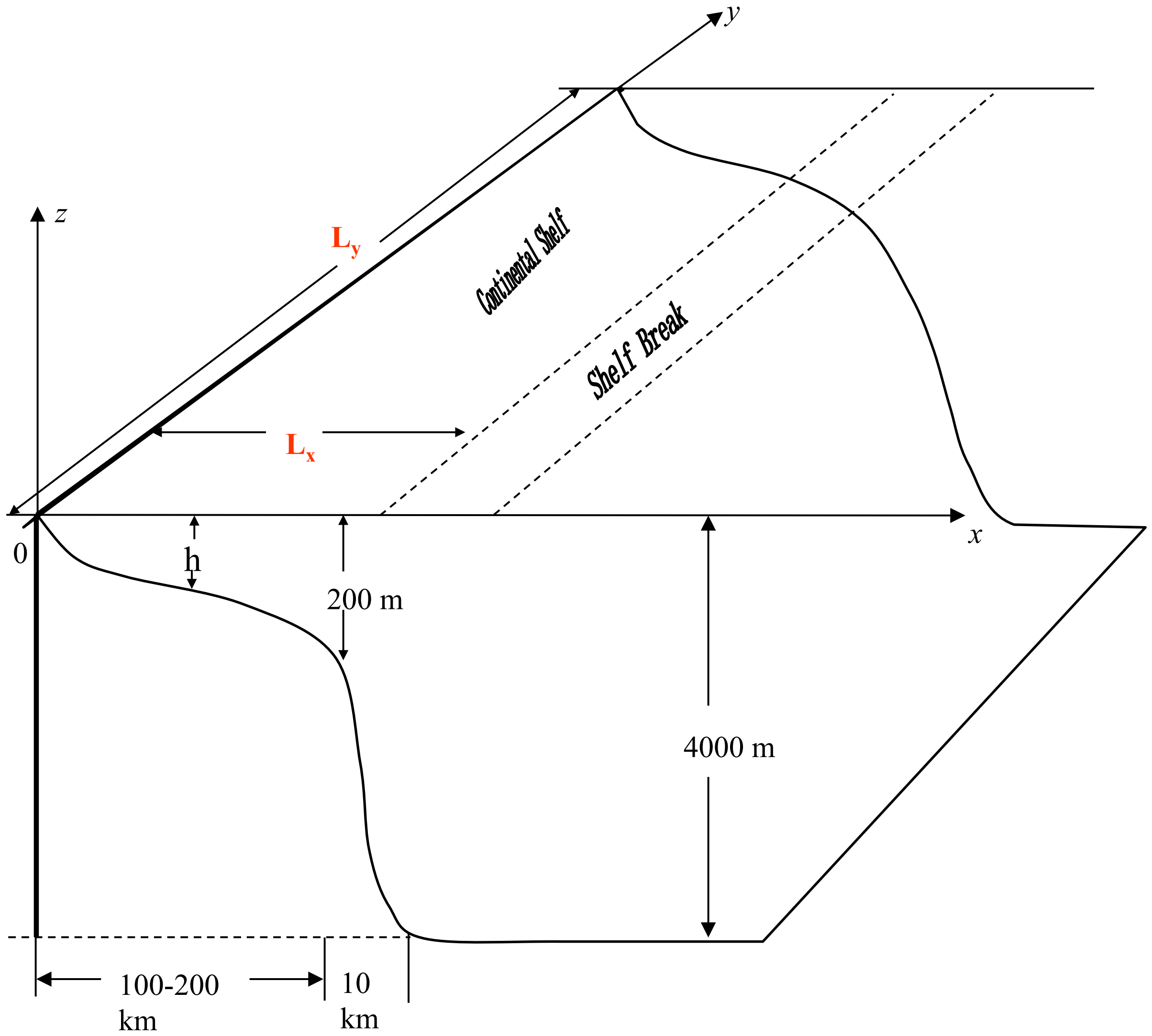
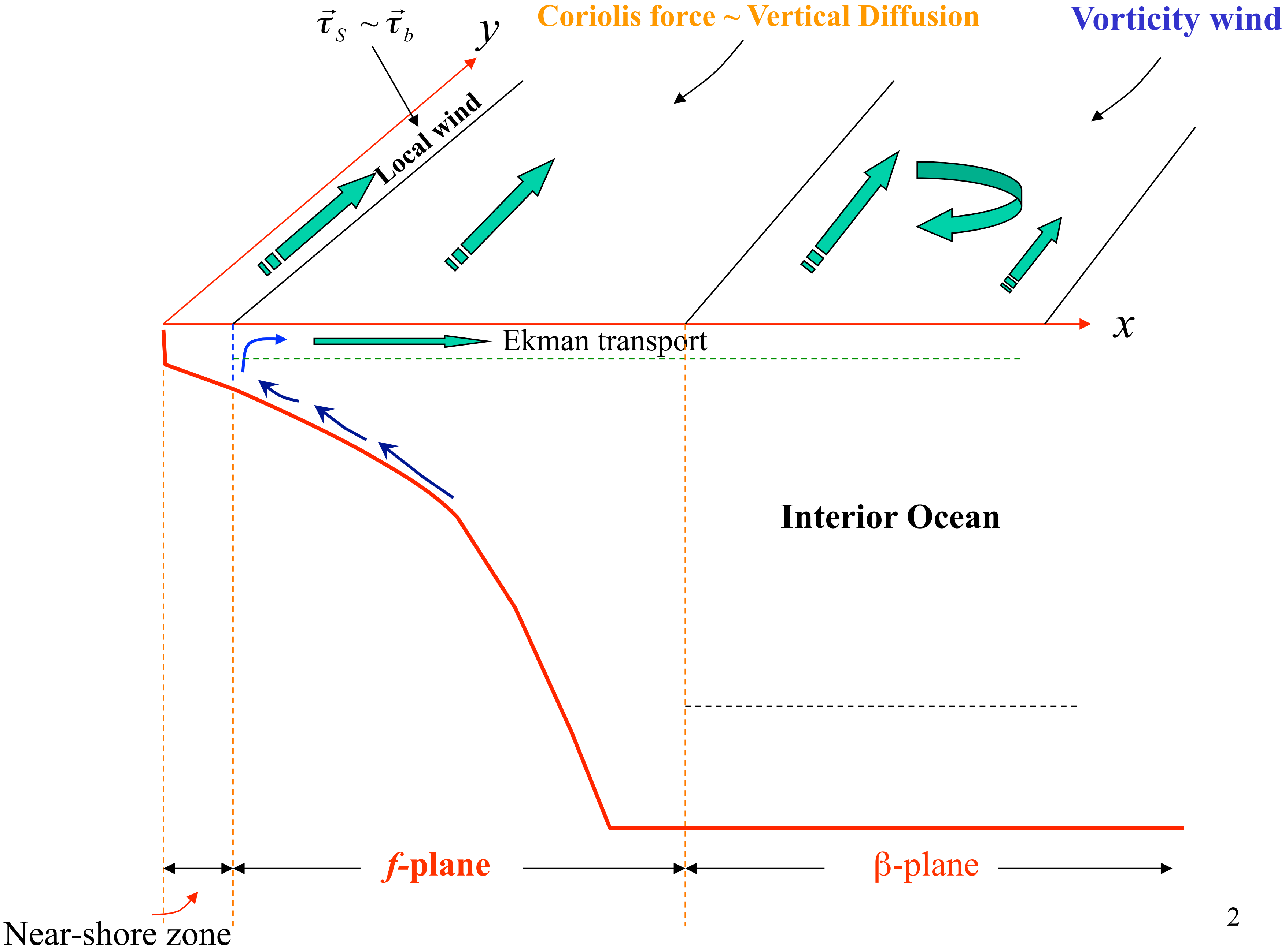
MAR650 Lecture 9: Ecosystem Processes in Coastal Oceans



- Coastal boundary
- $O(\Delta h) \sim O(h)$
- $L_x \ll L_y$
- Motion is constrained within the shelf;
- Significant time- and spatial variations.



$\vec{\tau}_S \sim \vec{\tau}_b$

y

Coriolis force ~ Vertical Diffusion

Vorticity wind

Local wind

x

Ekman transport

Interior Ocean

***f*-plane**

β-plane

Near-shore zone

Over the continental shelf,

$$\boxed{L_x << L_y}$$

Looking at the horizontal continuous equation,

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0$$

$$\downarrow \qquad \downarrow$$

$$O\left(\frac{U}{L_x}\right) \sim O\left(\frac{V}{L_y}\right) \xrightarrow{\qquad} U \sim V\left(\frac{L_x}{L_y}\right) << V$$

The cross-shelf velocity is one order of magnitude smaller than the along-shelf velocity.

Unlike the open ocean, the cross-shelf velocity over the continental shelf generally does not satisfy the geostrophic balance. The structure and distribution of the cross-shelf velocity is closed related to vertical mixing.

In the open ocean:

The motion is quasi-geostrophic with a slowly time variation scale

In the coastal ocean:

The motion is featured by strong nonlinear multiple-scale processes

Examples:

Small-scale high frequency surface waves → **Large-scale vertical resuspension of the sediments**

Small-scale turbulent mixing → **Formation of tidal mixing fronts**

Point freshwater discharge → **Large-scale buoyancy-driven flow**

Most interesting physical process:

1) Oceanic fronts, 2) Near-surface and bottom turbulent boundary layers; 3) Coastal trapped waves; 4) Steady and time-dependent wind- and density-driven flows; 5) Wind-mixing, tidal-mixing, tidal residual currents,

$- g\partial\zeta \,/\, \partial y$

Coastal Oceanic Fronts

1) Low-salinity front; 2) Tidal mixing front; 3) Shelf break front; 4) Upwelling front

1) Low-salinity front

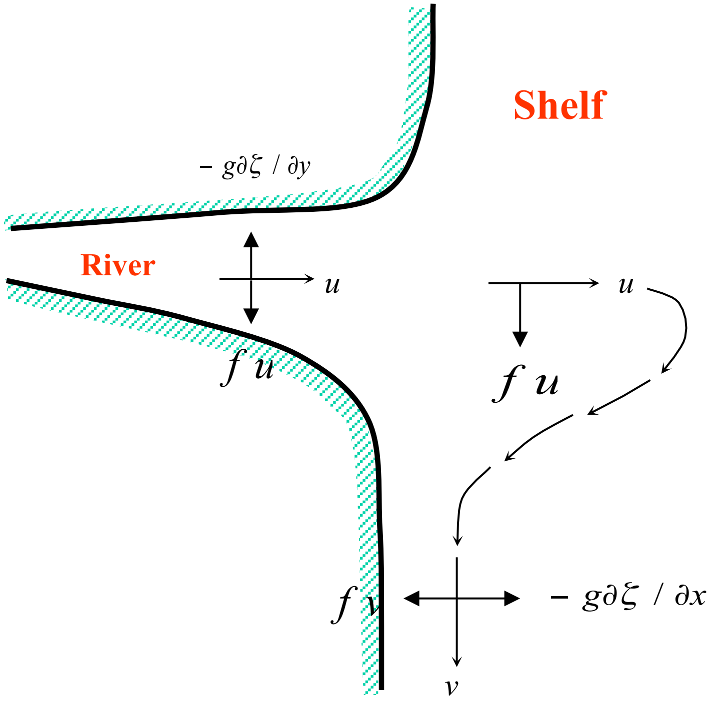
$$f\,u = -\frac{1}{\rho}\frac{\partial P}{\partial y}$$

$$\Big\downarrow$$

$$P = P_o + \rho g(\zeta - z)$$

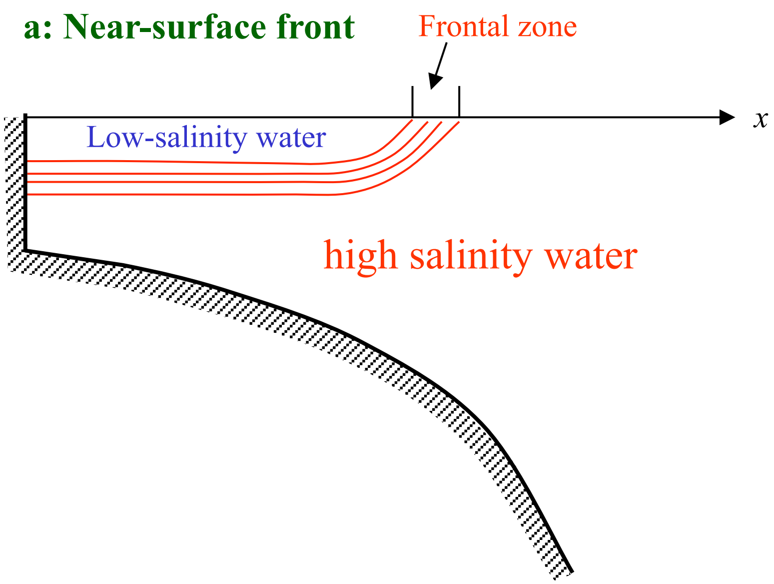
$$\Big\downarrow$$

$$f\,u = -g\frac{\partial \zeta}{\partial y}$$



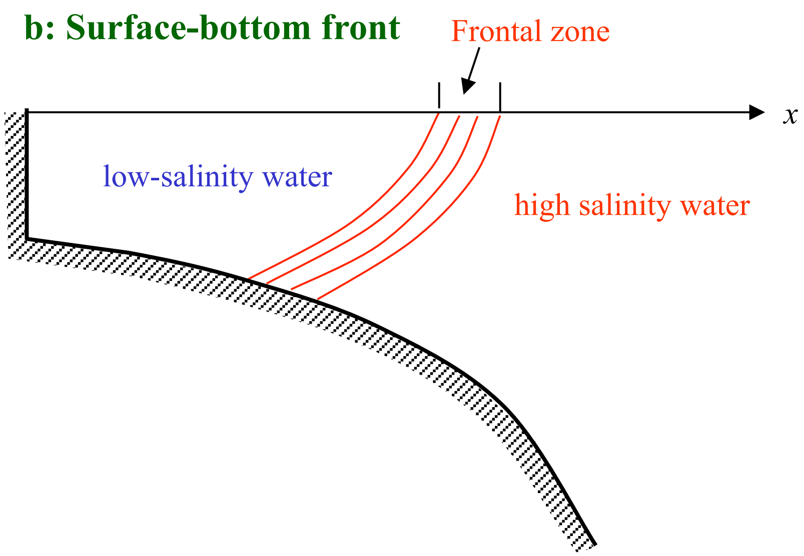
Low-salinity plume or estuarine plume

Decoupled from the bottom boundary layer


a: Near-surface front

Mixing is caused by shear instability at the interface between low and high salinity waters

Coupled with the bottom boundary layer


b: Surface-bottom front

Mixing is controlled by the dynamics of the bottom boundary layer.

Tidal Mixing Front

H/U^3 **(Simpson and Hunter , 1974)**

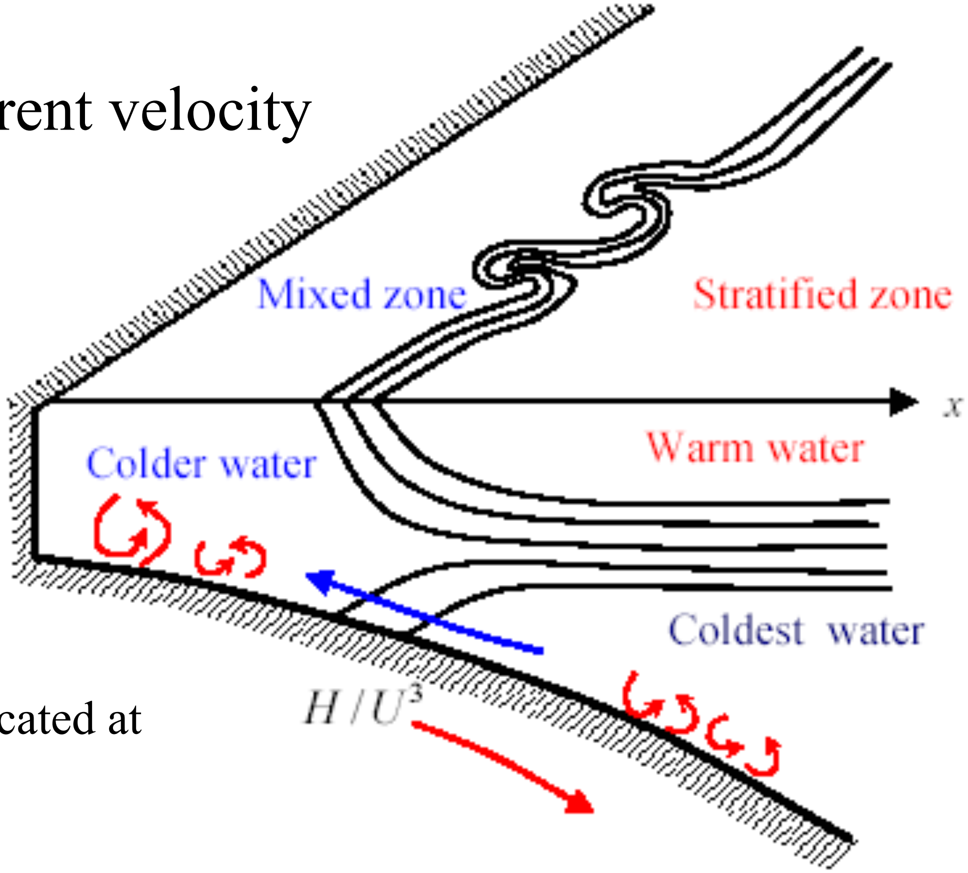
H: Water depth
U: Mean tidal current velocity

or

$$\log_{10}\frac{H}{D_t}$$

$$D_t = \rho C_D U^3$$

(turbulent dissipation)

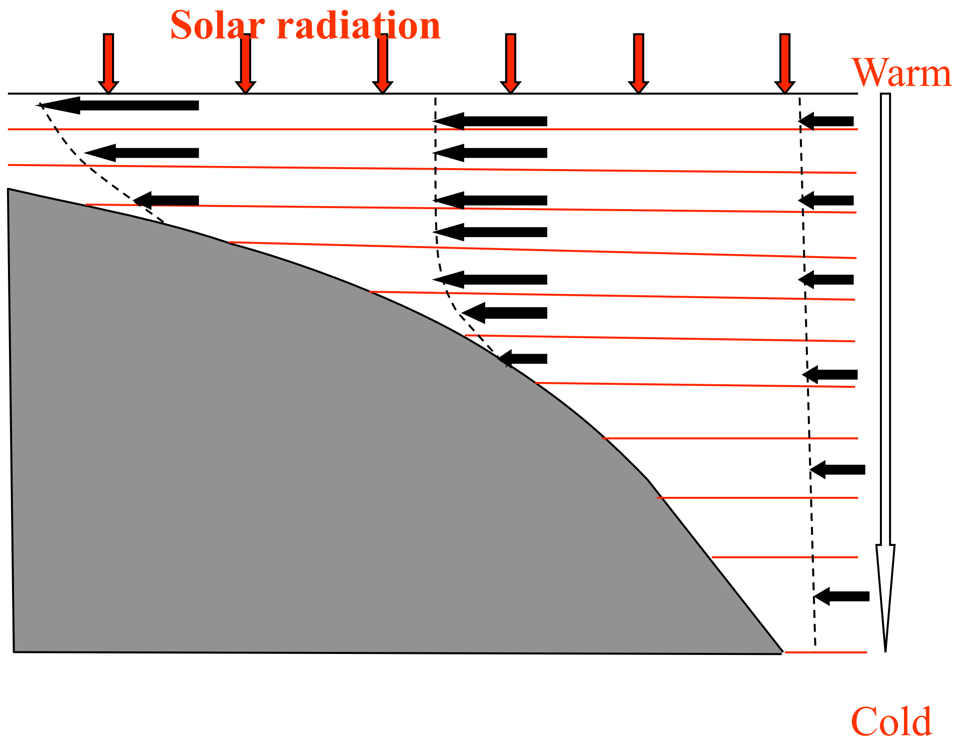


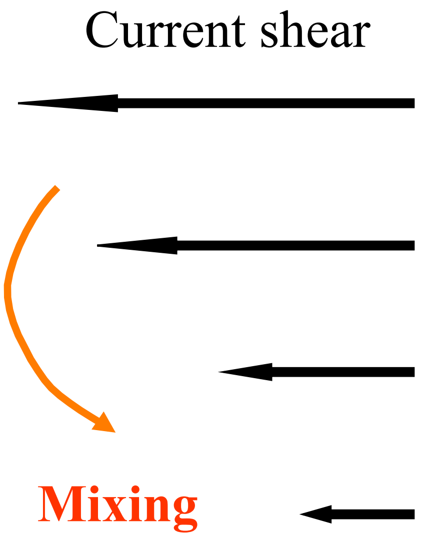
The tidal mixing front is located at

$$\log_{10}\frac{H}{D_t} = 1.9$$

Lecture 25: Coastal Ocean Process-Oceanic Frontal System (Continued)

1. Tidal Mixing Front (Tidal Front)

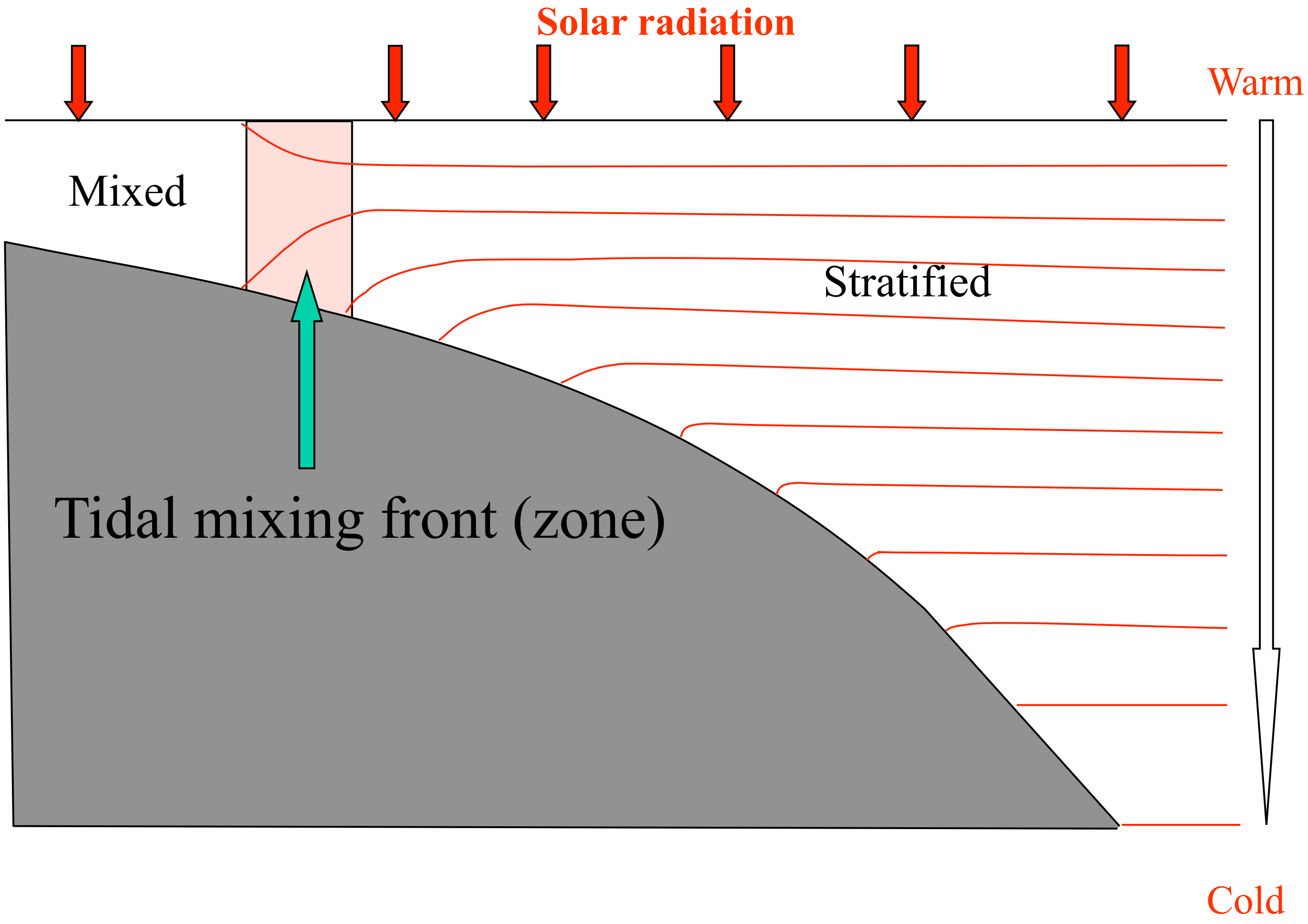




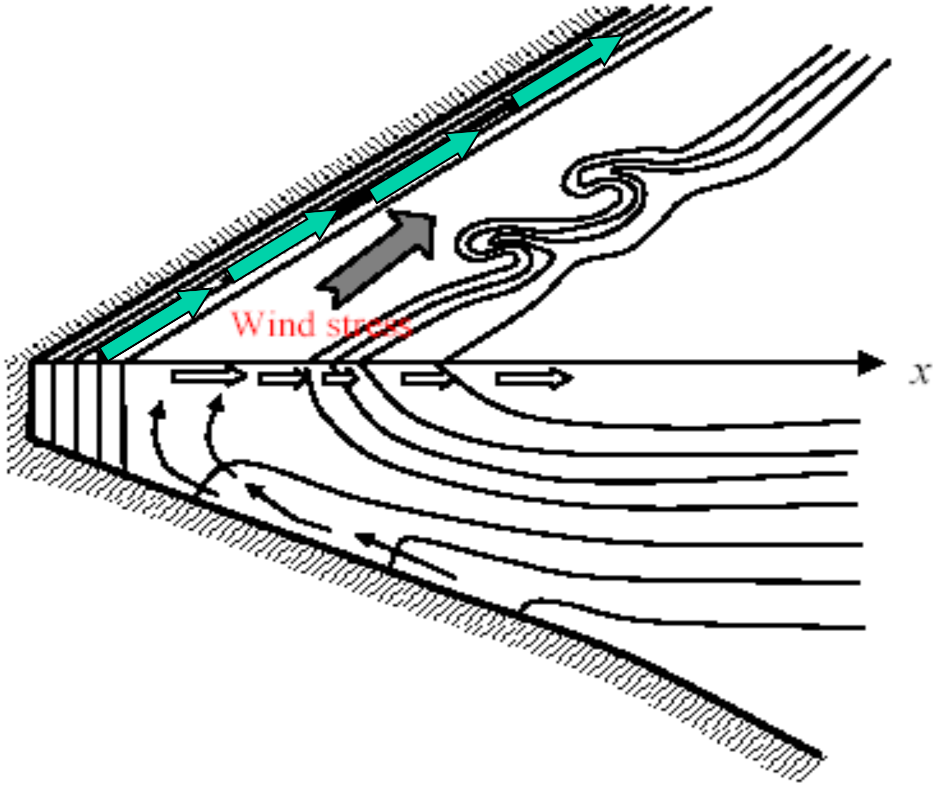
Two processes:

a) Surface buoyancy flux produced by the solar radiation: make the water stratified

b) Kinetic energy dissipation caused by tidal currents: mix the water

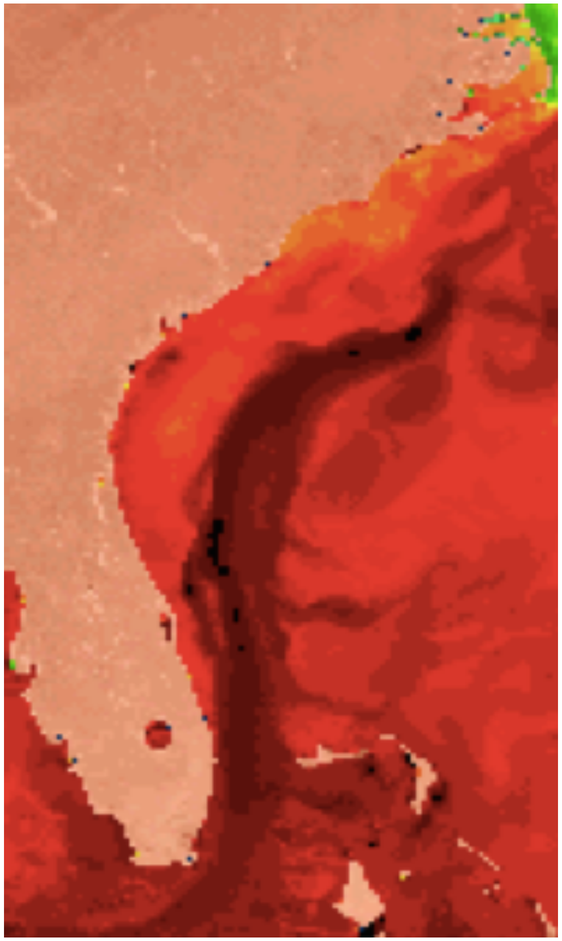


Upwelling Front

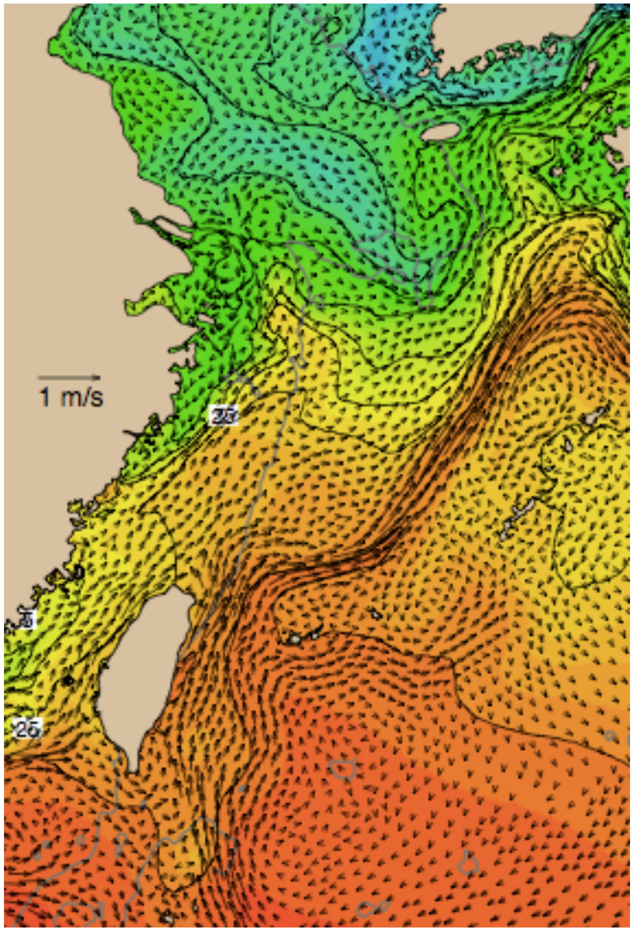


Shelf-break fronts

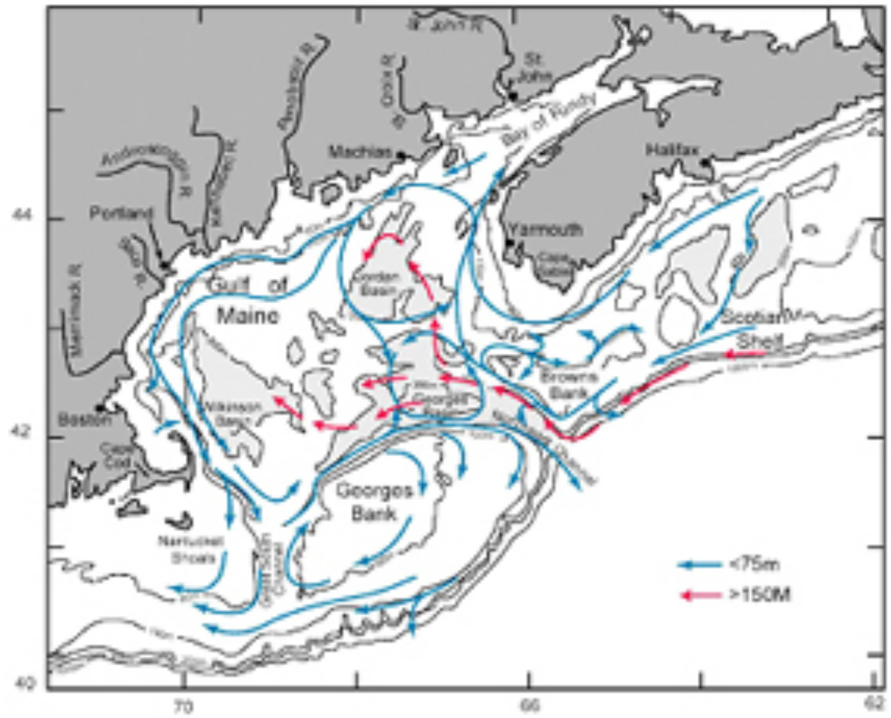
Gulf Stream

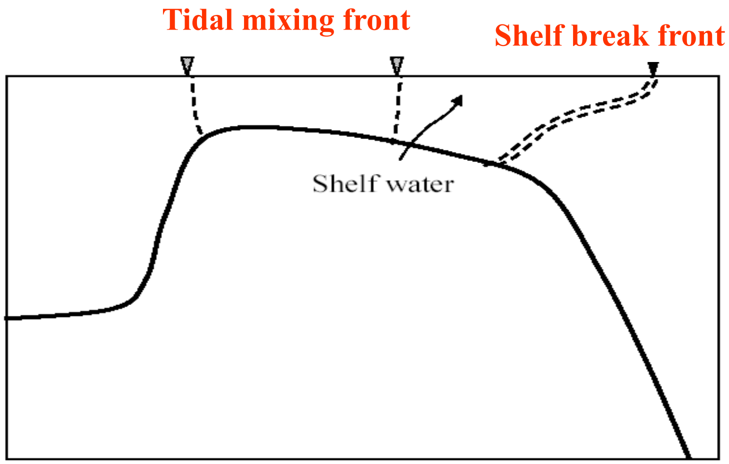


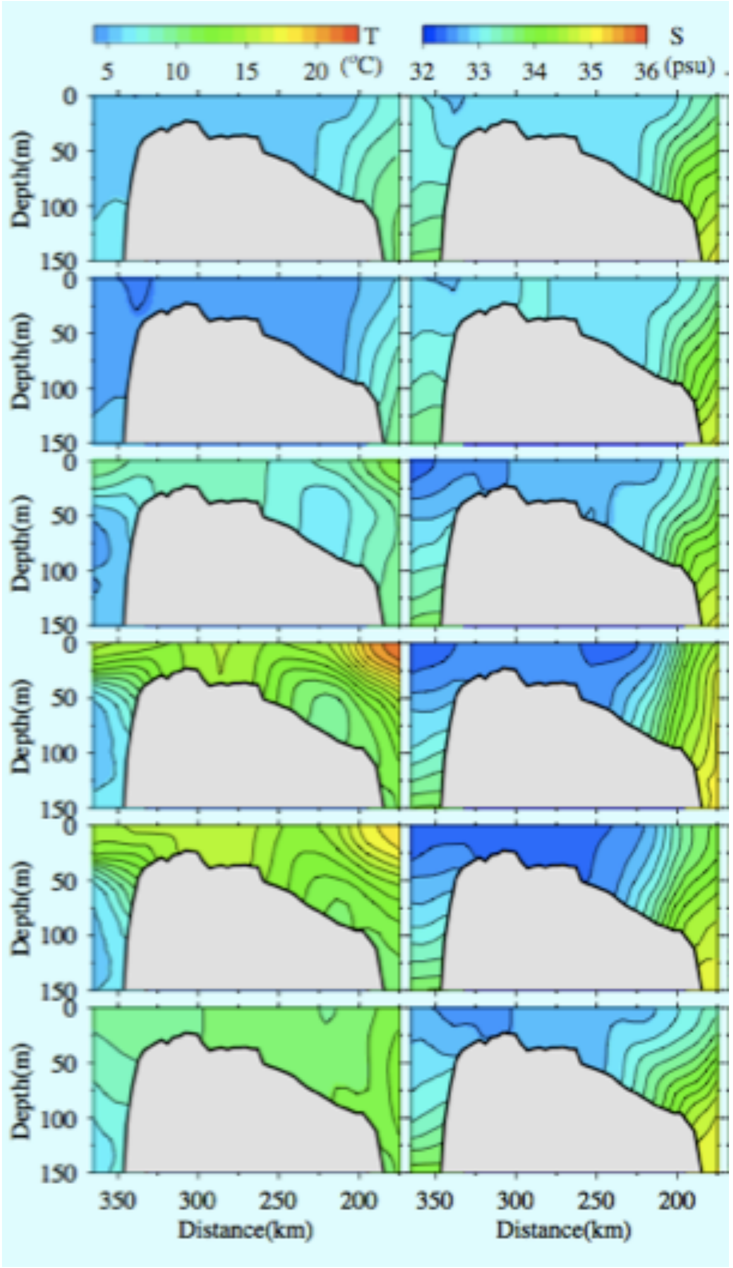
Kuroshio



Shelf Break Front on the southern flank of Georges Bank







Jan-Feb

Mar-Apr

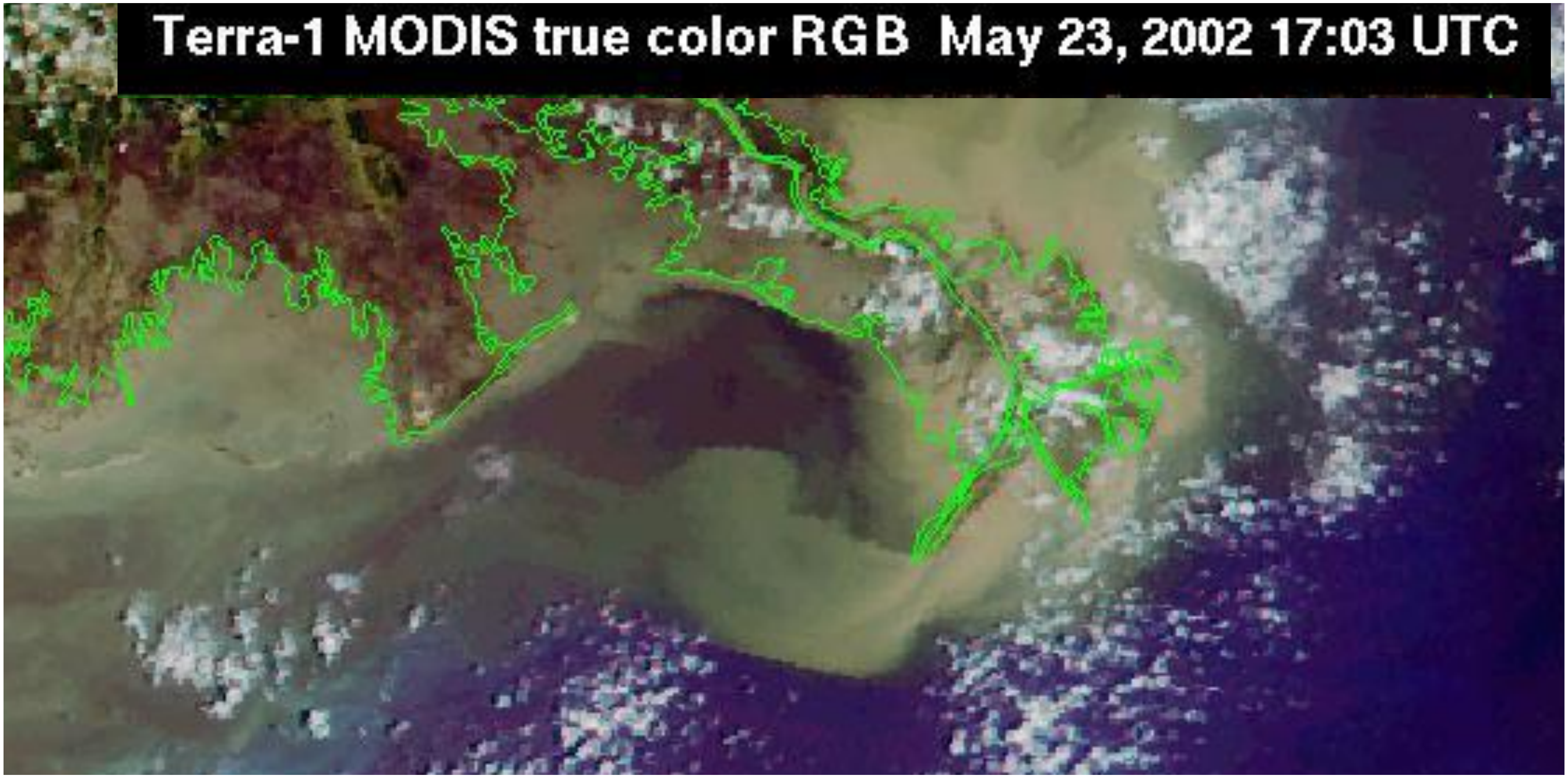
May-Jun

Jul-Aug

Sept-Oct

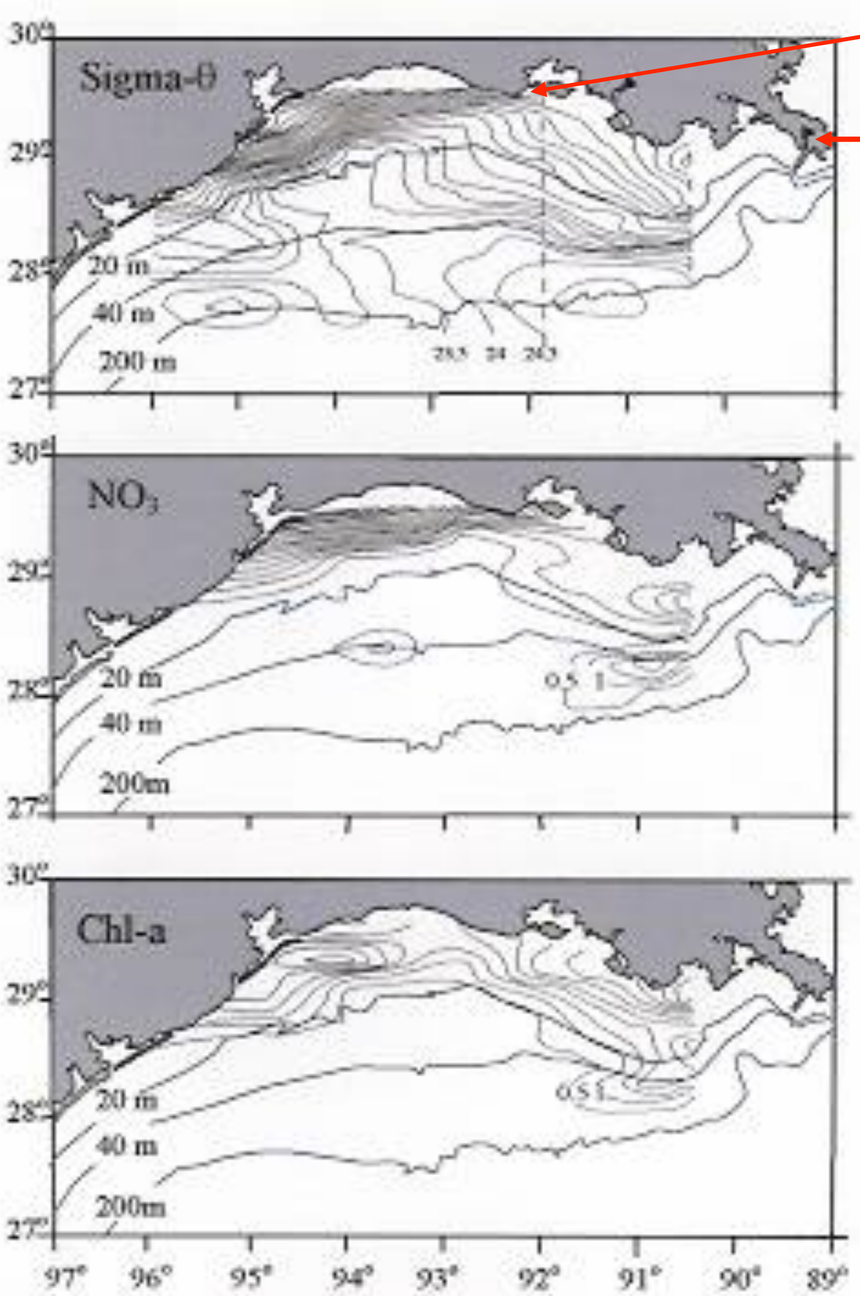
Nov-Dec

Example I of river plume: The Mississippi River



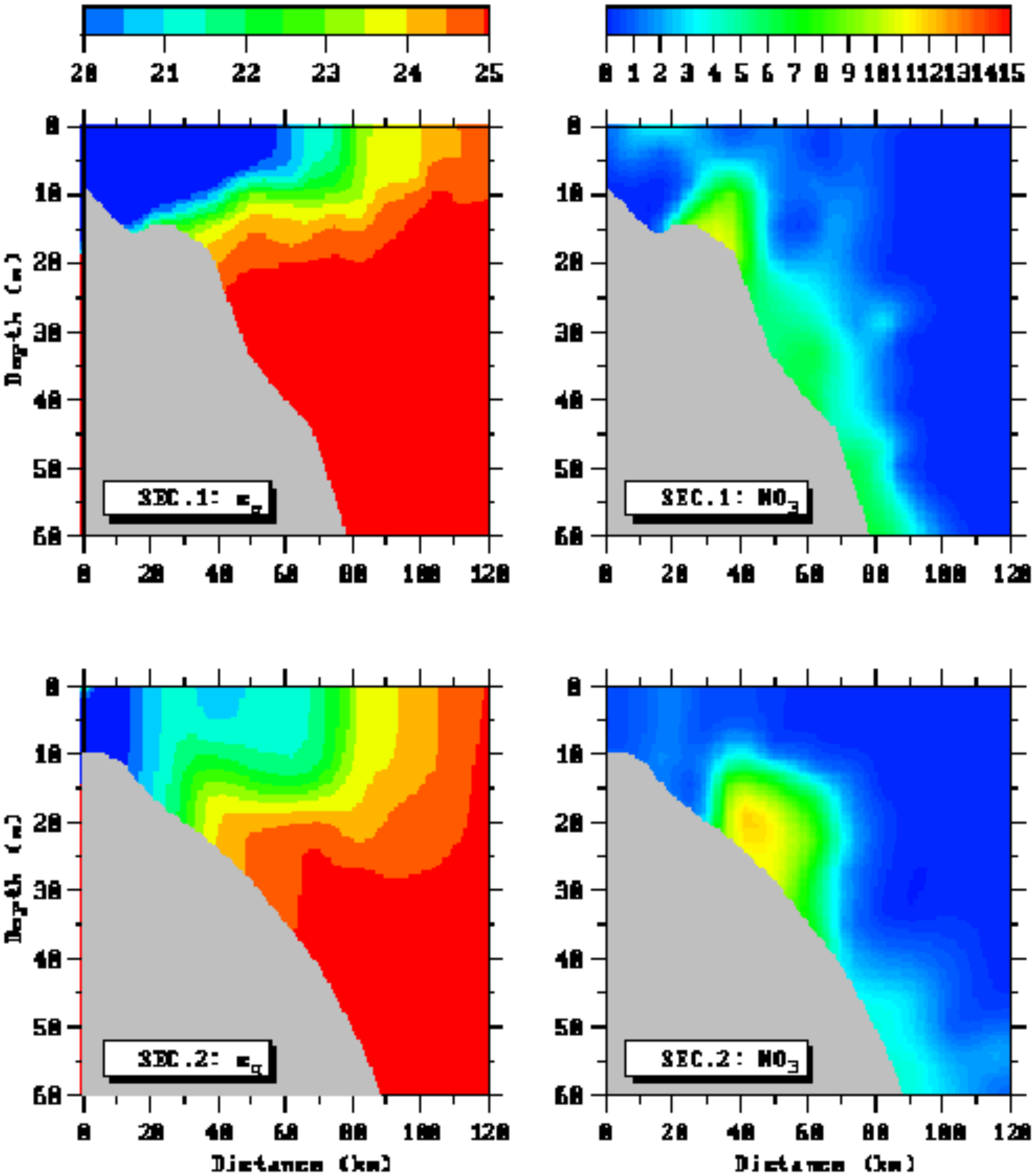
From Dr. Justic at LSU

LATEX shelf

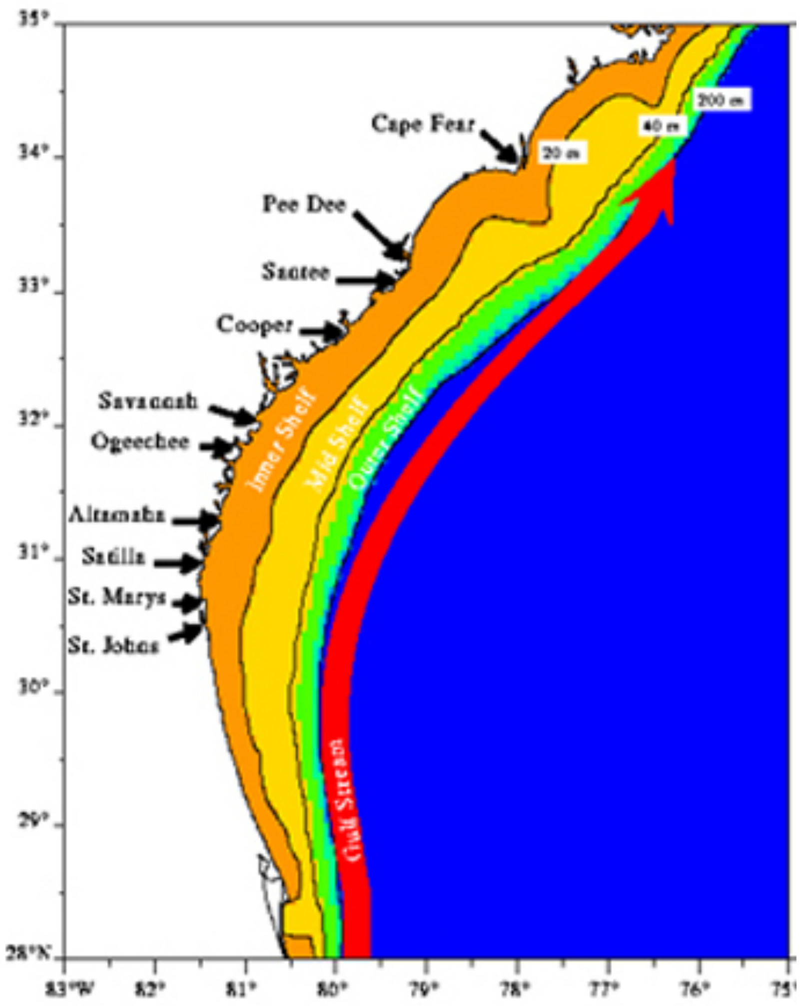


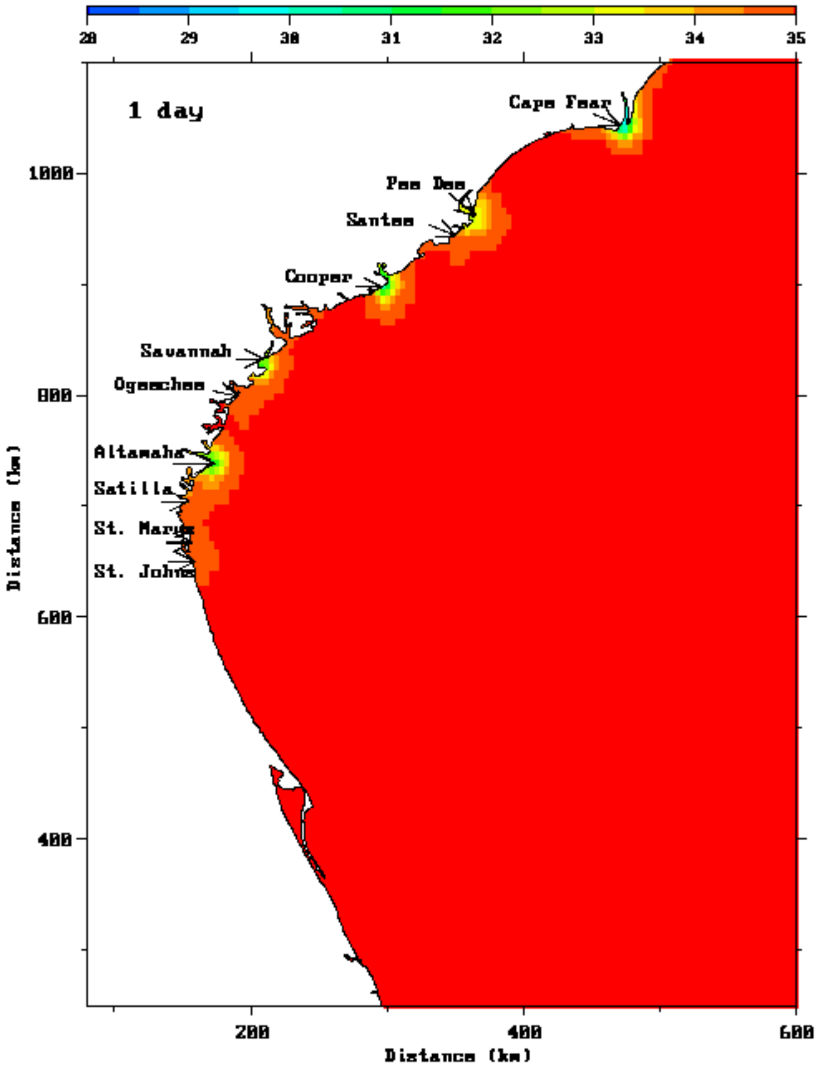
Atchafalaya River

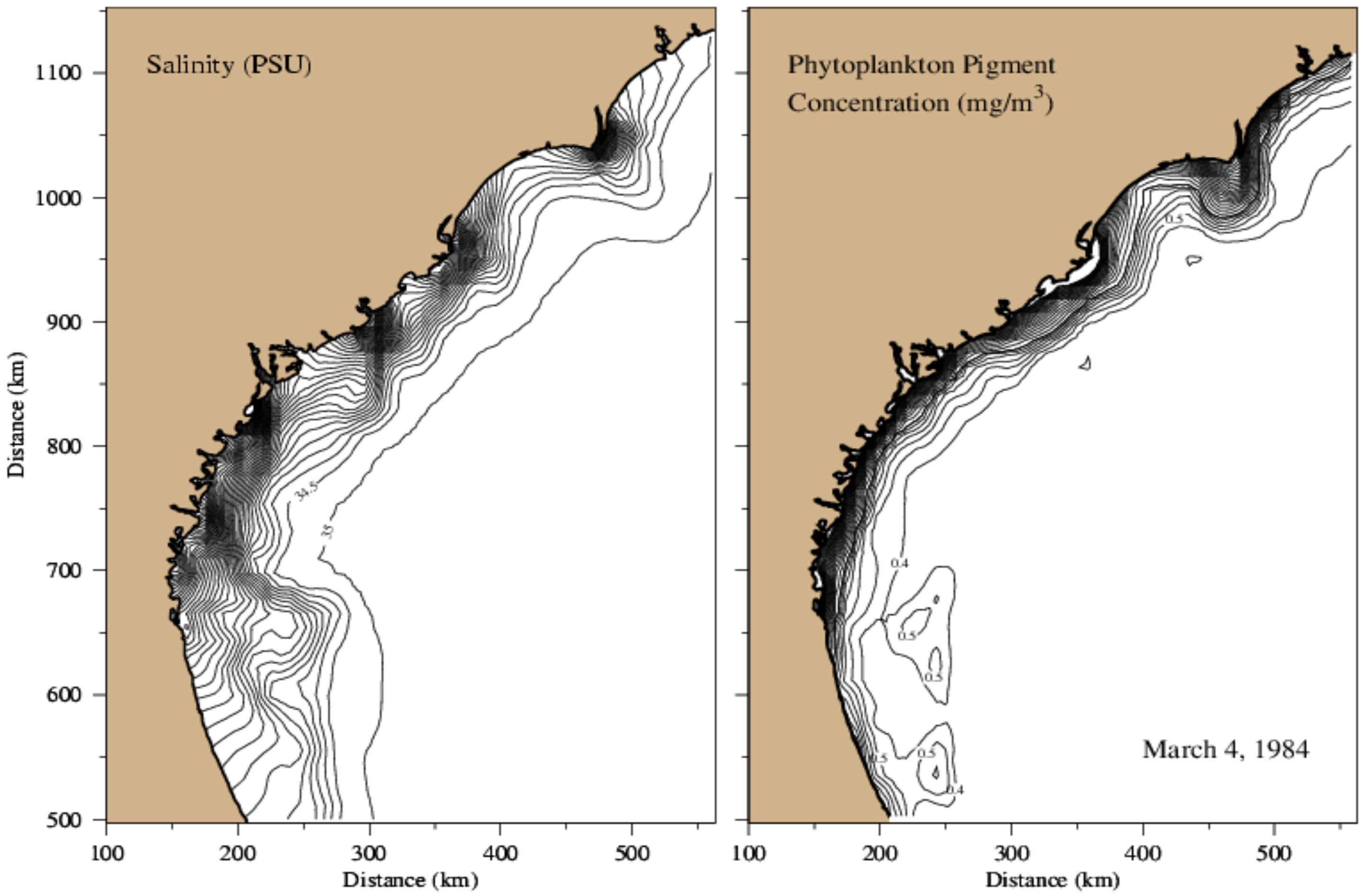
Mississippi River


20
21
22
23
24
25
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Depth (m)
0
10
20
30
40
50
60
SEC.1: σ_θ
SEC.1: NO_3
SEC.2: σ_θ
SEC.2: NO_3
0
20
40
60
80
100
120
Distance (km)

Example II of river plume: South Atlantic Bight



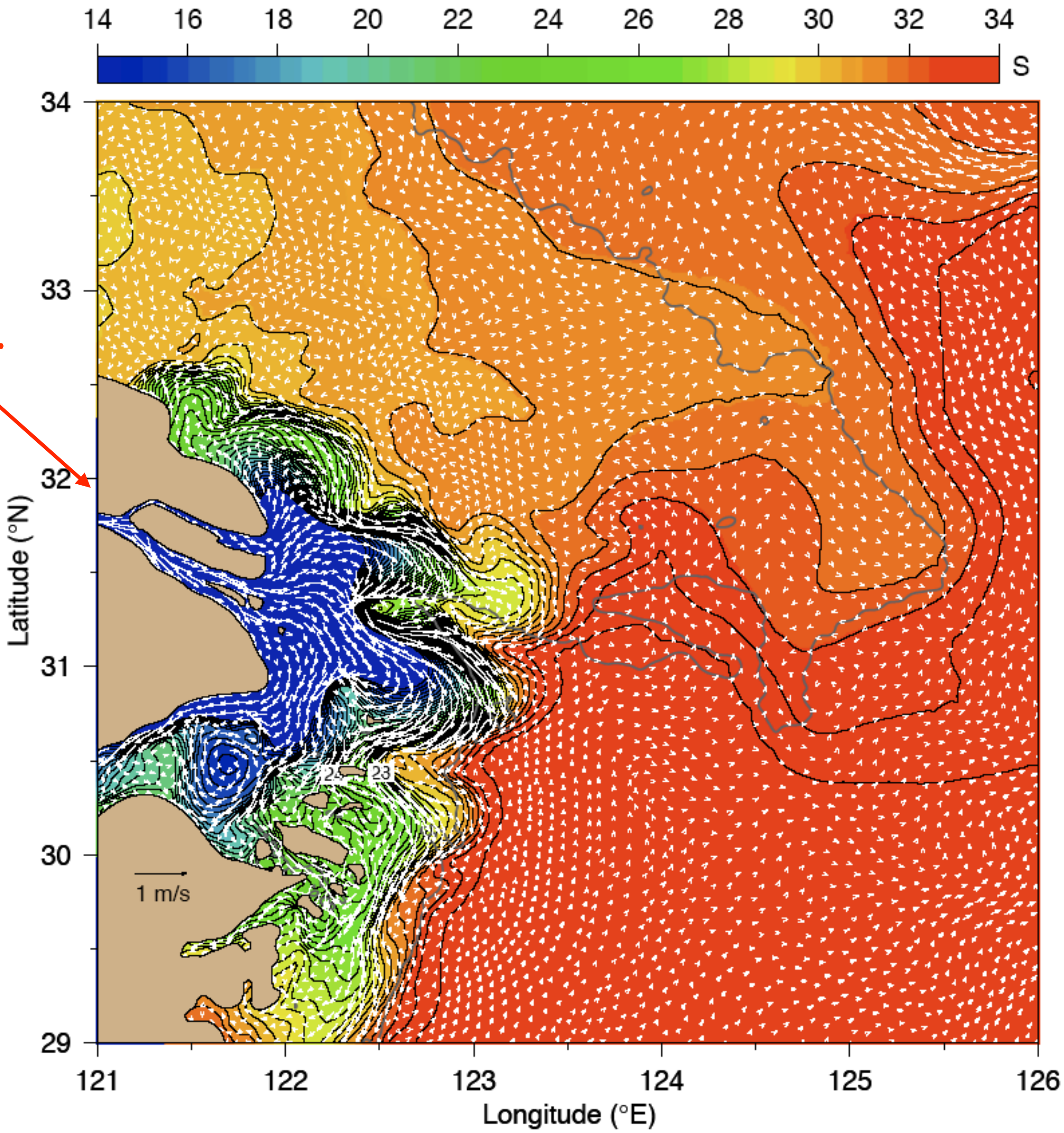



Salinity (PSU)

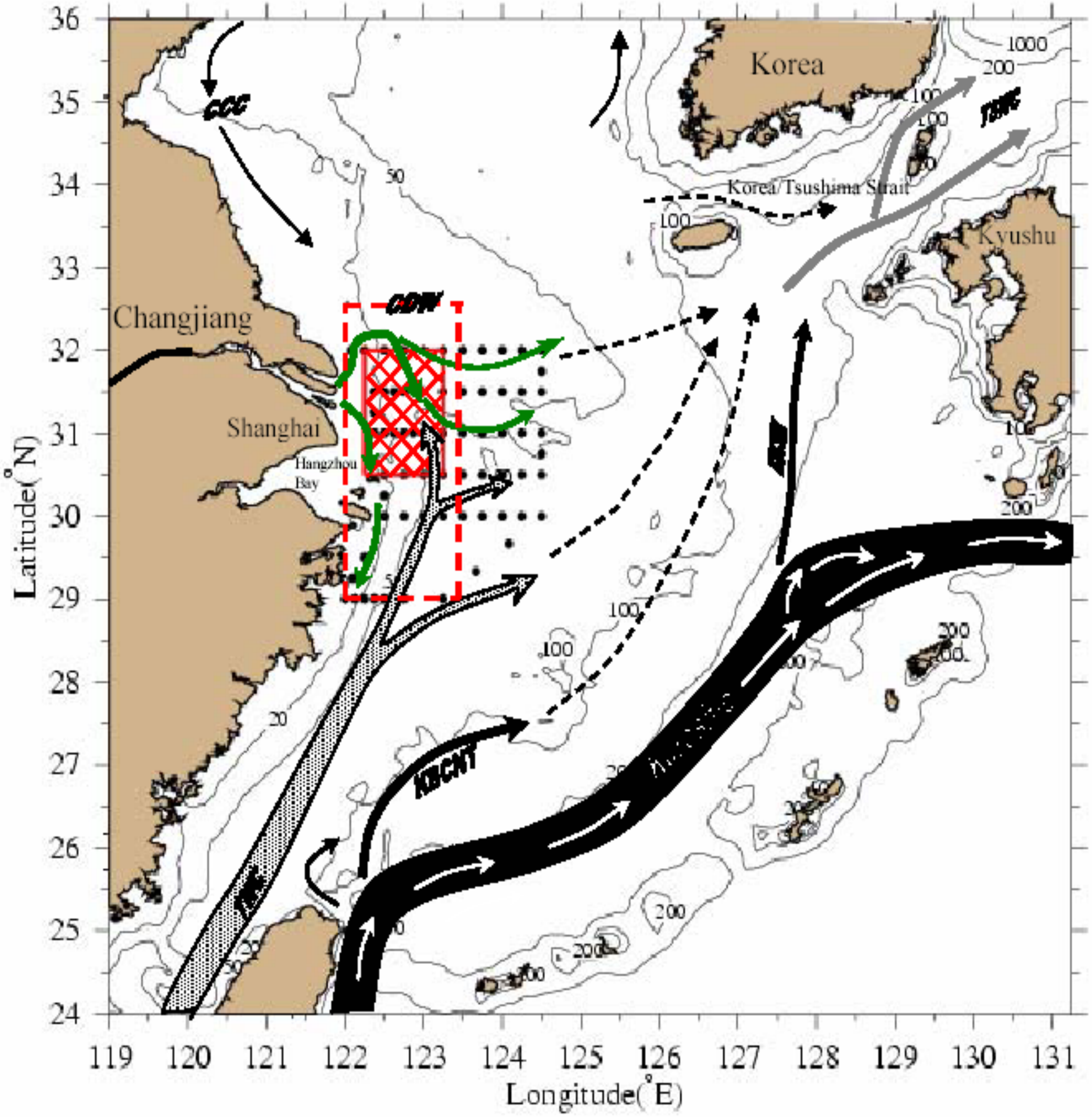
Phytoplankton Pigment Concentration (mg/m^3)

March 4, 1984

Example III of river plume: The Changjiang River



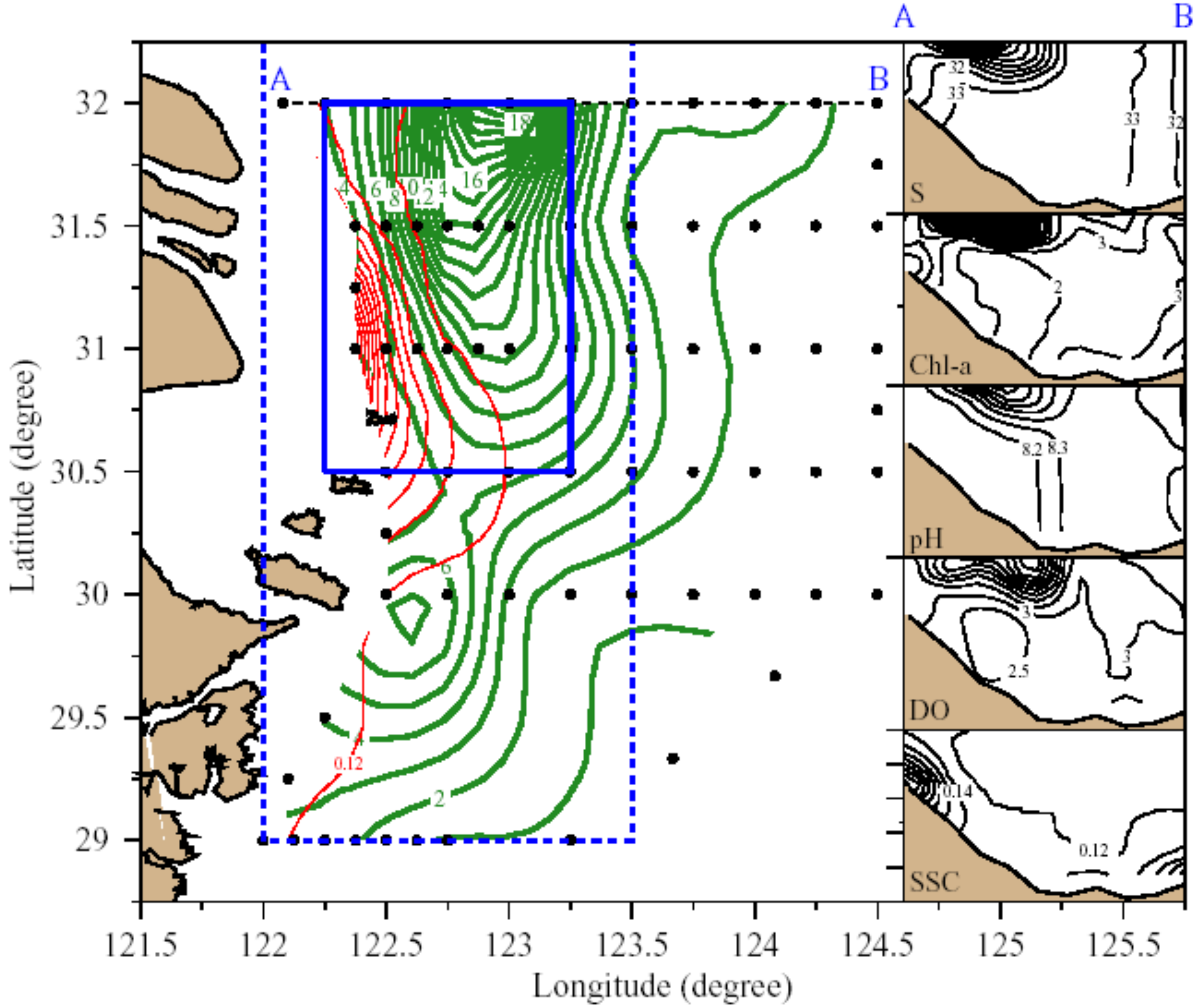
Changjiang River

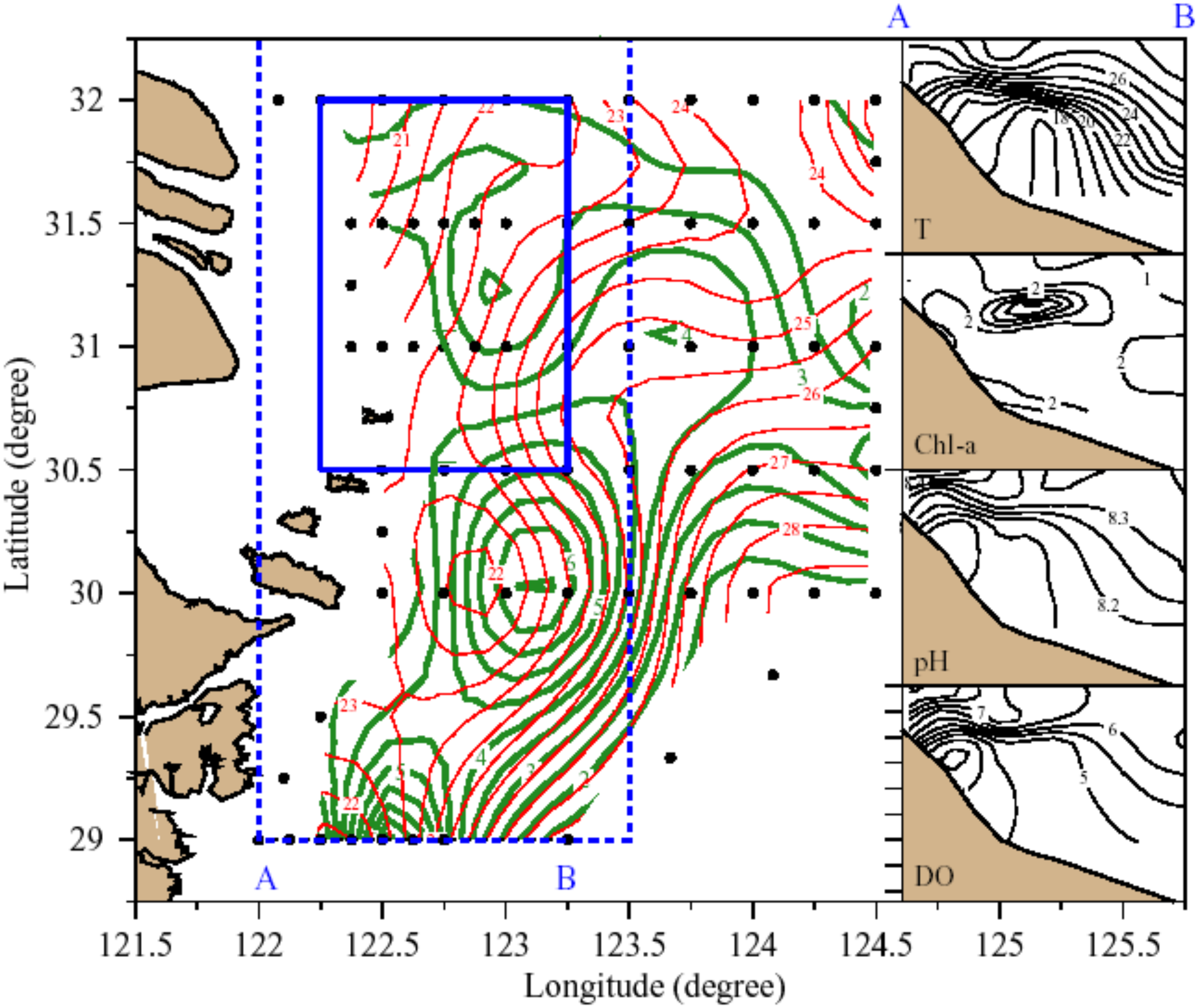

Korea
Kyushu
Korea/Tsushima Strait
Changjiang
Shanghai
Hangzhou Bay
CCC
CDW
TWC
KBCNT
Kuroshio
1000
200
100
50
20
Latitude(°N)
Longitude(°E)
36
35
34
33
32
31
30
29
28
27
26
25
24
119
120
121
122
123
124
125
126
127
128
129
130
131

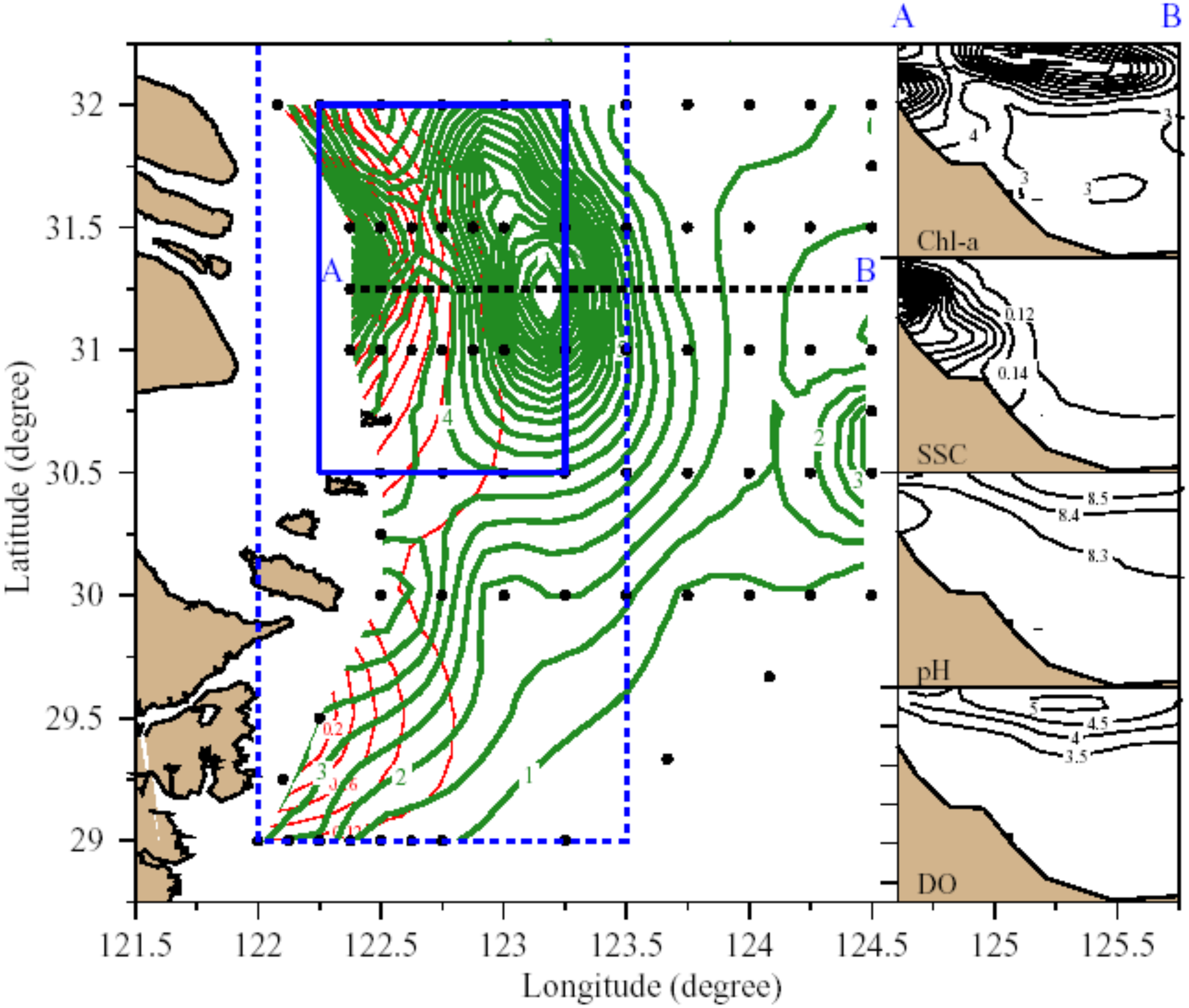
Nutrients due to the Changjiang River Discharge

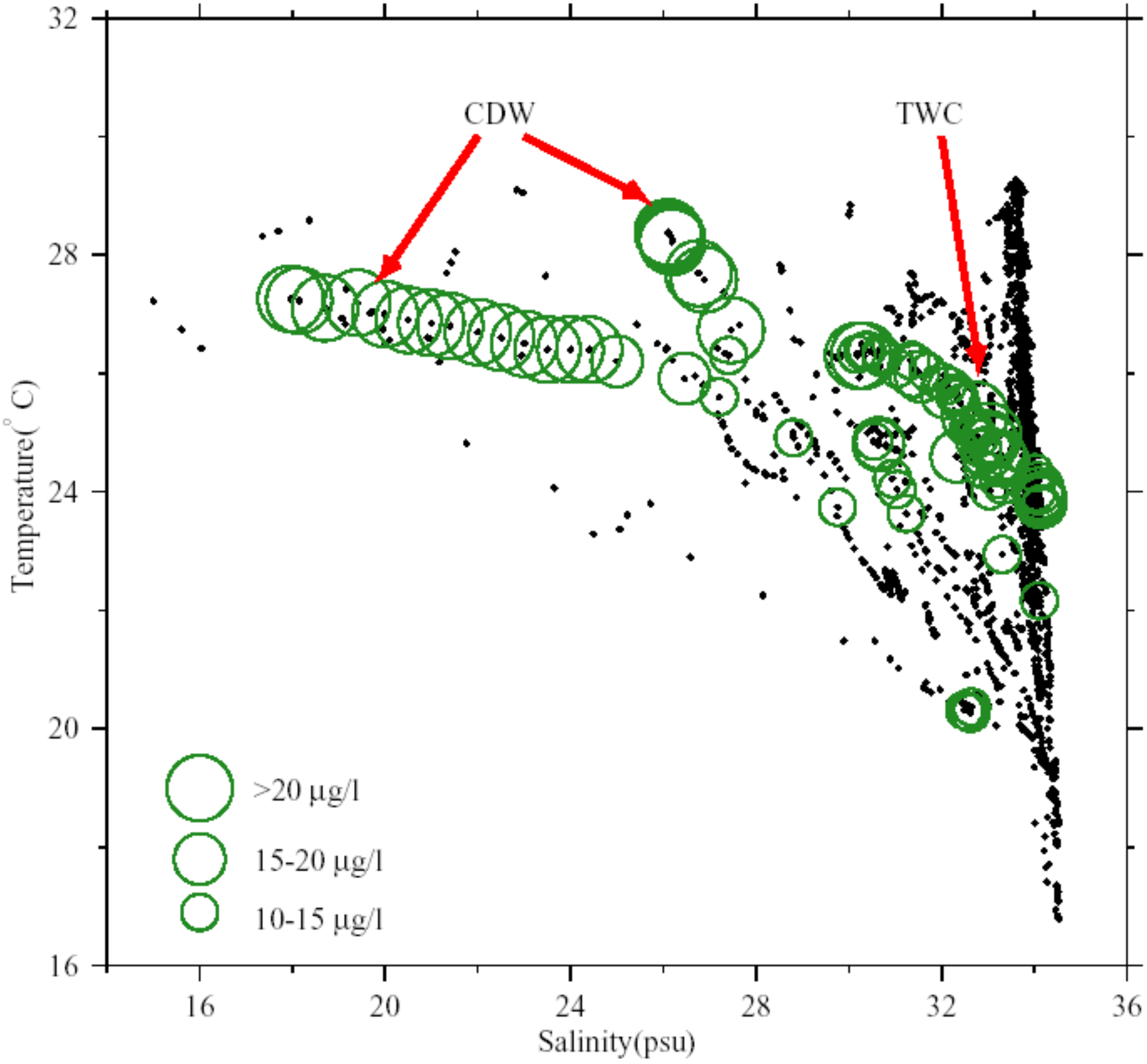
Year	DIN (μmol N/L)	DIP (μmol P/L)	DIN/DIP
1986	9	0.58	16
1992	56	0.68	82
1997	106	>0.91	117 (450)

DIN: Dissolved inogranic nitrogen
DIP: Dissovled inorganic phosphorus


A
B
A
B
Latitude (degree)
Longitude (degree)
32
31.5
31
30.5
30
29.5
29
121.5
122
122.5
123
123.5
124
124.5
125
125.5
18
16
4
6
8
10
12
14
6
2
0.12
S
32
33
33
32
Chl-a
3
2
3
pH
8.2
8.3
DO
3
2.5
3
SSC
0.14
0.12

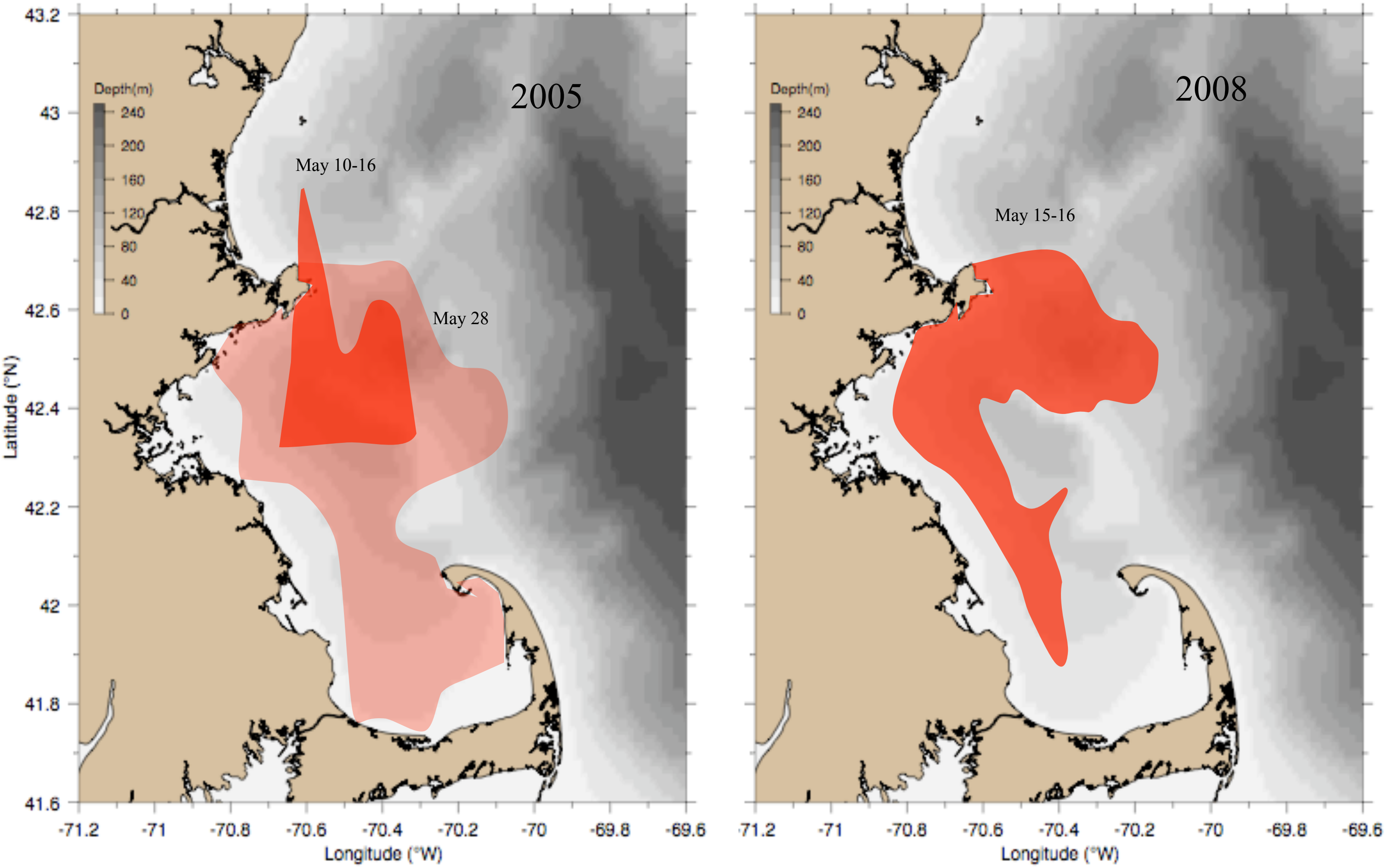

A
B
A
B
T
Chl-a
pH
DO
Latitude (degree)
Longitude (degree)
32
31.5
31
30.5
30
29.5
29
121.5
122
122.5
123
123.5
124
124.5
125
125.5
21
22
23
24
25
26
27
28
2
3
4
5
6
18
20
8.3
8.2
7


A
B
A
B
Latitude (degree)
32
31.5
31
30.5
30
29.5
29
Longitude (degree)
121.5
122
122.5
123
123.5
124
124.5
125
125.5
4
2
3
1
3
2
0.2
0.6
0.12
Chl-a
4
3
3
3
SSC
0.12
0.14
pH
8.5
8.4
8.3
DO
5
4.5
4
3.5

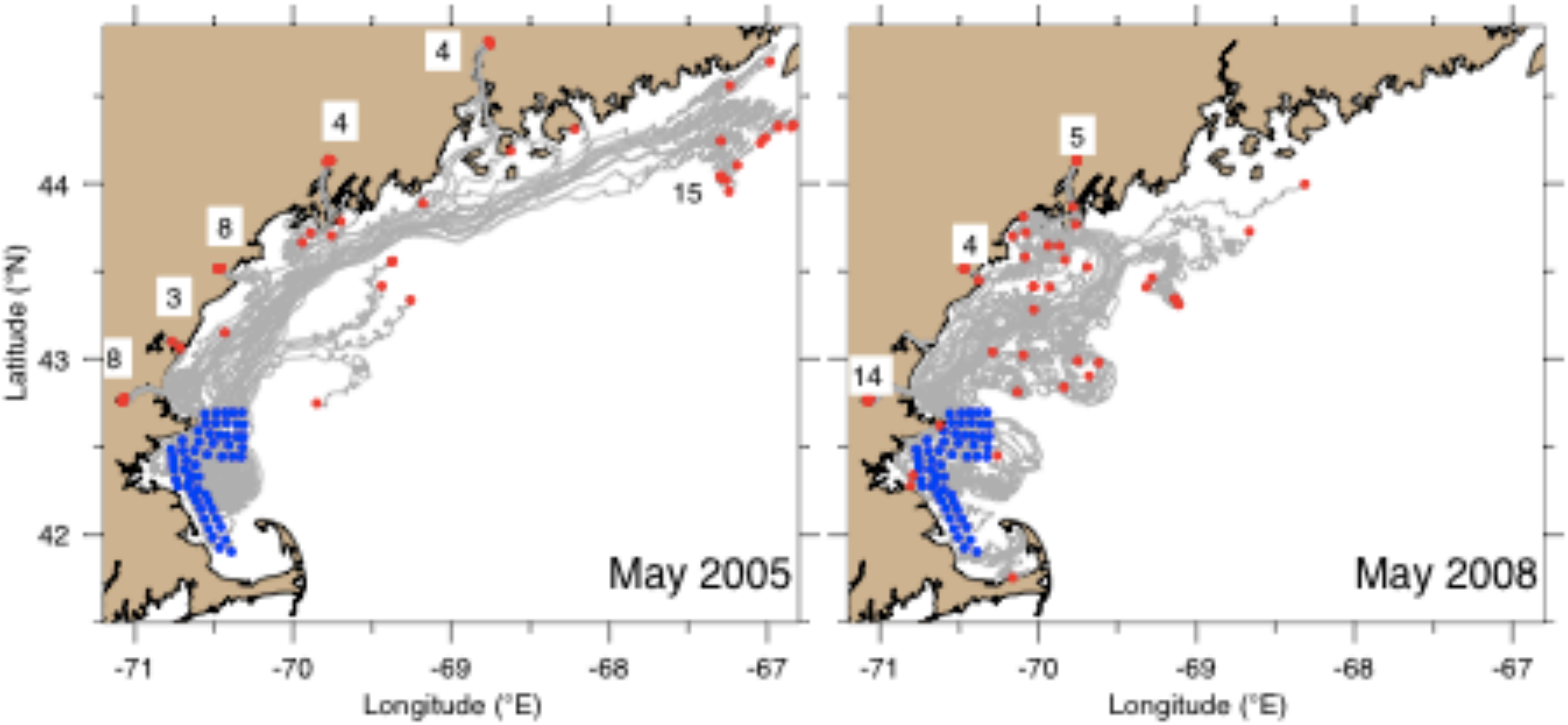


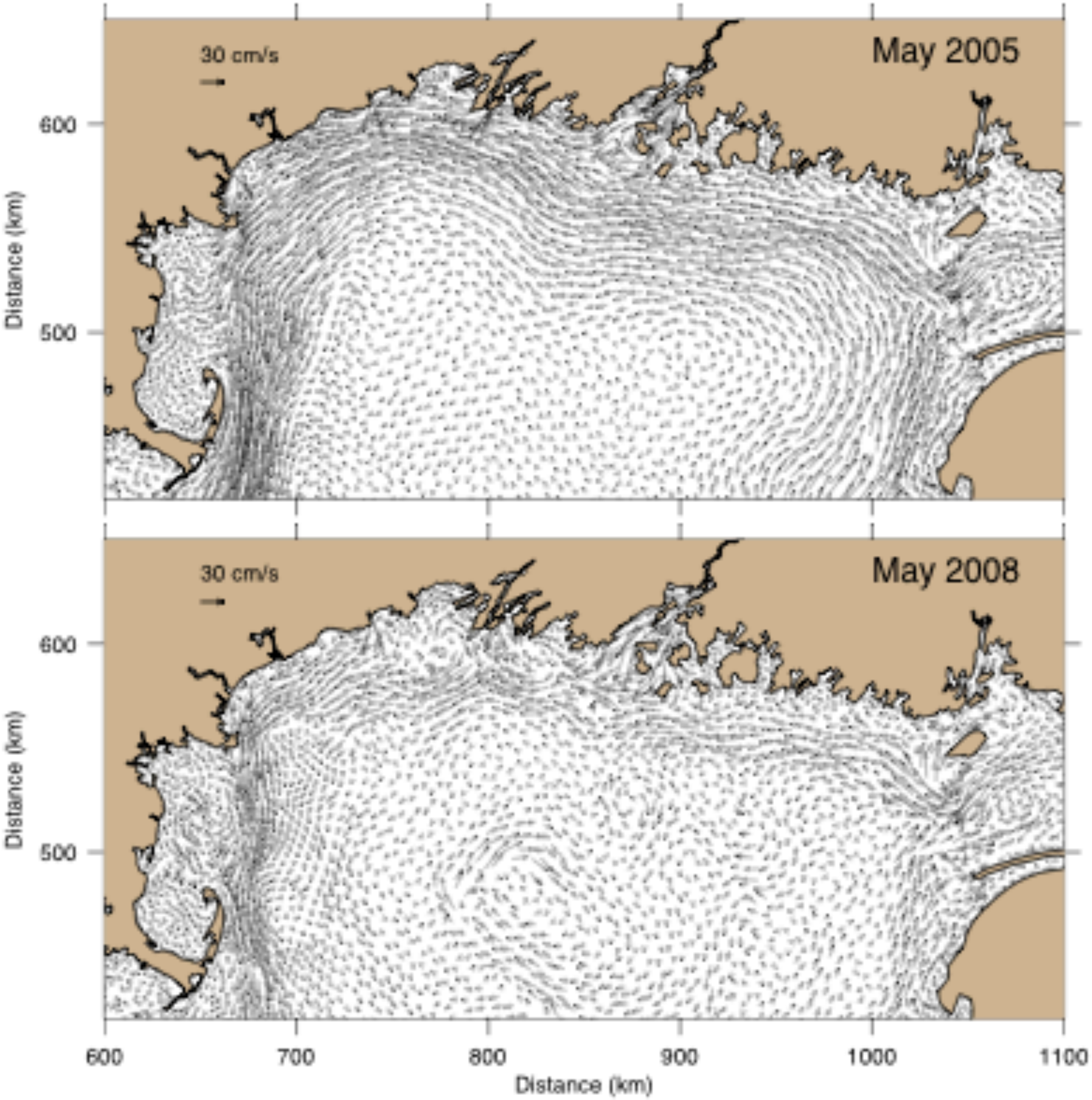
32
28
24
20
16
Temperature(° C)
16
20
24
28
32
36
Salinity(psu)
CDW
TWC
>20 µg/l
15-20 µg/l
10-15 µg/l

The Red Tide in the Massachusetts Bay

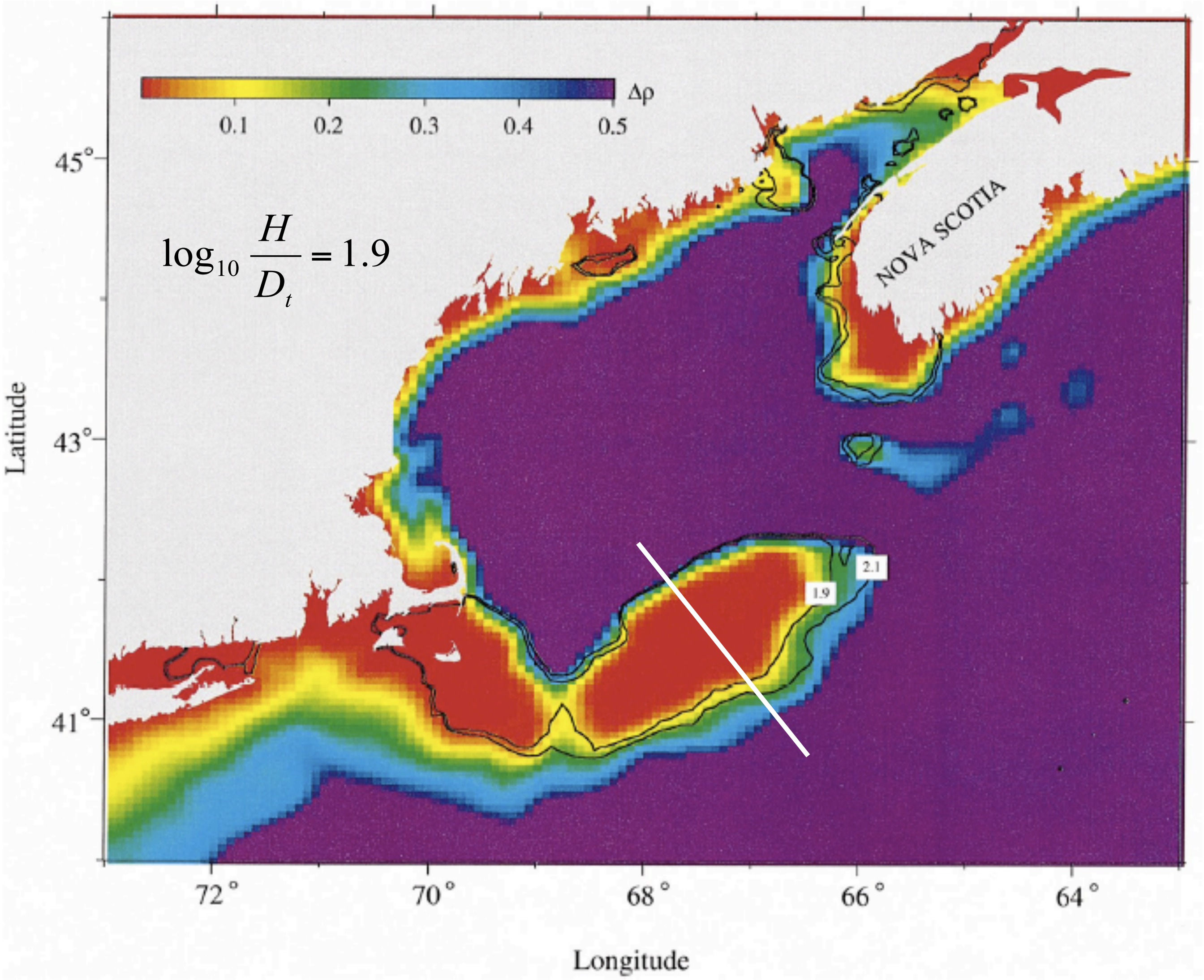


Inverse particle tracking

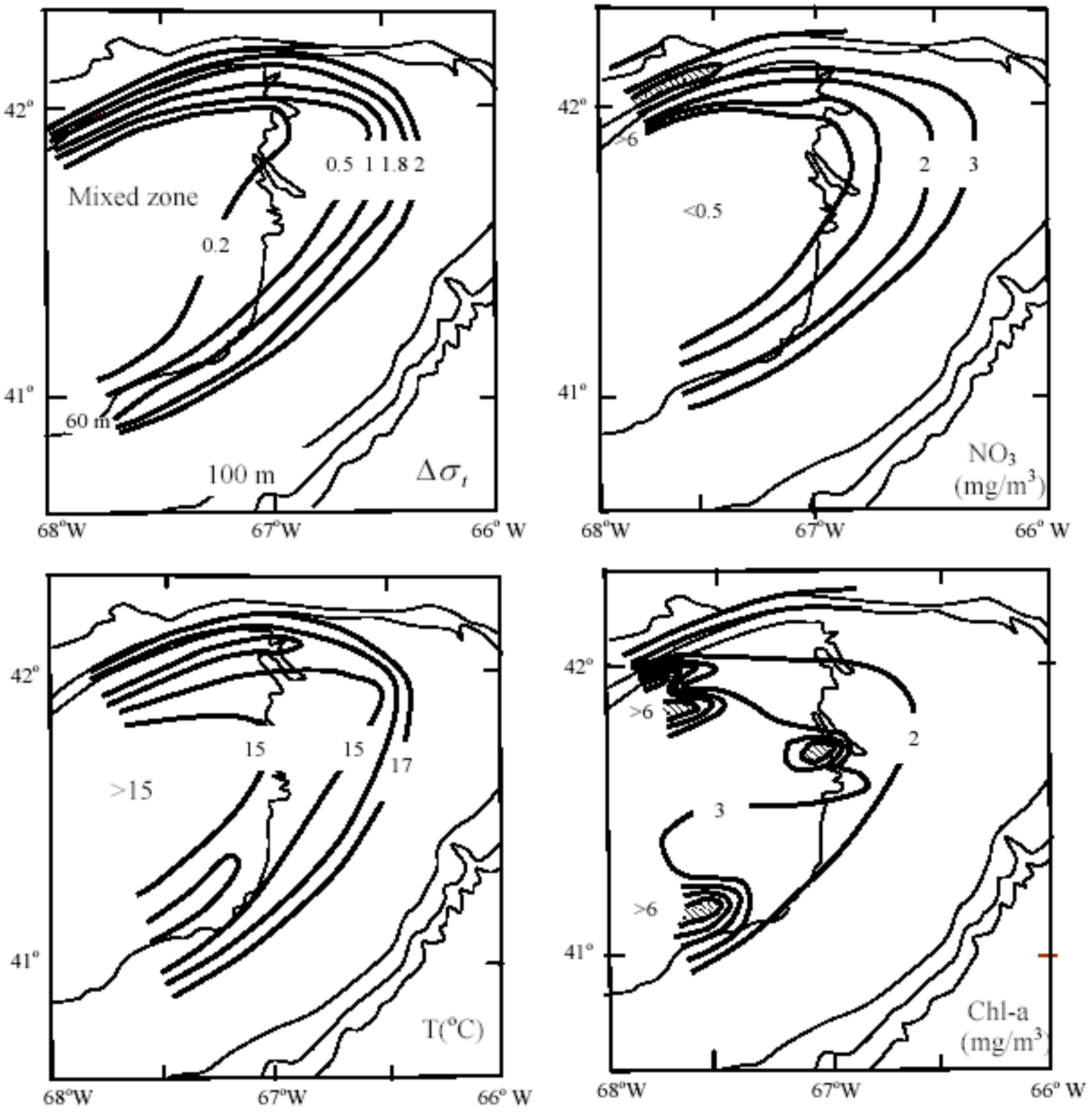


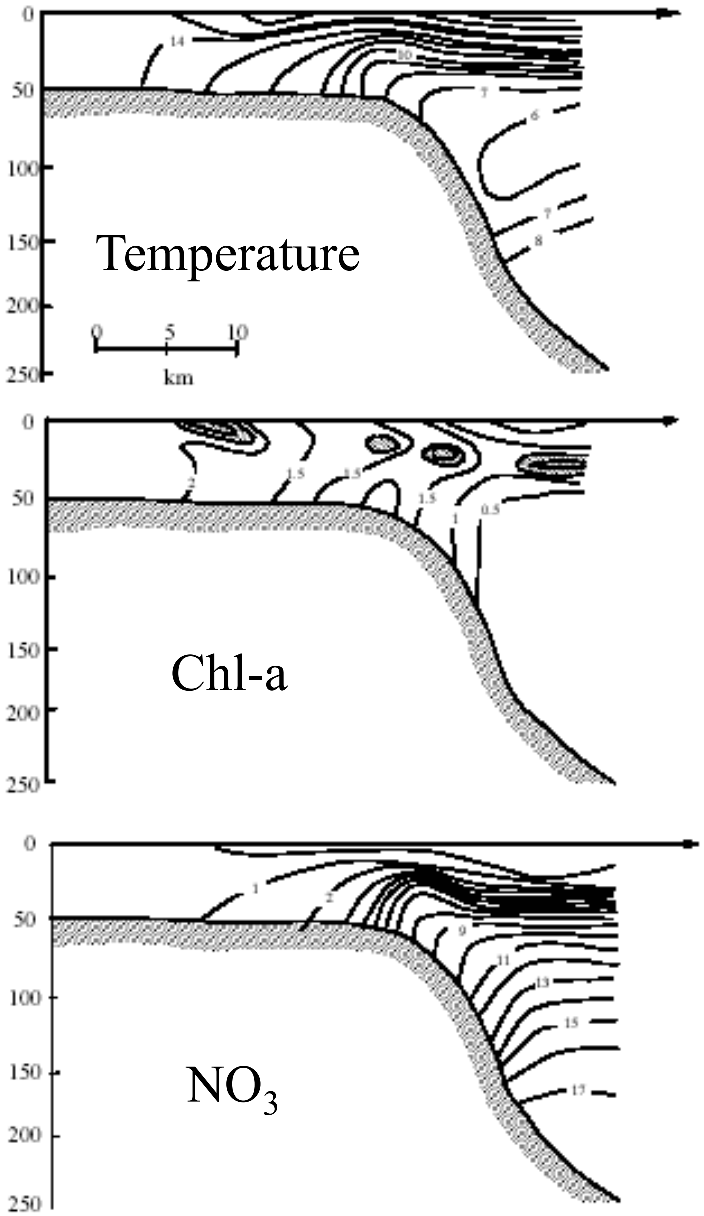

30 cm/s
May 2005
30 cm/s
May 2008
600
500
Distance (km)
600
700
800
900
1000
1100
Distance (km)

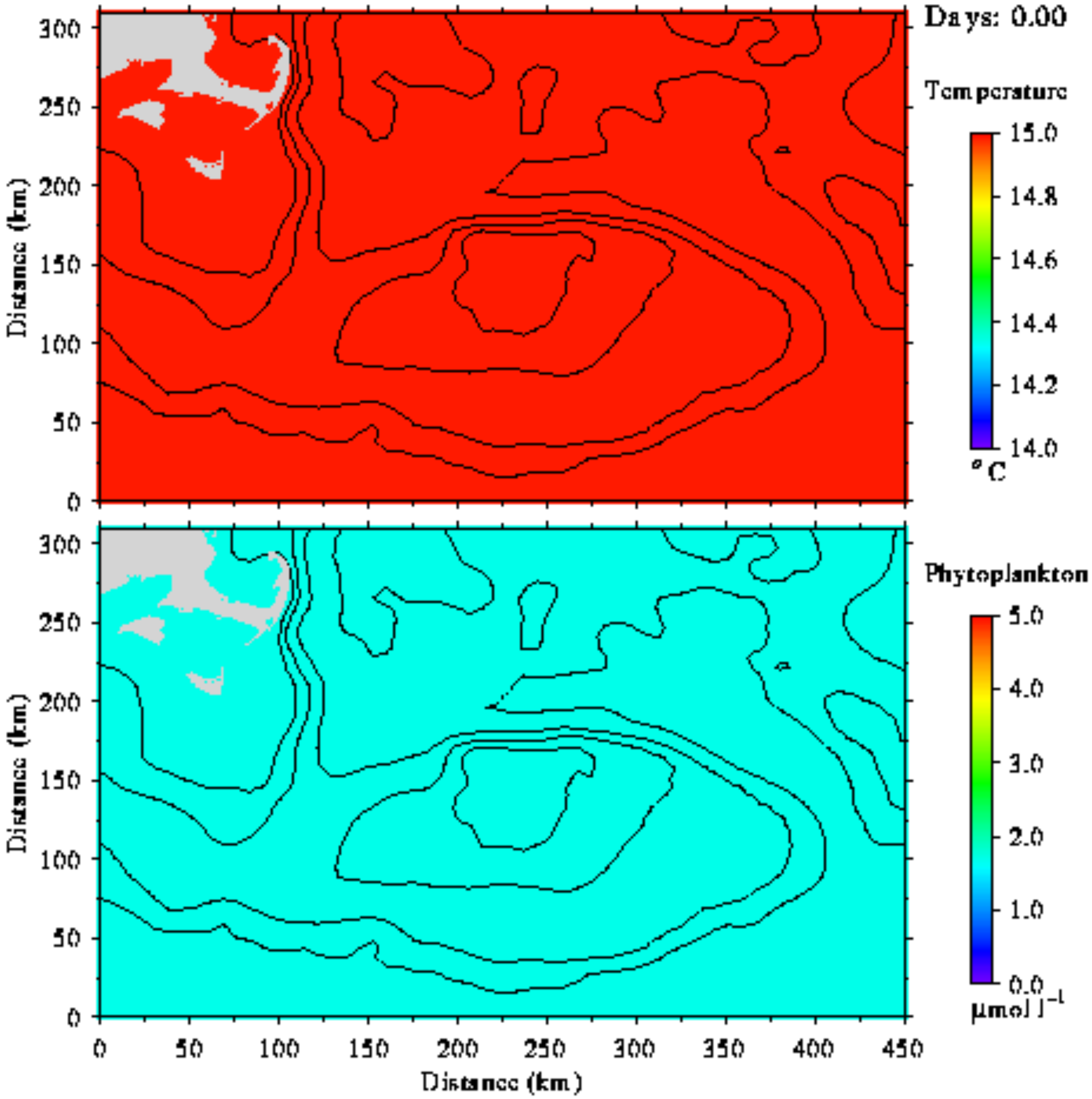
Example of tidal mixing front: The Gulf of Maine/Georges Bank

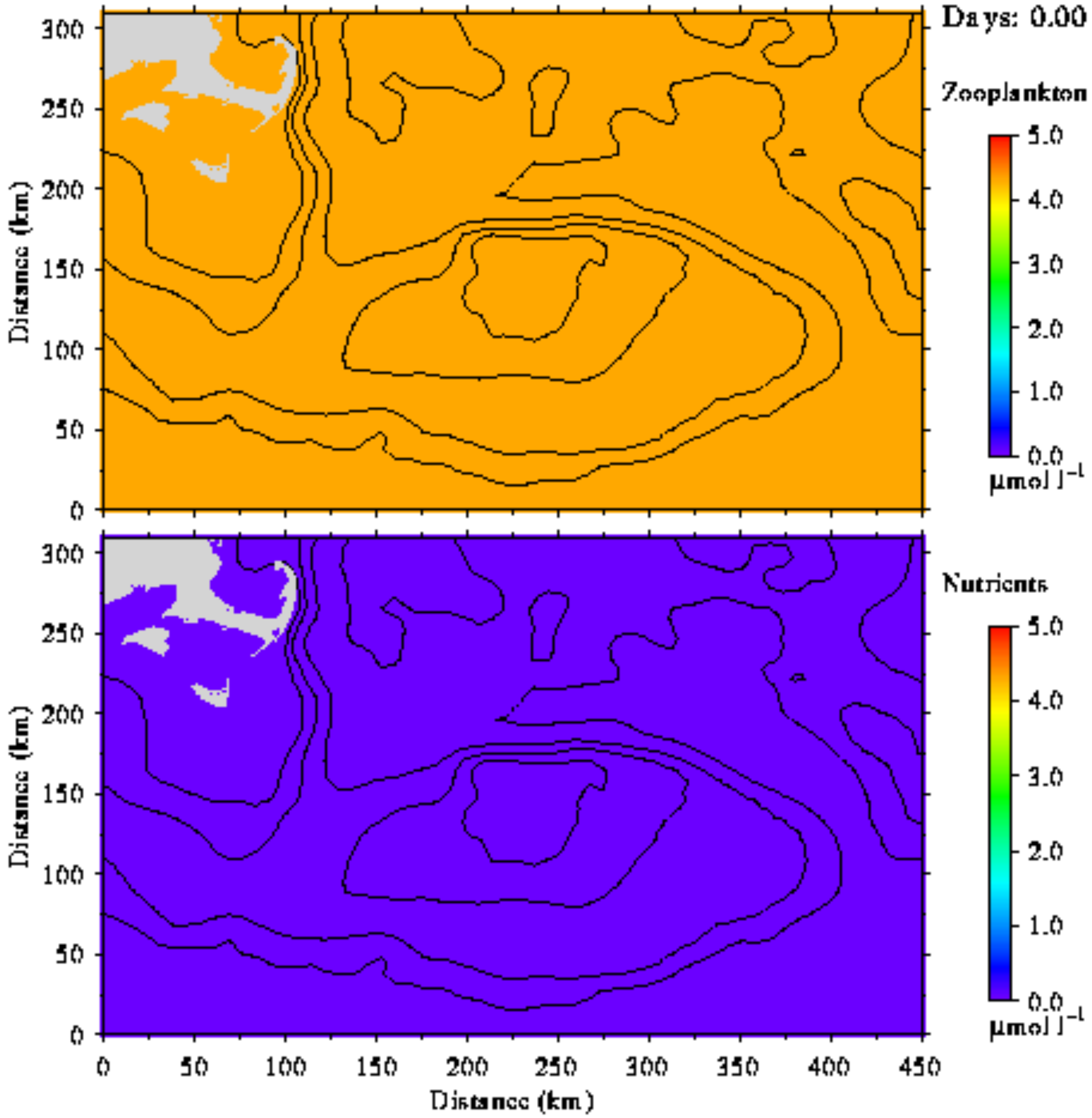


$$\log_{10}\frac{H}{D_t} = 1.9$$

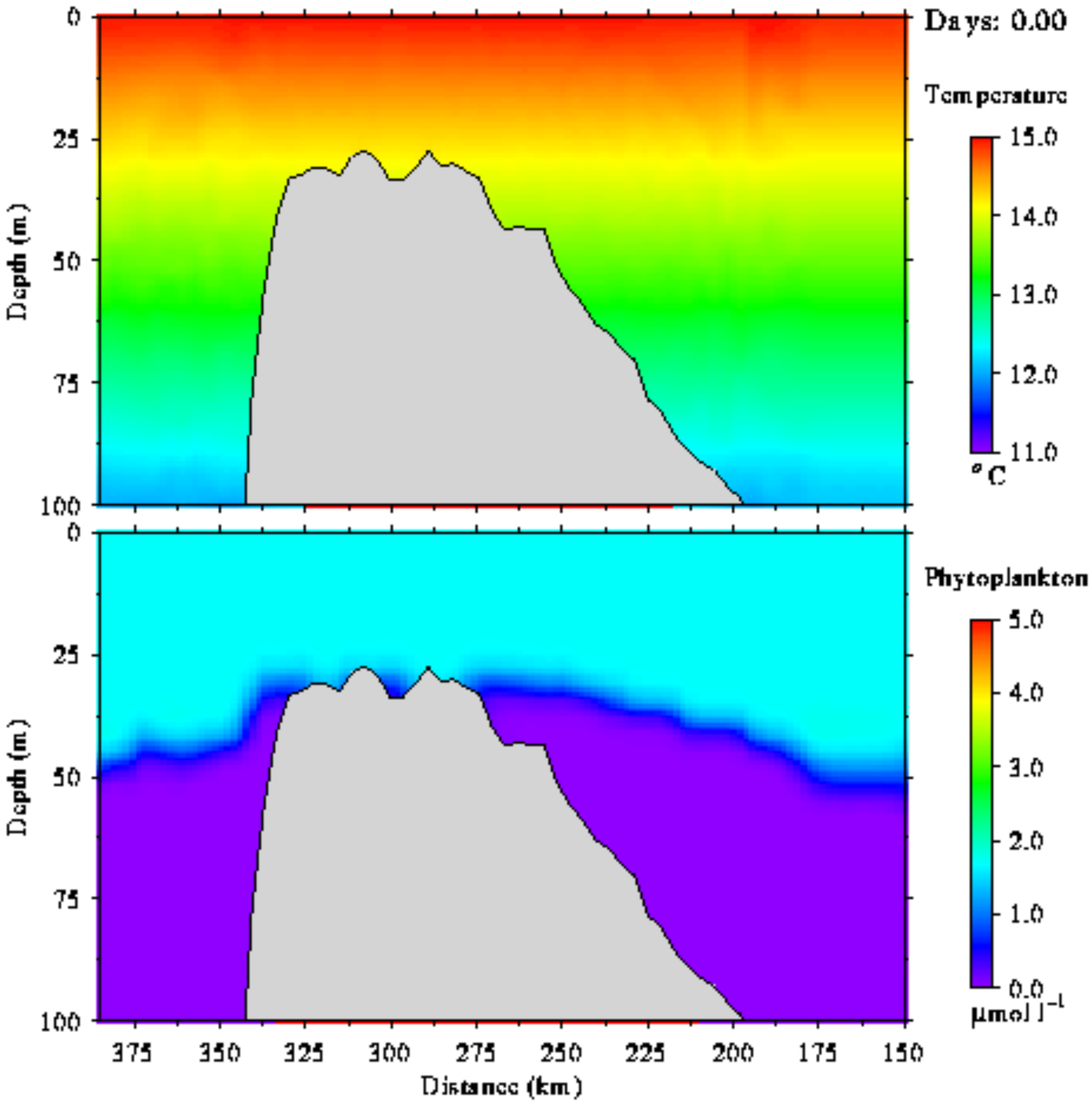

42°
41°
Mixed zone
0.2
0.5 1 1.8 2
60 m
100 m
$\Delta\sigma_t$
>6
<0.5
2 3
NO_3 (mg/m^3)
>15
15 15 17
T(°C)
>6
2
3
>6
Chl-a (mg/m^3)
68°W
67°W
66° W

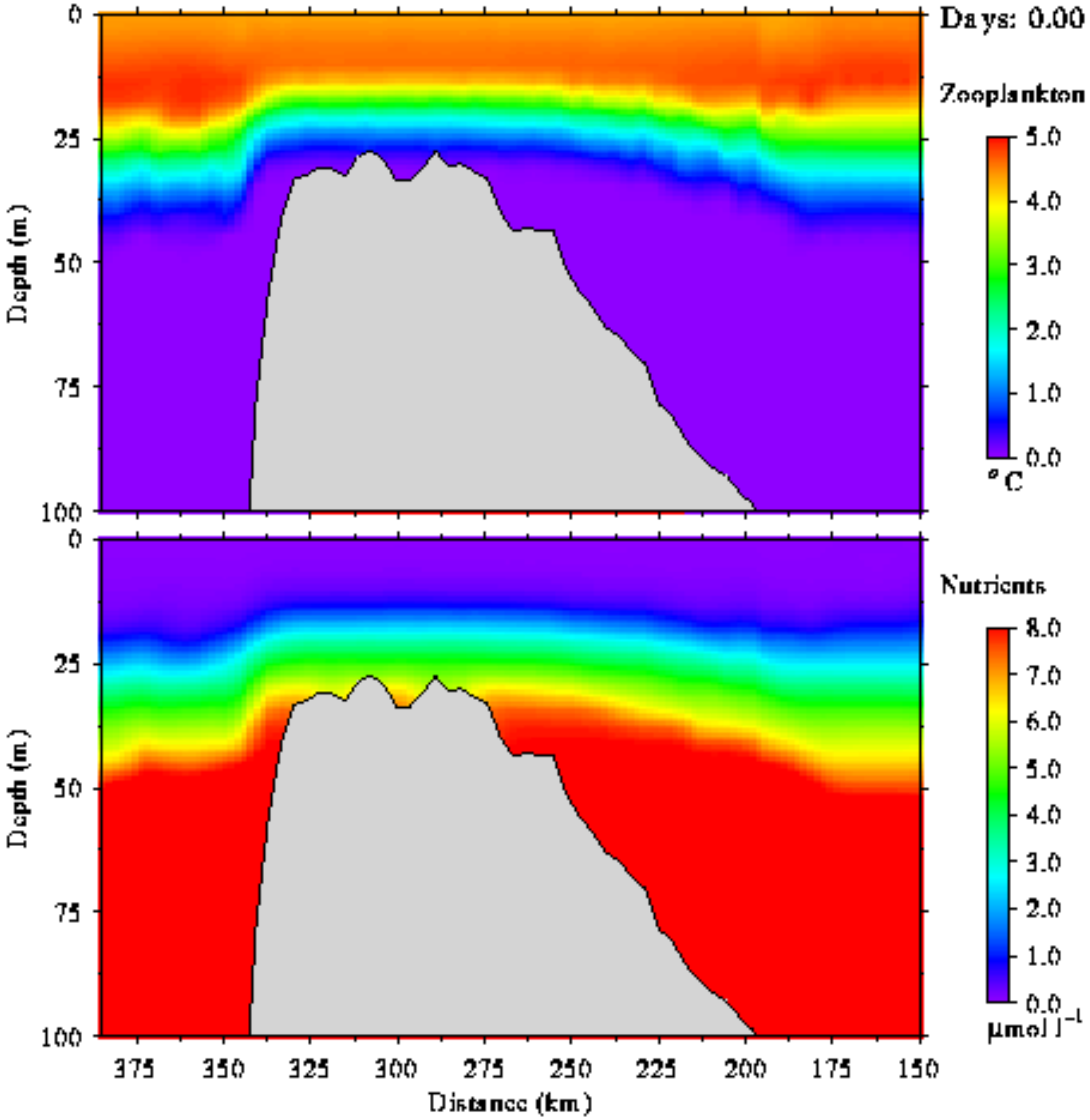

0
50
100
150
200
250
14
10
7
6
7
8
Temperature
0 5 10
km
0
50
100
150
200
250
2
1.5
1.5
1.5
1
0.5
Chl-a
0
50
100
150
200
250
1
2
9
11
13
15
17
NO_3

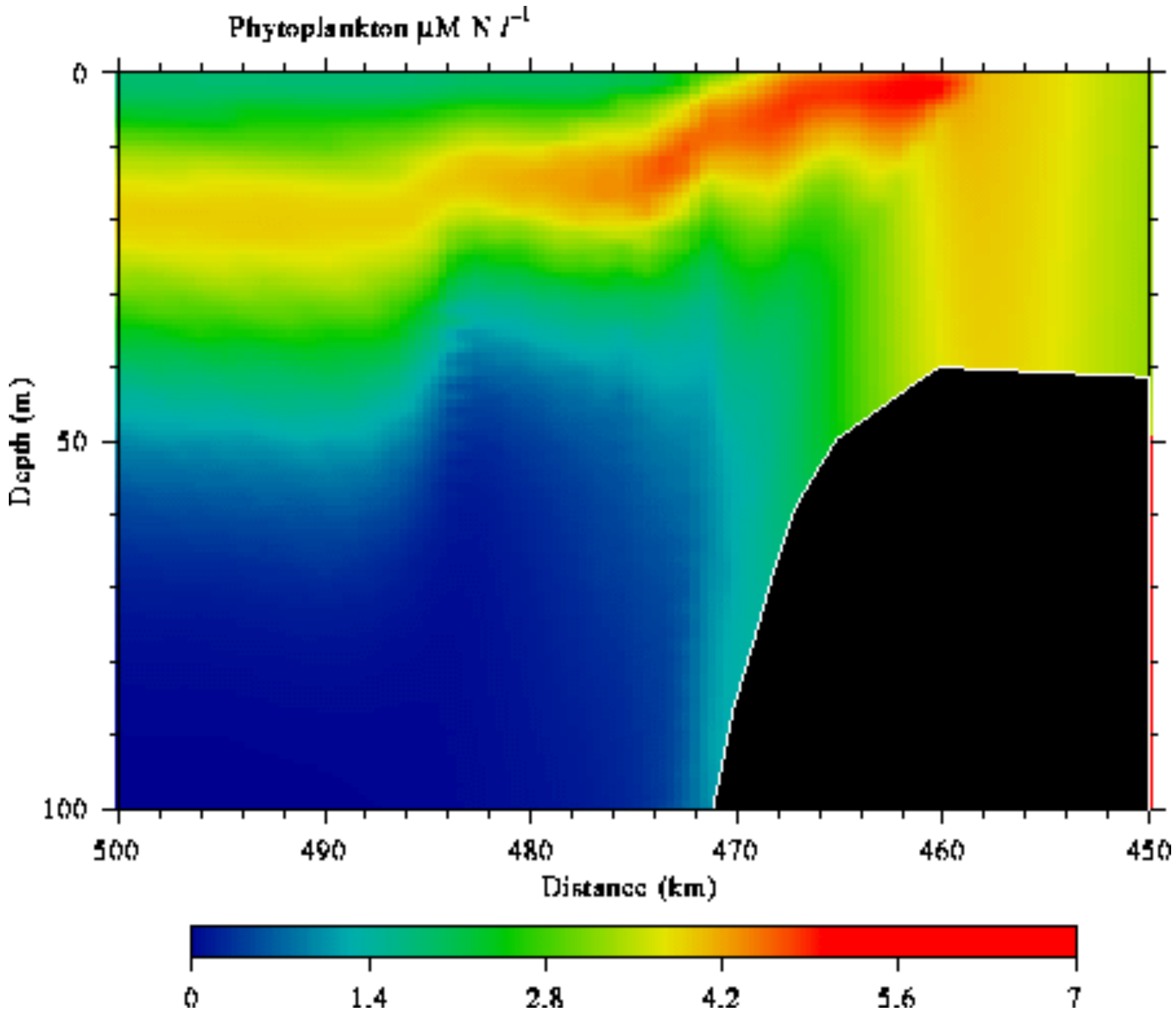

Days: 0.00
Temperature
15.0
14.8
14.6
14.4
14.2
14.0
°C
Phytoplankton
5.0
4.0
3.0
2.0
1.0
0.0
μmol l^{-1}
Distance (km)
300
250
200
150
100
50
0
Distance (km)
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
Distance (km)

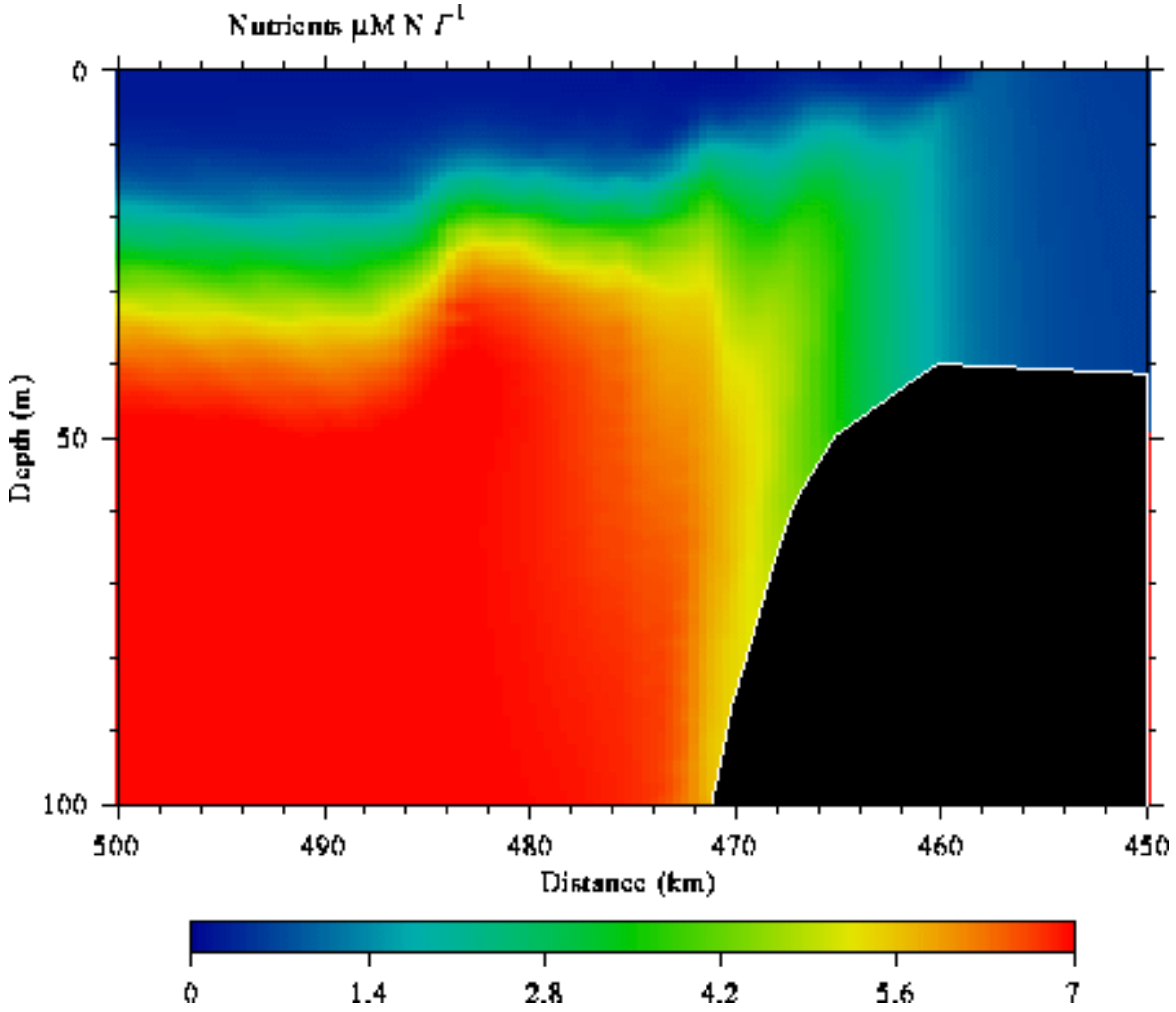


Days: 0.00
Zooplankton
5.0
4.0
3.0
2.0
1.0
0.0
µmol l⁻¹
Nutrients
5.0
4.0
3.0
2.0
1.0
0.0
µmol l⁻¹
Distance (km)
Distance (km)
Distance (km)
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450


Days: 0.00
Temperature
15.0
14.0
13.0
12.0
11.0
°C
Phytoplankton
5.0
4.0
3.0
2.0
1.0
0.0
μmol l⁻¹
Depth (m)
0
25
50
75
100
375
350
325
300
275
250
225
200
175
150
Distance (km)


Days: 0.00
Zooplankton
5.0
4.0
3.0
2.0
1.0
0.0
°C
Nutrients
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
μmol l⁻¹
Depth (m)
0
25
50
75
100
Distance (km)
375
350
325
300
275
250
225
200
175
150


Phytoplankton μM N l^{-1}
0
50
100
Depth (m)
500
490
480
470
460
450
Distance (km)
0
1.4
2.8
4.2
5.6
7


Nutrients μM N l^{-1}
0
50
100
Depth (m)
500
490
480
470
460
450
Distance (km)
0
1.4
2.8
4.2
5.6
7

Generally theory:

The front acts like a barrier to limit the water exchange across the front. In biology, it acts like a “retention zone”-----longer residence time.

QS: How are the nutrients transported across the front?

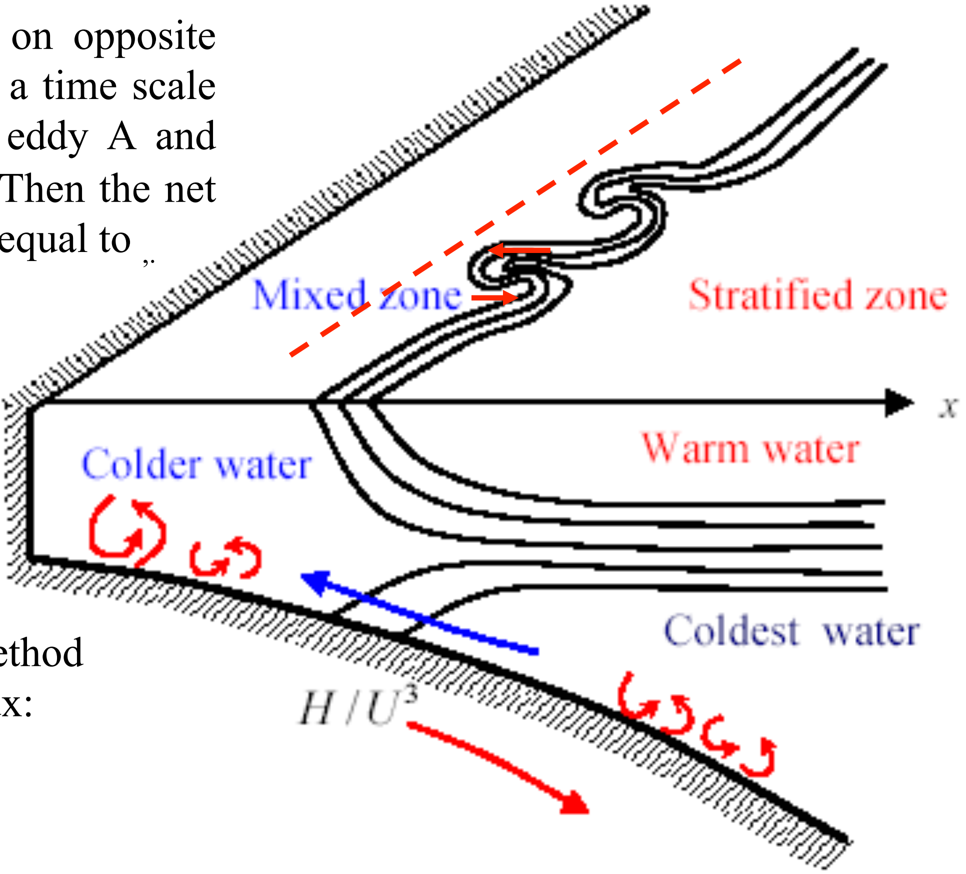
Main physical processes:

1) Frontal baroclinic instability-eddy formation
2) Nonlinear interaction of tidal currents
3) Asymmetric tidal mixing
4) Variable winds
5) Chaotic exchanges

1. Baroclinic instability

Simply an eddy like a cylinder with a depth of D and radius of $4L_R$, where L_R is the internal Rossby deformation radius ($L_R = \sqrt{g\Delta\rho\, D/\rho f^2}$),

Consider a pair of eddies moving on opposite directions in a length of 16 L_R over a time scale of T_E. Nutrient concentrations for eddy A and eddy B are specified as C_1 and C_2. Then the net nutrient flux across the front should equal to

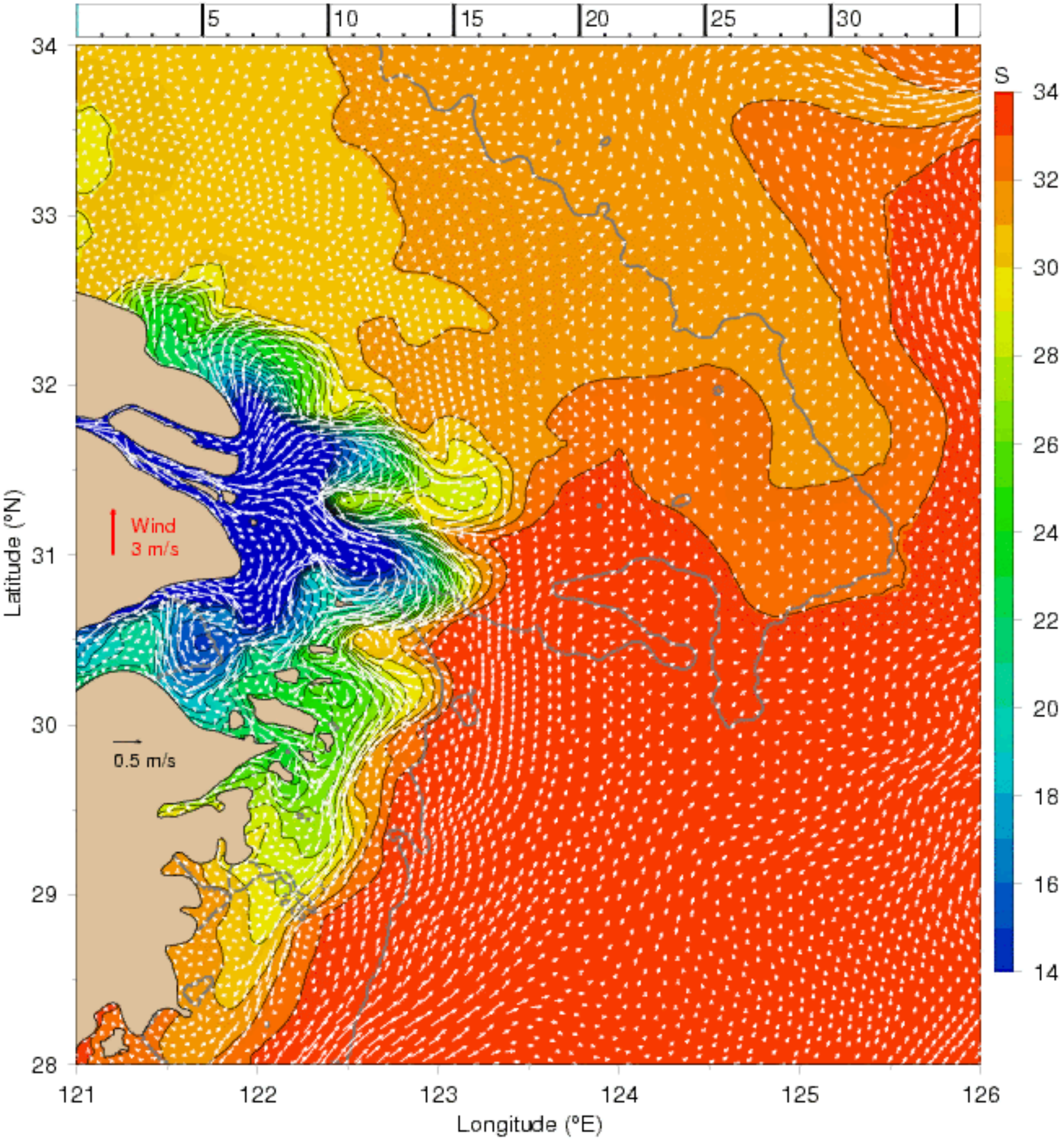


$$Q_E = \frac{16L_R^2\pi\, D(C_2 - C_1)}{16L_R T_E} = \pi\, D\Delta C\frac{L_R}{T_E}$$

An alternative way is to use the method for the eddy-induced polar heat flux:

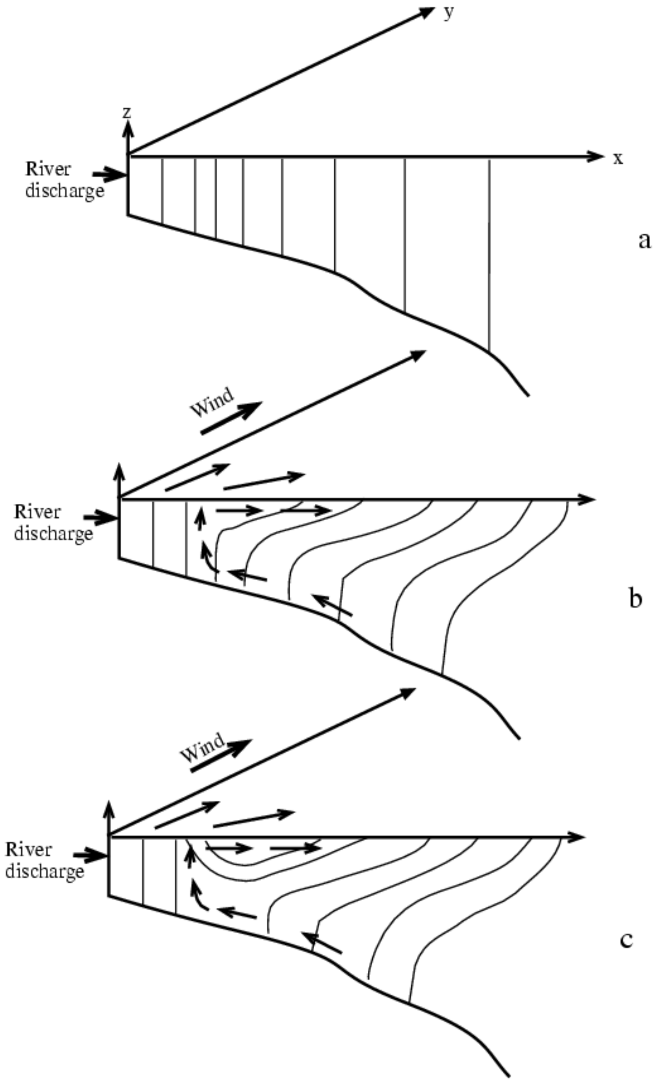
$$Q_E = \gamma\ \Delta C\sqrt{gD\frac{\Delta\rho}{\rho}} = \gamma\Delta C\sqrt{g'D}$$

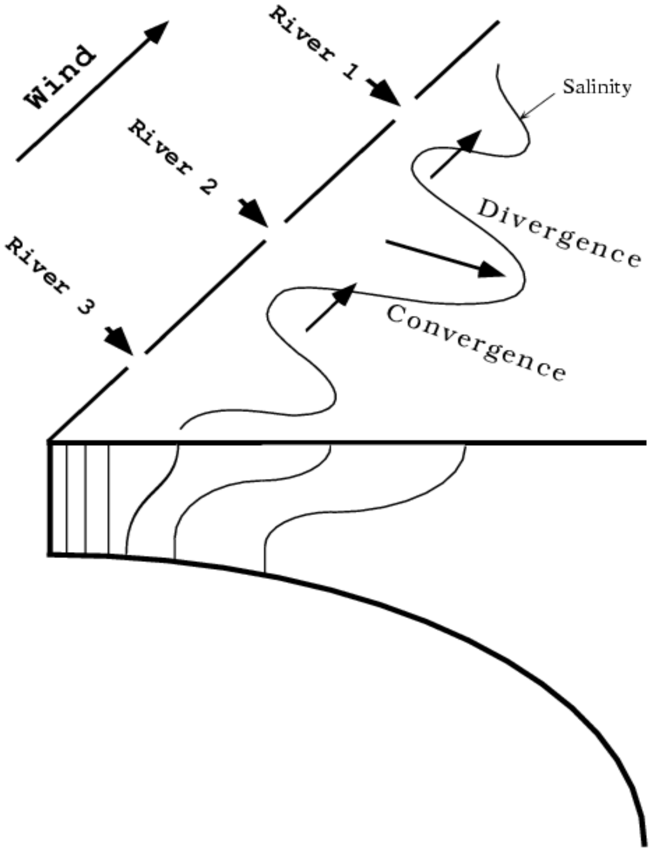
where ΔC is the cross-frontal difference of nutrient concentration

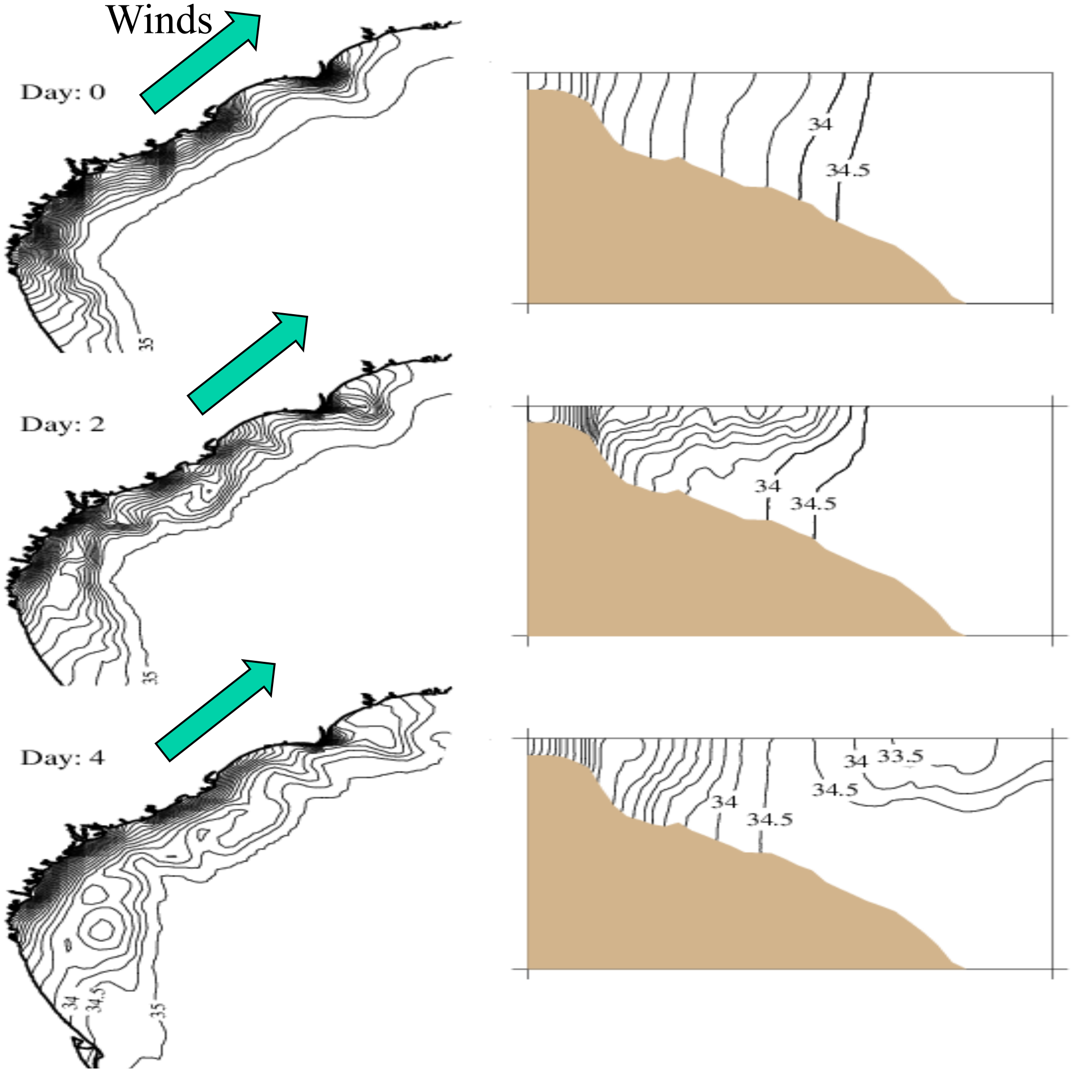

5
10
15
20
25
30
S
34
32
30
28
26
24
22
20
18
16
14
Wind
3 m/s
0.5 m/s
Latitude (°N)
34
33
32
31
30
29
28
121
122
123
124
125
126
Longitude (°E)

Wind-driven cross-frontal transport for the low-salinity front

The 2-D Ekman theory




Wind
River 1
River 2
River 3
Salinity
Divergence
Convergence


Winds
Day: 0
35
34
34.5
Day: 2
35
34
34.5
Day: 4
34
34.5
35
34
34.5
34
33.5
34.5

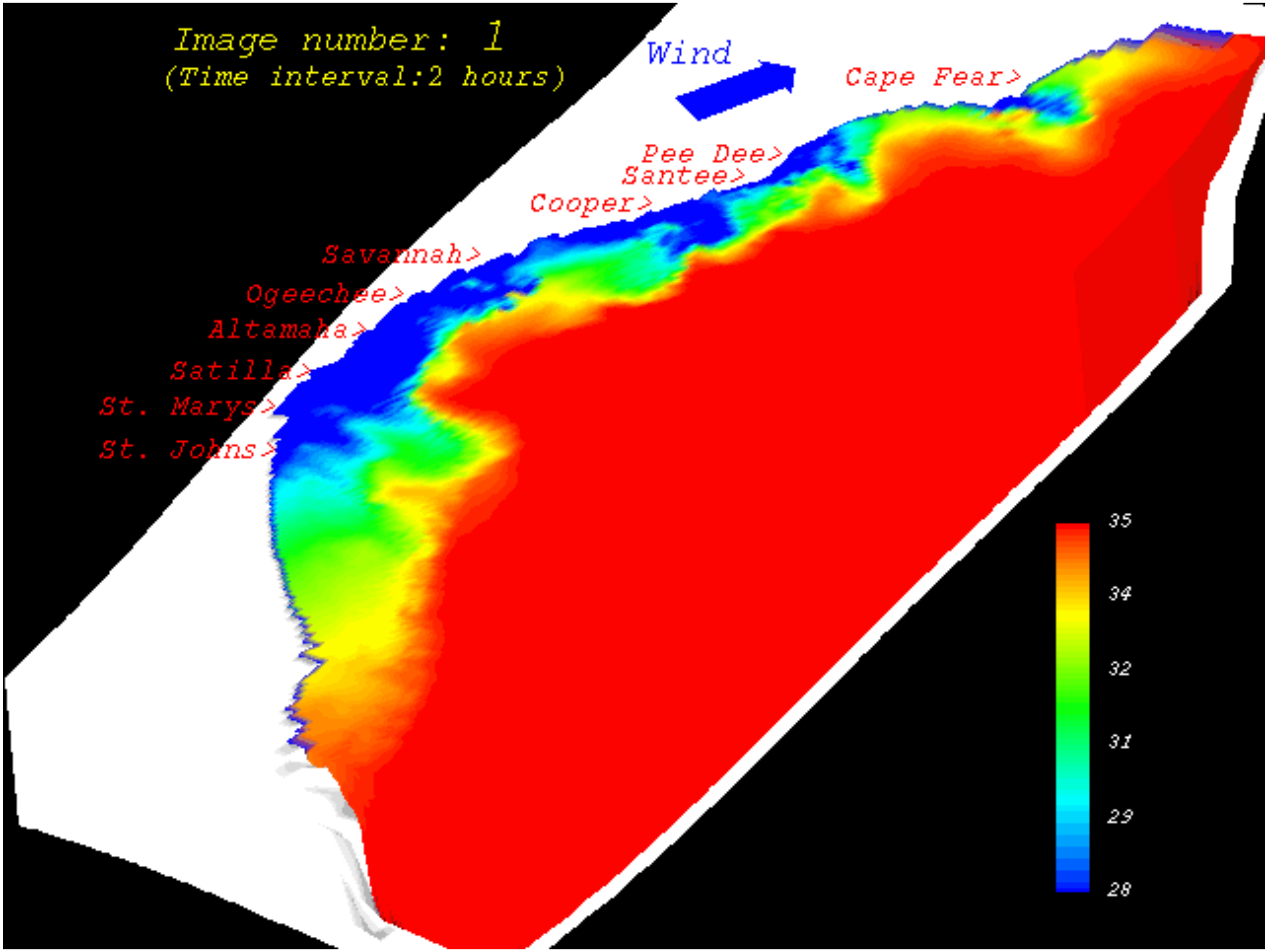
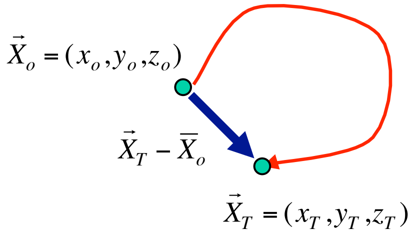


Image number: 1
(Time interval:2 hours)
Wind
Cape Fear>
Pee Dee>
Santee>
Cooper>
Savannah>
Ogeechee>
Altamaha>
Satilla>
St. Marys>
St. Johns>
35
34
32
31
29
28

2. Nonlinear interaction between tidal currents

Lagrangian velocity: $\vec{V}_L = \dfrac{\vec{X}_T - \vec{X}_o}{T}$



T: The M_2 tidal period,

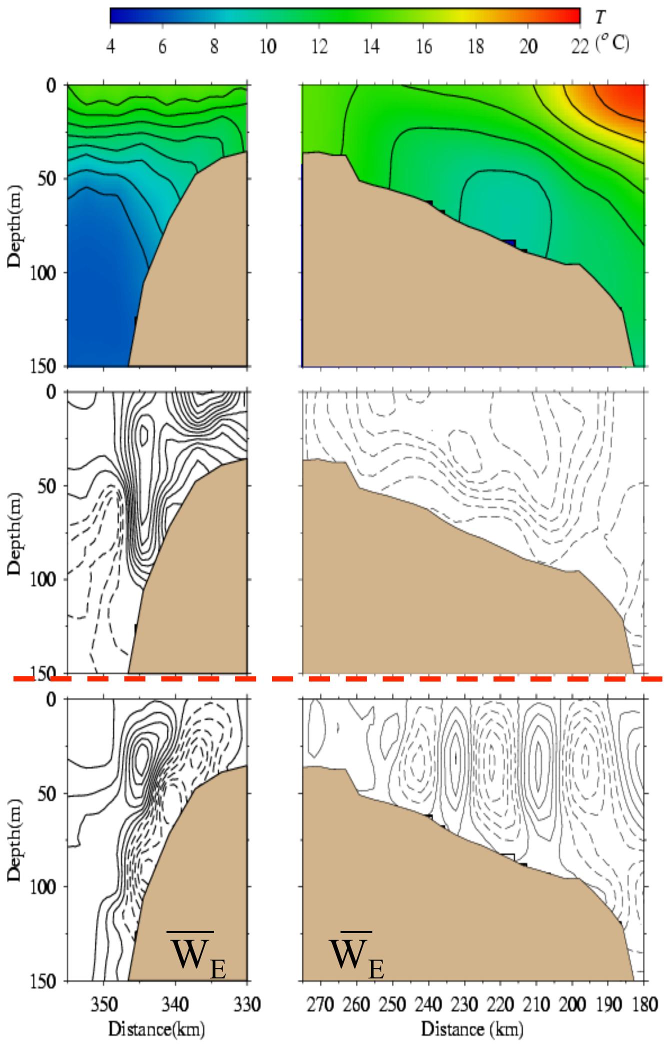
$\vec{X}_o$, $\vec{X}_T$: The positions at starting point and end point over a tidal cycle.

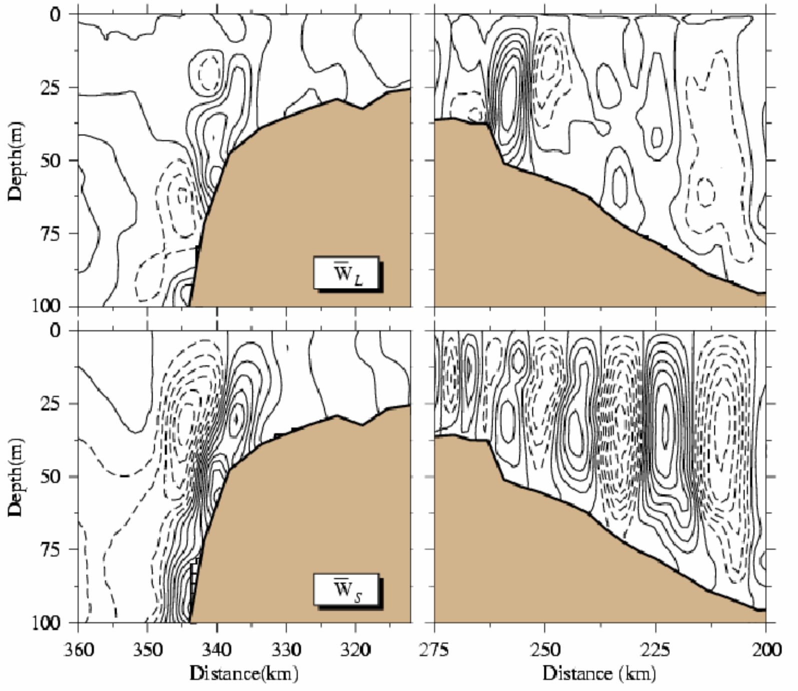
Let $\vec{V}_E$ be the Eulerian velocity (measured at a fix location), the Stokes' velocity is defined as

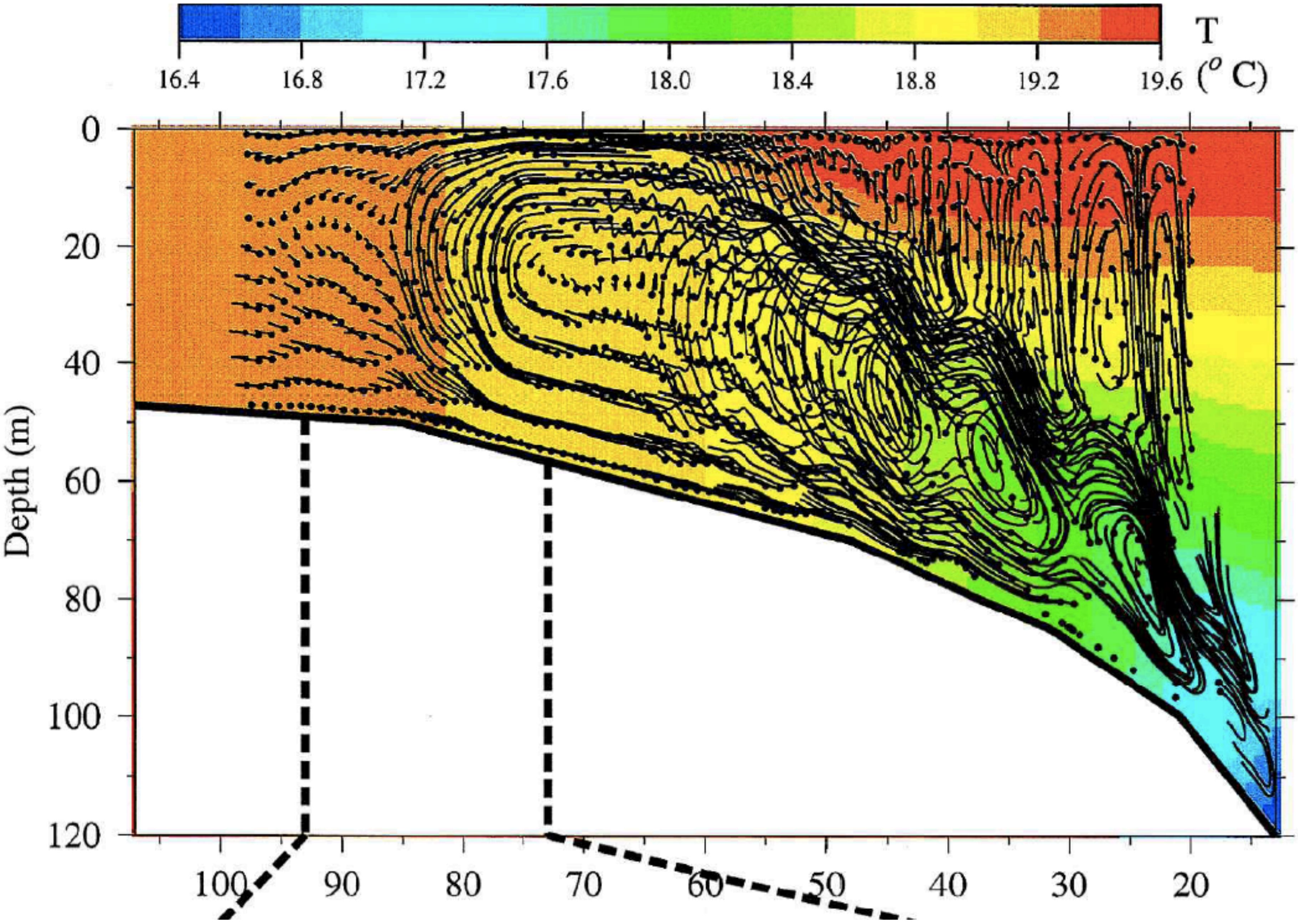
$$\vec{V}_S = \vec{V}_L - \vec{V}_E$$

- If the flow field is linear, the residual flow equal to zero.
- If the flow field is weak nonlinear, the Stokes' velocity should be one order of magnitude smaller than the Eulerian velocity;
- If the flow field is strong nonlinear, the Stokes' velocity could be the same order of magnitude as the Eulerian velocity.

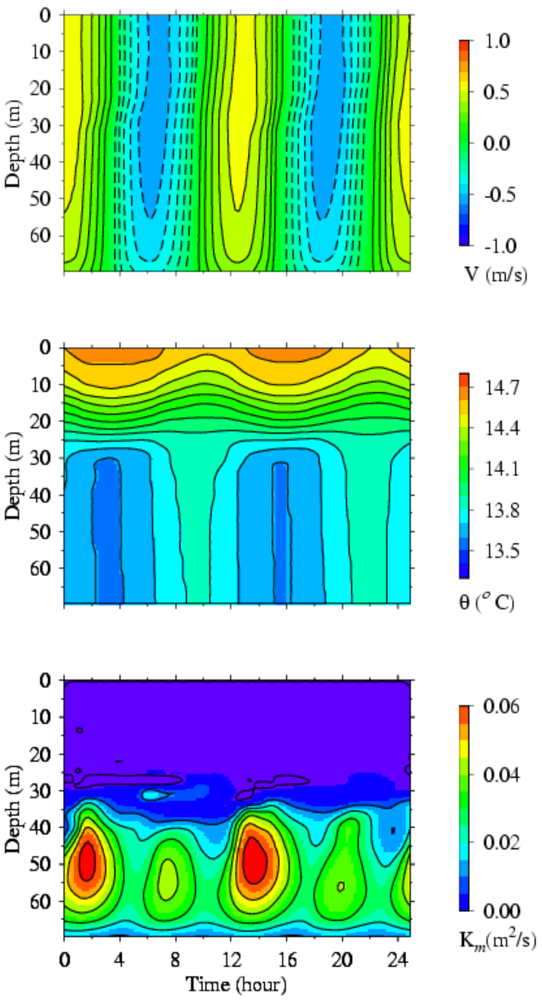
On Georges Bank, the nonlinearity is strong, Lagrangian velocity on the northern flank can be opposite to the Eulerian velocity

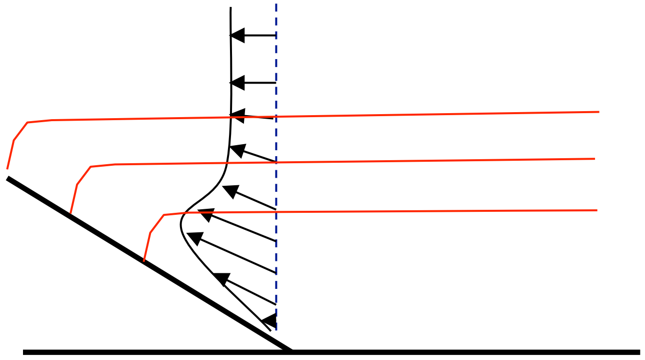





T
(°C)
16.4
16.8
17.2
17.6
18.0
18.4
18.8
19.2
19.6
Depth (m)
0
20
40
60
80
100
120
100
90
80
70
60
50
40
30
20

3. Asymmetric tidal mixing over tidal cycles





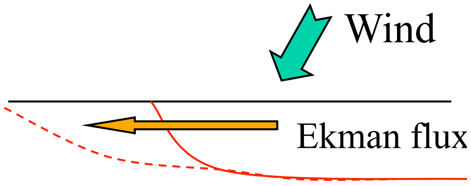
During the flood period:

Mixing is caused by shear instability plus gravitational instability---stronger

During the ebb period:

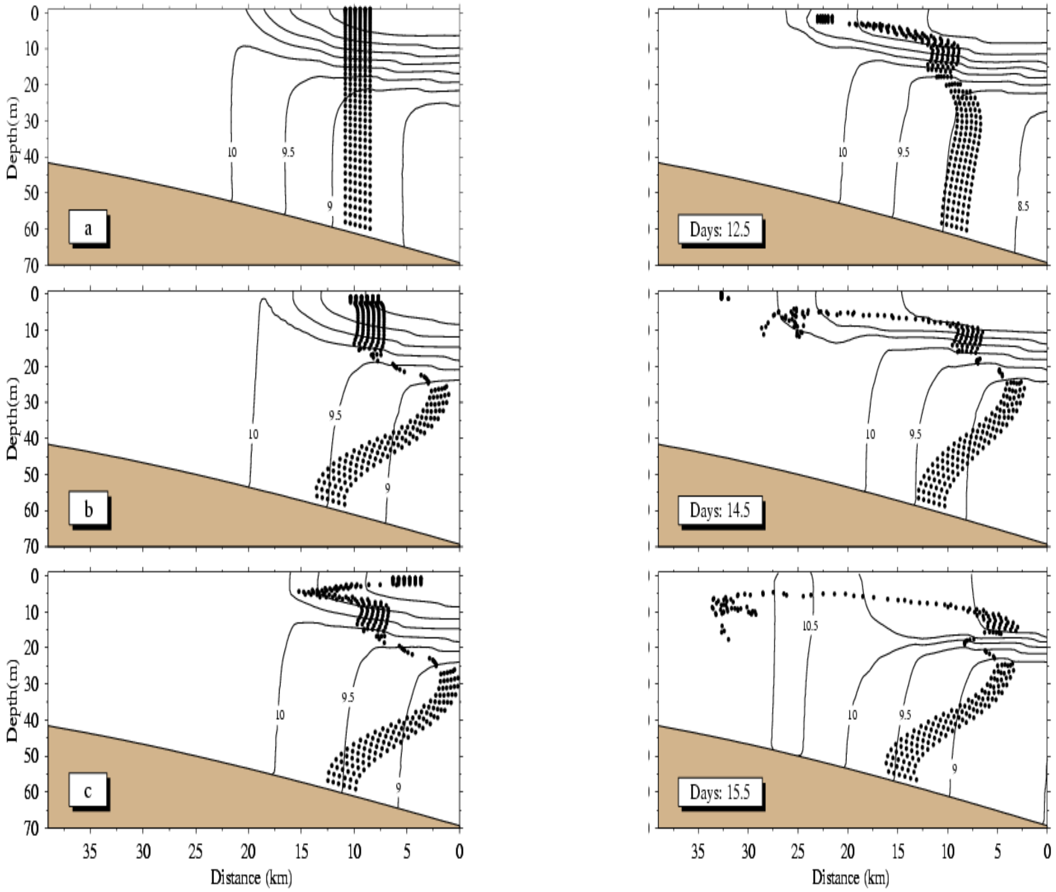
Mixing is caused mainly by shear instability

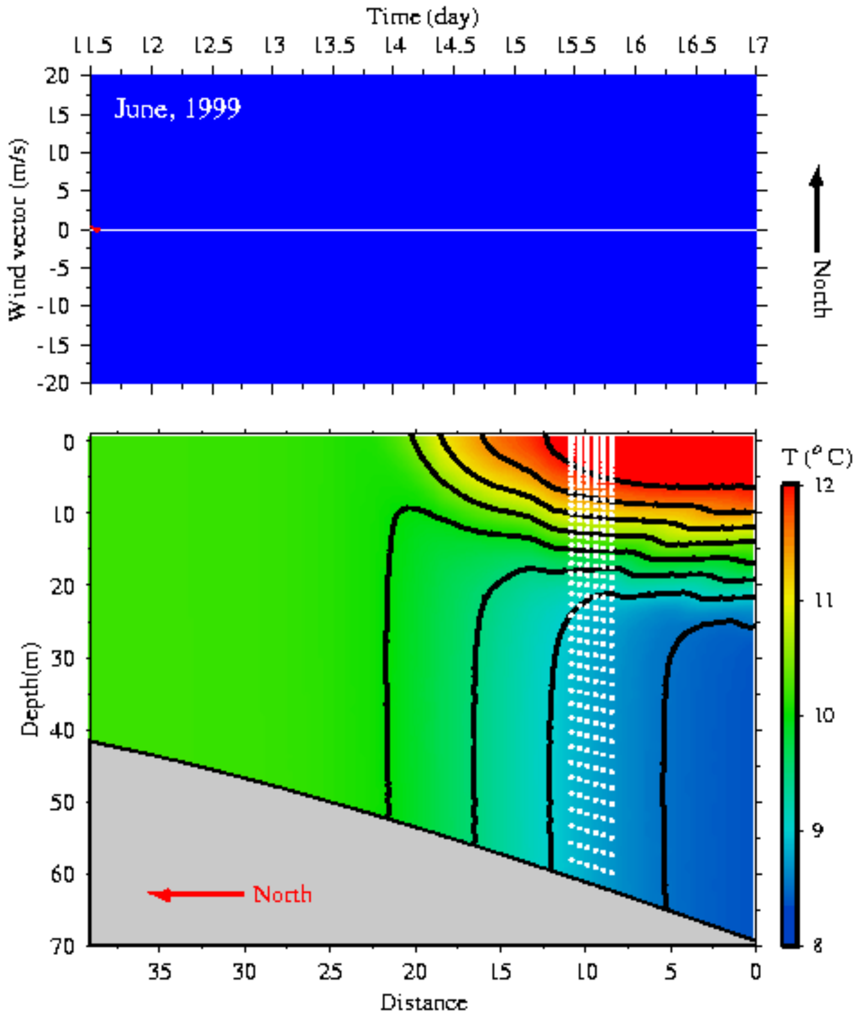
4) Variable winds

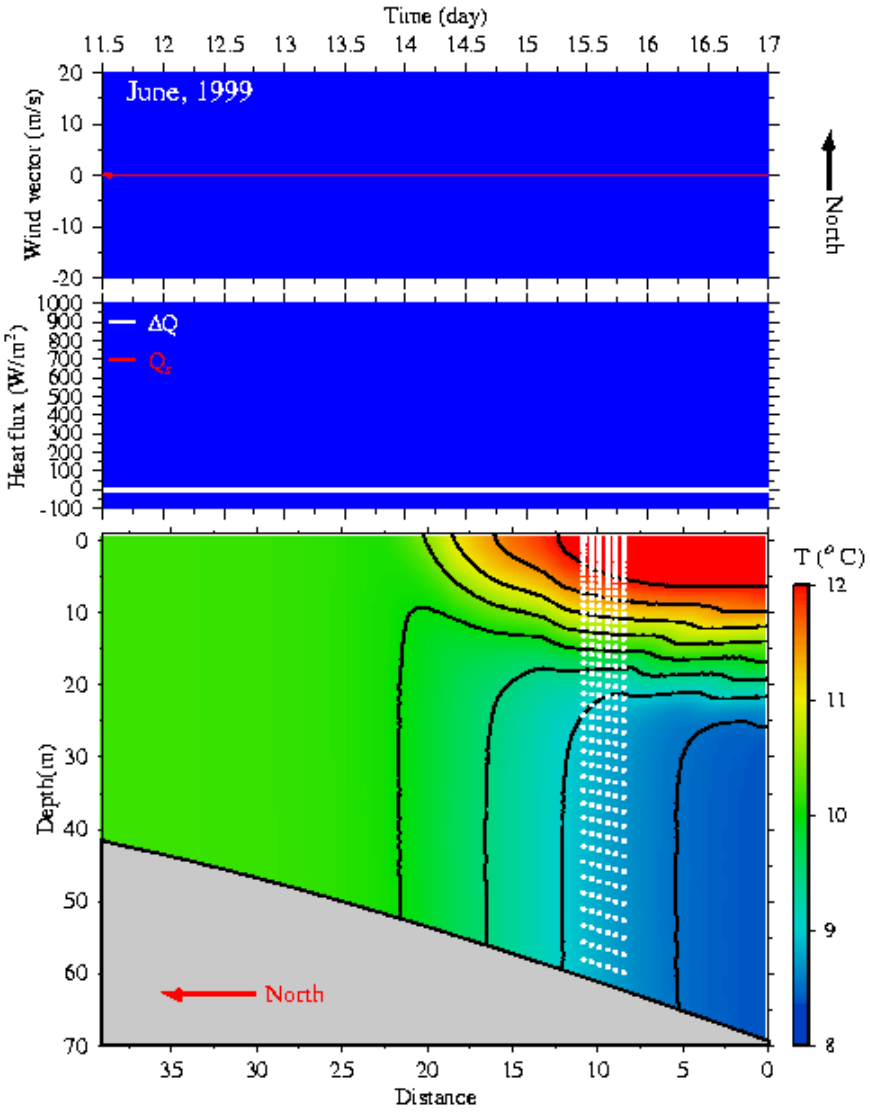


For a constant wind, if no an other forcing exists, the fron would move to the direction o the Ekman transport, no cross frontal transport could occur.

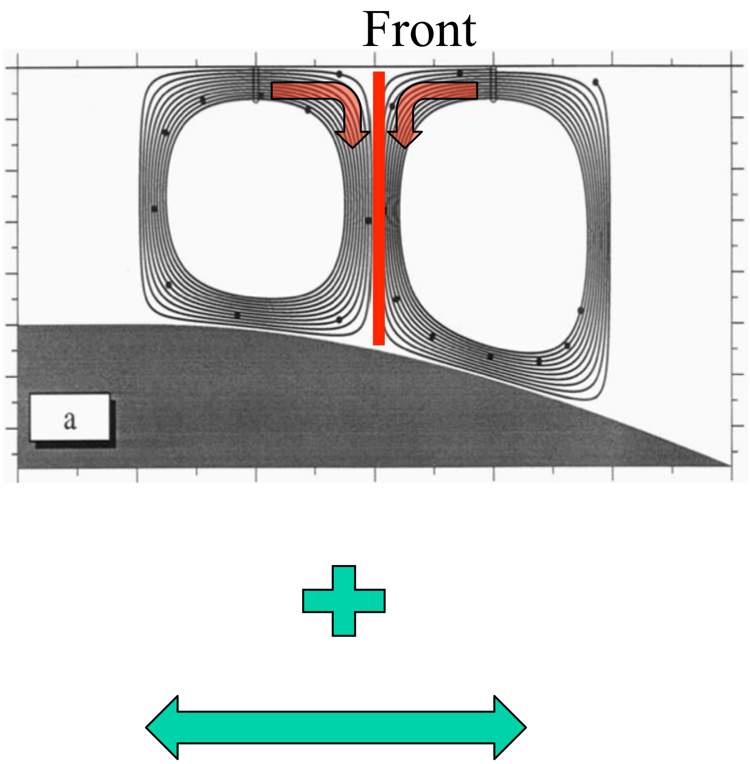
However, if the cross-frontal exchange could happen if tidal mixing exist under a variable wind condition.




Time (day)
11.5
12
12.5
13
13.5
14
14.5
15
15.5
16
16.5
17
Wind vector (m/s)
20
15
10
5
0
-5
-10
-15
-20
June, 1999
North
Depth(m)
0
10
20
30
40
50
60
70
North
35
30
25
20
15
10
5
0
Distance
T (° C)
12
11
10
9
8


Time (day)
11.5
12
12.5
13
13.5
14
14.5
15
15.5
16
16.5
17
June, 1999
Wind vector (m/s)
20
10
0
-10
-20
North
Heat flux (W/m^2)
1000
900
800
700
600
500
400
300
200
100
0
-100
ΔQ
Q_s
Depth(m)
0
10
20
30
40
50
60
70
North
T (^{o}C)
12
11
10
9
8
35
30
25
20
15
10
5
0
Distance

Chaotic transport



Periodic tidal currents

Chaotic water exchange