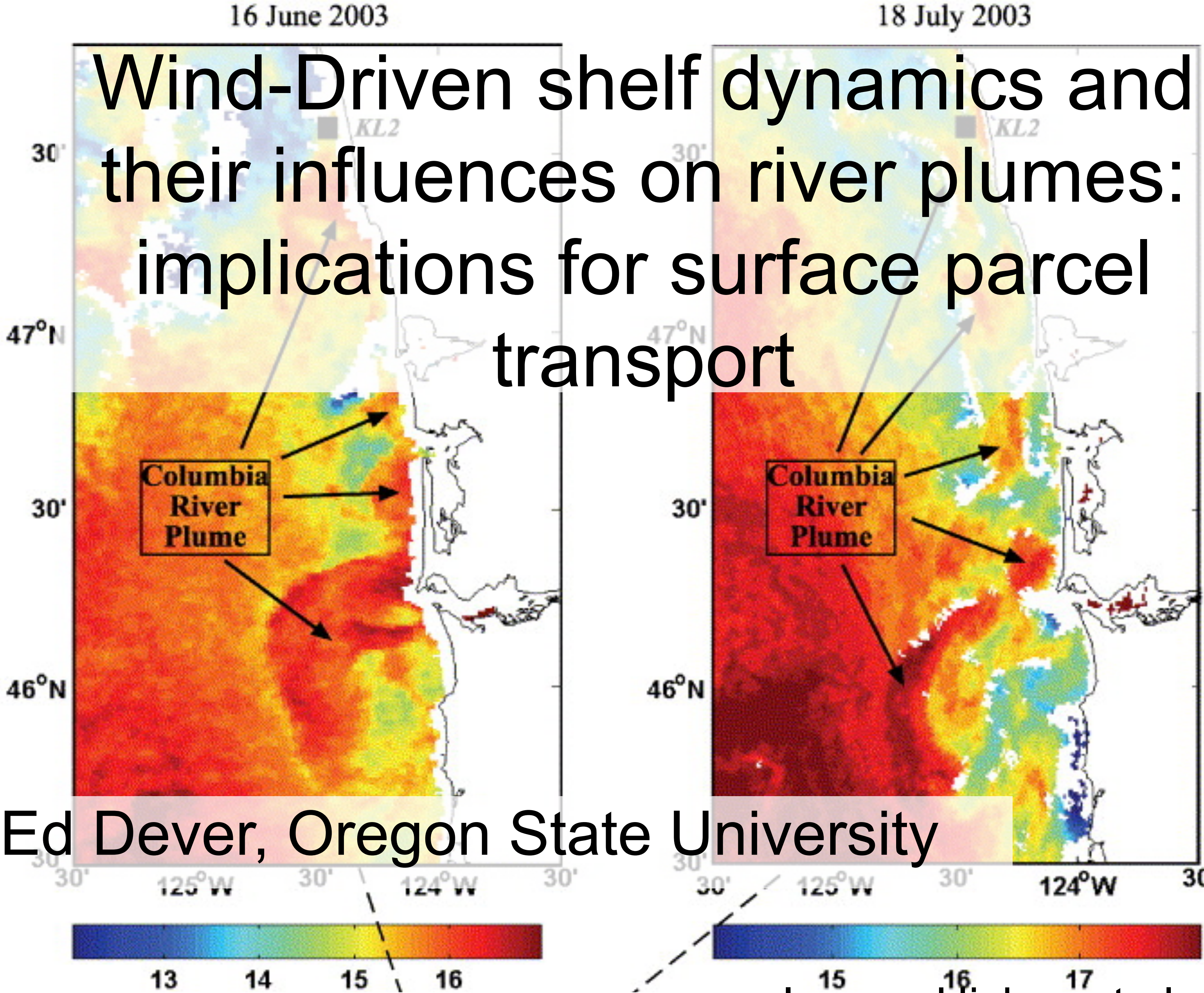
Wind-Driven shelf dynamics and their influences on river plumes: implications for surface parcel transport



Ed Dever, Oregon State University

Image: Hickey et al. (2005)

Outline

- Scope of the talk
- Conclusions
- Upwelling/downwelling without river plumes
- River plumes without upwelling/downwelling
- River plumes impacted by upwelling/downwelling
- Conclusions
- Some unrelated drifter animations

Scope of Talk

- Local wind forcing
- Time scales of weather systems (a couple of days to two weeks or so)
- Attention on continental shelf
  - 30-250 m (15-150 fm) total water depth
  - 0-50 km (0-30 nm) from coast
  - 50 km (30 nm) or more in the along-shelf direction
- Effect on surface parcels

Conclusions

- The thinness of river plumes means that the Ekman transport response is confined to the near surface. This can lead to surprisingly large velocities in response to relatively moderate wind forcing events.

- For downwelling favorable winds, onshore Ekman transport pushes the river plume close to the coast trapping it there. On the west coast, this implies poleward flow that reinforces the tendency of river plumes to turn to the right after leaving the river mouth.

- For upwelling favorable winds, offshore Ekman transport pushes the river plume away from the coast. On the west coast, upwelling implies equatorward flow that overwhelms the tendency of river plumes to turn to the right after leaving the river mouth.

- Fluctuating wind forcing leads to a bidirectional river plume with remnant pieces of the river plume both north and south of the river mouth.

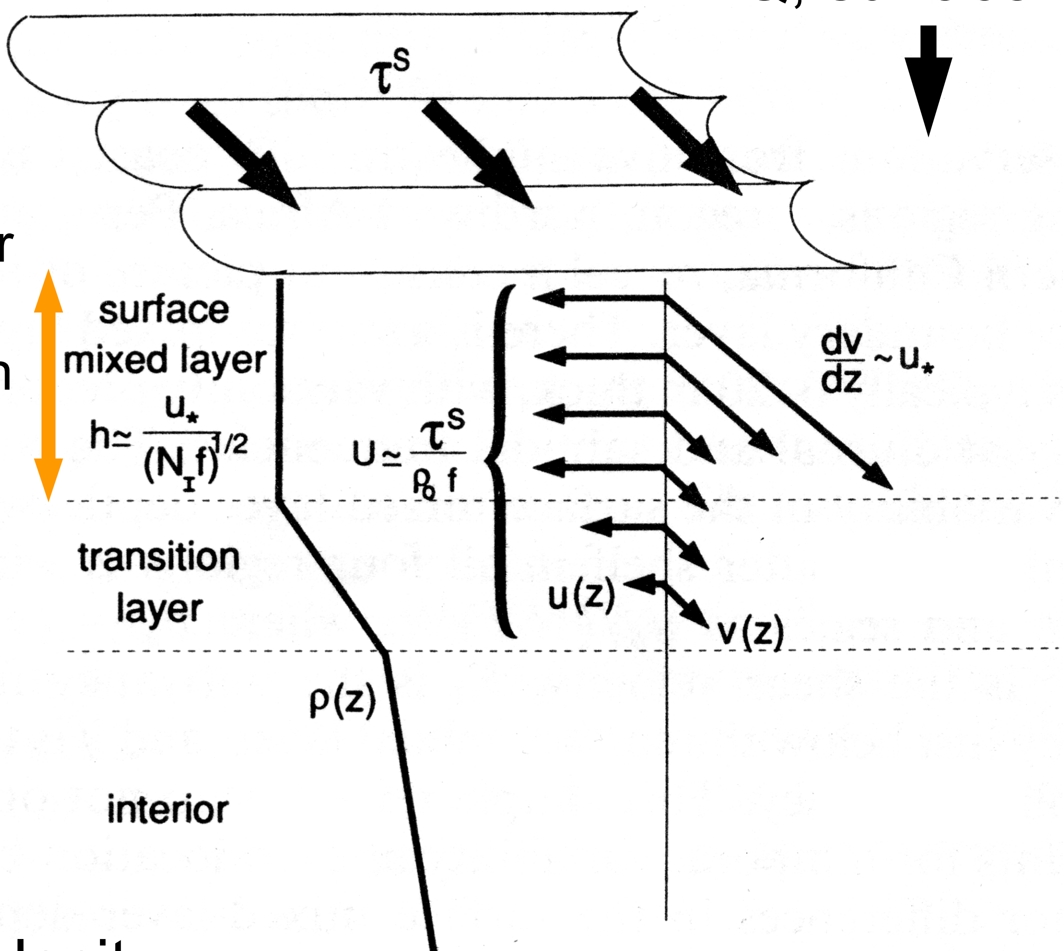
Upwelling/downwelling without river plumes

- The Ekman layer

What does the oceanic surface boundary layer look like?

Q, surface heat flux

“slab-like” layer velocity 90° to right of wind (in northern hemisphere), well-mixed



u_*, shear velocity

FIG. 20. Schematic summarizing some of the characteristics of the surface boundary layer in a coastal upwelling region: $u_* = (\tau^S/\rho_0)^{1/2}$ is the shear velocity and U is the cross-shelf transport in the surface mixed layer plus the transition layer.

Lentz, 1992

Surface Layer: Ekman transport

- net transport integrated through surface boundary layer is 90° to the right of the wind (Northern Hemisphere)
- transport magnitude grows in proportion to the wind stress τ and inversely with *f*, $\tau/\rho f$
- Surface boundary layer depth depends on wind stress, τ, stratification, N_l, and surface heat flux, Q

Ekman transport in coastal upwelling regions

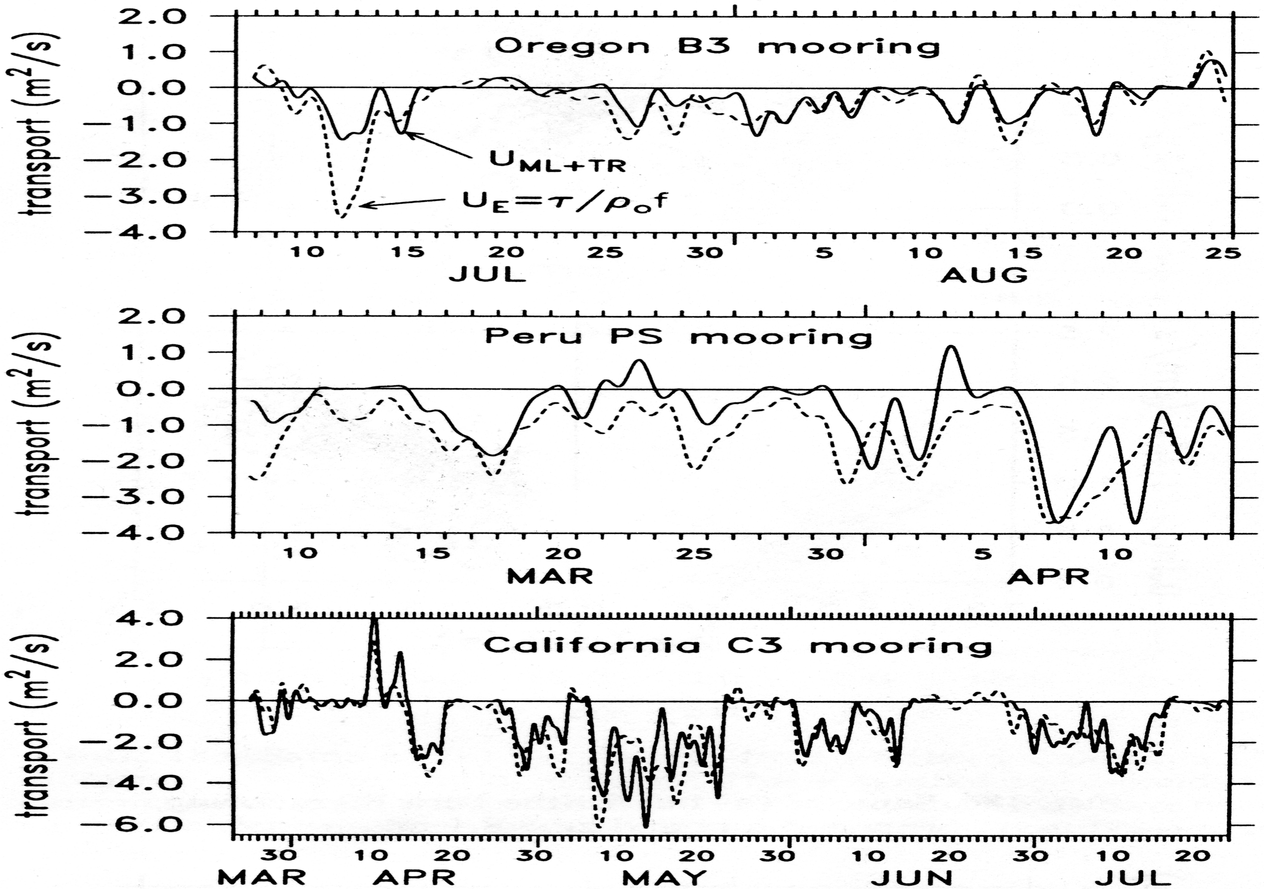


FIG. 16. Time series of the cross-shelf transport in the surface boundary layer U_{ML+TR} (solid line) and the Ekman transport $U_E = \tau^S/\rho_0 f$ (dashed line) from the Oregon B mooring, the Peru PS mooring, and the 1982 northern California C3 mooring.

Lentz, 1992

How big are surface velocities due to Ekman transport?

$U_{SE} = \tau/\rho f = 10^{-1}Pa/(10^3 kg/m^3 * 10^{-4} sec^{-1}) = 1\ m^2/s$

For a slab-like mixed layer, an estimate of the surface velocity is simply the Ekman transport divided by the depth of the surface boundary layer

$$u_{SE} = U_{SE}/H_{SML}$$

Off northern California, H = 20 m → u_{SE} = 1/20 = 0.05 m/s

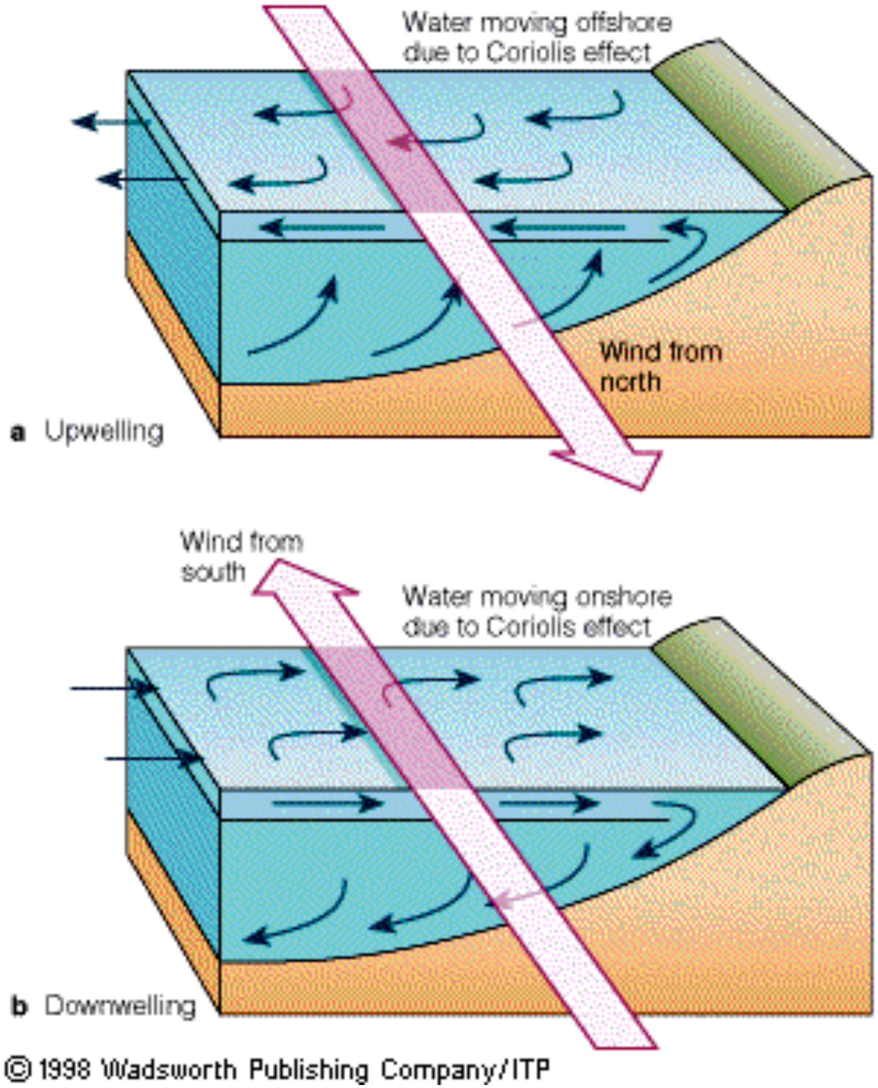
Off Oregon, H = 10 m → u_{SE} = 1/10 = 0.10 m/s

In the Columbia River plume, H = 5 m → u_{SE} = 1/5 = 0.20 m/s

Upwelling/downwelling without river plumes

- The Ekman layer
- Upwelling/downwelling

Coastal Upwelling/Downwelling:

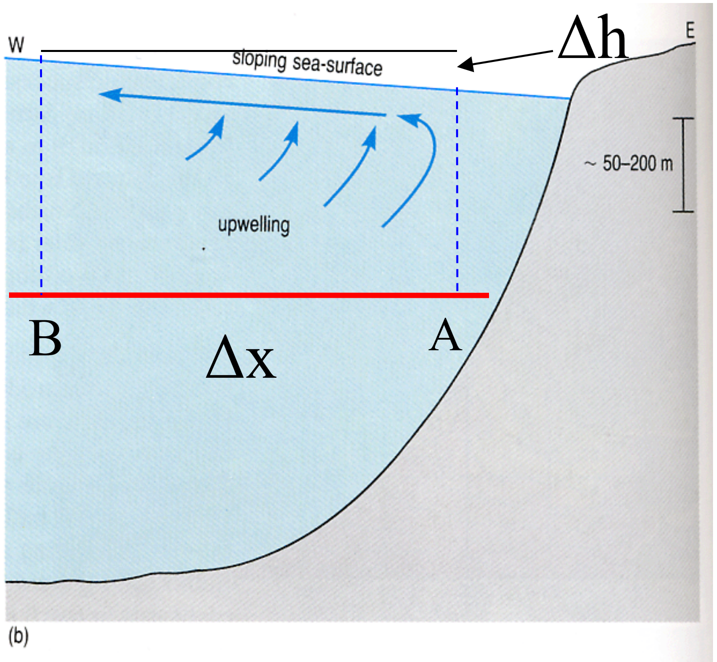


Coastal Upwelling:
Wind to South. Ekman transport in surface layer is to right of wind (West). Flow is divergent at the coast. Deeper water is ***upwelled*** into near-surface.

Coastal Downwelling:
Wind to North. Ekman transport in surface layer is to right of wind (East). Flow is convergent at the coast. Deeper vertical velocity is downward.

Courtesy Mike Kosro

Unstratified Water: pressure gradient caused by slope in sea surface elevation



Geostrophic balance

$$-v = -\frac{g}{f}\frac{\Delta h}{\Delta x}$$

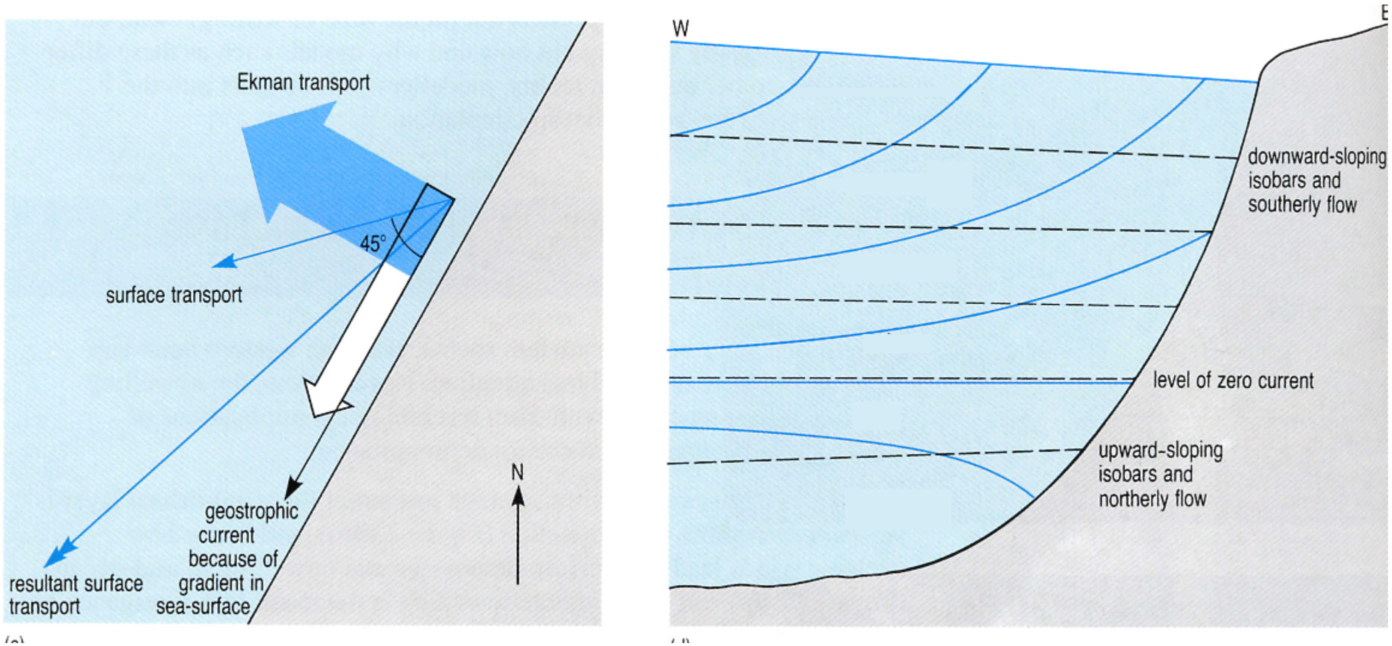
How big is the along-shelf current?
A typical Δh is − 0.05 m
If Δx is 10 km = 10^4 m, and
$g \approx 10$ m/s^2 and $f \approx 10^{-4}$s^{-1}, then

$$v = \frac{10\text{m/s}^2}{10^{-4}\text{s}^{-1}} \cdot \frac{5\times 10^{-2}\text{m}}{10^4\text{m}} = \underline{-0.50\text{m/s}}$$

This is a strong current: about 1 knot. Much stronger than the cross-shelf current (estimated earlier at about 0.05-0.20 m/s).

Courtesy Mike Kosro

What if the water is stratified?



Sloping blue lines are constant density
Dashed lines (isobars) are constant pressure.
Pressure lines (isobars) slope because

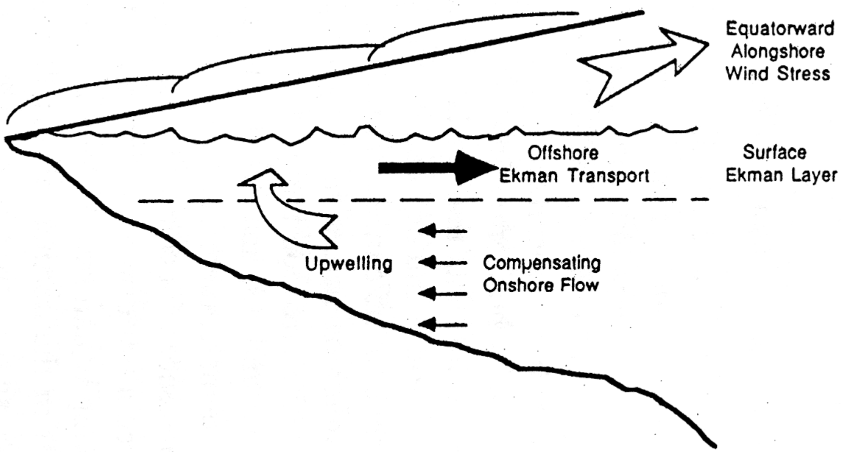
(1) the sea surface is tilted and

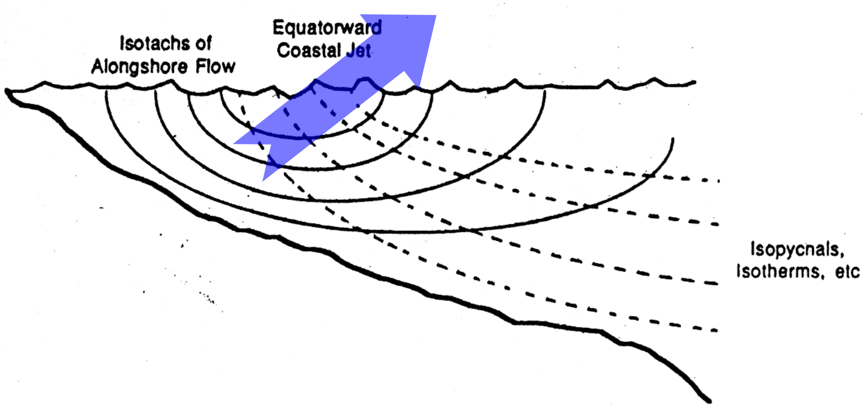
(2) the density of water above them varies from on to off shore.

Now, the pressure gradient varies is strongest at the surface, weaker as you go down in the water column → v is strongest at the surface, weaker at depth.

Courtesy Mike Kosro

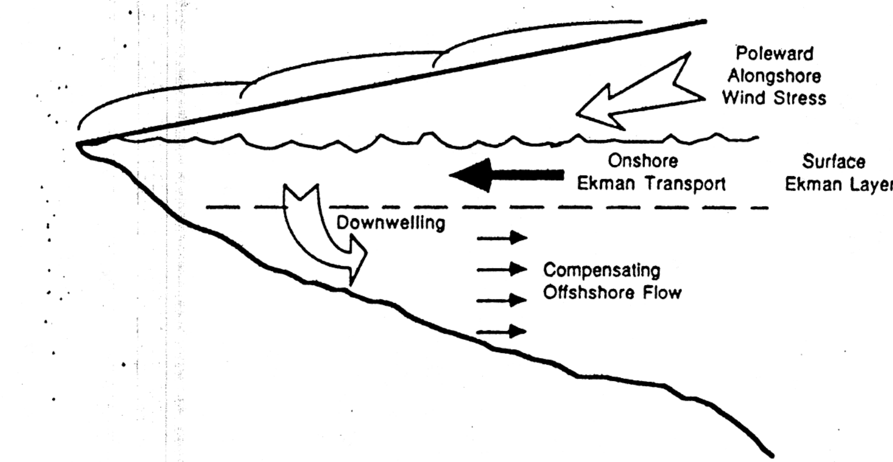
Upwelling

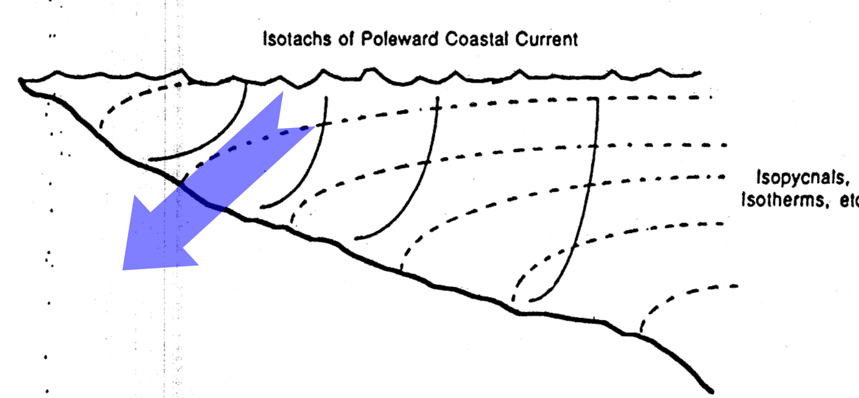




Equatorward coastal jet

Downwelling

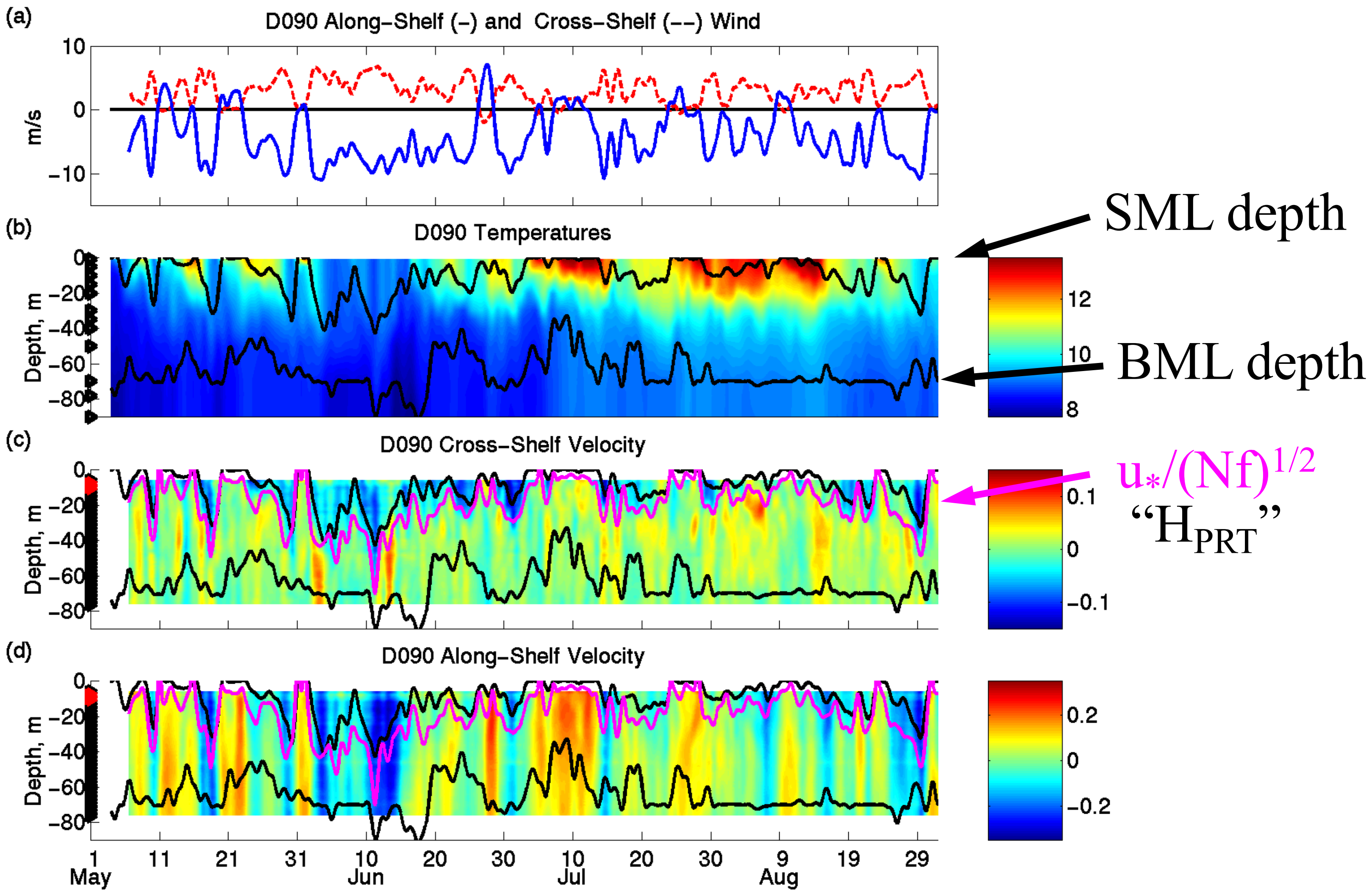




Poleward coastal current

Huyer (1990)

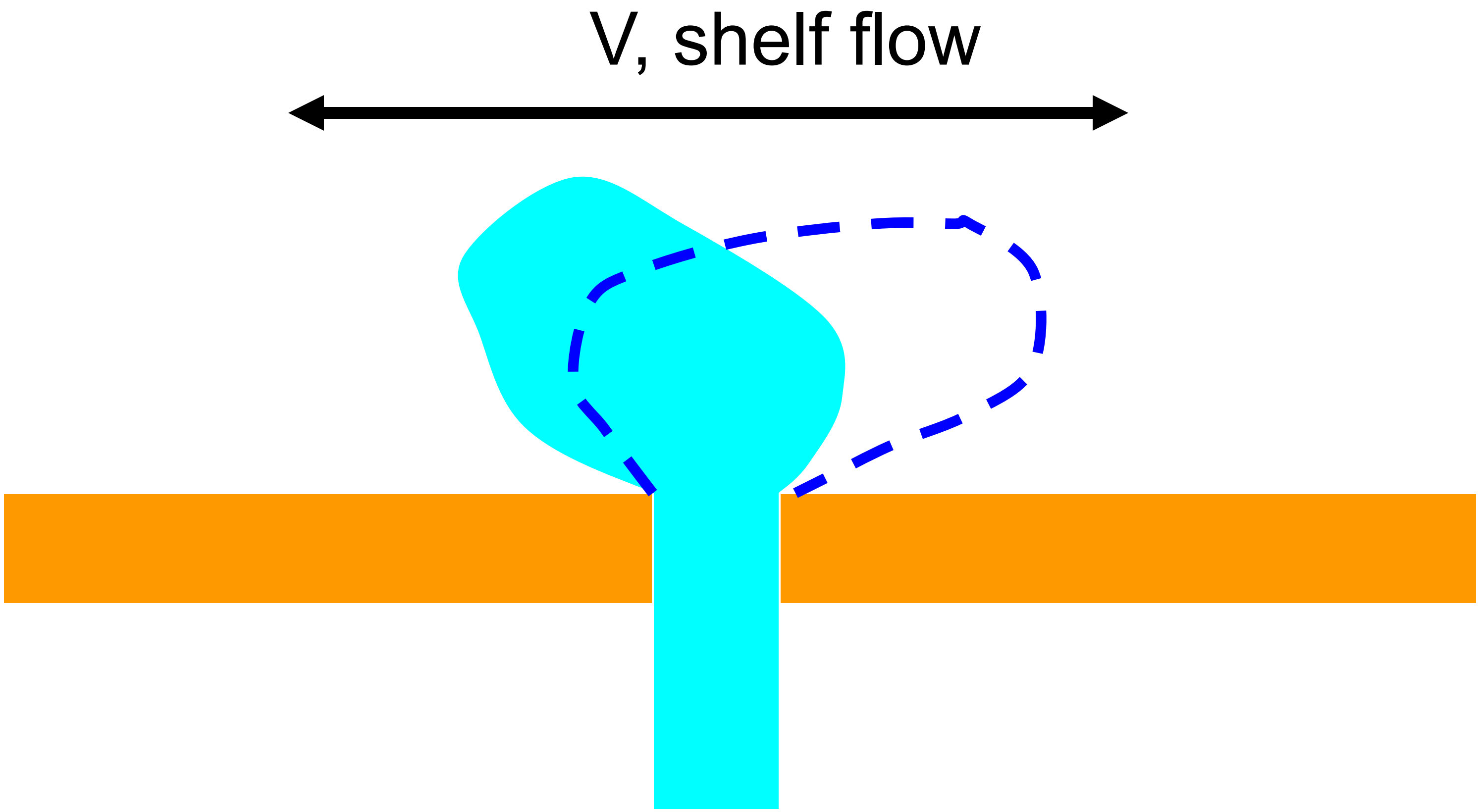
Wind-driven circulation off northern California



Dever et al. (2006)

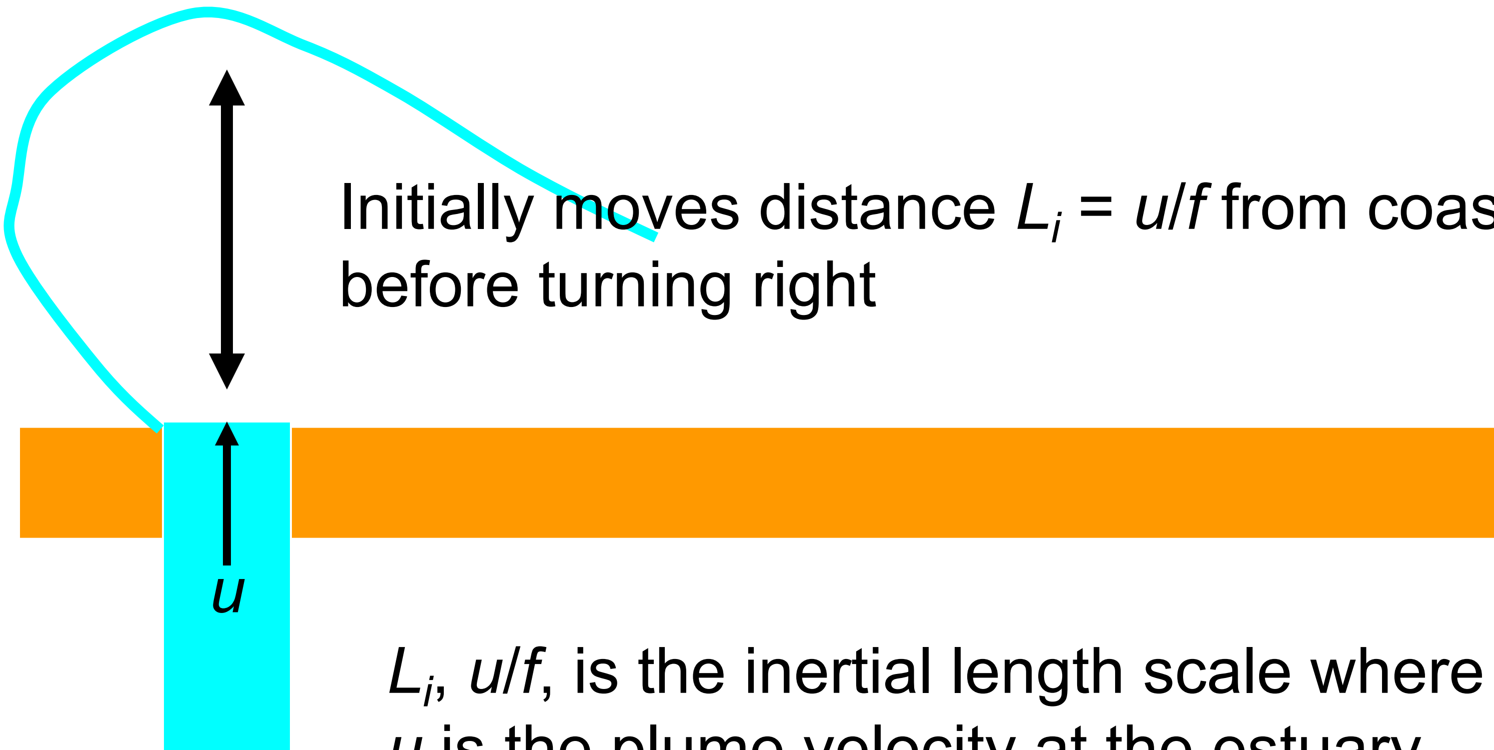
River plumes without Upwelling/downwelling

Small plume, $W<L_R$, unaffected by earth's rotation



Rotation is unimportant and the plume just responds to whatever the existing flow is outside the estuary.

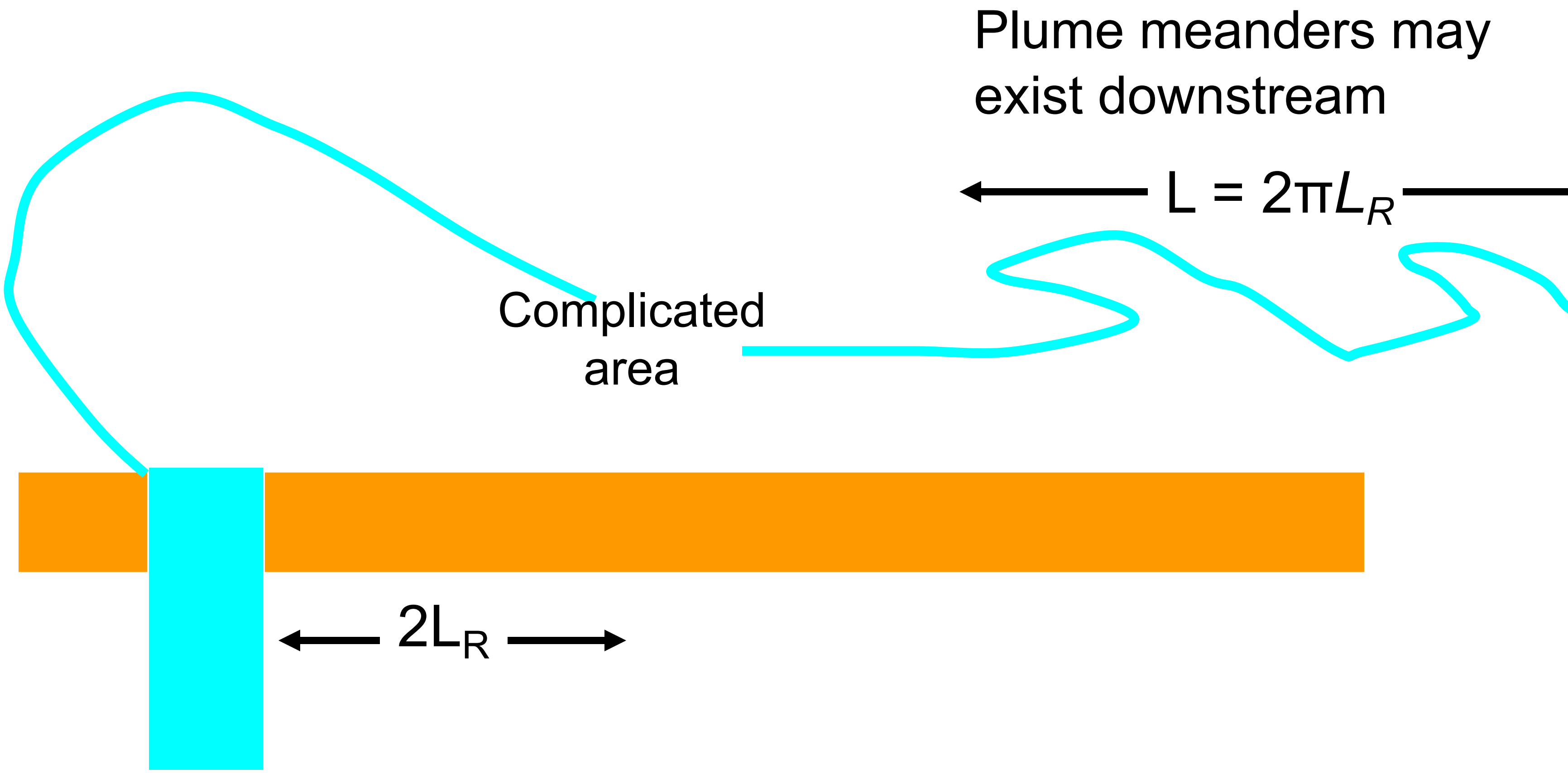
For a big plume, $W > L_R$, rotation is important and plume turns right at the coast (in the northern hemisphere)



Initially moves distance $L_i = u/f$ from coast before turning right

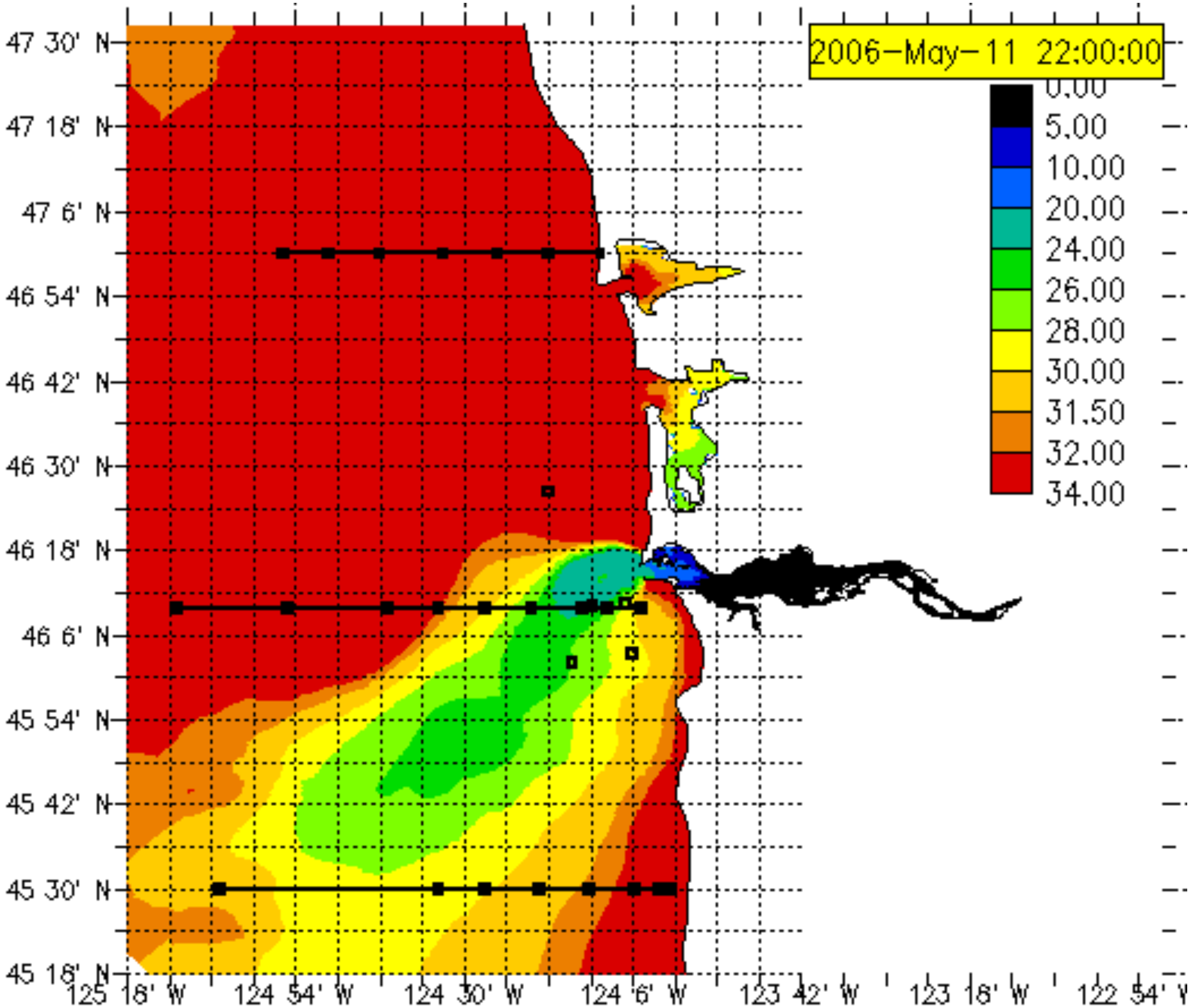
L_i, u/f, is the inertial length scale where u is the plume velocity at the estuary mouth

Under influence of rotation, plume reattaches to coast downstream about 2 L_R from estuary mouth



River plumes impacted by upwelling/downwelling

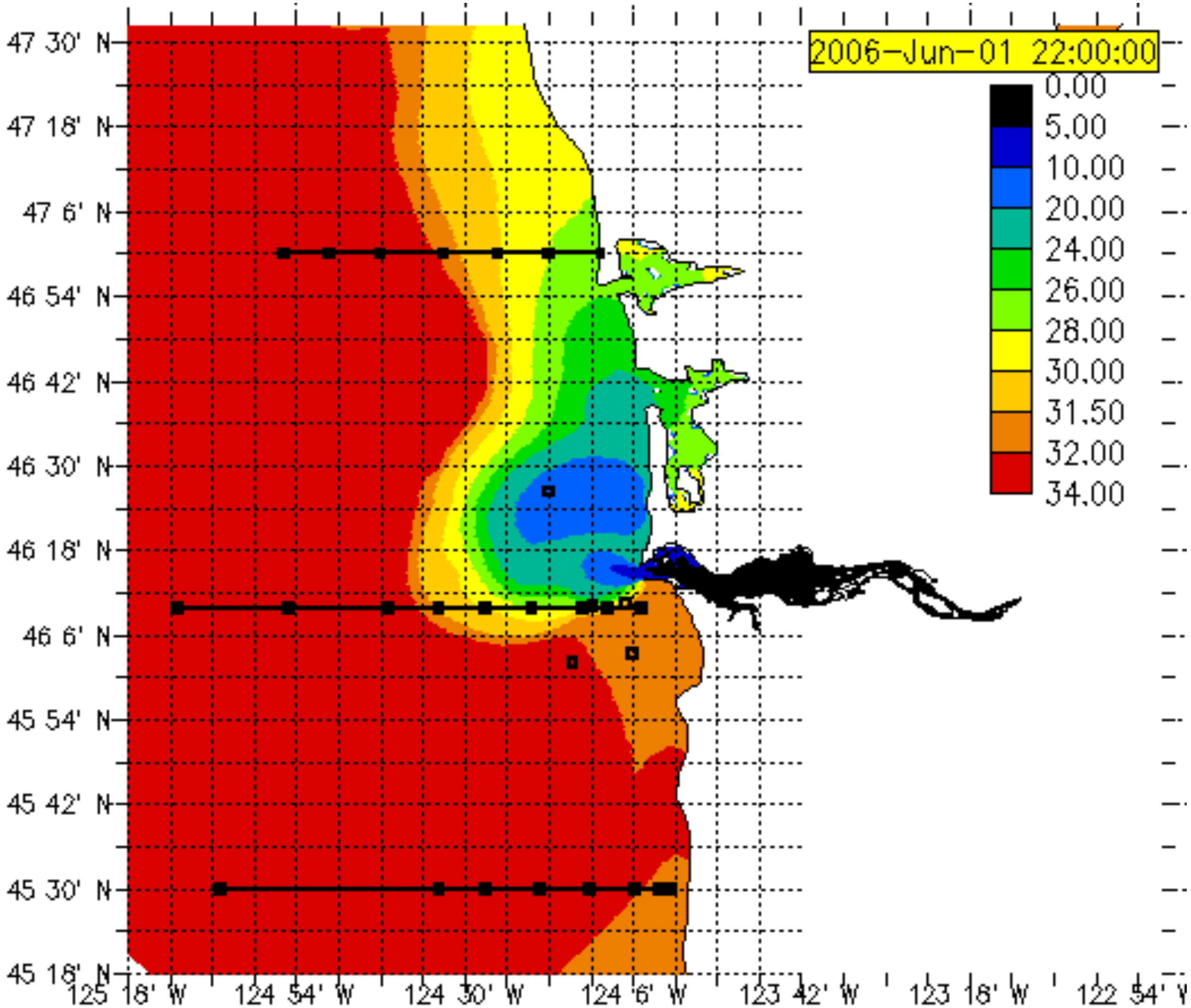
In reality, winds fluctuate throughout the summer over the Oregon and Washington shelves moving the plume north and south.



Model view of plume under upwelling conditions

http://www.ccalmr.ogi.edu/CORIE/cruises/wecoma/plume_images_dev.html

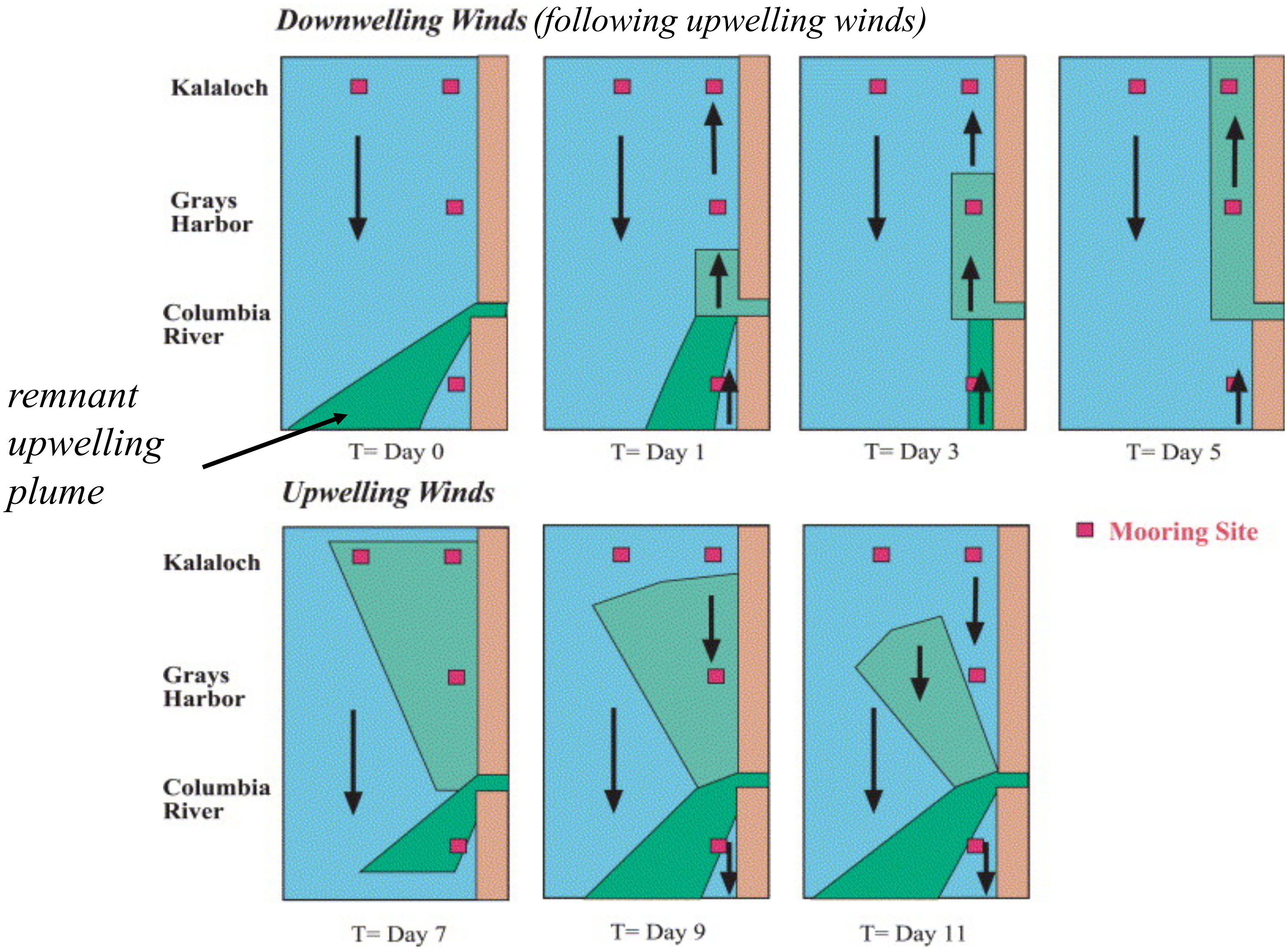
In reality, winds fluctuate throughout the summer over the Oregon and Washington shelves moving the plume north and south.



Model view of plume under downwelling conditions

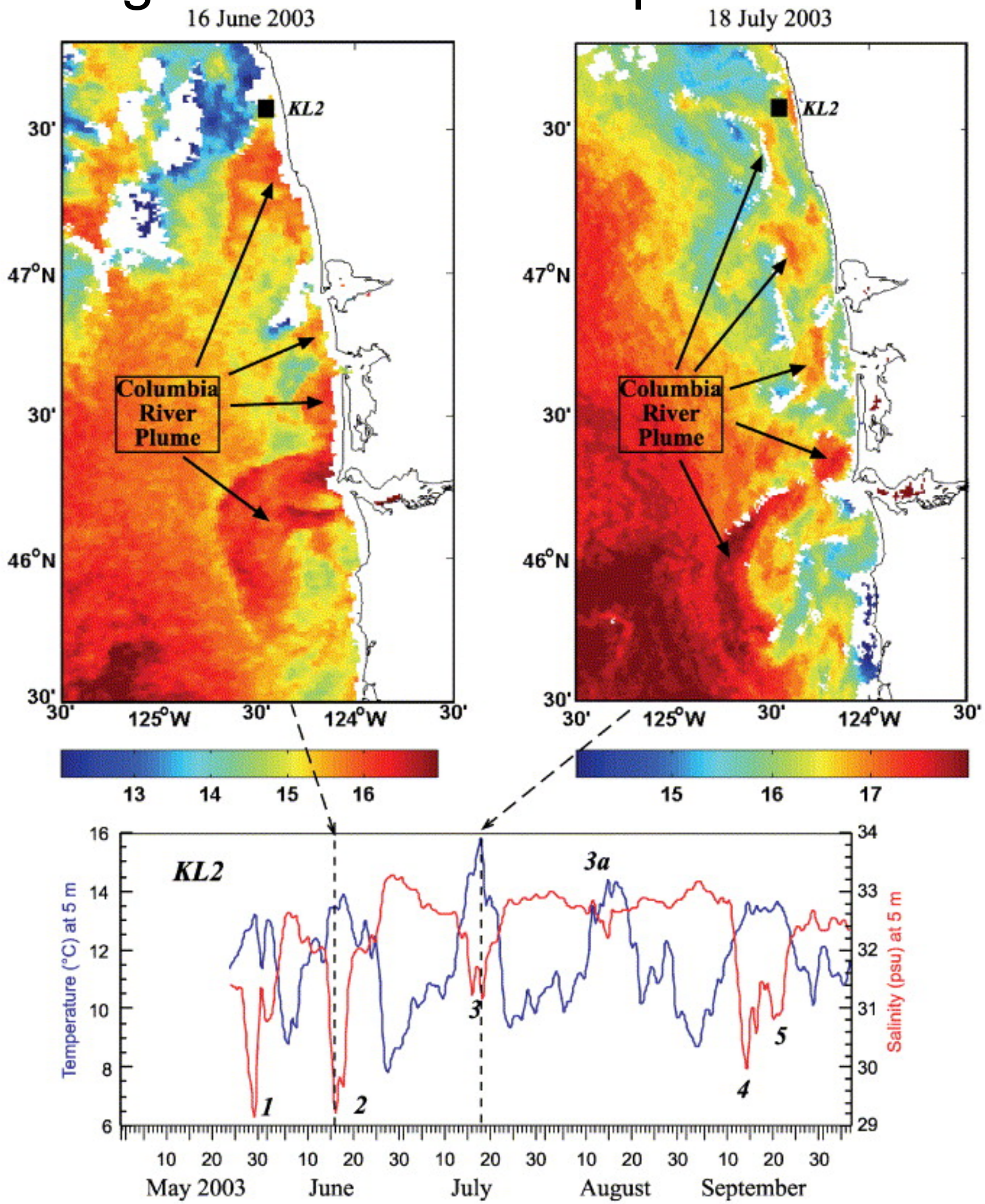
http://www.ccalmr.ogi.edu/CORIE/cruises/wecoma/plume_images_dev.html

Conceptual model of plume influence by variable winds



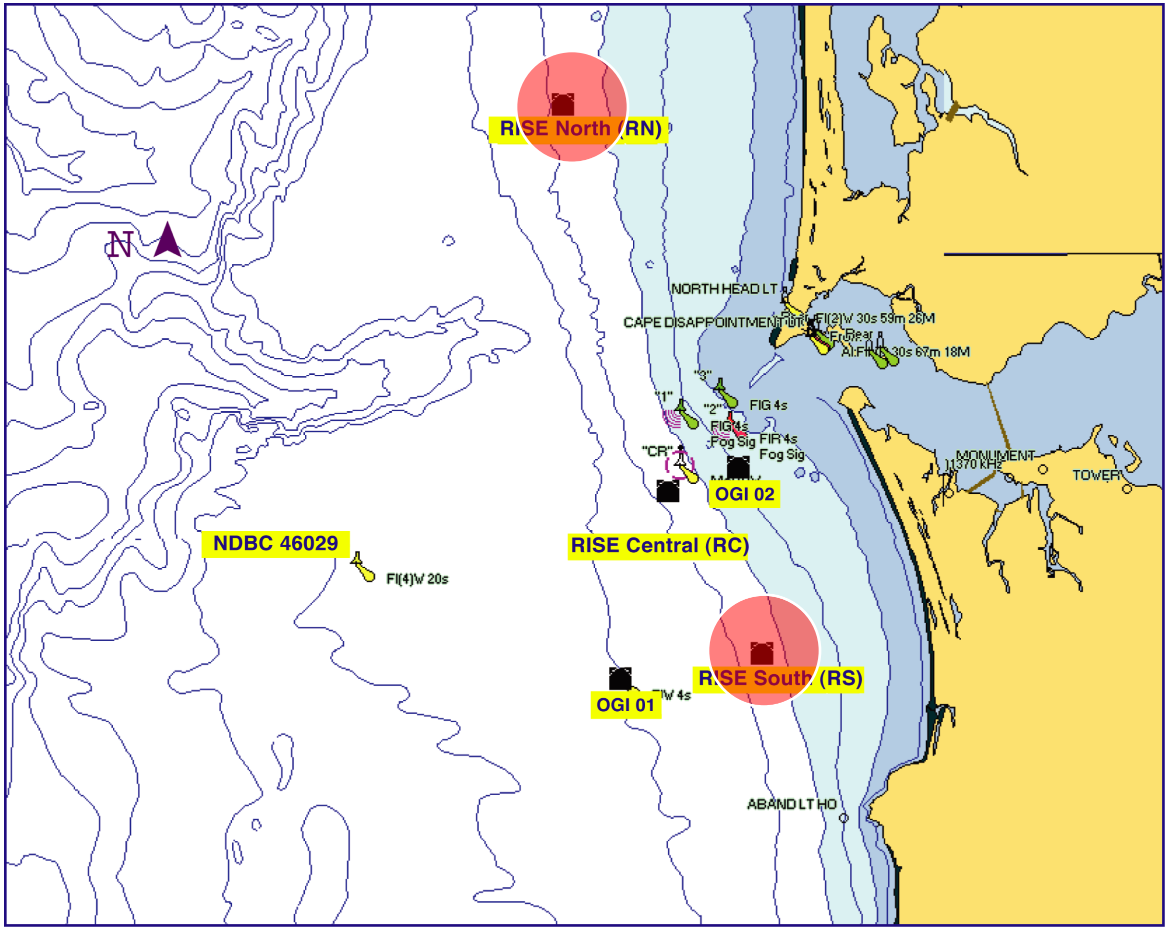
Hickey et al. (2005)

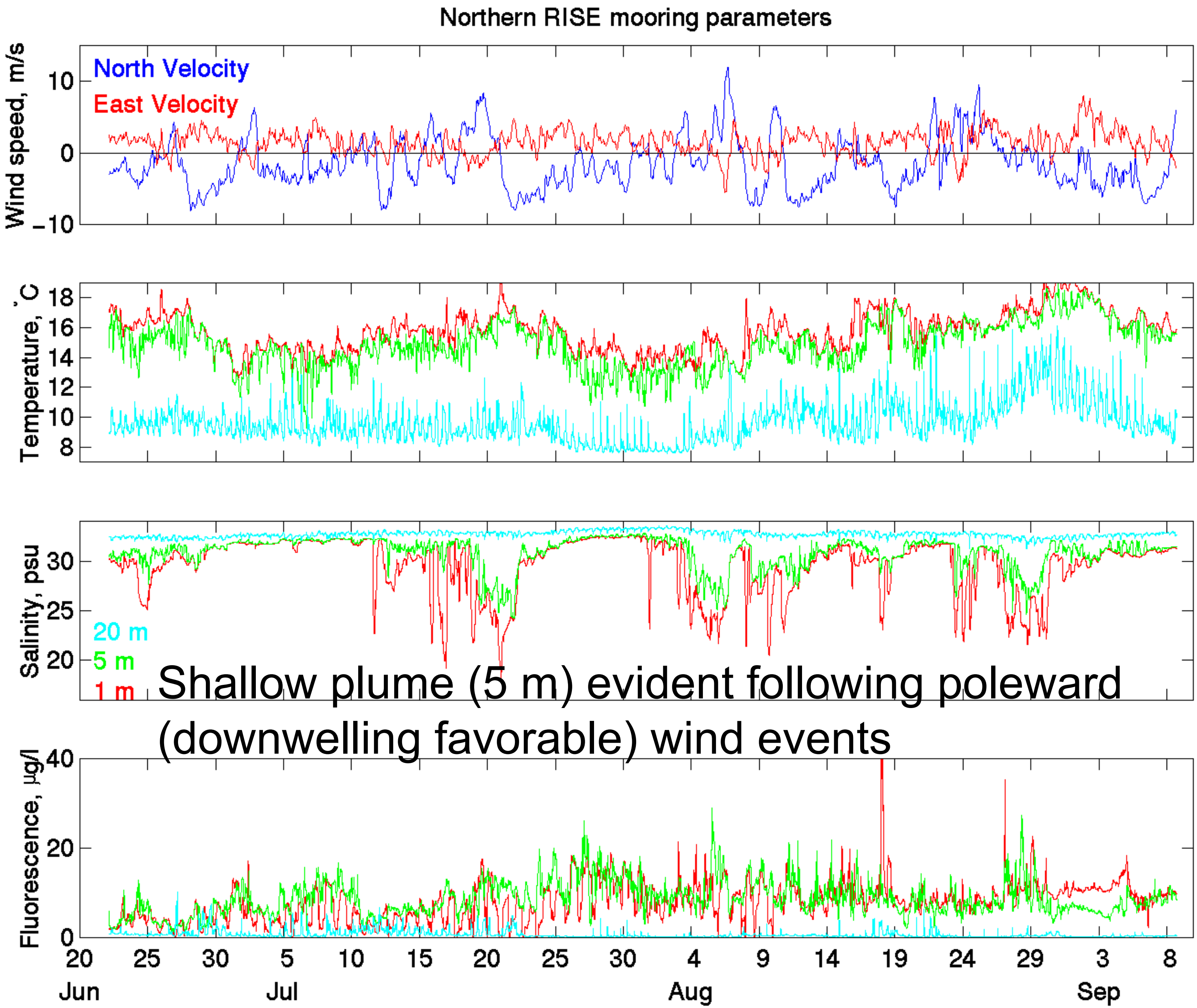
Satellite images show remnant plume after several wind events

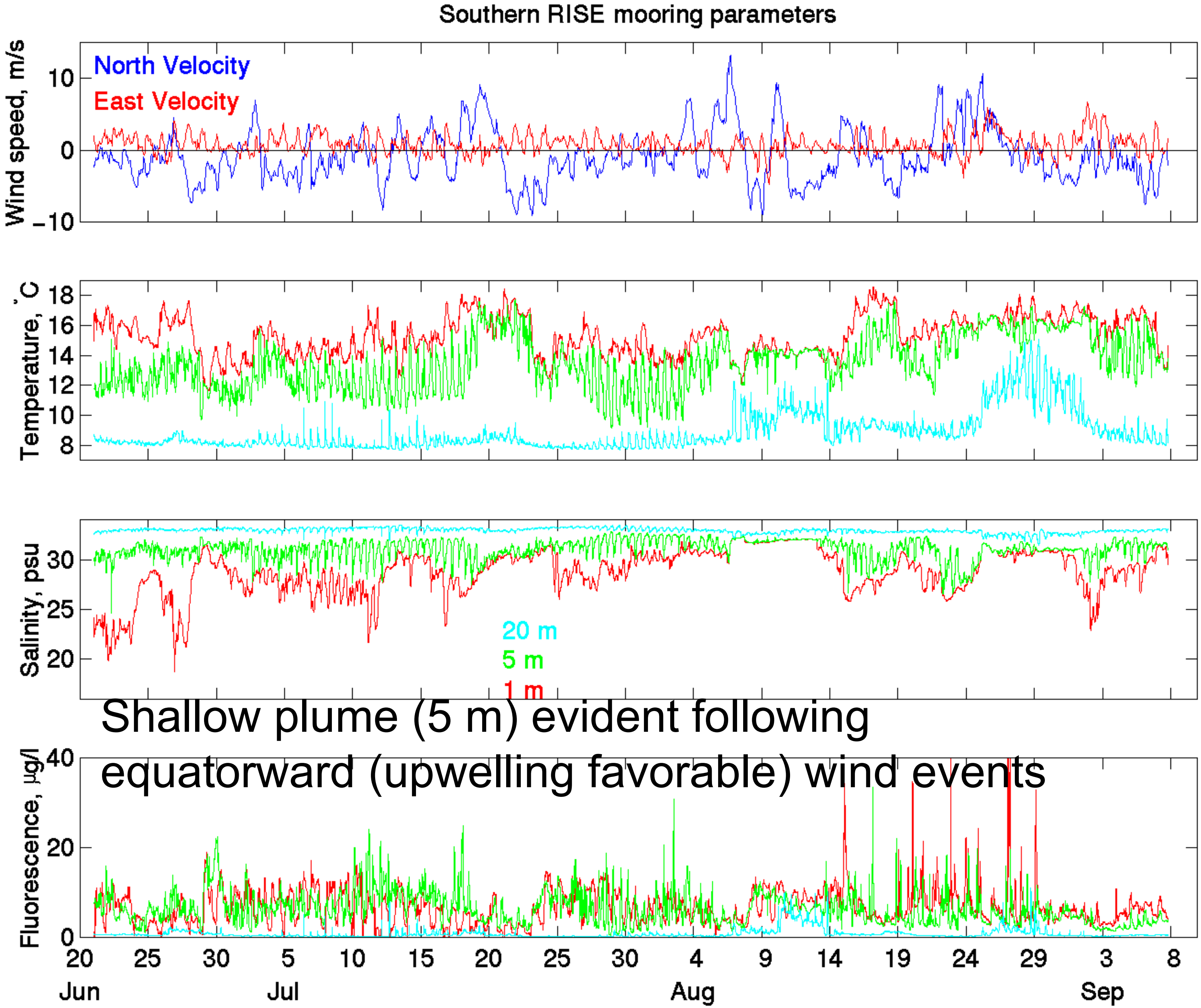


Hickey et al. (2005)

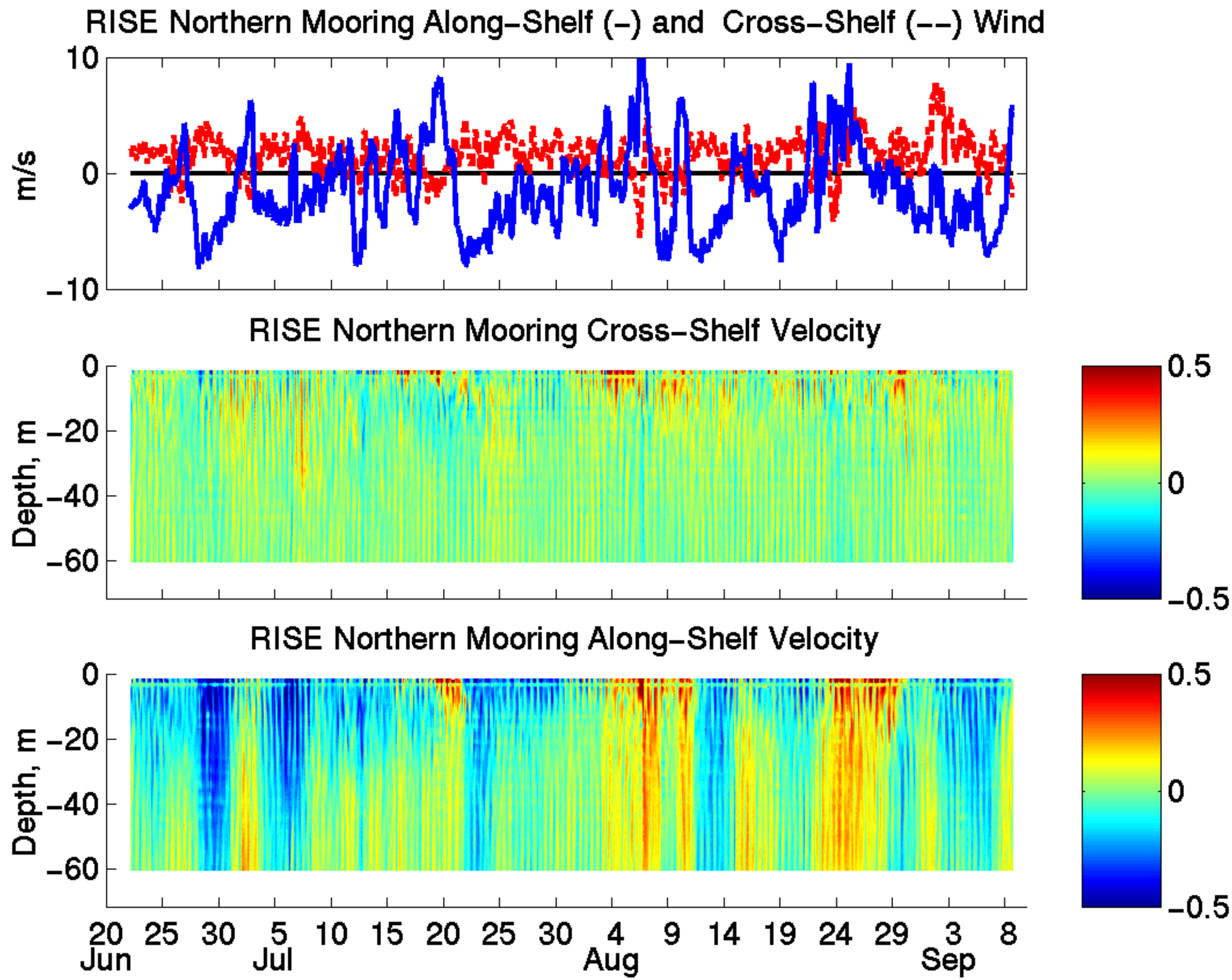
Mooring records from 2004 River Influences on Shelf Ecosystems (RISE) study




Northern RISE mooring parameters
North Velocity
East Velocity
Wind speed, m/s
Temperature, °C
Salinity, psu
20 m
5 m
1 m
Shallow plume (5 m) evident following poleward (downwelling favorable) wind events
Fluorescence, μg/l
Jun
Jul
Aug
Sep



Shallow plume (5 m) evident following equatorward (upwelling favorable) wind events


RISE Northern Mooring Along-Shelf (-) and Cross-Shelf (--) Wind
m/s
10
0
-10
RISE Northern Mooring Cross-Shelf Velocity
Depth, m
0
-20
-40
-60
0.5
0
-0.5
RISE Northern Mooring Along-Shelf Velocity
Depth, m
0
-20
-40
-60
0.5
0
-0.5
20 Jun
25
30
5 Jul
10
15
20
25
30
4 Aug
9
14
19
24
29
3 Sep
8

Conclusions

- The thinness of river plumes means that the Ekman transport response is confined to the near surface. This can lead to surprisingly large velocities in response to relatively moderate wind forcing events.

- For downwelling favorable winds, onshore Ekman transport pushes the river plume close to the coast trapping it there. On the west coast, this implies poleward flow that reinforces the tendency of river plumes to turn to the right after leaving the river mouth.

- For upwelling favorable winds, offshore Ekman transport pushes the river plume away from the coast. On the west coast, upwelling implies equatorward flow that overwhelms the tendency of river plumes to turn to the right after leaving the river mouth.

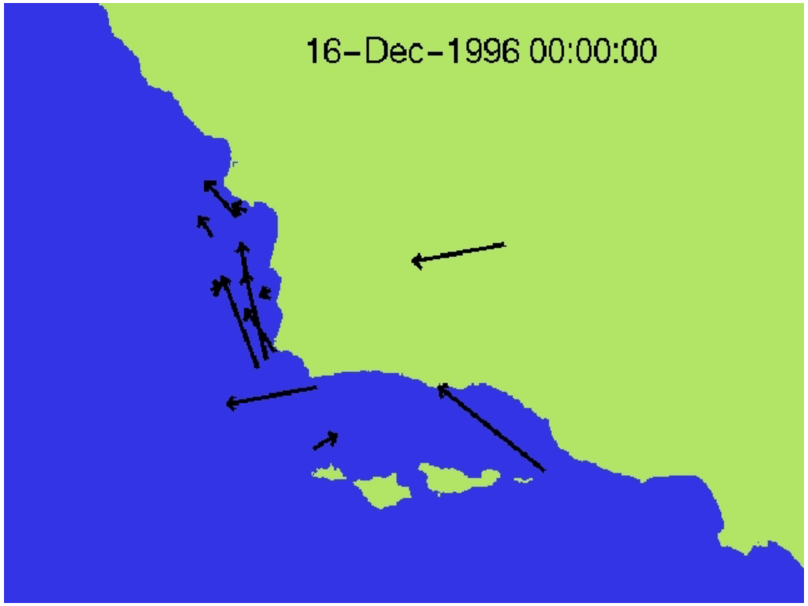
- Fluctuating wind forcing leads to a bidirectional river plume with remnant pieces of the river plume both north and south of the river mouth.

Summary

- Local wind-forcing affects circulation in predictable ways (upwelling/downwelling).
- There is a well known latitudinal gradient in wind forcing off the west coast of North America.
- Actual response to wind forcing is complicated by 3-dimensional processes.
- As the depth of the surface boundary layer decreases, the near surface velocities due to wind forcing can increase.
- Wind forcing affects river plumes as well

Drifter animations

- http://www.ccs.ucsd.edu/research/sbcsmb/animations/



Drifter animations

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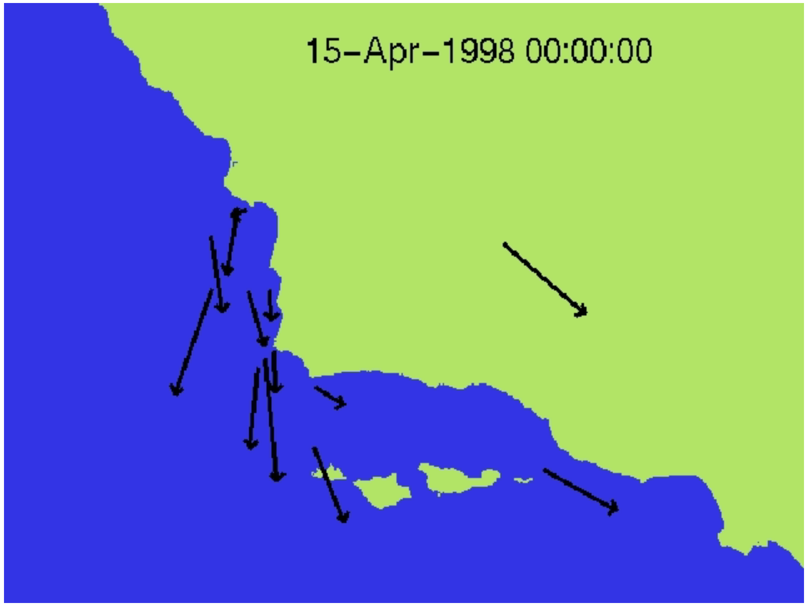

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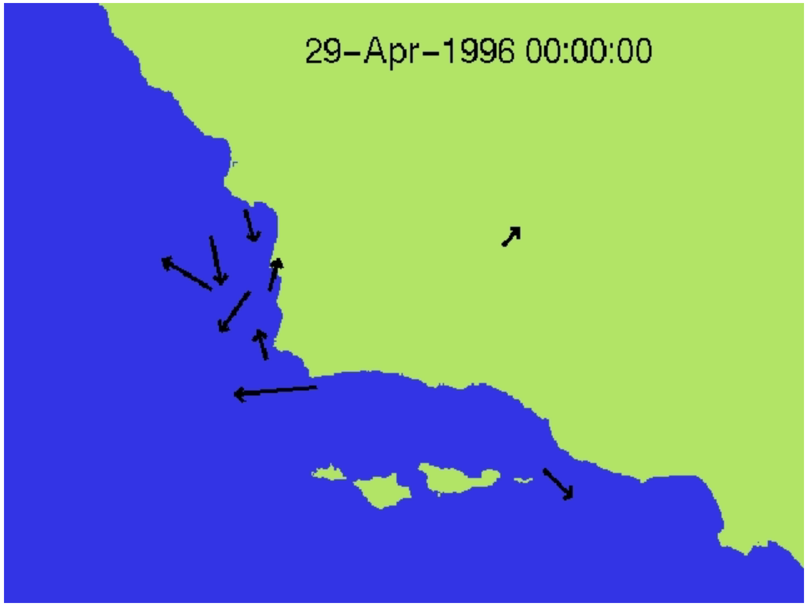

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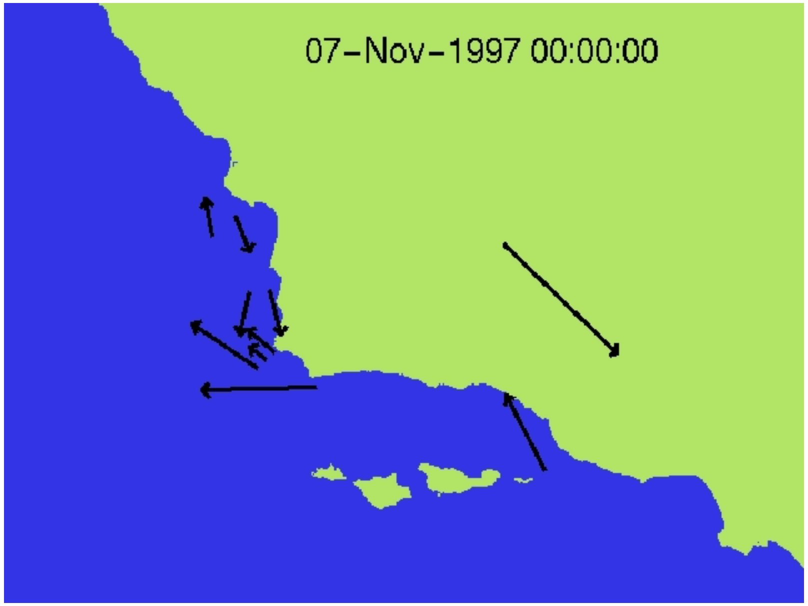


Actual seasonal cycle of winds (and hence upwelling/downwelling) varies with latitude

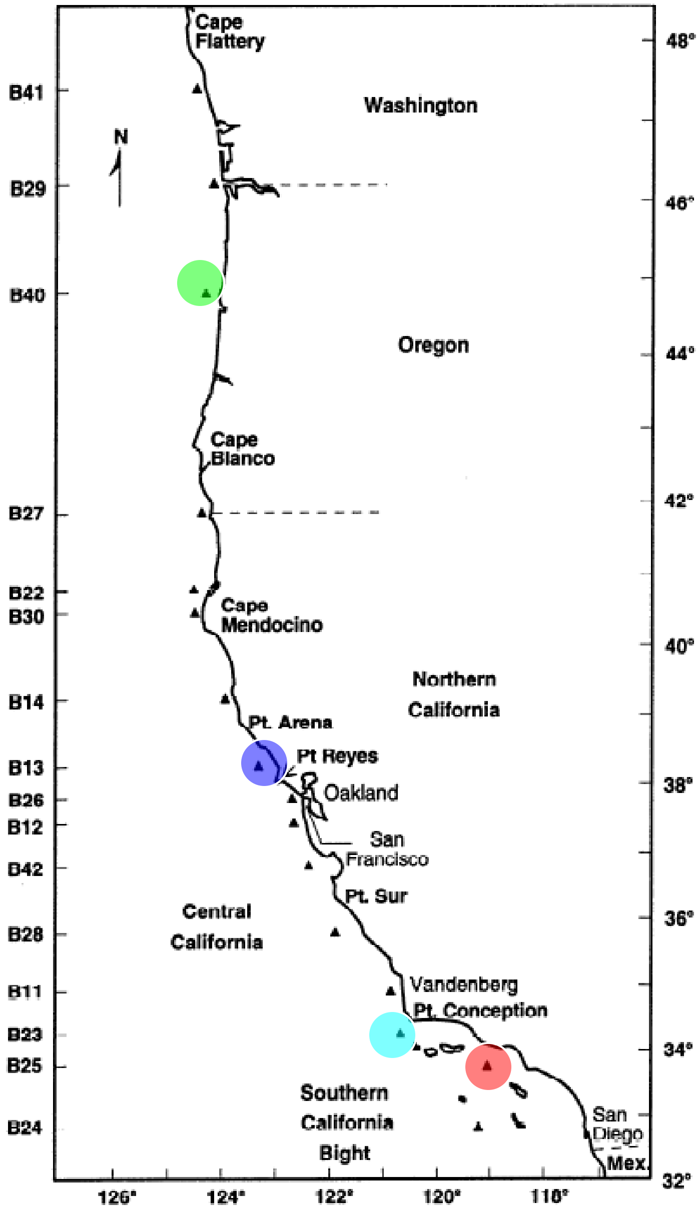


Figure 1. The west coast of the continental United States, showing the location of the National Data Buoy Corporation (NDBC) buoys and free balloon release sites.

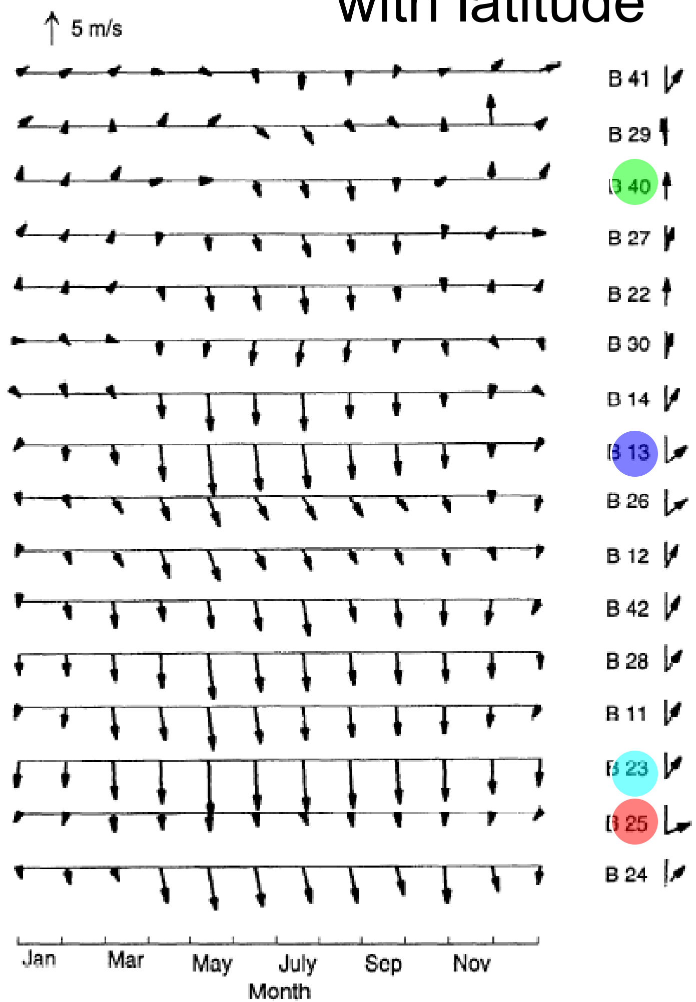
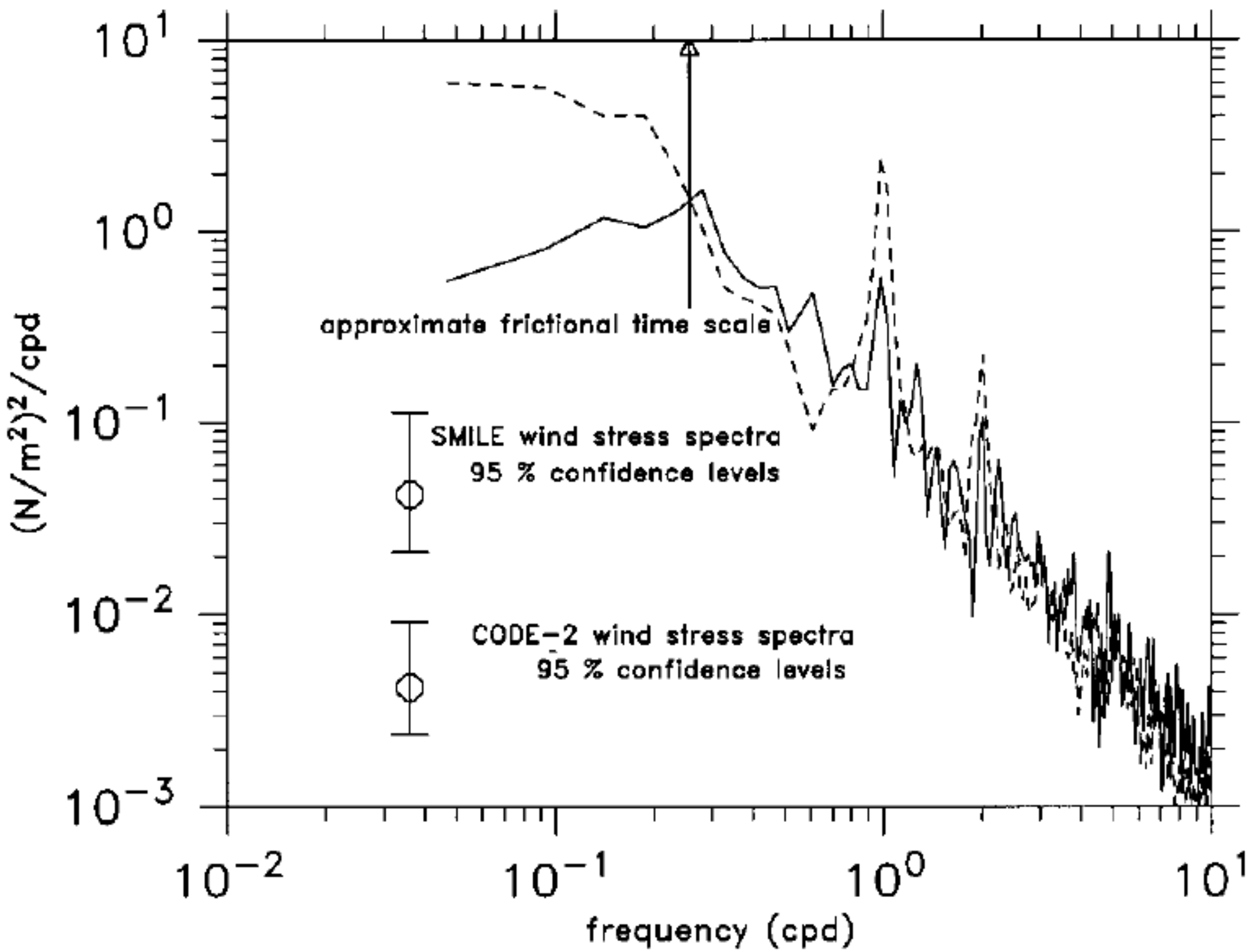
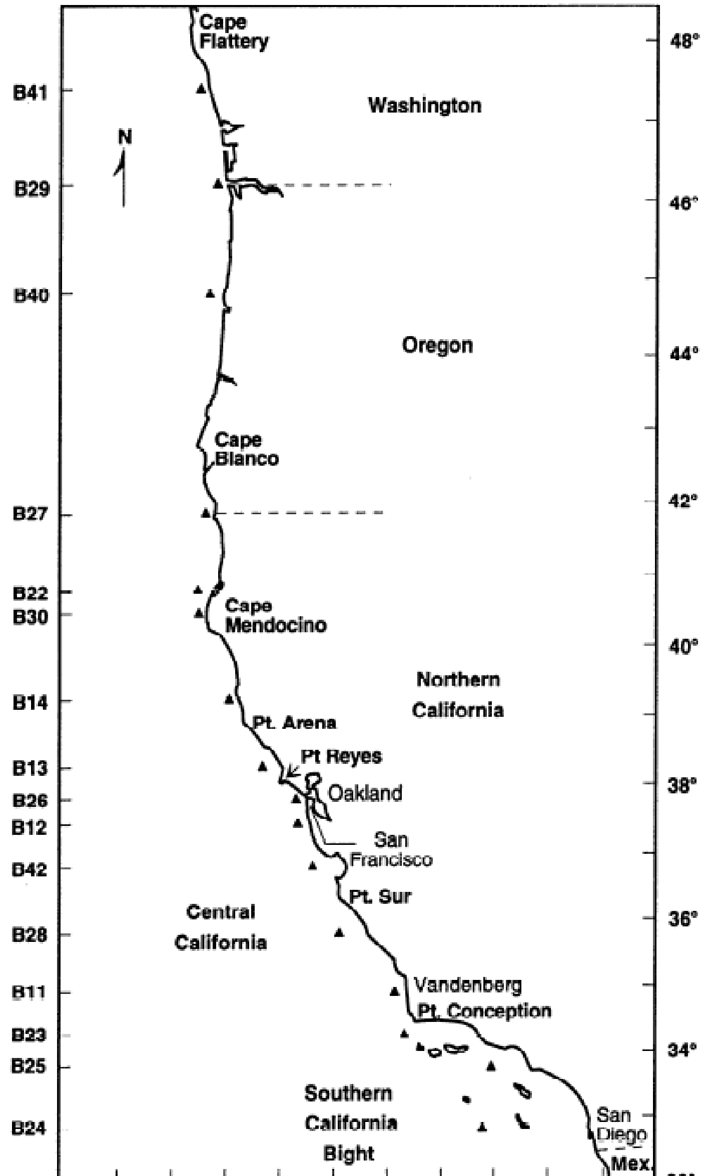


Figure 5. Annual cycle of the wind. For each location the vertical direction corresponds to the direction of the principal axes listed in Table 2. The relative orientation of that direction from north is sketched on the right-hand side, with the vector pointing toward north. The locations of the buoys are given in Table 1.

Dorman and Winant (1995)



10^1
10^0
10^-1
10^-2
10^-3
(N/m^2)^2/cpd
approximate frictional time scale
SMILE wind stress spectra
95 % confidence levels
CODE-2 wind stress spectra
95 % confidence levels
10^-2
10^-1
10^0
10^1
frequency (cpd)



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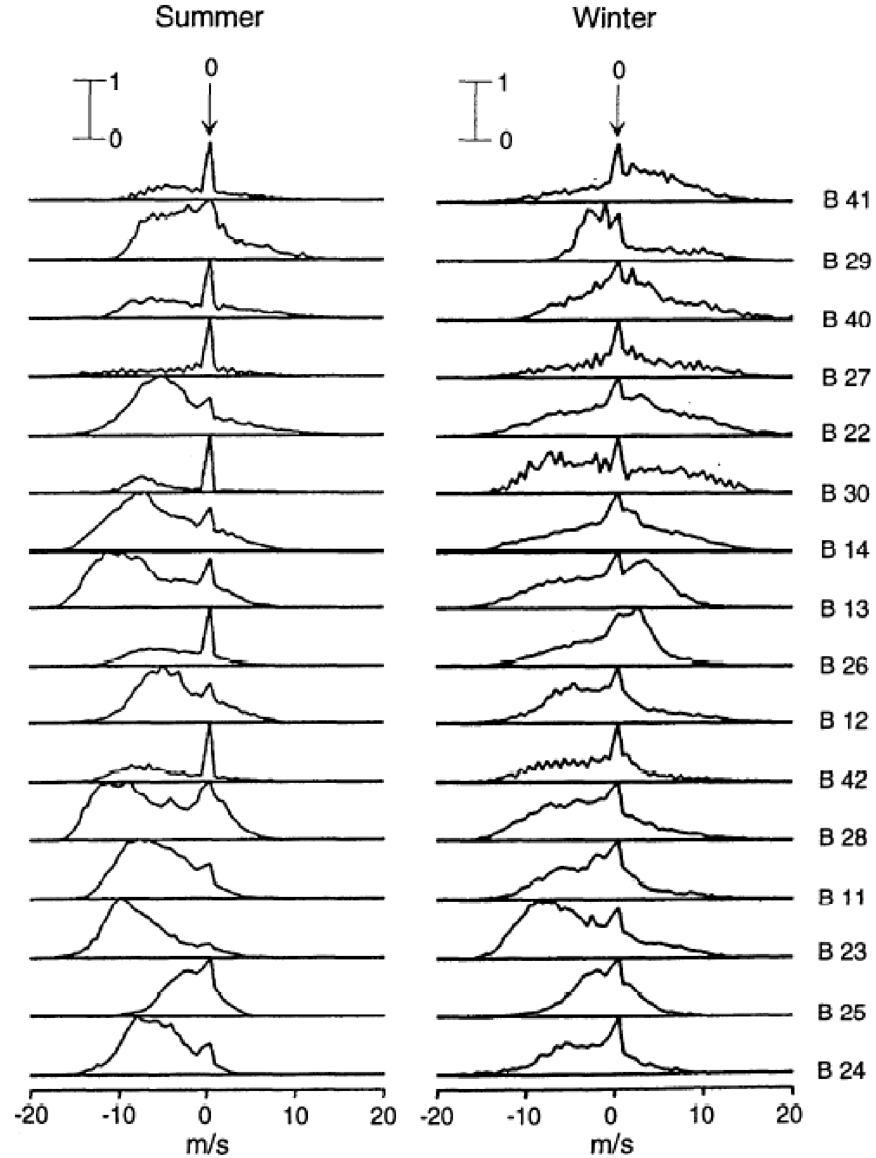
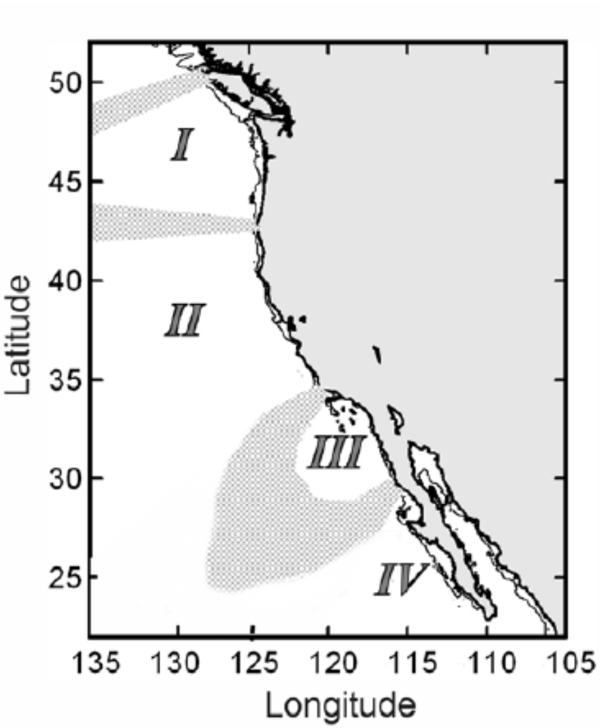


Figure 11. Probability density functions for the wind component parallel to the principal axes listed in Table 2 for (left) summer (May-August) and (right) winter (December- March) seasons.

Region locations	Property/ Process	Region I	Region II	Region III	Region IV
Core regions indicated by roman numerals, transition zones by shading 	Storms	Winter storms frequent and strong	Moderate winter storms	Fewer winter storms	Infrequent tropical storms
	Winds	Seasonal wind stress reversals	Winds very strong, mostly upwelling favorable	Alongshore minimum in wind stress	Modest and persistent alongshore wind stress
	Upwelling	Moderate and episodic upwelling in spring/summer	Strong upwelling in spring/summer	Weak upwelling	Moderate upwelling year-round
	Freshwater input	Large	Minor	Negligible	Negligible
	Coastal relief	Linear coastline, interrupted by several estuaries	Major coastal promontories	Concave coast, containing islands and enclosed basins	Several major promontories
	Continental shelf width (typical)	Moderate (50-100 km)	Narrow (<50 km)	Very narrow (<25 km)	Moderate (50-100 km)
	Advective shelter & nurseries	Several major estuaries & nursery grounds	A few bays/nurseries	Entire SCB region is sheltered and a major nursery	Several sheltered bays
	Alongshore advection & recirculation	Moderate advection (seasonal reversal) & mesoscale activity,	Strong advection and extreme mesoscale activity	Local recirculation, weak mesoscale activity, strong stratification	Moderate advection & mesoscale activity

Mackas (2005)