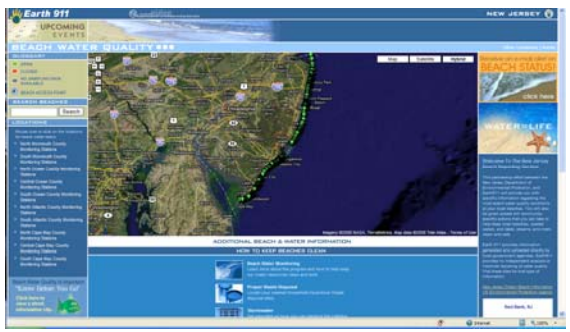
What a water quality manager needs to know about estuarine physics.

Bob Chant, Scott Glenn & Josh Kohut
IMCS Rutgers University

Q, C_{in}

Q, C_{out}

$$\frac{\partial c}{\partial t} = \ldots.$$



http://www.earth911.org/waterquality

$$\frac{dc}{dt} = -\frac{\partial}{\partial z}(\overline{c'w'}), \qquad (9)$$

where the primes indicate turbulent quantities and c and w are dye concentration and vertical velocity. Integrating vertically over the boundary layer height and substituting in (8) we obtained

$$\overline{c'w'} = -\delta \frac{dc_o}{dt} \int_0^{\zeta} f(\zeta')\, d\zeta' + c_o \frac{d\delta}{dt} \int_0^{\zeta} \zeta'\, df, \qquad (10)$$

where $\zeta = z/\delta$ and ζ' is a variable of integration. Integrating the second term on the right in parts we obtain

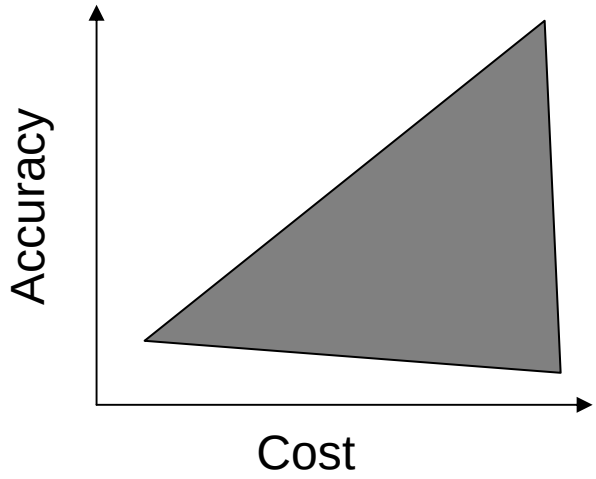
$$\overline{c'w'} = -\frac{d}{dt}(c_o\delta) \int_0^{\zeta} f(\zeta')\, d\zeta' + c_o \frac{d\delta}{dt} \zeta f(\zeta). \qquad (11)$$

$$\overline{|w's'|} = \bar{h} \frac{d\bar{s}}{dt} \frac{|\zeta \tanh[\alpha(1-\zeta)]|}{|\tanh[\alpha(1-\zeta)]|} \approx 0.4\bar{h} \frac{d\bar{s}}{dt}. \qquad (16)$$

Outline

1) Flushing time– an number of classic methods

- Tidal Prism
- Fresh water residence
- Salt conservation
- Modeling (Hierarchy)
- Dye Studies



2) Recent Results on estuarine dispersion

- Processes that drive dispersion
- Dispersion estimates from salt budgets and dye studies
- Effects of stratification

3) Dispersion and the nature of material

Dissolved, particulate, conservative or reactive.

4) Dispersion of discharge into coastal ocean.

Use of salt budgets to Estimate dilution

$$Q_o S_o = (Q_o + Q_e + Q_f) S$$

$$Q_o = (Q_e + Q_f) S / (S_o - S)$$

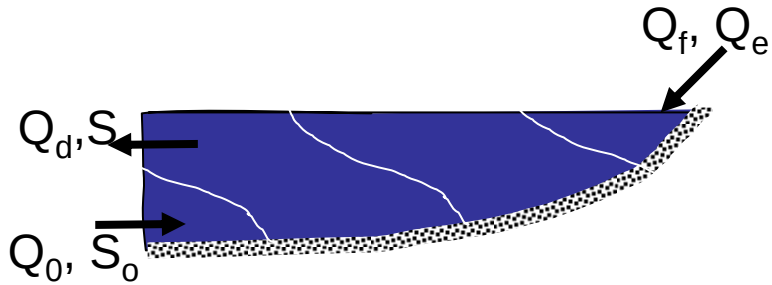
The total flow to dilute effluent is

$$Q_d = Q_f + Q_o + Q_e = (Q_e + Q_f) S_o / (S_o - S)$$

The mean concentration near the discarge can estimated as

$$C_d = M / Q_d$$

Knudson balance



Works well if cross channel and vertical mixing is rapid

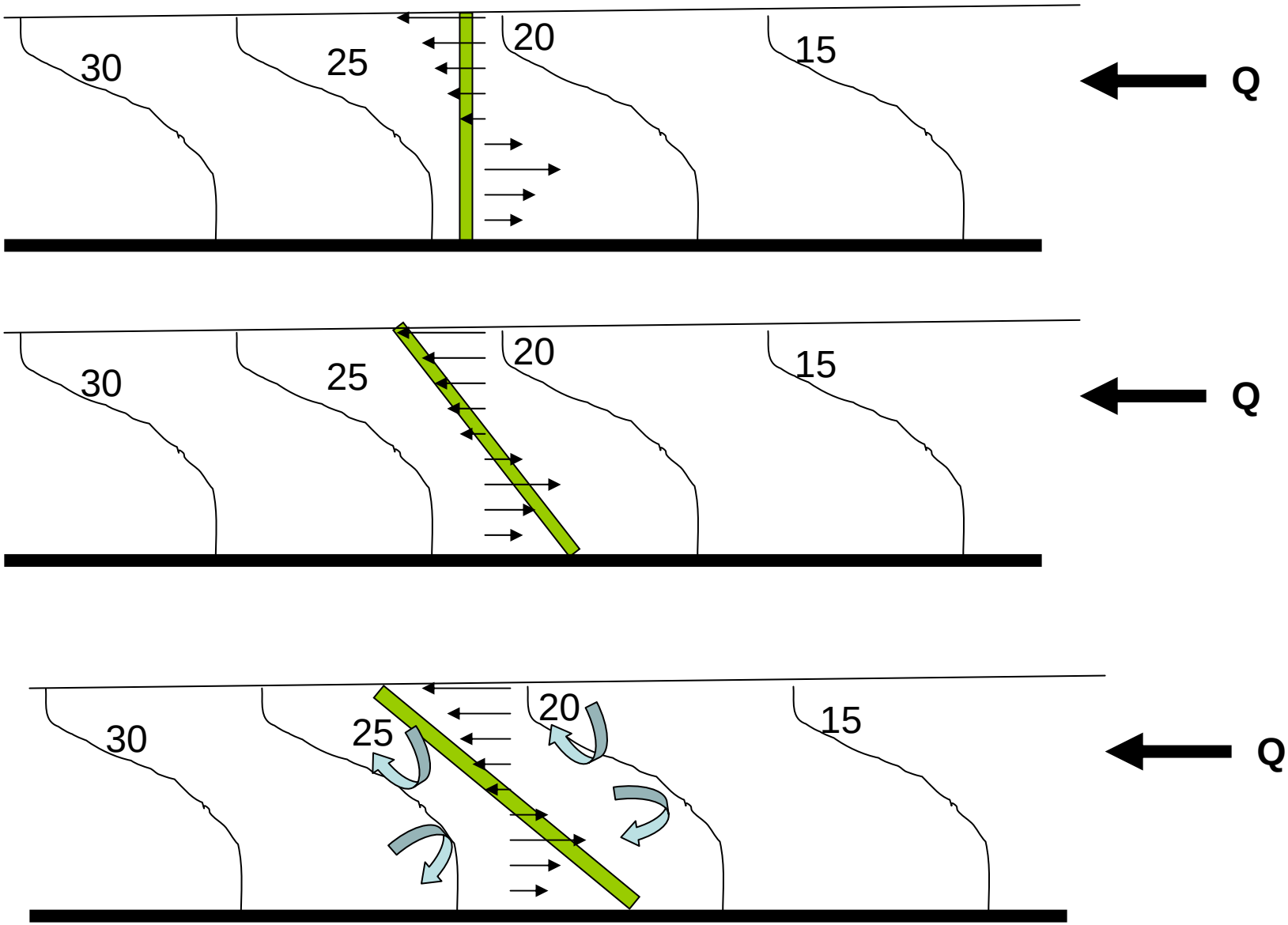
Biggest contributor to dilution is the estuarine circulation (Q_o)

Because $Q_o > Q_f > Q_e$ (But with River flow there is no Estuarine Circulation)

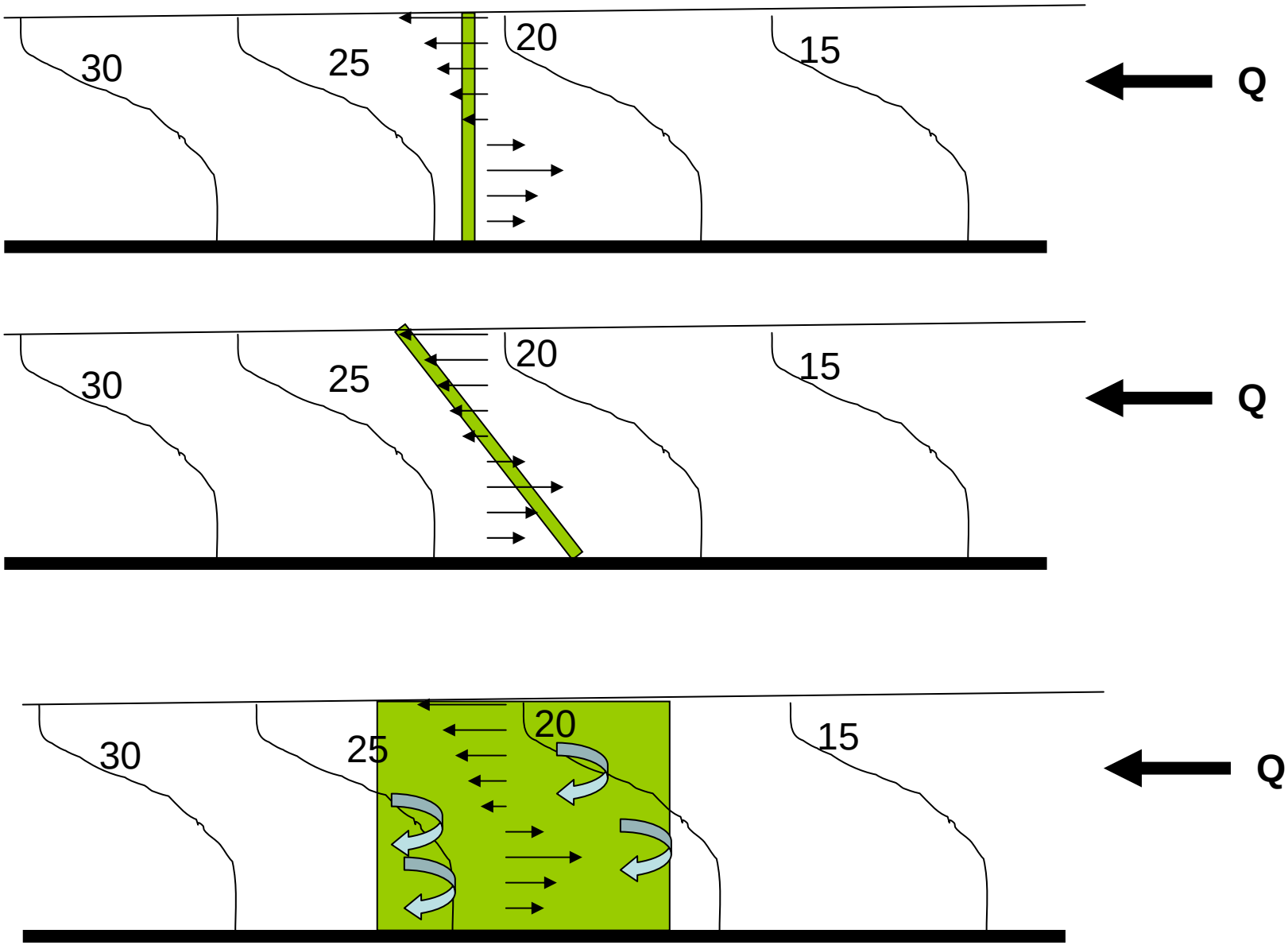
<u>Ultimately a dispersive process!!</u>

Fischer et al (1979)

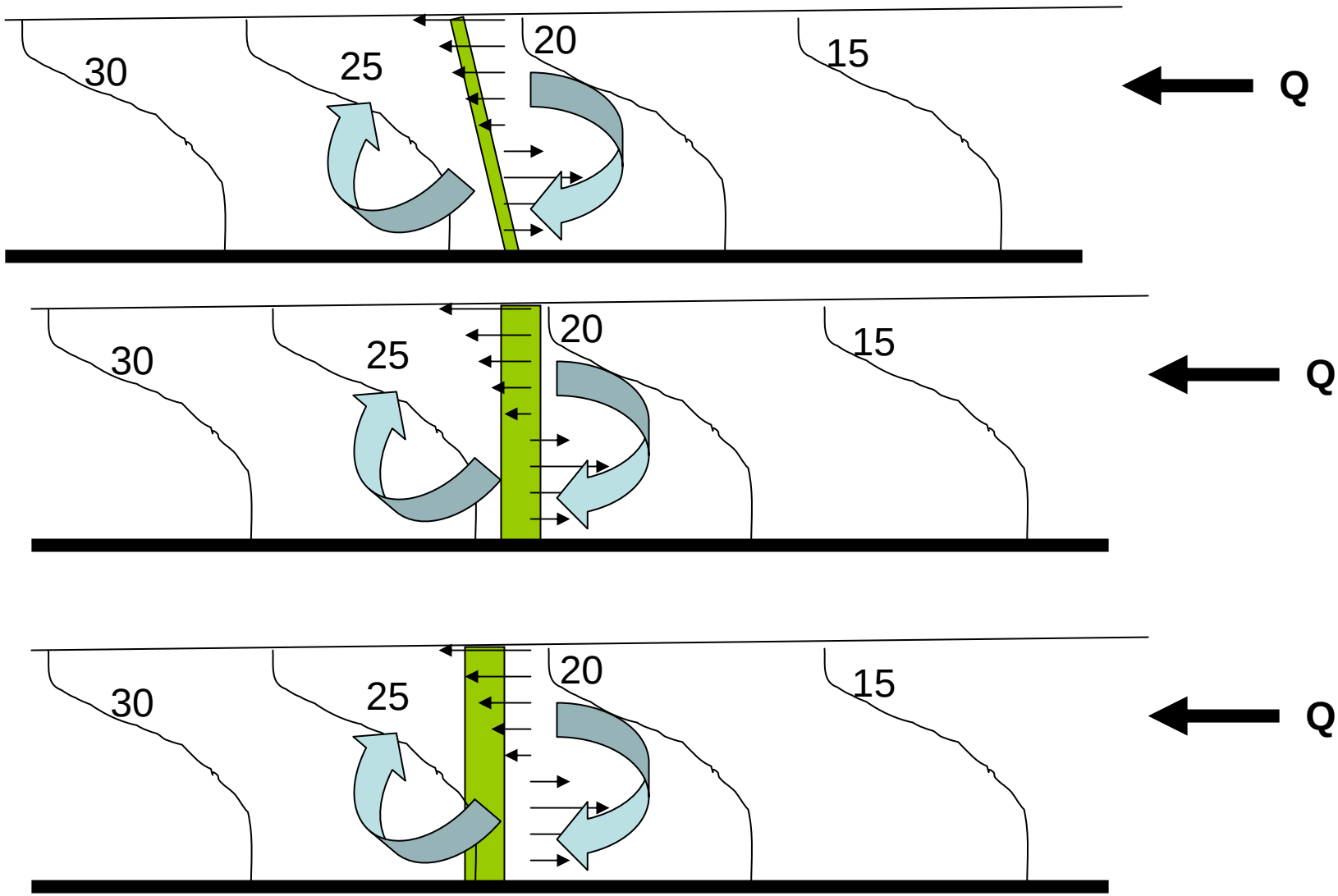
Estuarine Dispersion (weak vertical Mixing)



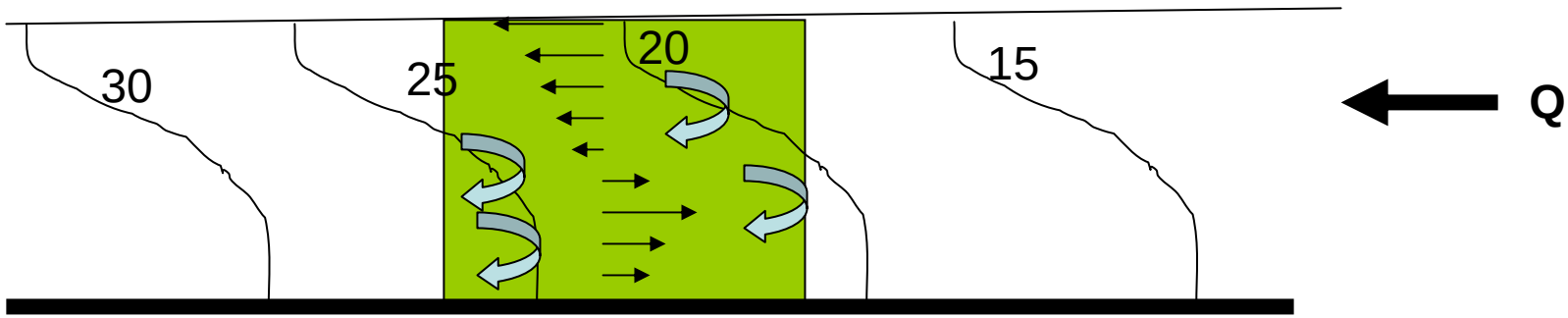
Estuarine Dispersion (weak vertical Mixing)



Estuarine Dispersion (Strong Vertical Mixing)



Estuarine Dispersion

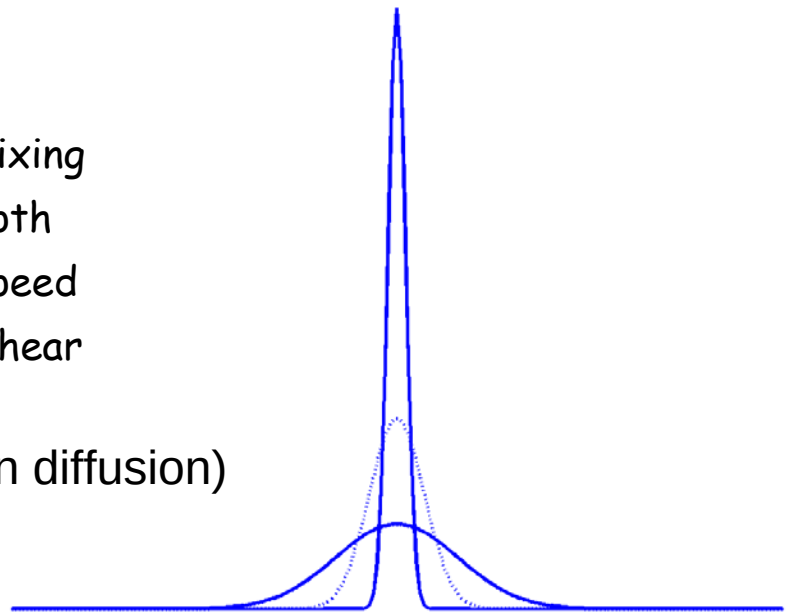


Shear Dispersion Taylor (1954)

$$K_x = \alpha \frac{U^2 H^2}{K_v}$$

K_v Vertical Mixing
H Water Depth
U Current Speed
α Vertical Shear

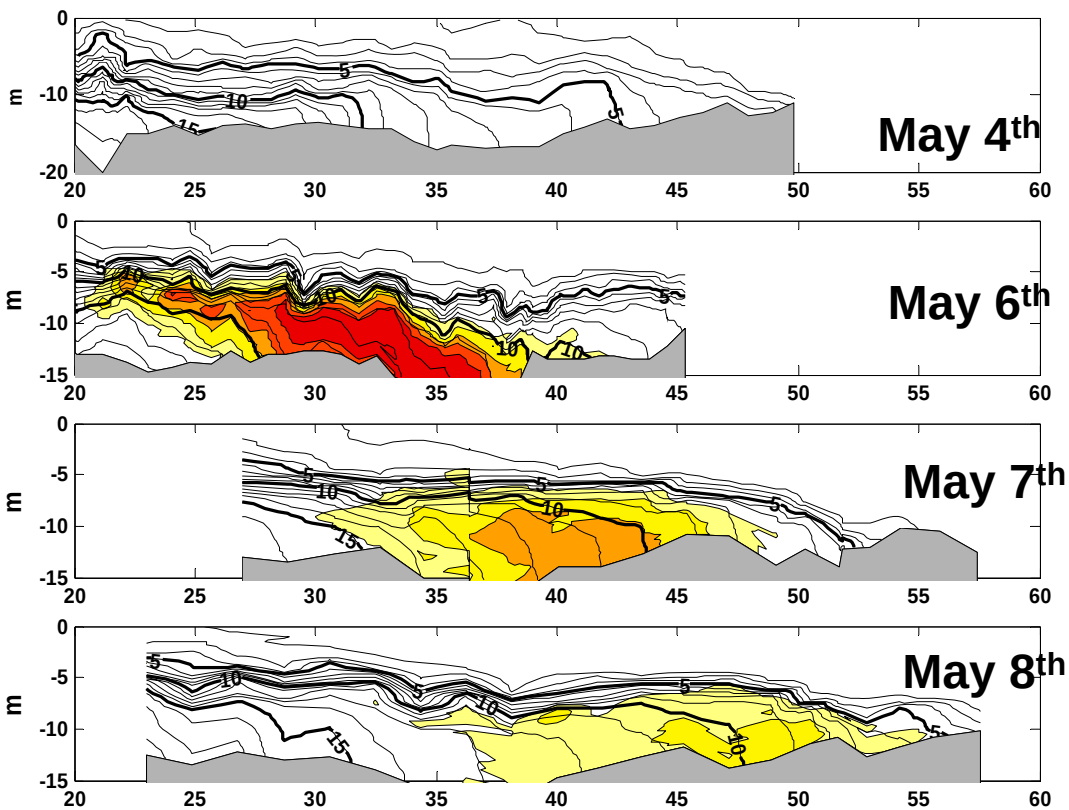
Drives Down Gradient flux (identical to Fickian diffusion)

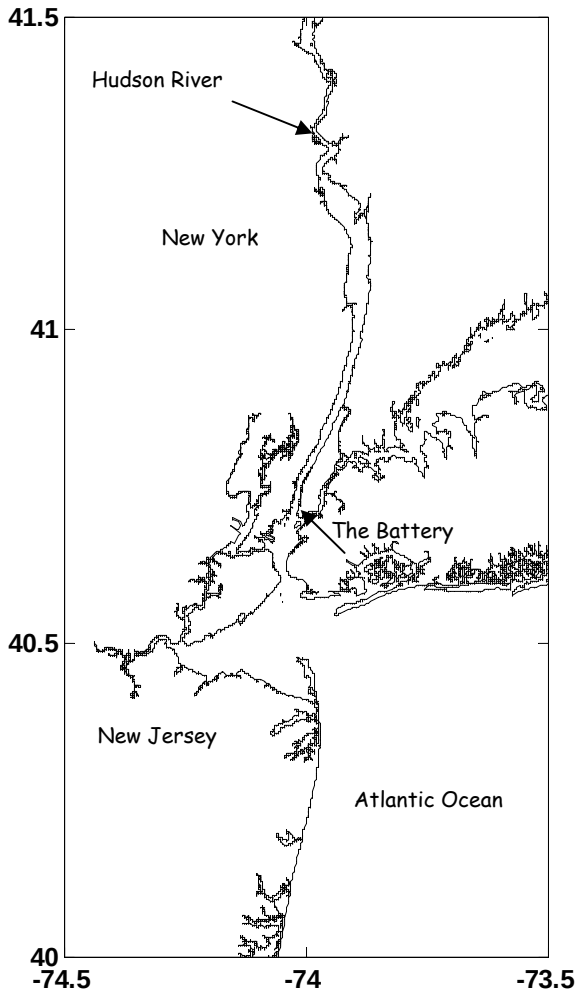


But again only applicable for time-scales long compared to mixing time scales

Mixing time – how long does it take material to mix in ALL three dimensions?

Use example in Hudson (Chant et al. JPO 2007; Geyer and Chant JGR 2008)

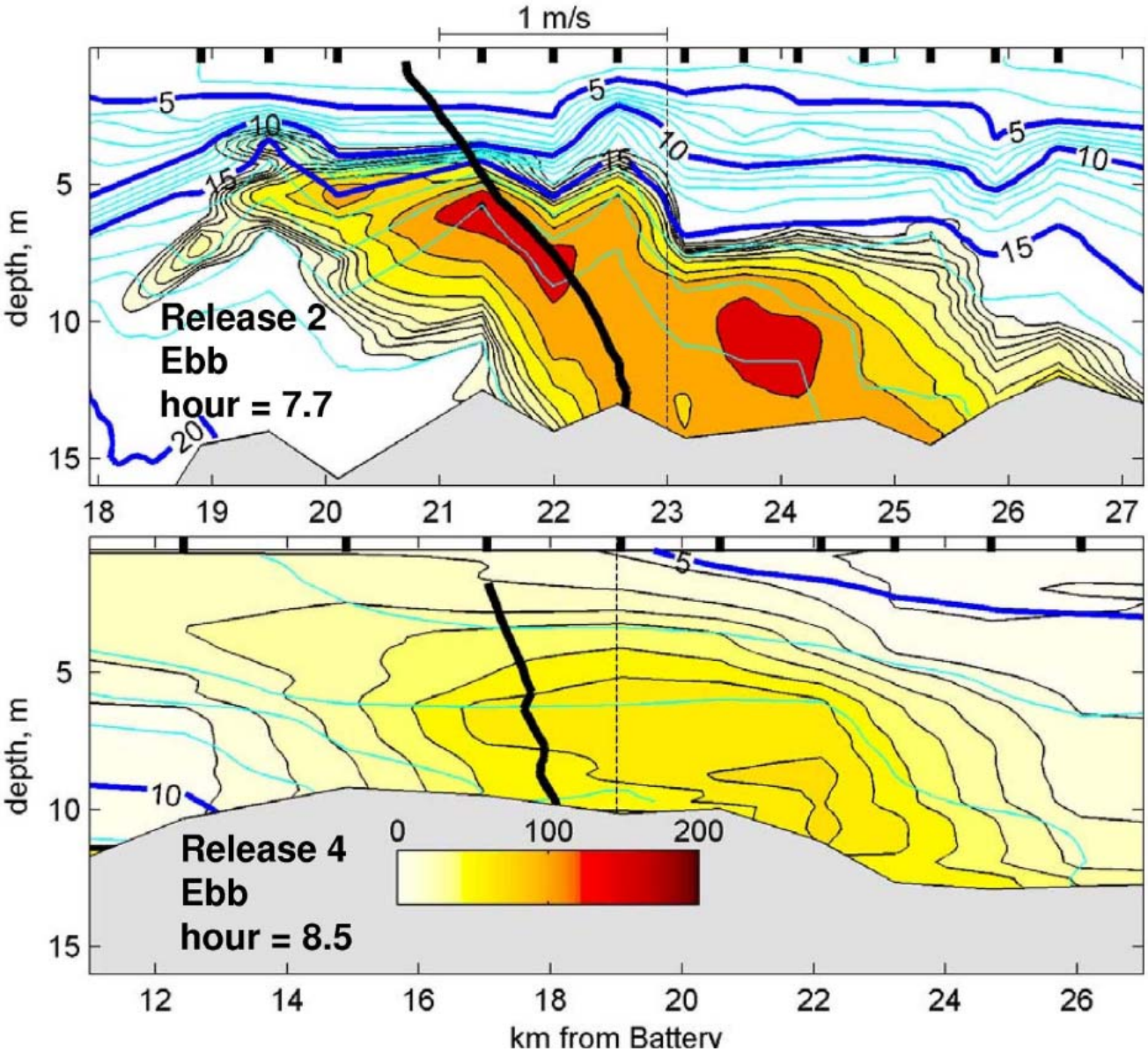




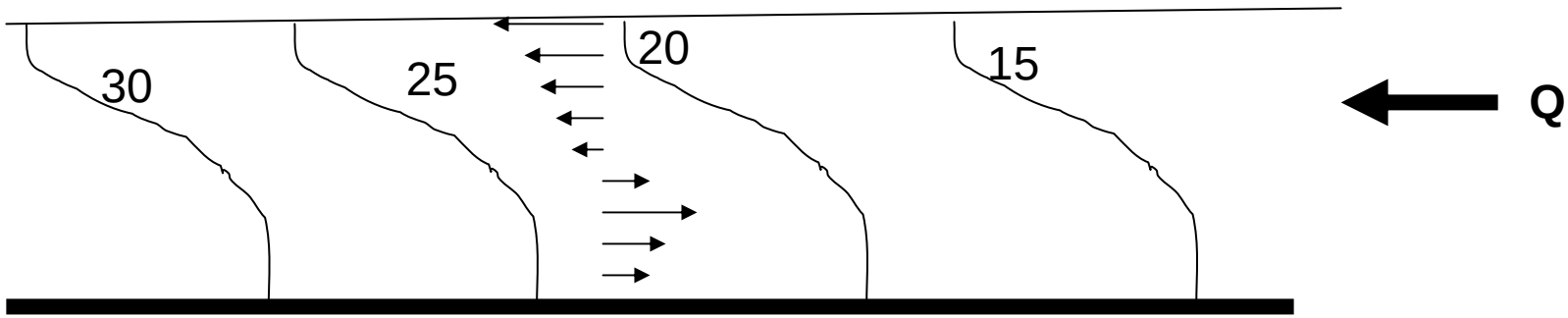
During neap tides mixing time is long– many days

Mixing weak– but so is dispersion!

During spring tide vertical mixing is rapid
But again dispersion is weak (but here consistent with theory)



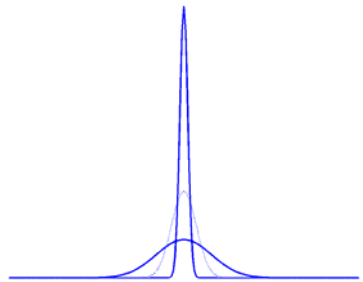
Estuarine Dispersion Estimated with salt field



$$U_r S = K_{eff} \frac{\Delta S}{\Delta x}$$

Assuming steady salt balance

U_R=River flow velocity (Q/A)



$$K_{eff} = \frac{Q_o}{A} \frac{S_o \Delta x}{\Delta S}$$

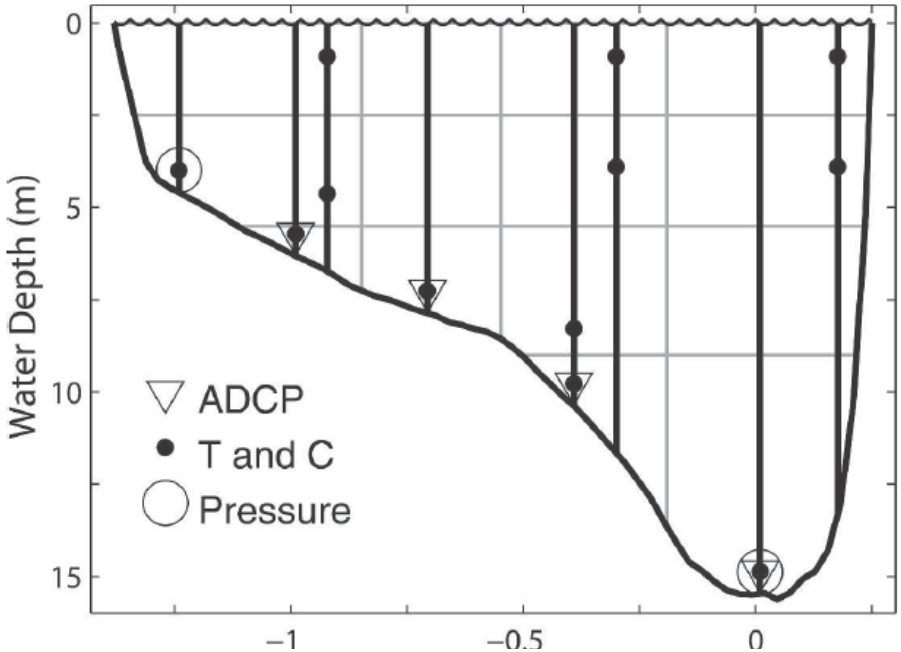
$$\frac{\Delta S}{\Delta x} = \frac{S_o}{L}$$

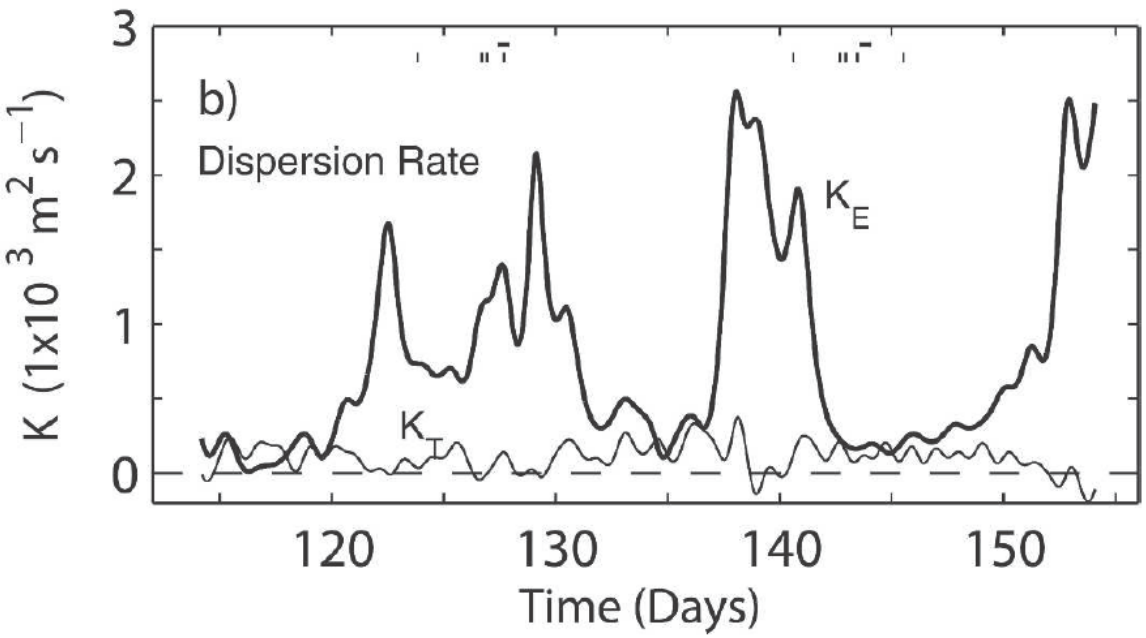
$$K_{eff} = \frac{Q_o L}{A}$$

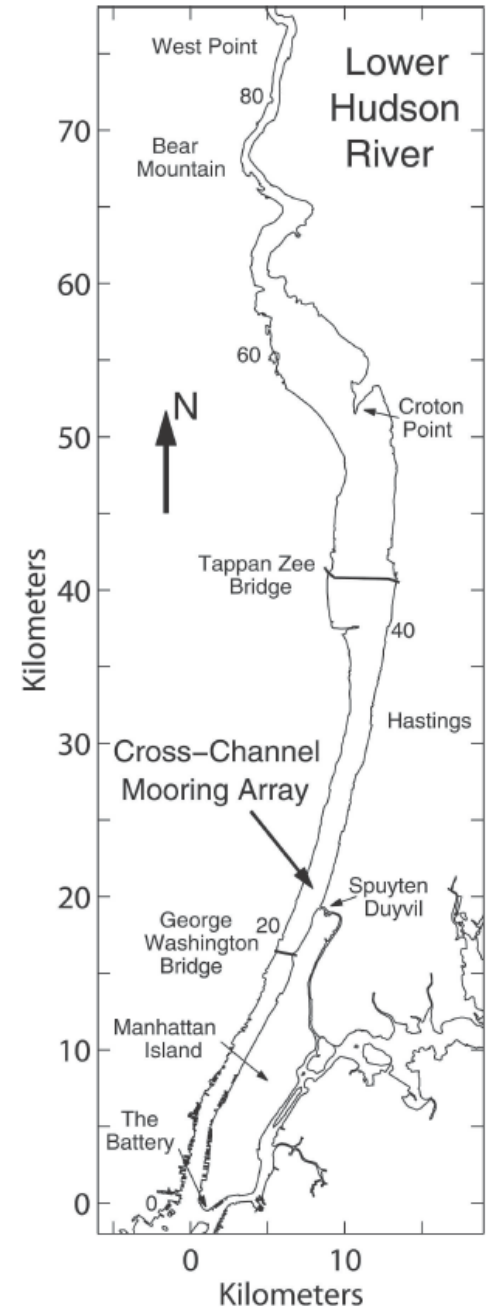
Using typical values for the Hudson K_{eff}~1000 m^2/s

Note that L inversely proportional to Q

Lerczak, Geyer and Chant (JPO 2006)

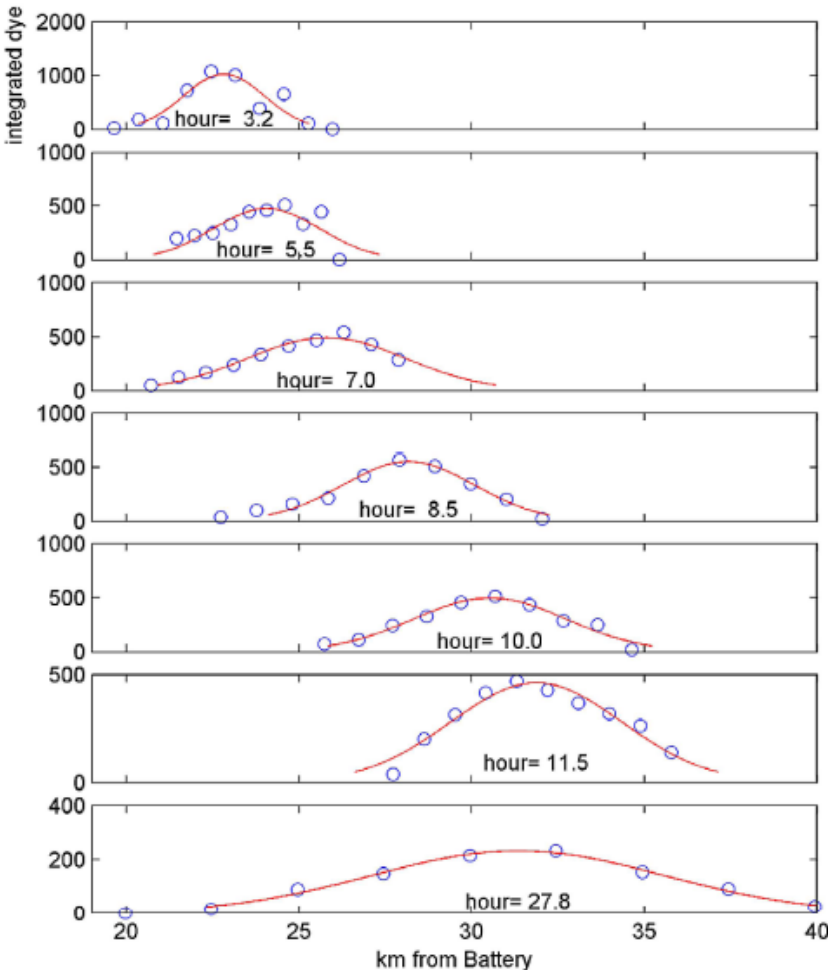


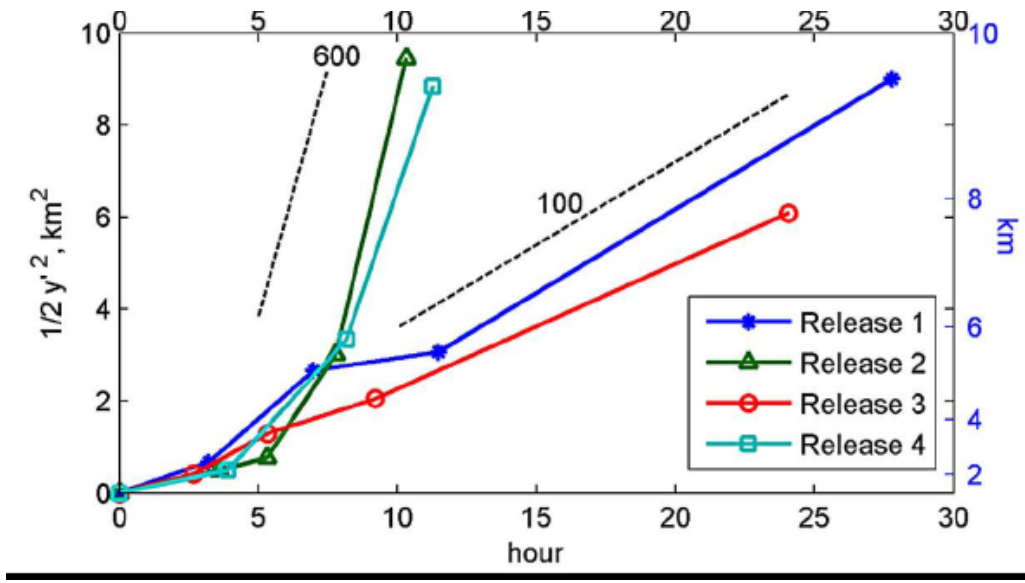




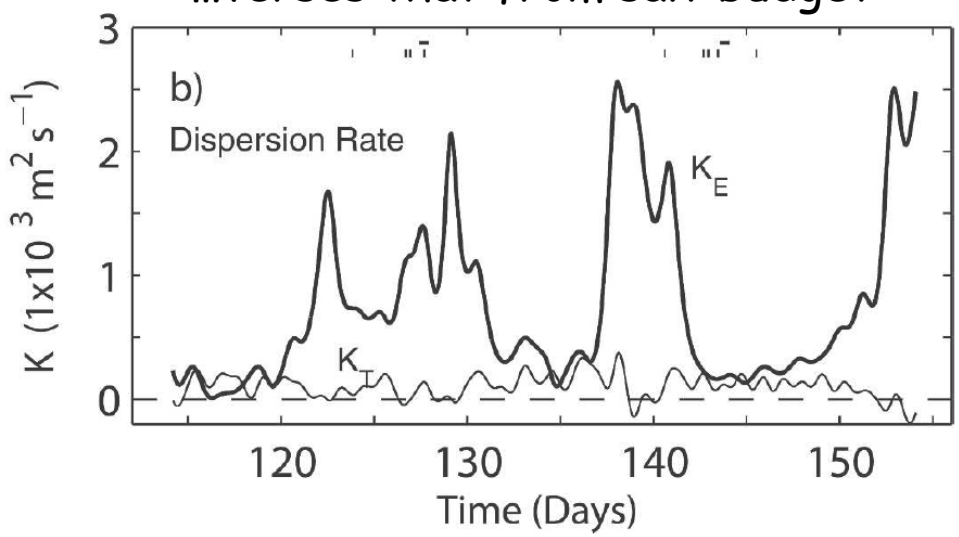
Estimate of dispersion from Dye release….

Geyer, Chant and Houghton (JGR 2008)





…verses that from salt budget



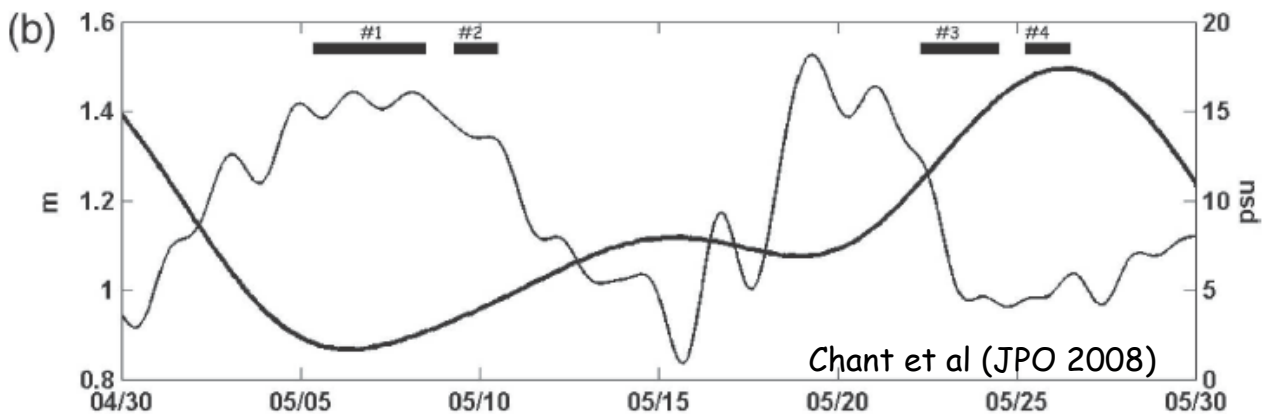
Lerczak, Geyer and Chant (JPO 2007)

Estimates of dispersion from dye ALWAYS less than that from salt

The large value of shear dispersion is only applicable to substances (such as salt) that have been in the estuary long enough to be broadly distributed in the vertical.

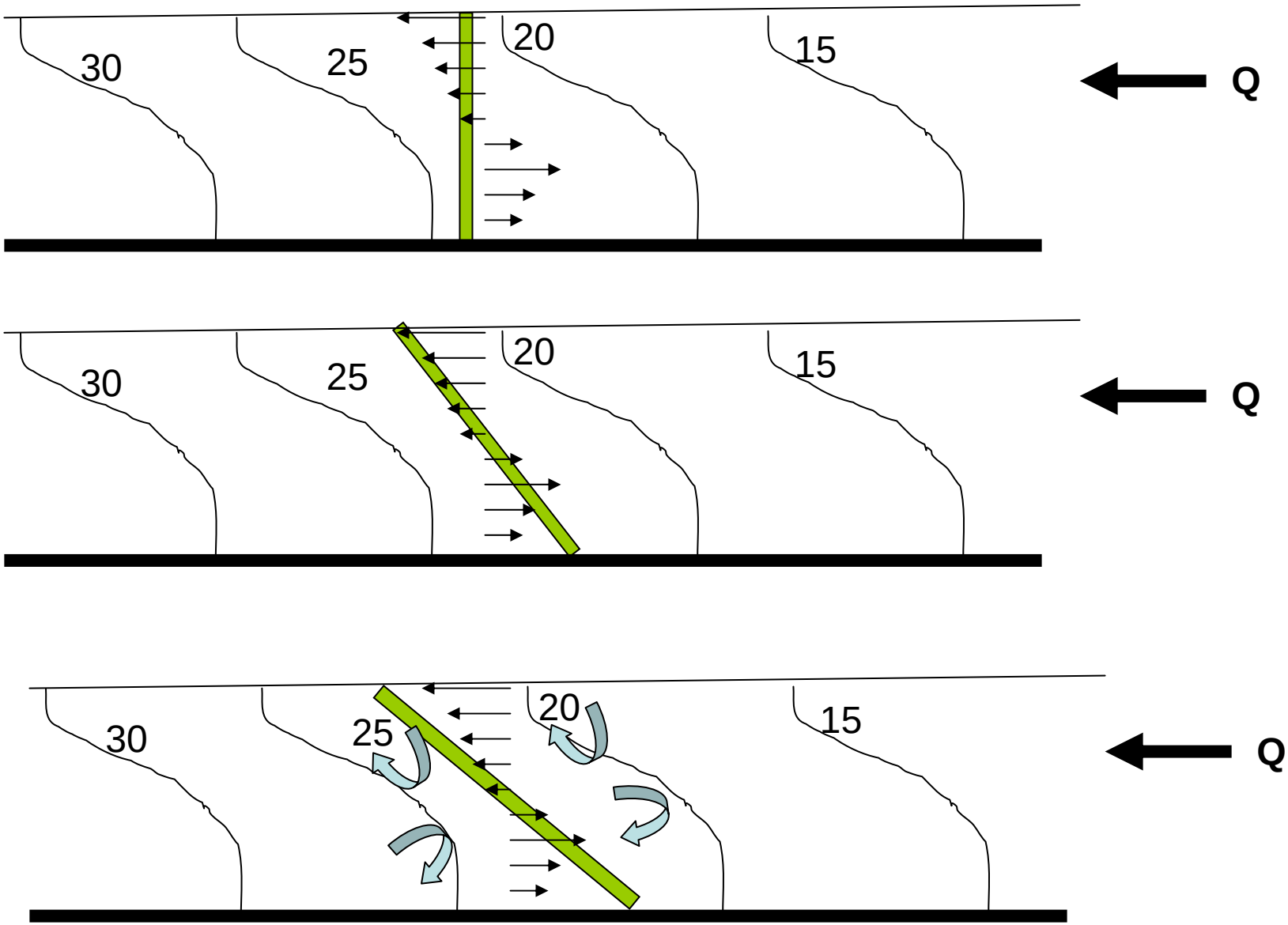
Material in surface waters in stratified estuaries will not experience strong dispersion and thus will quickly be ejected from estuary.

Ejection of surface waters is most pronounced during neap tides when river is highly stratified.



After exiting the estuary discharge and associated material is subject to plume dynamics

Estuarine Dispersion (weak vertical Mixing)



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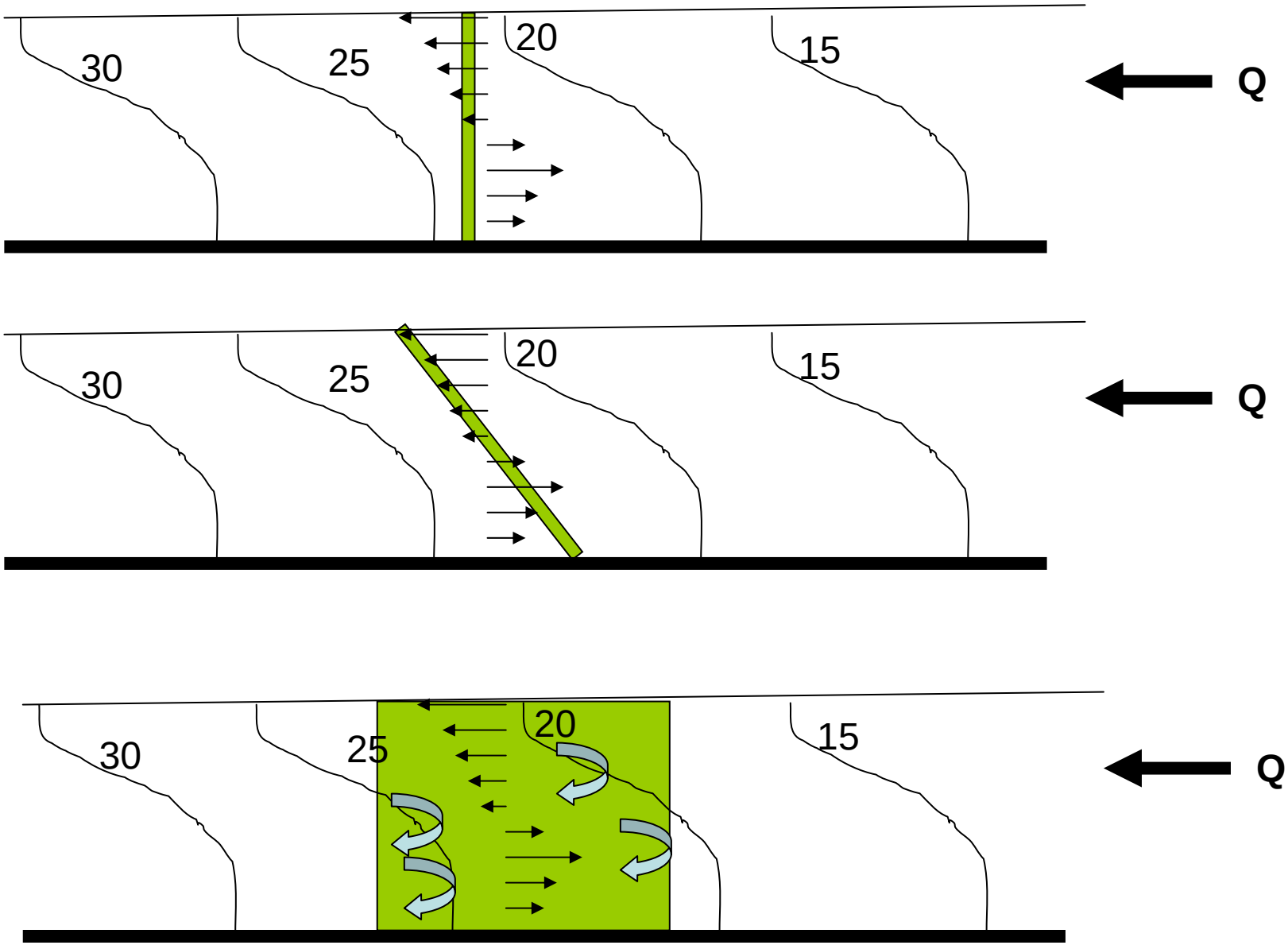

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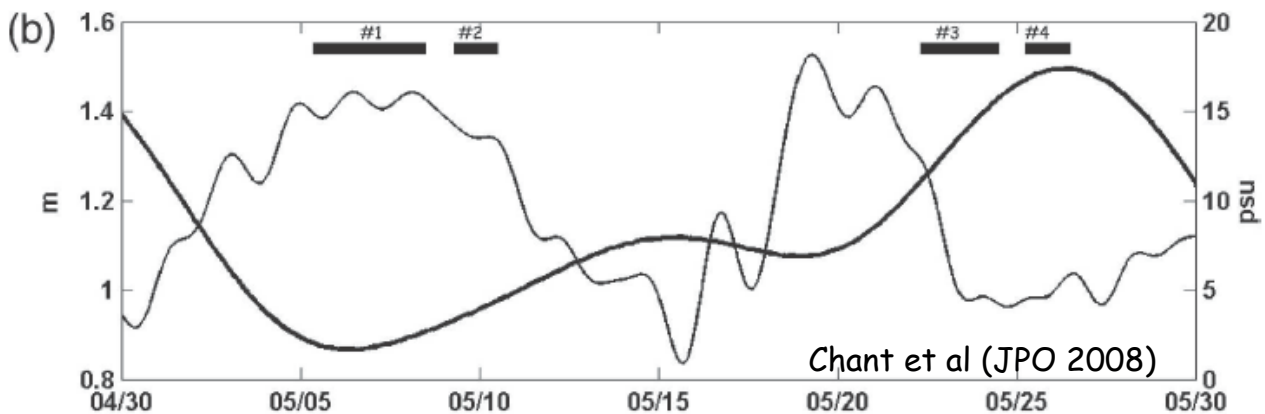
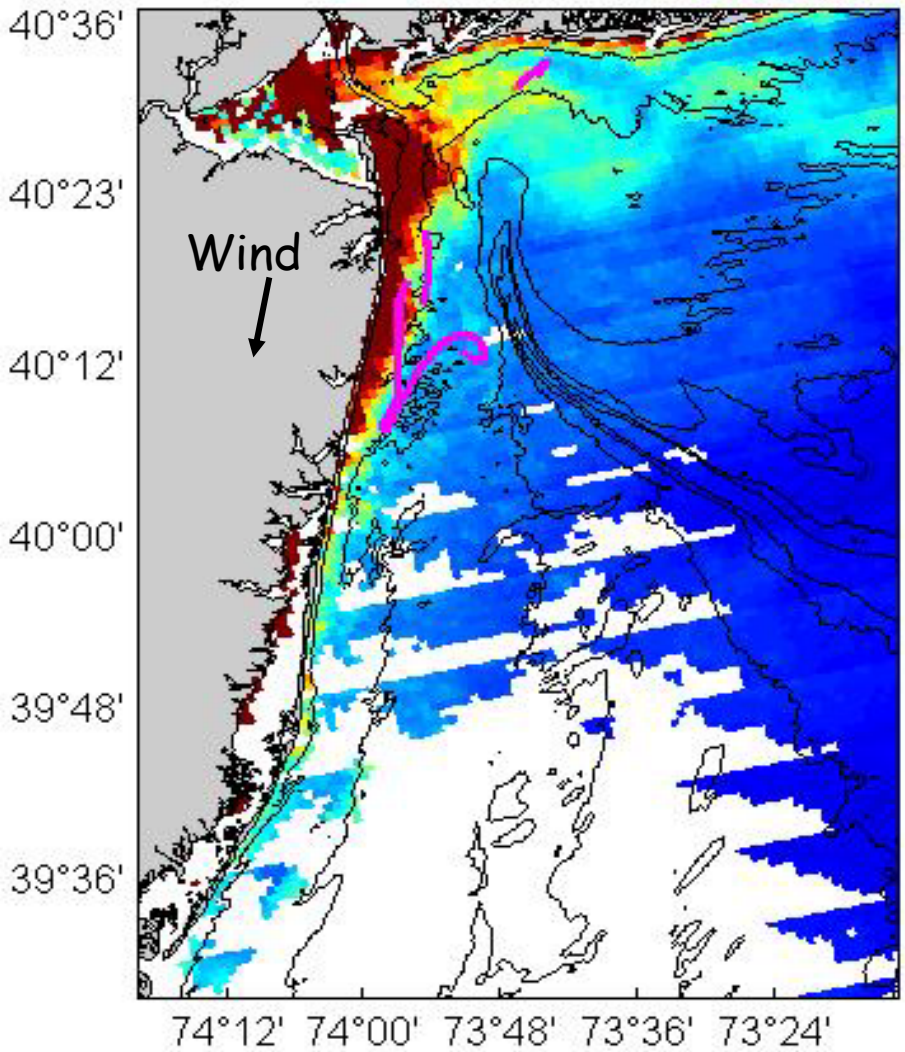
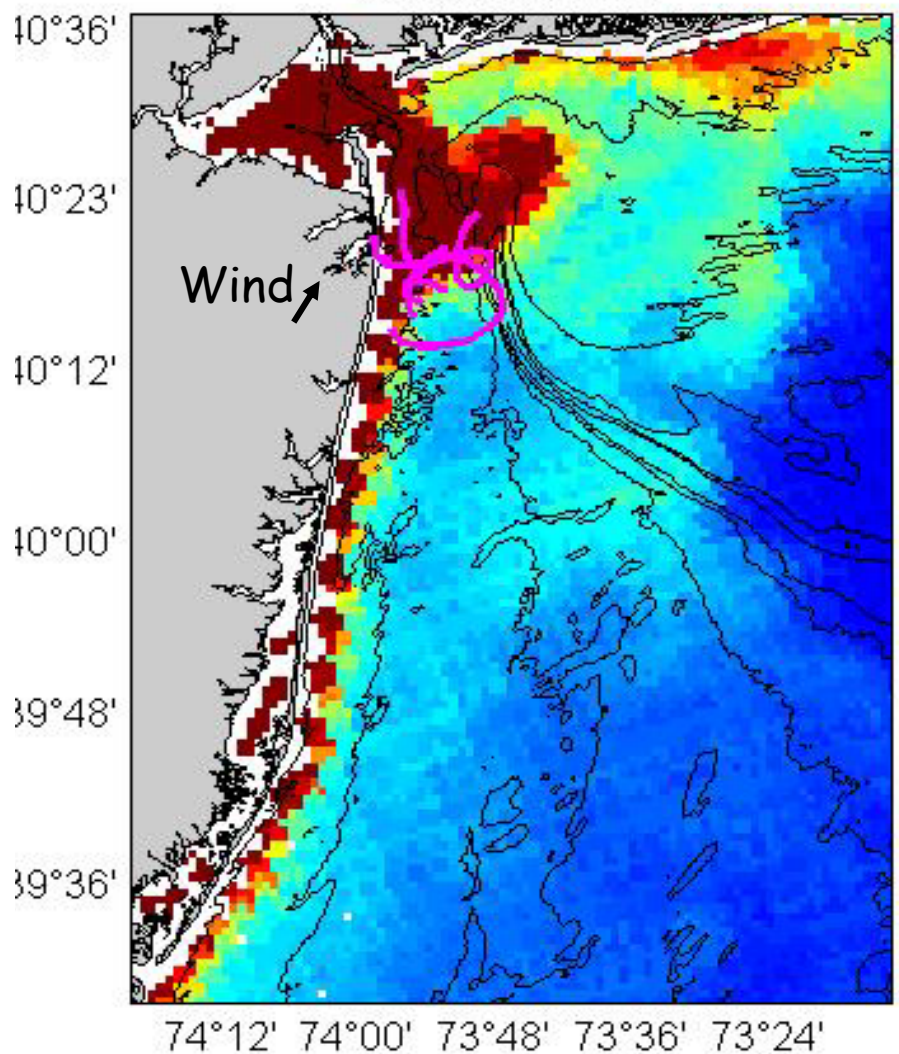


After exiting the estuary discharge and associated material is subject to plume dynamics

Down-welling – rapid moving current Trapped To New Jersey Coastline

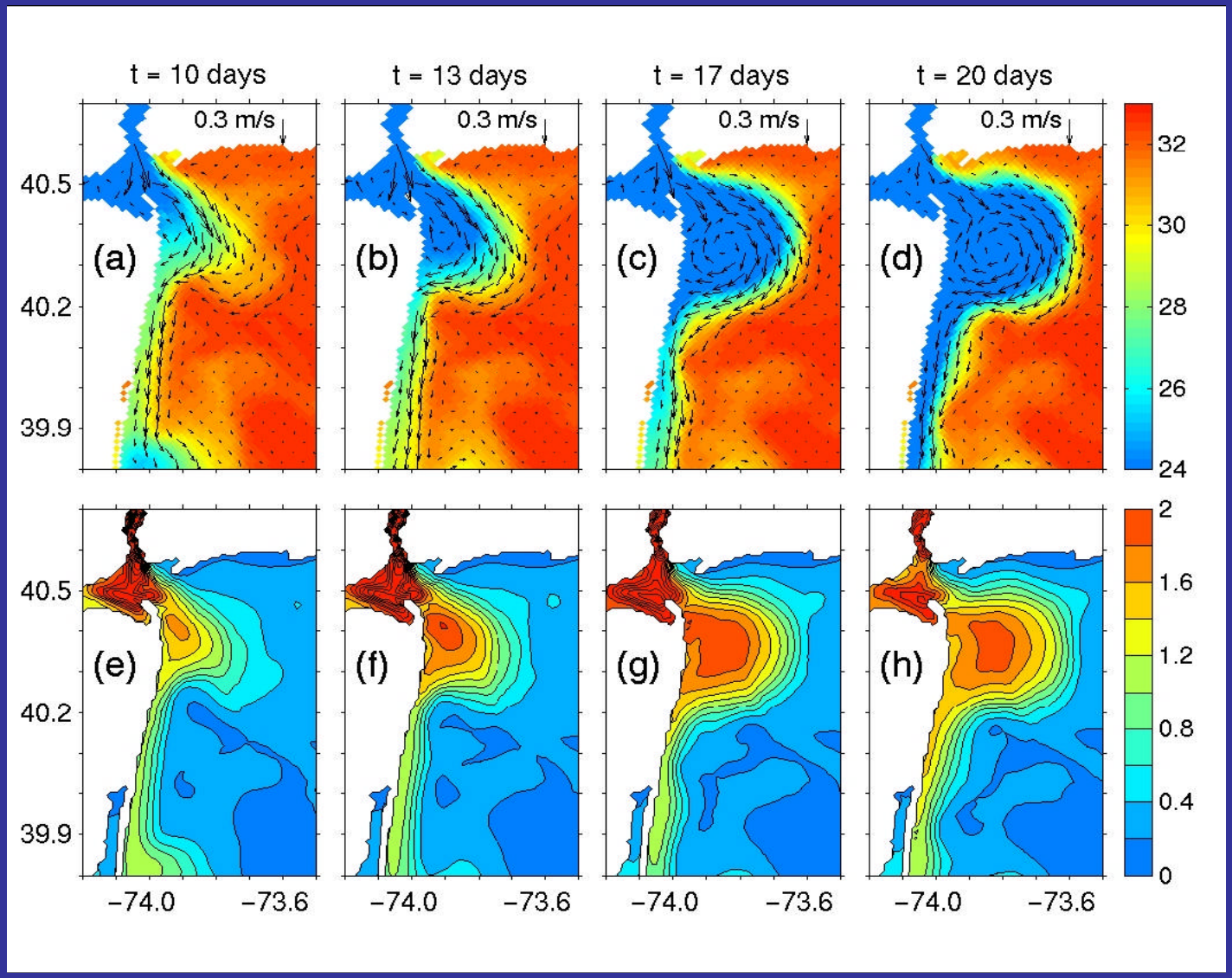


Upwelling and weak winds Bulge and transport along LI coast.



Hunter, Chant and Wilkin (submitted to JGR)

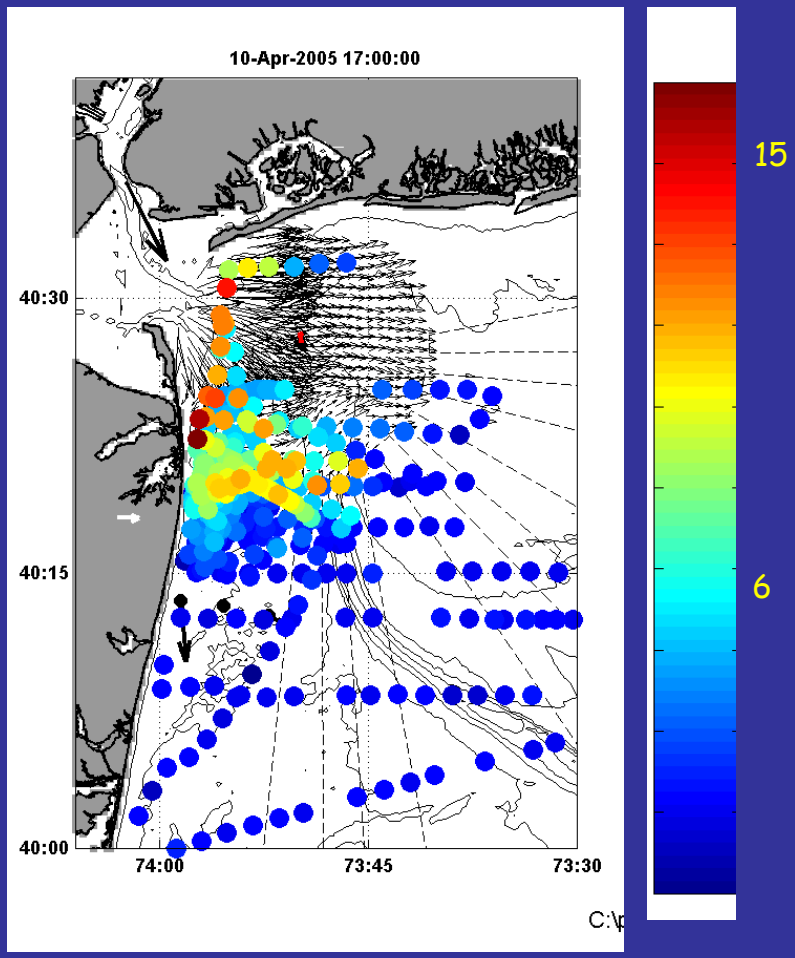
Structure and impact of "Bulge" formation

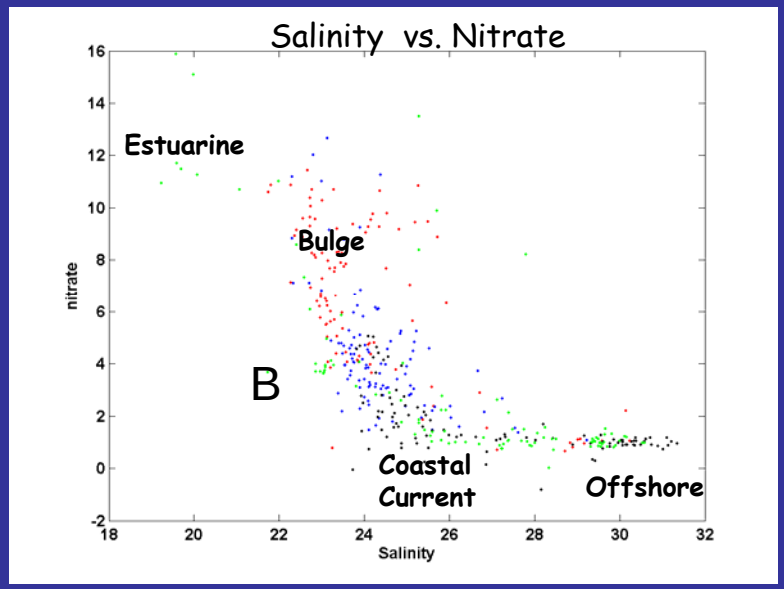


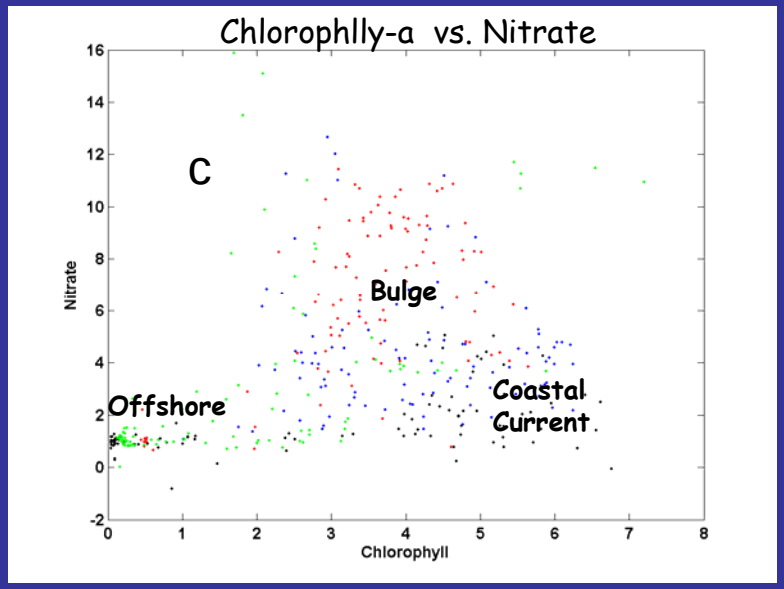
Choi and Wilkin (JPO 2007)

- Limits flow to coastal current
- Provides "Chemostat for biogeochemical processes (Wright et al. Frazer et al, Chen et al. Cahill et al. Xi et al.)
- Bulge highly sensitive to winds and ambient shelf circulation (Zhang et al. Castelao et al.)

Surface Nitrate Concentration (µM/L)

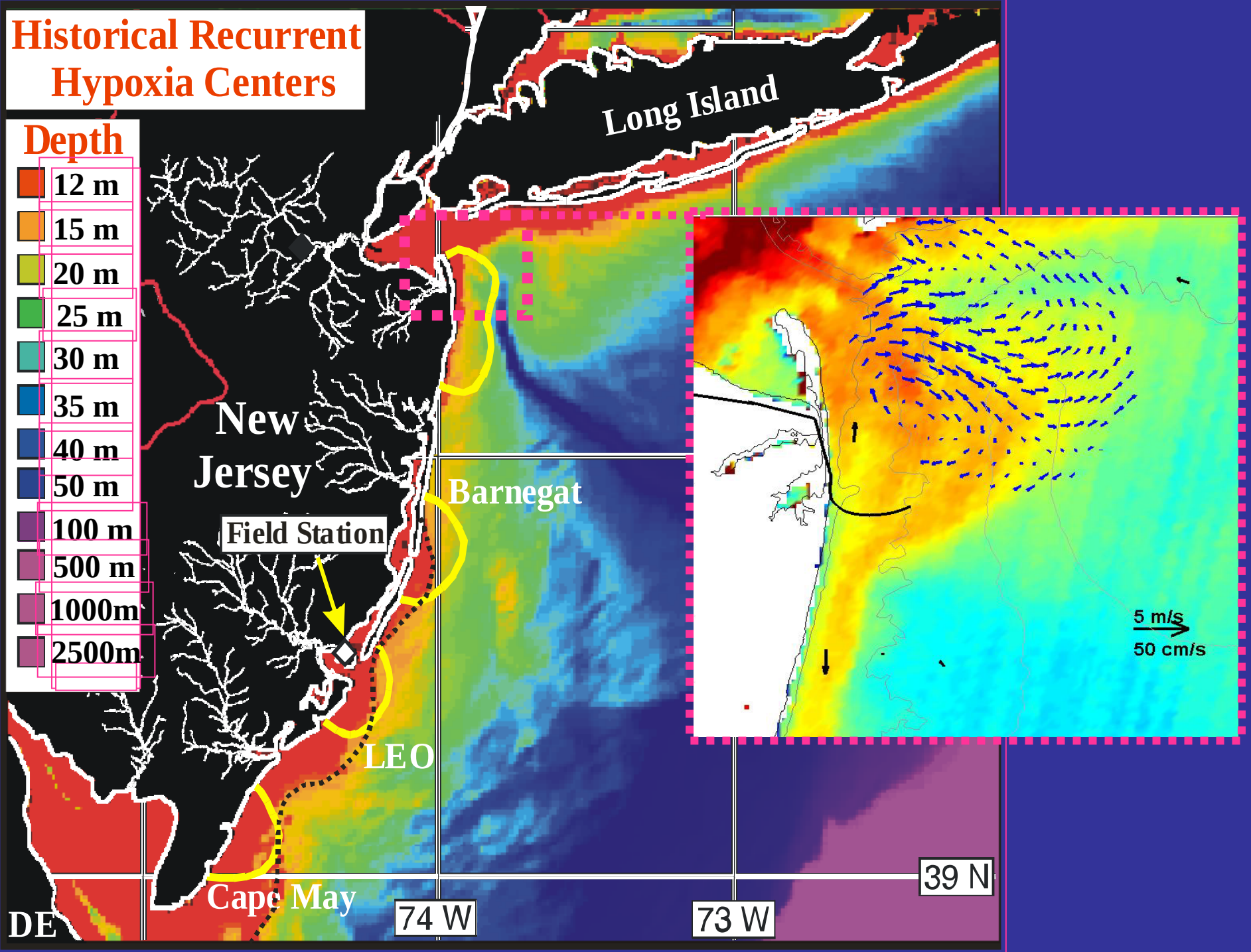




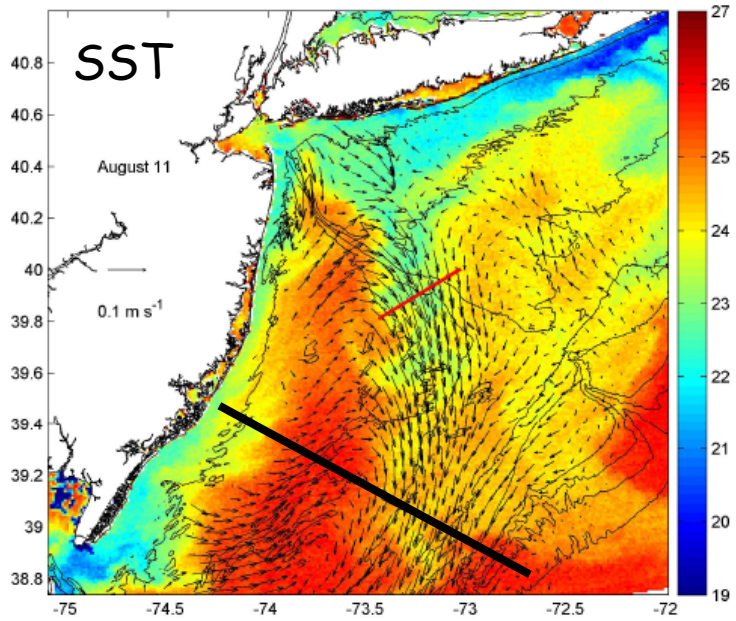


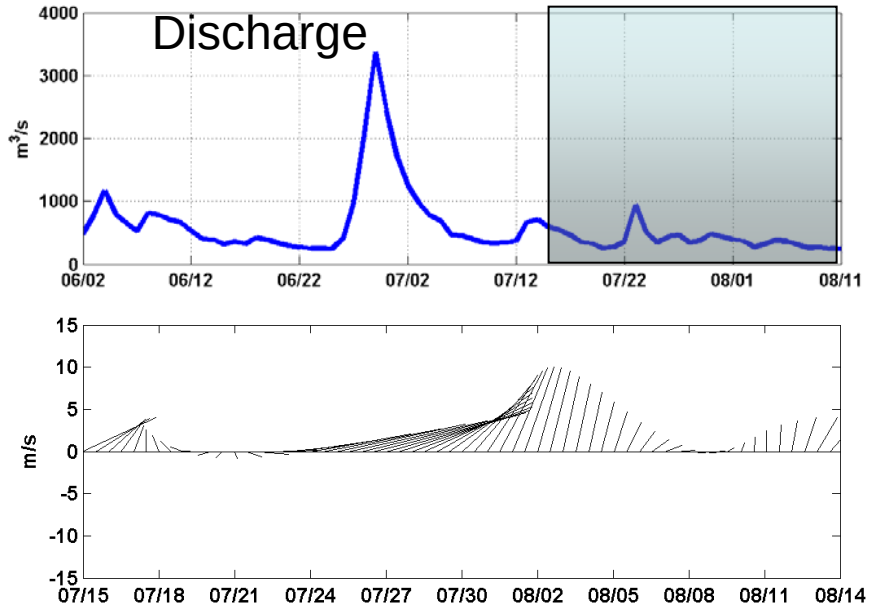
Rapid drawdown of Nutrients in bulge region. Low in-organic nitrate transport in coastal current but rather transport of assimilated nitrogen (and metal contaminants!)

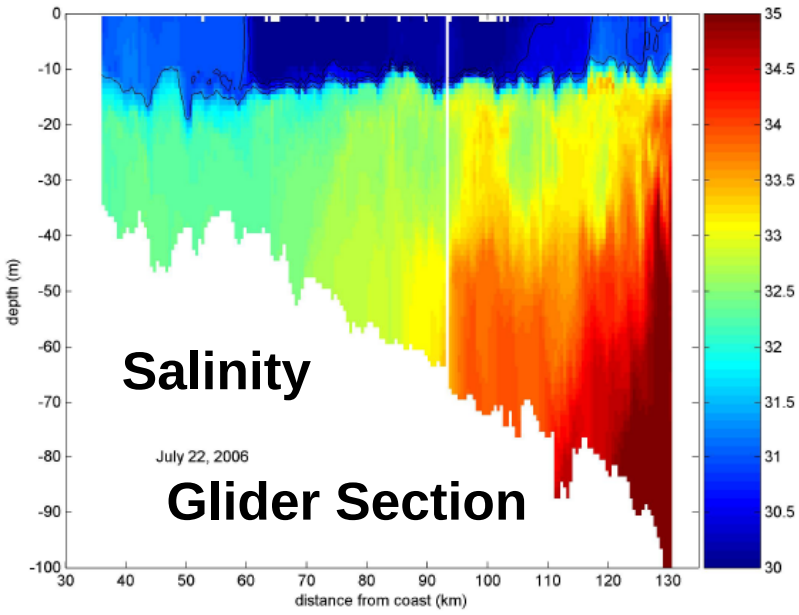
Schofield et al (submitted to JGR)


Historical Recurrent Hypoxia Centers
Depth
12 m
15 m
20 m
25 m
30 m
35 m
40 m
50 m
100 m
500 m
1000m
2500m
Long Island
New Jersey
Field Station
Barnegat
LEO
Cape May
DE
74 W
73 W
39 N
5 m/s
50 cm/s

Pathways for less reactive dissolved material







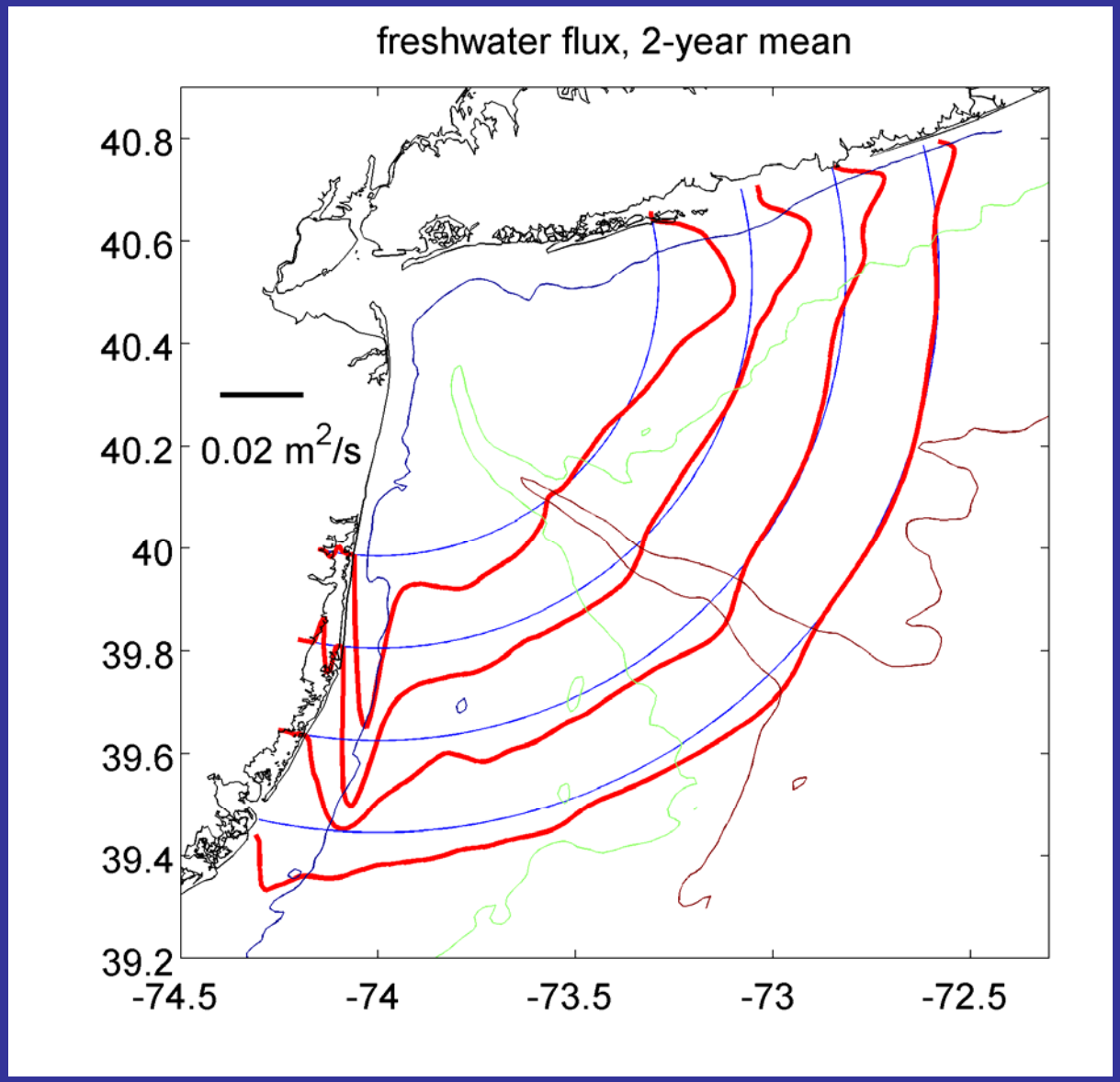
Inner shelf appears more responsive to persistent upwelling winds.

Flow converges at mid-shelf front producing jet

Bulge in Apex feeds mid-shelf jet

Rapid cross-shelf transport

Castelao et al. in press (JGR), GRL(2007)



Red line depicts mean 2005-2006 fresh water Transport

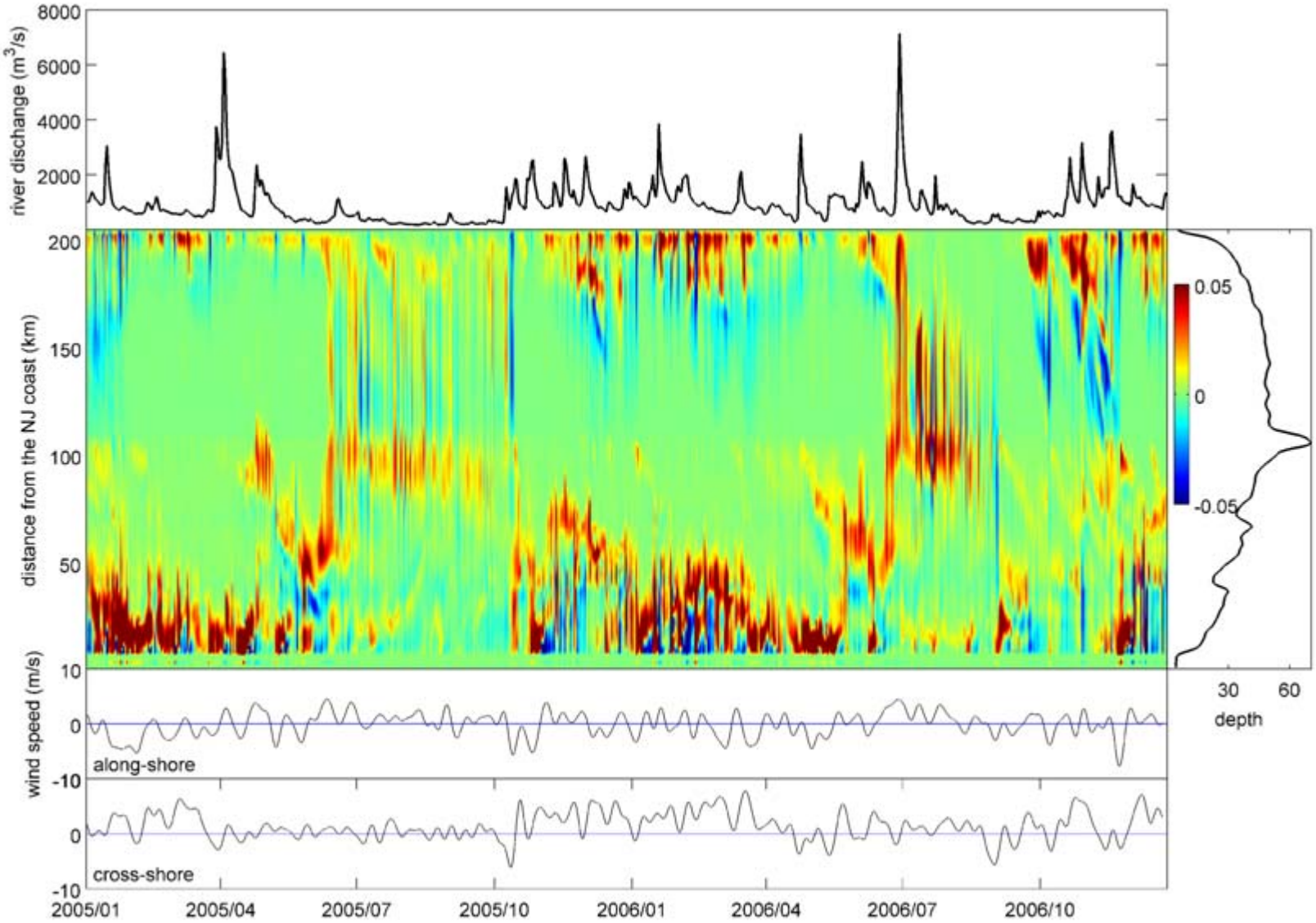
Broad recirculation Off LI coast

Off-shore jet on NJ Coast

Broadly distributed by 100 km down stream and Cut-off at shelf valley

Zhang, Chant and Wilkin (submitted to JPO)

Seasonal Variability in fresh water pathways



Zhang, Chant and Wilkin (submitted to JPO)

Conclusions

1) Water quality models need to carefully consider effects of estuarine stratification. Critical parameters are the vertical and cross-channel mixing times.

2) Use of residence time only valid for substances with comparable distribution and time residency of salt field.

3) Material discharged in surface of stratified estuary will be poorly modeled using standard flushing time models.

4) Fate of material on shelf complex– but captured in observational and modeling studies

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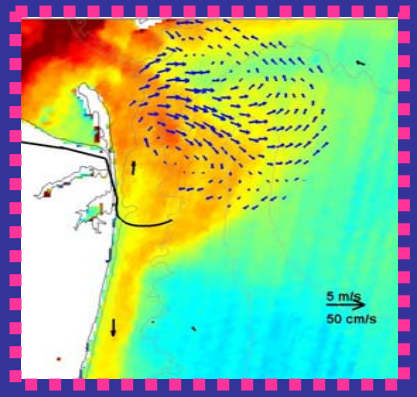

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