# Juan de Fuca Eddy Generation and its Relevance to Harmful Algal Blooms along the outer Washington coast

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# Acknowledgements

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NSF

## Other participants in the ECOHAB PNW Project

ECOHAB
Pacific Northwest
www.ecohabpnw.org

## Related Talks

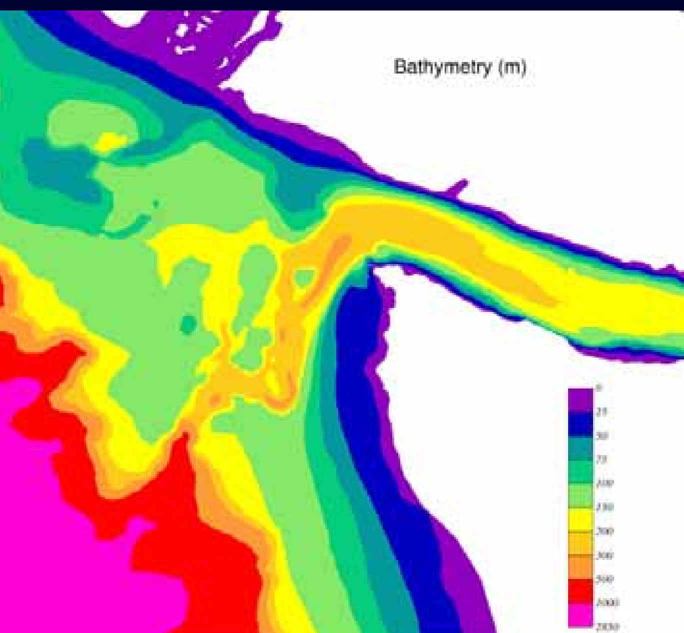
**9:10 MacFadyen**
**11:30 Peña**

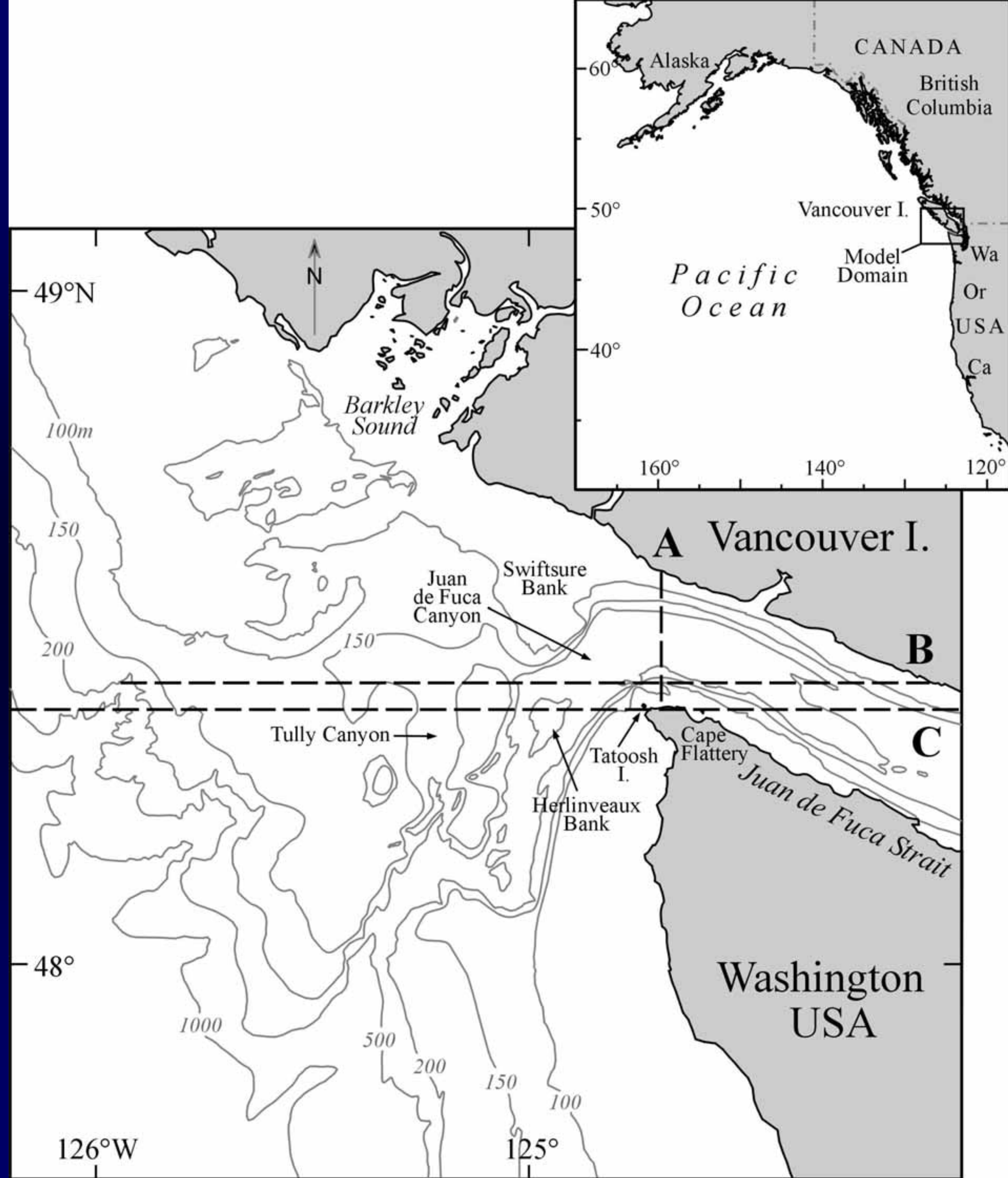
Fisheries and Oceans Canada
Pêches et Océans Canada

# Outline

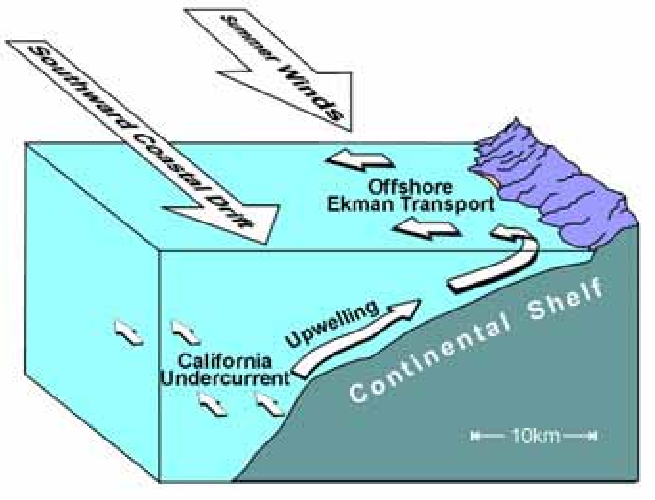
- Background
- Model details & validation
- Eddy generation studies
- Dynamics
- Relevance to HAB development & transport
- Climate change
- Summary & conclusions

# The Region of Interest

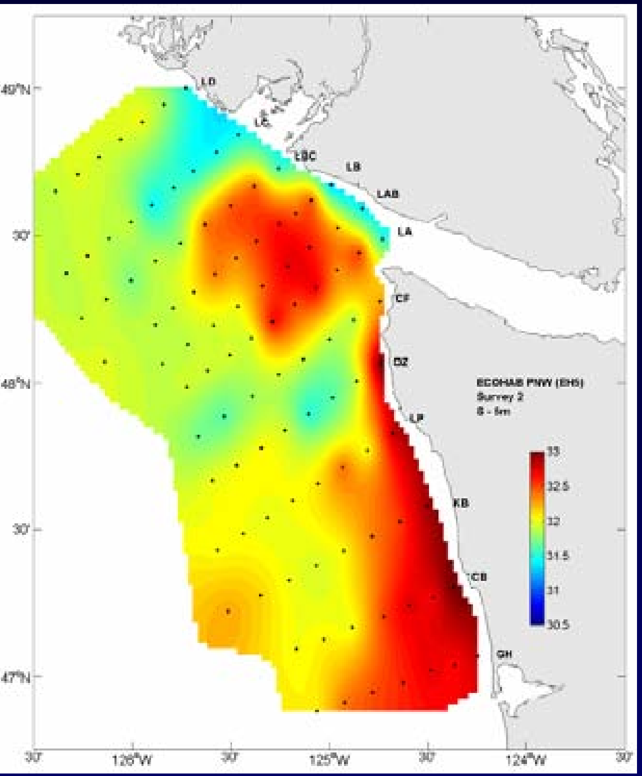


# Juan de Fuca (Tully) Eddy

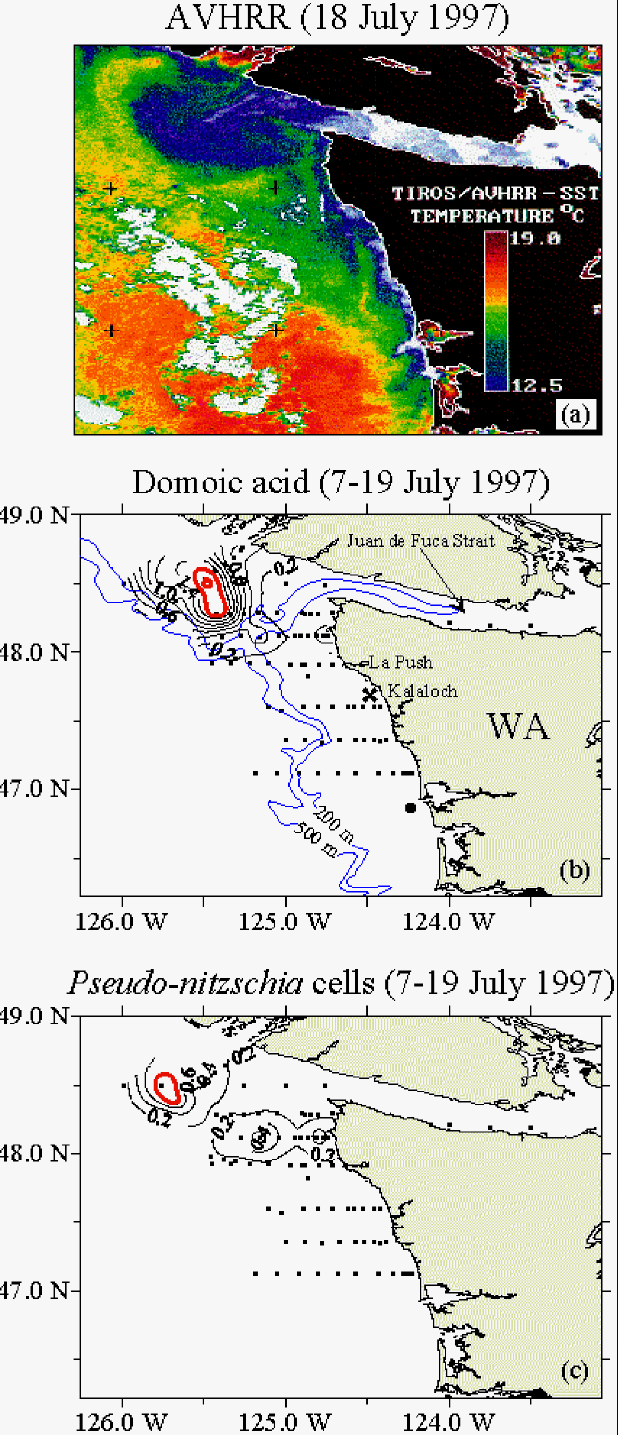



Courtesy of Rick Thomson



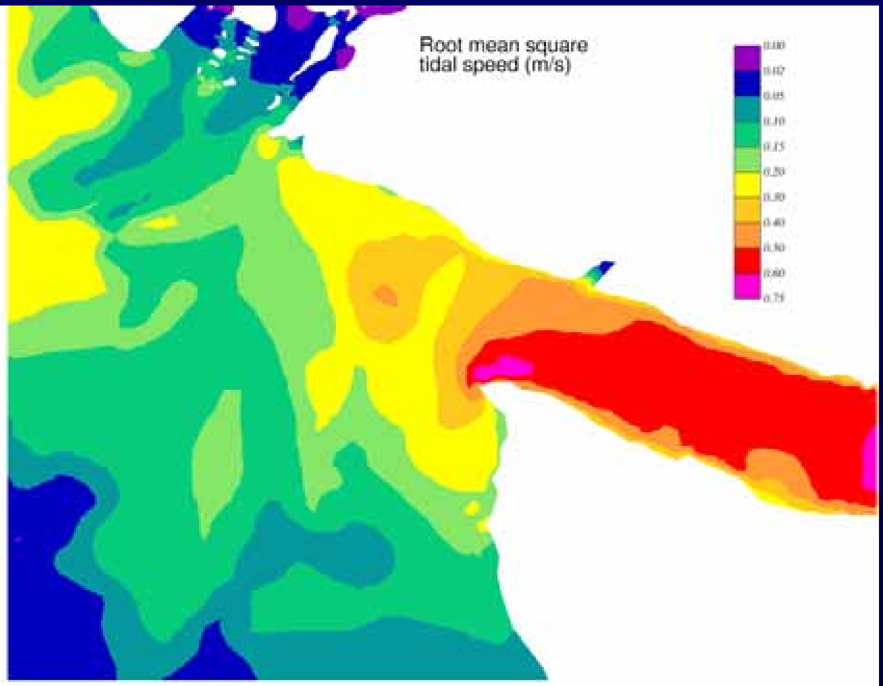

Sept 2005 salinity at 5m depth

- ***summer*** **upwelling feature off the entrance to Juan de Fuca Strait**
- **Not classical upwelling, as off WA, OR, CA**
- **comprised of nutrient-rich California Undercurrent water (Freeland & Denman, 1982) that moves up the Juan de Fuca *and Tully* Canyons onto the shelf**
- **Makes the SW Vancouver Island shelf one of most productive fishing regions in the NE Pacific (Ware & Thomson, 2005)**



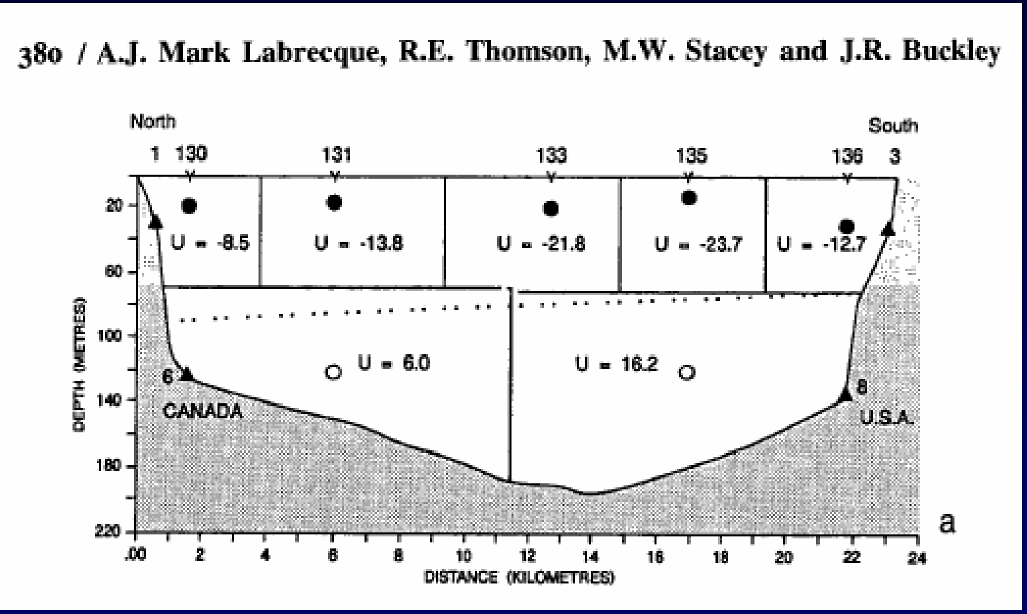

## More recently…

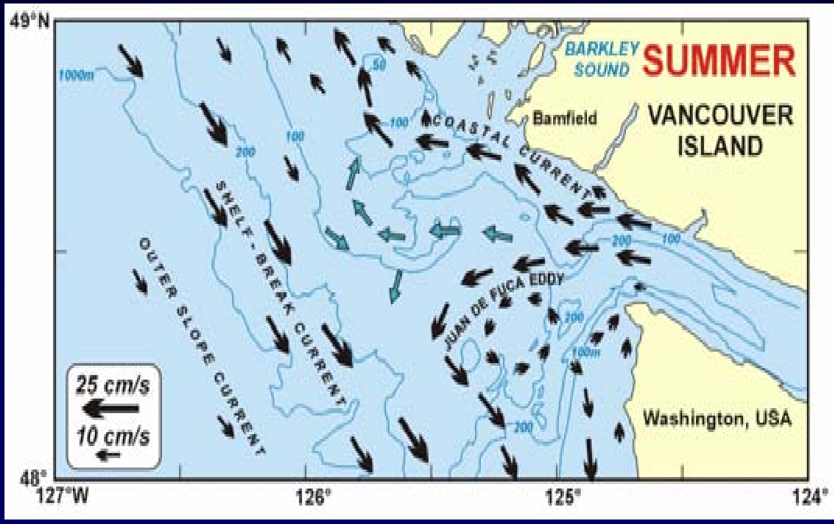
- **Eddy seems to be initiation site for toxic *Pseudo-nitzschia* that can impact clam & crab fisheries along the Washington coast (Trainer et al., 2002)**
- **ECOHAB PNW:**
  - **multi-disciplinary project to study ecology & oceanography of these harmful algal blooms (HABs)**
- **Eddy physical dynamics are important for understanding biochemistry and transport of these HABs**




# Regional Oceanography

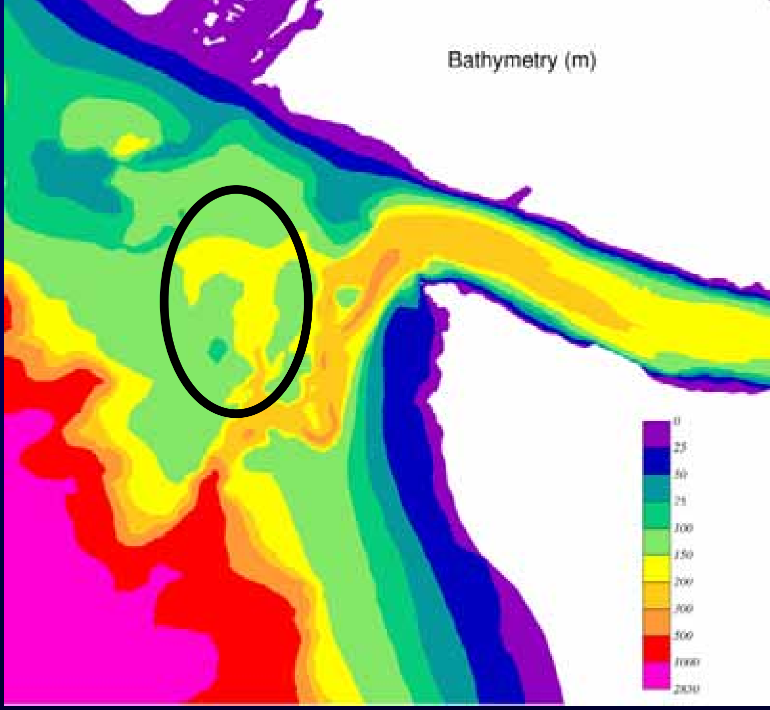
- Strong tidal, estuarine, & wind-driven flows in Juan de Fuca Strait
- Estuarine flow primarily from Fraser River
- Summer upwelling winds



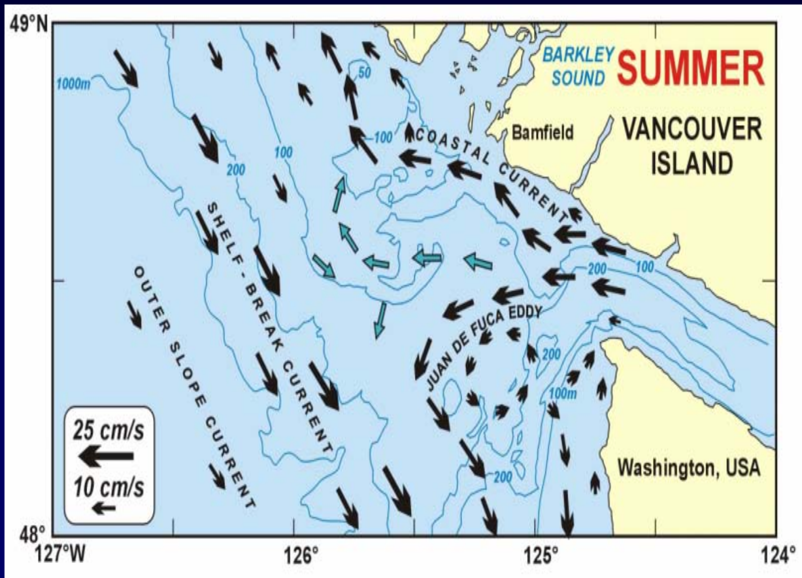




Courtesy of Rick Thomson

# *Freeland & Denman (1982) Hypothesis*



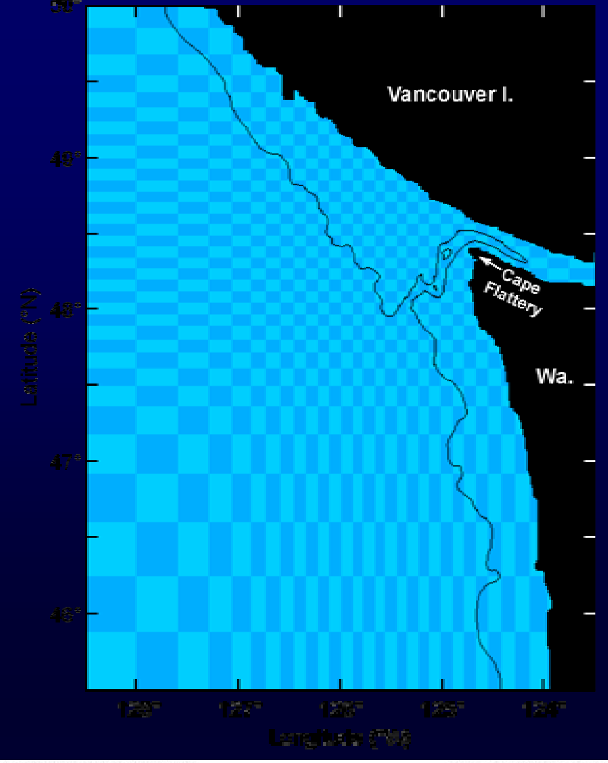

- **eddy closely associated with northern end of Tully Canyon**
- ***cyclonic eddy spins up when shelf edge currents reverse in spring***
- **near surface, inward pressure gradient largely balanced by outward Coriolis force**
- **further down water column, Tully Canyon suppresses transverse motions leaving only inward pressure gradient**
- **pressure gradient forces up-canyon flow, upwelling California Undercurrent water from shelf edge**

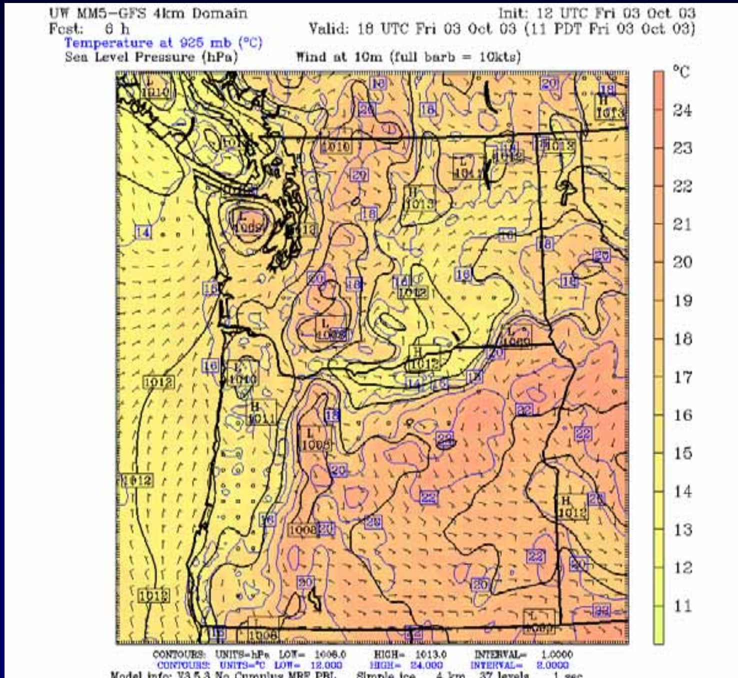


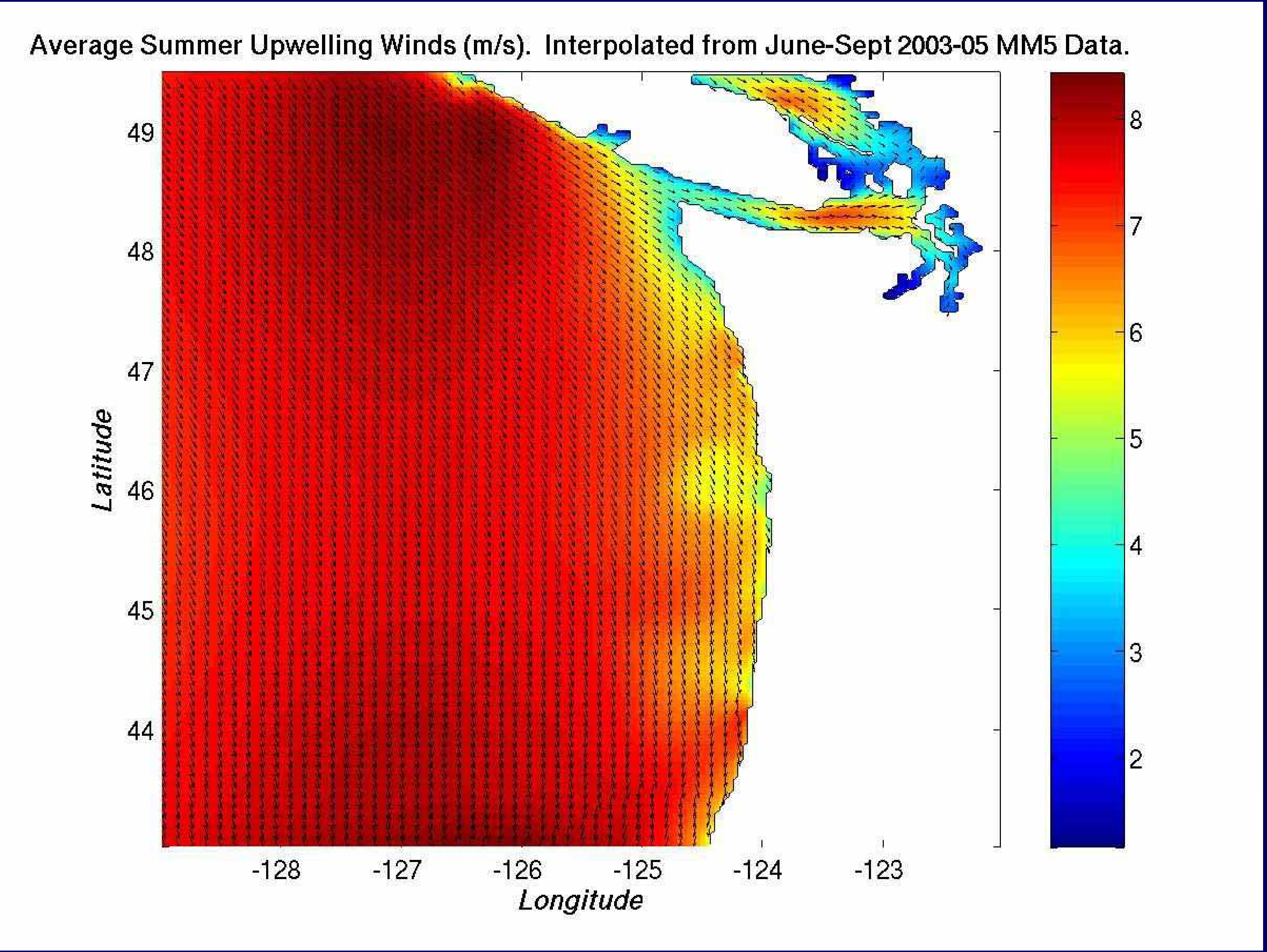

**We can test this hypothesis with numerical model experiments.**

# Modeling

- **ROMS = Regional Ocean Modeling System**
- **Objectives:**
  - ➢ **What combination of winds, estuarine flow & tides are necessary for eddy generation?**
  - ➢ **What are the specific dynamics?**
  - ➢ **How do wind variations affect retention & transport?**
- **Model details:**
  - ➢ **Stretched grid: 1 to 5 km**
  - ➢ **Temperature & salinity initial conditions from summer climatology**
  - ➢ **Average summer winds from UW MM5 atmospheric model (*next slide*)**
  - ➢ **$M_2$, $S_2$, $K_1$, $O_1$ tidal forcing**
  - ➢ **Strong TS nudging at JdF boundary to maintain estuarine flows**
  - ➢ **Radiation &/or nudging conditions on N, S, W boundaries**
  - ➢ **No Columbia discharge**





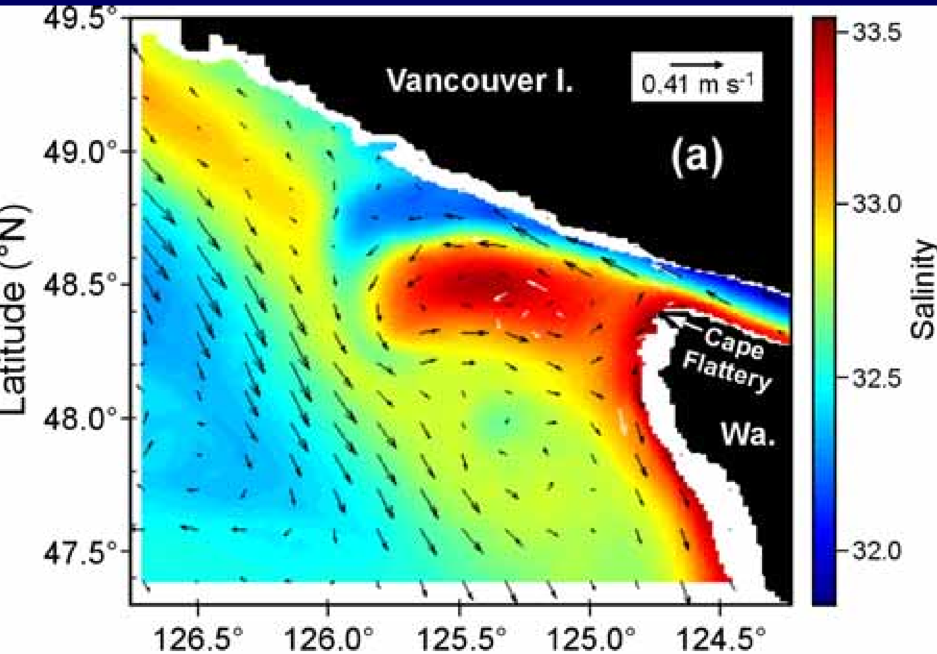

**Tinis et al. (2006) compared MM5 winds with buoy data**

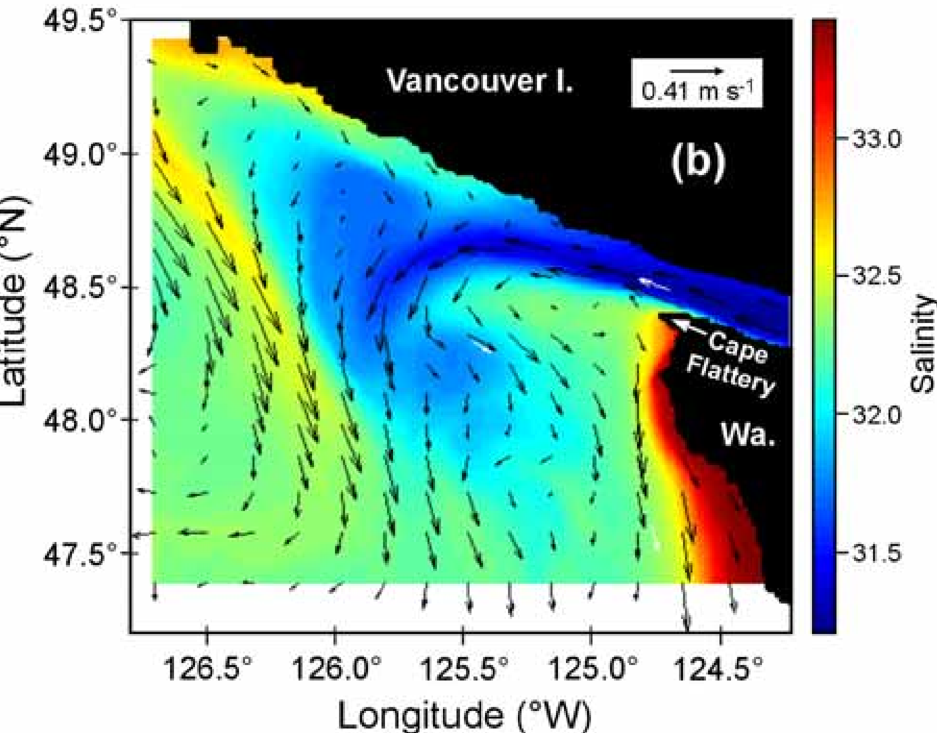
# Model Experiments to Study Generation

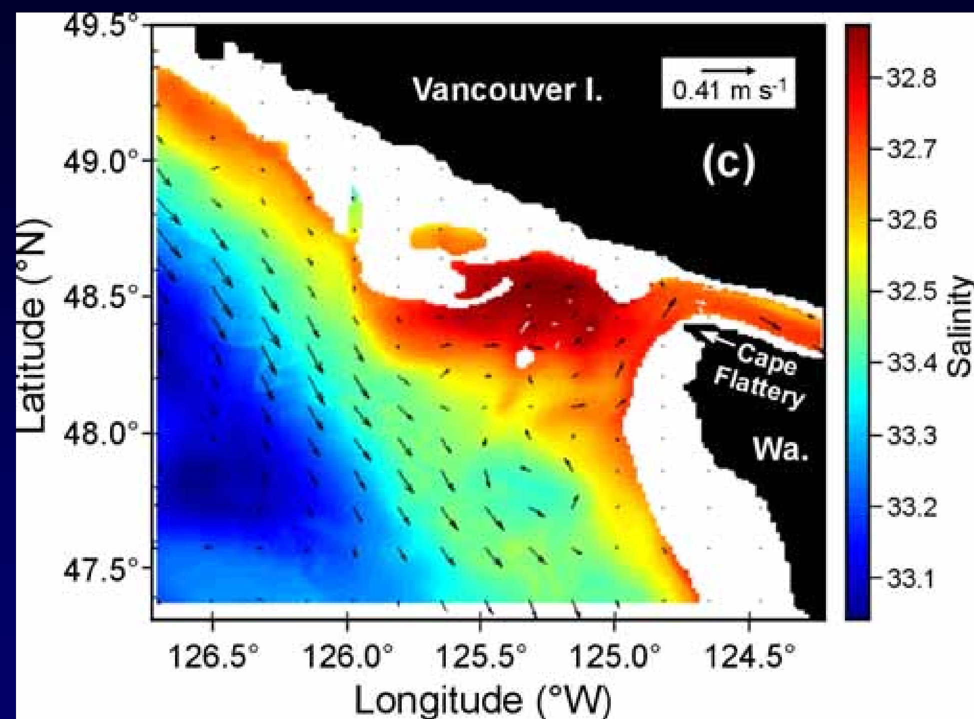
| *Experiment* | *Objective* | *Initial Conditions* | *Tides* | *Estuarine Flow* | *Winds* | *Duration* |
|---|---|---|---|---|---|---|
| **A** | **Baseline run** | **Summer climatology** | **yes** | **yes** | **yes** | **60 days** |
| **B** | **Role of winds** | **Summer climatology** | **no** | **yes** | **yes** | **60 days** |
| **C** | **Role of tides** | **Summer climatology** | **yes** | **yes** | **no** | **60 days** |
| **D** | **Role of estuarine flow** | **T and S profiles** | **yes** | **no** | **yes** | **60 days** |

# Baseline Run Validation:

**Average (days 46-60) flows & salinity at 0, 35, 100 m depths**

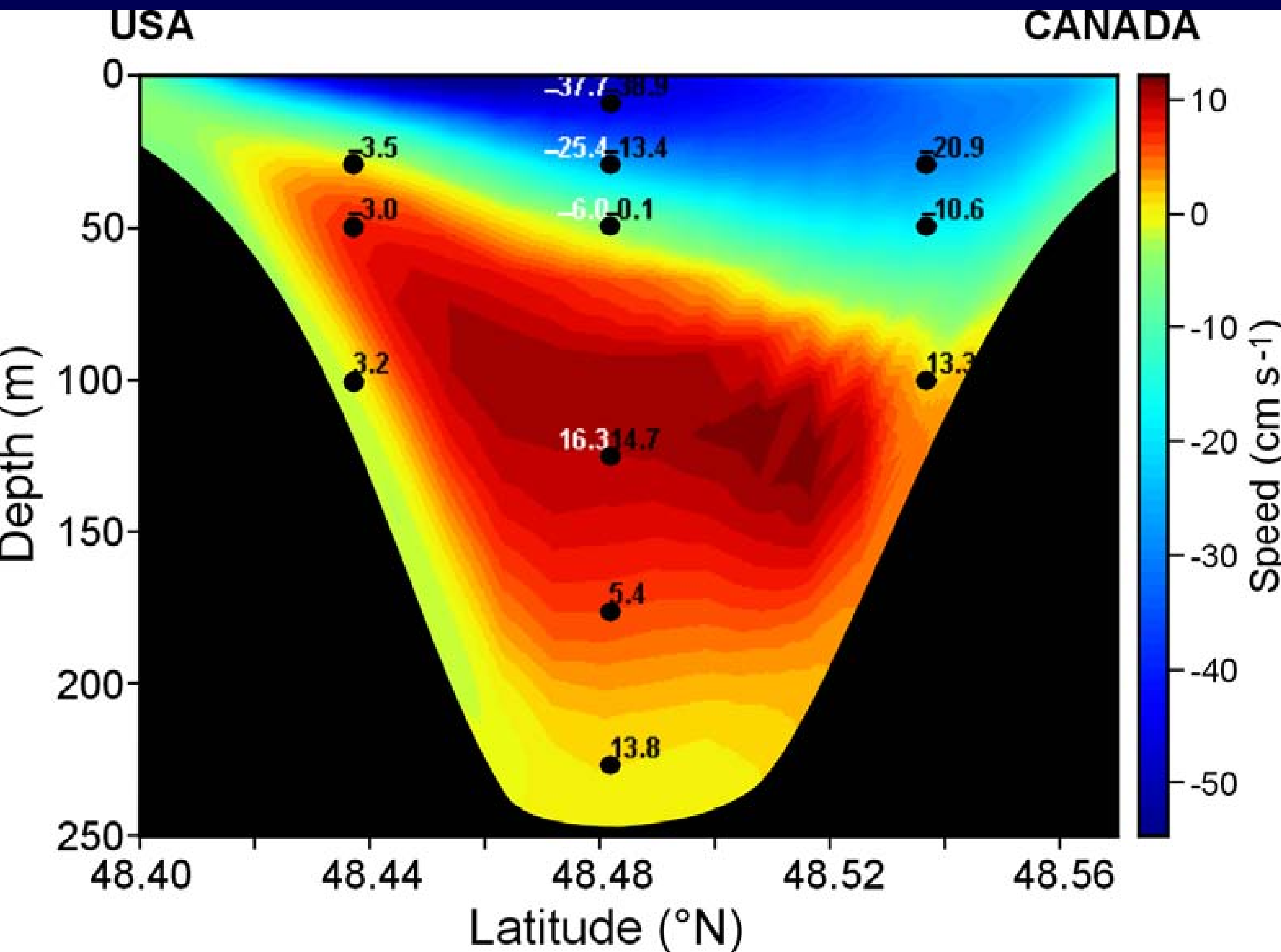


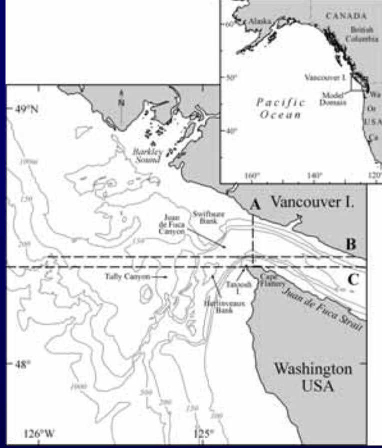



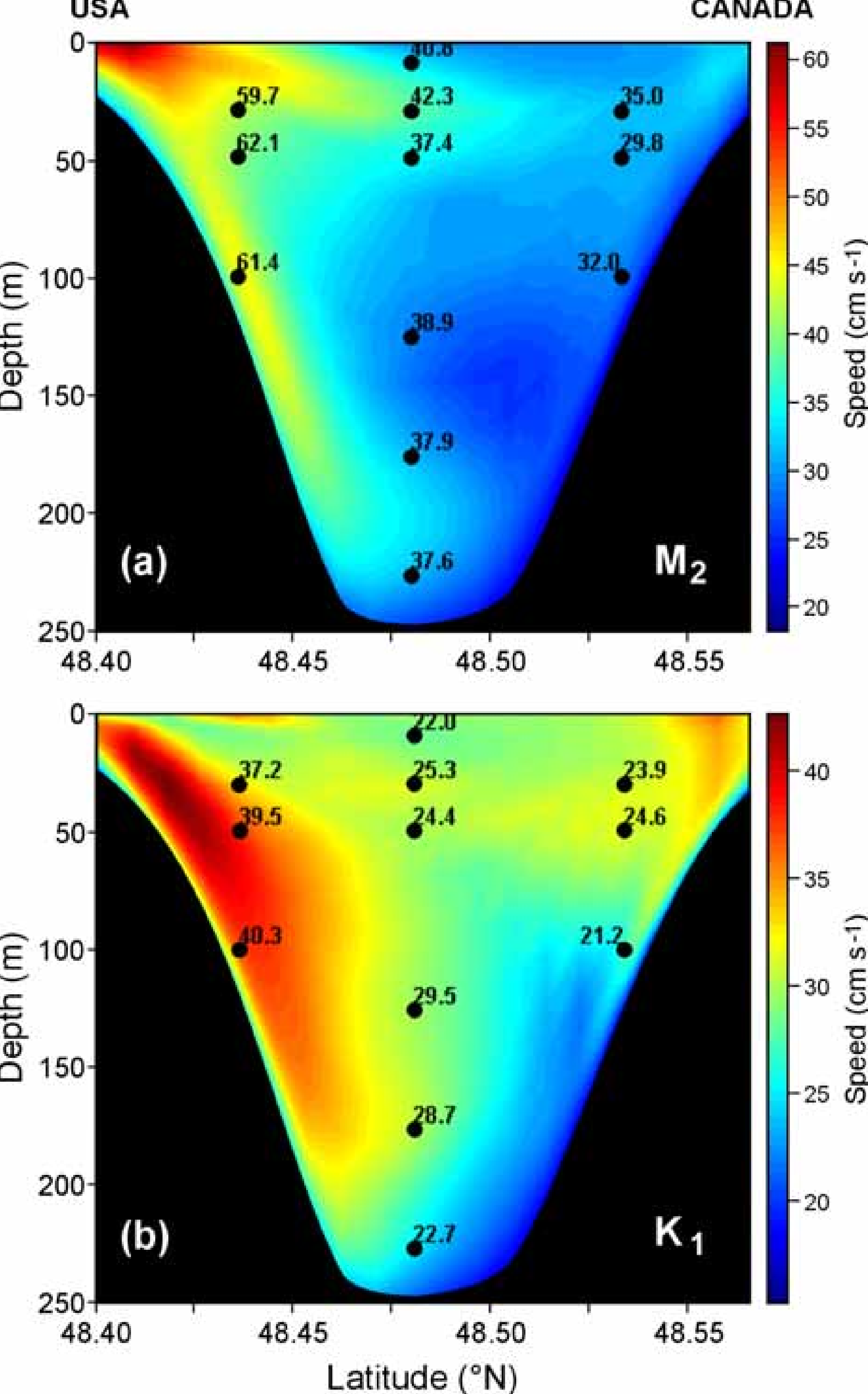



# Baseline Run Validation:

## Mean flows in Juan de Fuca Strait



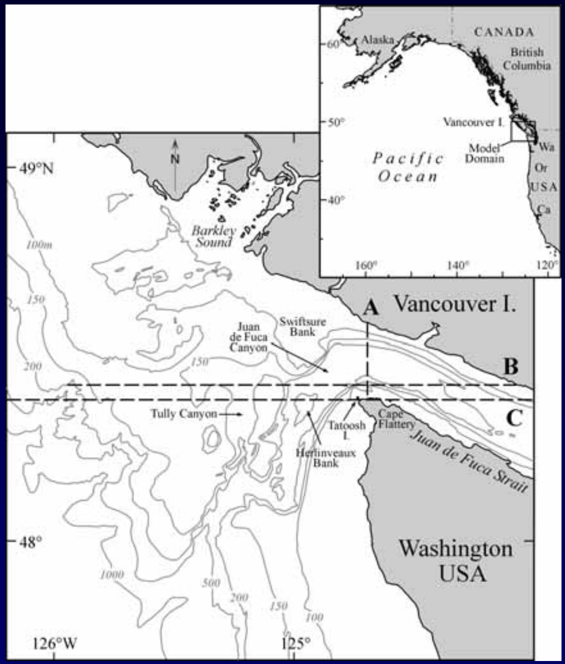






# Baseline Run Validation:

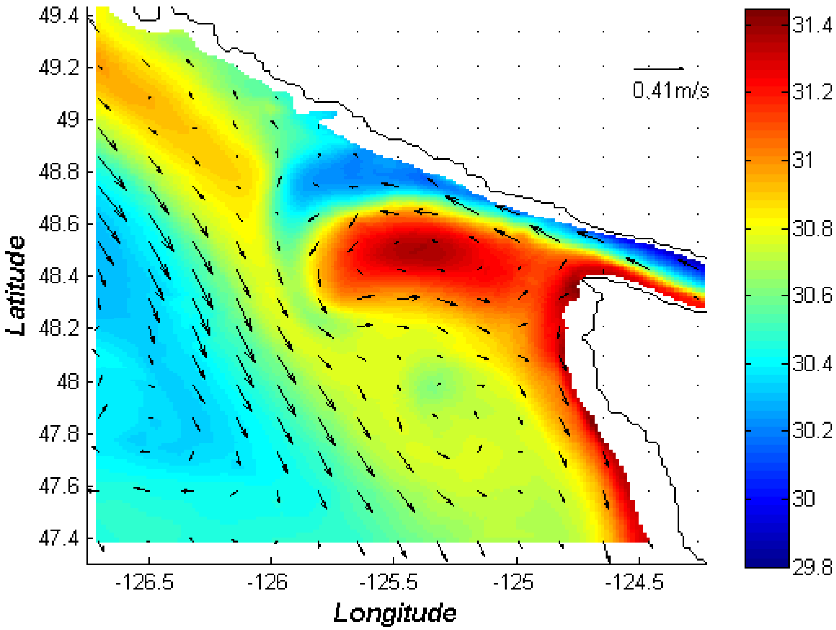
## $M_2$ & $K_1$

**along-strait maximum speeds (major semi-axes cm/s)**



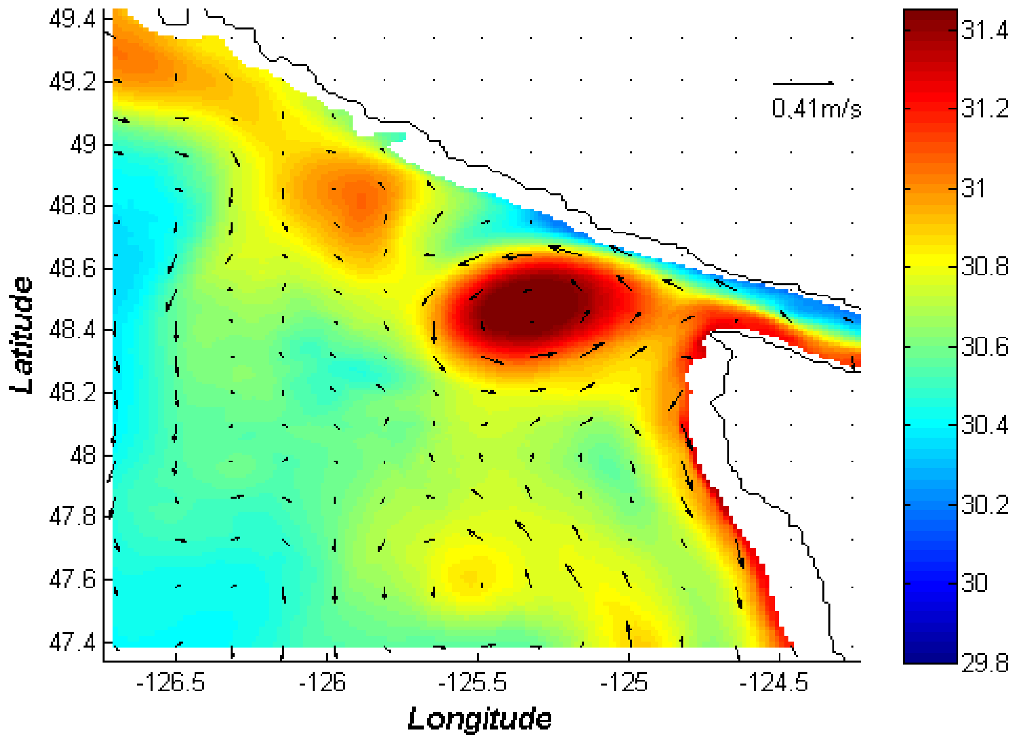
# No Tides Run

## Average (days 46-60) flows & salinity at 35 m depth

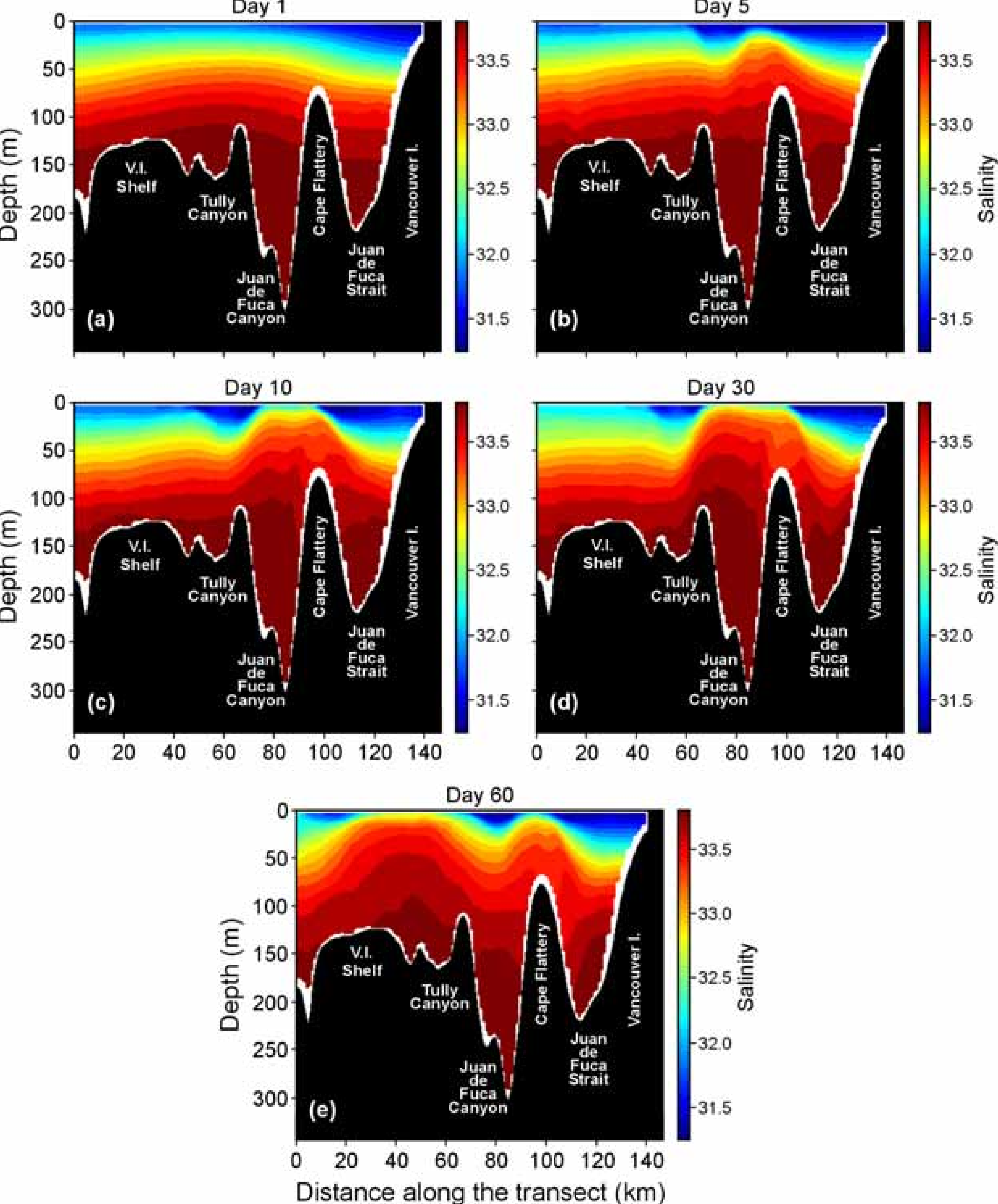


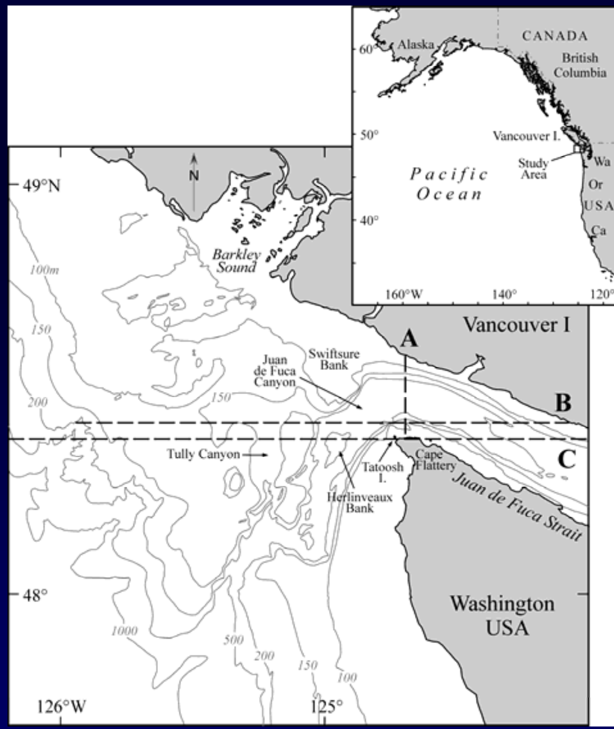

**Baseline**

**No Tides**

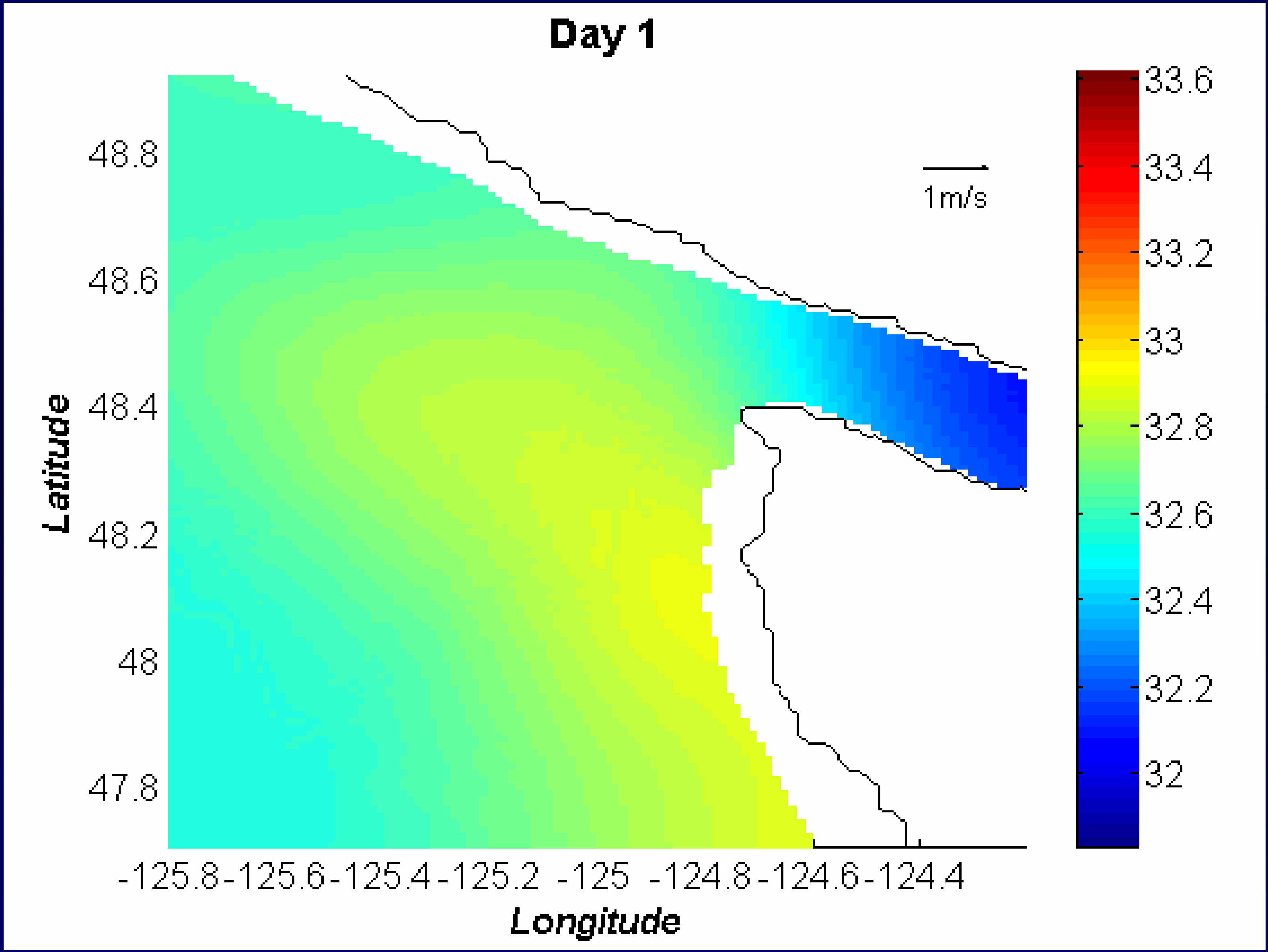


# Eddy Development with No Tides



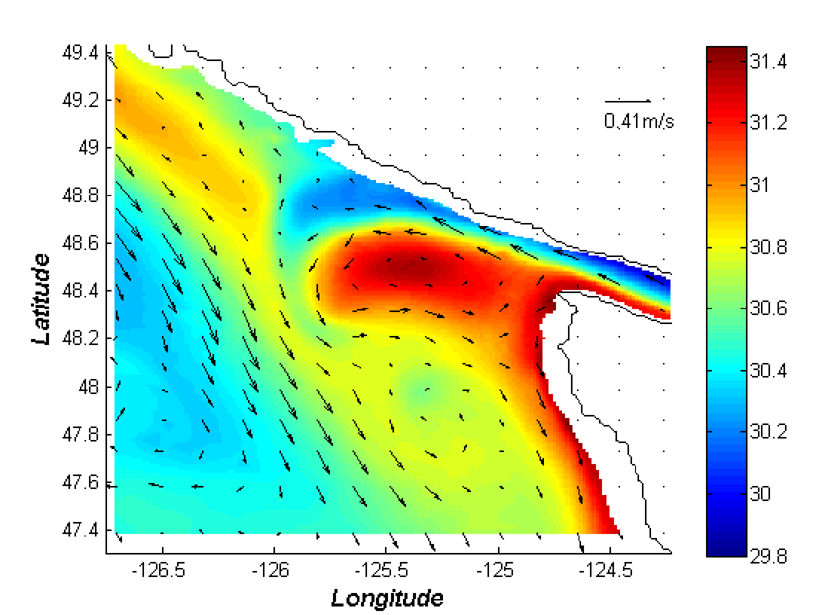



# Eddy Development with No Tides

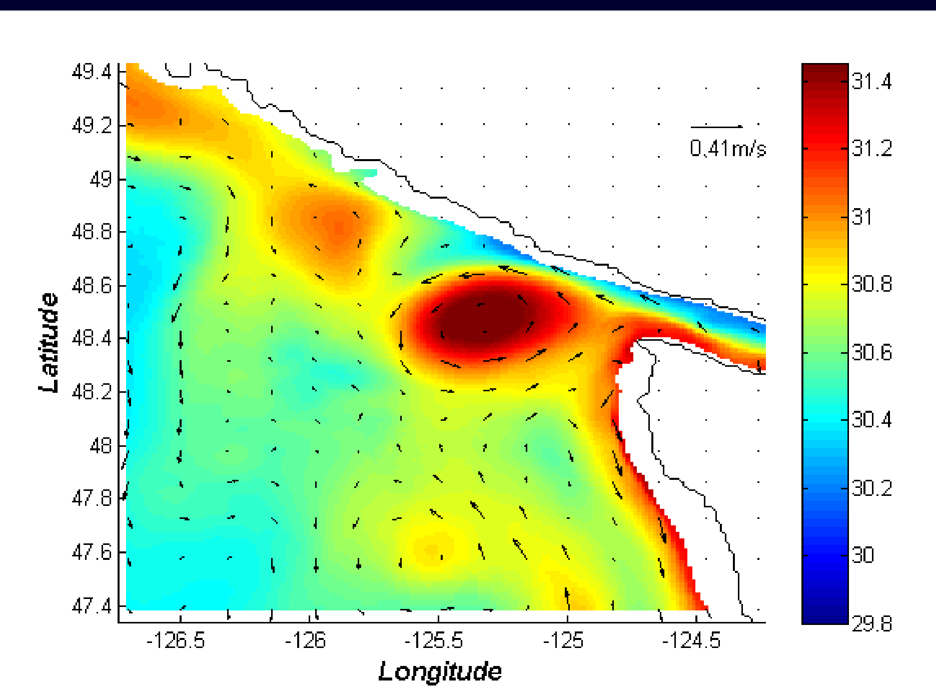


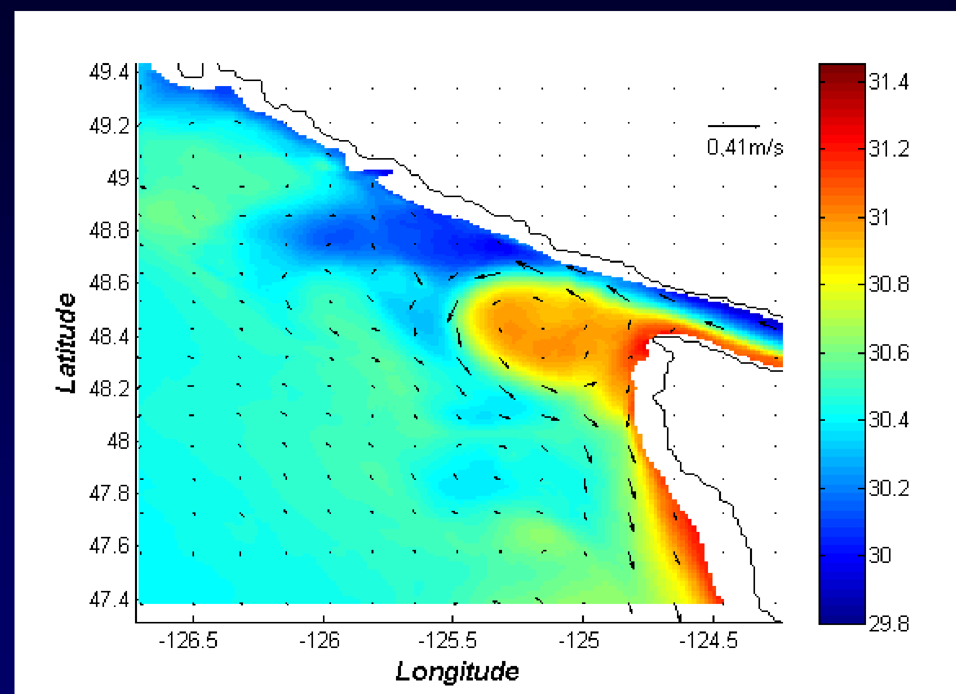

Daily 35m salinity and velocity

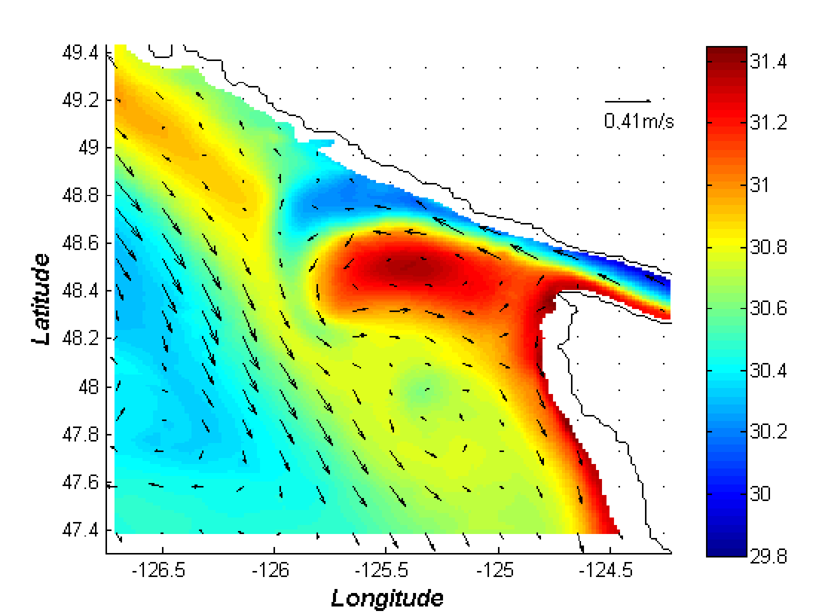
# Baseline vs No Tides vs No Winds




Average (days 46-60)
flows & salinity at 35 m depth

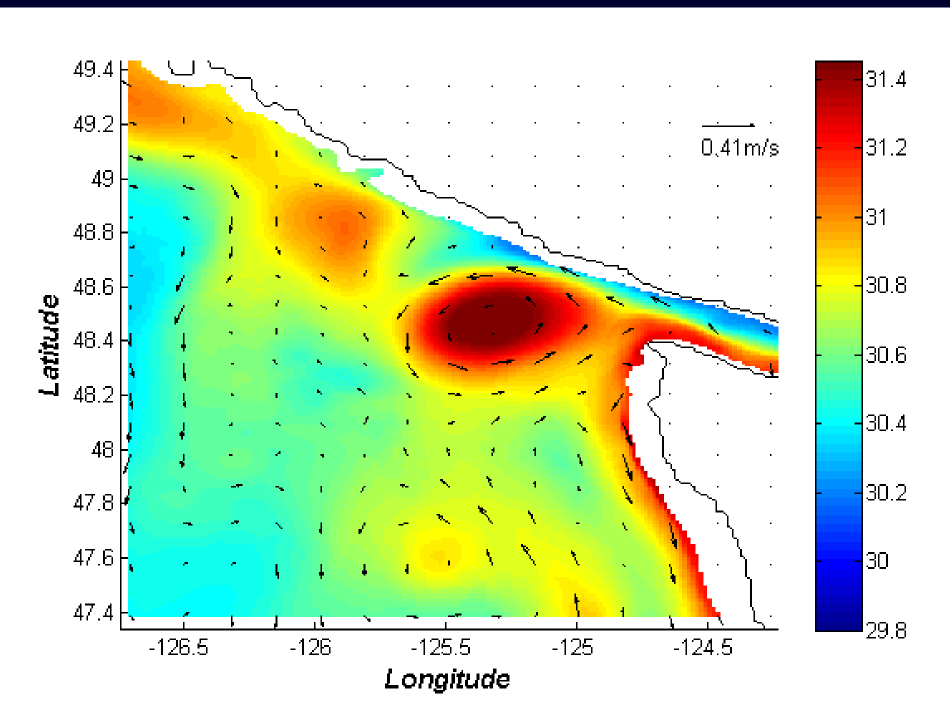


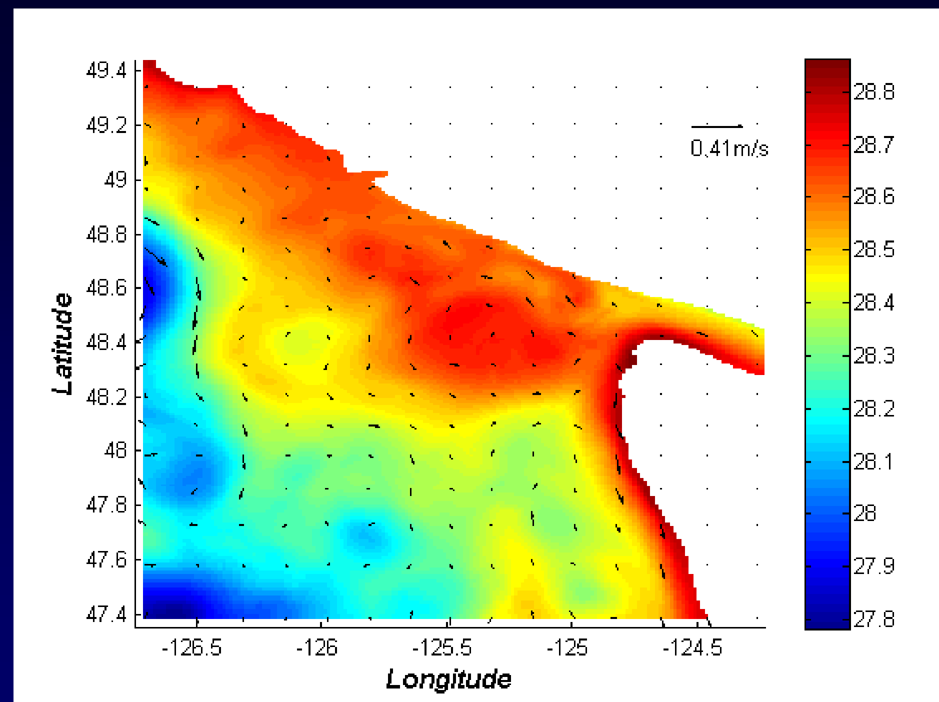






# Baseline vs No Tides vs No Estuarine Flow

**Average (days 46-60) flows & salinity at 35 m depth**



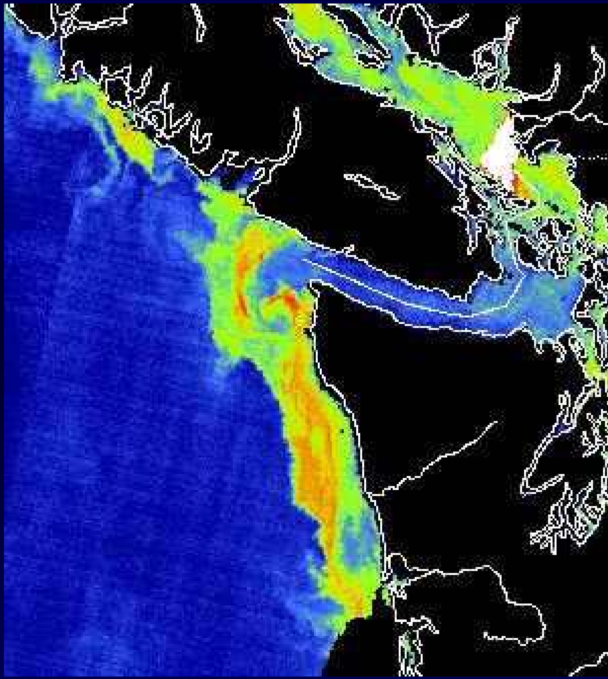



# Summary of Numerical Experiments

- **Eddy formed from enhanced upwelling off Cape Flattery**

- **Winds, tides & no estuarine flow**
  - ➢ **A very weak eddy**
  - ➢ **Comparable to upwelling along coasts**

- **Winds &/or tides with estuarine flow**
  - ➢ **Stronger eddy**
  - ➢ **Wind-driven eddy stronger than tidal-driven**

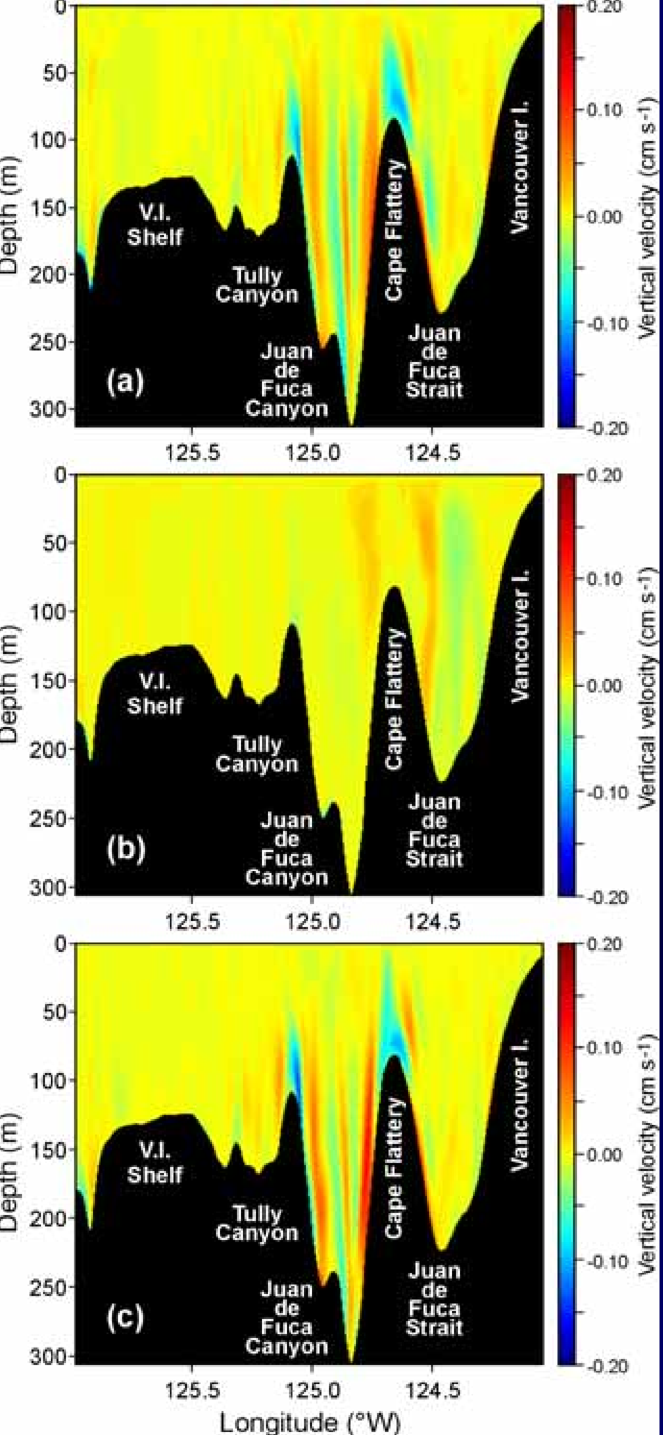


MERIS chlorophyll image: June 3, 2003
Courtesy of Jim Gower & Steph King

**What causes the:**

i. **Enhanced upwelling off Cape Flattery ?**

ii. **Cyclonic eddy formation ?**




# Upwelling Mechanisms:

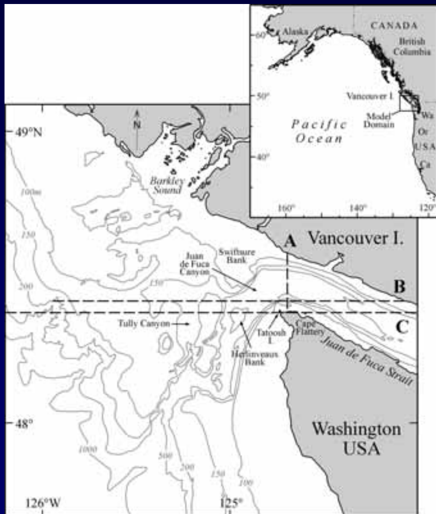
## 1. Mean vertical velocity (along transect B)

**Baseline**

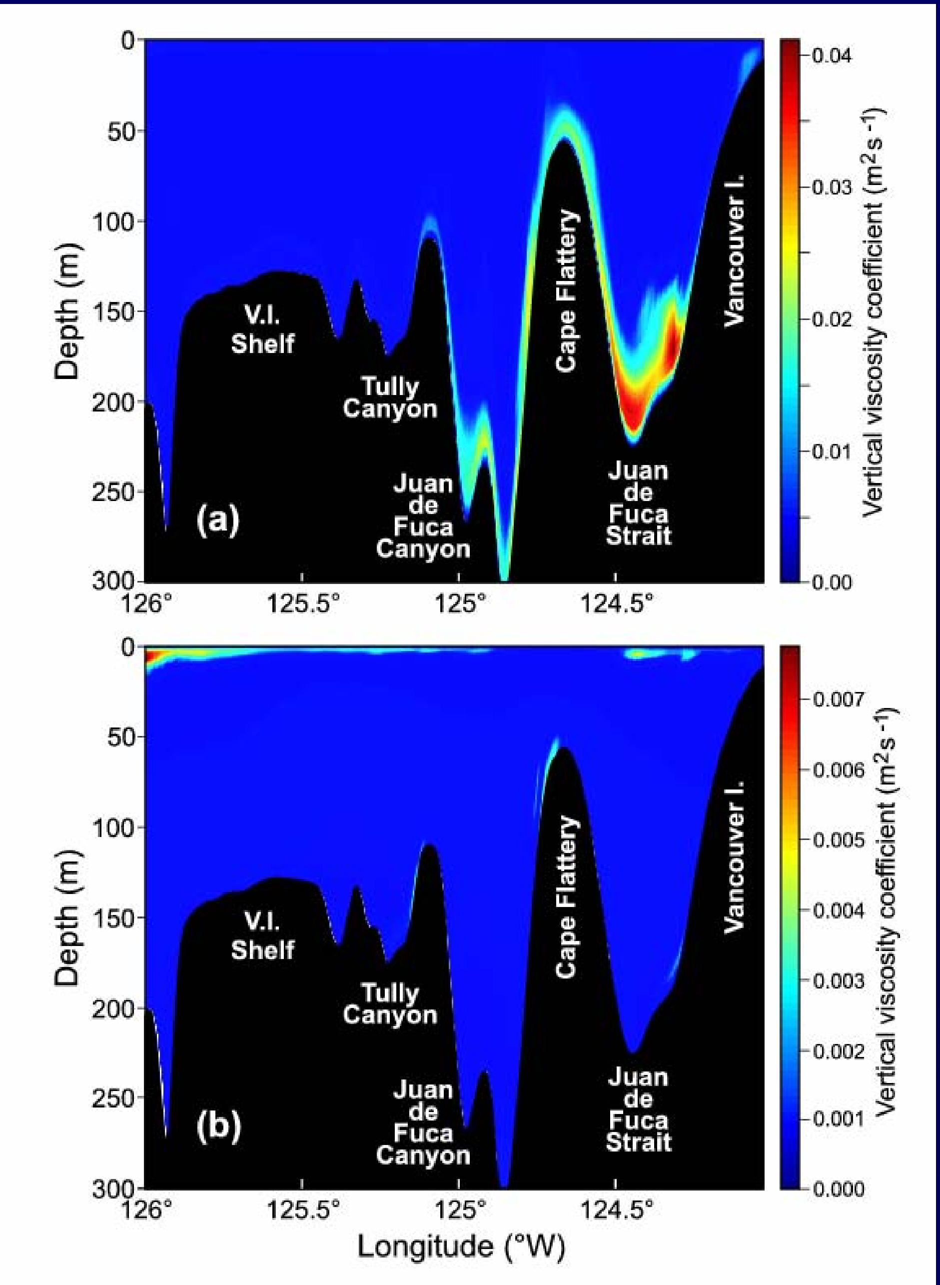
**No Tides**

**No Winds**

➢ ***a) & c) suggest vertical tidal residuals: Garrett & Loucks (1976) ?***



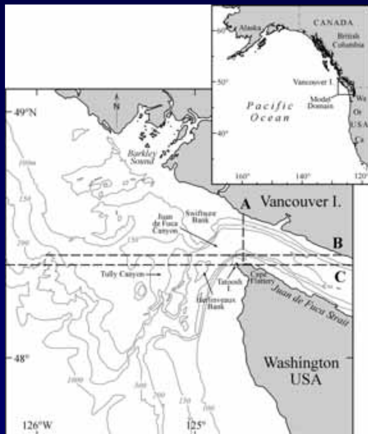
# Why stronger eddy with no tides ?

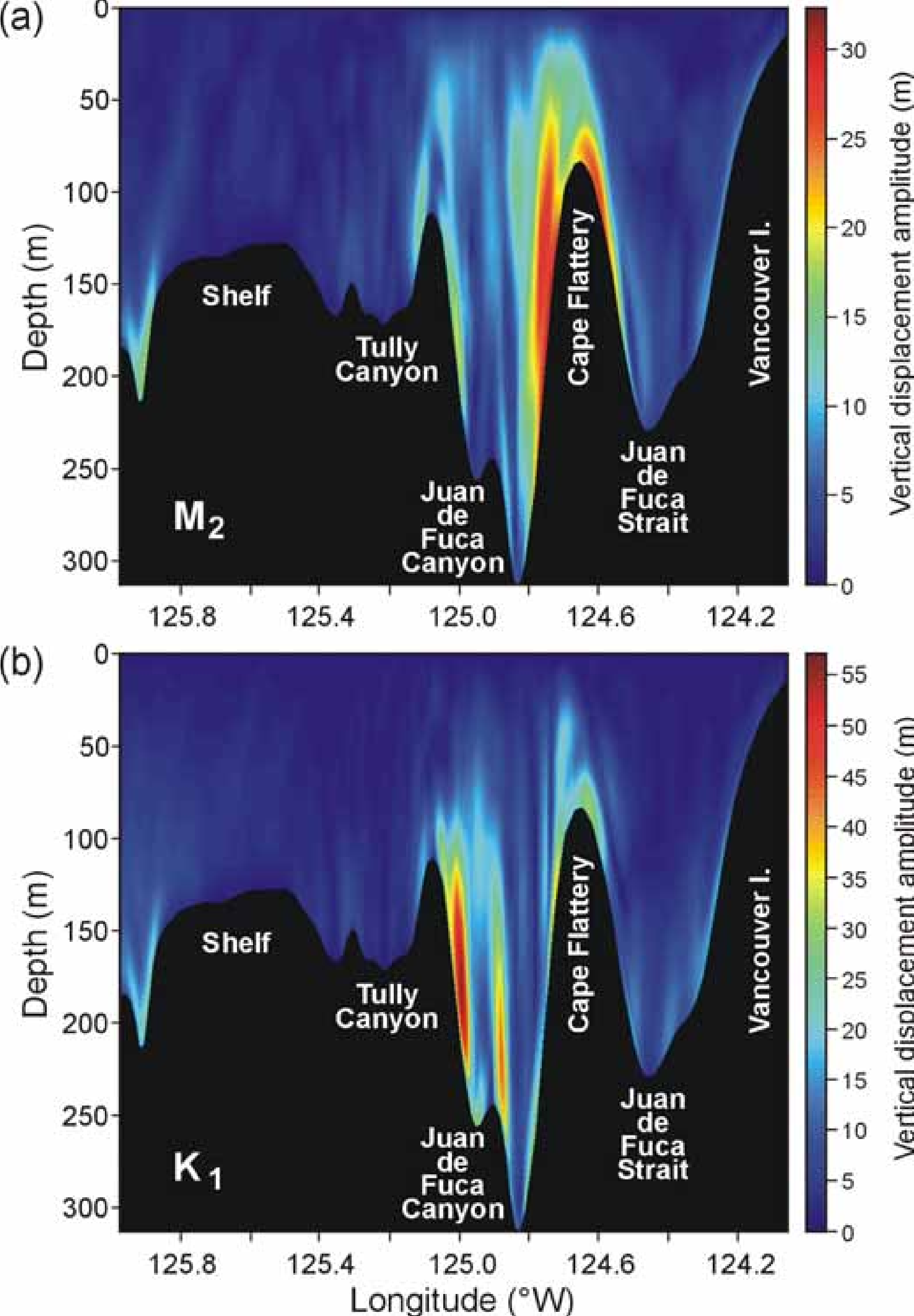



Winds & tides

Winds but no tides

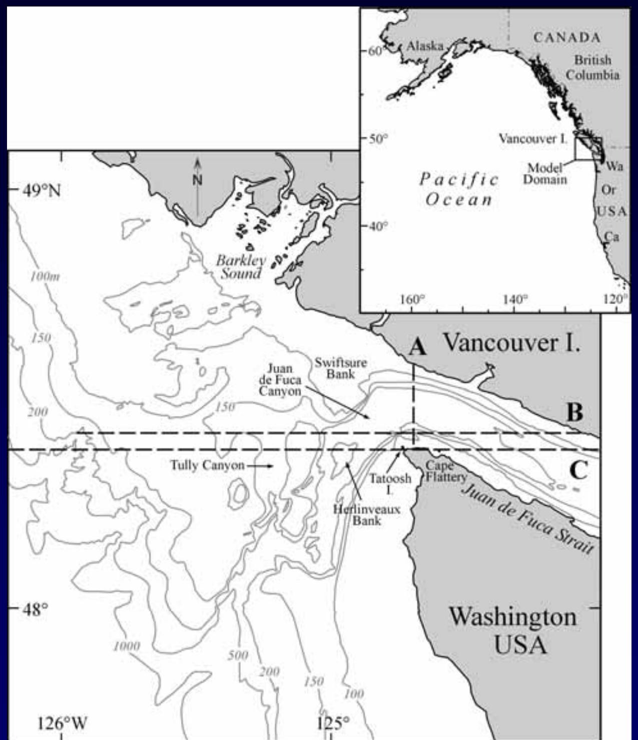
*Average vertical viscosity along transect B*






# Upwelling Mechanisms:

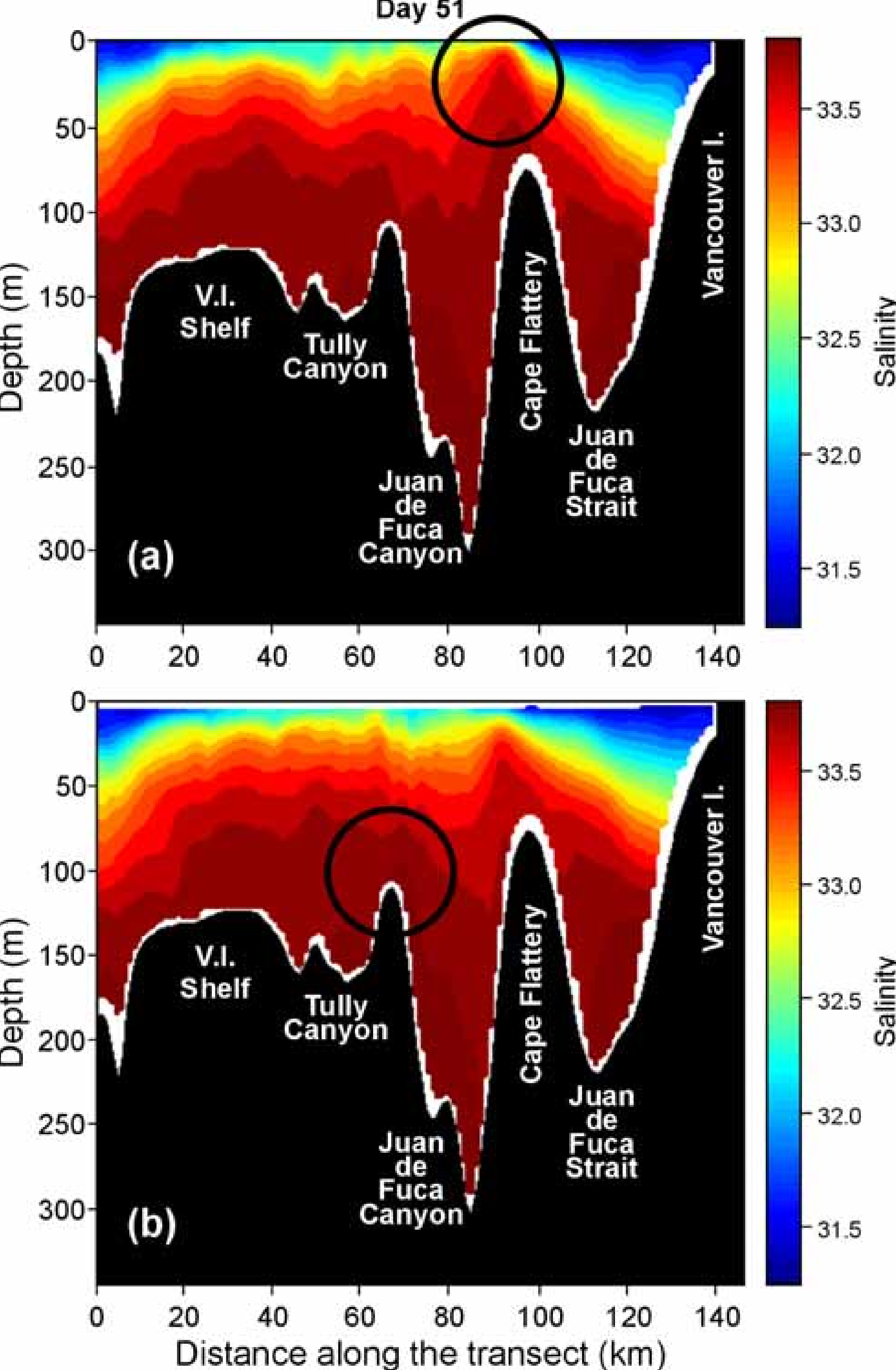
**2. Tidal vertical displacement amplitudes (along transect B)**



# Upwelling Mechanisms:

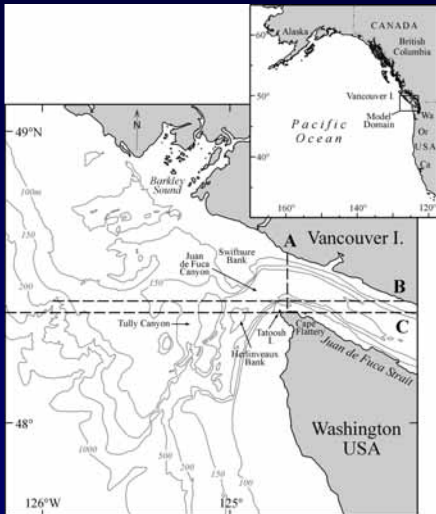
## 3. Cross canyon waves (internal tides?)

**Salinities across transect B**




hour 23 = flood tide

hour 16 = ebb



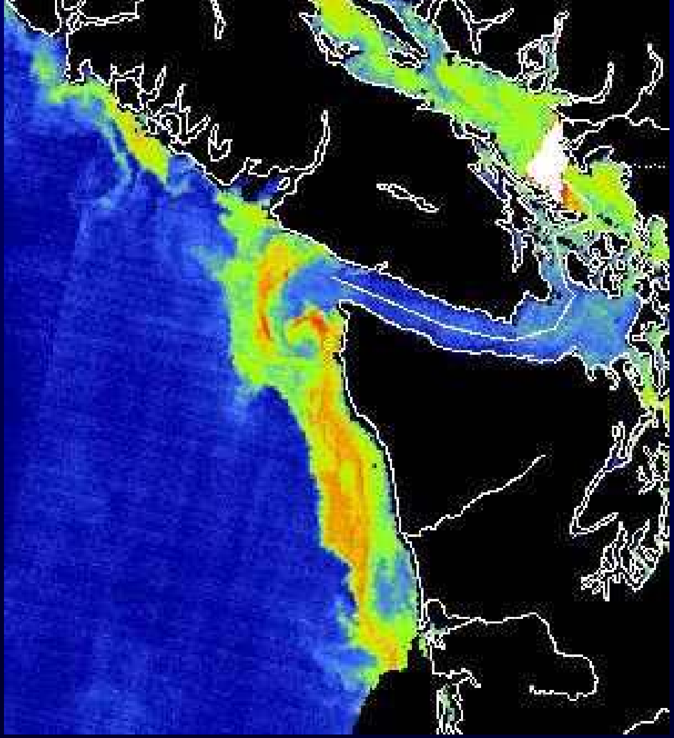
# Why

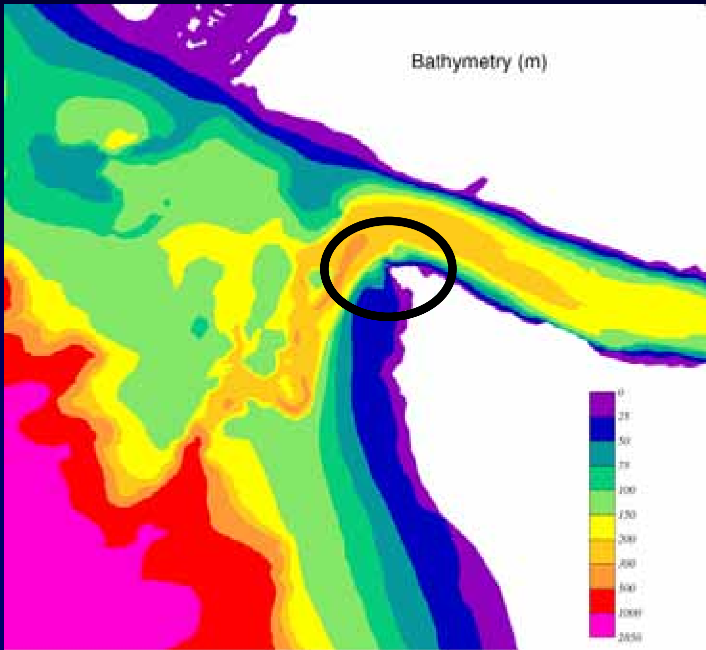
## i) a cyclonic eddy?

- upwelled denser water causes a surface depression & inward pressure gradients
- geostrophy → cyclonic eddy

## ii) enhanced upwelling off Cape Flattery?

- proximity of dense water in bottom estuarine flow
- 200m depth contour only 4km away

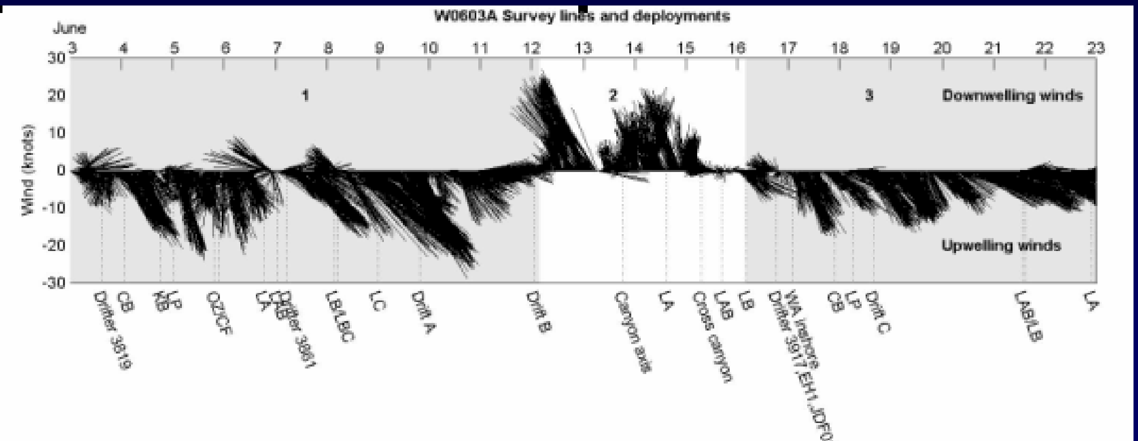


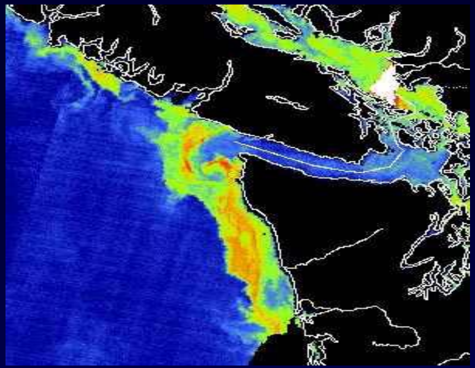


# Relevance to HAB Development & Transport

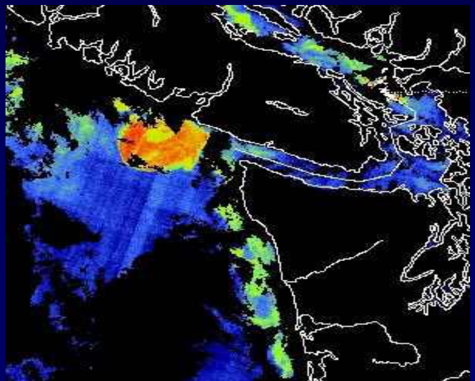
- **Eddy can retain *Pseudo-nitzschia* & provide nutrients for them to grow – "bio-reactor"**
  - **low iron/copper availability seems to correlate with high toxin concentration**
- **Variations in winds (& tides) will affect phytoplankton retention & transport**
  - **MacFadyen et al.**

**June 2003 winds**



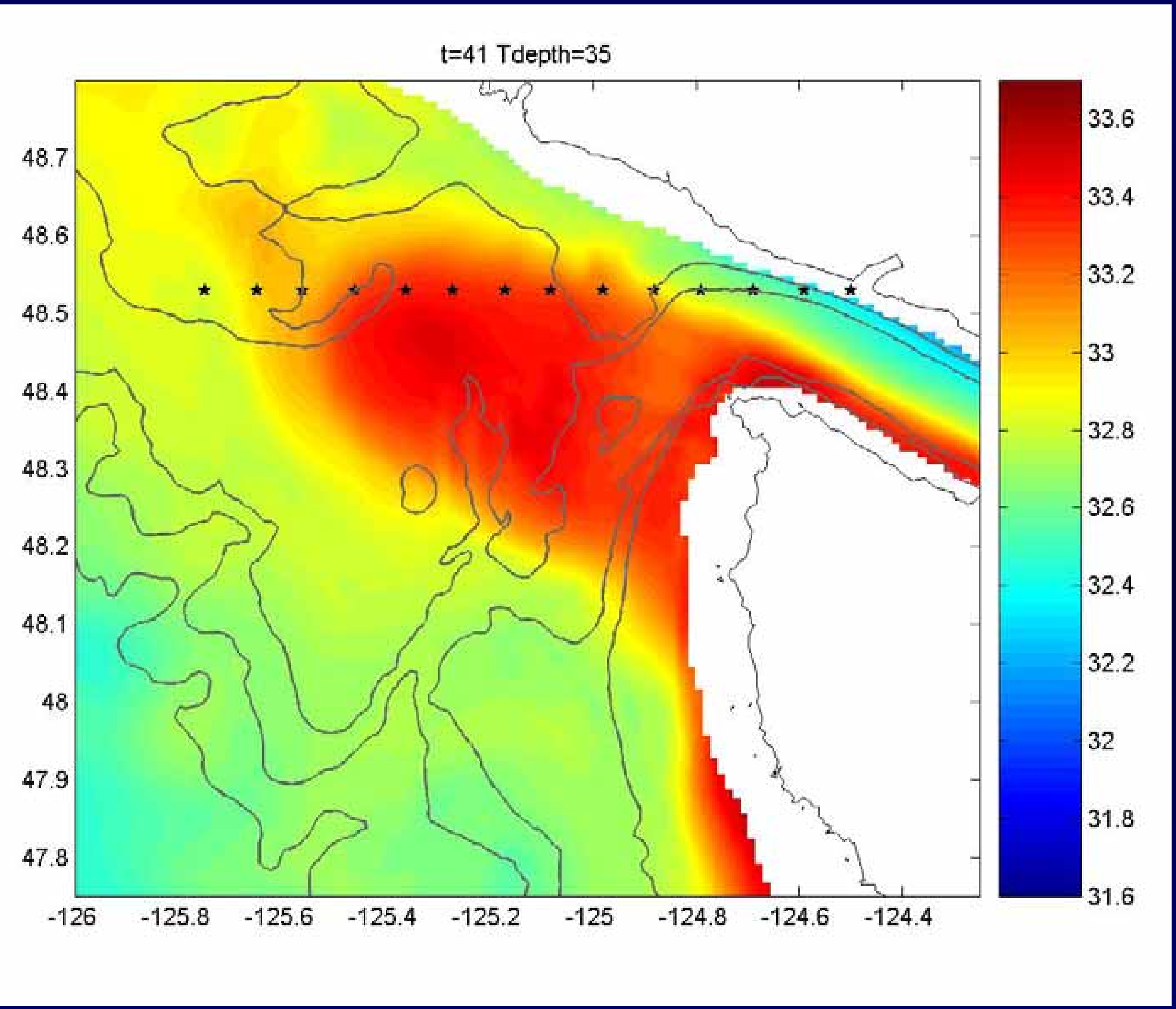
**June 6**



**June 15**

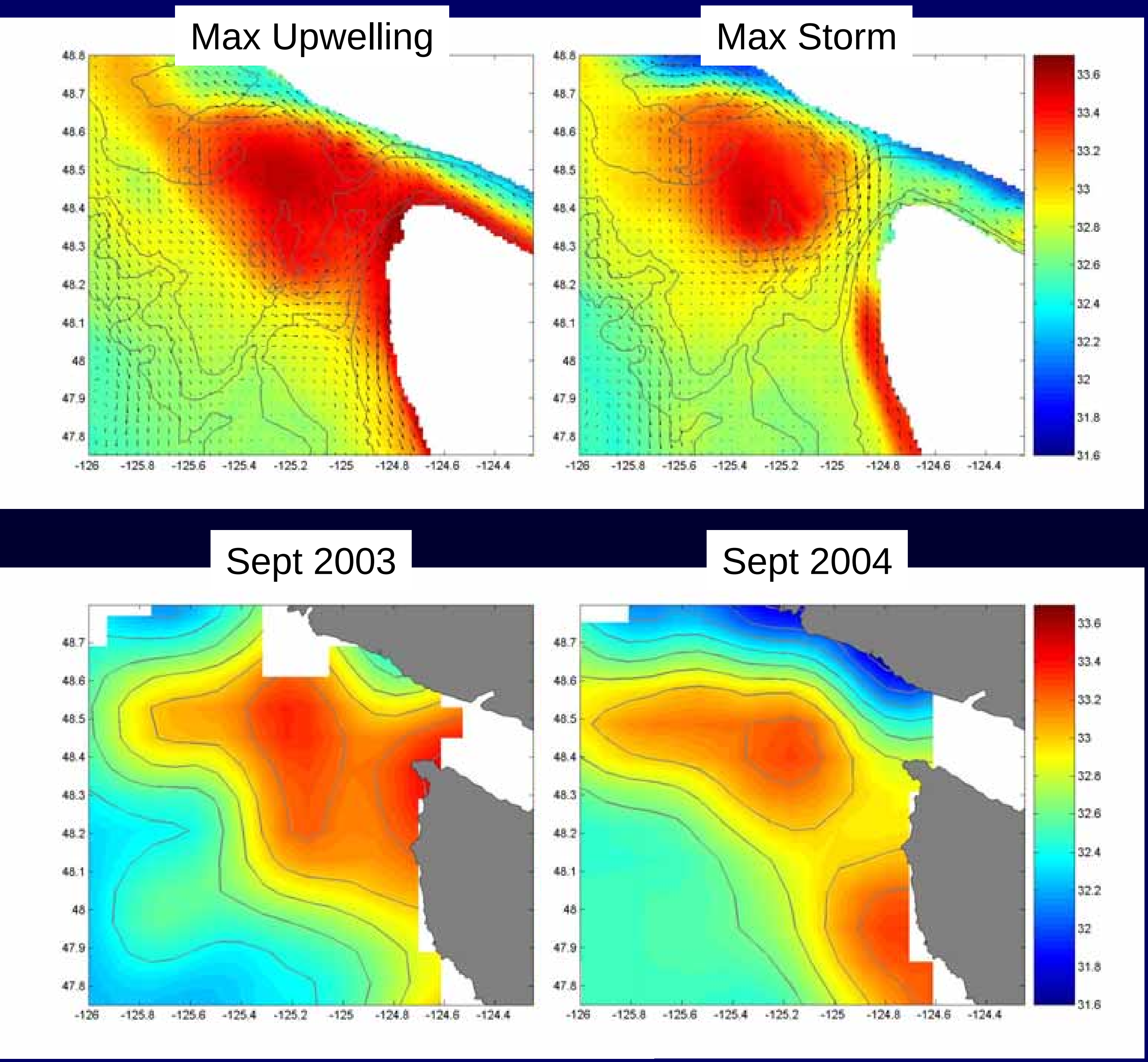
**MERIS images courtesy of Jim Gower & Steph King**

# ROMS Variable Wind Forcing Experiments




- **initialized from 40-day run with average upwelling winds**
- **wind forcing either strong upwelling or storm, ramped up over 5 days, returned to average over next 5 days**
- **near-surface drifters "deployed" in locations shown**

**Salinity at 35m, day 40**




**ROMS**

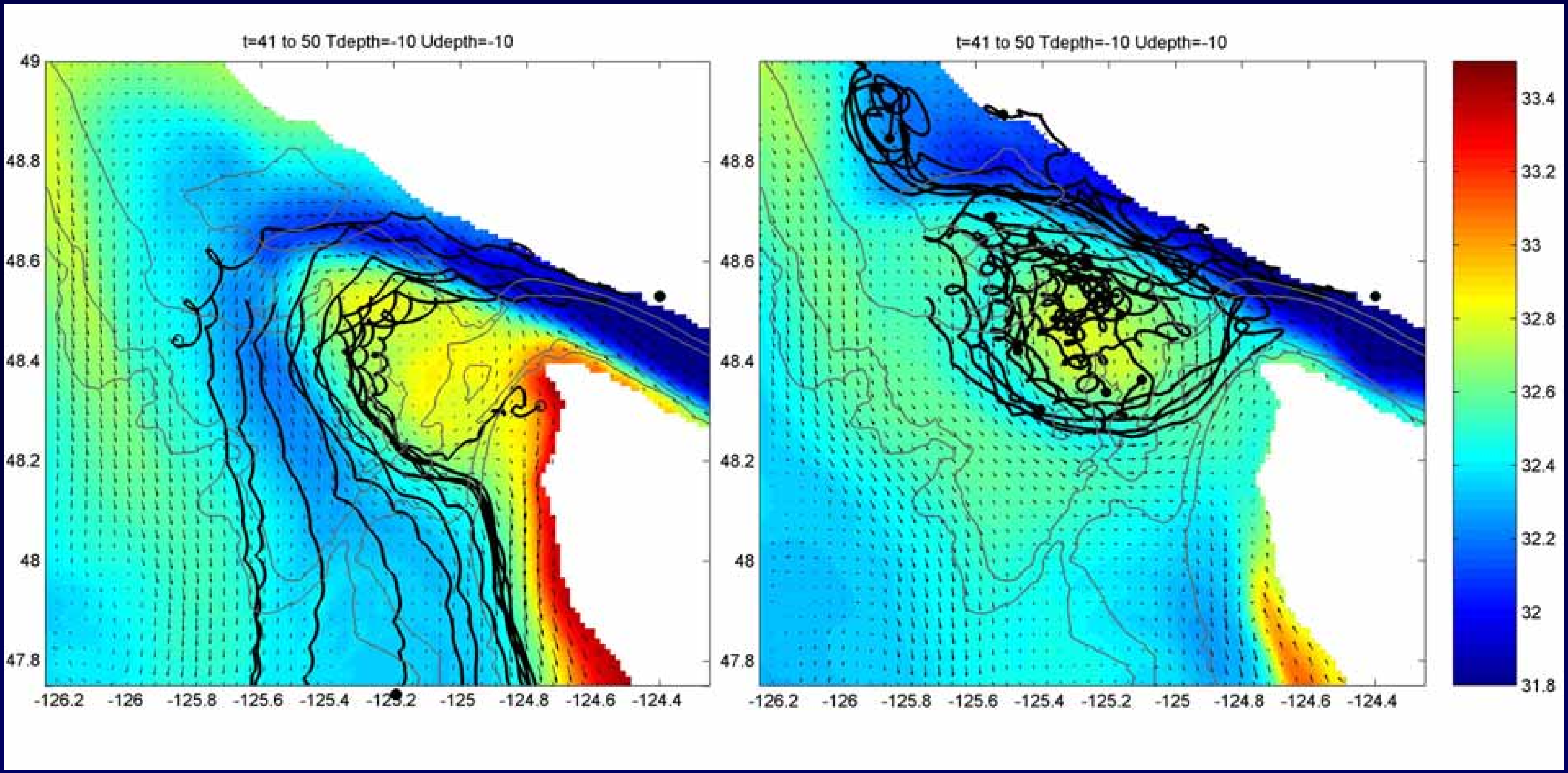
**ECOHAB PNW surveys**

**Salinity at 35 m**

# Transport under Wind-driven Variability

## ROMS run with time varying winds – initialized from 40-d previous run

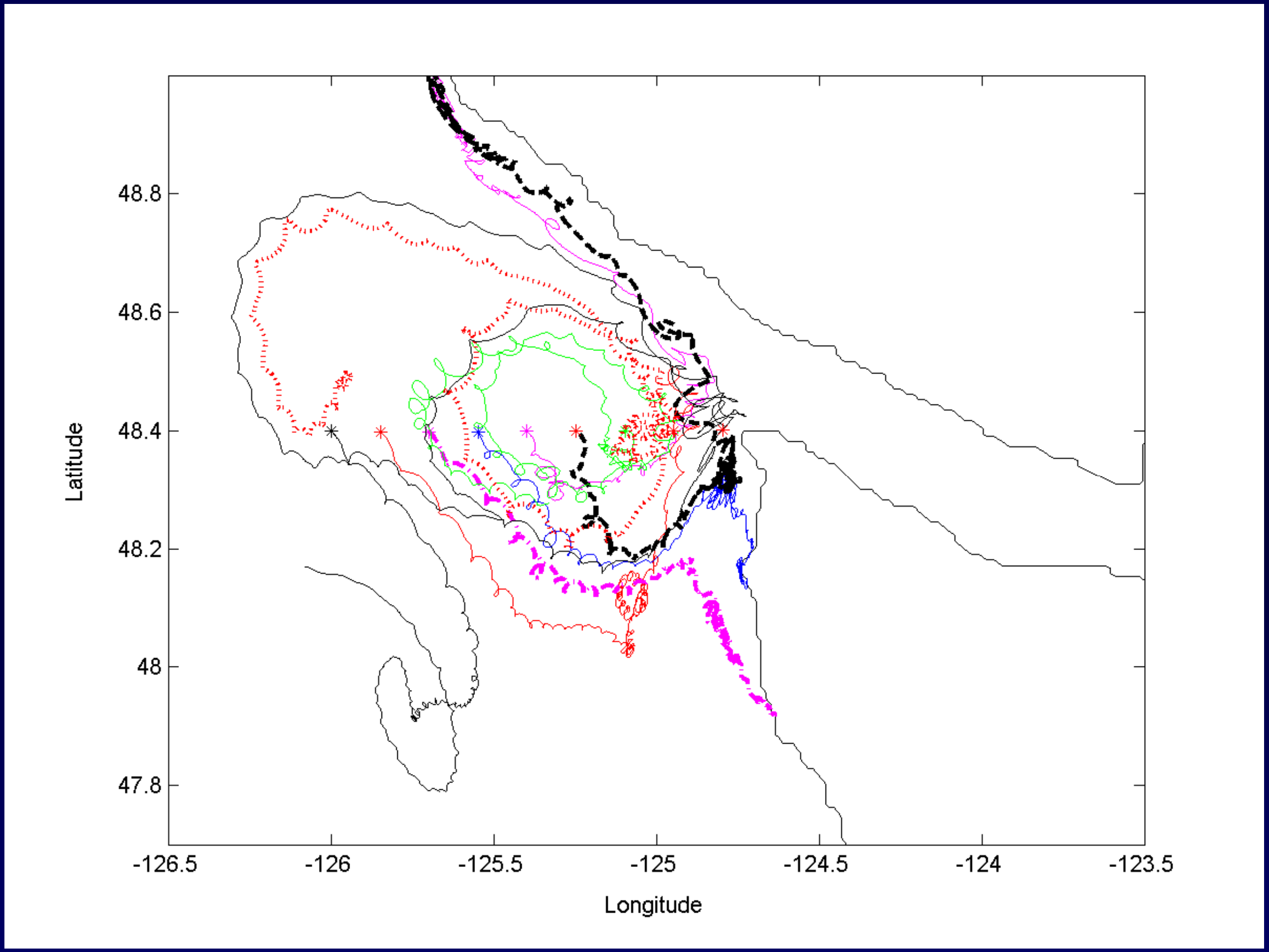
### Average salinity over 10-d period with surface drifter tracks




**Strong upwelling event** **Storm**

# Transport under Wind-driven Variability

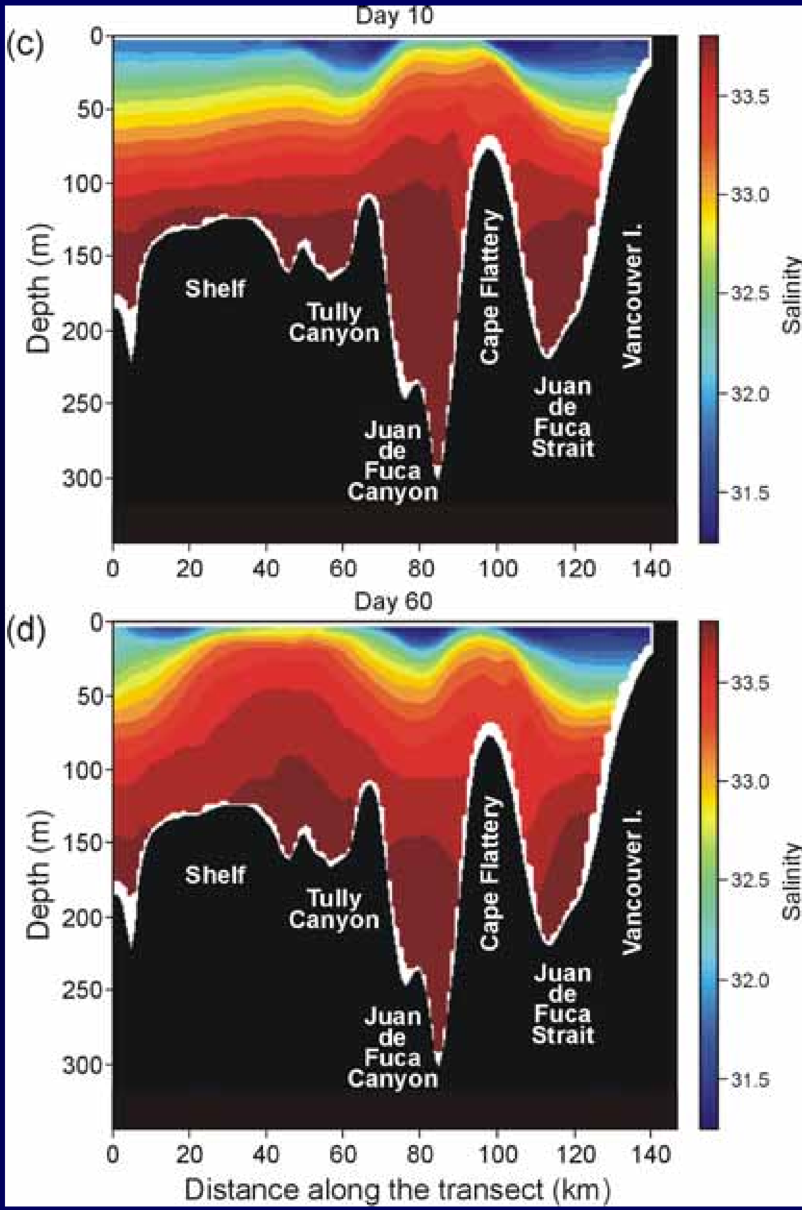
## Mean summer wind (days 1-30), 50 % stronger summer wind (days 31-35), winter wind (days 36-40)




**9 particles released at 35m depth at day 5**

# Summary & Conclusions

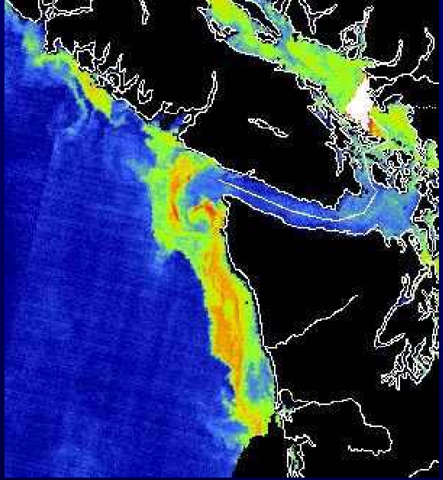
- Model runs suggest Juan de Fuca Eddy is generated by enhanced upwelling off Cape Flattery (Allen, 2000)
- *Not* deep flows up Tully Canyon & onto shelf (Freeland & Denman, 1982)
- *However,* Tully Canyon flows may help sustain eddy after it forms & moves westward

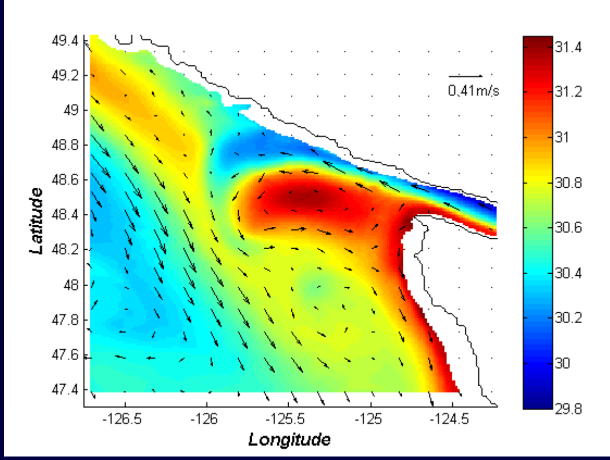


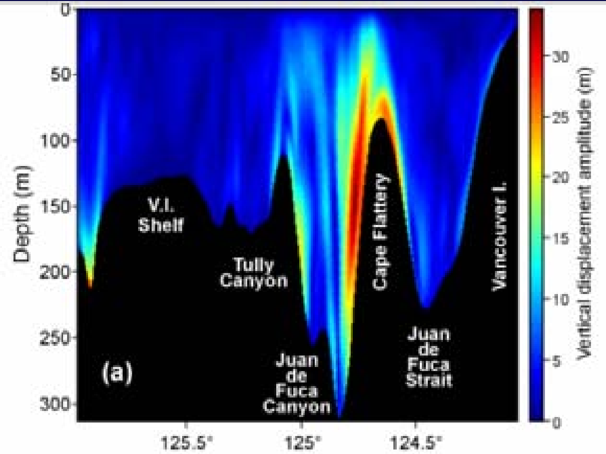

No tides simulation

# Summary (*cont'd*)

- **Reasonable agreement between summer observations & model**
  - ➢ **Confidence in model dynamics**
- **Eddy generated with estuarine flow and upwelling winds &/or tides**
  - ➢ **Key: proximity of dense water to Cape Flattery**
    - ➢ **Bottom estuarine flow in strait & canyon**
- **Tidal upwelling arises in three ways**
  1. **Vertical displacements off Cape Flattery (during flood tides)**
  2. **Vertical tidal residual flows**
  3. **Sloshing across canyon bottom & onto Vancouver Island shelf during ebb tide**
     - ➢ **Internal tides ?**

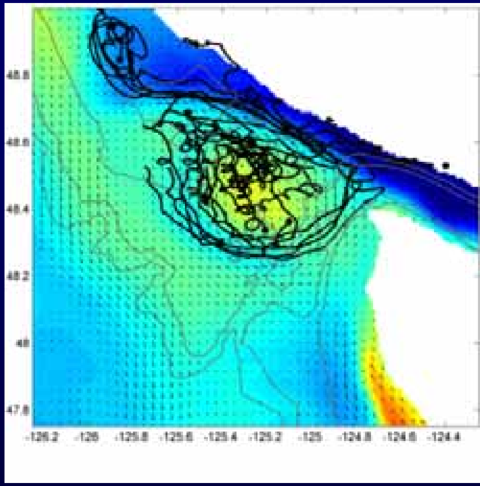


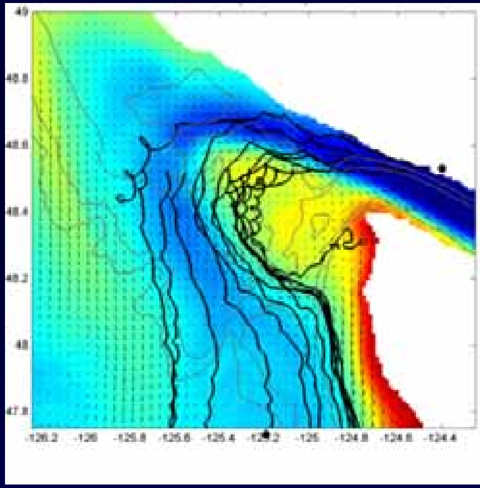


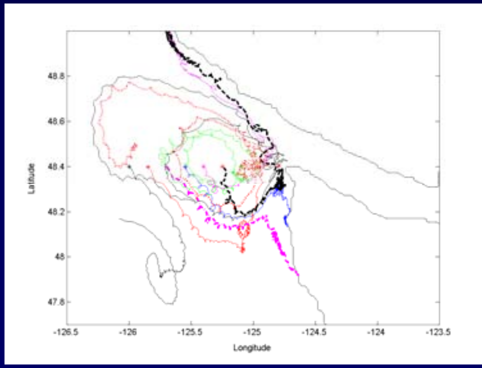



# Summary (*cont'd*)

- **Variations in wind will affect eddy retention and transport**
  - **Storms after average upwelling strengthen retention & push particles northward**
  - **Strong upwelling pushes particles to south**
  - **Strong upwelling followed by storm can push particles to Washington coast & impact shellfish**
- **Climate change & the eddy (FUTURE)**
  - **Still have tides & wind**
  - **Estuarine flow may change**
  - **Upwelled water properties (CUC) may change**
    - **Less productive ?**
  - **More work needed**







# Thanks for your interest!