_29.jpeg)

$$M_{E} = -\frac{\tau}{f}.$$
where,  $M_{E} = Ekman \ mass \ transport.$ 
 $\tau = wind \ stress.$ 
 $f = Coriolis \ parameter = 2\omega \ \sin \theta$ 
(5.06)

- 5.2.2.2. A typical wind stress of 0.1 N m<sup>-2</sup> at 45 ° gives  $M_E$  of 1000 kg m<sup>-1</sup> s<sup>-1</sup> one metric tone of water per second flowing 90° to the right of the wind for every meter parallel to the wind.
- 5.2.3. The width of coastal upwelling and the Rossby deformation scale [Skim or skip]

Box 5.02. Derivation of the internal Rossby deformation scale.

- 5.2.4. Variations in upwelling
  - 5.3. The Canary current system
    - 5.3.1. Upwelling and primary production
      - 5.3.1.1. Huntsman & Barber (1977): High productivity results from alternating periods of upwelling and calm periods.
        - 5.3.1.1.1. [Note that Mann & Lazier get the assimilation number story slightly wrong. Assimilation number was used by H & B to document shade adaptation.]
        - 5.3.1.1.2. Mini spring blooms during the calm periods between intense mixing events.
      - 5.3.1.2. Minas et al. (1982): annual production 730 g C m<sup>-2</sup>y<sup>-1</sup> or 2 g C m<sup>-2</sup>d<sup>-1</sup>
      - 5.3.2. Upwelling and zooplankton
      - 5.3.3. Upwelling and fish
      - 5.3.4. Regeneration of nutrients
  - 5.4. Comparison with the Peruvian upwelling system

#### 5.4.1.1. MacIsaac et al. (1985)

5.4.2. Interannual variability in the Peru upwelling system

5.4.2.1. El Niño years

- 5.4.2.1.1. 1965, 1969, 1972, 1976, 1982-1983
- "... but in 1982-1983 an ENSO event occurred with a severity
- that is considered very rare, occurring with a periodicity of 100
- years or more."

5.4.2.1.2. During the 1982-1983 El Niño productivity had dropped to 10 mg C m<sup>-3</sup> d<sup>-1</sup>, but returned to 219 mg C m<sup>-3</sup> d<sup>-1</sup>.

- 5.4.3. Total primary production in the Peruvian upwelling system
- 5.4.4. Secondary production in the Peruvian upwelling system
- 5.4.5. Exploitation of the Peruvian Anchoveta stocks.
- 5.5. The California current system
  - 5.5.1.1. Productivity, Eppley (1972): 150 g C m<sup>-2</sup> y<sup>-1</sup>.
  - 5.5.2. Fish production in the California Current System
  - 5.5.3. The survival of first-feeding larvae
    - 5.5.3.1. Lasker (1975): Stable-ocean hypothesis.
      - 5.5.3.1.1. First-feeding anchovy larvae require high concentrations of the naked dinoflagellate *Gymnodinium splendens*.
      - 5.5.3.1.2. Larvae don't feed much on chain-forming diatoms.
      - 5.5.3.2. Lasker (1978): identified conditions favorable to larvae: a stable ocean with a subsurface Chl *a* maximum
      - 5.5.3.3. Strong winds, turbulence, and strong upwelling, by themselves are unfavorable for larvae.
      - 5.5.3.4. Cury & Roy (1989): identified wind speeds and turbulent conditions favorable for Peruvian Anchoveta and Pacific sardine and W. African sardines and sardinellas: recruitment increases to 5-6 m s<sup>-1</sup> and then declined.
      - 5.5.3.5. Strong winds also transport larvae offshore

![](_page_11_Picture_39.jpeg)

- 5.6. The Benguela upwelling system
  - 5.6.1.1. Waldron & Probyn (1992) established regression between sea surface temperature and NO<sub>3</sub><sup>-</sup>. Using satellite, they estimated total NO<sub>3</sub><sup>-</sup> upwelled. After converting NO<sub>3</sub><sup>-</sup> to carbon equivalents, they estimated total new production:  $4.7 \times 10^{13}$  g C y<sup>-1</sup>, about 0.6-1.4% of total global production.
  - 5.6.2. A 'Benguela Niño'
- 5.7. Some smaller-scale upwelling systems
  - 5.7.1. Summer upwelling off Nova Scotia
  - 5.7.2. Summer upwelling on the west coast of Spain
- 5.8. Conclusions

### Ryther, J. H., D. W. Menzel, E. M. Hulburt, C. J. Lorenzen and N. Corwin. 1971. The production and utilization

of organic matter in the Peru Coastal current. Inv. Pesq. 35: 43-59 [See also Lorenzen (1968) and Dugdale (1972) for analyses of the same cruise data.]

- 1. Introduction.
  - a. Peruvian upwelling during March-April 1966
  - b. Upwelling identified by a drop in surface temperature.
  - c. Buoyed parachute drogue deployed & followed for 5 days.
  - d. 3 times each day, the ship was brought up to the drogue and observations were made.
- 2. Methods
  - a. Stations occupied at 6 AM, 12N, and 6 PM each day.
  - b. 5 light levels chosen for P vs. I curves: 100, 50, 25, 10 and 1 % of incident radiation.
  - c. water samples collected
  - d. Dissolved organic matter (DOM) excretion was measured
  - e. Phytoplankton were counted live

### 3. Results

- a. Phytoplankton
  - i. 9 species described
  - ii. enumerated daily, *Chaetoceros debilis* was the most numerous
- b. Chemistry
  - i. euphotic layer ranged between 11 and 28 m
  - ii. O<sub>2</sub> increased and phosphate, nitrate and silicate decreased in the upper 50 m
- c. Primary production:
  - i. Estimated using 3 different techniques, assuming a RKR = O:C:N:P = 276:106:16:1 and C/Chl ratio of 35
  - ii. <sup>14</sup>C measurements made at each station: 3 separate estimates of carbon assimilation made over the 3-day period
    - (1) Carbon assimilated during that 24 hour period, starting with 6 AM stations
    - (2) carbon uptake over 24 hours added to that initially present 12 Noon stations
    - (3) carbon accumulated over the following 24 hours added to the respective amounts initially added from 18:00 stations.
- Fig. 3. Changes in organic carbon as determined by different criteria and integrated between the surface and 50 m (A and B) or the base of the euphotic layer c.
  - iii. Since the population maintained the same RKR ratios throughout the 5-day period, some factor other than nutrient deficiency was responsible for the decline in phytoplankton
  - iv. Comparison of the 3 methods
    - (1) Nutrient balances are the most variable
    - (2) phosphate most reliable
    - (3)  $O_2$  not conservative
    - (4) Changes in  $NO_3^-$  curve due to denitrification in the sub-euphotic depths
  - v. Generalizations
    - (1) organic production calculated from nutrient uptake and oxygen production was appreciably higher at all times than indicated by direct measurement of the particulate organic fraction [note changes in the scale of the ordinate]
    - (2) The chemical changes in the water suggest a net production of organic matter throughout the period, despite the decline of the standing crop of particulate organic matter during the latter half of the study

![](_page_12_Picture_45.jpeg)

#### EEOS 630 Biol. Ocean. Processes Upwelling, P. 14 of 27.

- (3) The <sup>14</sup>C methods gave substantially the same result as results based on particulate N, P and Chl a accumulation.
  - (a) differences in the <sup>14</sup>C curves are due to the slightly different Y intercepts.
  - (b) slopes of the  ${}^{14}C$  curves are about the same.
- (4) Differences between the POC and <sup>14</sup>C methods may be due to 2 factors:
  - (a) the liberation of DOM during or following growth
  - (b) loss of particulate matter to the system
- d. Loss of DOM by phytoplankton
  - i. Fogg had studied 7% to 50% with mean=33.5% of carbon fixed
  - ii. Peru had one value of 45% of DOM release
- e. Loss due to sinking and grazing
  - i. Results of this study not due to sinking
  - ii. Some sinking occurred but it was not a heavy loss term
  - iii. Grazing:
    - (1) Not assessed because of grazing losses
    - (2) Peruvian anchovy is a major grazer, with a diet of 98% diatoms.
- 4. Discussion
  - Peruvian waters contained the highest levels of organic production ever measured ranging from 3.14 g  $Cm^{-2} d^{-1}$  to 11.74 g C  $m^{-2}d^{-1}$ .
- 5. Summary
  - a. The production and fate of organic matter was followed by following a parcel of newly-upwelled waters for 5 days.
  - b. Phytoplankton production averaged 10 g C  $m^{-2} d^{-1}$  over the 5-d period, but the population reached a maximum standing crop on the third day and thereafter declined nearly to its original level
  - c. Decline of the population believed due to grazing.

### SUPPLEMENTAL

#### Barber, R. T. and F. P. Chavez. 1986. Ocean variability in relation to living resources during the 1982-83 El Niño. Nature 319: 279-285.

- 1. Introduction
  - a. El Niño: name given to a series of ocean and atmosphere changes that spread across the Pacific from Australia and Asia to South America, then move north and south so that the Americas are affected from Alaska to the tip of Chile.
    - i. El ñNiño originally referred to a warm surface current that flows southward along the coast of Ecuador & Peru.
    - ii. El Niño is one facet of ENSO: El Niño southern oscillation
  - b. The coastal area off the west coast of South America is the most productive region of the world ocean  $(< 1\% \text{ of area}, \approx 50\% \text{ of protein from the sea})$ 
    - i. upwelling of cold, nutrient rich water
    - ii. subsurface waters are cool and separated by a thermal gradient, below which are high nutrients.
    - iii. productivity enhancement continues as long as winds are upwelling-favorable
    - iv. Upwelling is less than 1 % of the oceans surface area but provides more than 50% of the protein collected from the sea.
      - (1) Figure 1: Fish catch versus temperature anomaly
      - (2) When the ocean is warmer, fish catch is reduced.

2. Environmental setting.

- a. Upwelling is a response to local winds, but the winds along South America are part of the trade-wind system of the Pacific.
- b. Trade winds set up a basin-wide East-to-West slope in sea level and the thermal structure of the Pacific
  - i. Strong easterly trades exert a westward frictional drag, resulting in a piling up of warm water in the Western Pacific
  - ii. There is a 0.5 m higher water column in the western Pacific and a thermocline slope of 100 m with the Western Pacific being deeper.

![](_page_13_Picture_41.jpeg)

- iii. Normally, the thermocline is closer to the surface of the west Coast of South America Figure 3.
- During and after the El Niño: after the El Niño, there is a phenomenal tilt in the thermocline toward the surface Fig. 3. in the eastern boundary.
  - Overall effect of winds iv.
    - Provide the local driving force for vertical transport (1)
    - (2) they set up the basin-wide thermocline and nutricline slope that determines the temperature and nutrient content of the water that is entrained in upwelling circulation
    - (3) Equator-ward winds during upwelling did not weaken during the 1982-1983 El Niño. Coastal winds were strong through March 1983, but after 11/82, the surface waters were poor in nutrients. The upwelled water is entrained from 40-80 m Fig. 4.
    - the nutricline depression, not cessation of upwelling, is the process that initially (4) reduces the nutrient supply to the surface layer
    - From Dec. 82 to June 1983, nutrient concentrations were below the detection limit (5) of 0.02 µM.
  - Progression of the 1982-1983 El ñNiño event c.
    - August 1982, reached the Galapagos. i.
    - ii. late Sept. 1982, reached the cast of Peru
      - Nitrate before and after the event were 4-6  $\mu$ M. (1)
      - (2)Concentrations greater than 2µM are adequate for phytoplankton
    - Nov. 82: iii.
      - (1)thermocline depressed over 100 m deeper than normal off Peru
      - (2)nutrients less than the 0.02 µM detection limit
      - (3)High Chl *a* standing stock  $(1 \text{ mg m}^{-3})$ 
        - (a) extended only 30 km from coast under El Niño
          - (b) Normally at 150 km
  - d. Production:
    - El Niño PP=51 mg C m<sup>-3</sup>d<sup>-1</sup> i
      - Normal (Nov. 83): PP= 192 mg C m<sup>-3</sup>d<sup>-1</sup> 3.8 times higher ii.
    - Thermocline deepened iii.
  - March 1983: e.
    - production along 5°S transect reduced to 27 mg C m<sup>-3</sup>d<sup>-1</sup> i.
    - 9.2 times less than under normal conditions ii.
  - f. May 1983: maximum effects.
    - (1)onshore and pole-ward flow.
    - (2)productivity characteristic of a gyre
    - productivity dropped to 10 mg C m<sup>-3</sup>d<sup>-1</sup>, during July 1983 it was 219 mg C m<sup>-3</sup>d<sup>-1</sup> (3)
  - 21.3X higher July 1983 Recovery
  - g.

3.

g.

- EFFECTS ON LIVING RESOURCES
  - Well-known effects on Peruvian anchovy. a.
    - Opposing view: fish move offshore (wrong) i.
    - ii. Species did not just redistribute themselves.
    - iii. decrease in growth and reproduction
  - Hake did redistribute themselves. b.
  - Shrimp catches increased, (redistribution?) C.
  - Scallops increased during the El ñNiño: faster maturation, faster larval development, reduction of d. predators, and faster maturation of juvenile scallops
  - Jack Mackerel disappeared from catch in December. e.
  - f. Sardine: decreased to almost zero in Ecuador, and increased in the Chilean fishery: i.e., some movement.
    - distribution centered inshore where there is high Chl a. i.
    - oil content drastically reduced, and were caught easily as they moved into the nearshore zone. ii.
    - The catch of Peruvian anchovy (*Engraulis ringens*)
      - Once the world's largest fishery i.
      - ii. In 1983 was 118,000 tons, <1% of the catch of a decade ago.

![](_page_14_Picture_49.jpeg)

Upwelling Normal

- h. Northern anchovy (off California) *Engraulis mordax*: body wight low, spawning at smaller size, growth of juveniles was 36% less
- 4. March 1985, Anchovies back

Chavez, F. P., J. T. Pennington, C. G. Castro, J. P. Ryan, R. P. Michasaki, B. Schlining, P. Walz, K. R. Buck, A. McFadyen, and C. A. Collins. 2002. Biological and chemical consequences of the 1997–1998 El Niño in central California waters. Prog. Oceanogr. 54: 205-232. [Contains an historical review of the CA upwelling ecosystem, and the effects of El Niño]

#### Pickard, G. L. and W. J. Emery. 1982. Descriptive physical oceanography. Pergamon Press, New York. [Read pp. 215-218 on coastal upwelling] 8.2 Coastal upwelling.

- 5. Universitie a talaaa alaa alaa a
- 5. Upwelling takes place along eastern boundaries of oceans: Why?
- 6. Ekman (1905): Upwelling is the result of the effect of the rotation of the earth on bodies moving relative to the earth.
  - a. Fig. 8.1 Wind-driven currents-northern hemisphere (a) forces and motion of surface parcel P. (b) plan view of forces and motion and water velocity as a function of depth.
    - i. Forces at work
      - (1) F, frictional stress [wind shear stress]
      - (2)  $F_{\rm b}$  retarding force on the bottom parcel
      - (3) F<sub>c</sub> Coriolis force acting at right angles to the direction of motion
    - ii. Patterns:
      - (1) surface flow 45° to right of wind in northern hemisphere.

![](_page_15_Figure_15.jpeg)

Chavez et al. 2002. Fig 13 Nutrients, phytoplankton & Zooplankton in upwelling centers

- (2) Ekman mass transport is 90° to the right of wind
- in N. hemisphere, and 90° to the left of wind shear direction in the S. Hemisphere
   (3) Ekman spiral produced
- b.  $D_e = depth of frictional influence, or Ekman depth$ 
  - i. [the direction of the flow becomes opposite to the surface at  $z = D_E$ , where the speed has fallen to exp  $(-\pi) = 0.04$  of surface speed]
    - ii. Factors affecting  $D_E$ :
      - (1) eddy friction in the water
        - (2) Coriolis parameter.
    - iii. Examples of  $D_E$ :
      - (1) for wind speeds of 10 m/sec at 10, 45, and 80°, the  $D_E$  would be 100, 50 and 45 m respectively.
      - (2) For wind speed = 20 m/sec, the D<sub>E</sub> would be 200, 100 and 90 m respectively
- 7. Upwelling:

"If the wind blows parallel to the coast and toward the equator at the eastern boundary of an ocean, water in the Ekman layer will tend to move <u>away from the</u> <u>coast</u> in either hemisphere and will have to be replaced with water upwelling from below the layer."

- 8. It is important to note that upwelled water is not deep water. The source of the water is between 50 and 300 m. The shallow source of the water helps explain the relatively drastic consequences of El Niño.
  - a. Off North America from April to August, upwelled water off the coast from British Columbia to California comes from water no more than 300 m deep.
  - b. Off South America, upwelling comes from an average depth of 130 m.
- 9. Usually upwelling brings low salinity water to the surface, the exception is N. America where salinity increases with depth.

![](_page_15_Picture_33.jpeg)

EEOS 630 Biol. Ocean. Processes Upwelling, P. 17 of 27.

### Pond, S. and G. L. Pickard. 1978. Introductory dynamic oceanography. Pergamon Press, New York *[Skim pages 81-96]*

- 1. History of the effects of wind stress on coastal currents:
  - a. 1898 Nansen explained why currents are to the right of wind
  - b. 1902 Ekman explained how rotation of the earth affects flow.
  - c. 1947: Sverdrup showed how equatorial currents could be explained by wind
  - d. 1948: Stommel explained Western intensification of boundary current (*i.e.*, why there is a Kuroshio, Oyashio, and Gulf Stream, Brazil current)
  - e. 1950: Munk obtained an analytic expressions for wind-driven currents
  - P. 82: Fig. 9.1 forces on a parcel of water in the surface layer
- 3. Equations of motion with friction included:

2.

$$\frac{du}{dt} = fv - \alpha \frac{\partial \rho}{\partial x} + F_x$$

$$\frac{dv}{dt} = -fu - \alpha \frac{\partial \rho}{\partial y} + F_y$$
(9.1, p. 83)
  
re  $f = the \ Coriolis \ parameter = 2 \ \omega \ \sin \theta$  and

where, f = the Coriolis parameter  $= 2 \omega \sin \theta$ , and  $F_x$  and  $F_y = the$  components of friction per unit mass in the fluid.

If there are no accelerations (*i.e.*, a steady state and zero or negligible advective accelerations):

$$\frac{du}{dt} = \frac{dv}{dt} = 0.$$

$$fv + F_x - \alpha \frac{\partial \rho}{\partial x} = 0.$$

$$fu + F_y - \alpha \frac{\partial \rho}{\partial y} = 0.$$
(9.2)

i.e., Coriolis + friction + pressure = 0 (as shown in Figure 9.2)

Fig 9.2 Three forces in equilibrium on a parcel of water.

![](_page_16_Picture_17.jpeg)

- 4. Modeling frictional stress:
  - a. Newton:

tau = 
$$\tau$$
  
=  $\mu \frac{\partial u}{\partial z}$   
=  $\rho v \frac{\partial u}{\partial z}$   
where, tau = friction stress  
= force per unit area on a planeparallel to flow  
 $\mu$  = coefficient of (molecular) dynamic viscosity  
=  $10^{-3} kg m^{-1} s^{-1}$   
 $nu = v = \frac{\mu}{\rho}$   
= the coefficient of kinematic molecular viscosity  
= $10^{-6}m^2 s$ 

b. These numbers apply in laminar flow, Re < 1000, ( $Re = \frac{L v \rho}{\eta} = \frac{L v}{v}$ .)

c. kinematic eddy viscosity:

kinematic viscosity  $A_x$  and  $A_y = 10^5 \text{ m}^2 \text{ s}^{-1}$ 

. .

 $A_z = 10^{-1} m^2 s^{-1}$ 

- $\underline{n}.\underline{b}.$ , due to density stratification, horizontal eddy diffusion is one million times more intense than vertical eddy diffusion
- d. Eddy friction stress:  $\tau = \tau = \rho * A_z (\delta u / \delta z)$ : expresses the force of one layer of fluid on an area of its neighbor above or below,

~

e. For substitution in the equation of motion, we need an expression for the force on the mass of a fluid:

Force per unit mass 
$$= \frac{1}{\rho} \frac{\partial \tau}{\partial z} = \alpha \frac{\partial \tau}{\partial z}$$
.  
 $= \alpha \frac{\partial}{\partial z} \left( \rho A_z \frac{\partial u}{\partial z} \right)$ .  
where,  $\alpha = \frac{1}{\rho}$  = specific volume of water  
 $A_z$  = Vertical kinematic eddy viscosity.  
 $\tau$  = eddy friction stress, a force per unit area

If we assume  $\rho * A_z$  is constant:

Friction force per unit mass = 
$$A_z \frac{\partial^2 u}{\partial z^2}$$
. (9.5, p. 86)

f. Then the horizontal equations of motion become:

![](_page_17_Picture_15.jpeg)

EEOS 630 Biol. Ocean. Processes Upwelling, P. 19 of 27.

$$f\mathbf{v} + \alpha \frac{\partial \mathbf{\tau}_{\mathbf{x}}}{\partial \mathbf{z}} = f\mathbf{v} + A_{\mathbf{z}} \frac{\partial^2 \mathbf{u}}{\partial \mathbf{z}^2}.$$
  
$$= \alpha \frac{\partial \rho}{\partial \mathbf{x}}.$$
  
$$-f\mathbf{u} + \alpha \frac{\partial \mathbf{\tau}_{\mathbf{y}}}{\partial \mathbf{z}} = -f\mathbf{u} + A_{\mathbf{z}} \frac{\partial^2 \mathbf{v}}{\partial \mathbf{z}^2}.$$
  
$$= \alpha \frac{\partial \rho}{\partial \mathbf{y}}.$$
  
(9.6, p. 86)

- 5. Ekman's solutions to the equations of motion with friction present assumes:
  - a. No boundaries
  - b. infinitely deep water (to avoid bottom friction term)
  - c.  $A_z$  constant
  - d. a steady wind blowing for a long time
  - e. homogeneous water so that  $d\rho/dx = d\rho/dy = 0$  as long as the sea surface is level
- 6. Ekman's equations:

where,

$$f\mathbf{v} + A_z \frac{\partial^2 \mathbf{u}}{\partial z^2} = \mathbf{0}.$$
  
-f\mathbf{u} + A\_z  $\frac{\partial^2 \mathbf{v}}{\partial z^2} = \mathbf{0}.$  (9.8, p. 87)

*i.e.*, Coriolis + Friction = 0 Solutions:

$$\mathbf{u} = \pm V_o \cos\left(\frac{\pi}{4} + \left[\frac{\pi}{D_E}\right]\right) e^{\left[\frac{-\pi}{D_E}\right]}. \quad [+ for N. hem., - for southern hemisphere]$$
$$\mathbf{v} = V_o \sin\left(\frac{\pi}{4} + \left[\frac{\pi}{D_E}\right]\right) e^{\left[\frac{-\pi}{D_E}\right]}$$
$$V_o = \frac{\sqrt{2} \pi \tau_{yy}}{D_E \rho |f|}$$
(9.10)

= the total surface current.  $\tau_{yy} = magnitude of the wind stress \approx prop. (wind speed)^{2}.$  |f| = absolute value of the Coriolis parameter.  $= |2 \ \omega \ sin \ \theta |.$   $D_{E} = \pi \sqrt{\left(\frac{2 A_{z}}{|f|}\right)}$   $A_{z} = Vertical kinematic eddy viscosity$ a. Solutions: i. at sea surface u = ± V<sub>0</sub>\* cos 45° sea surface flows at a 45° relative to wind

ii. below the surface, current speed becomes smaller as depth increases =  $V_o e^{\overline{D_E}}$ .

![](_page_18_Picture_14.jpeg)

 $-\pi z$ 

![](_page_18_Picture_15.jpeg)

iii. the direction of the flow becomes opposite to the surface at  $z = D_E$ , where the speed has fallen to exp  $(-\pi) = 0.04$  of surface speed.

Table 2. 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 $f(W, wind speed \& \theta,$ latitude): $D_E \approx \frac{4.3 W}{\sqrt{\sin \theta}}$				
		]	Latitude	
		10°	45°	80°
V <sub>o</sub> /W		0.030	0.015	0.013
Wind	10  m/sec $D_{E} =$	100m	50 m	45 m
Speed	20/m/sec $D_E =$	200m	100 m	90 m
W= wind velocity V= the velocity of the sea surface D <sub>E</sub> = Ekman Depth				

- 7. Transport and upwelling
  - a. Upwelling at right angles to the wind direction in the Northern Hemisphere.
  - b. Equation of continuity requires that there must be inflow from the left of the wind direction (or from below) to replace the flow from the right
  - c. Upwelling: the vertical advection of water from below the surface near regions of Ekman transport
  - d. In the Northern hemisphere on the eastern oceanic margin, the wind must blow along the coast in a southerly direction
  - e. In general, upwelling will occur with the wind blows equator-ward along an eastern boundary of the ocean in either hemisphere or pole-ward along a western boundary, although this latter situation is less common.
  - f. The upwelled water does not come from great depths (200-300 m, maximum)
  - g. Upwelling areas constitute some 90% of the world's fisheries catches but only 2-3% of the ocean's surface area.
- 8. Upwelling or downwelling away from boundaries: convergences and divergences
- 9. Bottom friction and shallow water effects
- 10. Limitations of the Ekman theory
  - a. No boundaries not realistic but not too bad
  - b. infinitely deep water not exactly true.
  - c.  $A_z$  constant probably not true
  - d. Steady state solution and steady wind probably a real source of difficulty
  - e. Homogenous water distinctly unreal Sverdrup corrected this.

MacIsaac, J. J., R. C. Dugdale, R. T. Barber, D. Blasco, and T. T. Packard. 1985. Primary production cycle in an upwelling center. Deep-Sea Research 32: 503-529 [A 4 Zone classification of phytoplankton in upwelling systems is described: Zone 1: low Chl a concentrations, low nutrient uptake, Zone II: rapid nutrient uptake (shift up), Zone III: maximum nutrient uptake and production & onset of nutrient limitation, and Zone IV: High Chl a, lowered nutrient uptake (shift down), and significant nutrient limitation. The path through these 4 states takes 8-10 days.]

- 1. Generalizations:
  - a. Productivity reduced during times of dinoflagellate dominance
  - b. Peruvian upwelling more productive than the African upwelling

![](_page_19_Picture_24.jpeg)

- i. African upwelling production reduced due to high winds and resultant deep mixing
- ii. differences in the nutrient regime.
- iii. persistent upwelling centers important
- 2. 4 Zone phytoplankton classification proposed
  - a. Zone I
    - i. cold, nutrient rich water.
    - ii. low Chl a concentration
    - iii. phytoplankton growing with low nutrient uptake [chelation effects]
  - b. Zone II: Shift up.
    - i. water stabilized by solar heating
    - ii. phytoplankton P vs. I parameters adapt
    - iii. rapid nutrient uptake
    - iv. increased phytoplankton growth rate.
  - c. Zone III: Zone of maximal growth rates
    - i. maximum nutrient uptake
    - ii. rapid increase in phytoplankton biomass
    - iii. all rate processes at maximum rates
    - iv. onset of nutrient limitation
  - d. Zone IV: Shift down
    - i. High Chl a
    - ii. Significant nutrient limitation
    - iii. slowed nutrient uptake

#### Schreiber, R. W. and E. A. Schreiber. 1984. Central Pacific seabirds and the El Niño Southern oscillation: 1982-1983 perspectives. Science 225: 713-716. {9}

- 1. Abstract
  - 1.1. The breeding chronology of the seabird community on Christmas Island (2°N, 157° W) were interrupted by the 82-83 El ñNiño
  - 1.2. effects far distant from coastal upwelling
- 2. Introduction:
  - 2.1. El Niño is the periodic appearance of warm water off Ecuador and Peru.
  - 2.2. The breeding chronology and reproductive attempts of the seabird community on Christmas Island in the central Pacific (2°N, 157°W) were interrupted: failure and disappearance of the entire seabird community
    - 2.2.1. 1 large egg, long incubations, extended parental care, post-fledgling feeding of juveniles, deferred maturity, long life span.
    - 2.2.2. pelagic foragers.
    - 2.2.3. dependent on predator fish to drive squid and smaller fish toward the ocean surface.
    - 2.2.4. distribution restricted by low food availability.
  - 2.3. 40's through 1982 detected no total reproductive failures and birds breed at many times of year.
- 3. Early summer 1982
  - 3.1. Early nesting birds were not affected in the summer of 1982, but late nesters were totally unsuccessful
  - 3.2. Great frigate birds nested successfully, all starved by November.
- 4. November 1982,
  - 4.1. total reproductive failure of all species present.
  - 4.2. brown boobies all failed in nesting attempts.
- 5. May and June 1983
  - 5.1. some birds nesting
  - 5.2. 1% of normal sooties returned
  - October 1983: 20% of normal nesting.
- 7. Summary:

6.

- 7.1. Figure 1: bird population collapse
- 7.2. SST very high until summer '83
- 7.3. rainfall higher than normal
  - birds flooded out of nests.
- 7.4. sea-level higher than normal
- 7.5. seabirds die by the millions off Ecuador and Peru.
- 7.6. once a century ENSO catastrophe

![](_page_20_Picture_53.jpeg)

![](_page_20_Picture_54.jpeg)

- 7.7. primary productivity declined drastically.
- Other ENSO years:

8.

- 8.1. 1940-41
- 8.2. 1954
- 8.3. 1957-1958
- 8.4. 1963-1965
- 8.5. 1969
- 8.6. 1972-1973
- 8.7. 1976
- 8.8. 1982-1983

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- Barber, R. T. and J. H. Ryther. 1969. Organic chelators: factors affecting primary production in the Cromwell Current upwelling. J. exp. Mar. Biol. Ecol. 3: 191-199.
- Barber, R. T. and R. L. Smith. Coastal upwelling ecosystems. Pp. 31-68 in A. R. Longhurst, ed., Analysis of marine ecosystems. academic Press, New York. 741 pp.
- Barber, R. T. and W. O. Smith. 1981. The role of circulation, sinking, and vertical migration in physical sorting of phytoplankton in the upwelling center at 15° S. Pp. 366-371 in F. A. Richards (ed.), Coastal Upwelling. American Geophysical Union, Washington D.C. [This paper introduces the modeling approach dealt with more fully in Smith et al. 1983. Both papers address the question, 'Can the size structure of phytoplankton in upwelling systems be explained by cell sinking rates?']
- Barber, R. T. and F. P. Chavez. 1983. Biological consequences of El Niño. Science 222: 1203-1210. [Their Fig. 7, fisheries catch vs seasurface temperature anomaly, is especially interesting.]

- Barber, R. T. and F. P. Chavez. 1986. Ocean variability in relation to living resources during the 1982-83 El Niño. Nature *319*: 279-285.
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- Boyle, E. 1998. Pumping iron makes thinner diatoms. Nature 393: 733-734. [Commentary on Hutchins & Bruland 1998 & Takeda (1998) Fe affects uptake of Si relative to nitrate. Hutchins & Bruland (11998) look at Big Sur, with a low river input, narrow continental shelf, Fe spikes increased phytoplankton growth. Low Si:C ratios in Fe enhanced experiments results in little increase in Si removal despite higher diatom growth. Fe-limited diatoms growth thicker tests] {23}
- Breaker, L. C. and C. N. K. Mooers. 1986. Oceanic variability off the central California coast. Prog. Oceanogr. 17: 61-135. [Describes mesoscale variability off the coast of CA with field measurements, mathematical models, and satellite imagery from the Coastal Zone Color Scanner.]

![](_page_21_Picture_24.jpeg)

BY NC SF

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- Brown, P. C. and J. G. Field. 1986. Factors limiting phytoplankton production in a nearshore upwelling area. J. Plankton Research 8: 55-68. [Productivity was measured in water upwelled off the Benguela region of South Africa. Newly upwelled water (Stage I) has low production because of low phytoplankton standing stocks, mature upwelled water (Stage II) has high Chl a but slightly lower production due to nutrient limitation.]
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- Cushing, 1971. Upwelling and the production of fish. Pp. 255-334 in F. S. Russell & M. Yonge, eds. Advances in Marine Biology vol. 9 Academic Press, New York. [Short food chains produce large yields; Much of the material found here http://www.fao.org/docrep/89204E/89204E00.h tm]{?}
- Dugdale, R. C. 1972. Chemical oceanography and primary productivity in upwelling regions. Geoforum 11: 47-61. [The cruises and data described in this paper are also analyzed by Lorenzen (1968) and Ryther <u>et al.</u> (1971).] {13, 24, 25}
- Dugdale, R. C. and F. P. Wilkinson. 1989. New production in the upwelling center at Point Conception, California: temporal and spatial patterns. Deep-Sea Res. *36*: 985-1007.
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- Glynn, P. W. 1988. El Niño-Southern Oscillation 1982-1983: nearshore population, community and ecosystem responses. Ann. Rev. Ecol. Syst. *19*: 309-346.
- Huntsman, S. A. and R. T. Barber. 1977. Primary production off northwest Africa: the relationship to wind and nutrient conditions. Deep-Sea Research 24: 25-34. [Production inversely correlated with upwelling intensity! This surprising result is a consequence of the operation of Sverdrup's (1953) critical depth concept'.] {5, 12}
- Hutchins, D. A. and K. W. Bruland 1998. Iron-limited diatom growth and Si:N uptake ratios in a coastal upwelling regime. Nature 393: 561-564.
  [Commentary by Boyle 1998. Evidence for Fe limitation in the Big Sur region. Diatoms stressed by lack of iron deplete surface waters of silicic acid.. Fe limitation leads to faster sinking diatoms See also Bruland et al. 2001.] {23}
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![](_page_22_Picture_15.jpeg)

#### EEOS 630 Biol. Ocean. Processes Upwelling, P. 24 of 27.

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- MacIsaac, J. J., R. C. Dugdale, R. T. Barber, D. Blasco, and T. T. Packard. 1985. Primary production cycle in an upwelling center. Deep-Sea Research 32: 503-529. [A 4 Zone classification of phytoplankton in upwelling systems is described: Zone 1: low Chl <u>a</u> concentrations, low nutrient uptake, Zone II: rapid nutrient uptake (shift up), Zone III: maximum nutrient uptake and production & onset of nutrient limitation, and Zone IV: High Chl <u>a</u>, lowered nutrient uptake (shift down), and significant nutrient limitation. The path through these 4 states takes 8-10 days.]
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![](_page_23_Picture_14.jpeg)

![](_page_23_Picture_15.jpeg)

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- Schreiber, R. W. and E. A. Schreiber. 1984. Central Pacific seabirds and the El Niño Southern oscillation: 1982-1983 perspectives. Science 225: 713-716. [Nesting birds abandoned their fledglings at the onset of the El Niño.] {9}
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### **PACIFIC INTERDECADAL OSCILLATION**

- Chavez, F P., Ryan, J, Lluch-Cota, S. E., Miguel Niquen C.. 2003. From Anchovies to Sardines and Back: Multidecadal Change in the Pacific Ocean. Science 299: 217-221. [A review of the Pacific decadal oscillation] {5, 26}
- Karl, D. M., R. R. Bidigare and R. M. Letelier. 2001. Long-term changes in plankton community structure and productivity in the North Pacific subtropical gyre: the domain shift hypothesis. Deep-Sea Res. 48: 1449-1470. [Over 30 years, Chl <u>a</u> and primary production in the North Pacific subtropical gyre doubled while silicate and phosphorus decreased. This domain shift towards prokaryotes has altered geochemistry & food webs] {?}
- Mantua, N. J., S. R. Hare, Y Zhang, J. M. Wallace, R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteorological Soc. 78: 1069-1079. [Principal components analysis reveals decadal patterns of change in oceanographic, especially ecological, time series. Roemmich & McGowan (1995) had earlier documented changes in CA current macrozooplankton and temperature][?]

![](_page_24_Picture_16.jpeg)

#### EEOS 630 Biol. Ocean. Processes Upwelling, P. 26 of 27.

- McGowan, J. A, D. R. Cayan, and L. M. Dorman. 1998. Climate-ocean variability and ecosystem response in the Northeast Pacific. Science 281: 210-217. {5}
- Nichols, F. H. 1985. Abundance fluctuations among benthic invertebrates in two Pacific estuaries. Estuaries 8: 136-144. [Comparison of a shallow subtidal community in San Francisco Bay, and a community in the deepest part of Puget Sound (the 100-fathom hole in Elliot Bay). The latter community changed dramatically in 20 years, with the change attributed here to organic enrichment. Nichols (1988), Nichols (2001) & Nichols (2003) recanted this conclusion] {26}
- Nichols, F. H. 1988. Long-term changes in a deep Puget Sound benthic community: local or basin-wide? Pp. 65-71 in Proceedings of the 1st Annual Meeting on Puget Sound Research. Puget Sound Water Quality Authority, Olympia WA.
  [Pectinaria, among the dominants in the 1960s had disappeared by the early 80s, leading Nichols 1985 to conclude that organic enrichment had led to a Pearson-Rosenberg successional replacement. After Nichols (1985) published this conclusion, <u>Pectinaria</u> returned, leading Nichols to argue for long-term cycles] {26}
- Nichols, F. H. 2001. Is climate change a factor in observed interdecadal change in the deep Puget Sound benthos? Puget Sound Research Conference 2001 [pdf available online] {26}

Nichols, F. H. 2003. Interdecadal change in the deep

### Index

Conversion factors 

Puget Sound benthos. Hydrobiologia 493: 95-114. [Summarizes 30+ years of sampling of the 100-fathom hole in Puget Sound. The Pacific Decadal Oscillation is one of several factrors, including organic enrichment, and bulldozing, that may account for the differences in community structure] {26}

- Roemmich, D. and J. McGowan. 1995.Climatic warming and the decline of zooplankton in the California Current. Science 267: 1324-1326. [Since 1951 an 80% decline of macrozooplankton biomass and a 1.5°C increase in temperature] [25]
- Venrick, E. L., J. A. McGowan, D. R. Cayan and T. L. Hayward. 1987. Climate and Chlorophyll a: long-term trends in the central north Pacific Ocean. Science 238: 70-72. [Chl a concentration has nearly doubled between 1968 and the early 1980's due to changes in atmospheric and physical oceanographic forcing of nutrient flux. The higher rates of production observed in the 1980's may reflect real changes in production, not changes in methodology.] {?}
- Williams, J. G. 2003. Sardine Fishing in the early 20<sup>th</sup> century. Science 300: 2003. [A letter to the editor in response to Chavez et al. (2003) Chavez had stated low sardines in the 1920s. Williams disagrees.]

### Miscellaneous

Eppley, R. W. 1972. Temperature and phytoplankton growth in the sea. Fish. Bull. 70: 1063-1085. [

![](_page_25_Picture_15.jpeg)

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![](_page_26_Picture_3.jpeg)