Ocean Nutrients in the Bay: Are they important?

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Motivation

California ocean characterized by upwelling of cold, nutrient-rich water – strongest in early summer.

Nitrate concentration of ~35µM in 8.5^{o}C water.

Water at mouth transported far into Bay each tidal cycle

– may intrude further as density-driven lower layer.

- *How do nutrient levels vary in ocean source waters?*

  What controls this loading?

  When are concentrations highest?

- *How is nutrient-rich water transported into the Bay?*

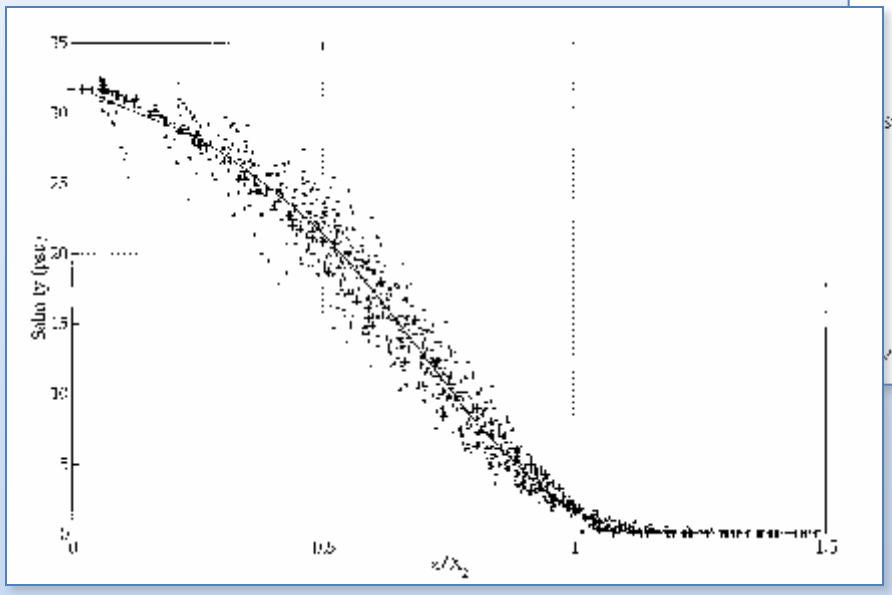
  How long does it reside in the Bay?

  How far does it go? Where is ocean loading important?

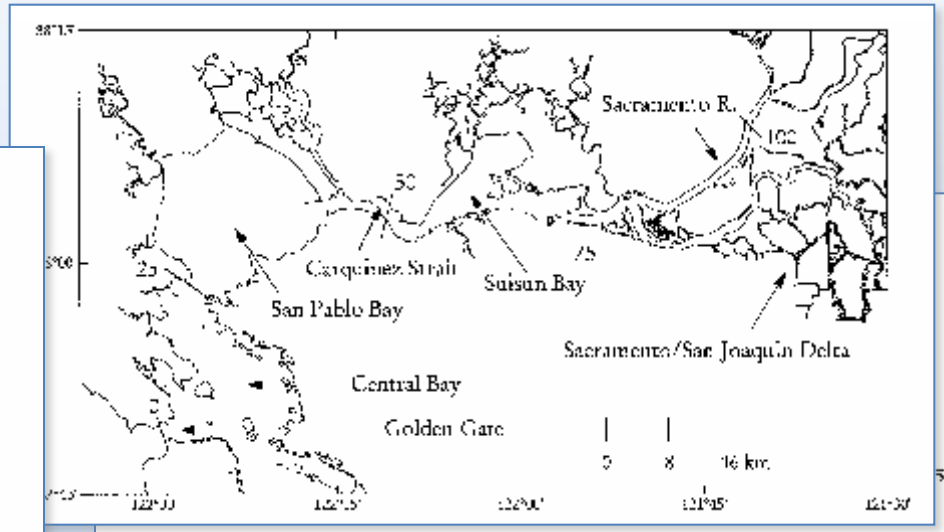
- *How do ocean and land-derived loading compare?*

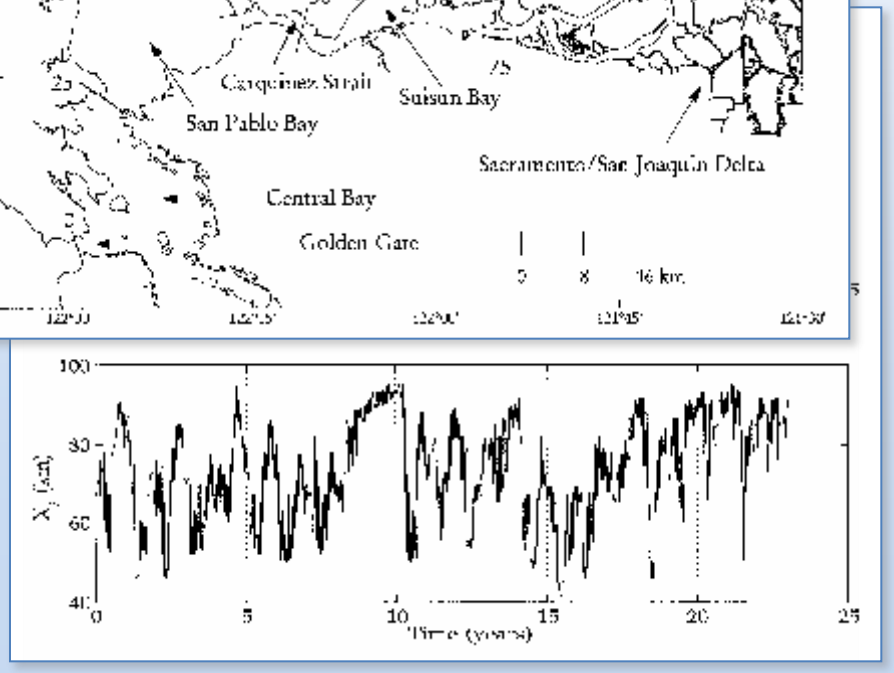
Estuaries: ocean & freshwater

Traditionally Bay-Delta science focused on freshwater – source of biogenic material, controls estuarine circulation, etc. <u>But</u>, bulk of water is from the ocean … *%ocean = S/S_{oc}*



Monismith et al 2002





The “ocean watershed”

Recognize 2 watersheds –
waters collected on land & waters collected in ocean.

What is the nature of the “ocean watershed”?

On west coast, ocean watershed characterized by coastal upwelling, delivering enriched waters …

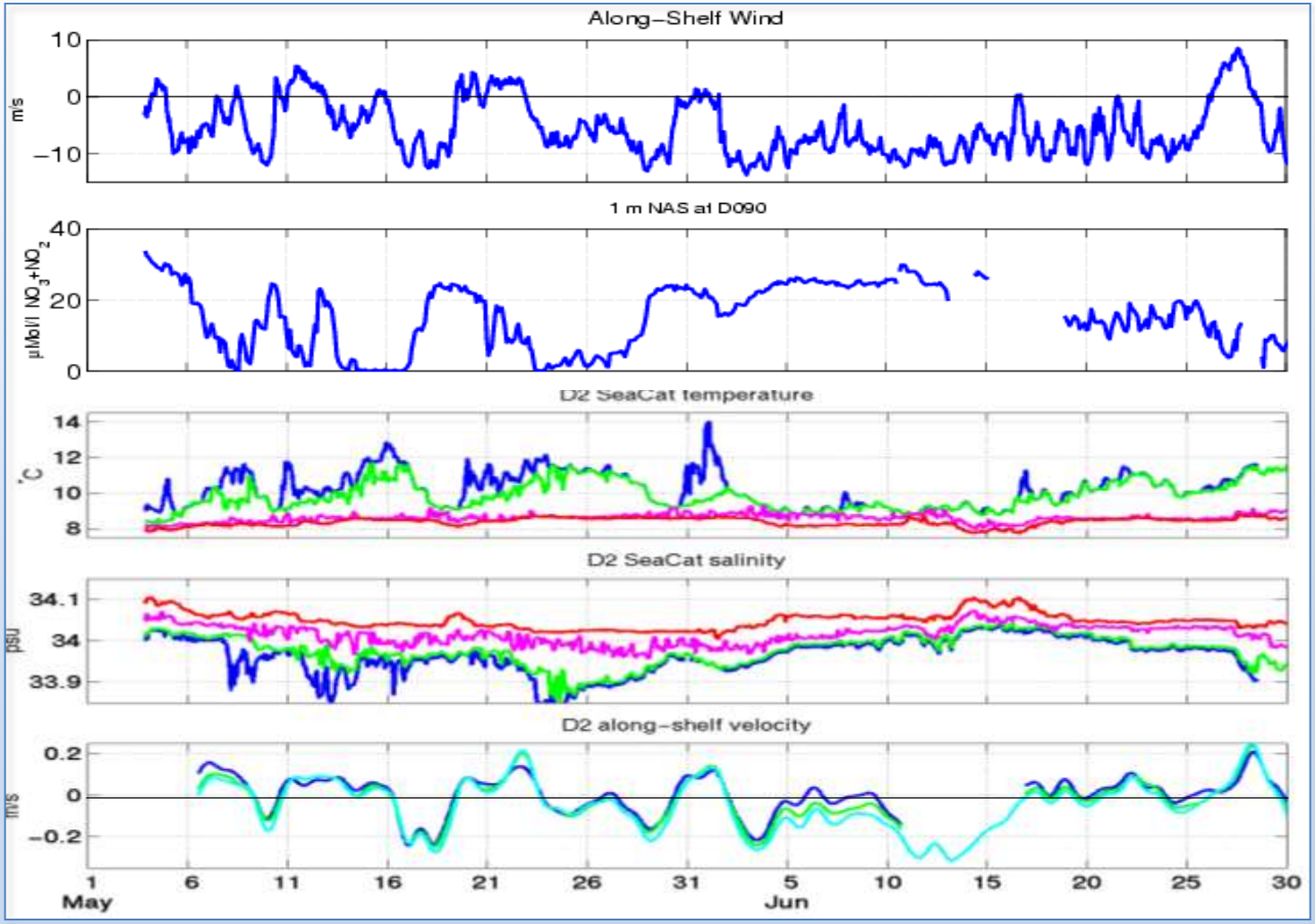
- High nitrate
- Low oxygen
- Low pH
- Plankton

The “ocean watershed”

High nitrate concentrations vary with upwelling.

N

T



Largier et al 2006

The “ocean watershed”

High nitrate concentrations vary with upwelling.

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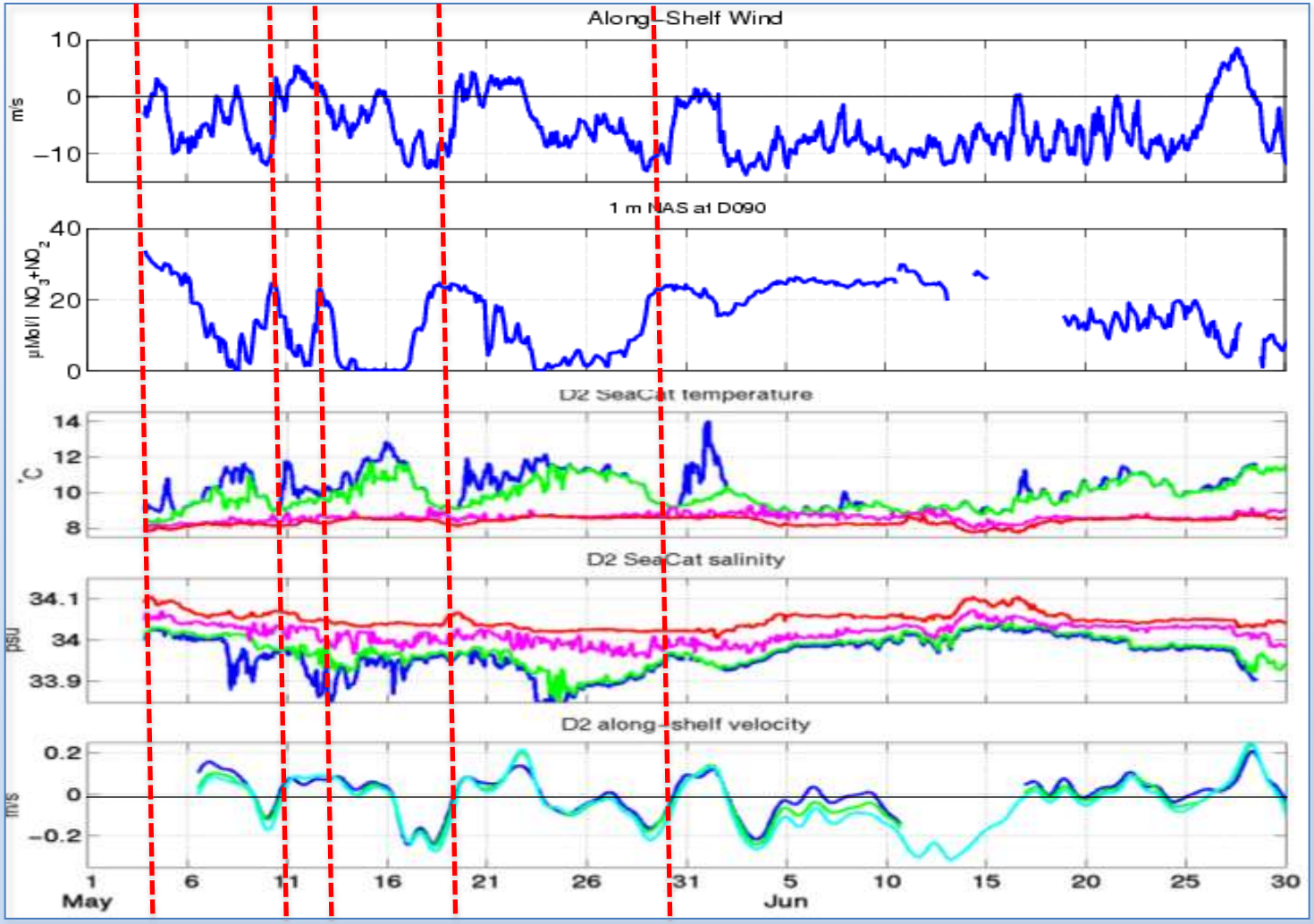


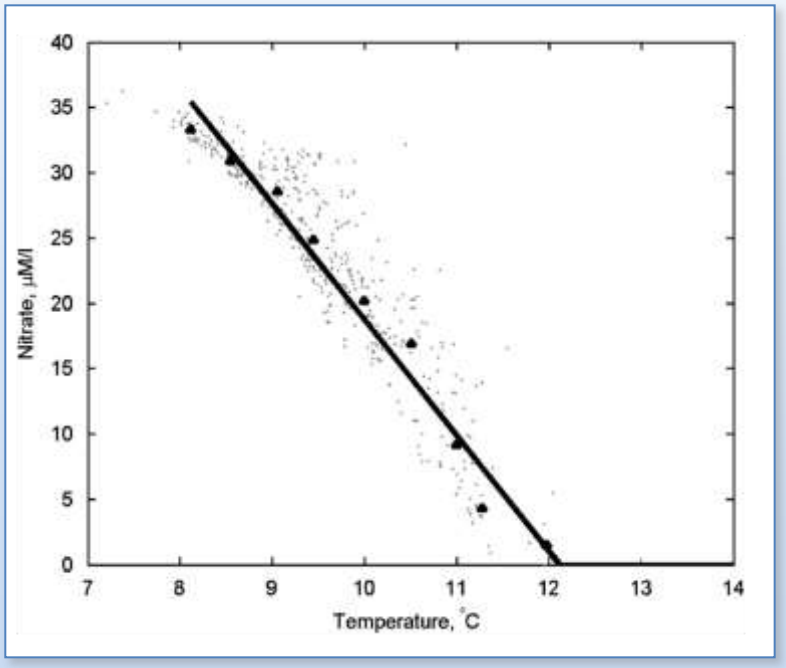
Largier et al 2006

The “ocean watershed”

Deep upwelled water is cold and nitrate-rich.

… warming & primary production in parallel

… observe linear T-N relationship.



Dever et al 2006

Dever et al 2006 (upwelling); Garcia-Reyes 2013 (all seasons); Kimbro et al 2009 (Tomales); Palacios et al 2013 (CalCOFI); others …

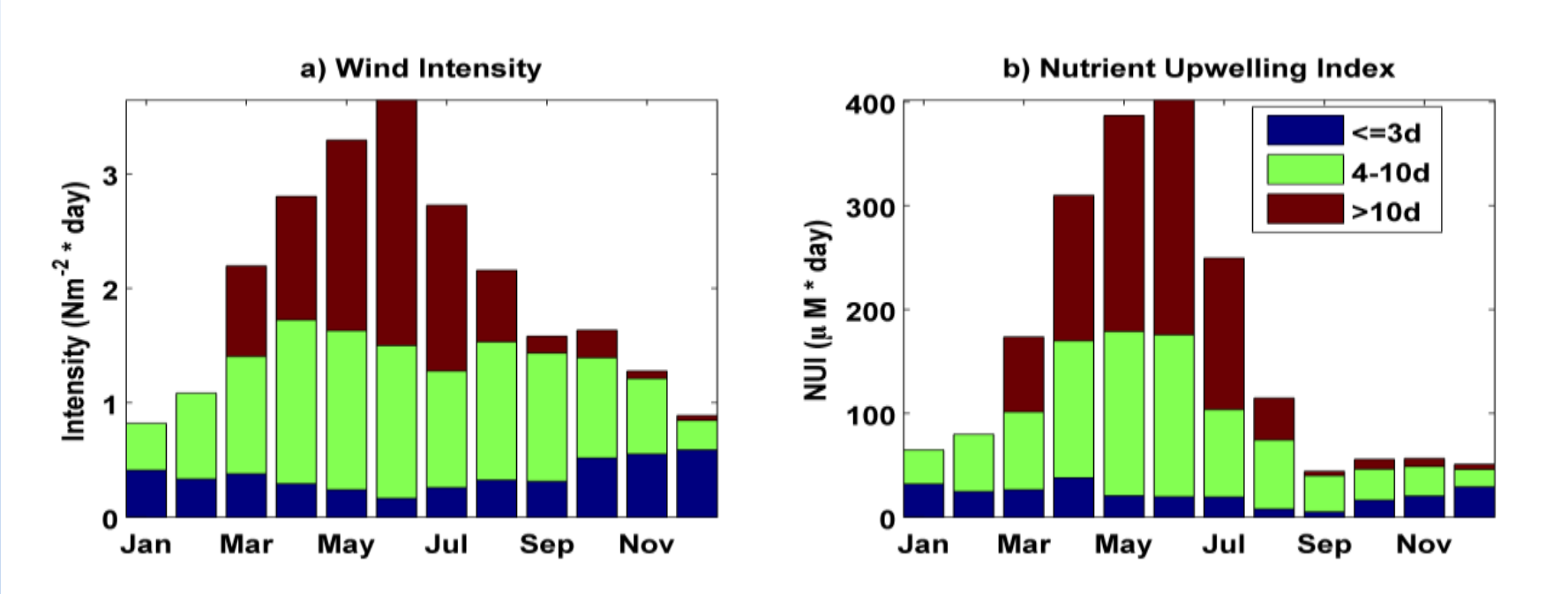
The “ocean watershed”

Seasonal cycle in wind forcing …

… and “nutrient upwelling index” (concentration*days)

Thirty years of data from buoy off Bodega-Reyes.

May-June exhibit persistent enrichment events.



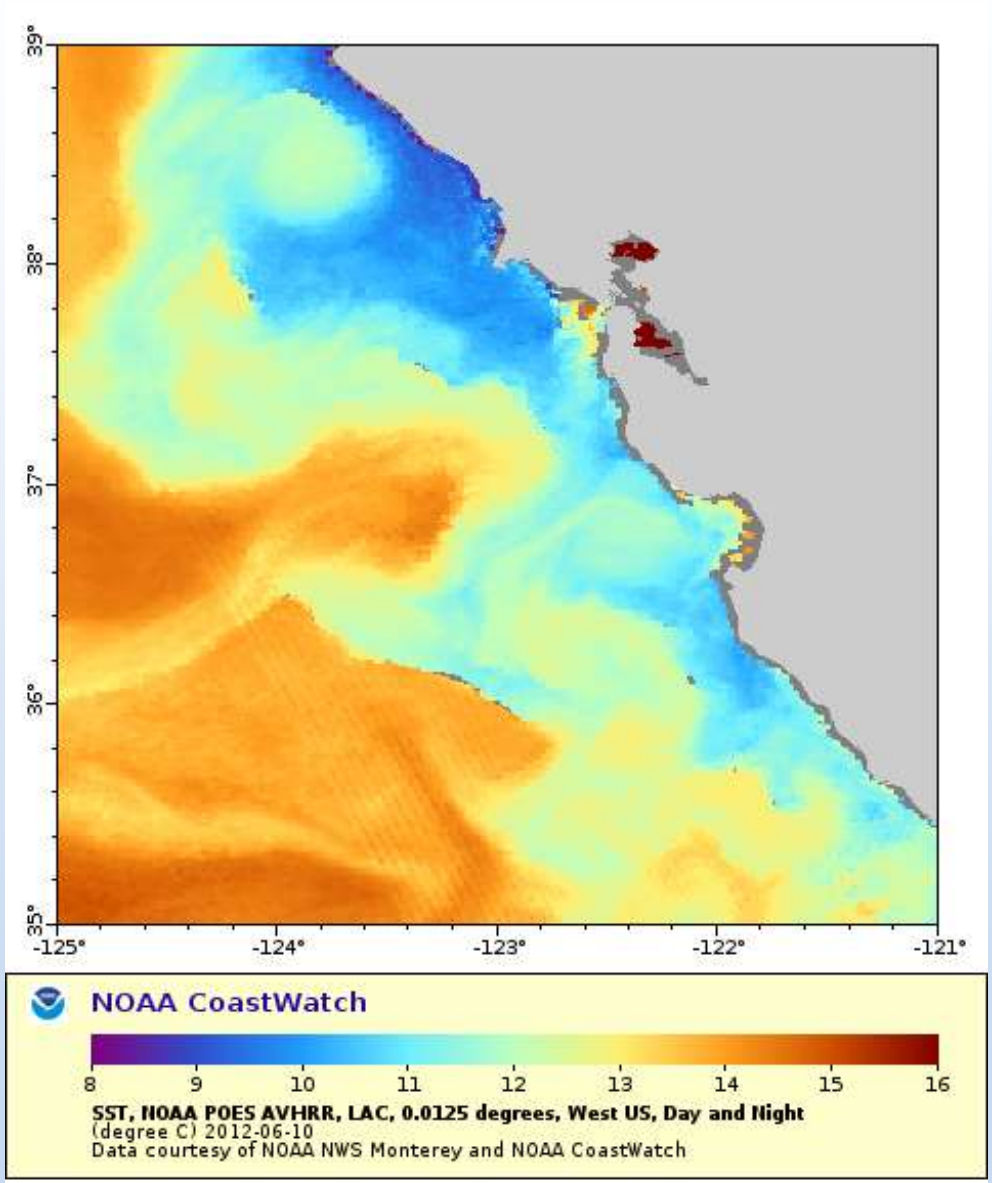
Garcia-Reyes et al 2014

The “ocean watershed”

Sea-surface temperature.

Cold ocean waters …
… dark blue 9°C ~30µM
… light blue 11°C ~15µM
… yellow 13°C ~0µM

Winds, currents, tides and bay outflow control the type of water at the mouth that can be imported by an incoming tide.

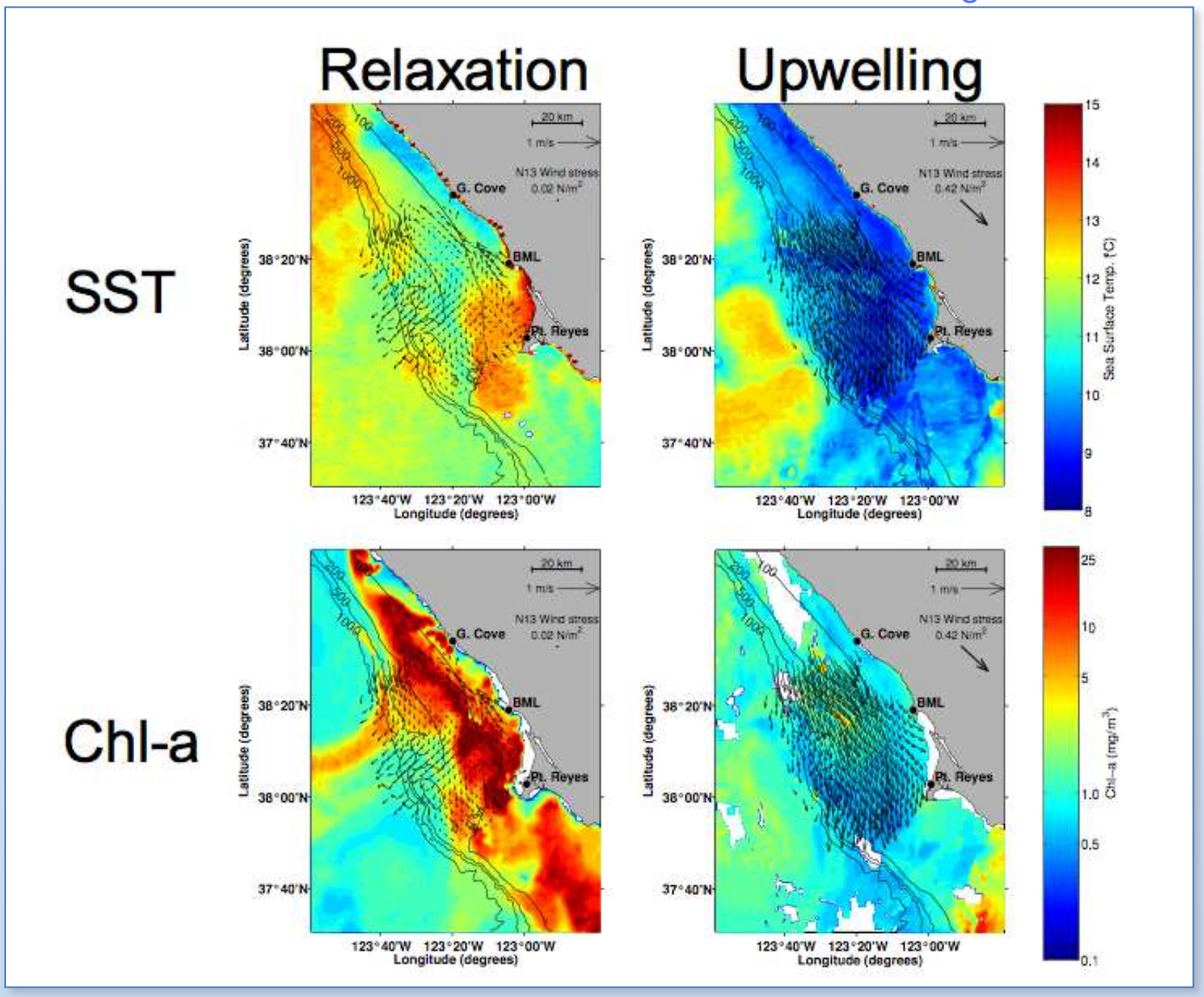


The “ocean watershed”

Largier et al 2006

Spatial pattern of cold water along coast during upwelling

… and Chl. in relaxation events



Nitrate loading: ocean to bay

How much nitrate can be imported on a flood tide?

Newly upwelled waters at mouth of SF Bay …

$N \sim 30\ \mu M$

Intertidal volume comprised of upwelled waters …

$V \sim 2*10^9\ m^3$

Nitrate mass imported to Bay during flood tide …

$M_N \sim 4*10^6$ kg ~ 4,000 tons

But not entirely deep-upwelled, not entirely ocean water, etc.

Nitrate loading: ocean to bay

More realistically, only ~10% of flood-tide inflow is newly upwelled water (also bay outflow waters and aged upwelled waters) … M_N ~ 400 tons.

But only part of it remains in the Bay.

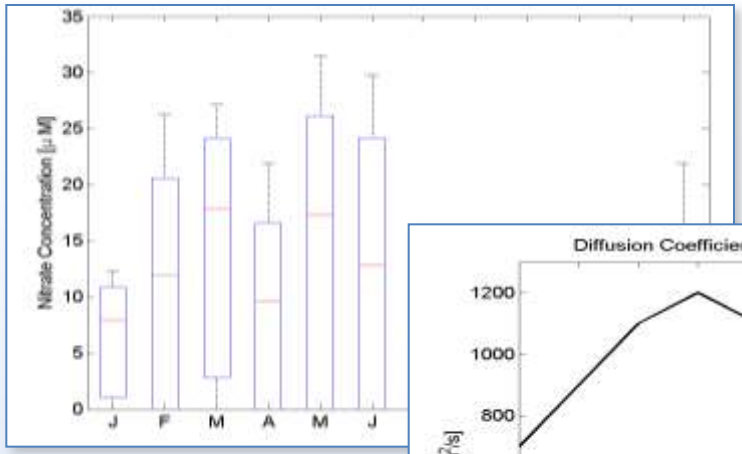
Make estimates using tidal diffusion approach …

$$Flux = -K.dN/dx \sim -K.\Delta N/L$$

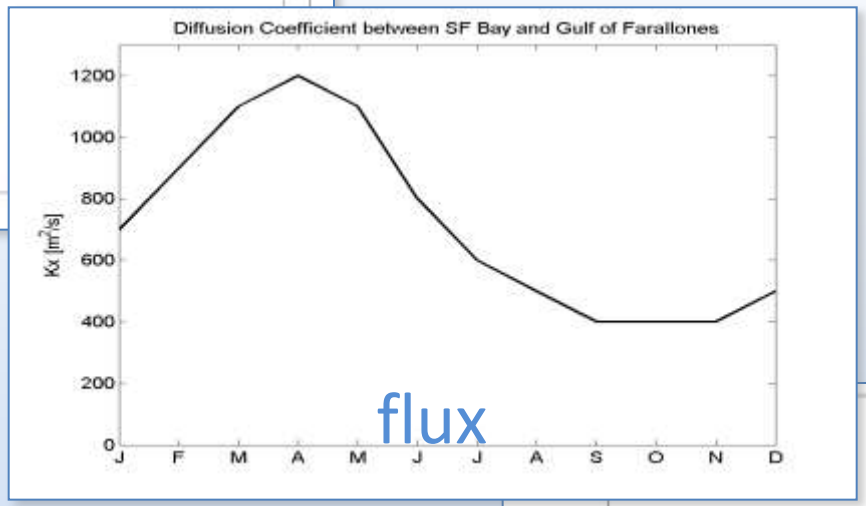
where K is tidal diffusivity,
ΔN is bay-ocean concentration difference,
L is bay length scale

Tidal diffusive flux: ocean to bay

Nitrate concentration N_{ocean}



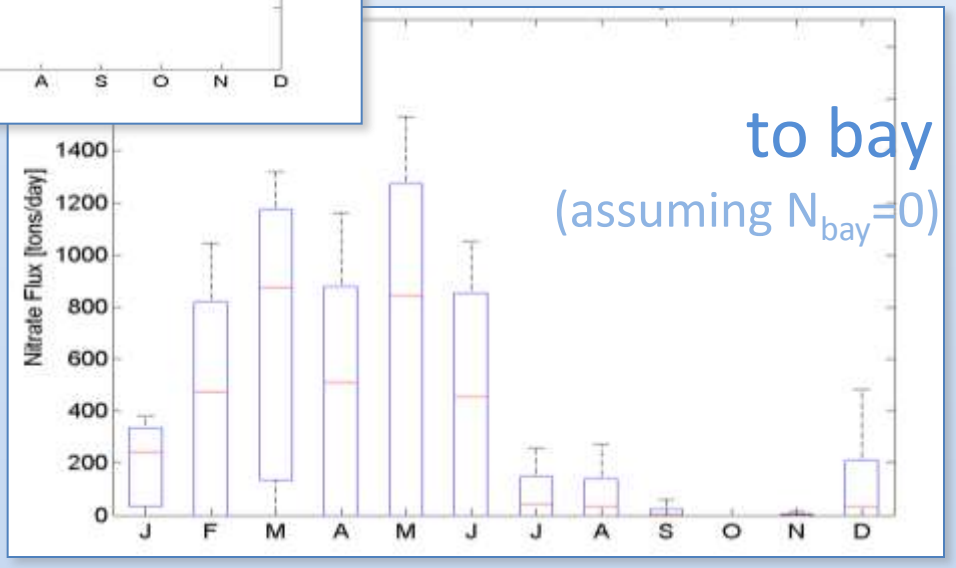
Tidal diffusivity



Fram et al 2006

Nitrate flux to bay

(assuming N_{bay}=0)



Net flux depends on relative nitrate concentration

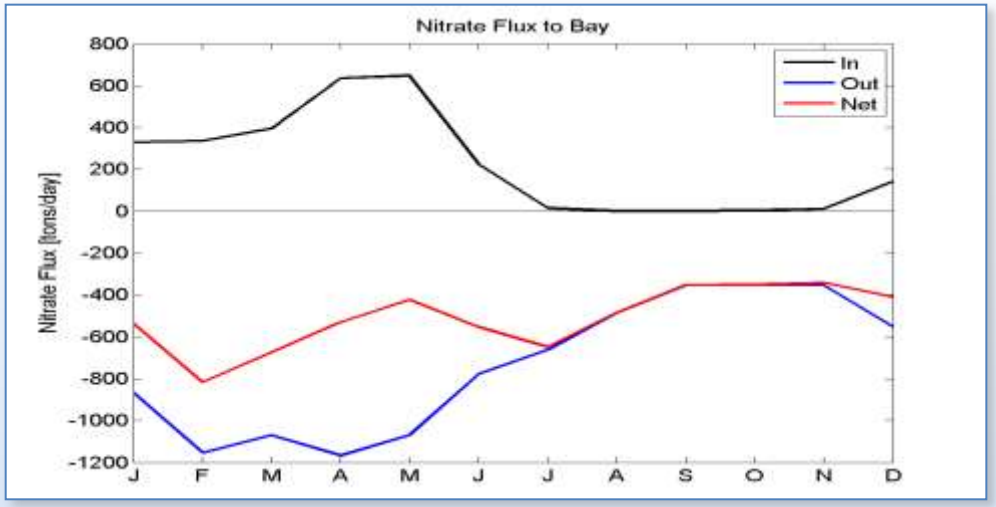
$(N_{ocean} - N_{bay})$

which varies seasonally.

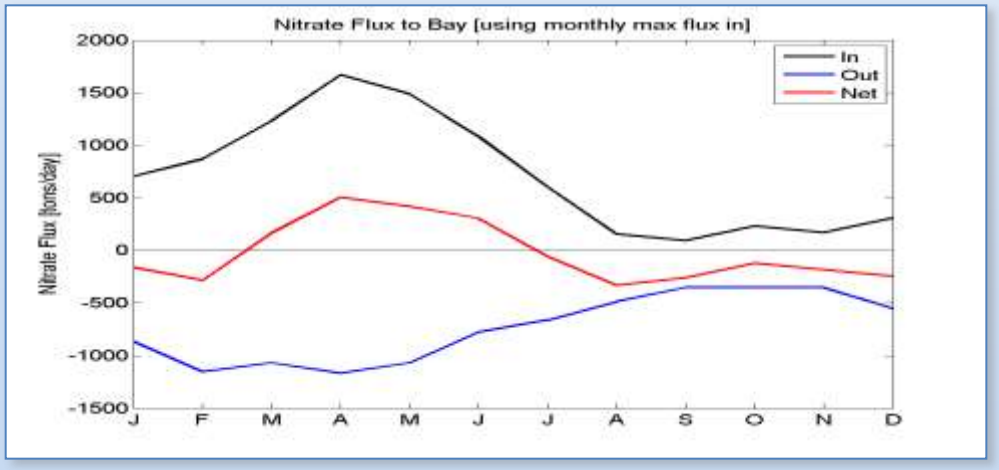
Net nitrate flux

Compare bay-ocean and ocean-bay fluxes …

Mean N



Max N

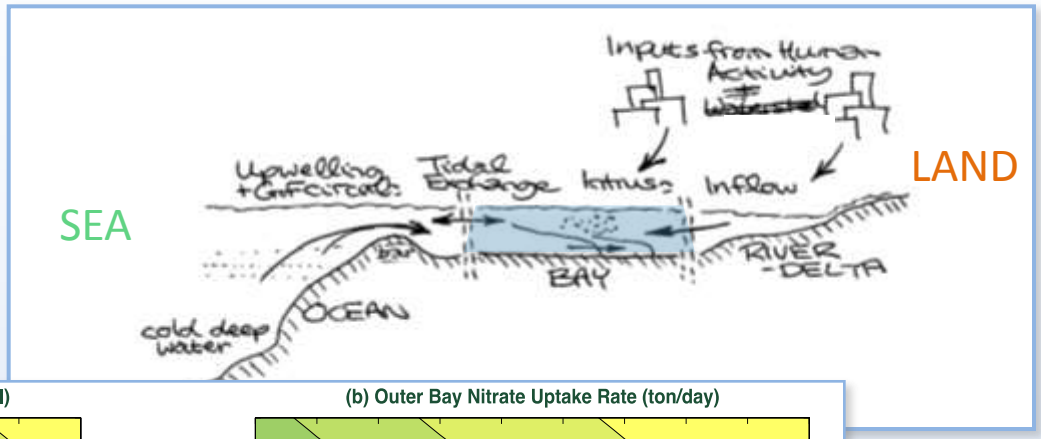


Note that N values estimated from T data, only available at surface.

Nitrate loading vs flushing

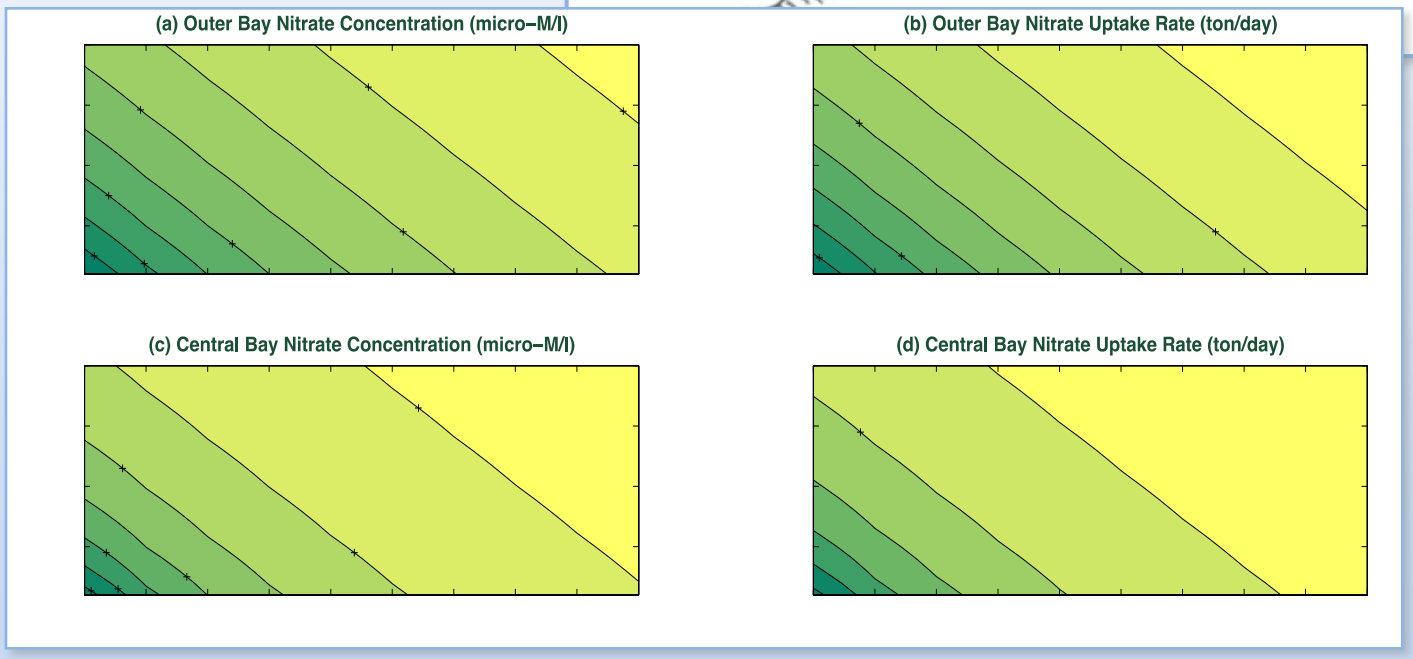
Impact of ocean load versus runoff loading.

Ocean load varies with ocean N, tidal K and Q_r



Outer Bay

Central Bay

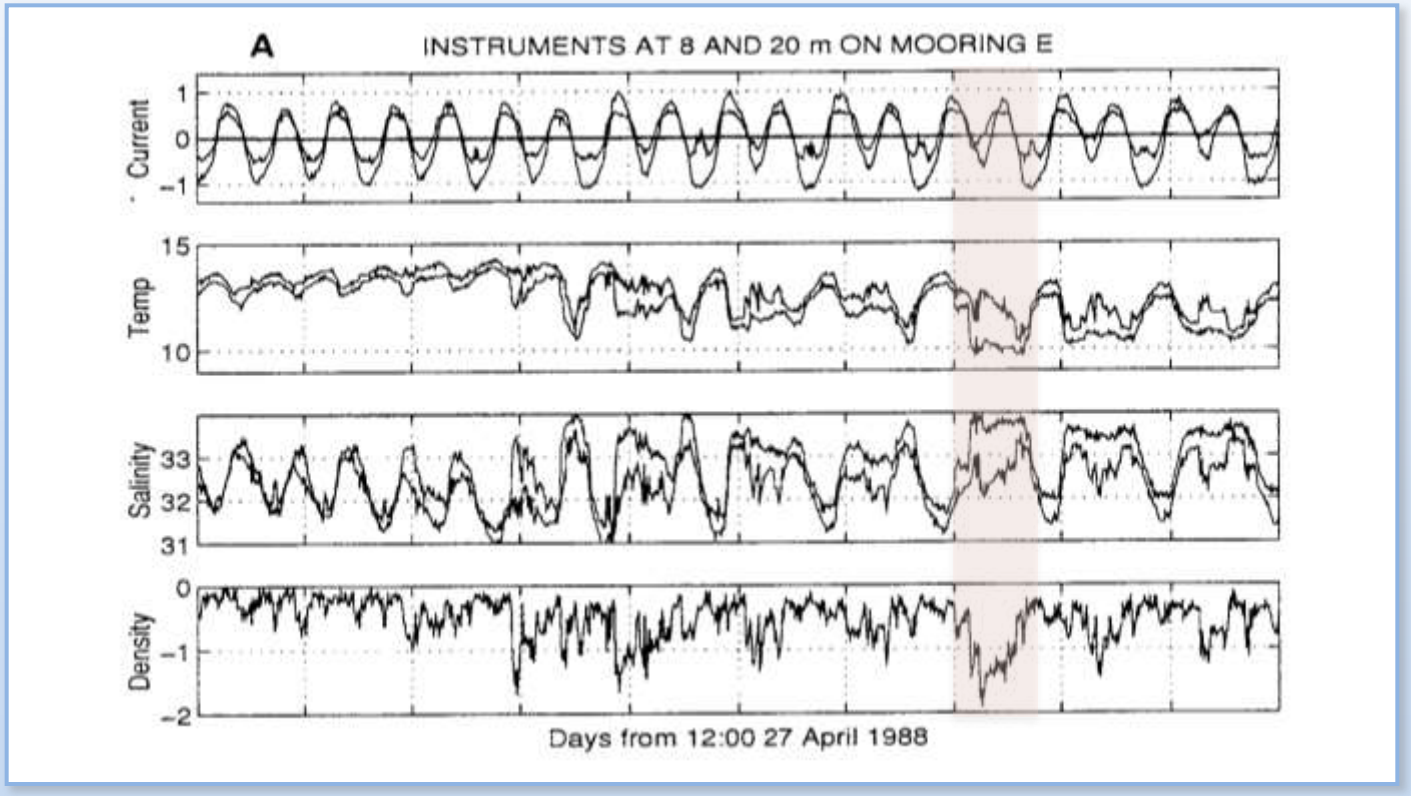


Nitrate Concentration

Nitrate Uptake

Which ocean water gets in?

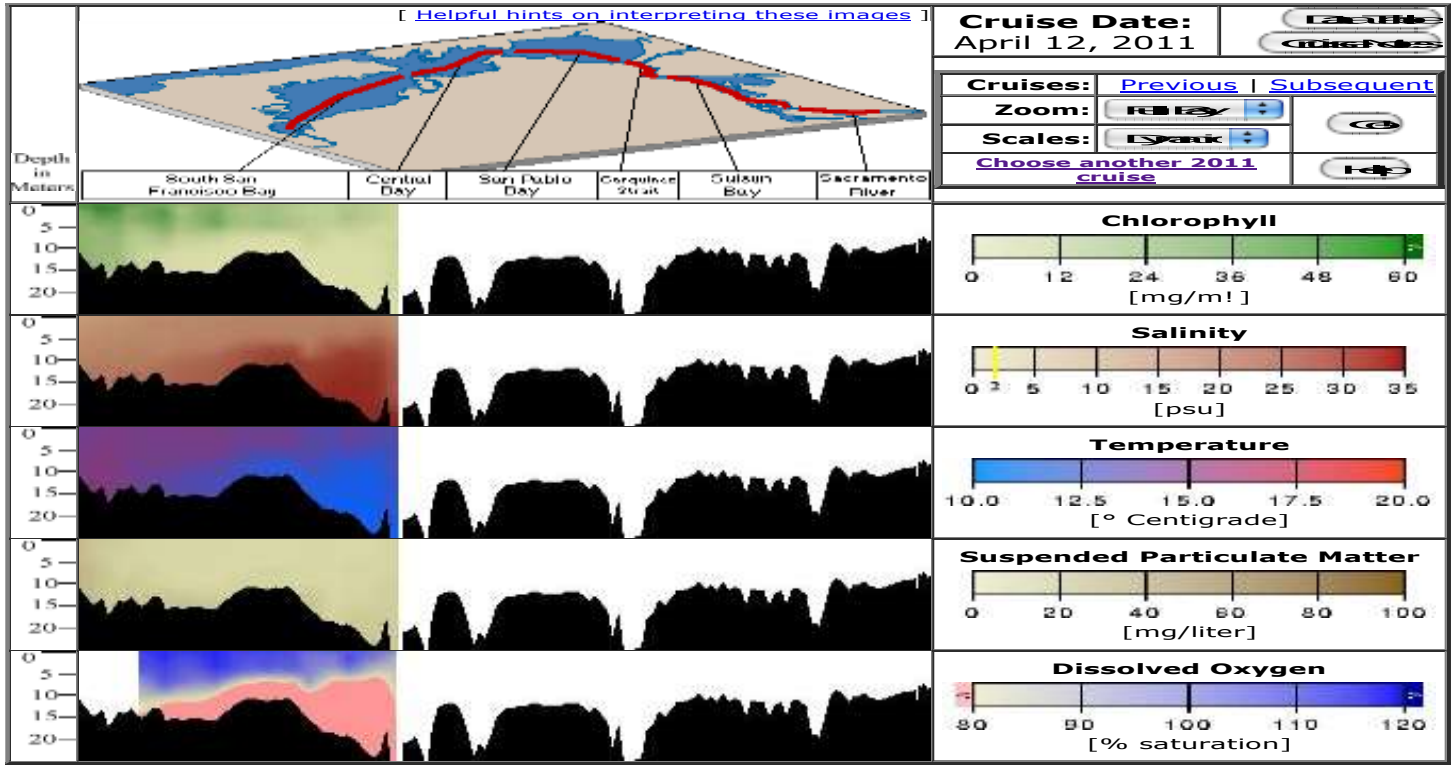
- Deepest water may be trapped by bar – thermocline depth at mouth.
- Intrusion observed at times, e.g., 4 May 1988



Largier 1996

Which ocean water gets in?

- Investigating intrusion of hypoxic ocean water – and potential intrusion of low-pH water.
- Lowest DO in coldest, deepest, richest water.
- 12 April 2011 example – USGS Polaris survey.



How far does it go?

Dense intrusion may …

•Continue as isolated lower layer, intruding far into Bay without mixing/exposure/photosynthesis.

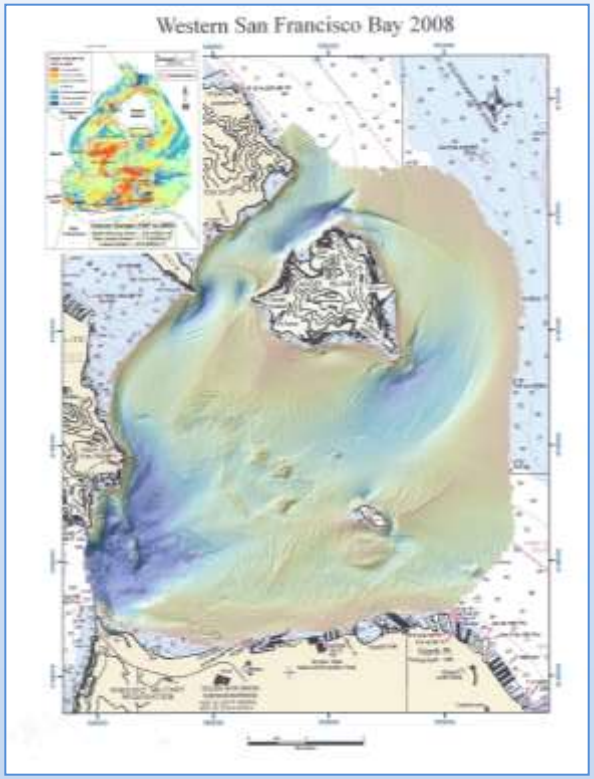
•Mix vertically, with longitudinal exchange only due to tidal mixing

•Mix and then re-stratify (retain nutrient load, but re-oxygenate)

Which when? What controls this?

How far does seawater go?

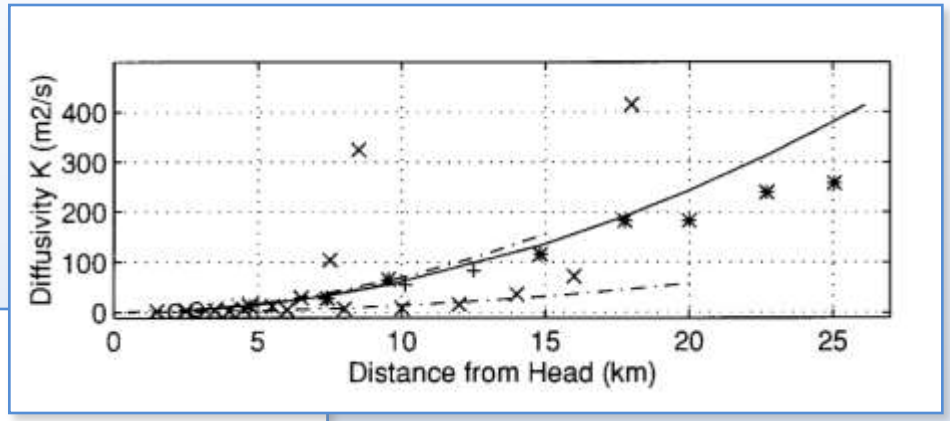
How quickly does it "age"?



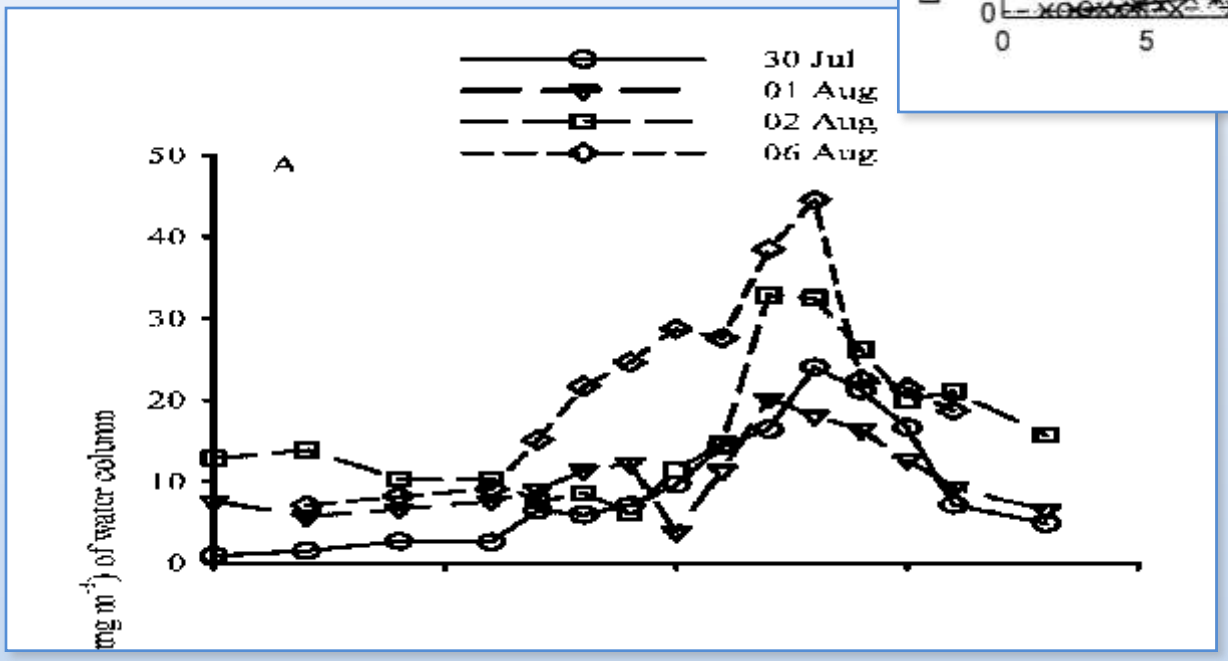
How far does it go?

Vertically mixed scenario … Tomales Bay

Largier et al 1997



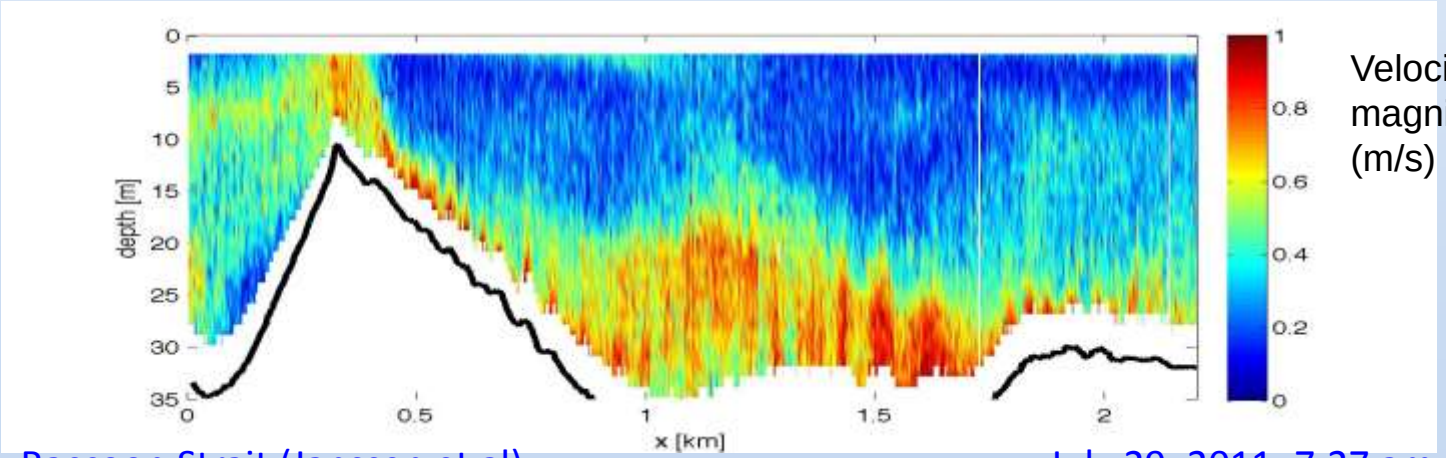
Mid-bay chlorophyll maximum.



Kimbro et al 2009

How far does it go?

Re-stratify scenario … Raccoon Strait & Pt Blunt.



Velocity magnitude (m/s)

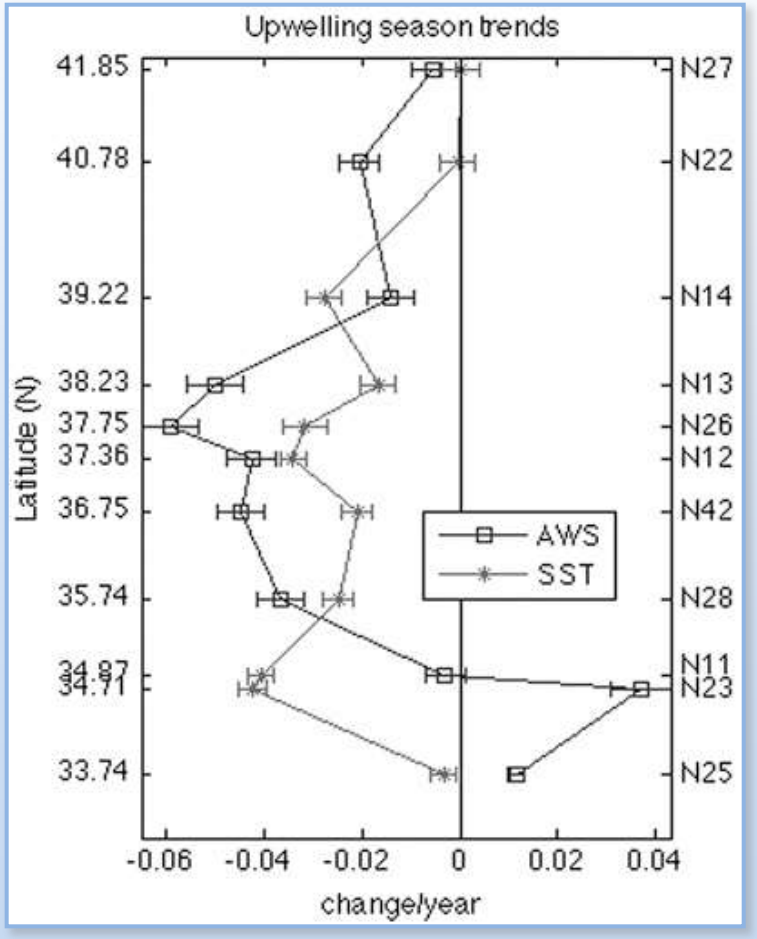
Raccoon Strait (Janssen et al)

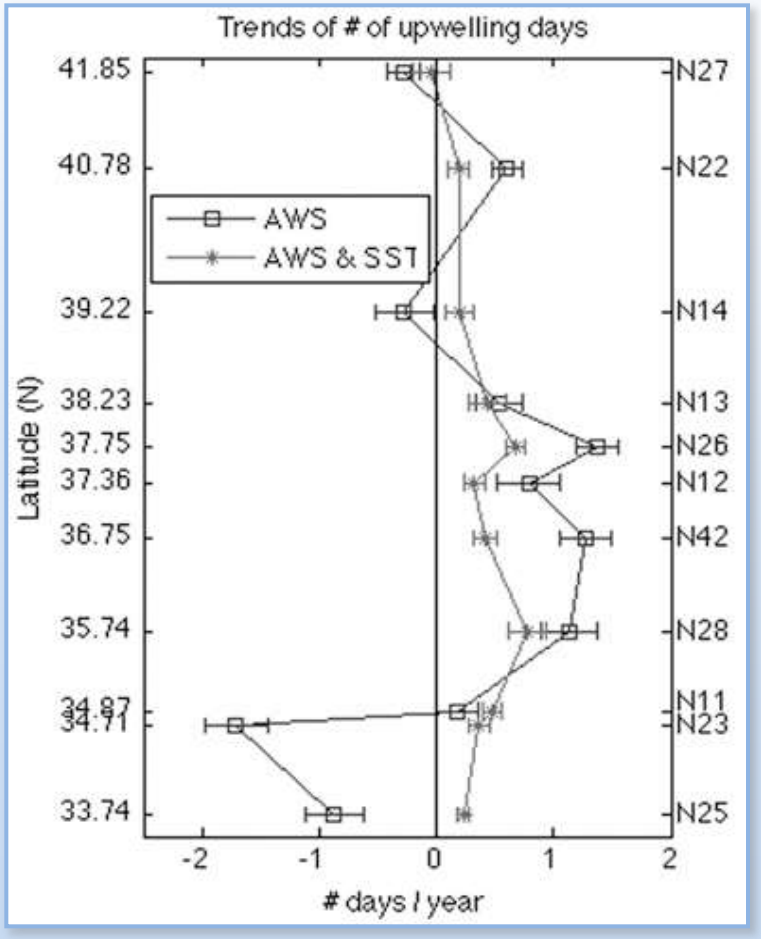
July 29, 2011, 7:27 am

Changing conditions

Increasing winds and colder ocean at NDBC buoys …

… trend of 0.04°C/yr represents increase of 3.5µM/decade





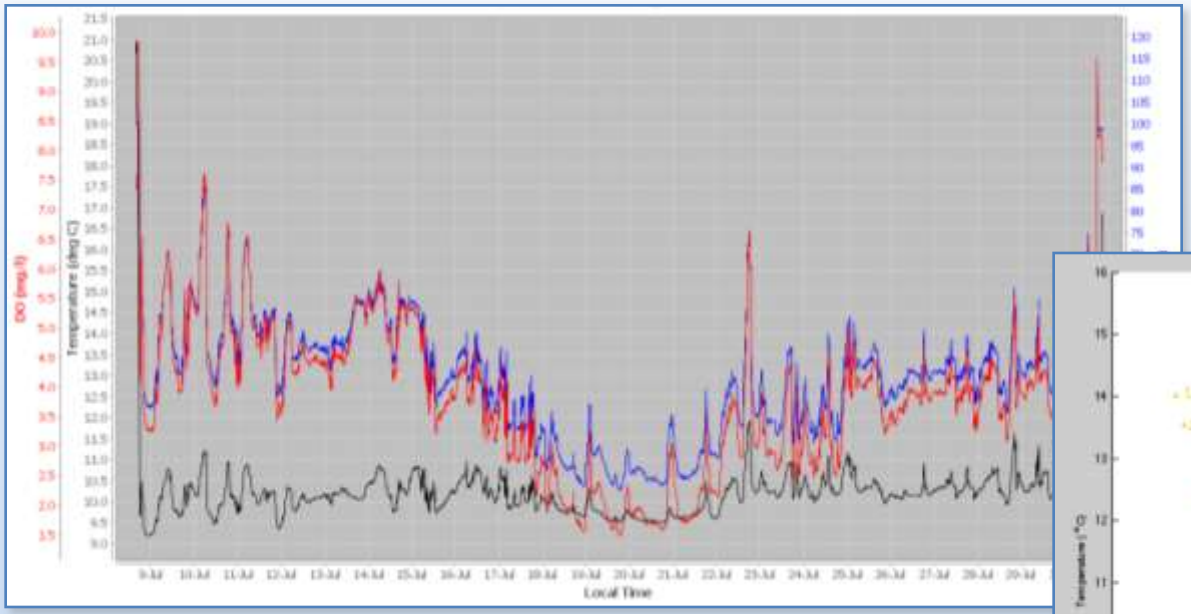
Garcia-Reyes & Largier 2010

Changing conditions

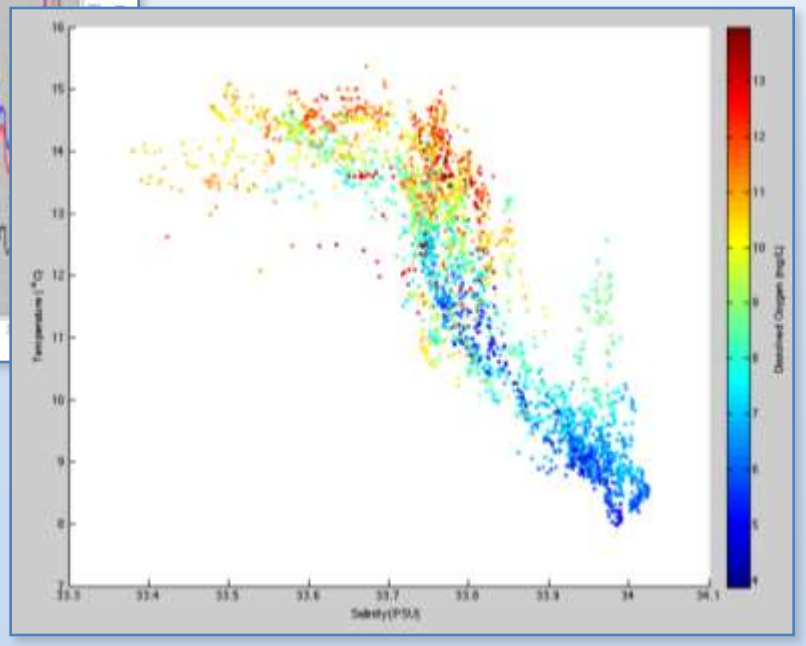
Hypoxic water nearshore off Bodega in 2013

(and again in 2014 – as well as off Pacifica)

BML/BOON data – bottom



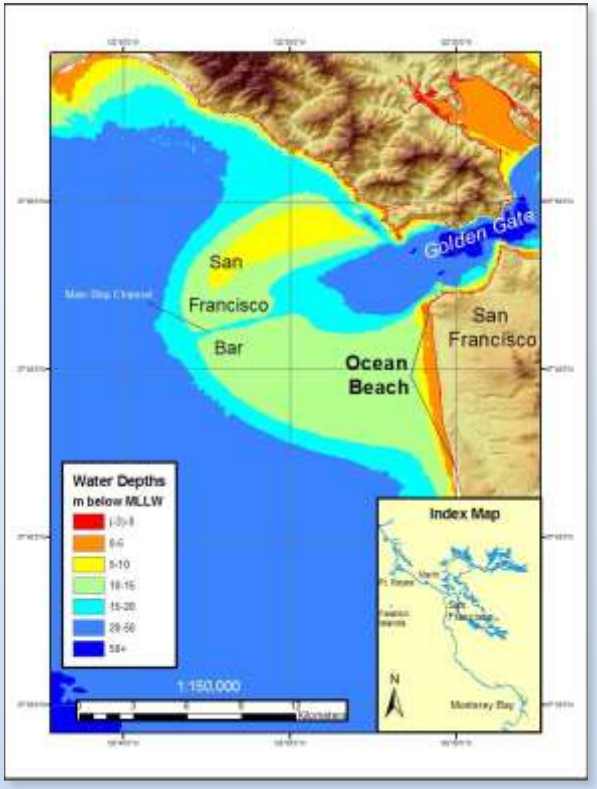
Surface BML/BOON data



Ocean Forcing

Intrusion of enriched waters (T, N, DO, pH)

- *Upwelling source water.*
- *Upwelling process.*
- *Local circulation in GoF.*
- *Deep intrusion or mixing.*
- *Residence time.*
- *Reaction rate (light).*



Many questions remain for San Francisco Bay …

Schematic – Oceanic Load

COASTAL OCEAN DYNAMICS … CONTROL NATURE OF WATER AT MOUTH OF BAY

→

BAY-OCEAN EXCHANGE DYNAMICS … CONTROL HOW MUCH WATER ENTERS BAY AND HOW MUCH IT MIXES BAY

→

BAY CIRCULATION DYNAMICS … CONTROLS WHERE OCEAN WATER GOES AND HOW LONG IT STAYS

Coastal upwelling.
Offshore currents.
Winds.
Tides.

Bay-ocean density.
Tides.
Wind setup.

Tides.
River flow.