# The Columbia River Estuary: Structure and Function


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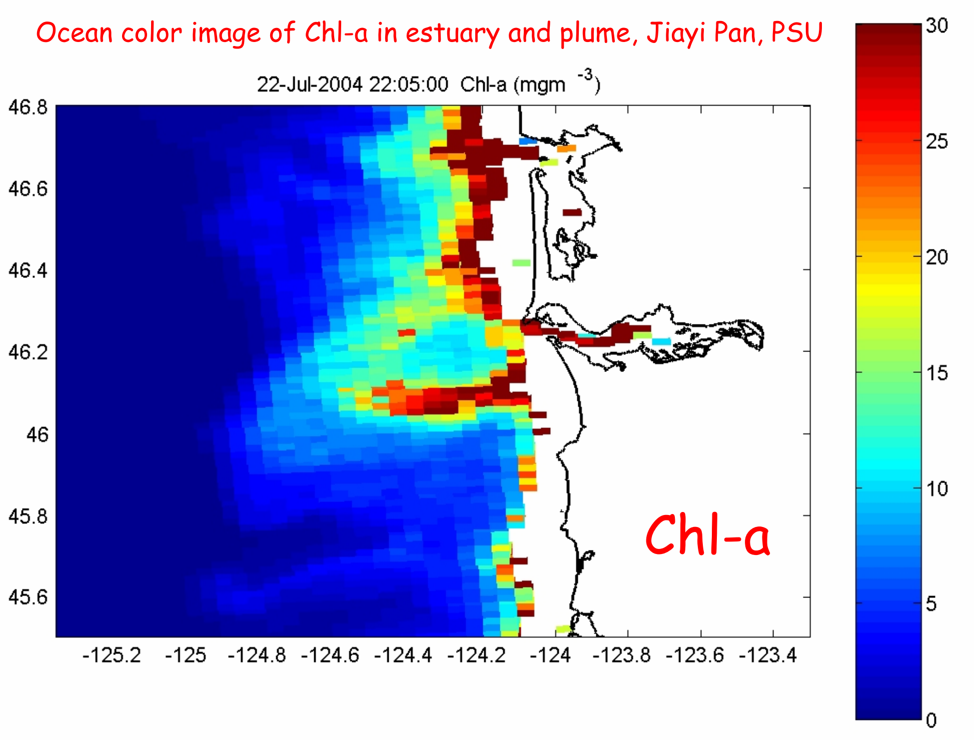


# The CR Estuary – A Conceptual View:

- A river estuary is defined by –
  - Salinity intrusion (~10-60 km in CR)
  - Tides (>200 km, to Bonneville)
  - Coastal mixing zone (the CR inner plume)
  - Adjacent wetlands and floodplain (including historical)

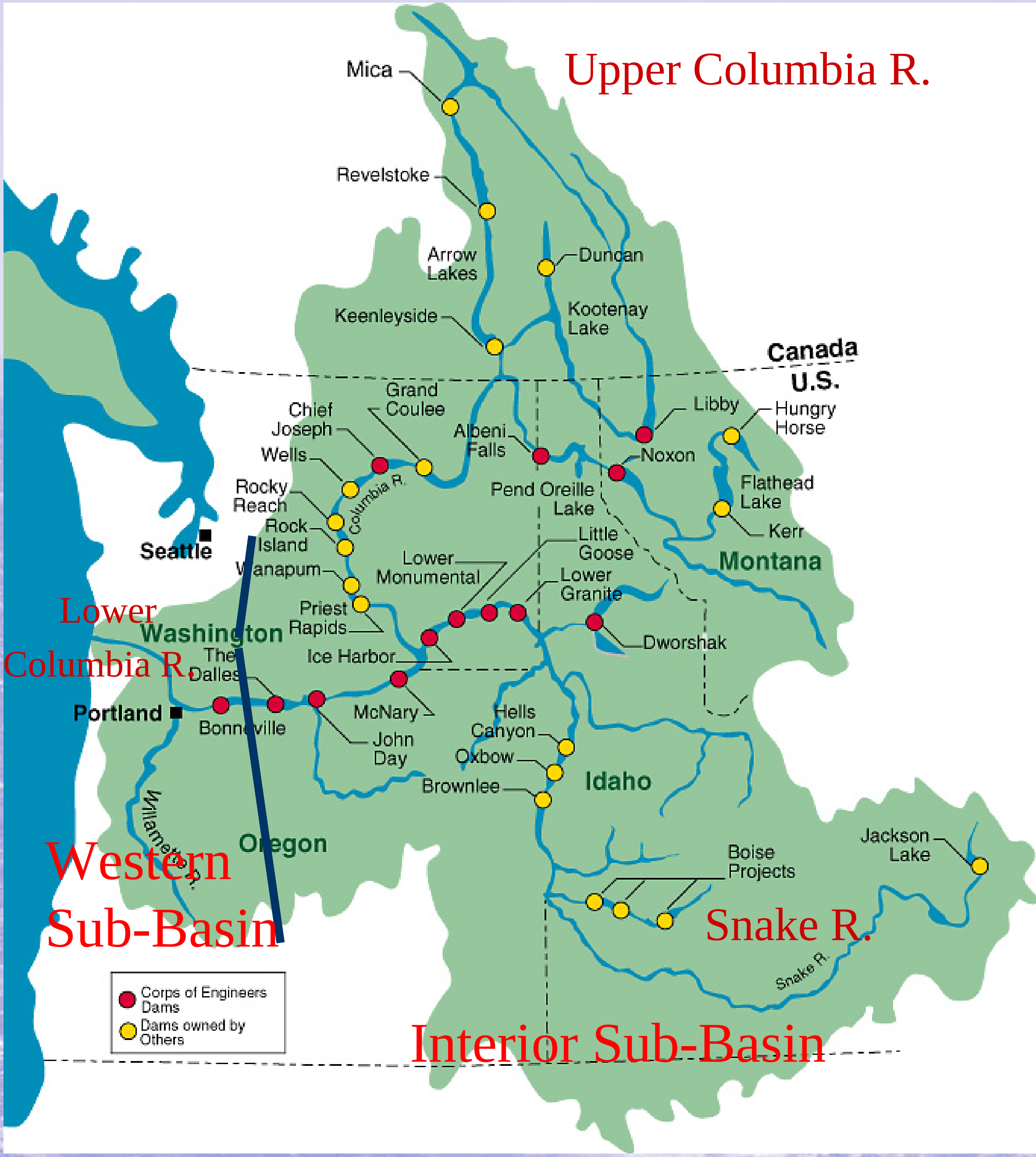
- The main components are:
  - The tidal-fluvial zone (Bonneville to limit of salinity intrusion)
  - The estuary proper (salinity limit to the bar)
  - The inner plume, where most of the mixing takes place

- Have to think about connection to coastal upwelling system, as well

- Today, we will look at the properties of each component

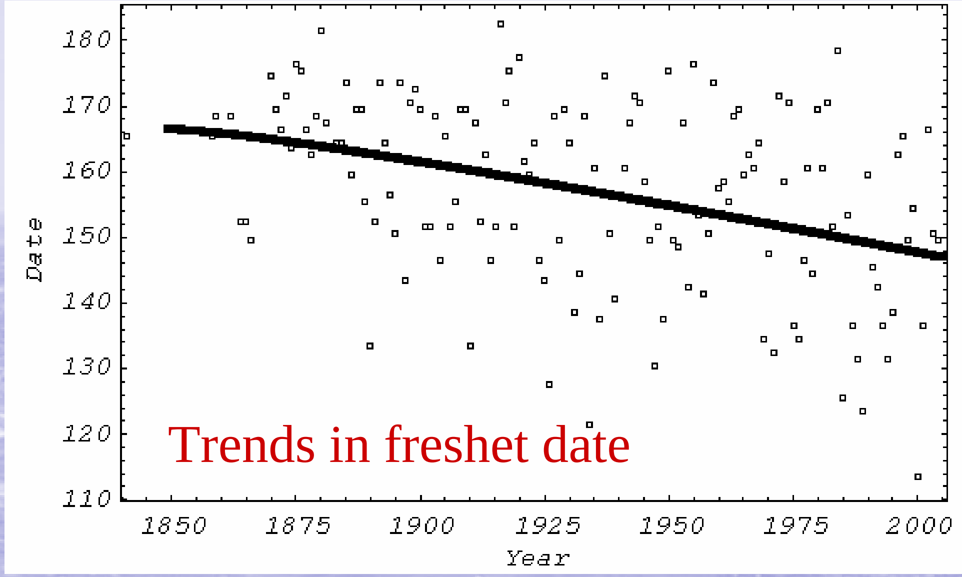
# CR Facts –

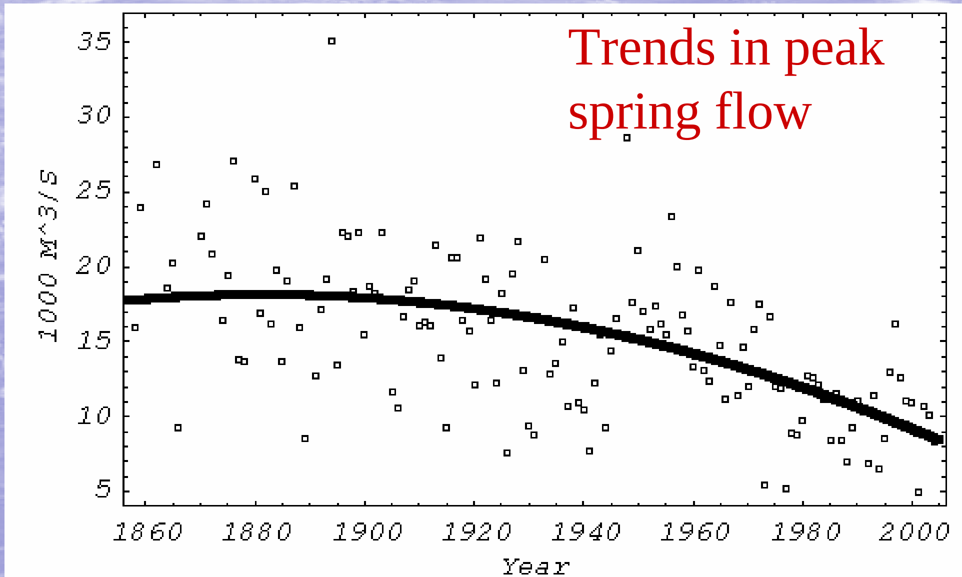
- CR basin: 650,000 km² in 7 states and two provinces
- Has one of the world's most developed hydropower systems
- Average river flow: 7,300 $m^3s^{-1}$ (cubic km in ~12 days)
- Peak flows in spring down to ~60% of natural levels due to dams and irrigation
- Sediment transport down to 30-50% of historic levels



# The CR and Climate Change -

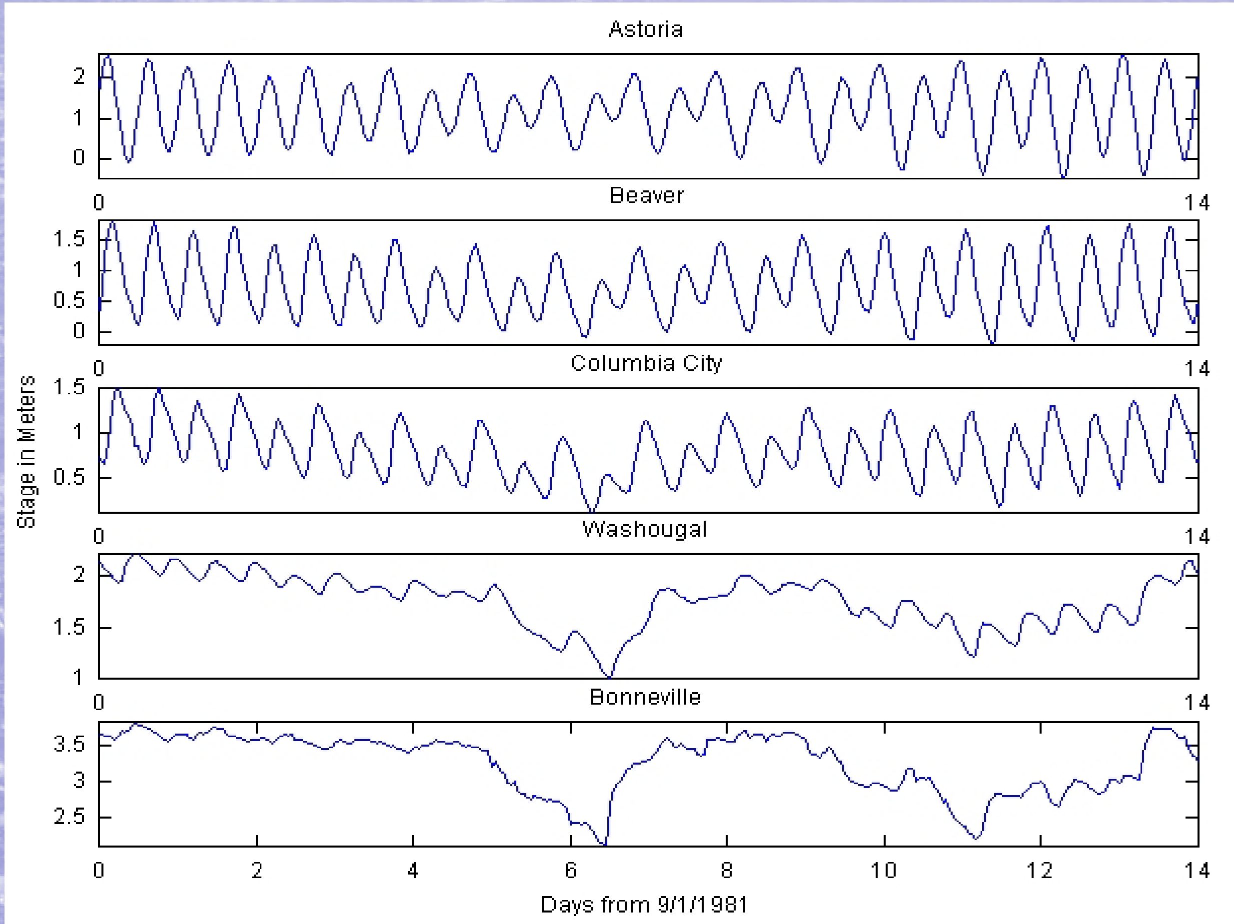
- Spring peak flow has been getting earlier ~150 years
- Rate of temperature rise in the West is predicted to accelerate
- Earlier snow melt (due to climate and deforestation) has and will likely continue to decrease spring flows
- Climate, regulation and irrigation diversion have reduced peak spring flows by a larger amount



# The Tidal River –

CR tides, from the ocean (top) to Bonneville dam (bottom)



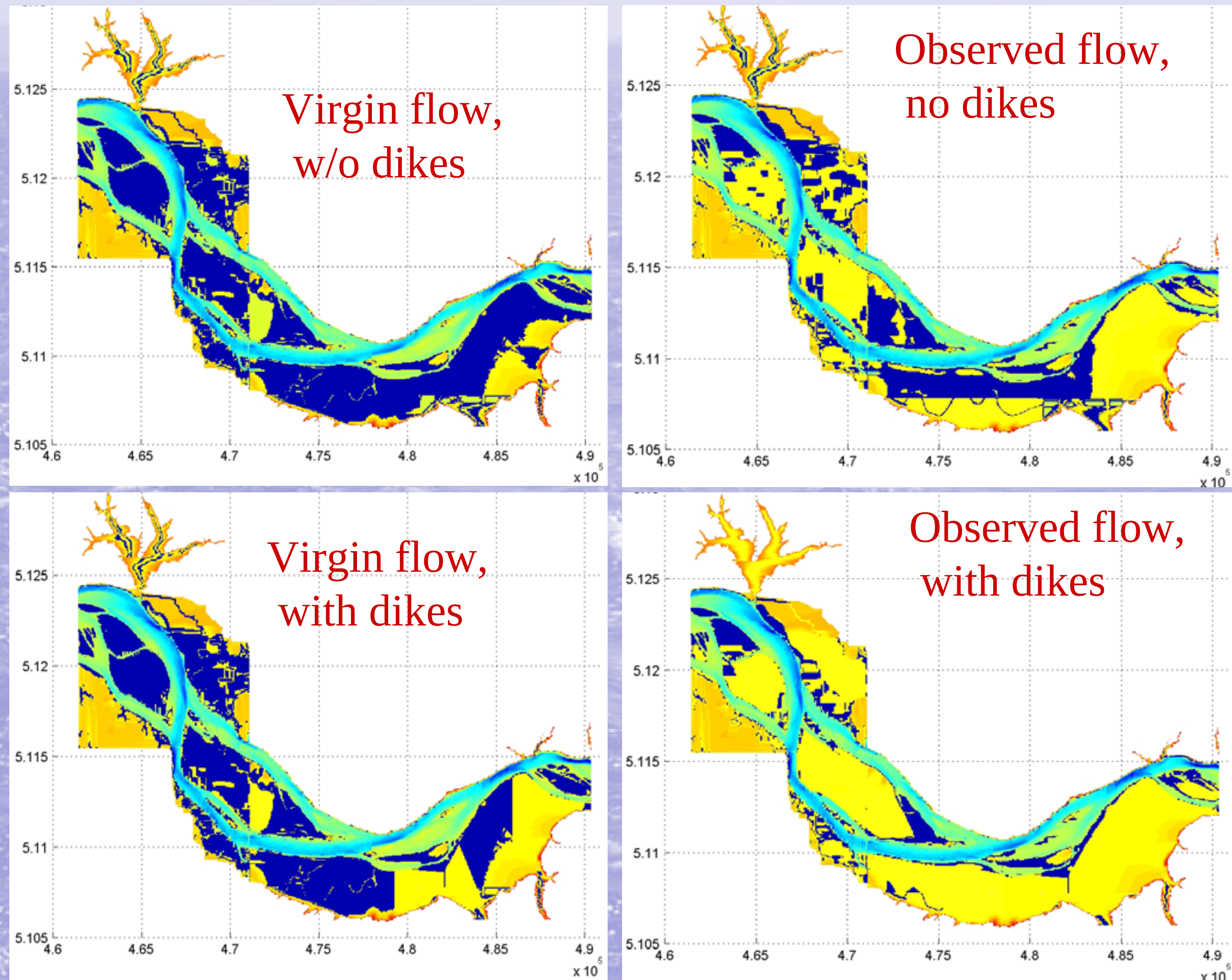

*Plot by Tobias Kukulka*

# Changes in Shallow-Water Habitat (SWHA) 1974-1998 –

- Area AND duration of SWHA decreased
- Virgin flow provides much more SWHA for a longer period
- Dikes account for more loss of habitat than loss of flow
- SWHA model is now being updated for larger area, better topopgraphy and historical changes in tides

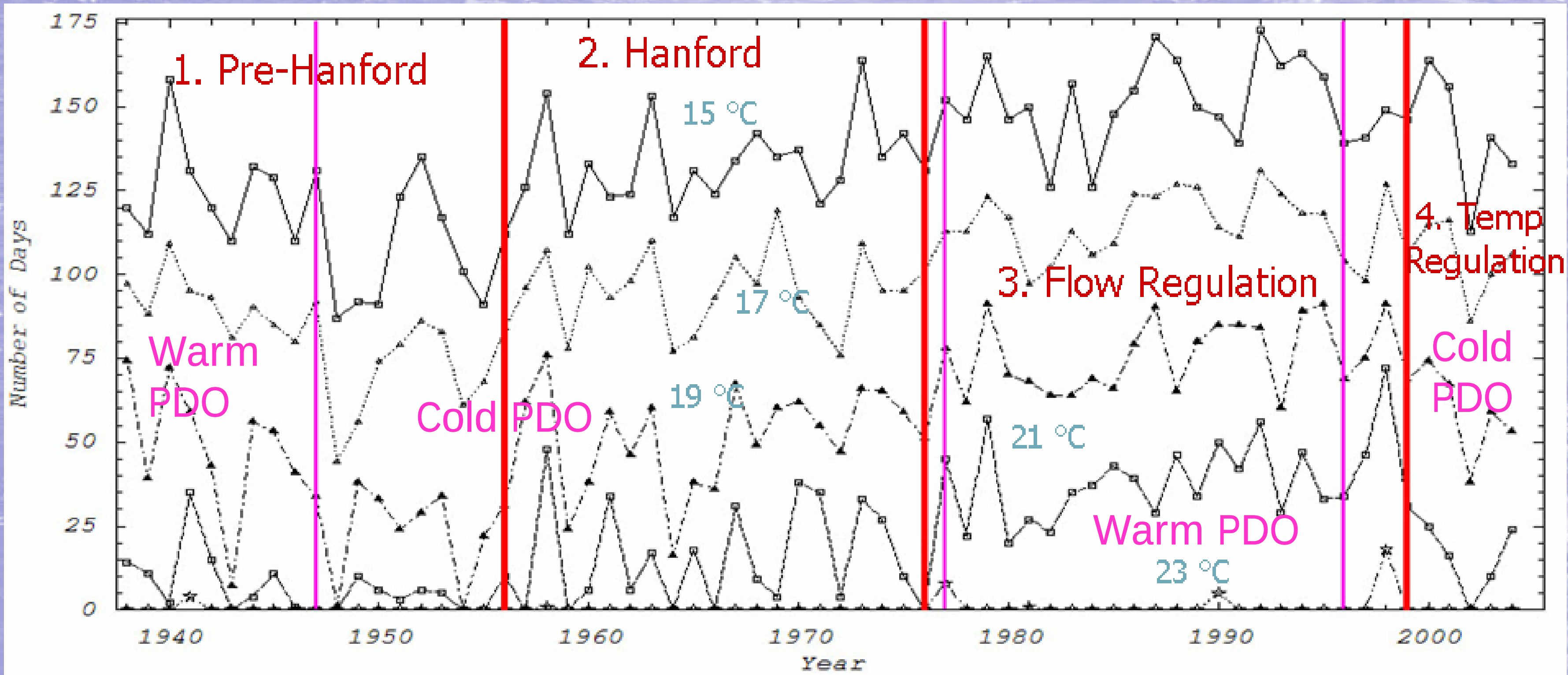
1974 Inundation

Dark blue = floodplain inundation
Yellow = dry area

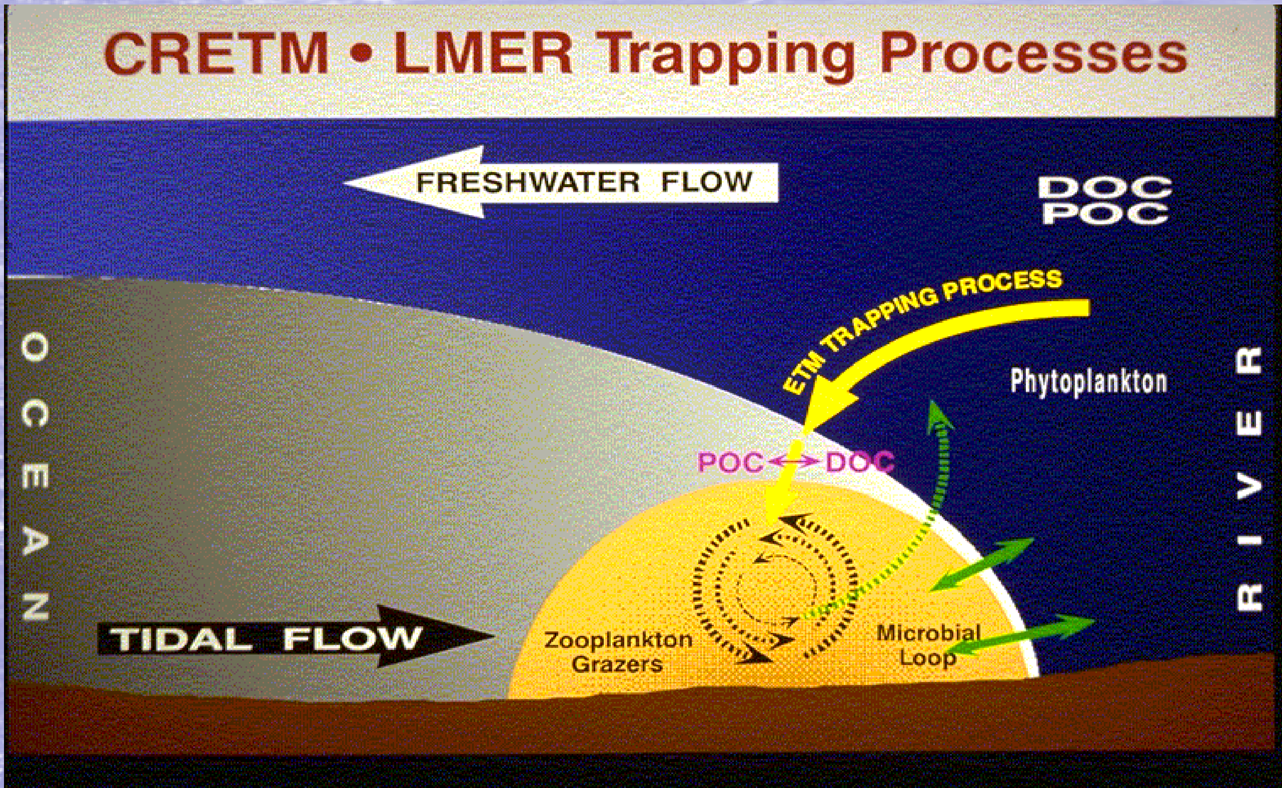


# Changes in CR Water Temperature –

- Water temps were high due to Hanford bomb factories 1956-1976
- Continued to increase due to reservoirs after 1976
- Improved reservoir management has caused some improvement since 199



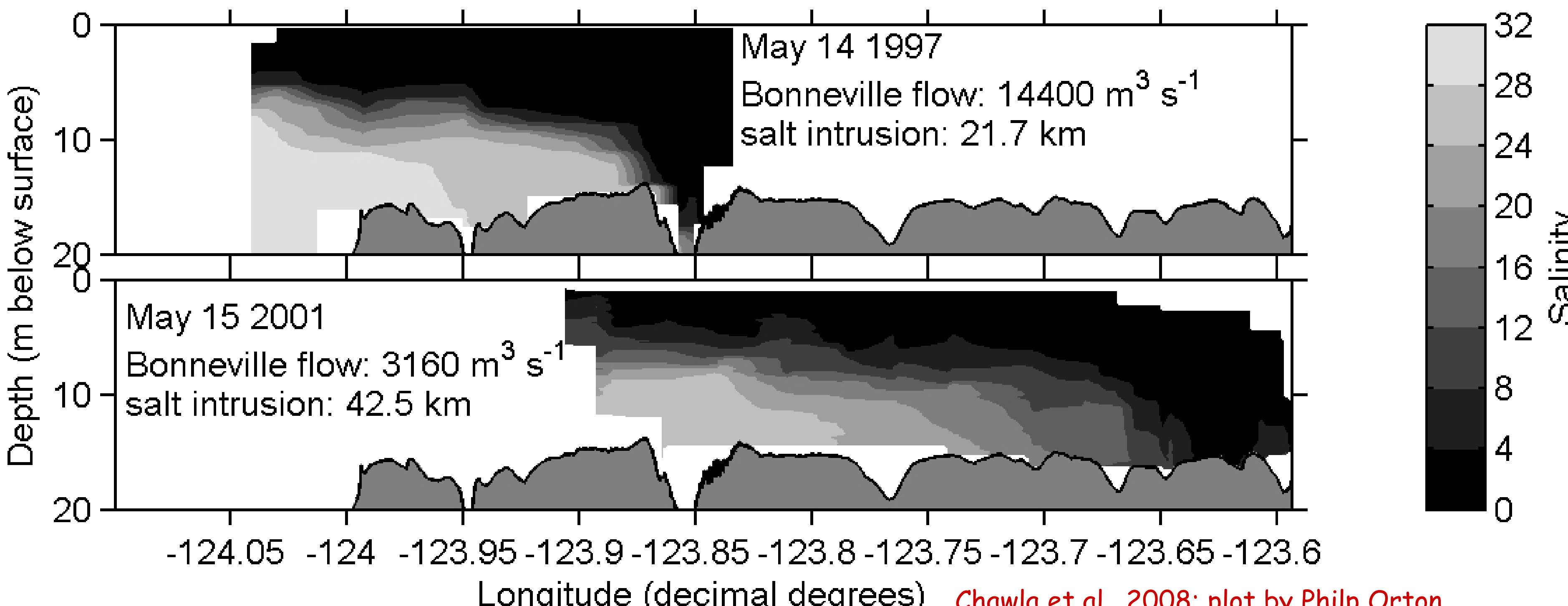
# *The Estuary -*




Schematic of CR estuarine turbidity maximum, by Si Simenstad

# Estuarine Salinity Intrusion –

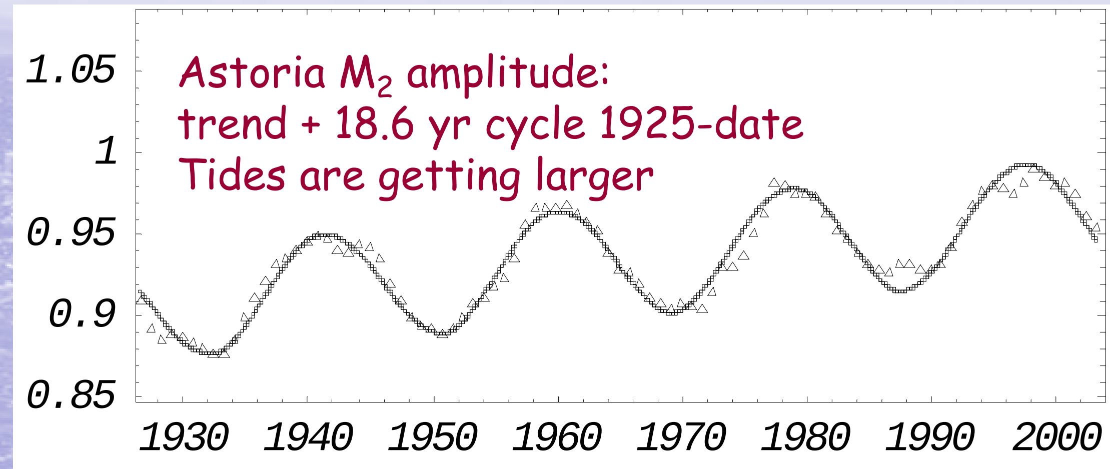
- Varies with ~the 1/square root of flow $Q_R$
- Spring tides cause more mixing and less salinity intrusion at depth, but higher salinities at the surface
- Upwelling/downwelling and winds affect salinity intrusion in subtle ways

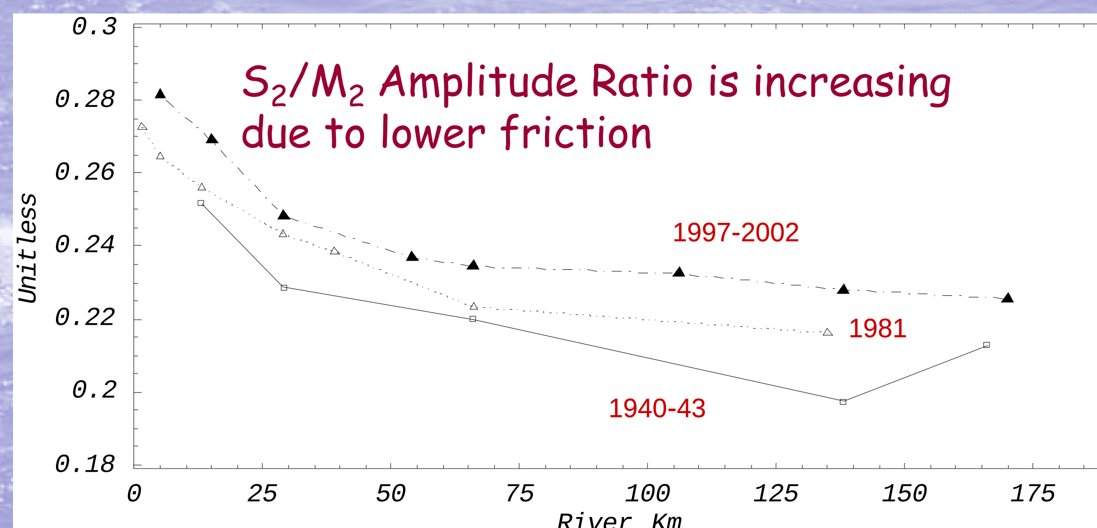



Chawla et al., 2008; plot by Philp Orton

# Estuarine Tides –

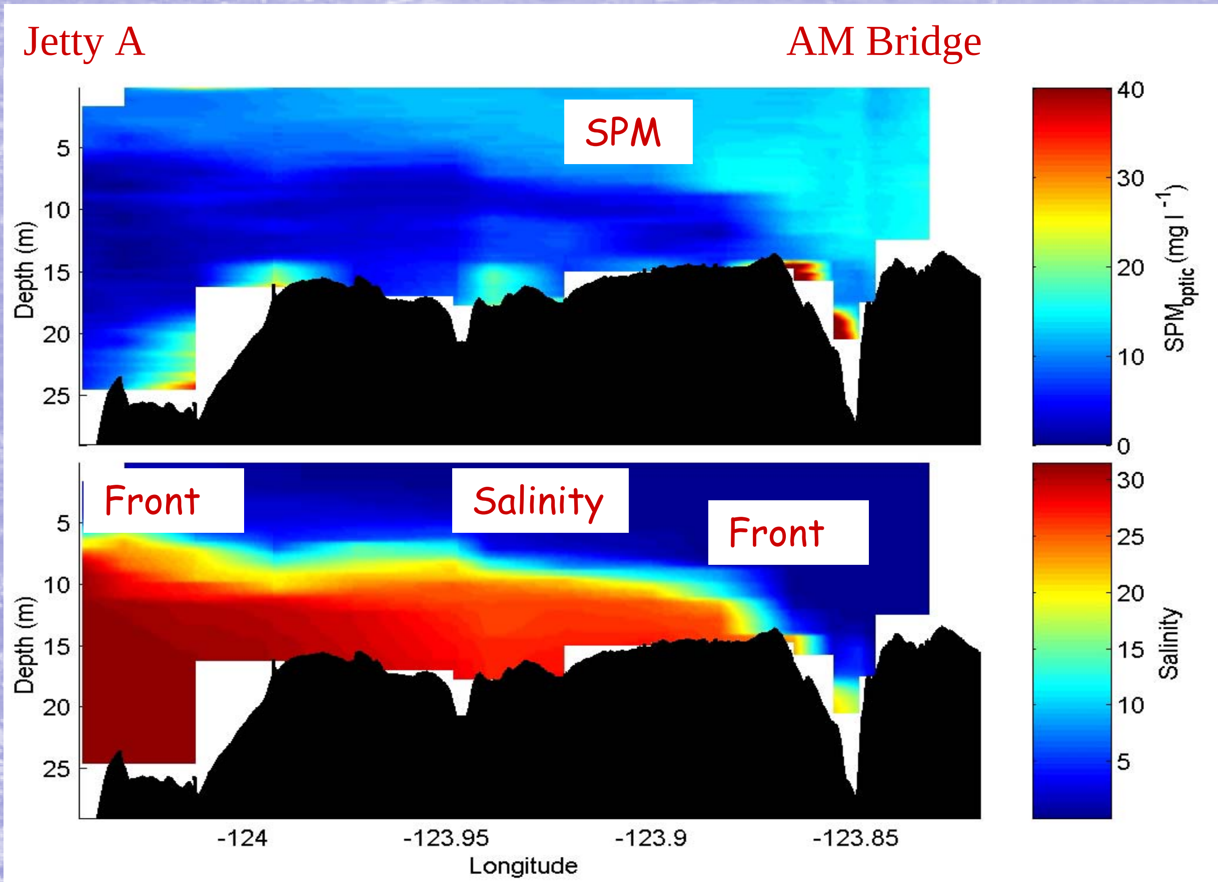
- Tidal range is increasing in Astoria (and upriver) due to:
  - Increased ocean tides along coast
  - Reduced friction in river (better alignment, deeper channels, lower river flows)
  - Increased bottom depths at entrance and (probably) upriver
- Astoria range is increasing at ~1 ft (30+ cm) per 100 years



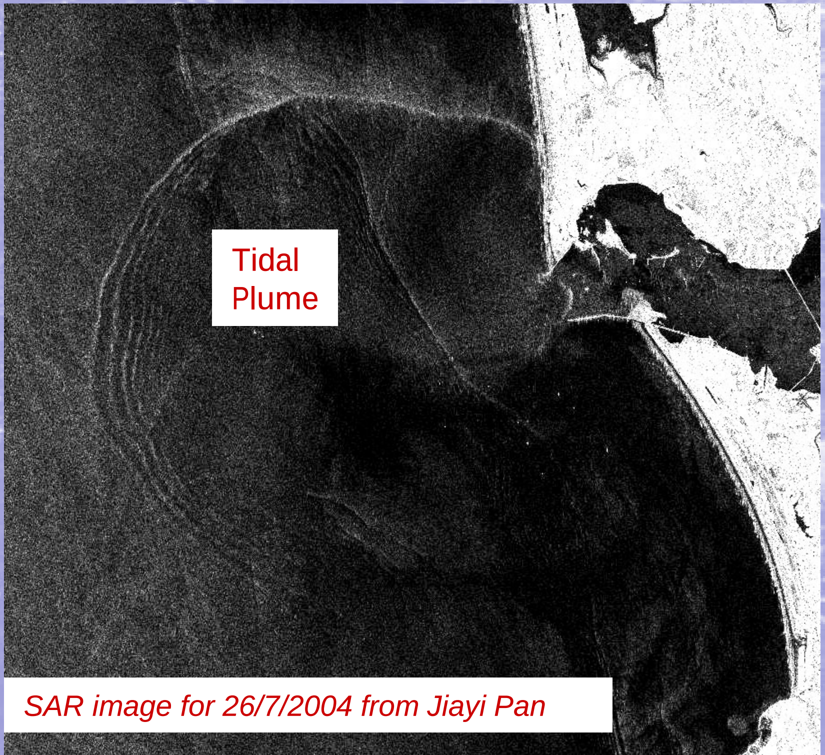



# Estuarine Anatomy and Sediment Trapping –

- The estuary is defined by density fronts on both ends:
  - Plume lift-off fronts at bar
  - Upstream limits of salinity intrusion
  - ETM can occur both places; landward ETM is the important one
- Sand is only exported when fronts are compressed together during high flows (zero-length estuary)
- Estuary traps SPM for weeks to months



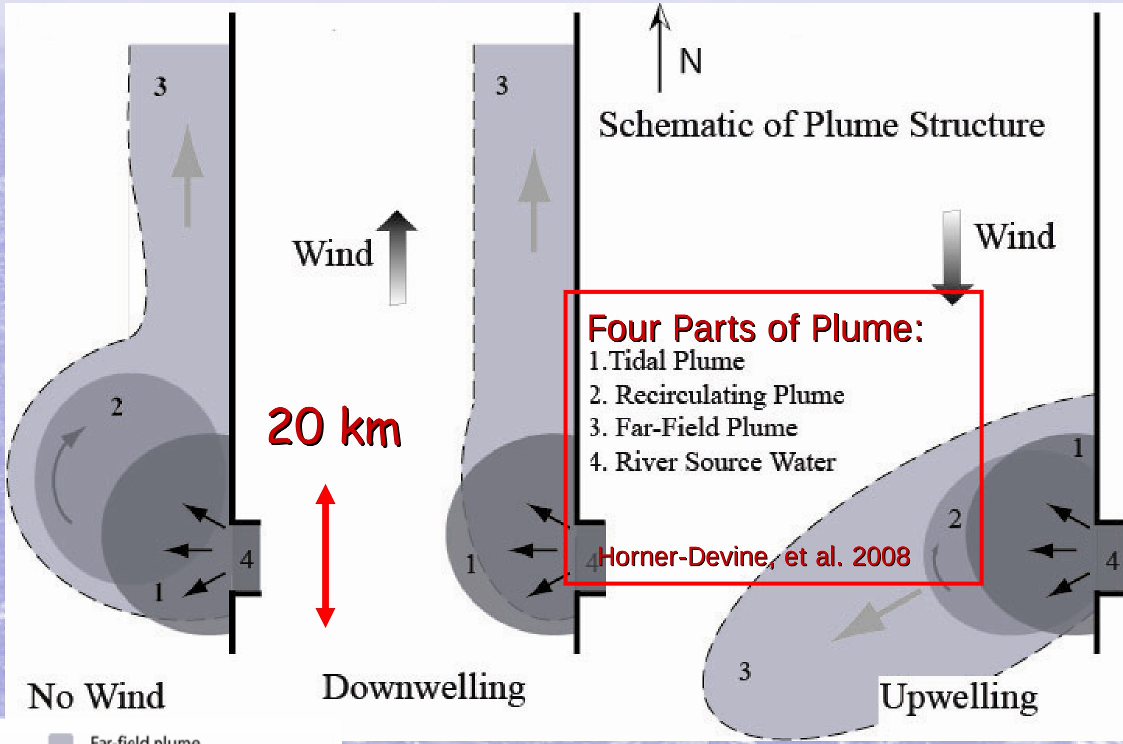
# The CR Plume and Regional Context –

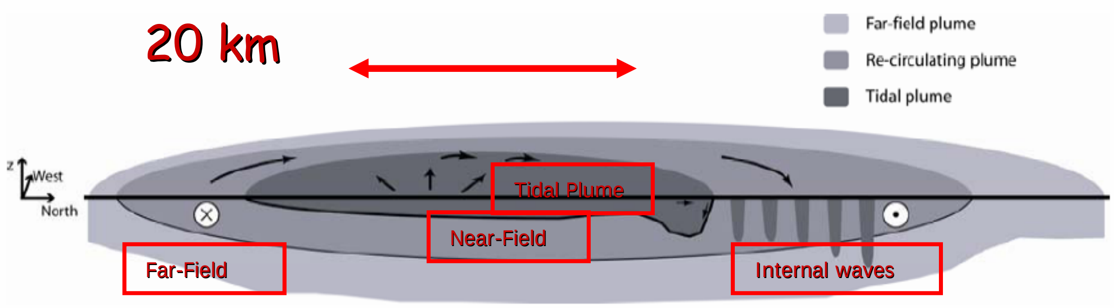



*SAR image for 26/7/2004 from Jiayi Pan*

# Plume Anatomy –

- Plume lift-off (4) occurs at the bar
- Strong fronts and internal waves come from "tidal plume" (1) – the initial expansion of outflow for first 6-12 hrs
  - Tidal plume fronts and internal waves communicate with rest of plume
- Near-field (2) is a rotating
- bulge with 2-4 days water
- Far-field (3) is the rest of the recent plume discharge
- Plume components (1), (2) & (4) are also effectively part of the estuary
- Plume motion strongly affected by the winds



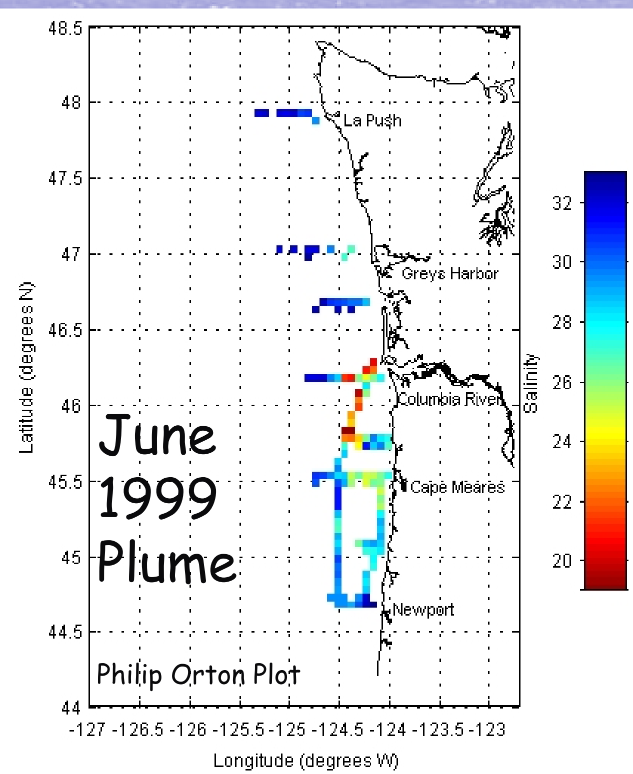




The Plume layer cake

Horner-Devine, et al. 2008

# CR Plume Changes, 1961 vs. 1999 –

- Plume is vital to coastal production
- CR spring flow is down >40% due to flow regulation, irrigation
- 1999 plume volume was only ~65% of that in 1961, even though the natural flows were very similar
- We know that plume habitat area has been reduced, but we don't know about habitat quality, or if lost plume habitat is limiting




June 1961 Plume

from Barnes et al., 1972

# What do we Still Need to Learn – ?

- Sediment budget: supply, export, changes in bathymetry, topography and processes
- How is the estuary proper changing? salinity intrusion, temperature, ETM processes, SPM retention
- How is climate affecting interaction of river, estuary, plume and coastal circulation? flows are earlier, but upwelling is starting (maybe) a bit later
- We know very little about the interactions of main estuarine channels with peripheral areas
- System geochemistry – e.g., changes in micronutrients related to dams

# Summary –

- The estuary includes the tidal river, estuary proper, and inner plume
- These components affect one another, with influences going both directions:
  - Landward (tides, upwelling/downwelling effects, sediment from ocean), and
  - Seaward (flow, plume internal waves, sediment)
- Tides are getting larger in the tidal river and habitat has been much reduced
- Increased flow and larger tides reduce salinity intrusion to estuary
- The plume interacts strongly with upwelling ecosystem and augments coastal production

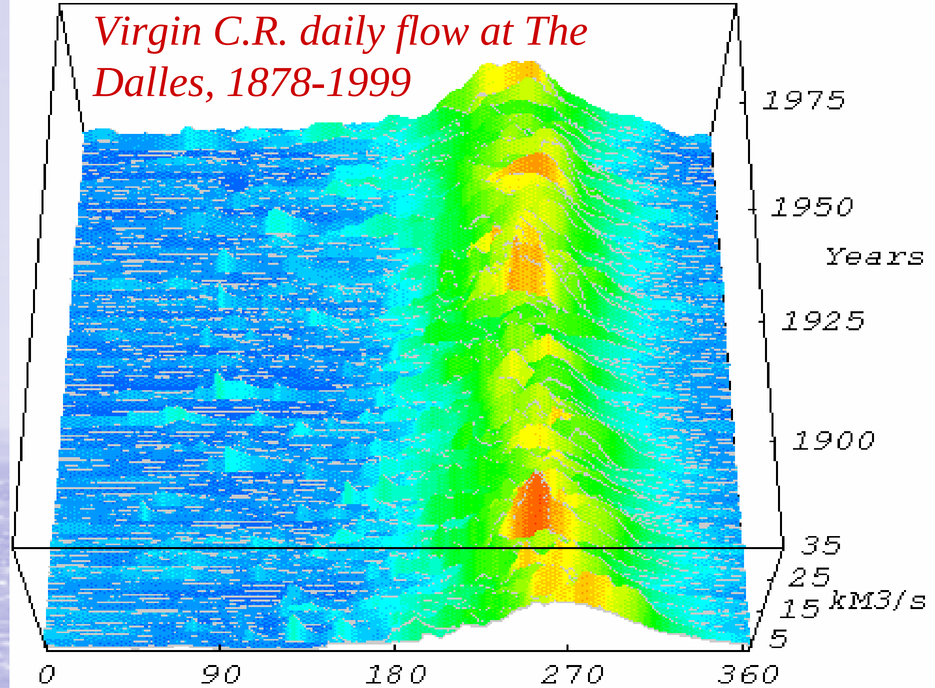
*I do not know much about gods; but I think that the river*
*is a strong brown god – sullen, untamed and intractable,*
*Patient to some degree, at first recognised as a frontier;*
*Useful, untrustworthy, as a conveyor of commerce;*
*Then only a problem confronting the builder of bridges.*
*The problem once solved, the brown god is almost forgetten*
*by the dwellers in cities—ever, however, implacable,*
*Keeping his seasons and rages, destroyer, reminder*
*Of what men choose to forget.*

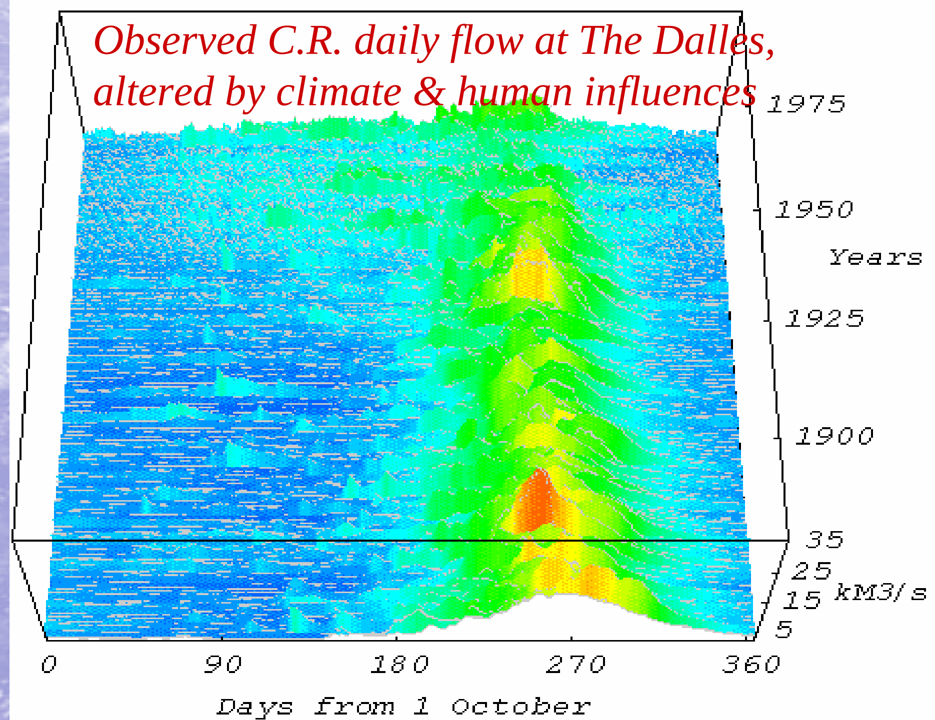
T. S. Eliot – Four Quartets

# Extra Slides

# Changes in CR Hydrology –

- Average flow $Q_R$ down -15% since 1900; irrigation+evaporation: -8%, climate change: -7-9%; de-forestation +1-2%
- Peak $Q_R$ down >40%, mostly hydropower, flood control
- Impacts on river and estuary:
  - Freshet lasts longer and starts earlier due to pre-release
  - Increased estuarine salinity intrusion, decreased salmon habitat
  - Decreased turbidity in spring, less annual estuarine productivity(?)

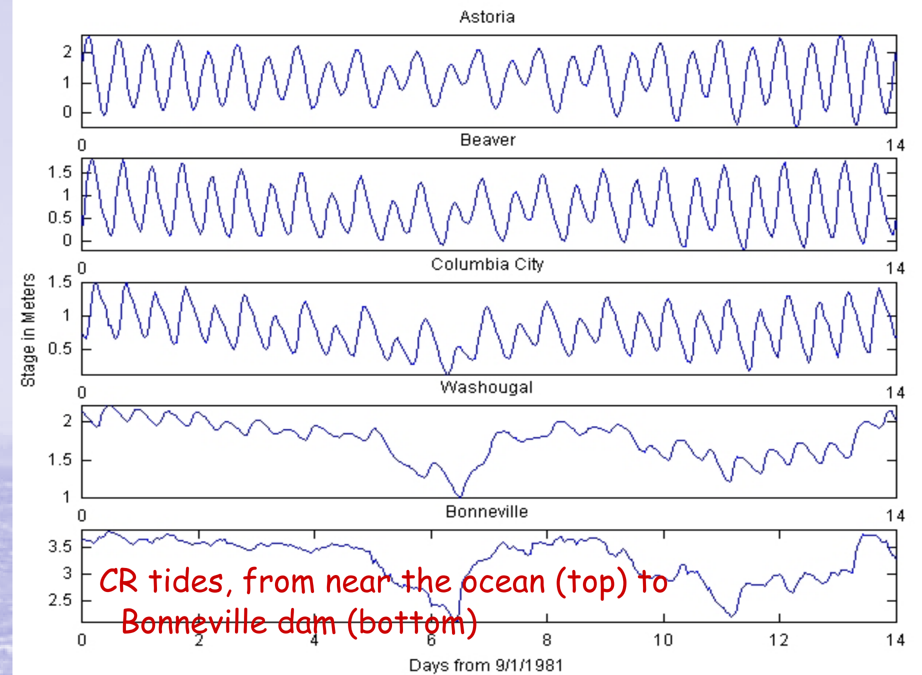


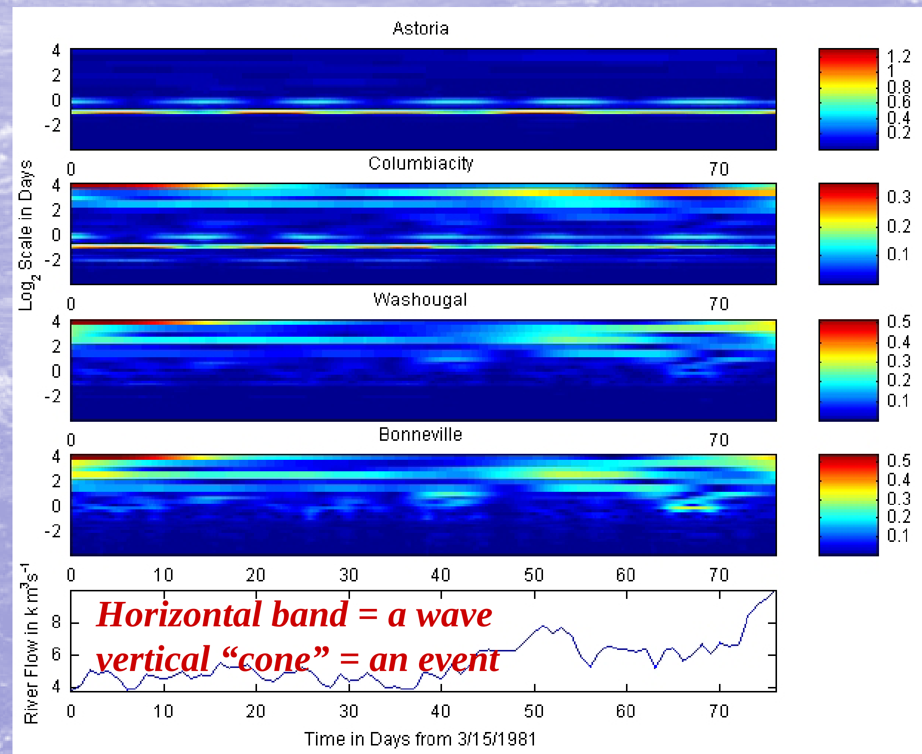




"Virgin flow" is the flow that would have occurred without dams and irrigation. "Observed flow" is measured by USGS

# River Tides –

- Governed by geometry, friction, wave steepening
- Tide propagates upriver; power-peaking (pseudo-tide) propagates to ocean
- Friction damps tides; $Q_R$ increases damping
- Tidal range ~$1/Q_R$
- Ocean tide is mostly semidiurnal, some diurnal
- Power peaking has irregular diurnal and weekly cycles, also damps tides
- Tides are non-stationary on a variety of time scales

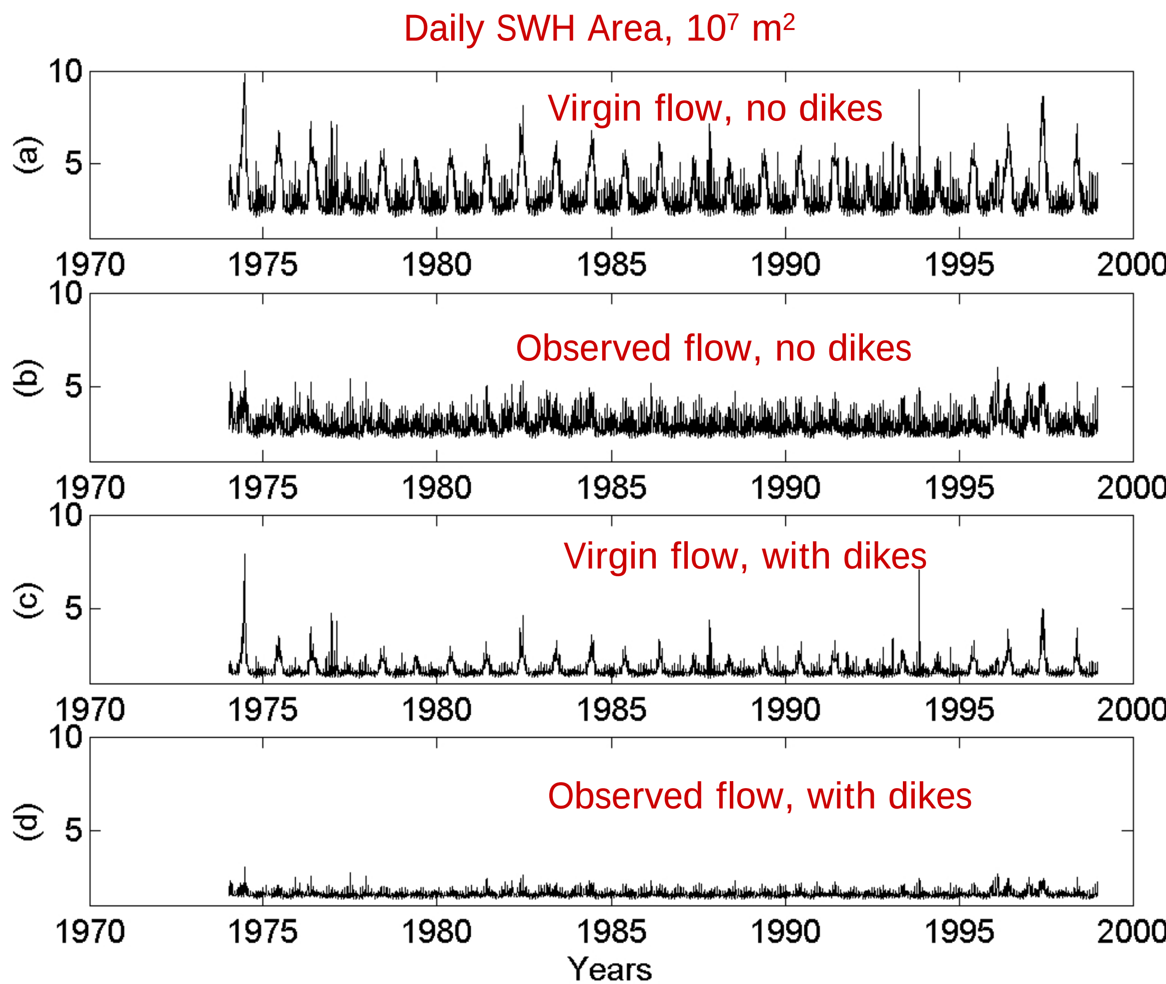


# Changes in SWHA, 1974 to 1998 –

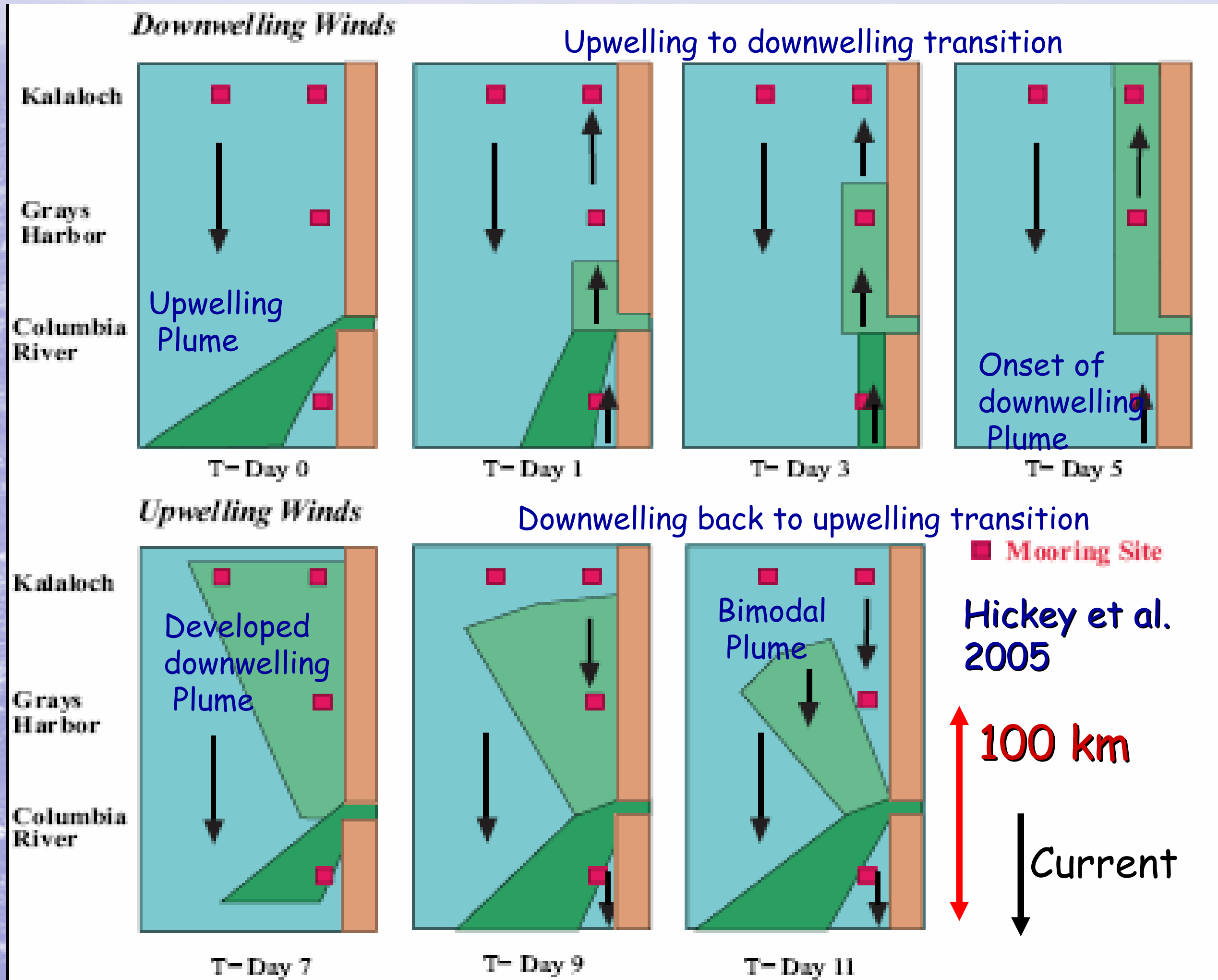
- Area AND duration of SWHA have decreased
- Virgin flow provides much more SWHA for a longer period
- Dikes account for more loss of habitat than loss of flow
- River flow damps tides; remaining habitat is more strongly tidal
- Simple models allow analysis of changes over long periods!
- Supplement with numerical models for details

| 1974 to 1998 Average SWHA, $10^7$ $m^2$ | Freshet Season (May to July) | Rest of Year (Aug. to April) |
|---|---|---|
| a) Virgin flow, no dikes | 4.5 | 3.0 |
| b) Observed flow, no dikes | 3.2 | 2.9 |
| c) Virgin flow with dikes | 2.2 | 1.6 |
| d) Observed flow, with dikes | 1.7 | 1.6 |



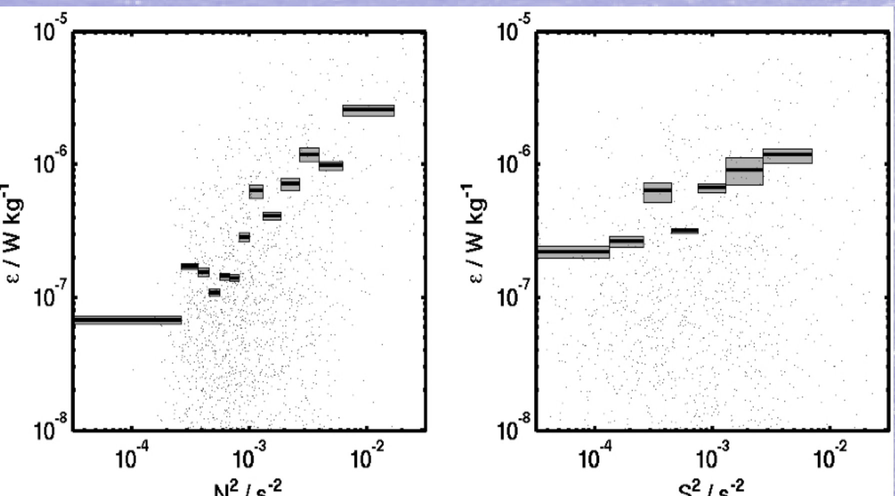
# Regional Response of CR Plume –

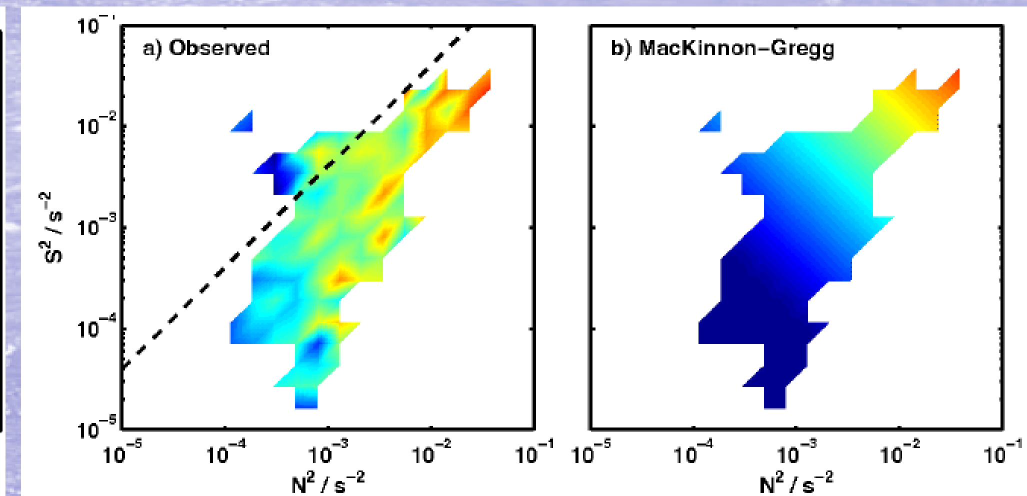
- Upwelling and downwelling alternate on weather time scales (~3-10 d)
- Plume water residence time >10 d, bi-directional plume is the result
- Sets background for tidal plume properties
- Upwelling winds are from the North
- Downwelling winds are from the South
- Upwelling winds in summer bring nutrients to the surface
- Plume interacts strongly with the upwelling ecosystem



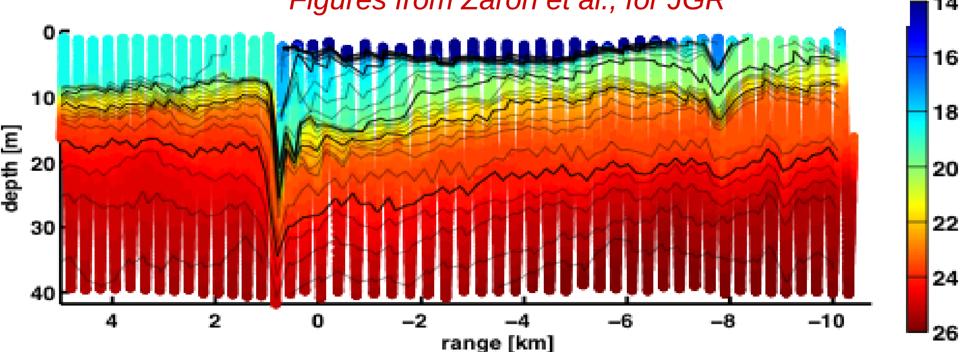
# Plume Front Anatomy and Mixing –

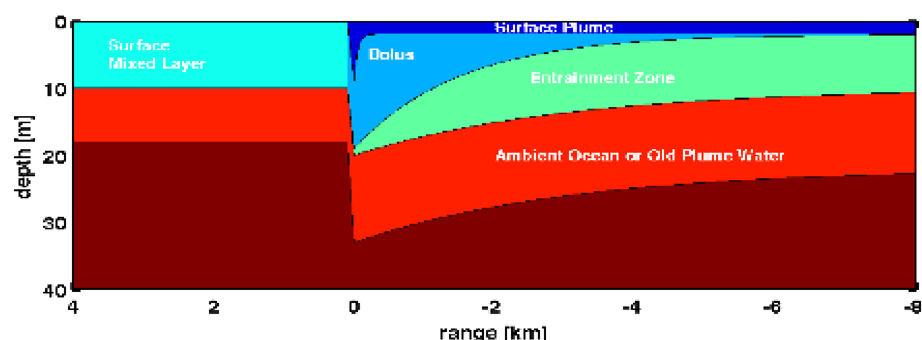
- Mixing analysis suggests:
  – Plume anatomy from mixing analysis is more complex than the earlier four-part structure
  – Paradox of mixing – strongest mixing is in areas of high shear AND stratification (like fronts and IW) – not predicted by $Ri_g$
  – Mixing involves interactions between small IW,shear and turbulence




*Figures from Zaron et al., for JGR*



# Mixing Nutrients to the Surface –

- Nutrients at surface are vital for productivity
- Just because there is strong mixing of salt into plume, doesn't mean that Nitrate (N) and other nutrients are mixed
- Mixing of N to surface is most likely during upwelling
- Confusing transition from upwelling to downwelling – freshwater on both sides of front!