# Time-series mapping of coastal currents from shore: building a national system

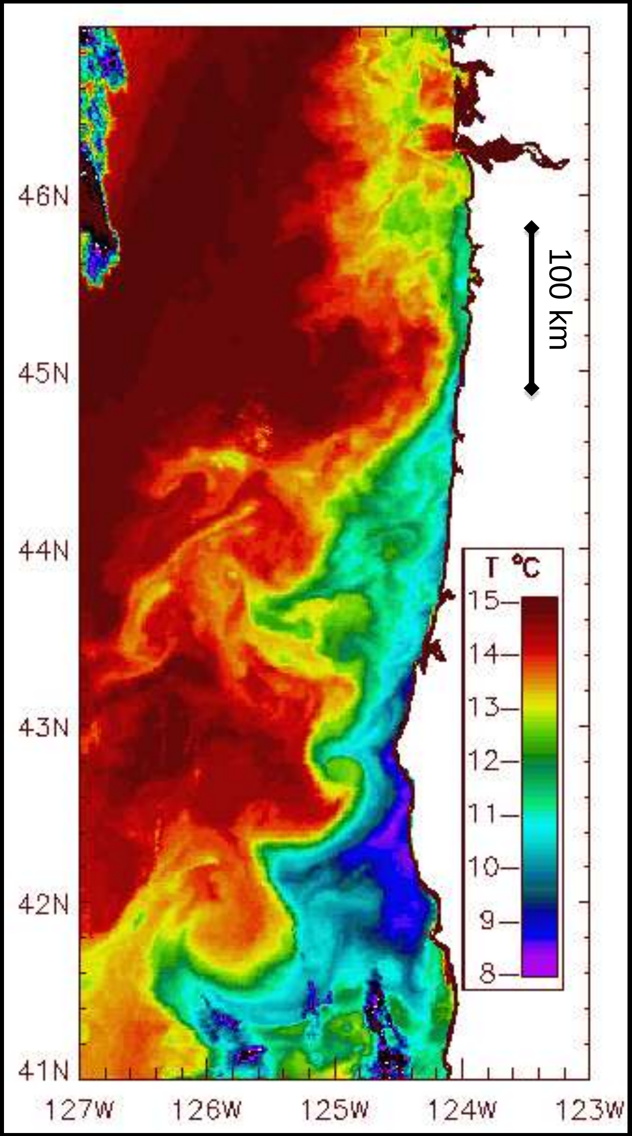
Mike Kosro, Oregon State University

May 16, 2011

# *Upper Ocean Observing Systems*- 'The Early Years'

# Changes: need distributions of properties, currents (and sources)

*Satellite Image of Sea Surface Temperature, Summer, Oregon*




The ocean varies strongly in time and over space. Here the ocean surface temperature is seen from a satellite infrared snapshot to vary strongly both across and along the coast. This mesoscale variability can drive differences in transports of properties in the coastal ocean.

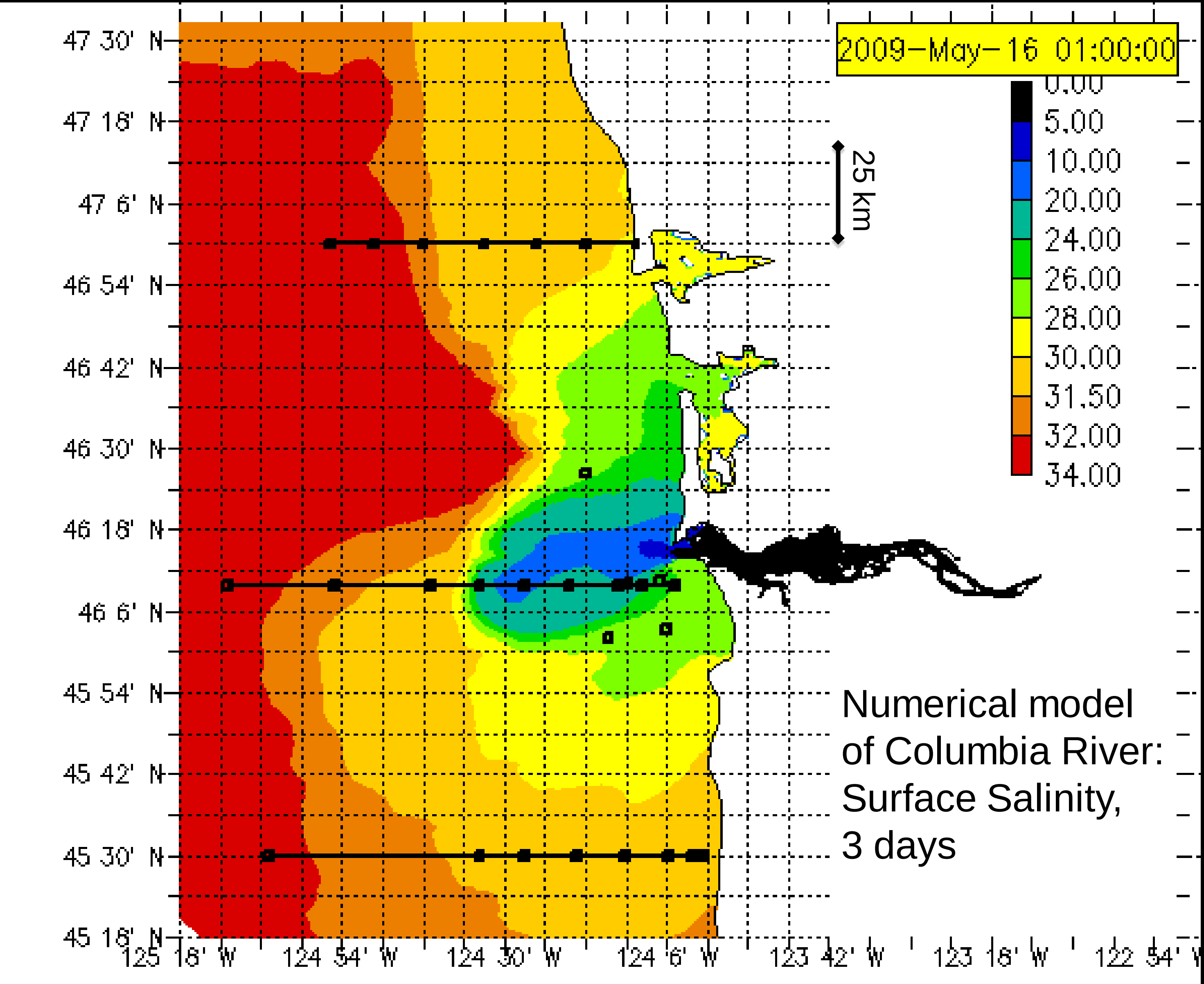
When skies are clear, satellite imagery can show properties: surface T, and also ocean color (which reflects the chlorophyll content). But it doesn't directly provide the accompanying current field.

Currents are crucial for dynamics and transport.

Spatial information on currents can be had from satellite altimeters. However:

- Time resolution is poor (O(5-30 days)
- Measurements are made along widely spaced tracks (variable spatial resolution)
- Measurements are subject to errors within 50 km of the coast.

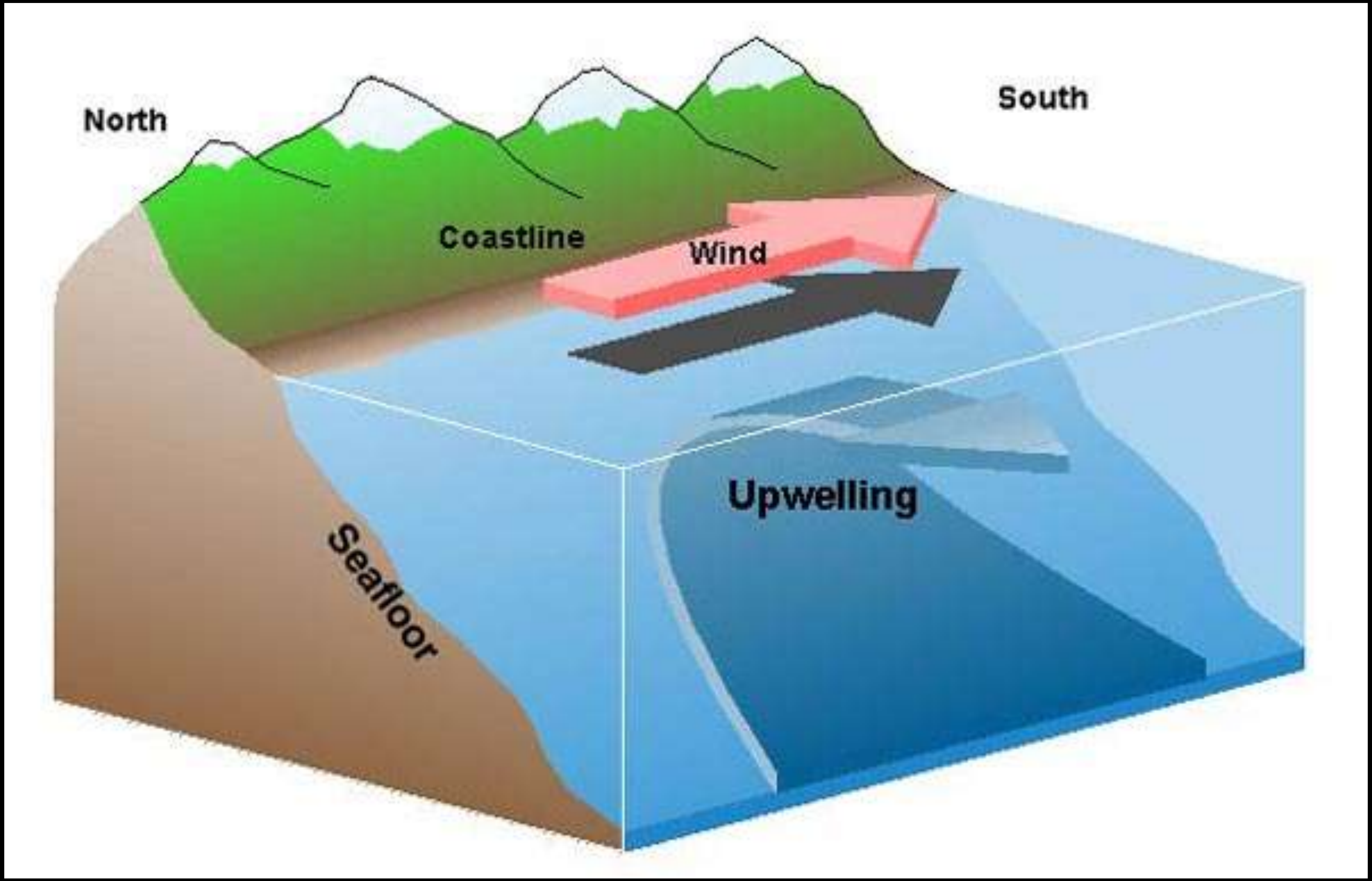
# Coastal Ocean varies in time & space: Tides



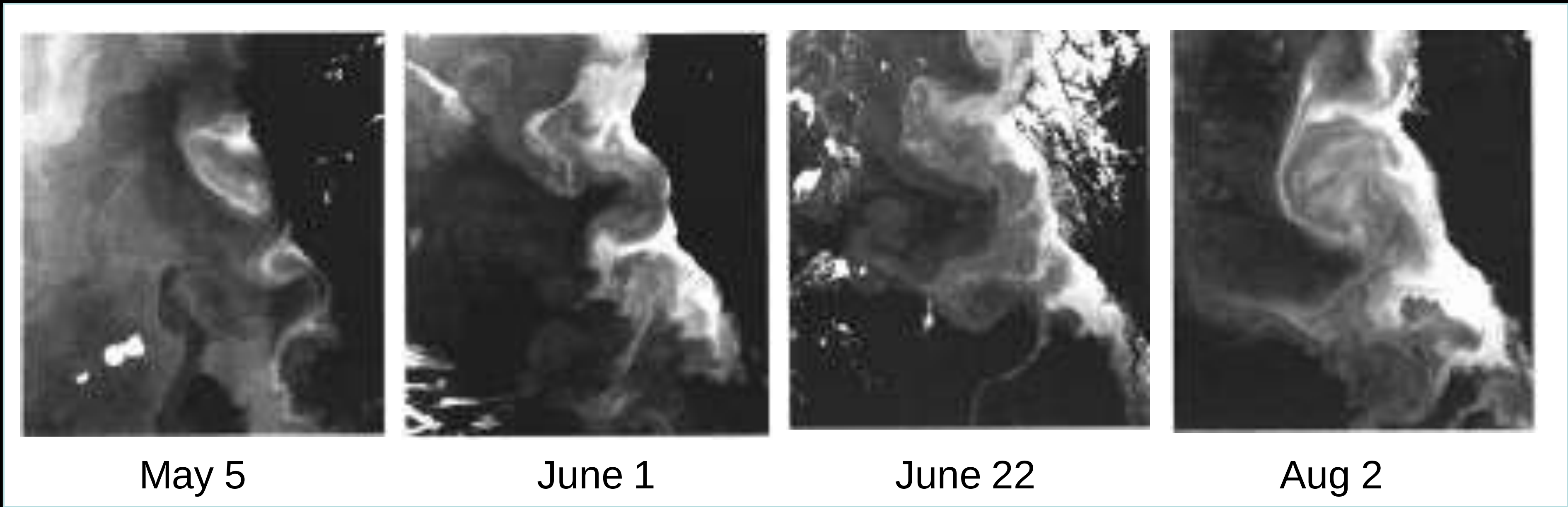

Numerical model of Columbia River: Surface Salinity, 3 days

Baptista, CMOP

# Coastal Ocean is highly variable in space and time: Coastal Upwelling



# Seasonal Development of Temperature Features

# Satellite Chlorophyll along West Coast

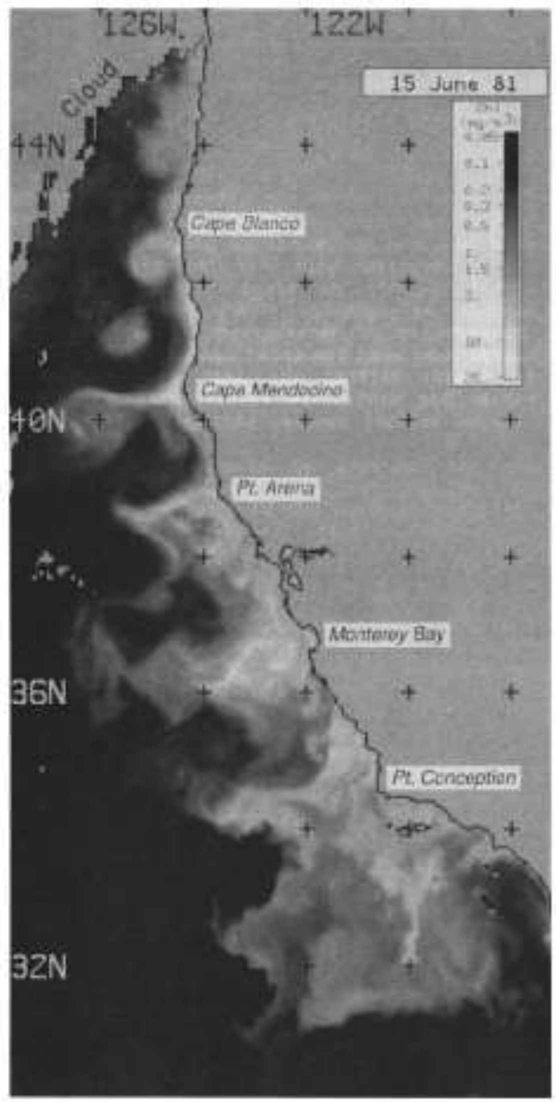
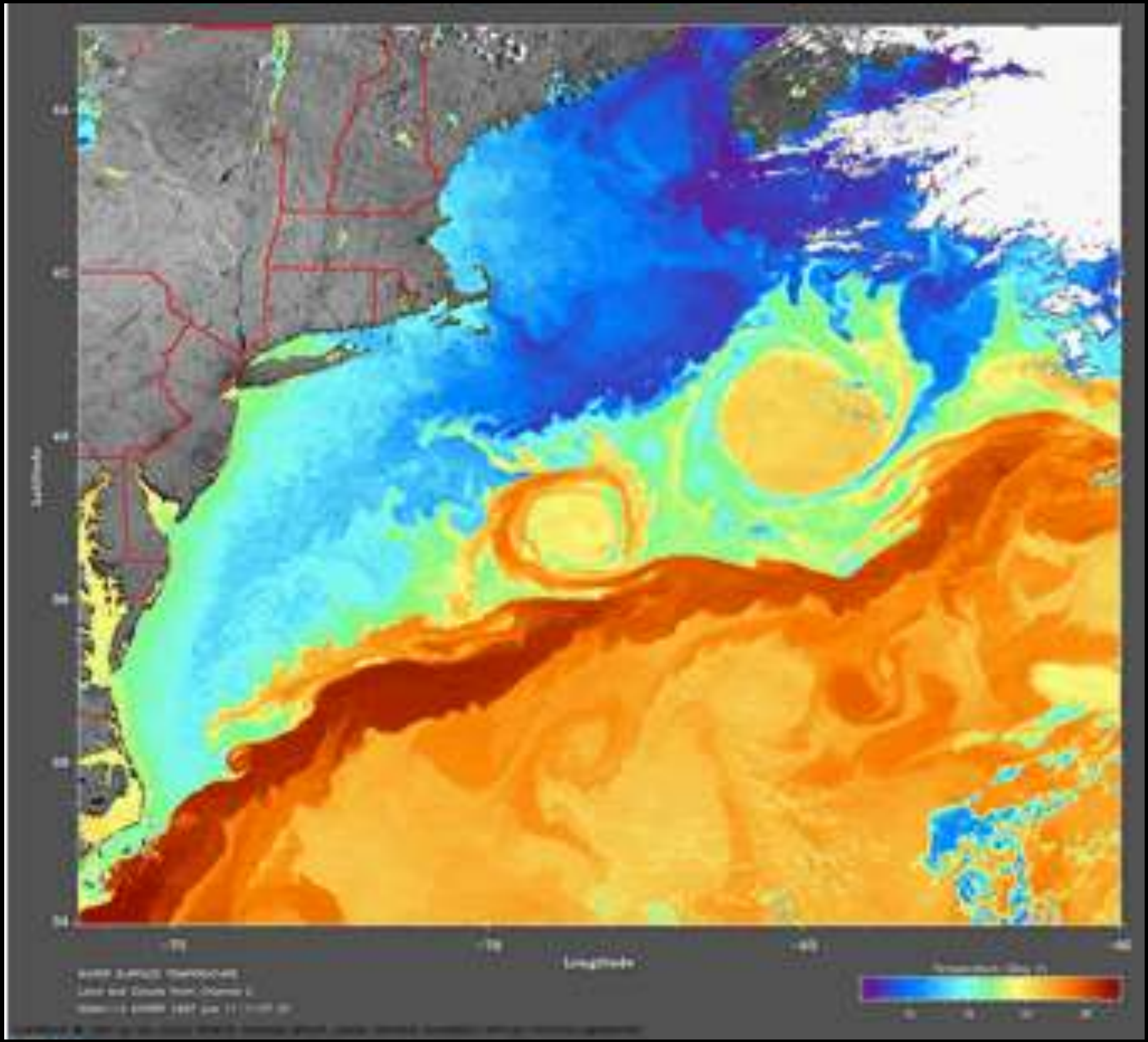



Fig. 17. Surface pigment concentration derived from the CZCS satellite data from June 15, 1981.

1500 km

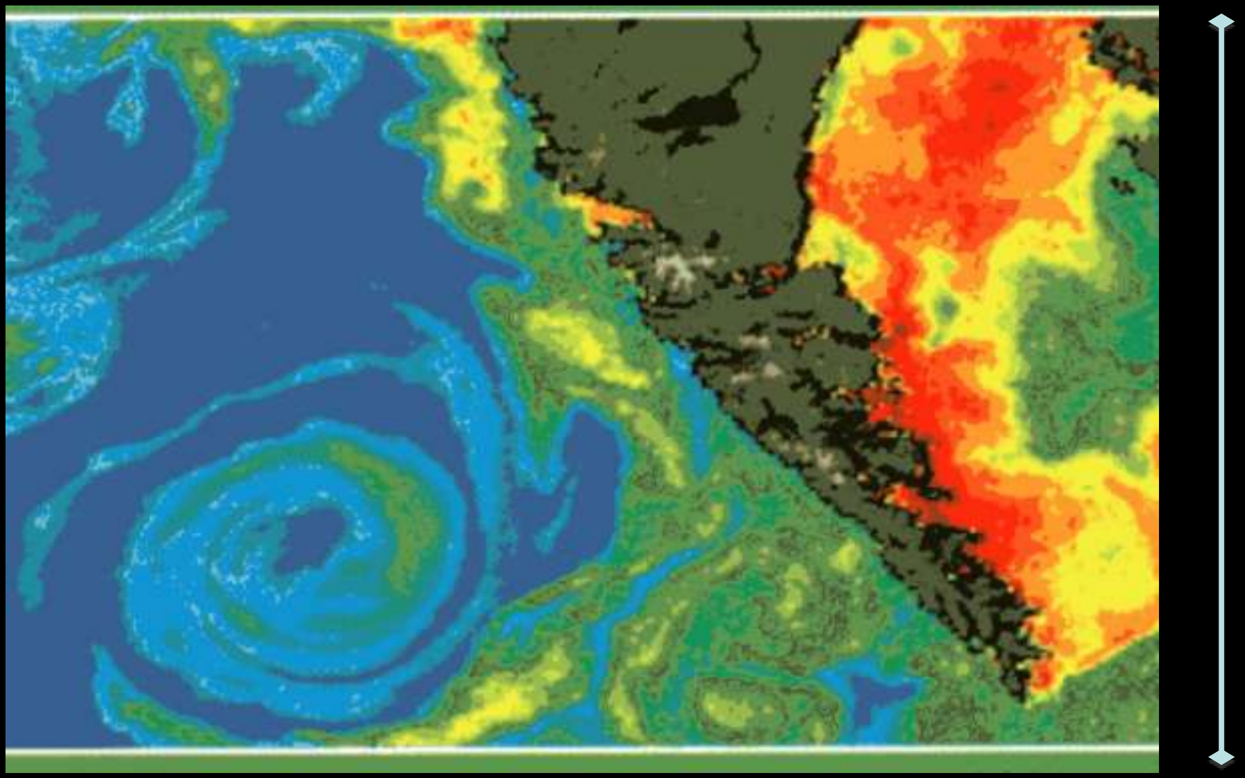
Strub, Kosro, Huyer et al., 1991

# Gulf Stream + Eddies (in Temperature)



JHU Ocean Remote Sensing Group

# Chlorophyll from satellite British Columbia, CANADA




Miller, 2004

# How to map currents in space and time?

Drifter

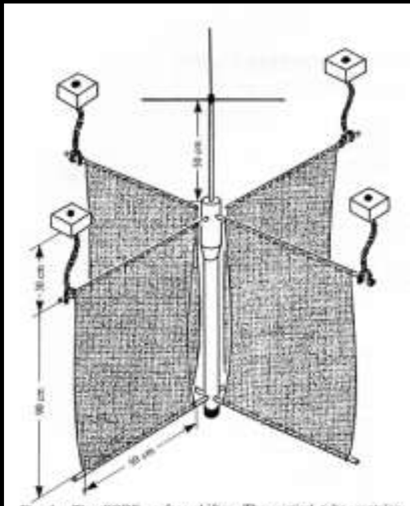
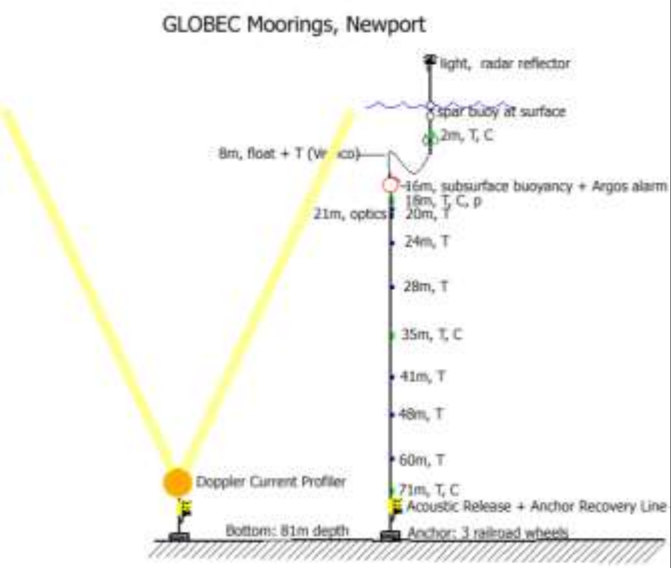
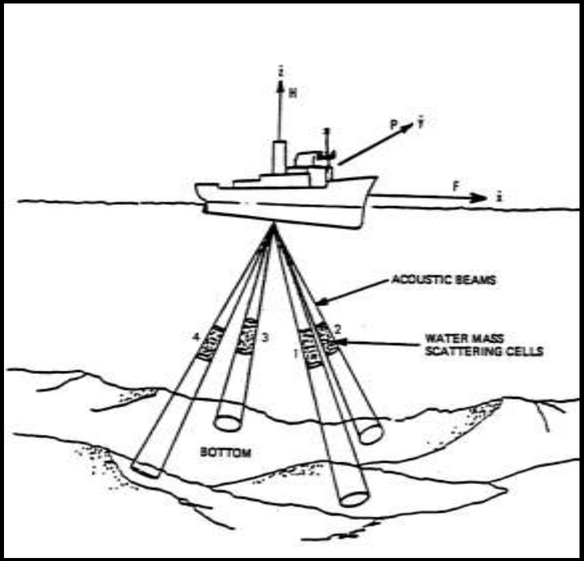


Fig. 1. The CODE surface drifter. The vertical tube contains transmitter and batteries and supports the antenna. Drag producing vanes are of plasticized cloth. Mass is 4.2 kg, hull displacement is 3.3 kg, and the four floats (attached by flexible lines) provide an additional 1.8 kg buoyancy.

Mooring

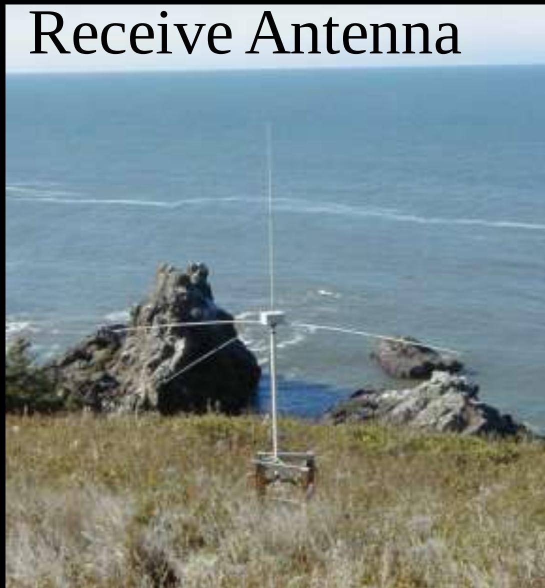



Ship ADCP



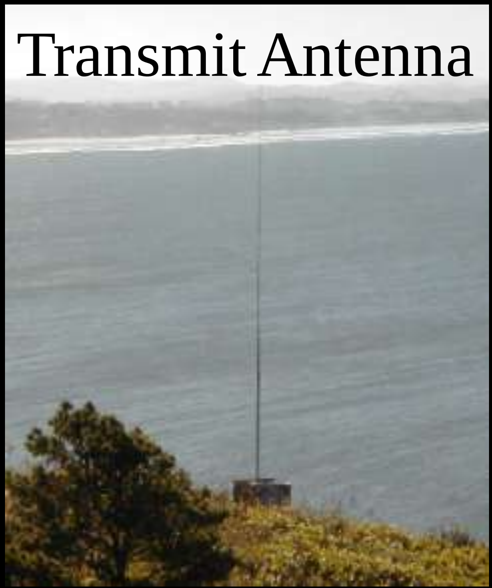

- Drifters: poor time resolution. Sampling depends on flow.
- Moorings: excellent time resolution, expensive for good space resolution
- Ship ADCP: good quasi synoptic surveys if tides are not dominant; expensive to get repeat mappings
- Satellite altimetry: very good at large scales, but poor time resolution (O(1 week-1month) and doesn't work close to the coast

# Mapping surface currents with HF backscatter




50 meters

13 MHz system




Site building houses computer, electronics, Internet

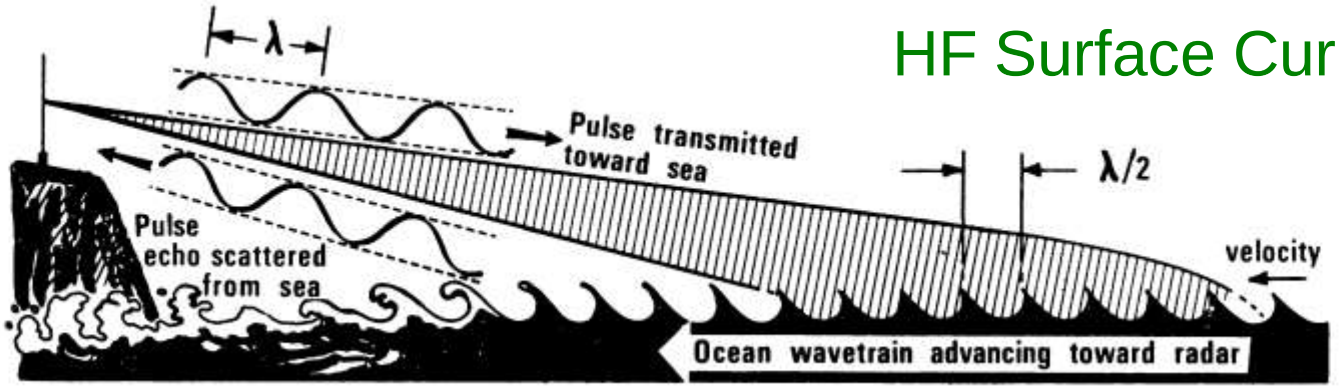
# Beyond the shelf: 5 MHz operation

## Long-Range System: Antennas

Receive

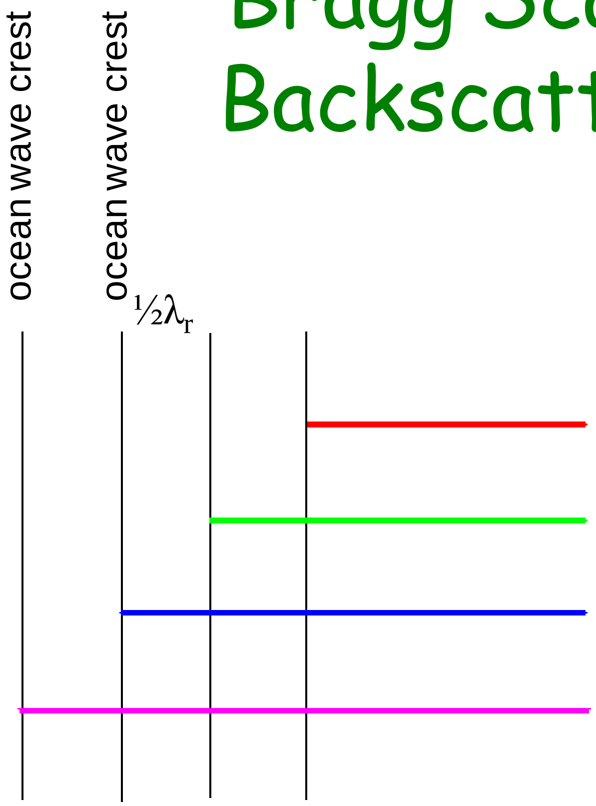
Transmit

# HF Surface Current Mapping




Barrick et al., 1977

## Bragg Scattering: Resonant Backscatter for $\lambda_{ocean} = \frac{1}{2}\lambda_{radar}$




- Incident radio waves (colored rays) scatter off different ocean wavefronts (black).
- Backscattered radio waves from different ocean wavefronts will intefere constructively only when the added path length is an integral number of radio wavelengths.
- Thus the ocean wavelength for "resonant" scattering is one-half of the wavelength for the incident radio waves

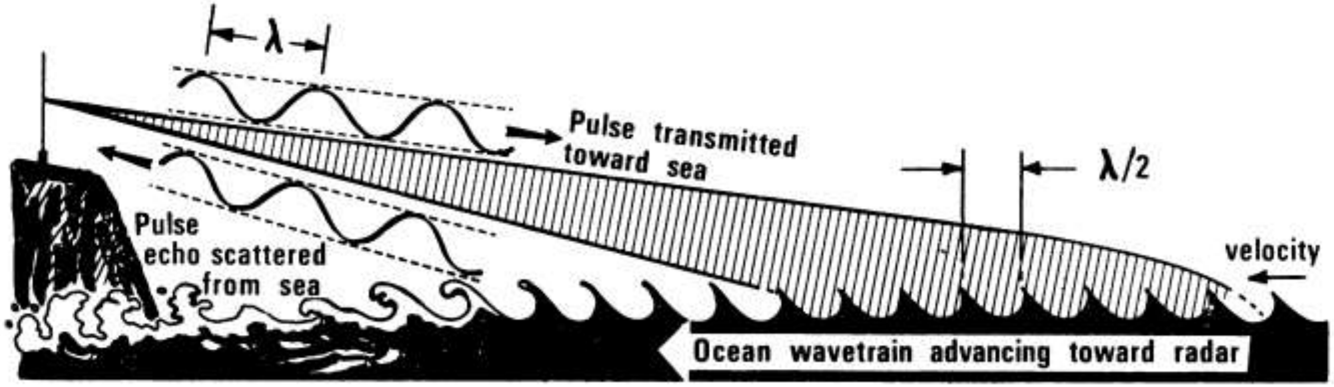
# Principles of Operation

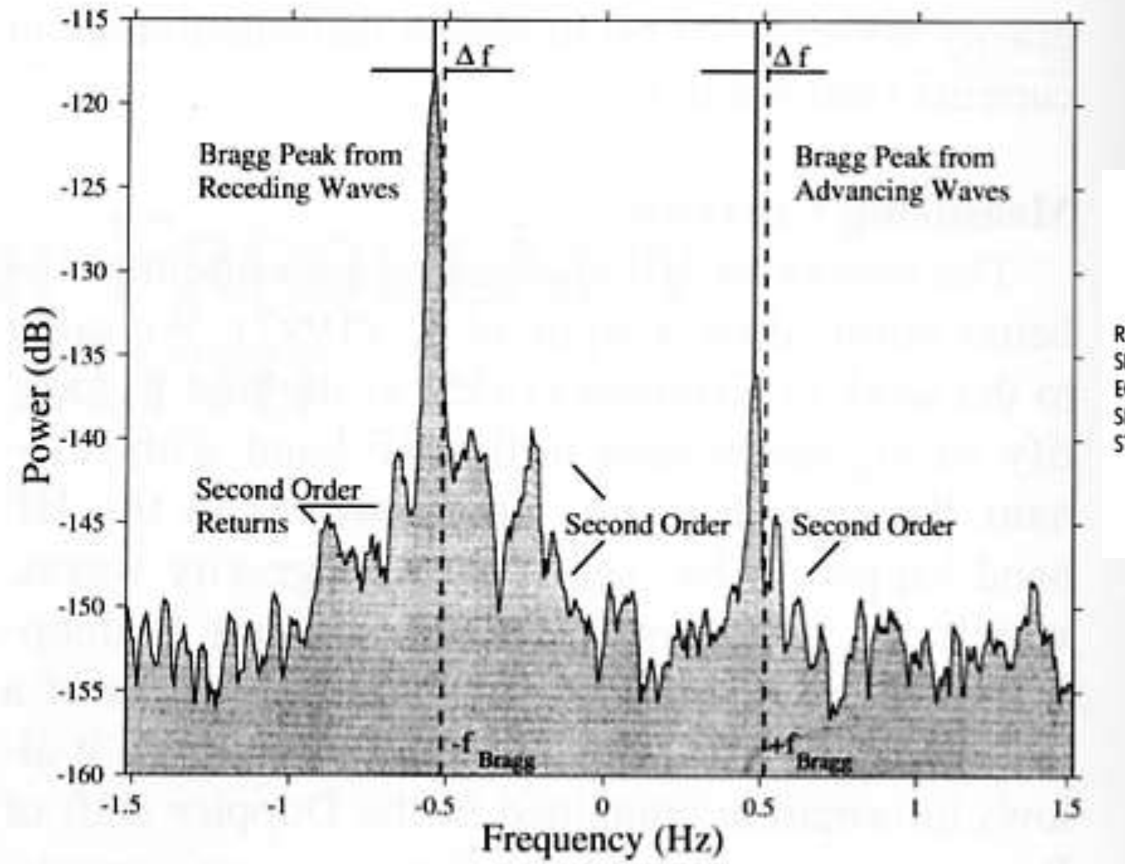
• **Bragg Scattering**: Radio waves are backscattered from ocean waves of fixed, known wavelength
$\lambda_{ocean} = \frac{1}{2} \lambda_{incident}$

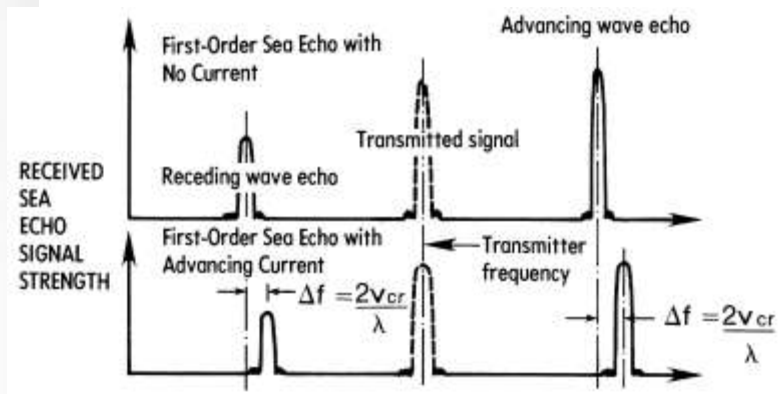
•**Doppler Shift**: Backscattered radio waves are shifted in frequency by the ocean waves' motion toward or away from the receiver.

•**Deep-Water Waves**: the speed of ocean waves depends only on their wavelength, $c = (g/k)^{1/2}$. (valid to 1 cm/s for $H > \lambda_{ocean}/2$ = 6m for this system).

So, expect 2 Bragg peaks (approaching and receding). Expect additional shifts due to currents. These are our signal.


λ
Pulse transmitted toward sea
λ/2
Pulse echo scattered from sea
velocity
Ocean wavetrain advancing toward radar


Δf
Δf
Bragg Peak from Receding Waves
Bragg Peak from Advancing Waves
Second Order Returns
Second Order
Second Order
-f Bragg
+f Bragg
Power (dB)
Frequency (Hz)
-115
-120
-125
-130
-135
-140
-145
-150
-155
-160
-1.5
-1
-0.5
0
0.5
1
1.5


RECEIVED SEA ECHO SIGNAL STRENGTH
First-Order Sea Echo with No Current
Advancing wave echo
Transmitted signal
Receding wave echo
First-Order Sea Echo with Advancing Current
Transmitter frequency
Δf = 2v_cr / λ
Δf = 2v_cr / λ

# HF Systems: Phased Array (WERA) vs. Direction-Finding (SeaSonde/CODAR)

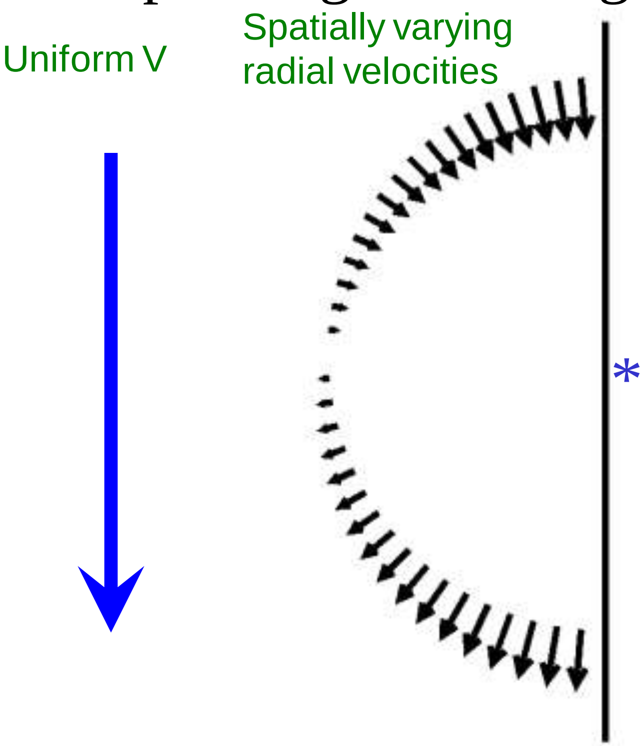
- Main difference is in the way the direction of the return is found.
- Phased array uses a long antenna array to examine one direction at a time. Simpler physics. But requires 80m of coastline at each site.
- Direction-finding uses a compact antenna with 2 directional loops to estimate direction of return. Trickier physics, but more deployable.
- 95% of US HF systems are compact, direction-finding.

Phased-array receive antenna

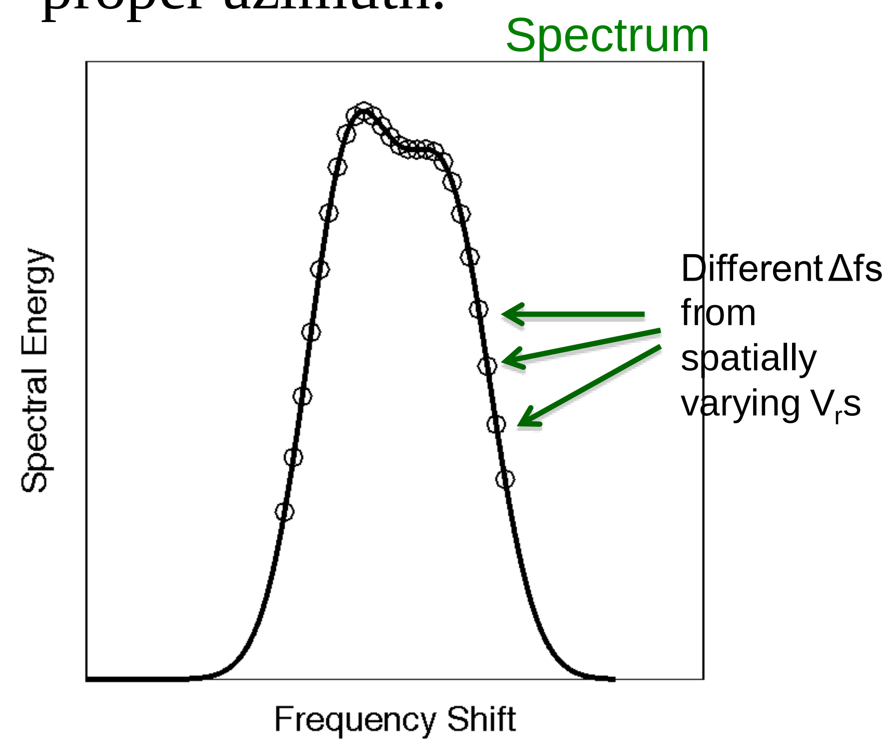
Direction-finding antenna

# Spectrum at each range produces multiple vectors

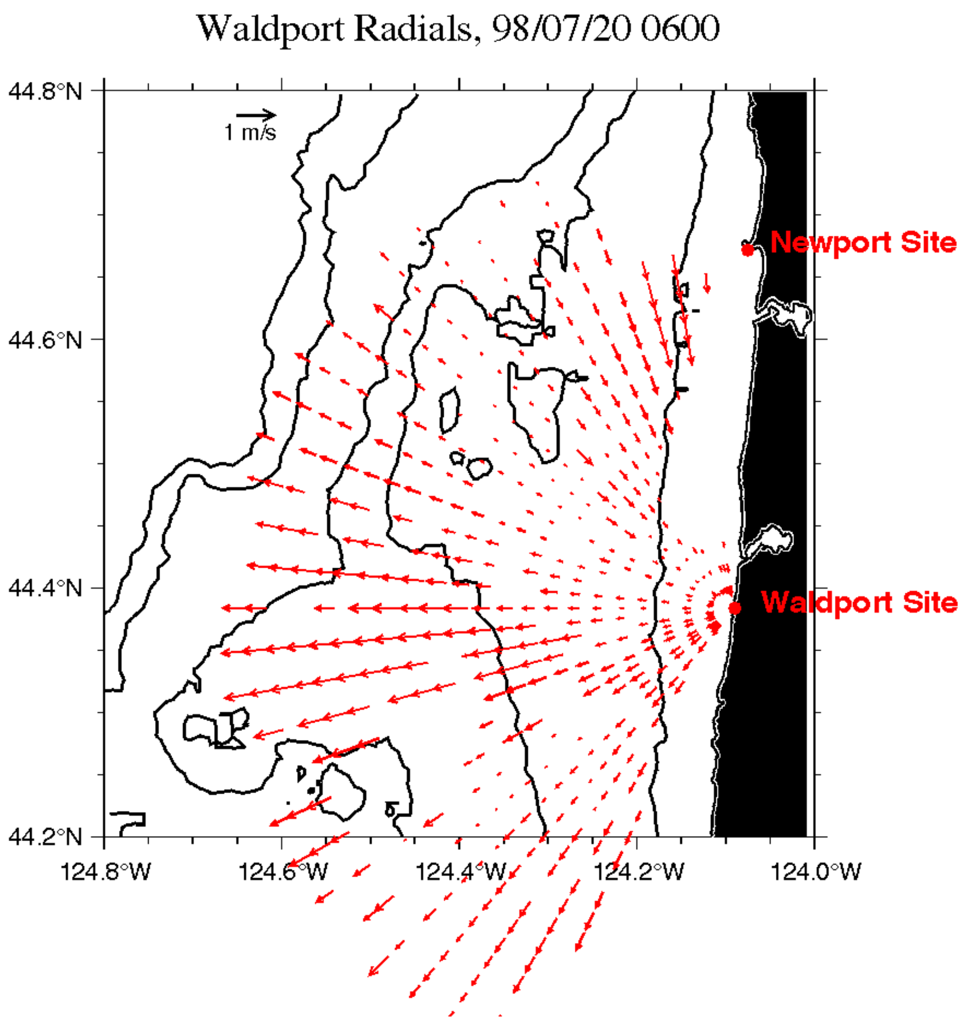
A spatially uniform southward current V => radial currents which vary from +V to -V, depending on the angle.

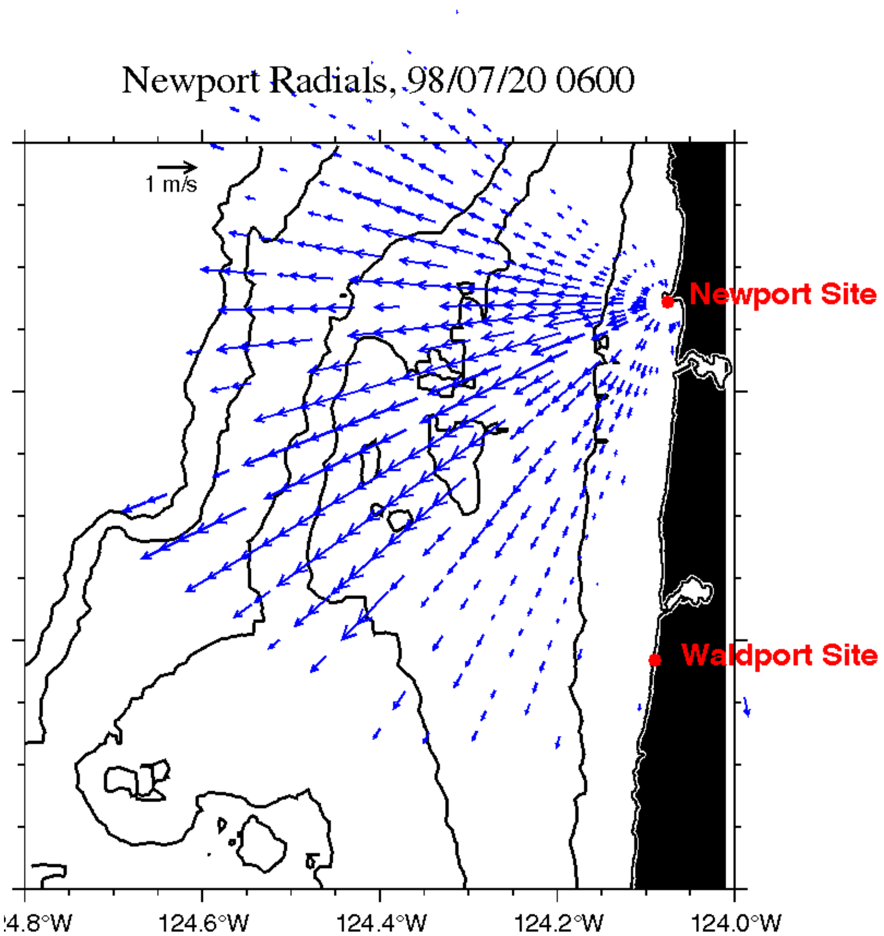



So, at any given range ring, can expect several Δf. Must use direction-finding to associate each Δf with the proper azimuth.

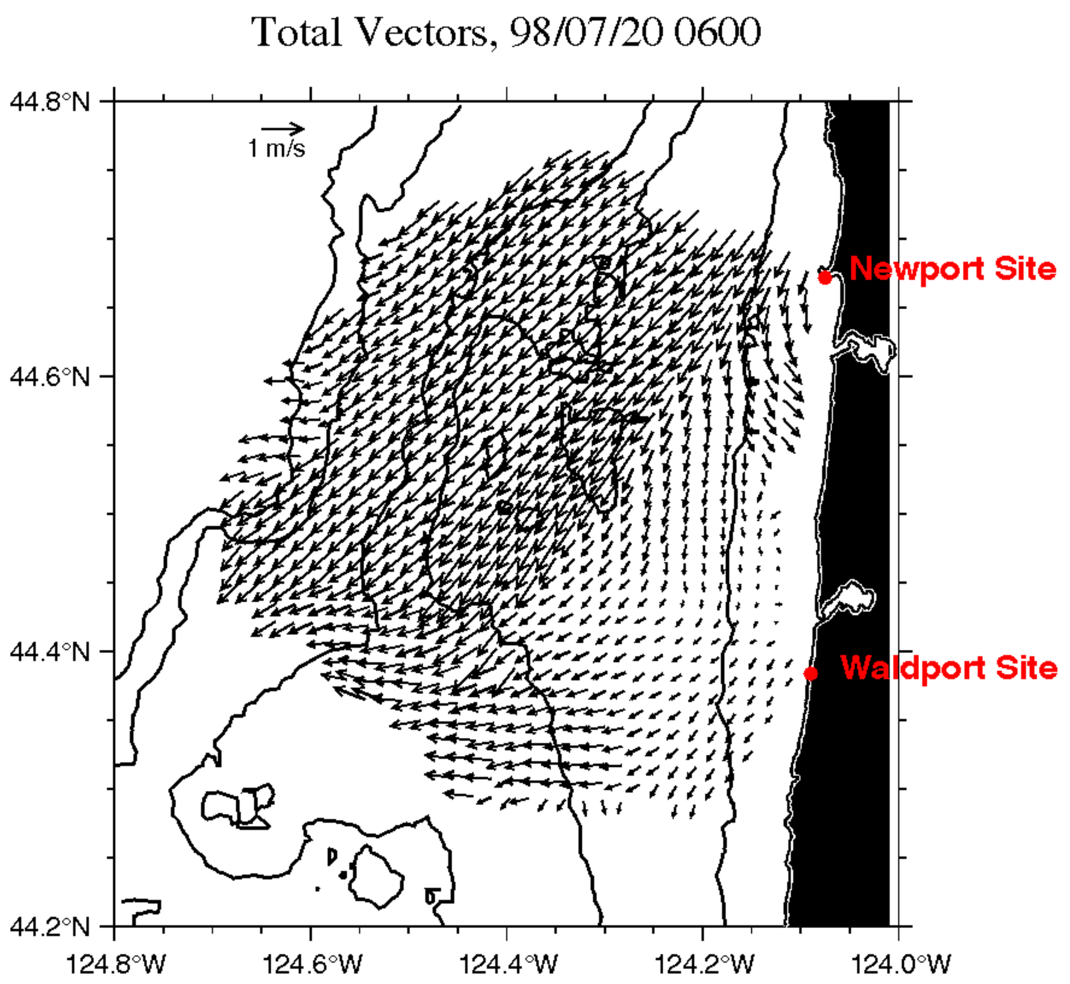


# HF backscatter gives map of radial currents



# Vector Combining of Radial Maps -> Total Vector Maps



# HF Systems: Scales, Ranges

| HFR Type[1] | Maximum Typical Range from Shore | Horizontal Resolution | Accuracy[2] (RMS Differences) | Temporal Resolution |
|---|---|---|---|---|
| High Res HFR Bays, Harbors<br>N=4 | 15-25 km<br>40.75-44.21 MHz | 0.5 km | 2-12 cm/s<br>2-4 cm/s Tidal and Sub-Tidal | 1 hr |
| Std HFR: Bays, Coastal<br>N=20 | 30-40 km<br>24.1-24.8 MHz<br>25.3-25.8 MHz | 1.0-2.0 km<br>BW=75-150 kHz | 2-12 cm/s<br>2-4 cm/s Tidal and Subtidal | 1 hr |
| Std HFR: Coastal Only<br>N=34 | 60-90 km<br>12.14-12.67 MHz<br>13.41-13.56 MHz | 1.5-3.0 km<br>BW=50-100 kHz | 2-12 cm/s<br>2-4 cm/s Tidal and Subtidal | 1 hr |
| Long Range HFR: Coastal Only<br>N=35 | 170-200 km<br>Between 4.785 and 5.325 MHz | 6 km<br>BW=26kHz | 5-12 cm/s<br>5-6 cm/s Tidal<br>Subtidal | 1 hr |

*Table 1: Resolutions, Range, and Accuracy of HF Radar Types*

*1 HFR type is arranged, top to bottom, from higher to lower transmit frequencies*
*2 Root-mean-square differences from numerous studies comparing HFR to in situ sensors*

Green numbers compiled for this talk from an informal survey of CORDC website

IOOS National Plan for Surface Currents, 2009

# Accuracy / Errors

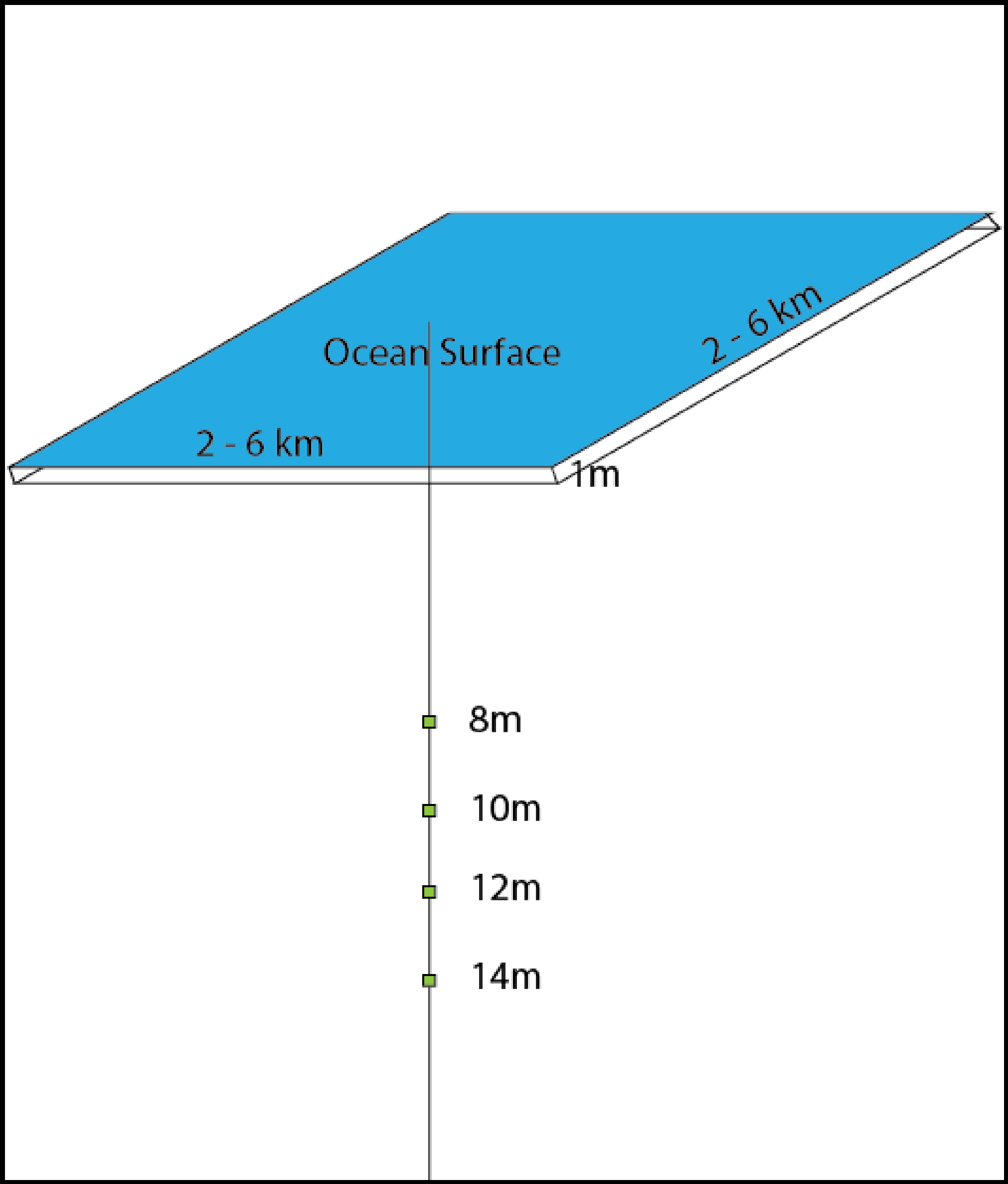
There's been lots of work on this.

A bibliography to 2007 lists more than 30 validation studies of CODAR-type direction-finding systems.
http://www.ioos.gov/library/technologydocs.html

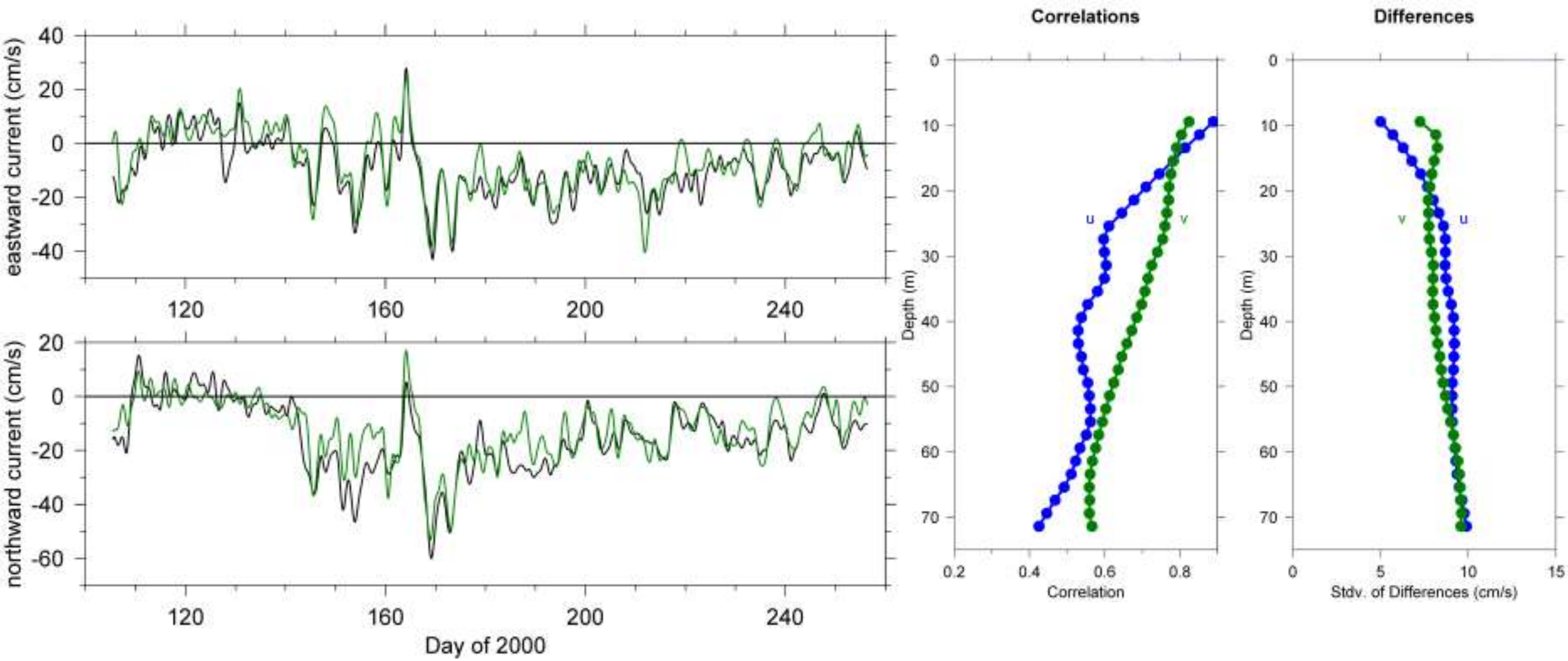
"For hourly data, the differences are approximately 6-12 cm/s when compared with point sensors, such as moored current meters and acoustic Doppler current profilers."
-IOOS National Plan for surface current mapping.

Answer is complicated by a large number of factors.

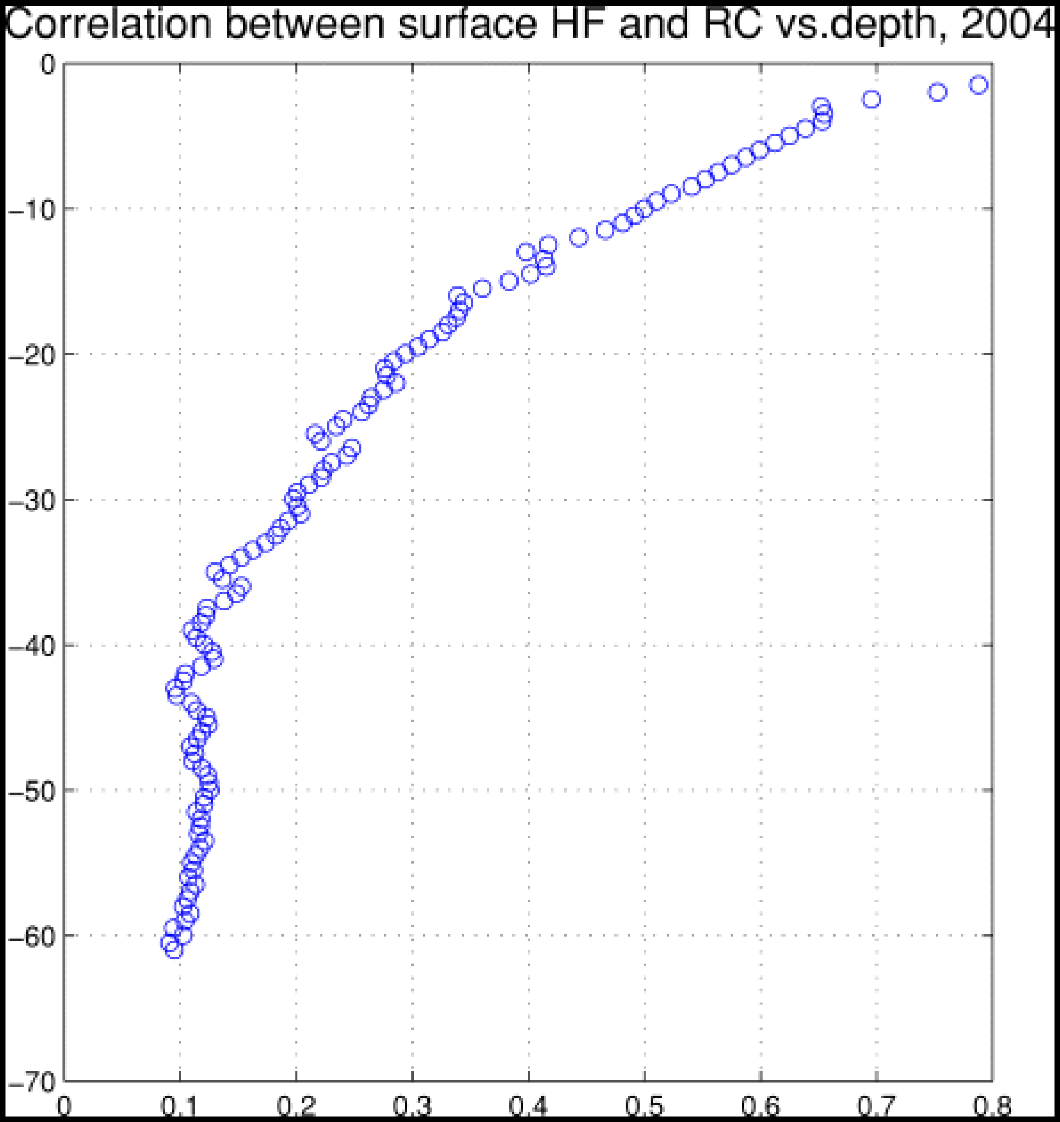
# Comparisons:
# Necessary, but some apples/oranges problems



# Comparison with moored ADCP, 9m depth bin



# Effect of vertical separation

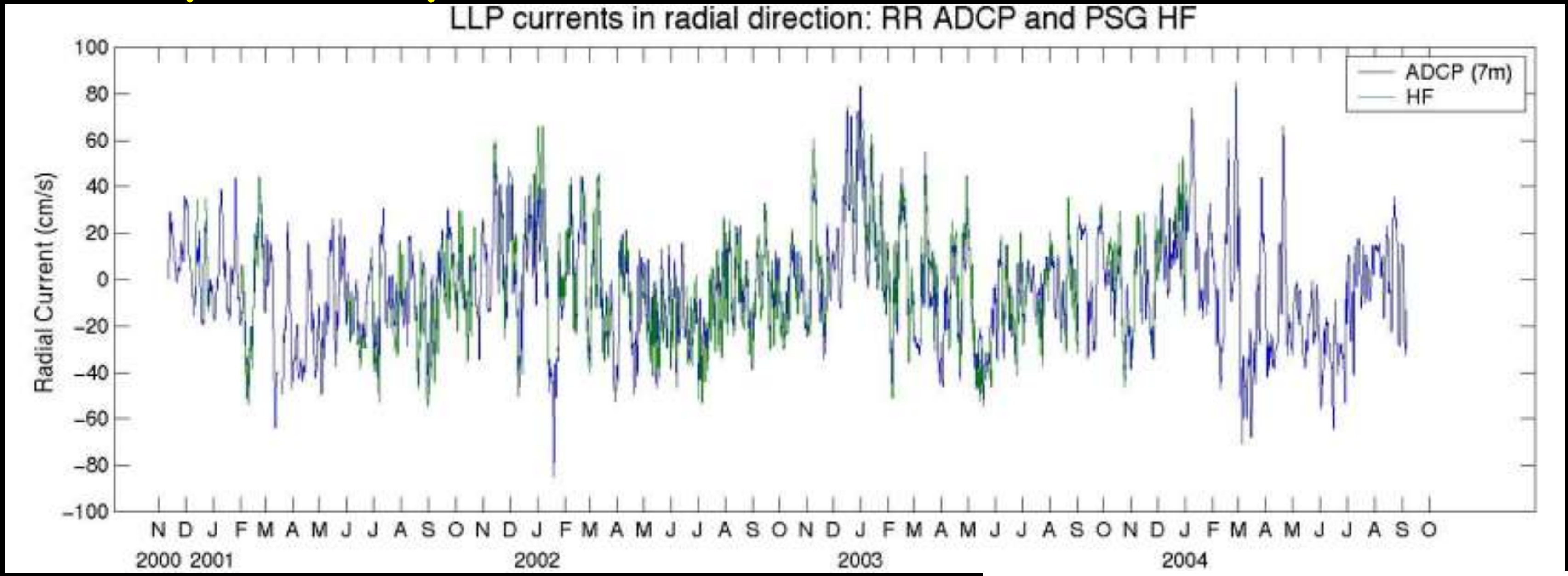



Depth

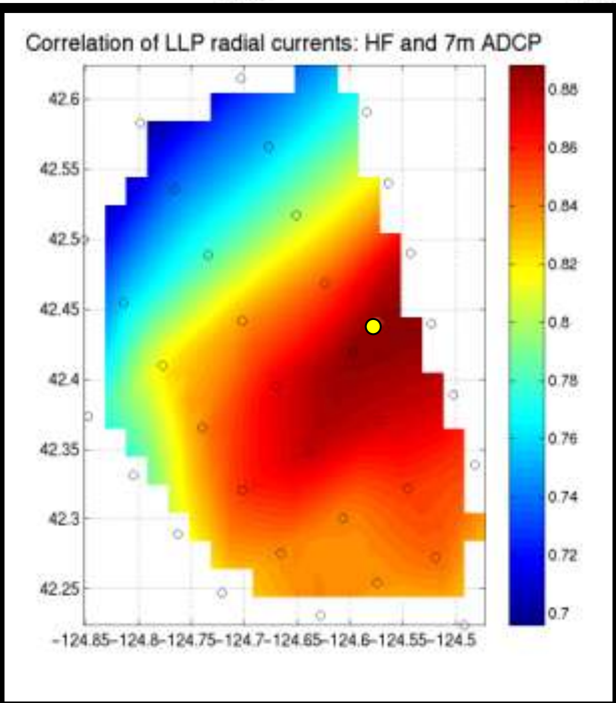
Correlation

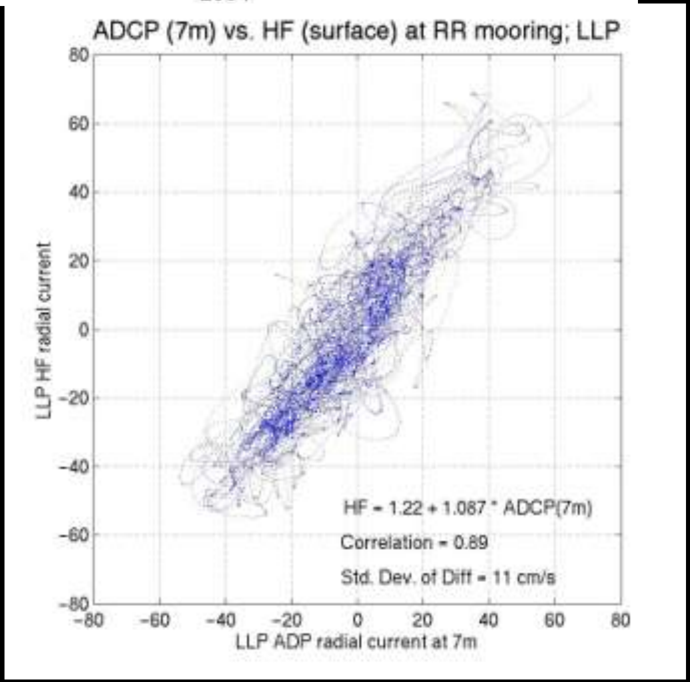
Top ADCP bin: 1.5m
ADCP Δz = 0.5 m
HF effective depth: 0.5m

# 3-yr comparison with moored ADCP (7m)

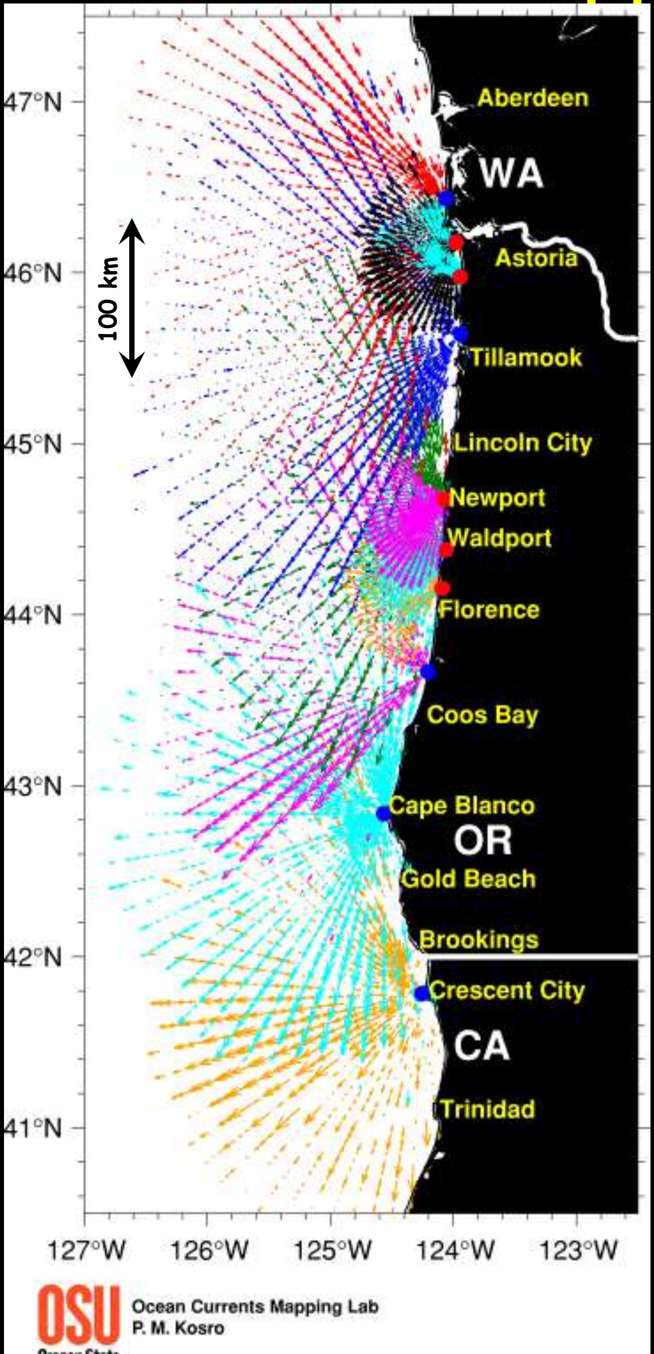



Effect of horizontal separation



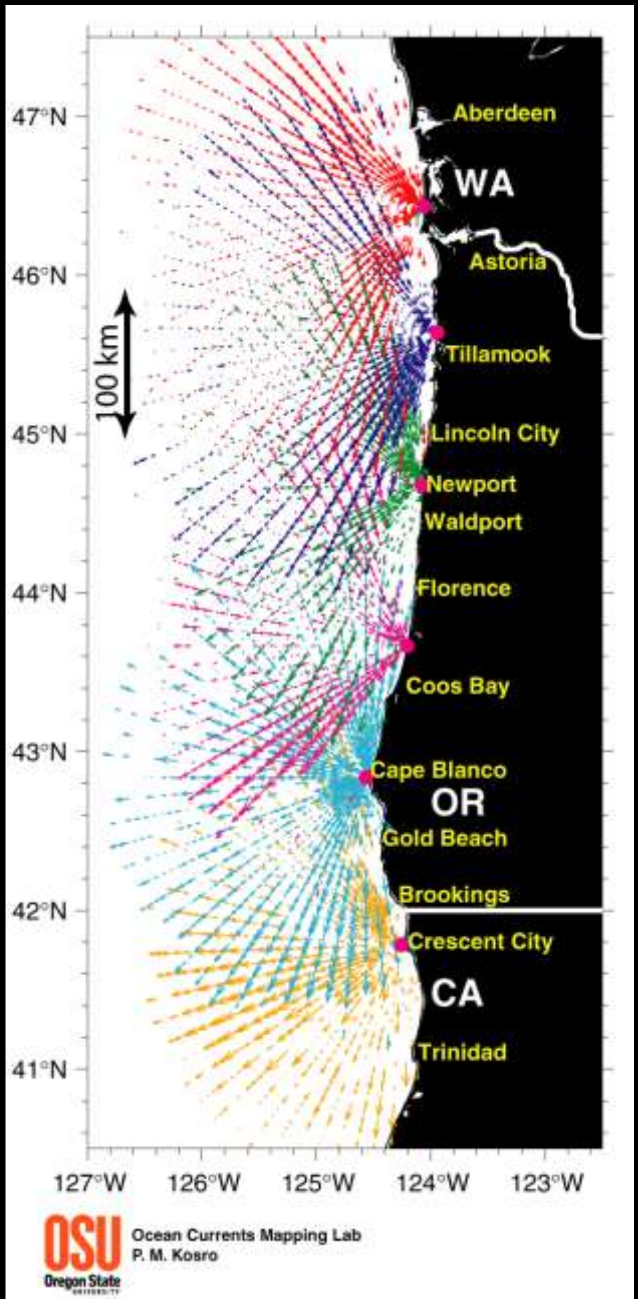
# Time-Series Mapping of Surface Currents

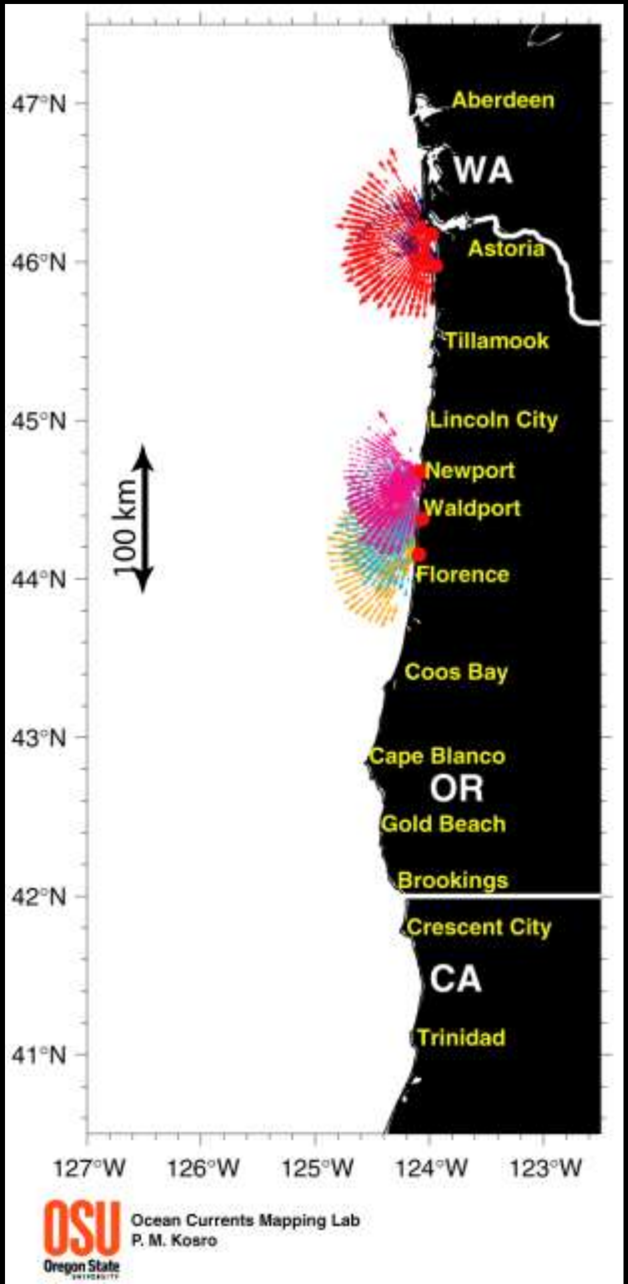



Mike Kosro, Walt Waldorf, Anne Dorkins, OSU

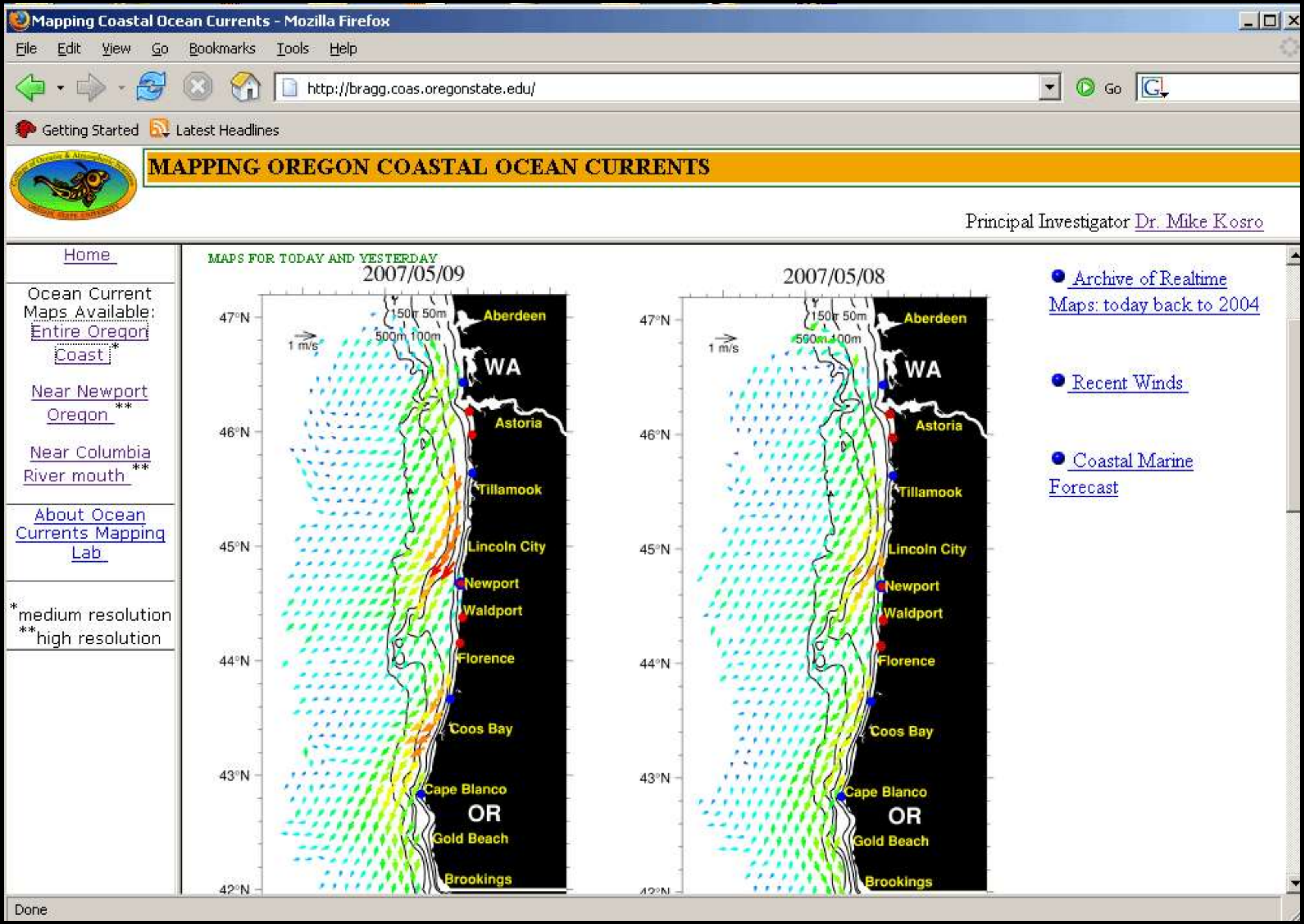
- Measure "radial" currents, toward/away from the HF sites.
- Current mapping where data from 2 or more systems overlap
- 2 types of mappers:
  - Std Range: 40km range, 2 km bins
    2 systems at mouth of CR
    operated May-Sept '04 and '05
    magenta & cyan arrows at left
  - Long Range: 180km range, 6 km bins
    6 systems operating on OR/WA;
    3 northernmost shown here
    red, blue and green arrows at left
    operated year-round

# Long-Range HF Array    Std-Range HF Array



# Real-time data:
# http://bragg.coas.oregonstate.edu

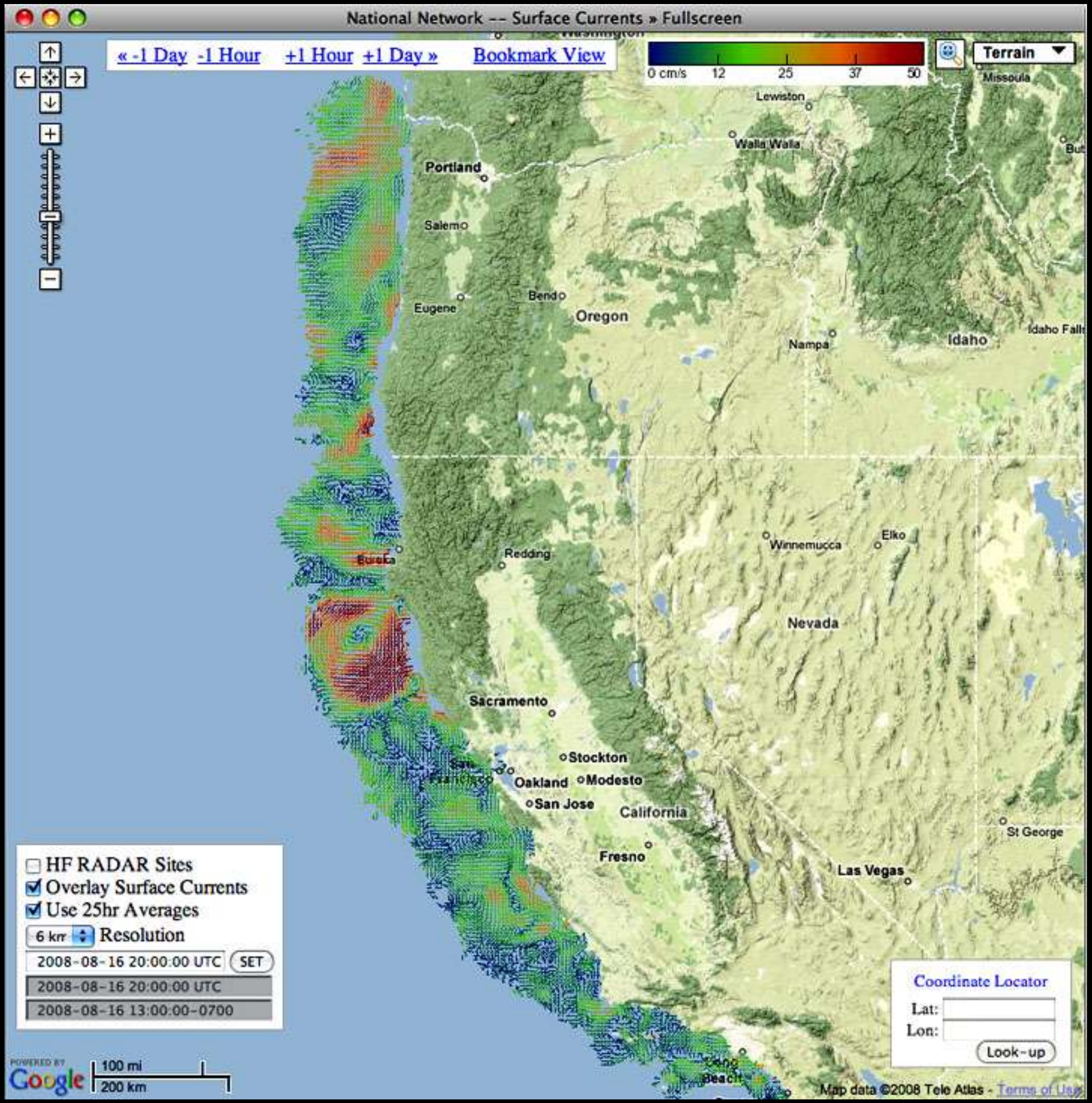


# Presently, 60 HF mappings sites on U.S. West Coast


## Participating Institutions:

| | | |
|---|---|---|
| Oregon State University | Kosro | 11 sites |
| Humboldt State University | Crawford | 1 site |
| Bodega Marine Lab | Largier | 4 sites |
| SF State University | Garfield | 8 sites |
| Naval Postgrad. School | Paduan | 8 sites |
| Cal Poly | Moline | 9 sites |
| UC Santa Barbara | Washburn | 7 sites |
| USC | Jones | 3 sites |
| Scripps Inst. Oceanogr. | Terrill | 8 sites |

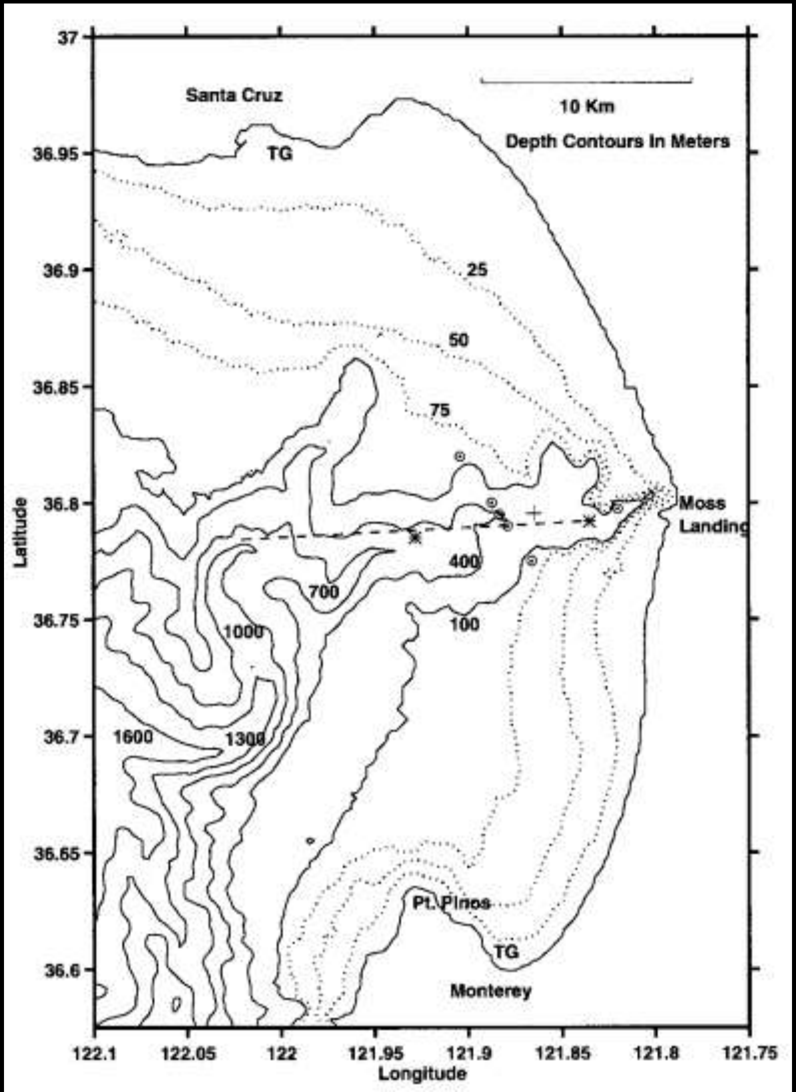
# Surface Current Mapping, West Coast

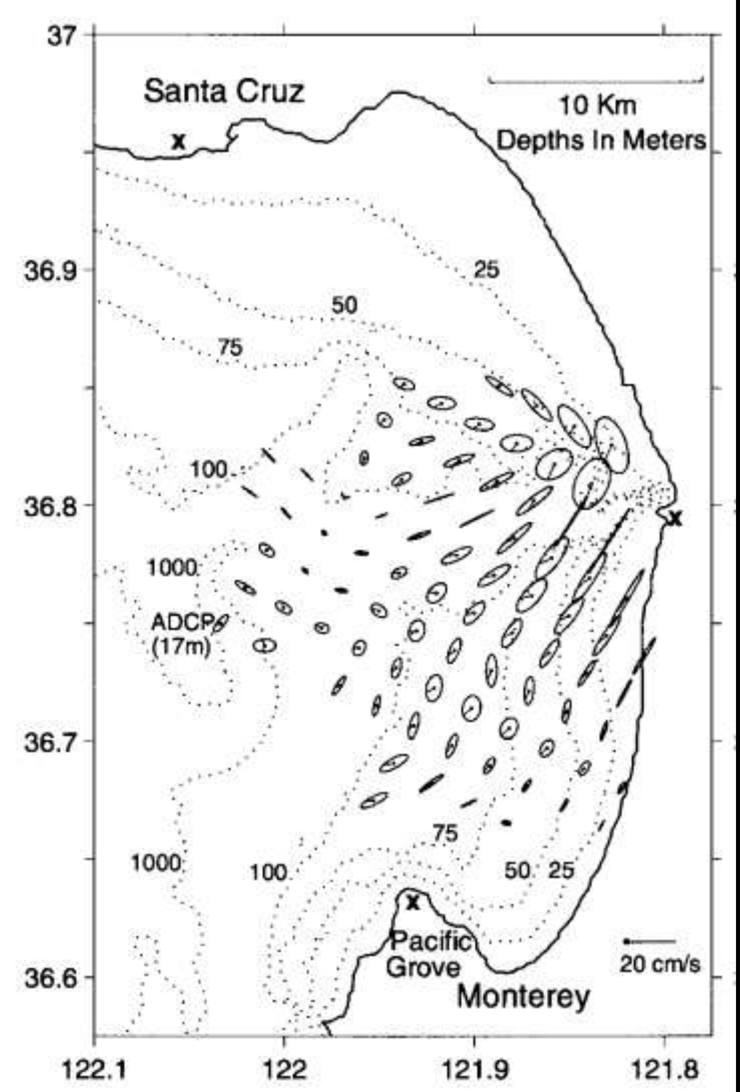



8/16/2008

# Tides

# 12.4 hr tide in Monterey Bay

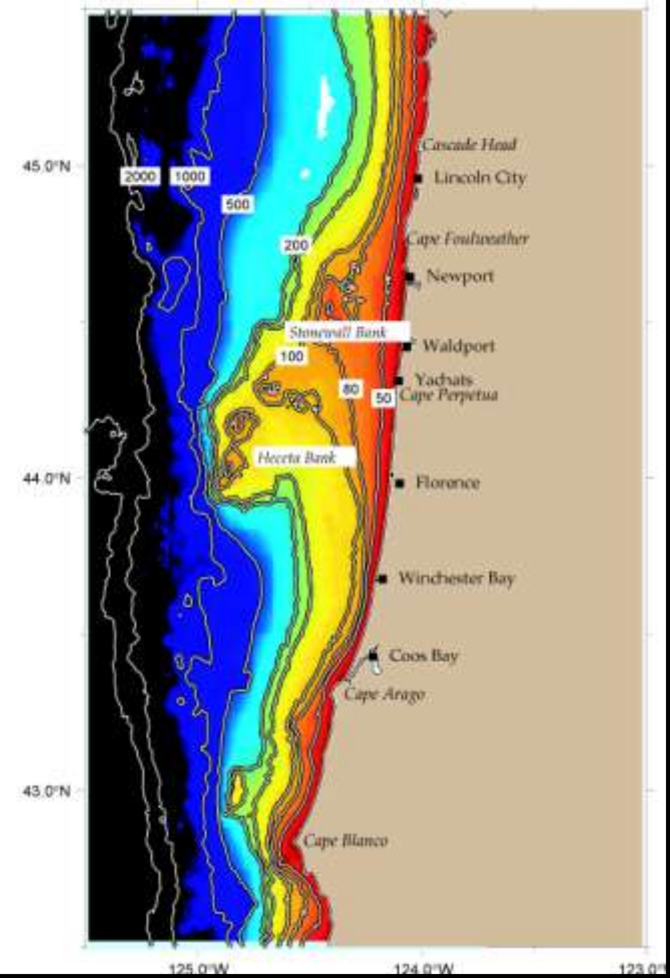


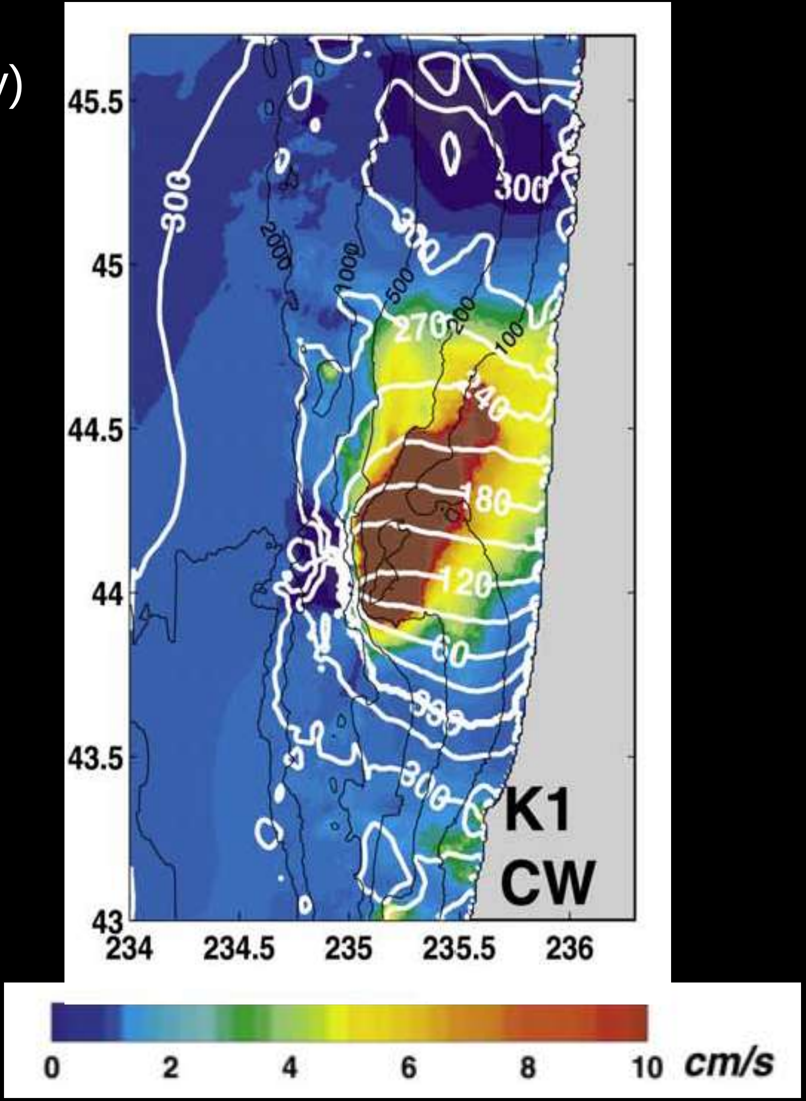

Petruncio, et al., JPO

# Tides on Heceta Bank, Oregon

Map of ocean depth (bathymetry)

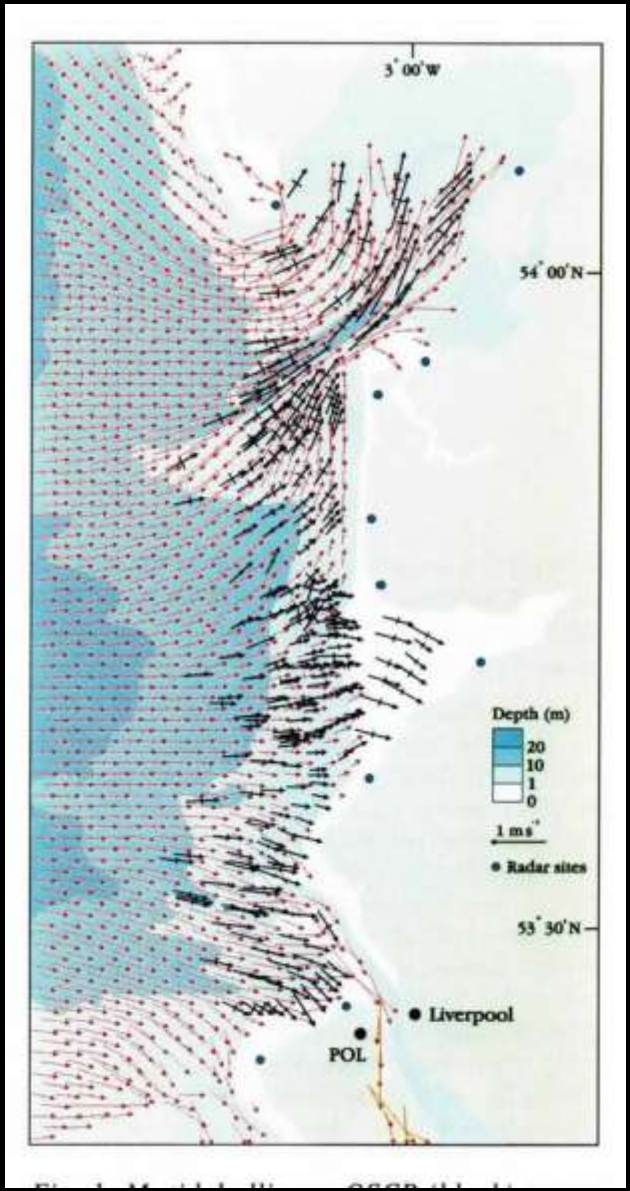



Strength of daily (K1) tide (clockwise) from model assimilating HF currentts



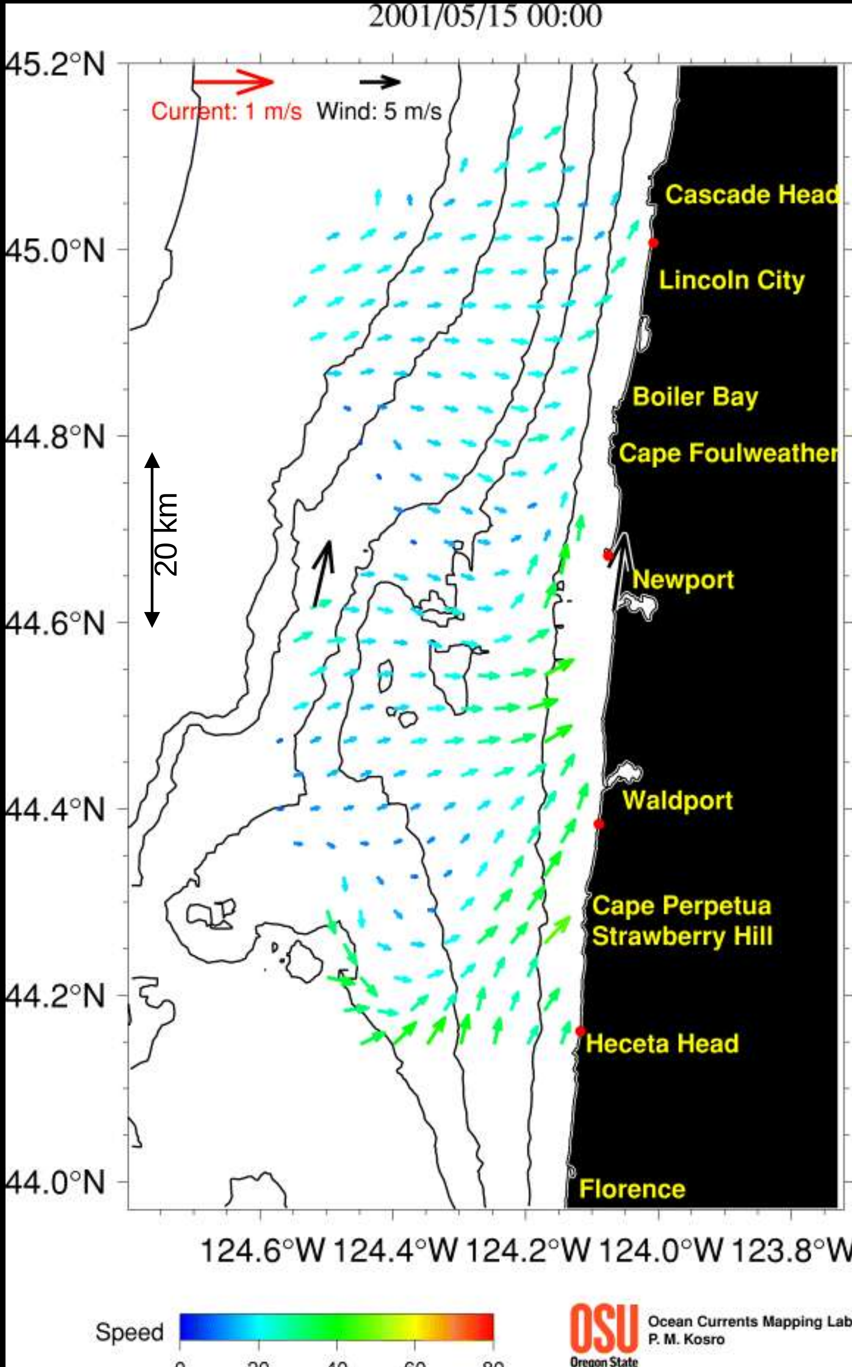

Erofeeva, Egbert & Kosro

# Tides off Liverpool: Modelled vs. measured

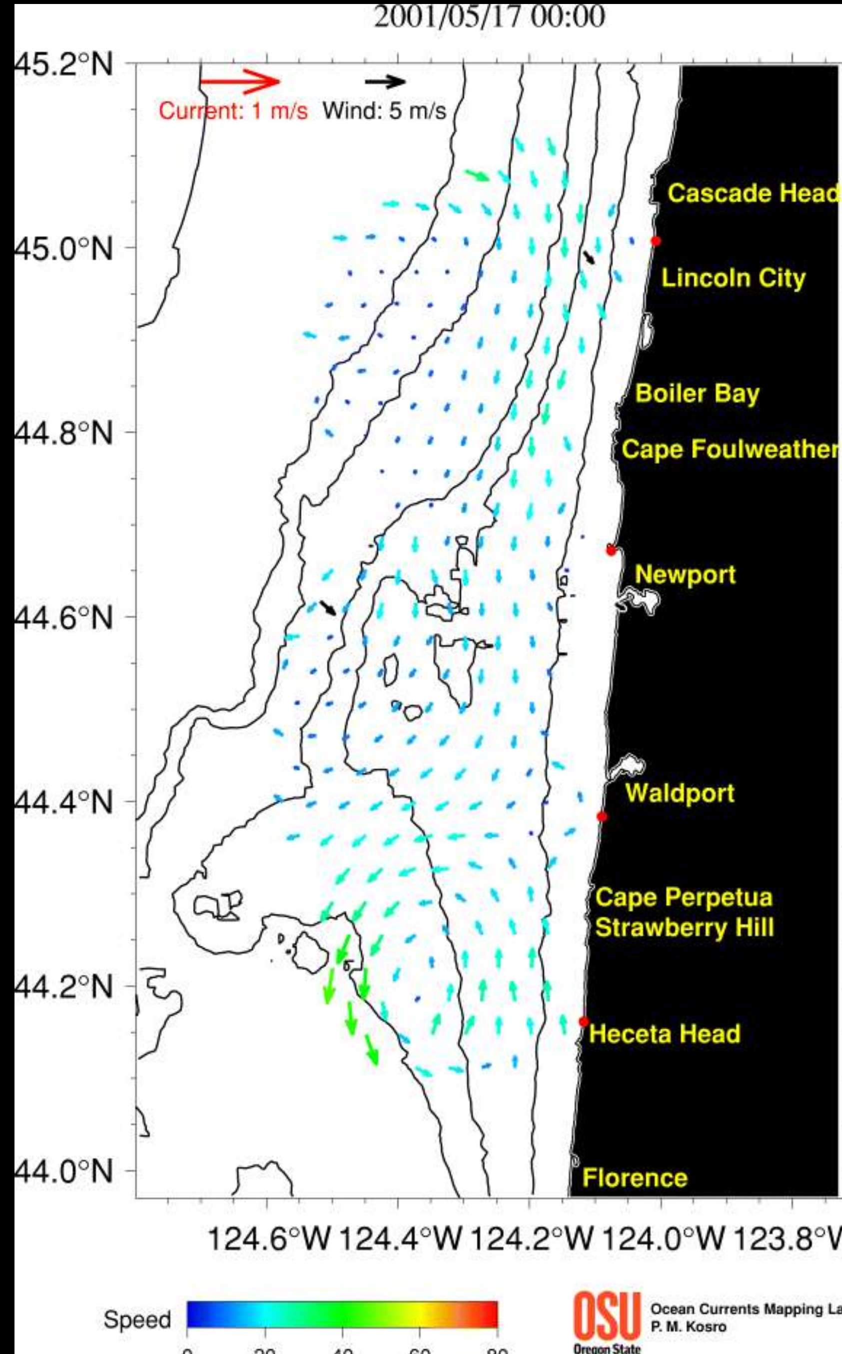



D. Prandle

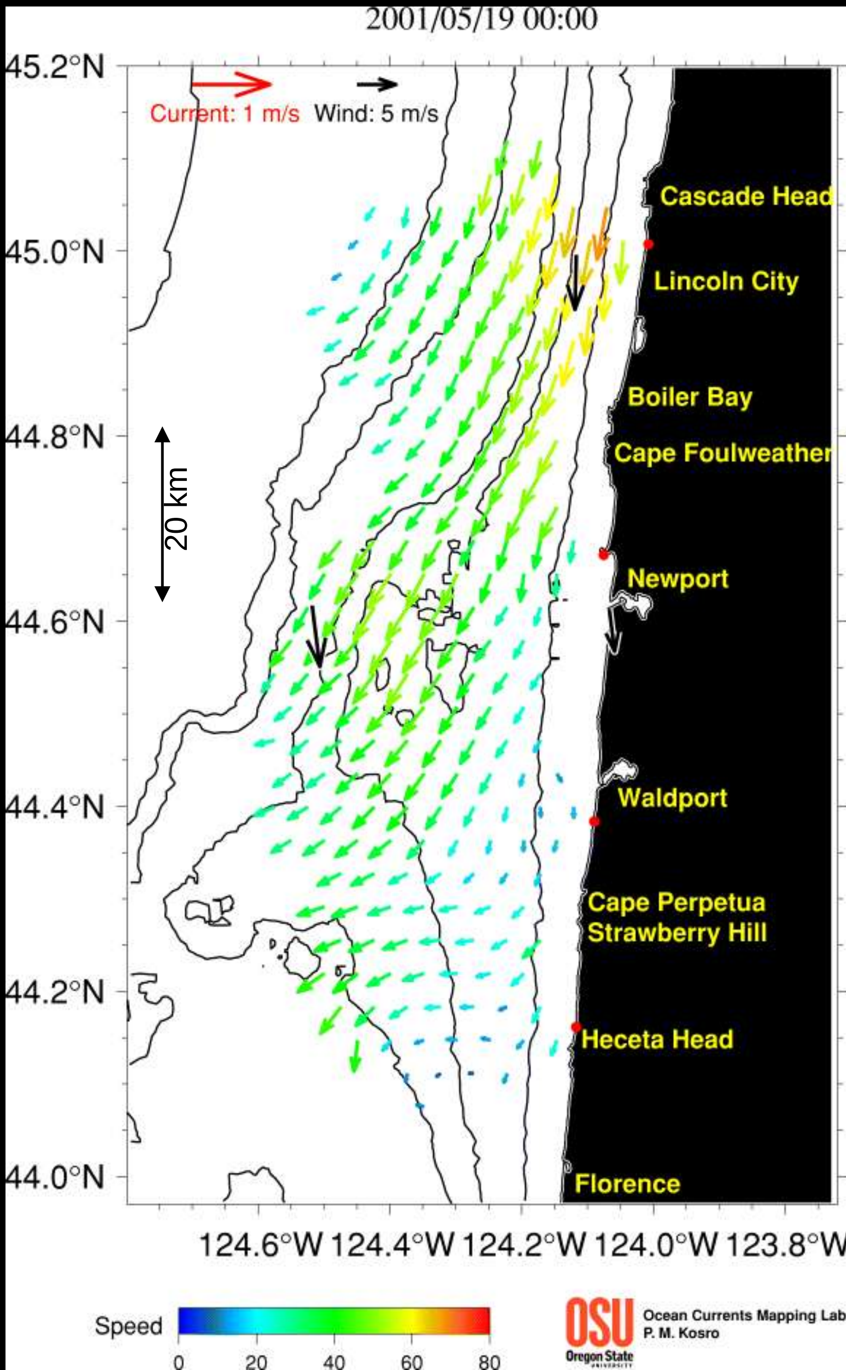
# Wind-Driven Currents: Heceta Bank, Oregon

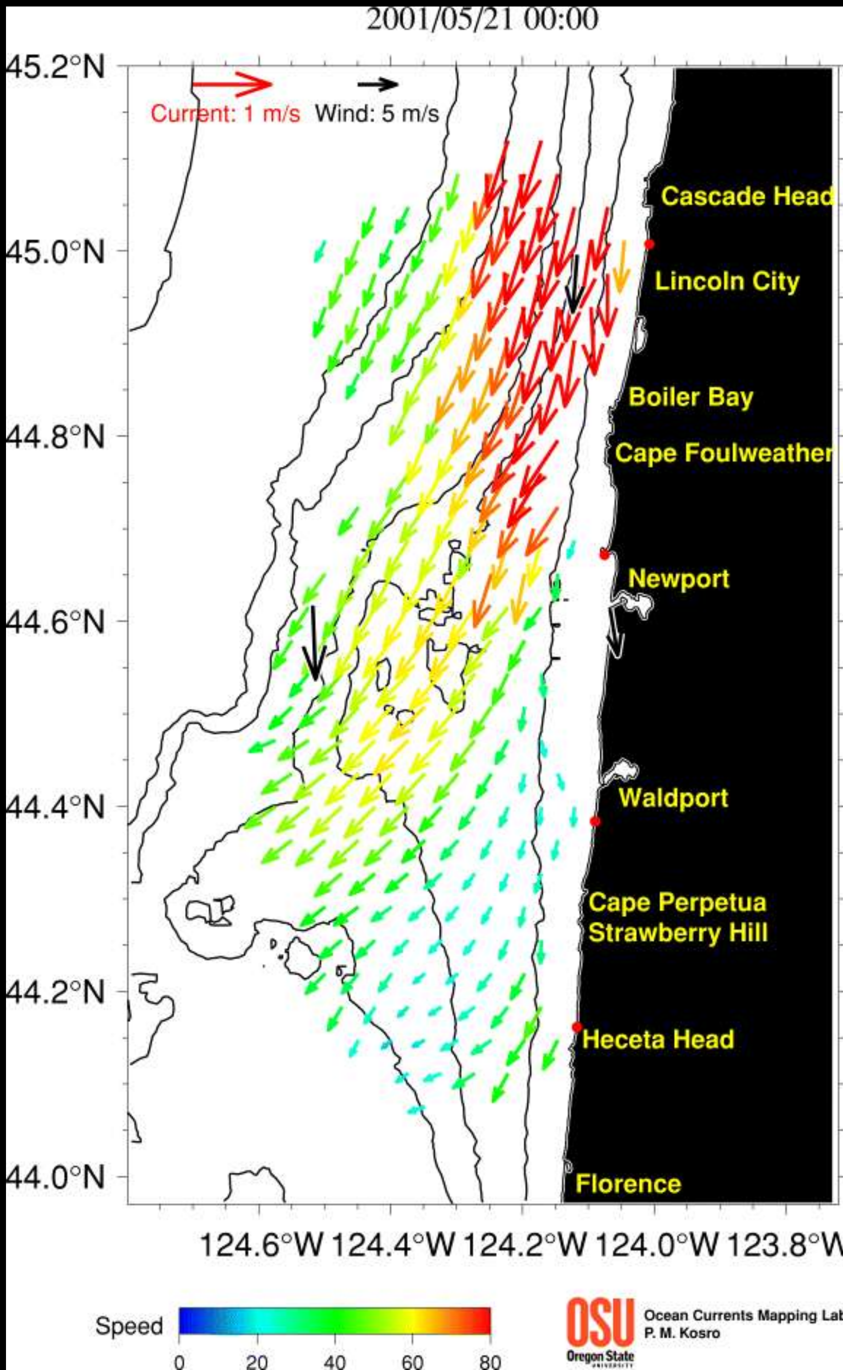


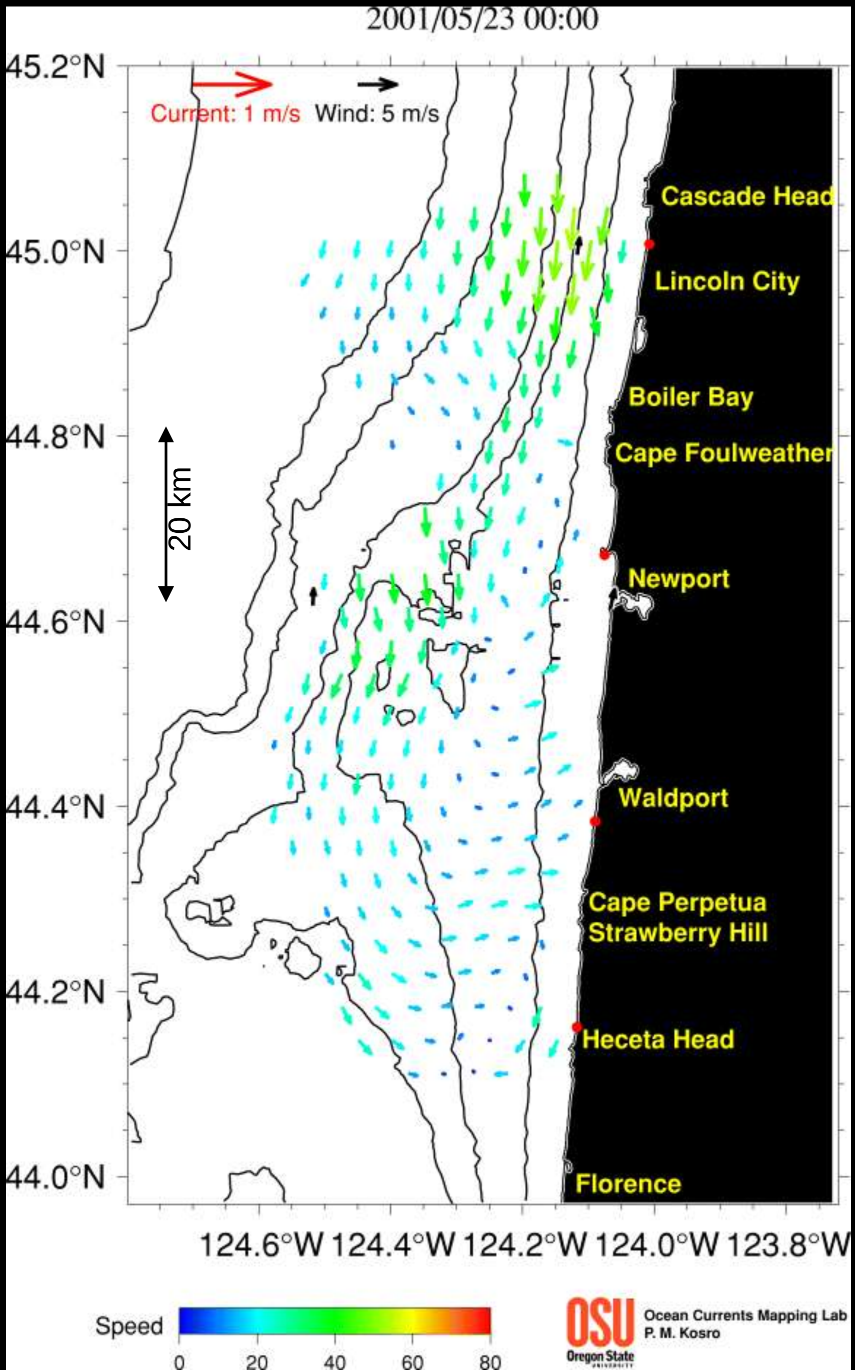
2001/05/15 00:00
Current: 1 m/s
Wind: 5 m/s
20 km
Cascade Head
Lincoln City
Boiler Bay
Cape Foulweather
Newport
Waldport
Cape Perpetua
Strawberry Hill
Heceta Head
Florence
45.2°N
45.0°N
44.8°N
44.6°N
44.4°N
44.2°N
44.0°N
124.6°W 124.4°W 124.2°W 124.0°W 123.8°W
Speed
0 20 40 60 80
OSU
Oregon State
Ocean Currents Mapping Lab
P. M. Kosro

2001/05/17 00:00
Current: 1 m/s
Wind: 5 m/s
Cascade Head
Lincoln City
Boiler Bay
Cape Foulweather
Newport
Waldport
Cape Perpetua
Strawberry Hill
Heceta Head
Florence
45.2°N
45.0°N
44.8°N
44.6°N
44.4°N
44.2°N
44.0°N
124.6°W 124.4°W 124.2°W 124.0°W 123.8°W
Speed
0 20 40 60 80
OSU
Oregon State
Ocean Currents Mapping Lab
P. M. Kosro


2001/05/19 00:00
Current: 1 m/s
Wind: 5 m/s
45.2°N
45.0°N
44.8°N
44.6°N
44.4°N
44.2°N
44.0°N
20 km
Cascade Head
Lincoln City
Boiler Bay
Cape Foulweather
Newport
Waldport
Cape Perpetua
Strawberry Hill
Heceta Head
Florence
124.6°W 124.4°W 124.2°W 124.0°W 123.8°W
Speed
0 20 40 60 80
Ocean Currents Mapping Lab
P. M. Kosro


2001/05/21 00:00
Current: 1 m/s
Wind: 5 m/s
45.2°N
45.0°N
44.8°N
44.6°N
44.4°N
44.2°N
44.0°N
Cascade Head
Lincoln City
Boiler Bay
Cape Foulweather
Newport
Waldport
Cape Perpetua
Strawberry Hill
Heceta Head
Florence
124.6°W 124.4°W 124.2°W 124.0°W 123.8°W
Speed
0 20 40 60 80
Ocean Currents Mapping Lab
P. M. Kosro


2001/05/23 00:00
Current: 1 m/s
Wind: 5 m/s
45.2°N
45.0°N
44.8°N
44.6°N
44.4°N
44.2°N
44.0°N
20 km
Cascade Head
Lincoln City
Boiler Bay
Cape Foulweather
Newport
Waldport
Cape Perpetua
Strawberry Hill
Heceta Head
Florence
124.6°W 124.4°W 124.2°W 124.0°W 123.8°W
Speed
0 20 40 60 80
Ocean Currents Mapping Lab
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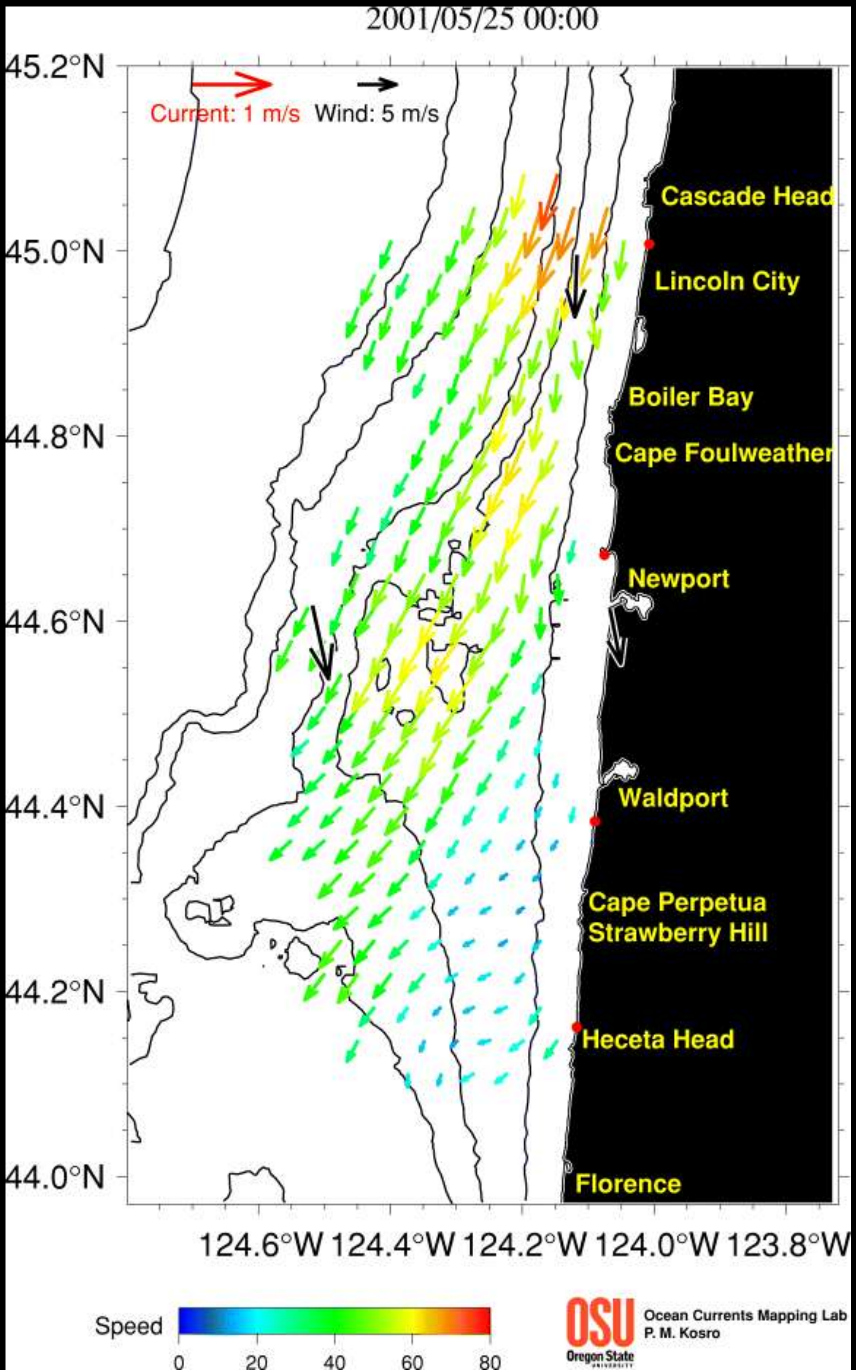
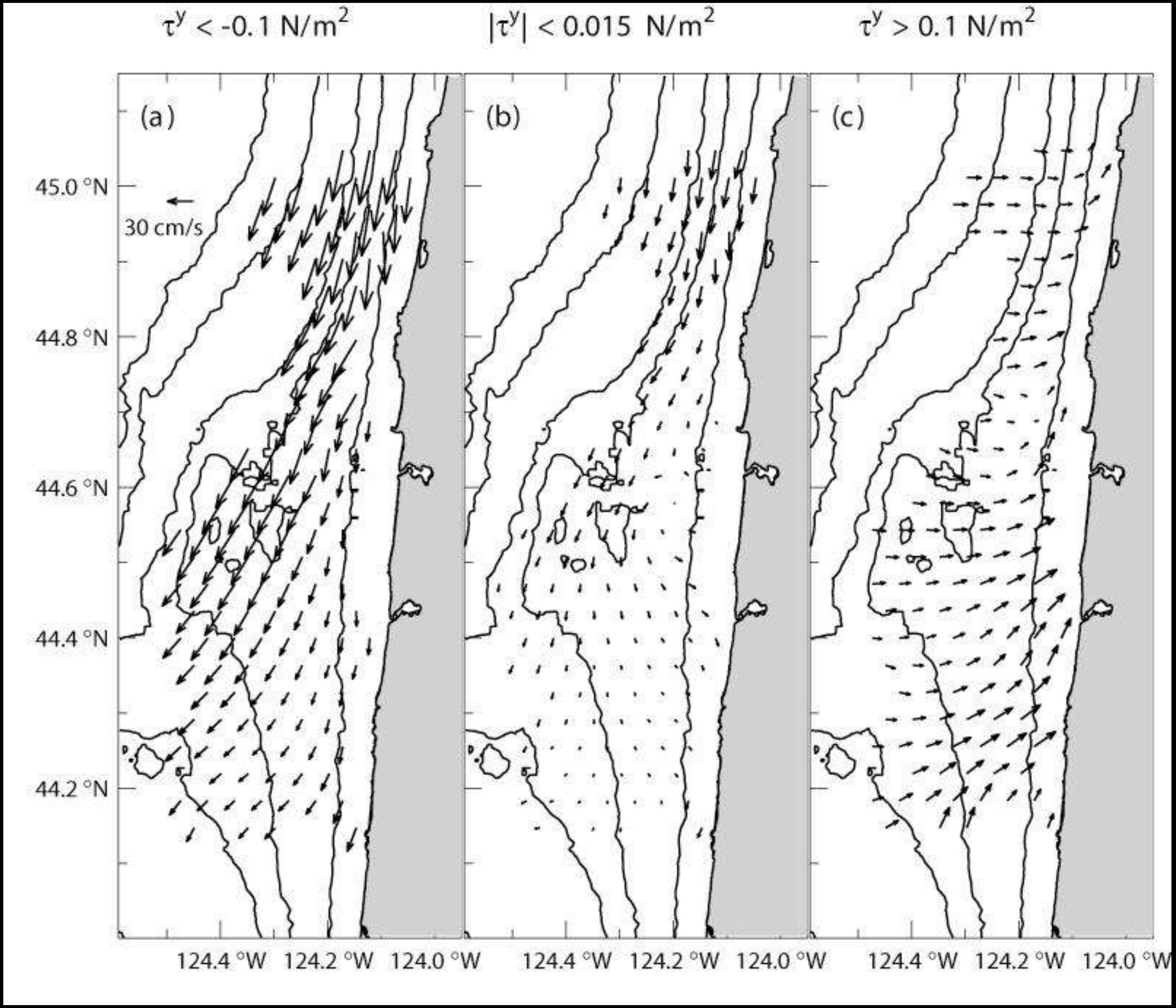

2001/05/25 00:00
Current: 1 m/s
Wind: 5 m/s
45.2°N
45.0°N
44.8°N
44.6°N
44.4°N
44.2°N
44.0°N
Cascade Head
Lincoln City
Boiler Bay
Cape Foulweather
Newport
Waldport
Cape Perpetua
Strawberry Hill
Heceta Head
Florence
124.6°W 124.4°W 124.2°W 124.0°W 123.8°W
Speed
0 20 40 60 80
Ocean Currents Mapping Lab
P. M. Kosro

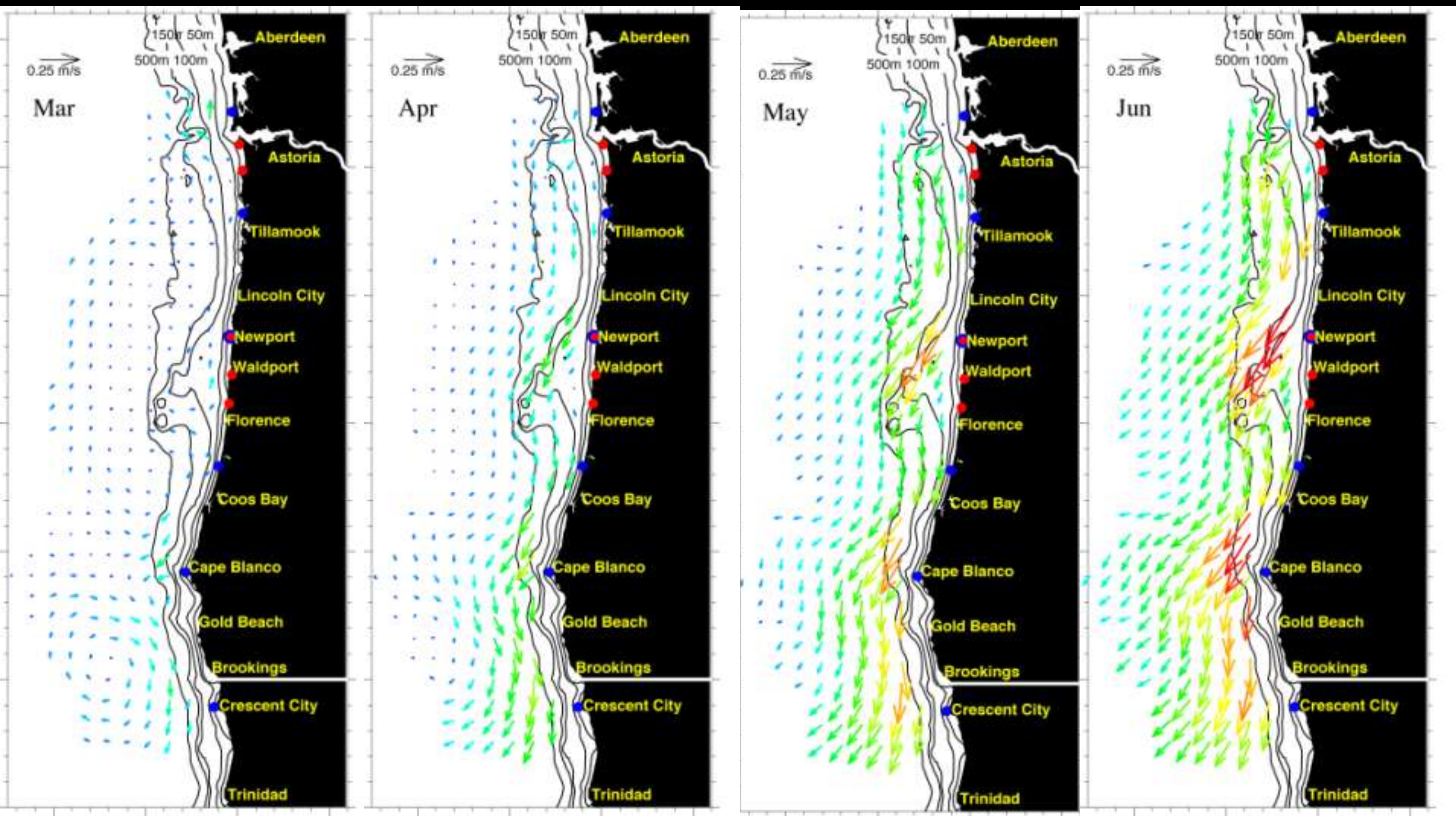
# Oregon: Spring/Summer Average Flow for Different Winds



# Seasonal Cycle in maps of surface current, Avg over 2001-2009

Kosro, in prep

## Mar Apr May Jun



# Monthly-Averaged Currents, Monterey Bay, CA

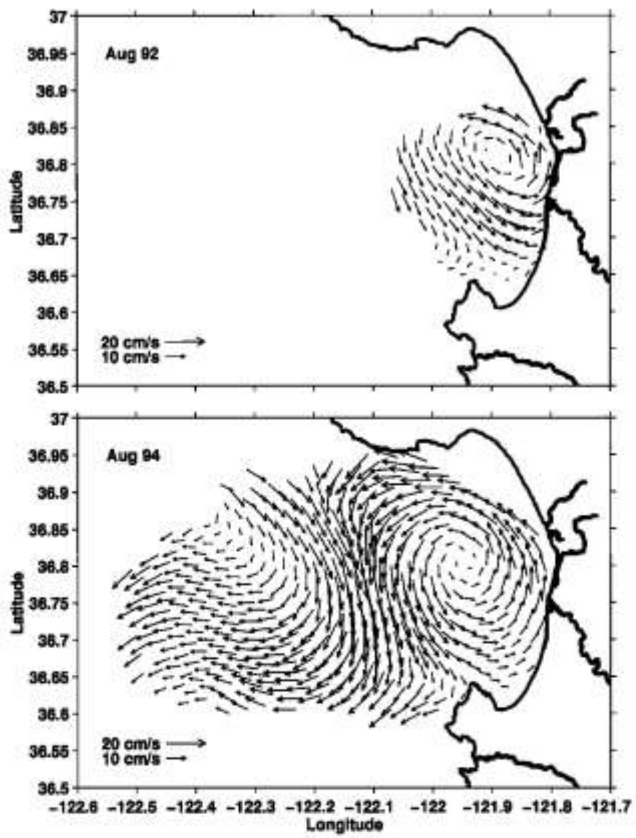



**Figure 12.** Average radar-derived current vectors for (top) August 1992 and (bottom) August 1994 for grid points with at least 50% temporal coverage.

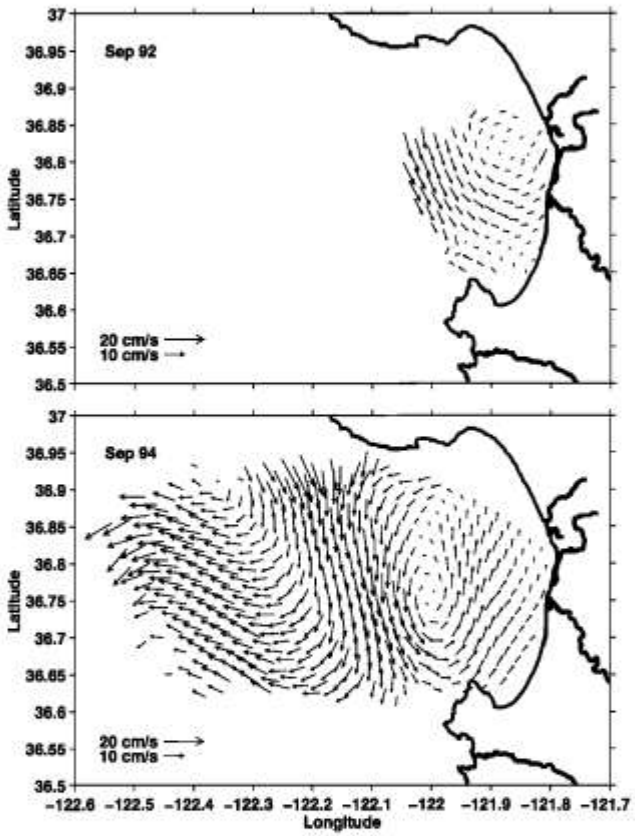



**Figure 13.** Average radar-derived current vectors for (top) September 1992 and (bottom) September 1994 for grid points with at least 50% temporal coverage.

Paduan and Rosenfeld

# 1-day average current, Monterey Bay, California

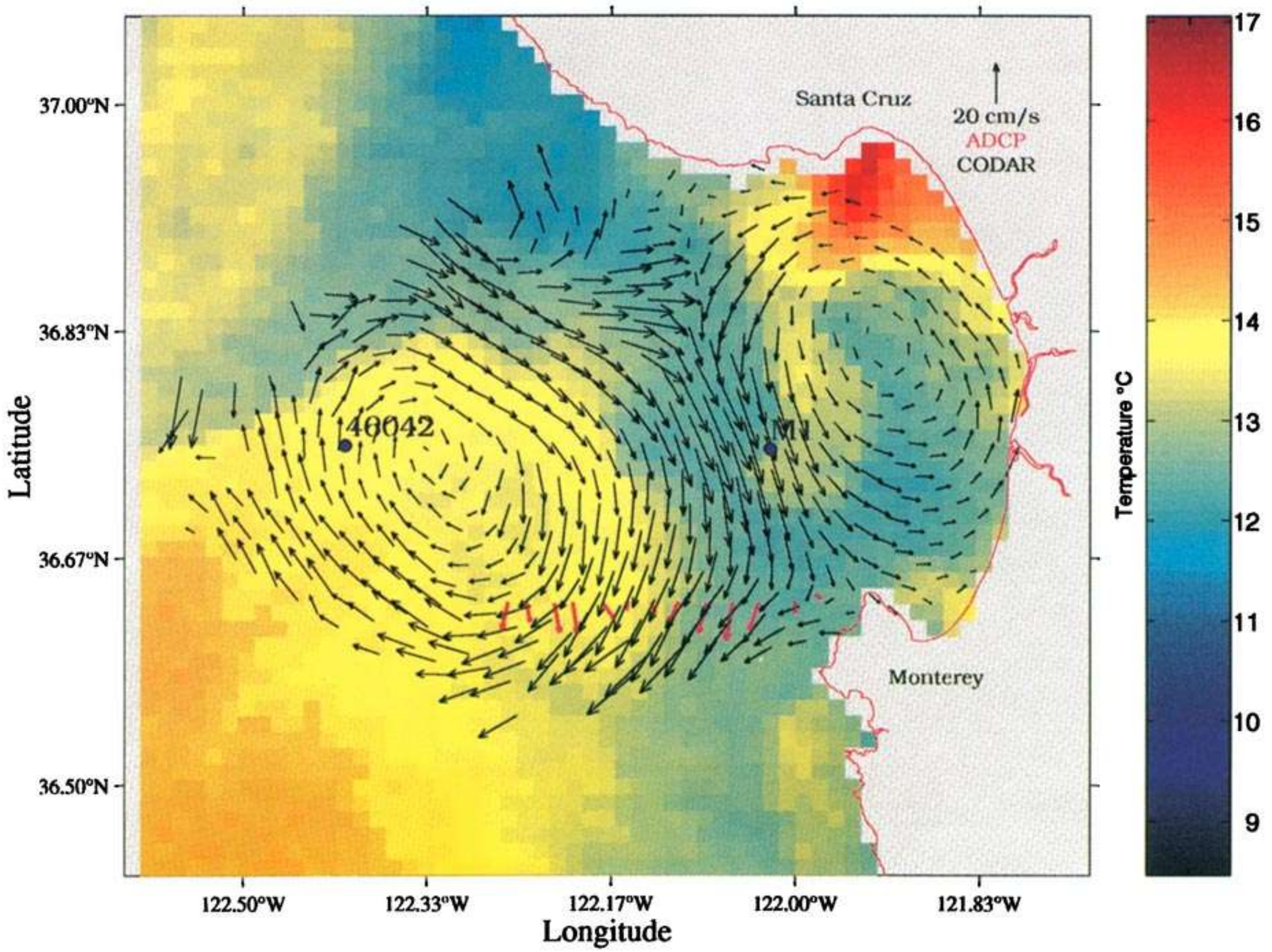
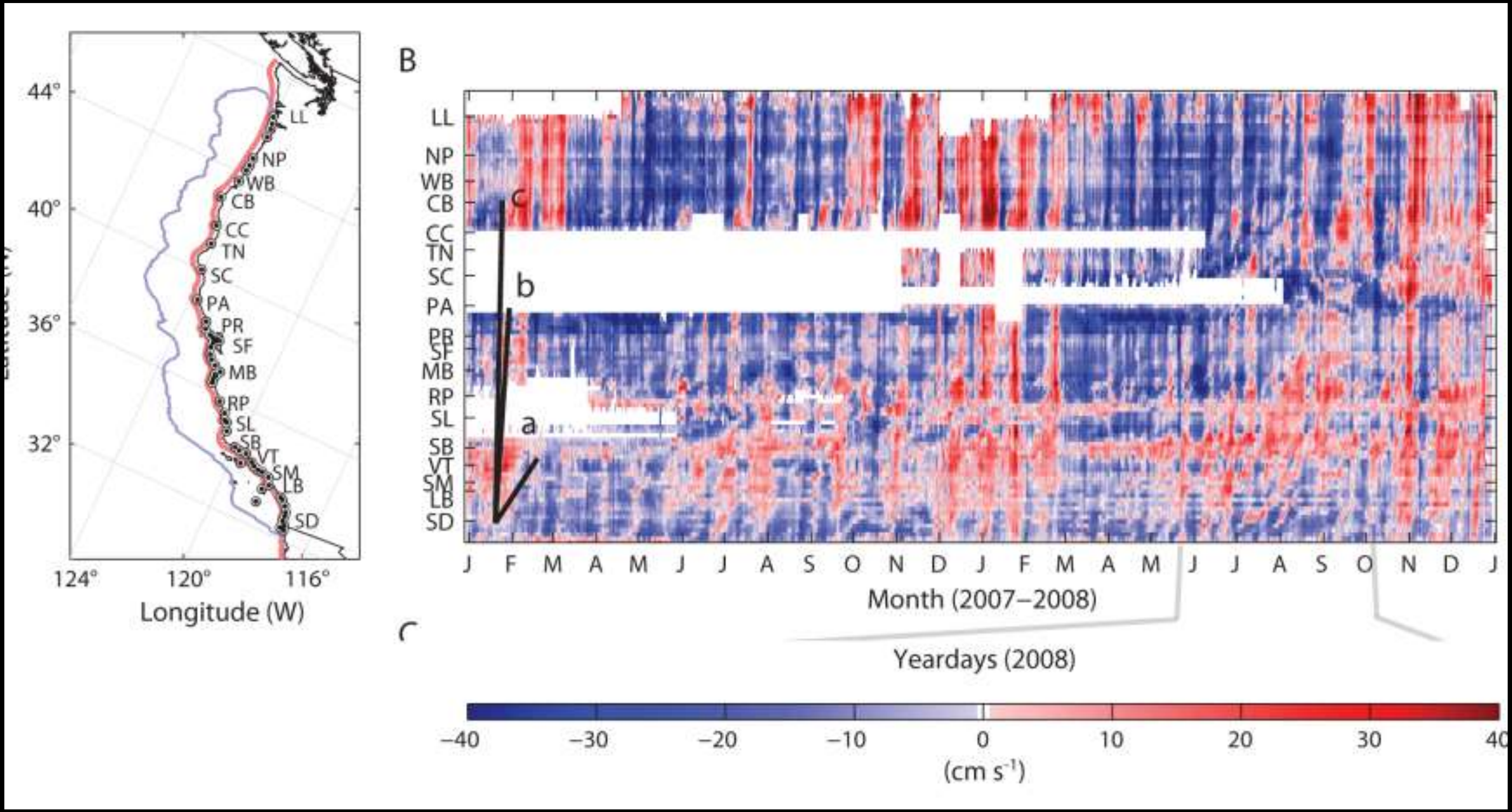



**Plate 1.** Average radar-derived vectors for the period 0900 UT on August 6 to 0700 UT on August 7, 1994 (black arrows), and average VM-ADCP vectors for the period 1016 UT on August 6 to 0524 UT on August 7, 1994 (magenta arrows), shown with uncorrected AVHRR channel 4 surface temperatures from 0300 UT on August 6, 1994.

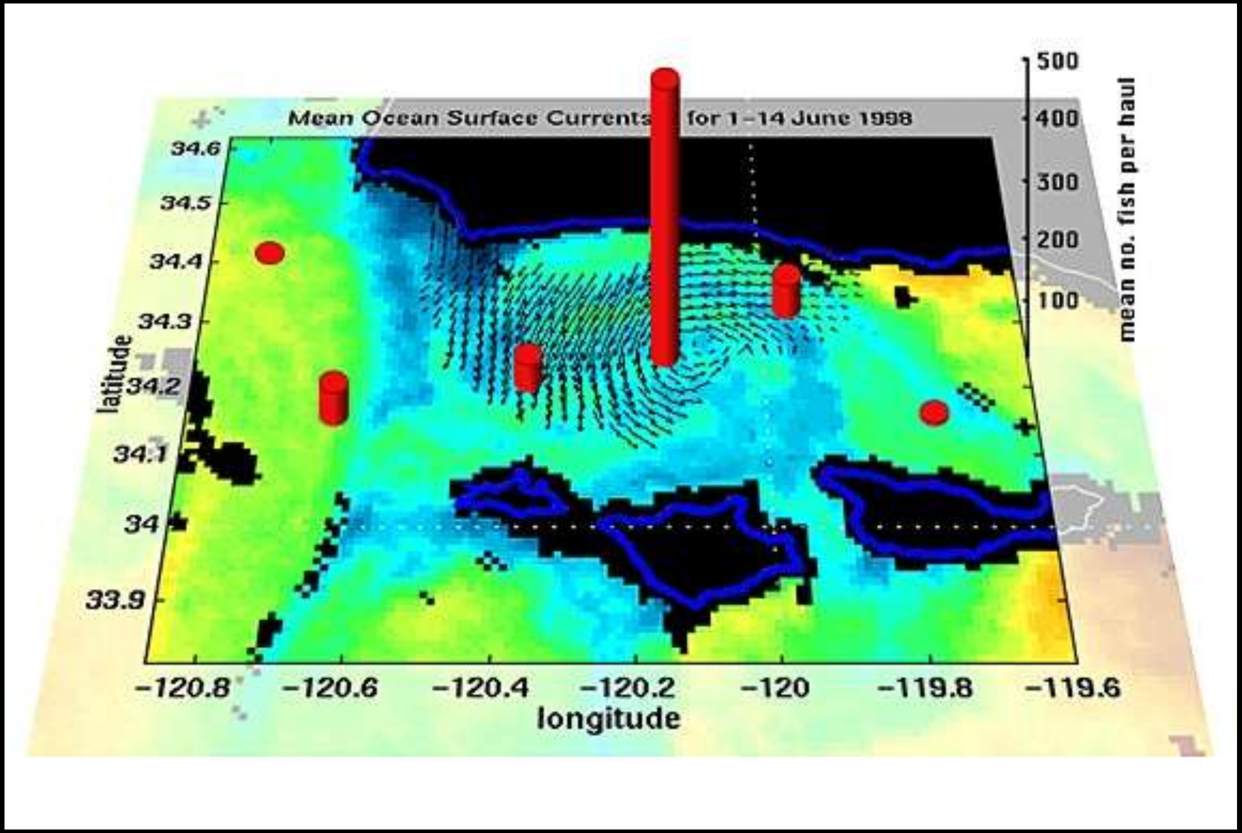
Paduan and Rosenfeld

# Alongshore current from West Coast HF array




Kim et al, JGR

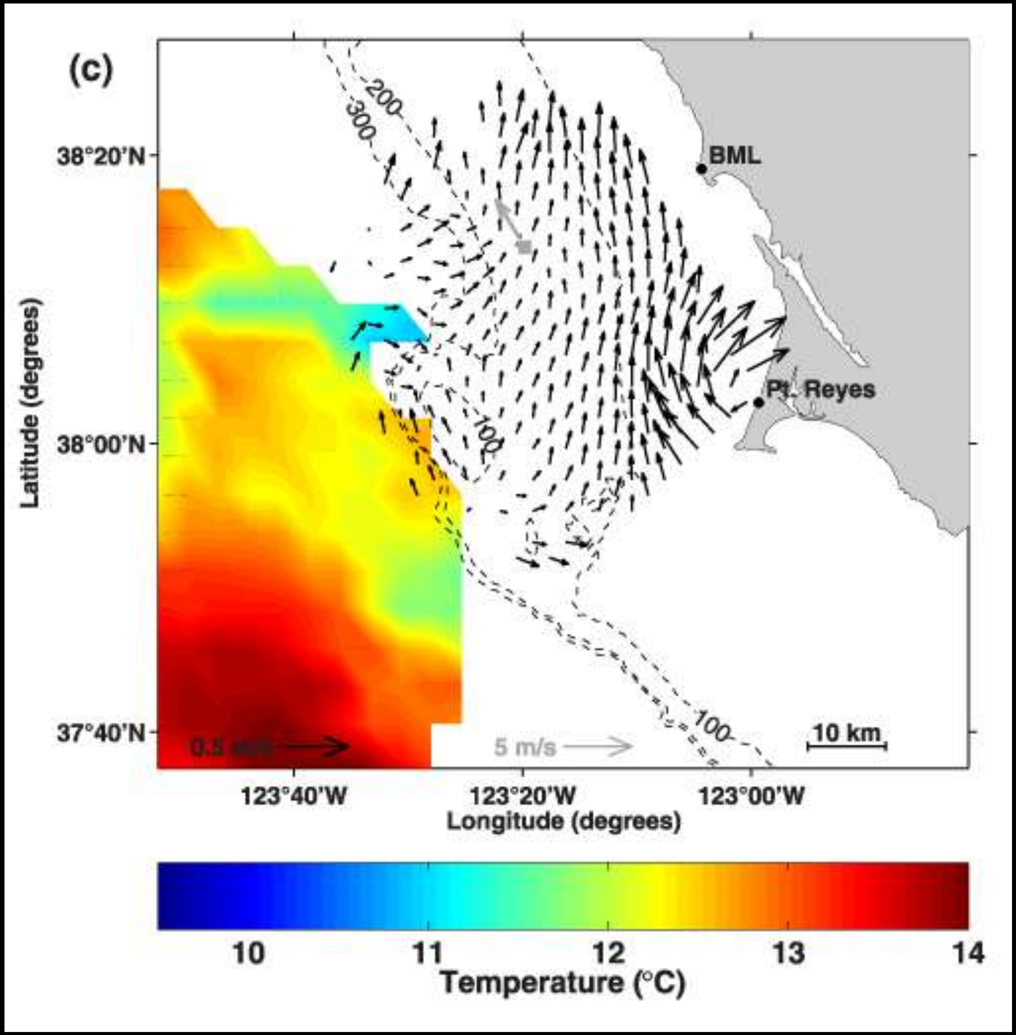
# Eddies in the Santa Barbara Channel




Measurements near Santa Barbara, CA, by Washburn & Nishimoto. Red = number of fish caught per net haul. A large spike appears near the center of the eddy (note current arrows).

# Wind Relaxation Flow, Pt. Reyes

May 21, 2001

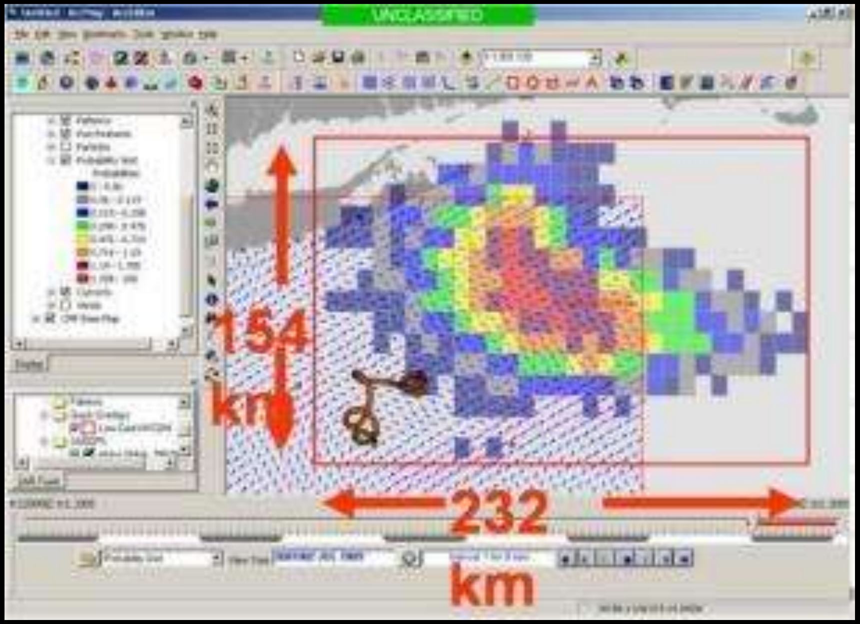



Kaplan, Largier and Botsford, JGR, 2005

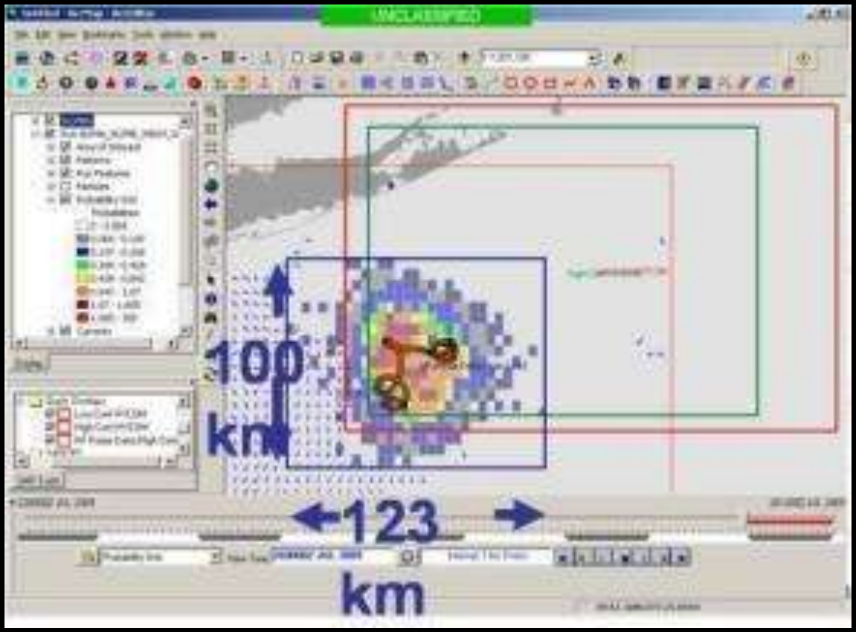
# Some Practical Applications

- Safety of Life at Sea (Search & Rescue)
- Marine Navigation
- Harmful Algal Bloom Forecasts
- Outfall planning and monitoring
- Fisheries and ecosystems
- Hazmat or Oil Spill Response (Deepwater Horizon)
- Hydrodynamic Modelling

# USCG search tool: after 96 hrs, with and without HF data



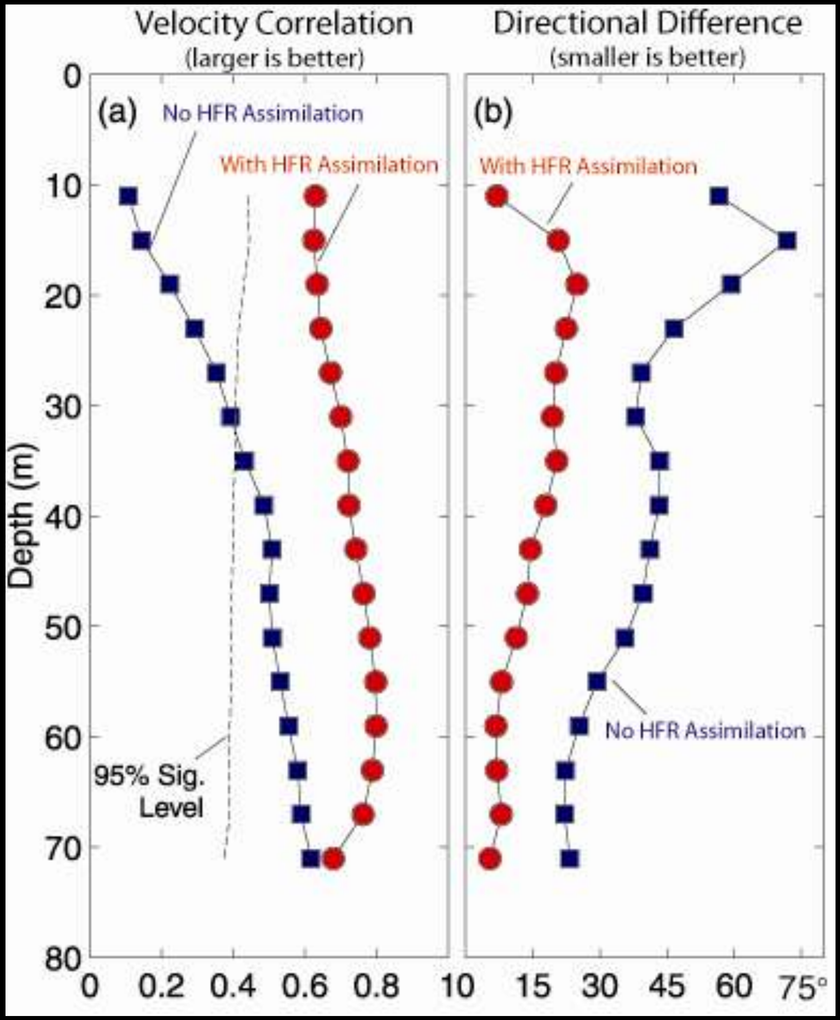

96 hr: Without
HFR
36,000 Km$^2$




96 hr: With HFR
12,000 Km$^2$

Figures courtesy of Jack Harlan

# Hydrodynamic Modelling: Results of assimilation of surface HF




One early example:

• Assimilated surface HF
• Projected downward and onto other fields using model-derived correlations

• Comparison against independent moored ADCP data:
  • Velocity correlation improved markedly at the surface
  • Velocity correlation improved at all depths
  • Directional difference improved over all depths

Numerous other studies show value of HF assimilation

Oke, Allen, Miller, Egbert & Kosro, JGR, 2002.

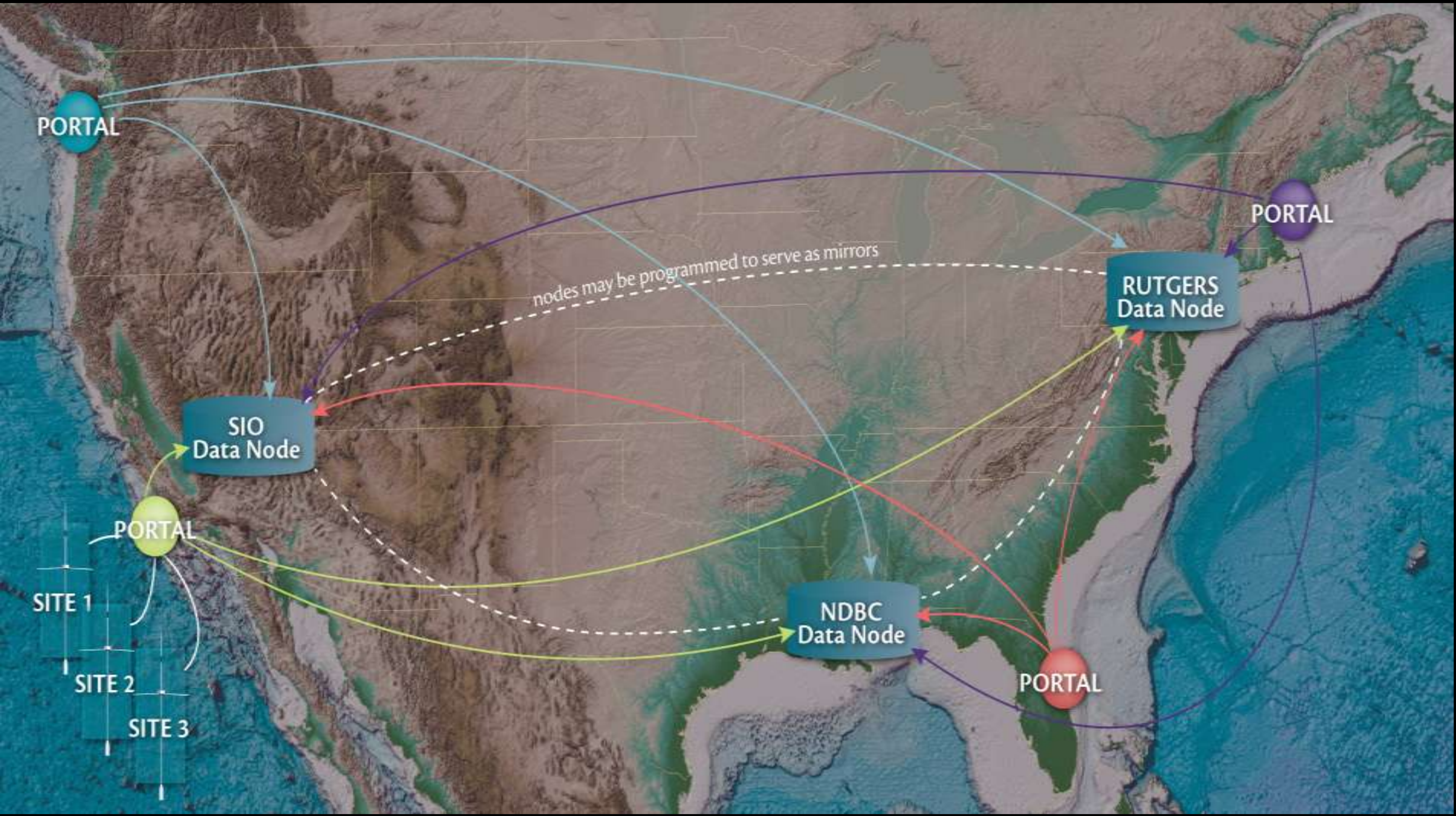
# The Big Picture

- Initially, small research arrays in 1990’s. Science Agency funding
- Value of long time series, larger, and operational systems became clear
- As part of “Ocean Observing System” initiatives, groups sought to maintain and expand arrays.
- Beginning in 2004, in partnership with the Integrated Ocean Observing System, a national data server was established.
- System growth continued to increase.
- IOOS is now a significant funding mechanism via NOAA, but not yet uniform.
- President’s budget for coming FY has a line-item funding to work toward maintaining the national network.
- A “National Plan” for HF surface current mapping has been written (http://www.ioos.gov/hfradar/)
- A National Steering Committee for HF Surface Current mapping has been formed.

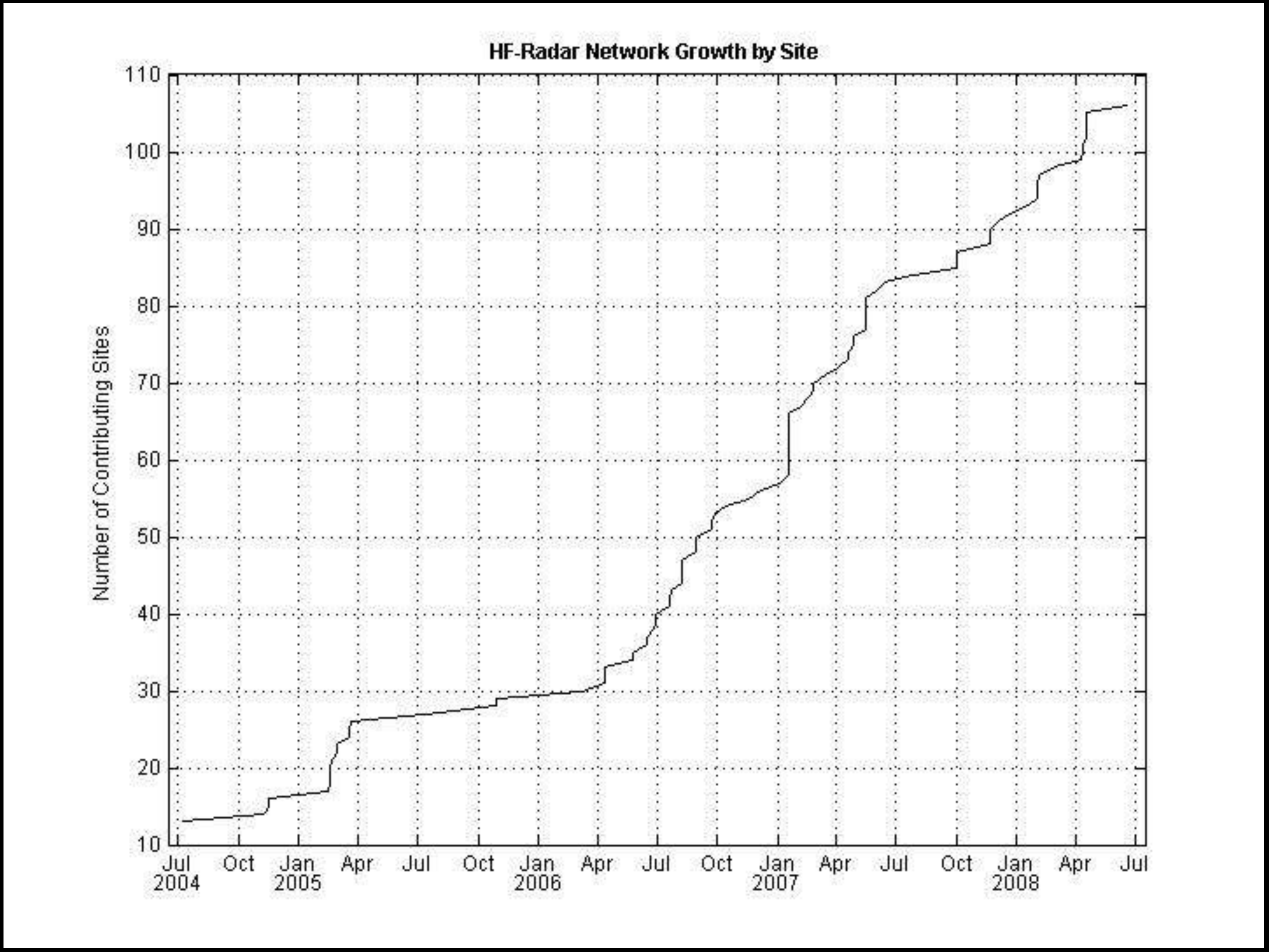
# National Network of Regional Associations


- 11 RA s serve the entire US Coastline, including Great Lakes, the Caribbean and the Pacific Territories
- RAs are the legal entities that seek out user needs, design and implement the Regional Coastal Ocean Observing Systems (RCOOS)

# Network Data Infrastructure

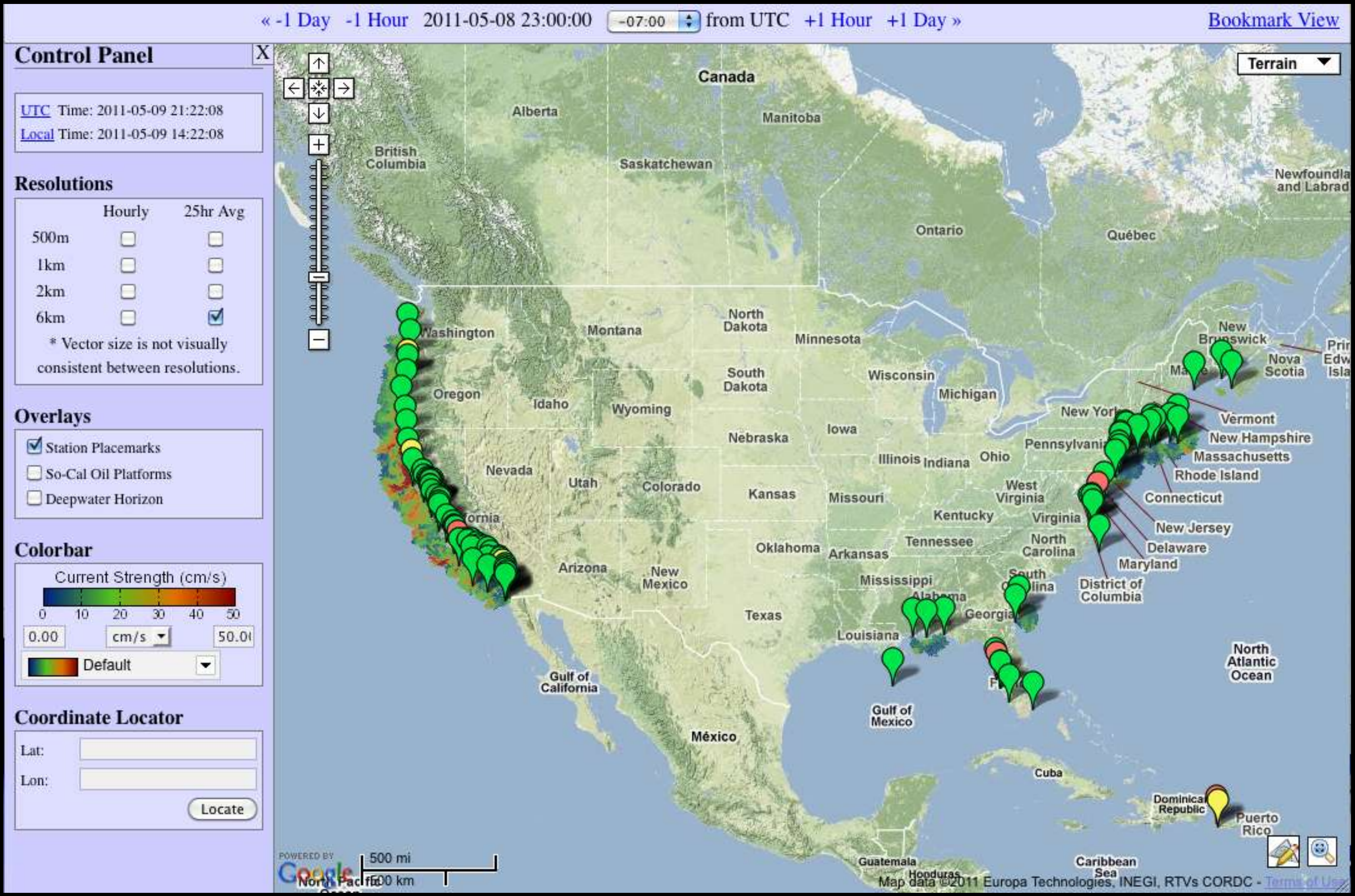


# Growth of the IOOS network



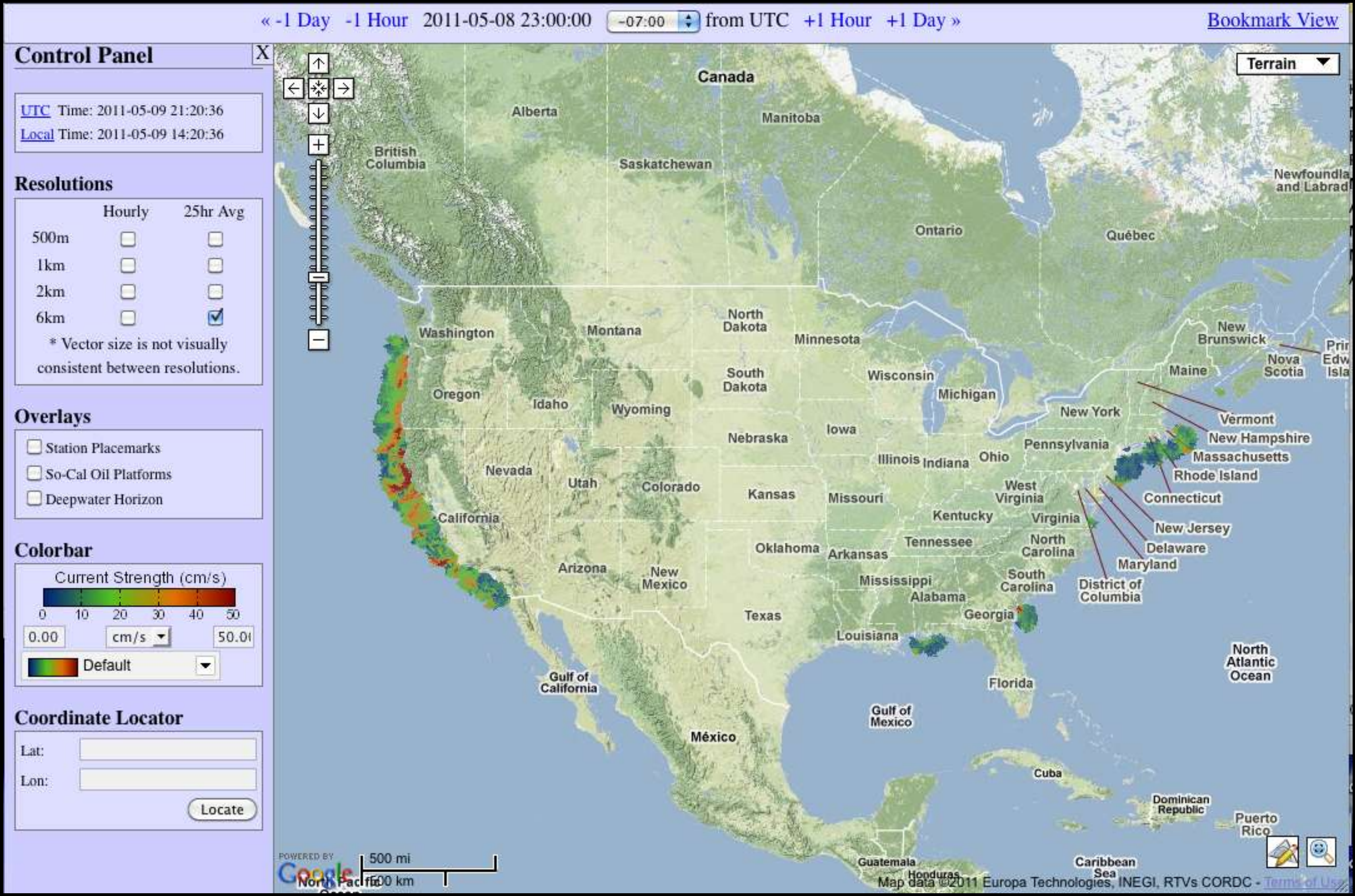
# National Network

Alaska & Hawaii too



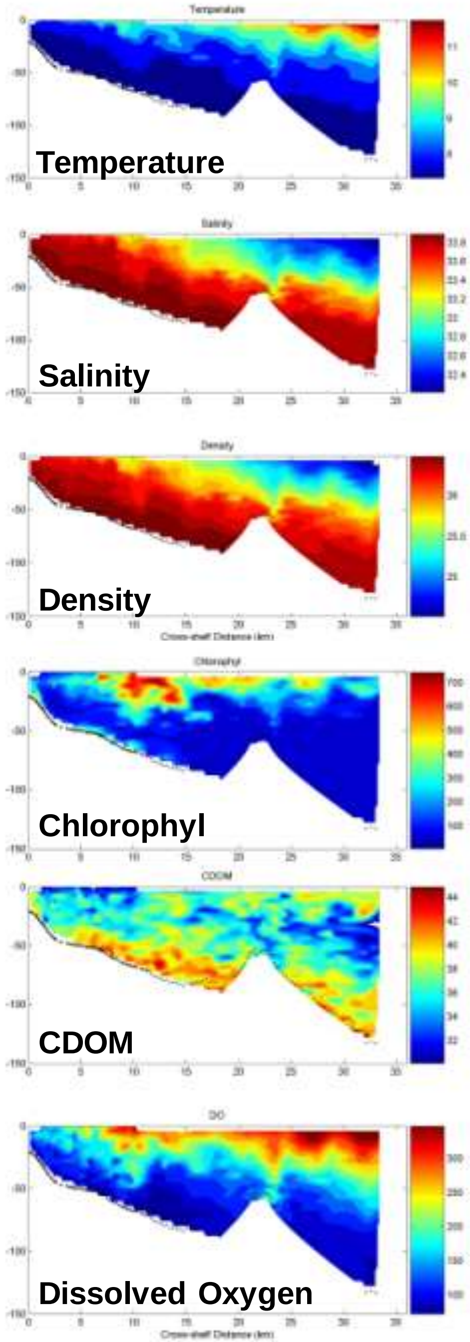
# National Network

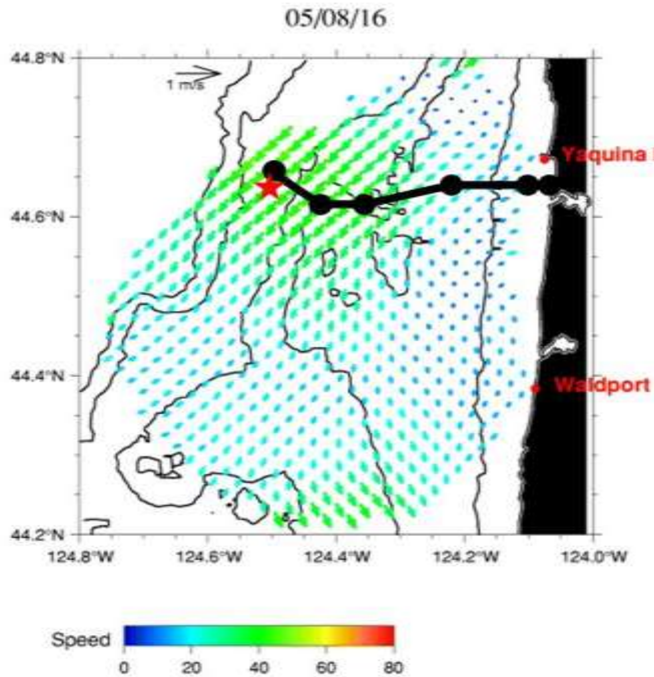
Alaska & Hawaii too



# Issues and Opportunities

- Licensing.  Presently, we operate as secondary users.  IOOS (Jack Harlan) is leading a vigorous campaign for dedicated frequencies.
  - GPS time-slicing to allow multiple systems on same frequency
- O&M for present system (O($11M/yr).
  - Present funding is well below this, and comes from regional associations, who have very low funds.
  - Good trend:  President's budget for the first time has a line for HF, but at $5M/yr.
- Funds for gap-filling needed.
- Aging infrastructure:  replacement schedule advisable
- Value of HF was clearly shown in the Deepwater Horizon disaster.  3 systems were brought on-line very quickly, and contributed to the trajectory forecasts.
- Other observing system elements (gliders, moorings) are adding subsurface information which is highly complementary.




# OSU Glider Lab

2 Slocum electric, 200 m gliders

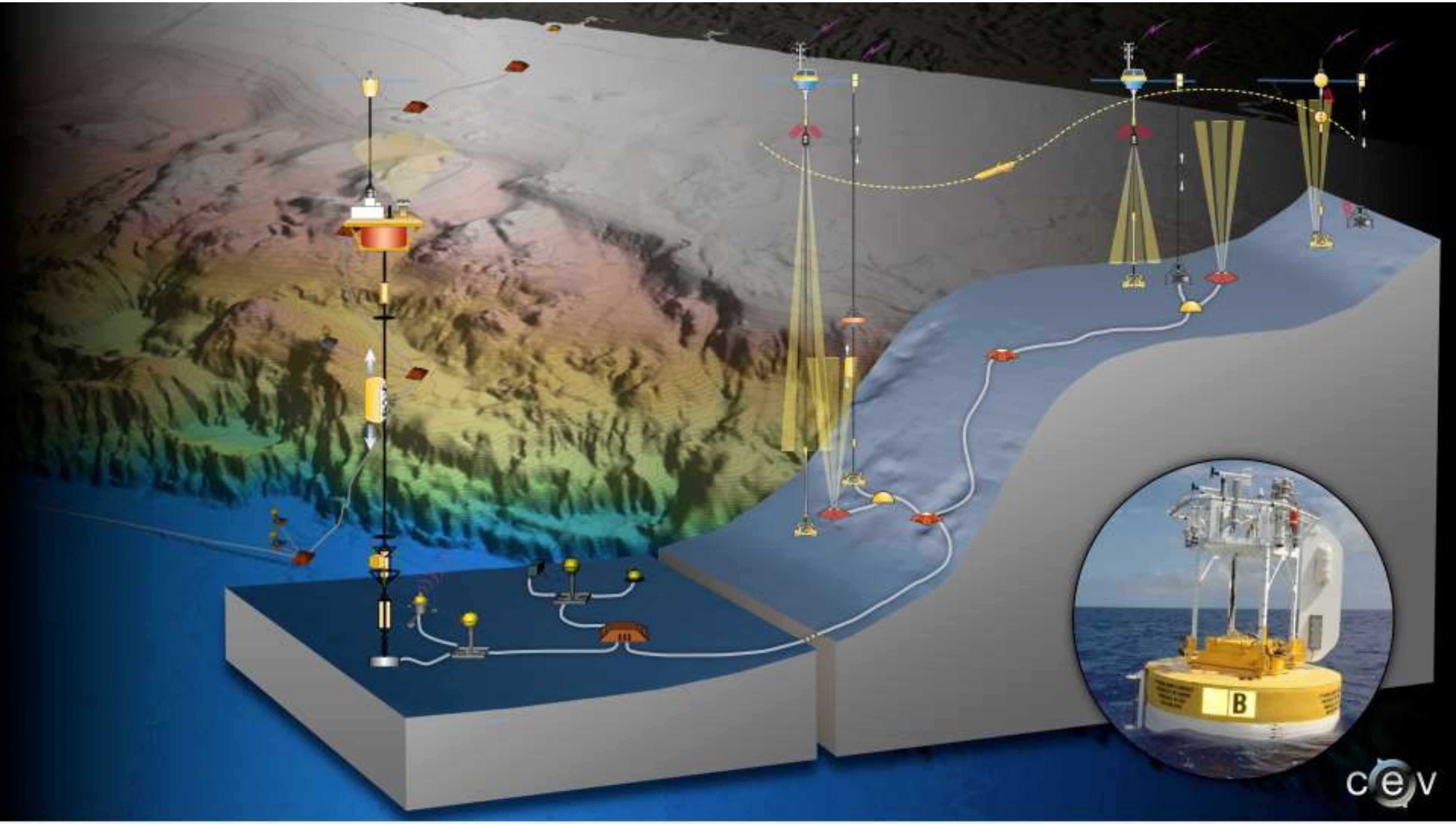
New 1000 m glider (spring 2006)

Endurance Lines off Newport and south of Heceta Bank

- started spring 2006
- 100 km offshore
- 10-15 day repeat cycle

Robotic Sampling of a coastal section

# Ocean Observing Intiative (OOI), Endurance Array (NSF)




OSU

UCSD