Lecture06-Estuary_Circulation_Freshwater_Outflows

October 7, 2025

1 Lecture06 - Estuary circulation and Freshwater outflows: example of CT River

Learning Objectives: river estuary, river charge & tidal effects on stratification - 4 types of estuaries, exchange flow, salt balance, river plume morphology (e.g., front, bulge, coastal current), CT river estuary stratification, river plume instability and mixing

Before class:

- Read the GroupProject_guidelines.ipynb carefully and form your group of 2-3 people for the final group project.

After class:

- Watch the amazing Coastal Perspectives Lecture "A Tale of Two Estuaries" by Patrick Lynch if you haven't yet! (strongly recommand)

Reference:

- Valle-Levinson, Contemporary Issues in Estuarine Physics, Cambridge University Press
- BS 9.2, Horner-Devine et. al., 2015
- Hansen and Rattray, Gravitational circulation in straits and estuaries, J Mar Res, 1965
- MacCready and Geyer, Advances in estuarine physics, Ann Rev Mar Sci , 2010
- Geyer and MacCready , The estuarine circulation , Ann Rev Fluid Mech , 2014

2 1. Estuary

> An estuary is (a) semi enclosed and coastal body of water, (b) with free communication to the ocean, and (c) within which ocean water is diluted by freshwater derived from land. – Cameron and Pritchard (1963)

Estuaries harbor unique plant and animal communities because their waters are **brackish** — a mixture of fresh water draining from the land and salty seawater.

Estuaries are some of the **most productive ecosystems** in the world. Many animal species rely on estuaries for food and as places to nest and breed. Human communities also rely on estuaries for food, recreation, and jobs.

Of the 32 largest cities in the world, 22 are located on estuaries. Not surprisingly, human activities have led to a decline in the health of estuaries, making them one of the most threatened ecosystems on Earth.

2.1 1) CT river estuary

The Connecticut River produces 70% of Long Island Sound's fresh water, discharging at 18,400 cubic feet (520 m^3) per second. The Connecticut River is the longest tidal river in the northeastern United States. With its headwaters in the Connecticut Lakes region of New Hampshire near the Canadian border, it flows for 410 miles before discharging into Long Island Sound. The tidal segment of the river and associated tidal wetlands are a haven for fish, wildlife, and plants including the endangered shortnose sturgeon, American bittern, and Parker's pipewort. As the only major river in the Northeast without a large port or harbor at its mouth, the Lower Connecticut River remains relatively undisturbed by development and offers a variety of nature-based outdoor recreational opportunities.

Figure 4. Land use and land cover of the Connecticut River watershed. The watershed is 75% forested. About 10% of the watershed is developed, primarily around the cities of Springfield, Massachusetts and Hartford, Connecticut at the southern end of the watershed.

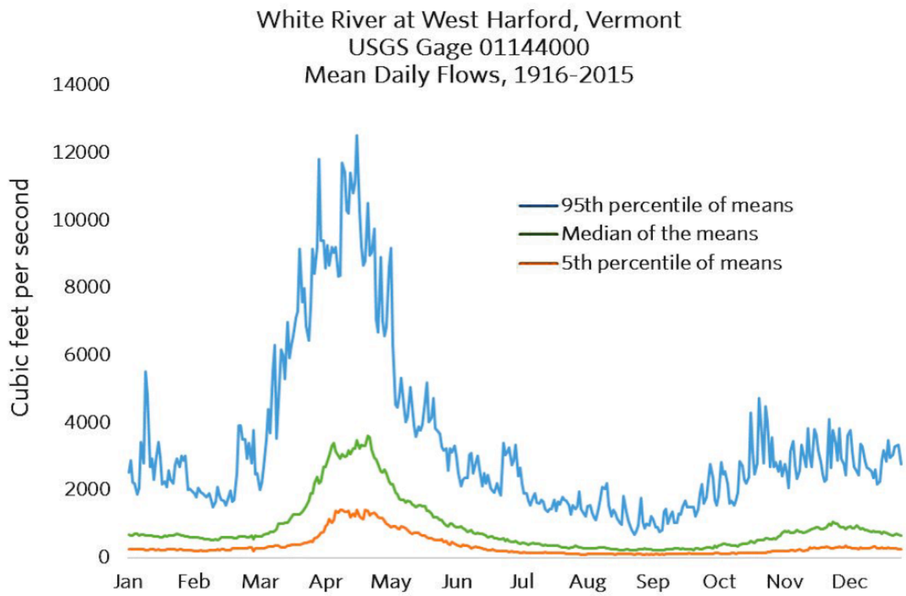


Figure 5. Annual hydrograph for the White River, Vermont. The White River is the largest unregulated tributary of the Connecticut River watershed. The annual pattern of flow is typical of the natural pattern of streamflow throughout the Connecticut River watershed: high flows in the spring, followed by lower summer and early-fall flows, a slight increase in flows in late fall and early winter, and then a slight decrease through the winter months. The median of mean daily flows foryears 1916-2015 is presented (green line), as well as the 95thpercentile of daily means (blue line) and the 5th percentile of daily means (orange line) to demonstrate the hydrological range of mean daily flows in this system. Data are from USGS stream gage 01144000.

[Airborn picture by Larissa Graham during high river discharge conditions after tropical storm Irene. (should be during ebb tide, we will explain later)]

[1]:
```
# import python libraries
import pandas as pd
import numpy as np
from matplotlib import cm
import matplotlib.pyplot as plt
```

[2]:
```
# load salinity data at Essex and Old Lyme, CT, respectively
# Essex: https://waterdata.usgs.gov/monitoring-location/USGS-01194750/
 ↪#dataTypeId=continuous-90860-698975713&period=P365D&showFieldMeasurements=true
# Old Lyme: https://waterdata.usgs.gov/monitoring-location/USGS-01194796/
 ↪#dataTypeId=continuous-90860-1995605579&period=P365D&showFieldMeasurements=true
salinity_essex = pd.read_csv('../data/lecture06/
 ↪Essex_salinity_202401005-20251005.txt', comment='#', sep='\t', header=1,␣
 ↪names=['agency_cd', 'site_no', 'datetime', 'tz_cd', 'salinity_top',␣
 ↪'salinity_top_cd', 'salinity_bottom', 'salinity_bottom_cd'])
salinity_oldlyme = pd.read_csv('../data/lecture06/
 ↪OldLyme_salinity_202401005-20251005.txt', comment='#', sep='\t', header=1,␣
 ↪names=['agency_cd', 'site_no', 'datetime', 'tz_cd', 'salinity_top',␣
 ↪'salinity_top_cd', 'salinity_bottom', 'salinity_bottom_cd'])
salinity_oldlyme
```

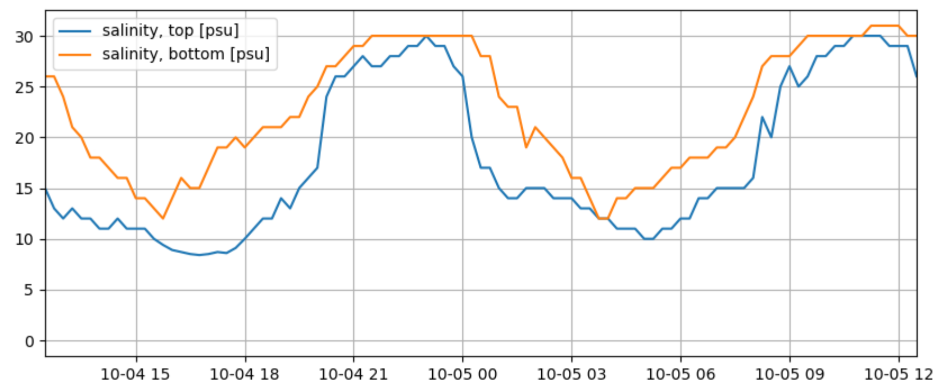
[2]:
```
      agency_cd  site_no          datetime tz_cd  salinity_top  \
0          USGS  1194796  2024-10-05 13:30   EDT          28.0
1          USGS  1194796  2024-10-05 13:45   EDT          27.0
2          USGS  1194796  2024-10-05 14:00   EDT          27.0
3          USGS  1194796  2024-10-05 14:15   EDT          28.0
4          USGS  1194796  2024-10-05 14:30   EDT          26.0
…           …        …               …   …            …
34977      USGS  1194796  2025-10-05 11:45   EDT          29.0
34978      USGS  1194796  2025-10-05 12:00   EDT          29.0
34979      USGS  1194796  2025-10-05 12:15   EDT          29.0
34980      USGS  1194796  2025-10-05 12:30   EDT          26.0
34981      USGS  1194796  2025-10-05 12:45   EDT          25.0

      salinity_top_cd  salinity_bottom salinity_bottom_cd
0                   P             29.0                  A
1                   P             29.0                  A
2                   P             29.0                  A
3                   P             29.0                  A
4                   P             29.0                  A
…                 …              …                 …
34977               P             31.0                  P
34978               P             31.0                  P
34979               P             30.0                  P
34980               P             30.0                  P
34981               P             30.0                  P
```

[34982 rows x 8 columns]

2.1.1 a. stratification

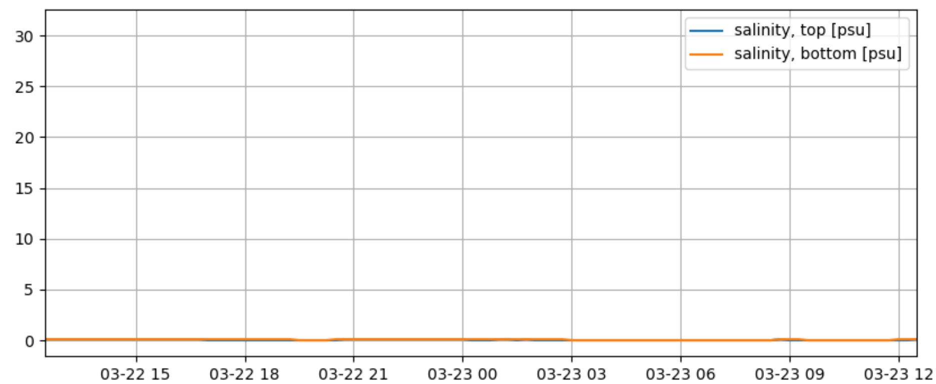
[3]:
```
# plot salinity at river surface and bottom over a day, Old Lyme
%matplotlib widget
fig, ax = plt.subplots(nrows=1, ncols=1, figsize=(10,4))
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_top, label='salinity, top [psu]')
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_bottom, label='salinity, bottom [psu]')
ax.grid(True) # add grids
ax.legend() # add legends
ax.set_xlim([pd.to_datetime('2025-10-04 12:30'), pd.to_datetime('2025-10-05 12:
 ↪30')])
```

[3]: (np.float64(20365.520833333332), np.float64(20366.520833333332))



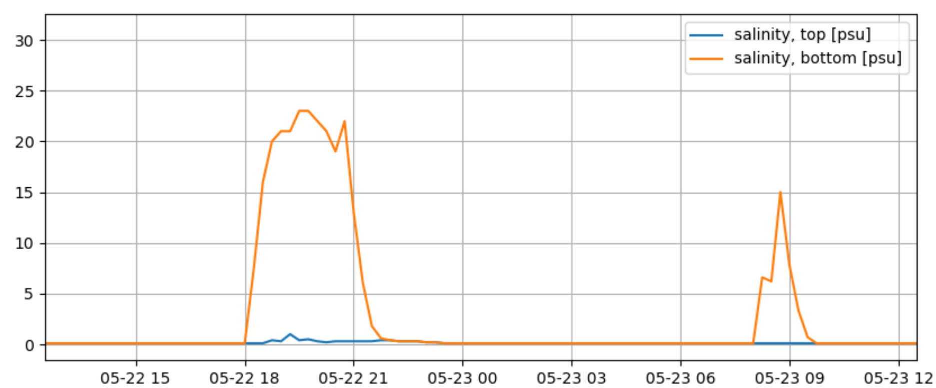
[4]:
```
# plot salinity at river surface and bottom over a day, Old Lyme
%matplotlib widget
fig, ax = plt.subplots(nrows=1, ncols=1, figsize=(10,4))
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_top, label='salinity, top [psu]')
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_bottom, label='salinity, bottom [psu]')
ax.grid(True) # add grids
ax.legend() # add legends
ax.set_xlim([pd.to_datetime('2025-03-22 12:30'), pd.to_datetime('2025-03-23 12:
 ↪30')])
# ax.set_ylim([0, 2])
```

[4]: (np.float64(20169.520833333332), np.float64(20170.520833333332))




```
[5]: # plot salinity at river surface and bottom over a day, Old Lyme
%matplotlib widget
fig, ax = plt.subplots(nrows=1, ncols=1, figsize=(10,4))
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_top, label='salinity, top [psu]')
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_bottom, label='salinity, bottom [psu]')
ax.grid(True) # add grids
ax.legend() # add legends
ax.set_xlim([pd.to_datetime('2025-05-22 12:30'), pd.to_datetime('2025-05-23 12:
 ↪30')])
# ax.set_ylim([0, 2])
```

[5]: (np.float64(20230.520833333332), np.float64(20231.520833333332))



2.1.2 b. tidal varibility

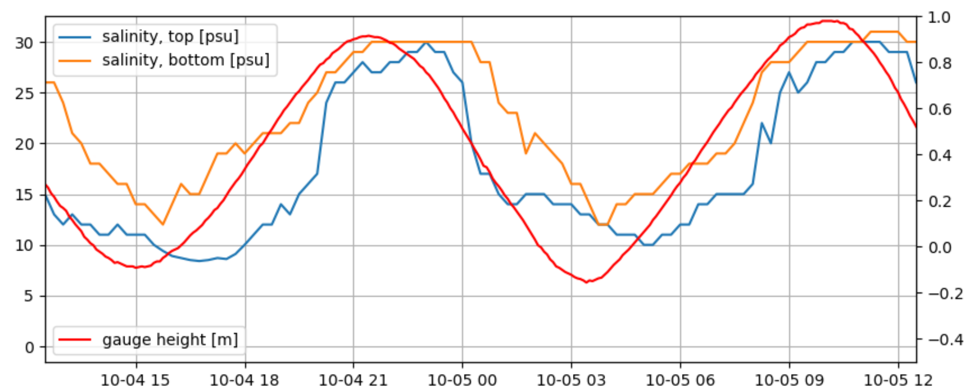
[6]:
```
# load gaugeheight data at Essex and Old Lyme, CT, respectively
# Essex: https://waterdata.usgs.gov/monitoring-location/USGS-01194750/
↪#dataTypeId=continuous-90860-698975713&period=P365D&showFieldMeasurements=true
# Old Lyme: https://waterdata.usgs.gov/monitoring-location/USGS-01194796/
↪#dataTypeId=continuous-90860-1995605579&period=P365D&showFieldMeasurements=true
gaugeheight_essex = pd.read_csv('../data/lecture06/
↪Essex_gaugeheight_202401005-20251005.txt', comment='#', sep='\t', header=1,␣
↪names=['agency_cd', 'site_no', 'datetime', 'tz_cd', 'gauge_height',␣
↪'gauge_height_cd'])
gaugeheight_oldlyme = pd.read_csv('../data/lecture06/
↪OldLyme_gaugeheight_202401005-20251005.txt', comment='#', sep='\t',␣
↪header=1, names=['agency_cd', 'site_no', 'datetime', 'tz_cd',␣
↪'gauge_height', 'gauge_height_cd'])
gaugeheight_oldlyme
```

[6]:
```
       agency_cd  site_no          datetime tz_cd  gauge_height  \
0           USGS  1194796  2024-10-05 13:30   EDT          3.18
1           USGS  1194796  2024-10-05 13:35   EDT          3.16
2           USGS  1194796  2024-10-05 13:40   EDT          3.13
3           USGS  1194796  2024-10-05 13:45   EDT          3.10
4           USGS  1194796  2024-10-05 13:50   EDT          3.08
…            …       …                …     …             …
104535      USGS  1194796  2025-10-05 12:35   EDT          1.64
104536      USGS  1194796  2025-10-05 12:40   EDT          1.56
104537      USGS  1194796  2025-10-05 12:45   EDT          1.46
104538      USGS  1194796  2025-10-05 12:50   EDT          1.40
104539      USGS  1194796  2025-10-05 12:55   EDT          1.33

       gauge_height_cd
0                    A
1                    A
2                    A
3                    A
4                    A
…                  …
104535               P
104536               P
104537               P
104538               P
104539               P

[104540 rows x 6 columns]
```

[7]:
```
# plot salinity at river surface and bottom over a day, Old Lyme
%matplotlib widget
```

```
fig, ax = plt.subplots(nrows=1, ncols=1, figsize=(10,4))
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_top, label='salinity, top [psu]')
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_bottom, label='salinity, bottom [psu]')
ax.grid(True) # add grids
ax.legend() # add legends

# plot meters instead of feet
ax1 = ax.twinx()
ax1.plot(pd.to_datetime(gaugeheight_oldlyme.datetime), gaugeheight_oldlyme.
 ↪gauge_height*.3048, 'r', label='gauge height [m]')
ax1.set_ylim([-.5, 1])
ax1.legend(loc="lower left") # add legends

ax.set_xlim([pd.to_datetime('2025-10-04 12:30'), pd.to_datetime('2025-10-05 12:
 ↪30')])
```

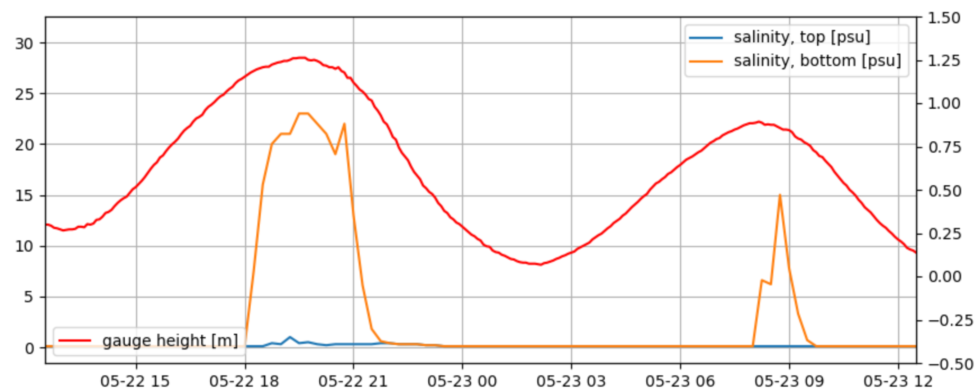
[7]:
```
(np.float64(20365.520833333332), np.float64(20366.520833333332))
```



[8]:
```
# plot salinity at river surface and bottom over a day, Old Lyme
%matplotlib widget
fig, ax = plt.subplots(nrows=1, ncols=1, figsize=(10,4))
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_top, label='salinity, top [psu]')
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_bottom, label='salinity, bottom [psu]')
ax.grid(True) # add grids
ax.legend() # add legends

# plot meters instead of feet
```

```
ax1 = ax.twinx()
ax1.plot(pd.to_datetime(gaugeheight_oldlyme.datetime), gaugeheight_oldlyme.
 ↪gauge_height*.3048, 'r', label='gauge height [m]')
ax1.set_ylim([-.5, 1.5])
ax1.legend(loc="lower left") # add legends

ax.set_xlim([pd.to_datetime('2025-05-22 12:30'), pd.to_datetime('2025-05-23 12:
 ↪30')])
```

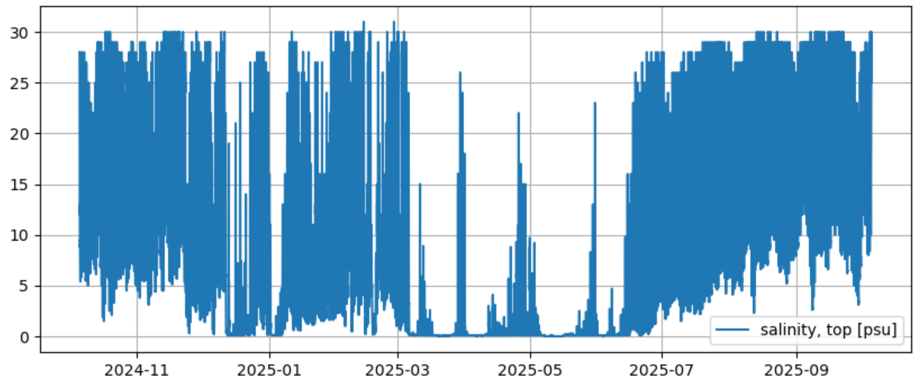
[8]: (np.float64(20230.520833333332), np.float64(20231.520833333332))



2.1.3 c. seasonality

[9]:
```
# plot salinity at river surface over an entire year, Old Lyme
%matplotlib widget
fig, ax = plt.subplots(nrows=1, ncols=1, figsize=(10,4))
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_top, label='salinity, top [psu]')
# ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_bottom, label='salinity, bottom [psu]')
ax.grid(True) # add grids
ax.legend() # add legends
# ax.set_xlim([pd.to_datetime('2025-10-04 12:30'), pd.to_datetime('2025-10-05␣
 ↪12:30')])
```

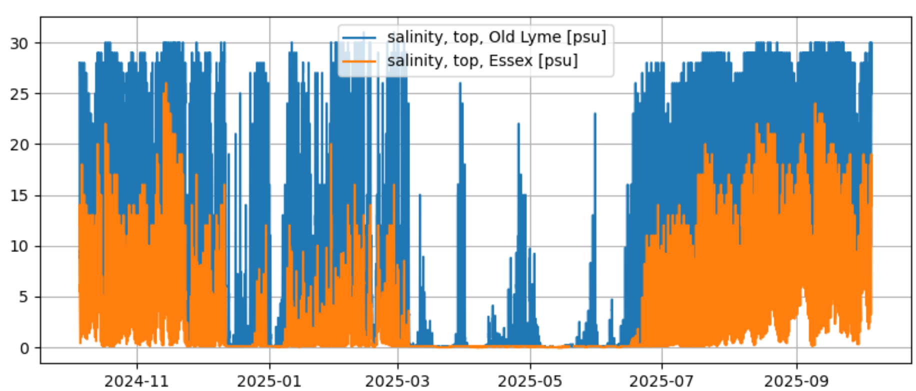
[9]: <matplotlib.legend.Legend at 0x32d8082d0>



2.1.4 d. longitudinal salinity variation

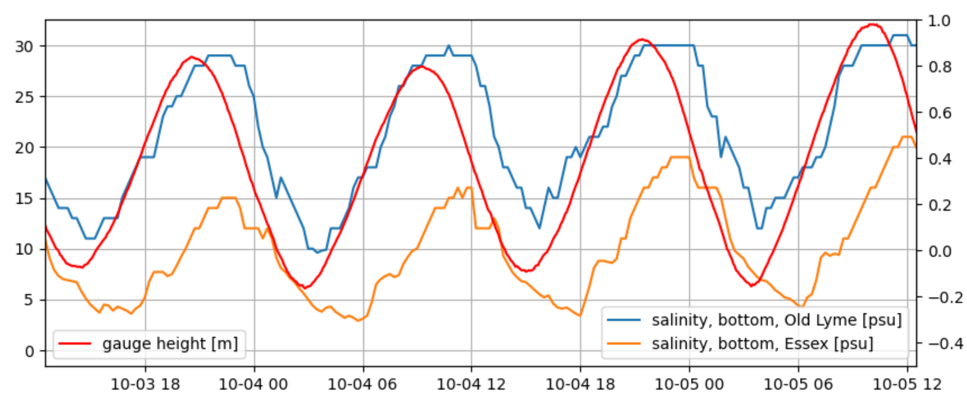
[10]:
```
# plot salinity at river surface over an entire year, Old Lyme vs Essex
%matplotlib widget
fig, ax = plt.subplots(nrows=1, ncols=1, figsize=(10,4))
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
    ↪salinity_top, label='salinity, top, Old Lyme [psu]')
ax.plot(pd.to_datetime(salinity_essex.datetime), salinity_essex.salinity_top,␣
    ↪label='salinity, top, Essex [psu]')
ax.grid(True) # add grids
ax.legend() # add legends
# ax.set_xlim([pd.to_datetime('2025-10-04 12:30'), pd.to_datetime('2025-10-05␣
    ↪12:30')])
```

[10]:
```
<matplotlib.legend.Legend at 0x32d86ead0>
```

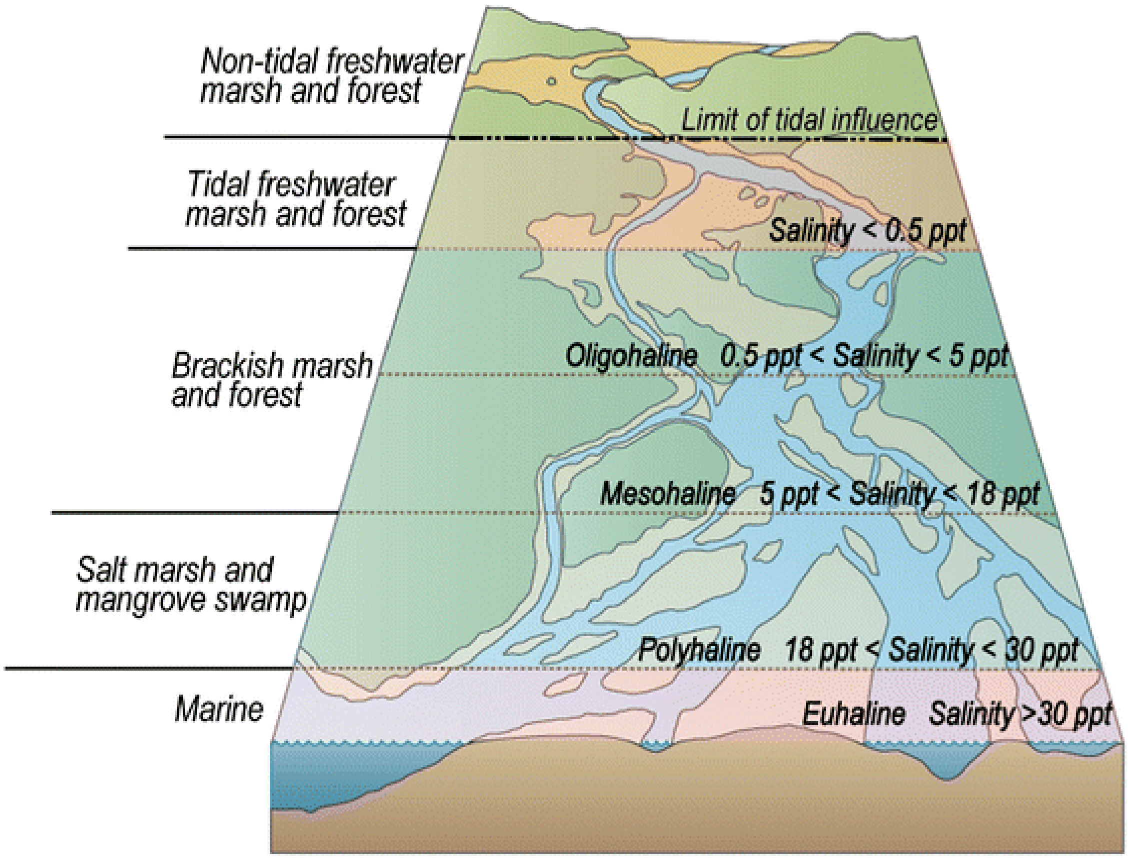


[11]:
```python
# plot salinity at river bottom over a few days, Old Lyme vs Essex
%matplotlib widget
fig, ax = plt.subplots(nrows=1, ncols=1, figsize=(10,4))
ax.plot(pd.to_datetime(salinity_oldlyme.datetime), salinity_oldlyme.
 ↪salinity_bottom, label='salinity, bottom, Old Lyme [psu]')
ax.plot(pd.to_datetime(salinity_essex.datetime), salinity_essex.
 ↪salinity_bottom, label='salinity, bottom, Essex [psu]')
ax.grid(True) # add grids
ax.legend() # add legends

# plot meters instead of feet
ax1 = ax.twinx()
ax1.plot(pd.to_datetime(gaugeheight_oldlyme.datetime), gaugeheight_oldlyme.
 ↪gauge_height*.3048, 'r', label='gauge height [m]')
ax1.set_ylim([-.5, 1])
ax1.legend(loc="lower left") # add legends

ax.set_xlim([pd.to_datetime('2025-10-03 12:30'), pd.to_datetime('2025-10-05 12:
 ↪30')])
```

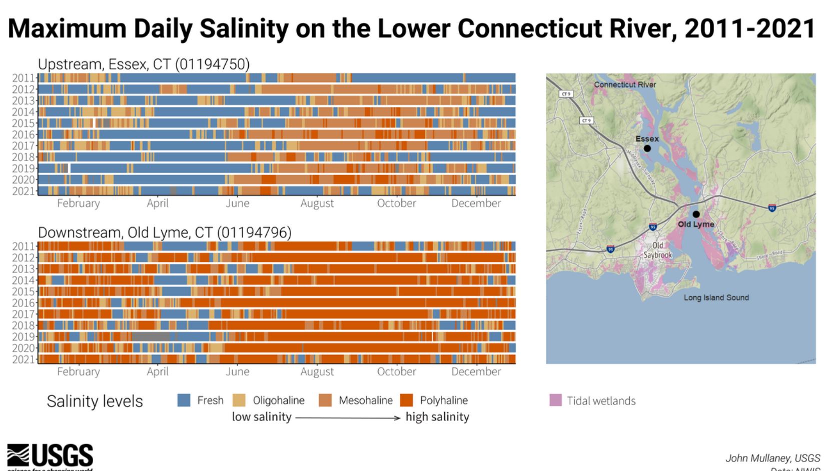
[11]:
```
(np.float64(20364.520833333332), np.float64(20366.520833333332))
```



The salinity gradient generally increases from the input source of an estuary, usually a stream or river, to the output source, the sea or ocean. Salinity is measured in gravimetrically as parts per thousand of solids in liquid or ppt. The salinity of the ocean is generally around 35 ppt (Antonov 2006). Another salinity unit is the practical salinity unit or PSU measurement, which is based on water temperature and conductivity measurements made by sondes and the ocean is also generally around 35 PSU (Antonov 2006). Using ppt or PSU gives similar results for the ocean's seawater salt content (Antonov 2006).



Tidal wetlands along an estuarine salinity gradient, which can be classified into four types according to salinity and tidal influence (Odum, 1988): (i) nontidal water marshes and forests, (ii) tidal freshwater marshes and forests (salinity < 0.5 ppt), (iii) brackish marsh and forest (salinity: 0.5–18 ppt), and (iv) salt marshes and mangrove swamps (salinity: 18–30 ppt); brackish wetlands can be further divided into oligohaline (salinity: 0.5–5 ppt) and mesohaline (5–18 ppt) components (Luo et al., 2019)



Timeseries plots of maximum daily salinity on the lower Connecticut River 2011-2021 for an upstream site on the river and a downstream site in the estuary. The timeseries chart uses tiles to show annual patterns in salinity compared across 10 years. At the upstream site, Essex CT (01194750), freshwater dominates the beginning of the year up until May, with some moments of low salinity levels (oligohaline). Starting in June, the upstream site increases in salinity, with moderate salinity levels (mesohaline) through November. At the downstream site, salinity levels are high (polyhaline) for the majority of the year, with short periods of freshwater during April. This reflects the timing of snowmelt and increased streamflow. Across years, the upstream site appears to be getting saltier earlier. There is no obvious trend across years at the downstream site. A map indicates that the two sites are relatively close (~6 km apart) in the Long Island Sound and surrounded by tidal marshes that require certain levels of salinity. (https://www.usgs.gov/media/images/maximum-daily-salinity-lower-connecticut-river-2011-2021)

2.2 2). Estuary type

2.2.1 a. Classification of estuaries on the basis of water balance

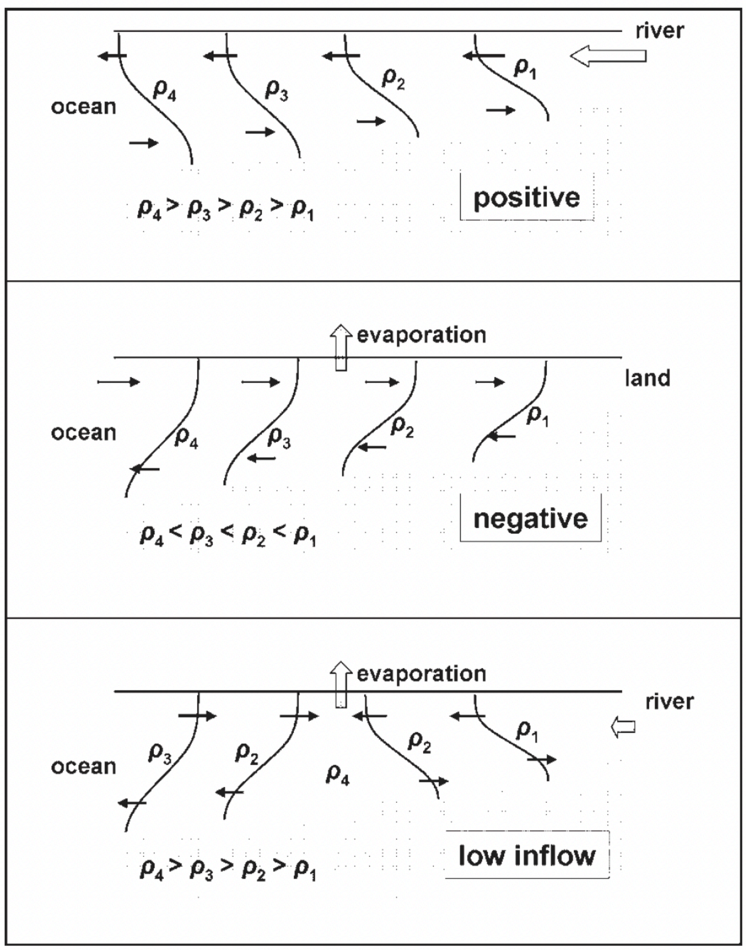


Figure 1.1. Types of estuaries on the basis of water balance. Low-inflow estuaries exhibit a “salt plug”.

Positive estuaries are those in which freshwater additions from river discharge, rain and ice melting exceed freshwater losses from evaporation or freezing and establish a longitudinal density gradient. In positive estuaries, the longitudinal density gradient drives a net volume outflow to the ocean, as denoted by stronger surface outflow than near-bottom inflow, in response to the supplementary freshwater. The circulation induced by the volume of fresh water added to the basin is widely known as “estuarine” or “gravitational” circulation.

Inverse estuaries are typically found in arid regions where freshwater losses from evaporation exceed freshwater additions from precipitation. There is no or scant river discharge into these systems. They are called inverse, or negative, because the longitudinal density gradient has the opposite sign to that in positive estuaries, i.e., water density increases landward. Inverse estuaries exhibit net volume inflows associated with stronger surface inflows than near-bottom outflows. Water losses related to inverse estuaries make their flushing more sluggish than positive estuaries. Because of their relatively sluggish flushing, negative estuaries are likely more prone to water quality problems than positive estuaries.

Low-inflow estuaries also occur in regions of high evaporation rates but with a small (on the order of a few m^3/s) influence from river discharge. During the dry and hot season, evaporation processes may cause a salinity maximum zone (sometimes referred to as a salt plug, e.g., Wolanski, 1986) within these low-inflow estuaries. Seaward of this salinity maximum, the water density decreases, as in an inverse estuary. Landward of this salinity maximum, the water density decreases, as in a positive estuary. Therefore, the zone of maximum salinity acts as a barrier that precludes the seaward flushing of riverine waters and the landward intrusion of ocean waters. Because of their weak flushing in the region landward of the salinity maximum, low-inflow estuaries are also prone to water quality problems.

2.2.2 b. Classification of estuaries on the basis of geomorphology

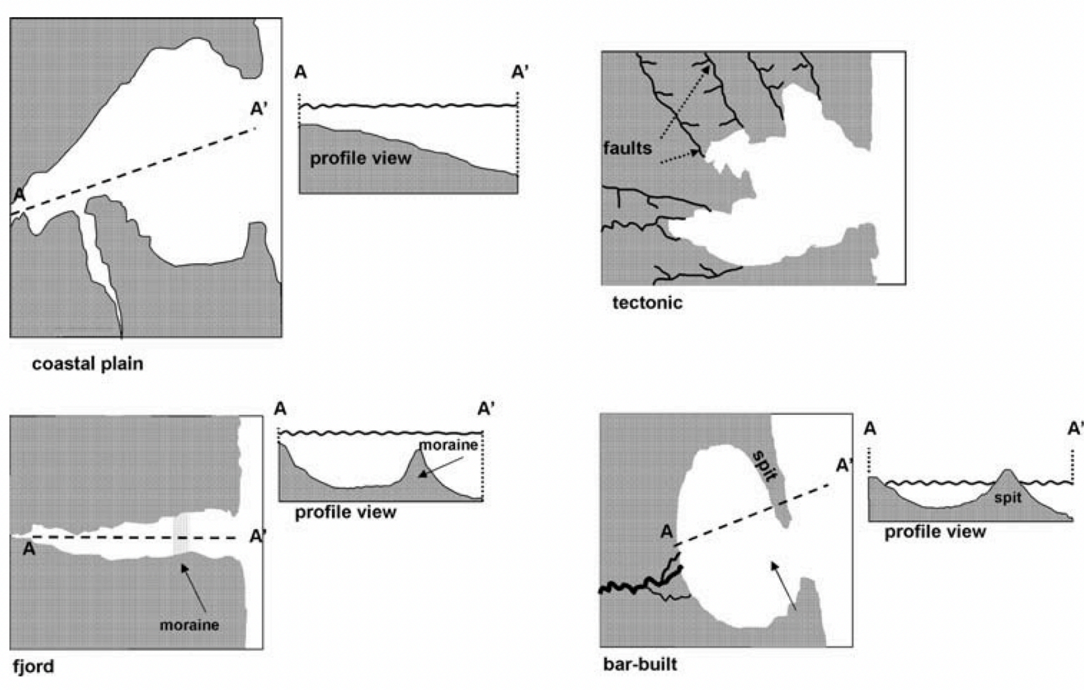


Figure 1.2. Classification of estuaries on the basis of geomorphology.

Coastal plain estuaries, also called drowned river valleys, are those that were formed as a result of the Pleistocene increase in sea level, starting ~15,000 years ago. Originally rivers, these estuaries formed during flooding over several millennia by rising sea levels. Their shape resembles that of present-day rivers, although much wider. They are typically wide (on the order of several kilometers) and shallow (on the order of 10 m), with large width/depth aspect ratios. Examples of these systems are Chesapeake Bay and Delaware Bay on the eastern coast of the United States.

Fjords are associated with high latitudes where glacial activity is intense. They are characterized by an elongated, deep channel with a sill. The sill is related to a moraine of either a currently active glacier or an extinct glacier. Fjords are deep (several hundreds of meters) and narrow (several hundreds of meters) and have low width/depth aspect ratios with steep side walls. Fjords are found in Greenland, Alaska, British Columbia, Scandinavia, New Zealand, Antarctica and Chile.

Bar-built estuaries, originally embayments, became semienclosed because of littoral drift causing the formation of a sand bar or spit between the coast and the ocean. Some of these bars are joined to one of the headlands of a former embayment and display one small inlet (on the order of a few hundred meters) where the estuary communicates with the ocean. Examples of bar-built estuaries abound in subtropical regions of the Americas (e.g., North Carolina, Florida, northernMexico) and southern Portugal.

Tectonic estuaries were formed by earthquakes or by fractures of the Earth's crust, and creases that generated faults in regions adjacent to the ocean. Faults cause part of the crust to sink, forming a hollow basin. An estuary is formed when the basin is filled by the ocean. Examples of this type of estuary are San Francisco Bay in the United States, Manukau Harbour in New Zealand, Guaymas Bay in Mexico and some Rias in NwSpain.

2.3 3). Stratification and Mixing

According to water column stratification or salinity vertical structure, estuaries can be classified as **salt wedge, strongly stratified, weakly stratified or vertically mixed**. This classification considers the **competition between buoyancy forcing from river discharge and mixing from tidal forcing** (Fig. 1.3). Mixing from tidal forcing is proportional to the volume of oceanic water entering the estuary during every tidal cycle, which is also known as the tidal prism.

Large river discharge and weak tidal forcing results in **salt wedge** estuaries such as the Mississippi (USA), Rio de la Plata (Argentina), Vellar (India), Ebro (Spain), Pánuco (Mexico), and Itajaí-Açu (Brazil). The Connecticut River is a tidal salt wedge estuary. These systems are strongly stratified during **flood** tides, when the ocean water intrudes in a wedge shape. Typical tidally averaged salinity profiles exhibit a sharp **pycnocline** (or halocline), with mean flows dominated by outflow throughout most of the water column and weak inflow in a near-bottom layer. The mean flow pattern results from relatively weak mixing between the inflowing ocean water and the river water.

Moderate to large river discharge and weak to moderate tidal forcing result in **strongly stratified estuaries** (Fig. 1.3). These estuaries have similar stratification to salt wedge estuaries, but the stratification remains strong throughout the tidal cycle as in fjords and other deep (typically >20m deep) estuaries. The mean flow exhibits well-established outflows and inflows, but the inflows are weak because of weak mixing with freshwater and weak horizontal density gradients.

Weakly stratified or partially mixed estuaries result from moderate to strong tidal forcing and weak to moderate river discharge. Many temperate estuaries, such as Chesapeake Bay, Delware Bay and James River (all in the eastern United States) fit into this category. The mean salinity profile either has a weak pycnocline or continuous stratification from surface to bottom, except near the bottom mixed layer. The **mean exchange flow** is most vigorous (when compared to other types of estuaries) because of the **mixing** between riverine and oceanic waters.

Strong tidal forcing and weak river discharge result in vertically **mixed estuaries**. Mean salinity profiles in mixed estuaries are practically uniform and mean flows are unidirectional with depth.

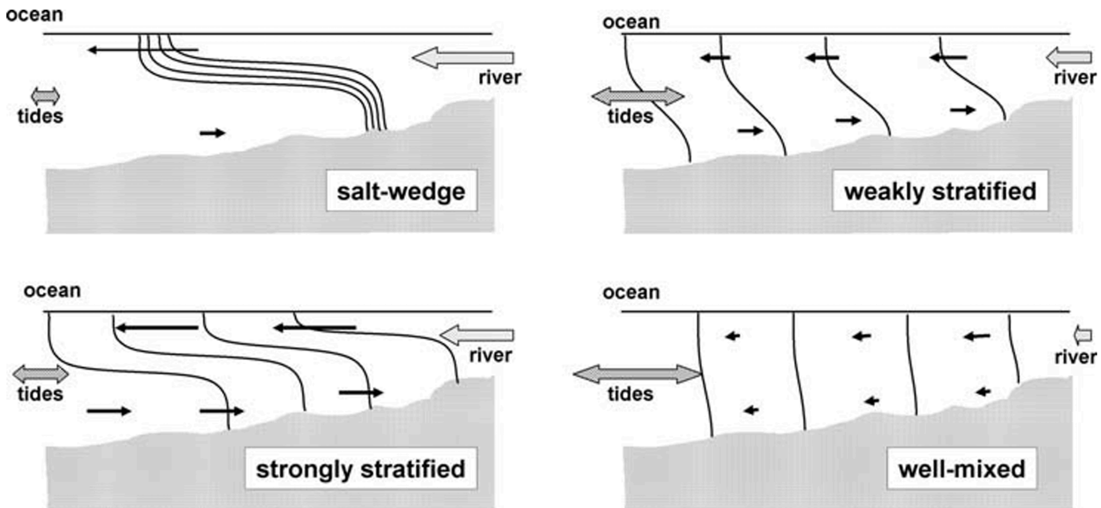


Figure 1.3. Classification of estuaries on the basis of vertical structure of salinity.

It is essential to keep in mind that many systems **may change** from one type to another in consecutive tidal cycles, or from month to month, or from season to season, or from one location to another inside the same estuary. For instance, the Hudson River changes from highly stratified during neap tides to weakly stratified during spring tides.

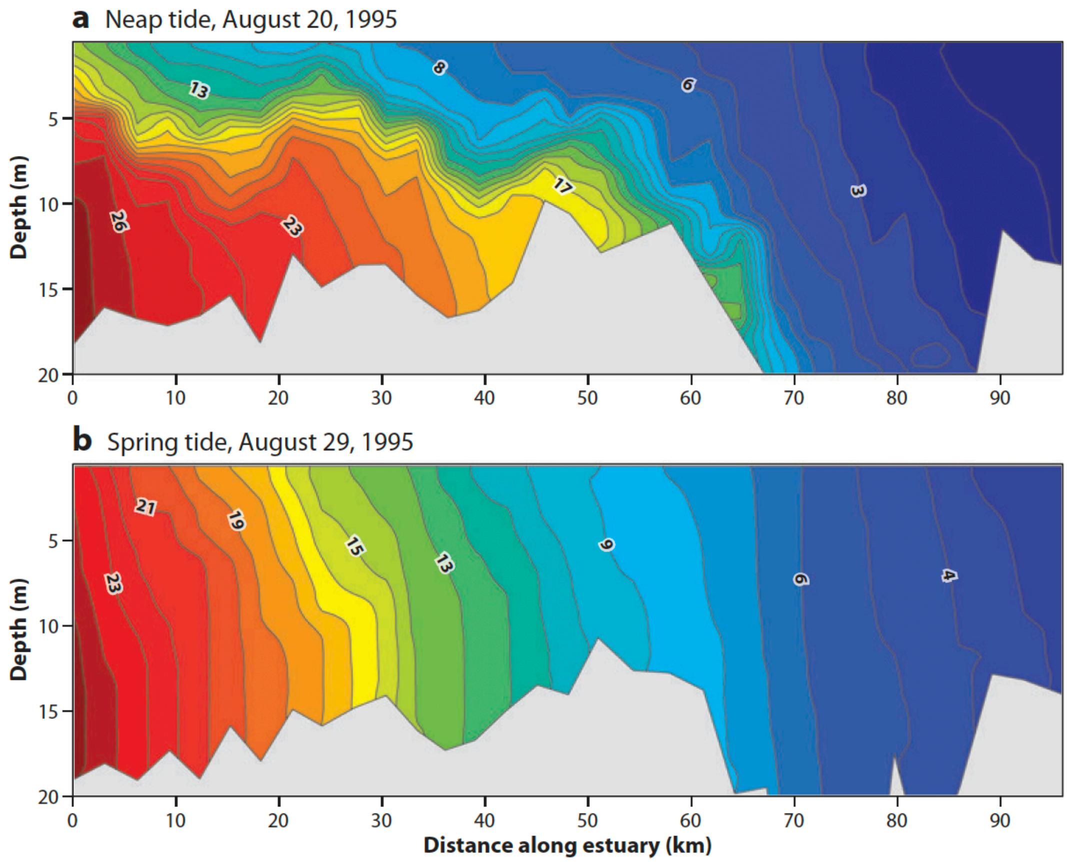


Figure 10

Along-estuary salinity contours in the Hudson River estuary during neap and spring tides, showing the strong spring-neap variation in stratification. The vertically averaged along-estuary salinity distribution changes only slightly, whereas the strength of the stratification changes by an order of magnitude.

2.4 4). Exchange flow in partially stratified estuaries

The tidally averaged circulation of many estuaries has two extraordinary features.

First, despite the net seaward flow due to the river through any cross-section, the deeper half of the water typically flows **landward**, as shown schematically in Figure 1a. This inflow gradually rises and joins the river flowing **outward** in the upper half of the estuary, resulting in an overall pattern called the **exchange flow**. The persistent inflow at depth and associated strong stratification traps particles, larvae, nutrients, and low-oxygen water, giving rise to both the high biological productivity and persistent water-quality problems that characterize estuaries worldwide.

Second, the volume flux of the exchange flow is often **many times greater** than that of the river alone. The corresponding salinity field (Figure 1b) has a gradual **along-channel salinity gradient**, from oceanic to fresh, because the deep inflowing ocean water is continually freshened by vertical turbulent mixing with the fresher water above. Here, the turbulence is driven by the tides.

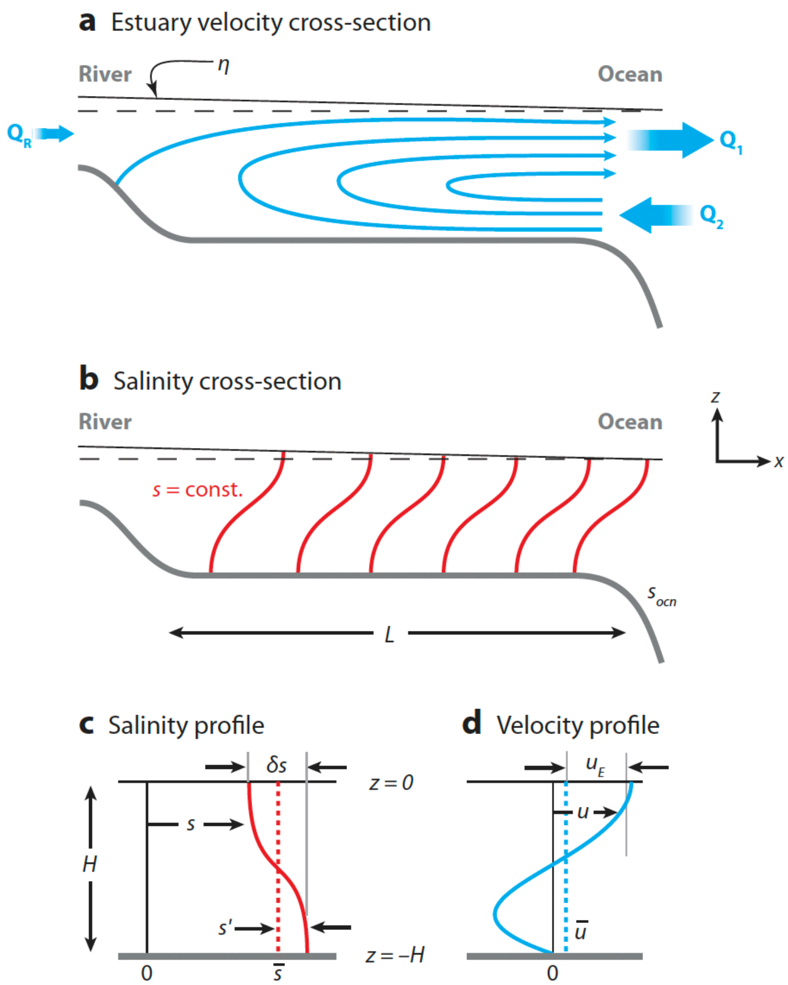
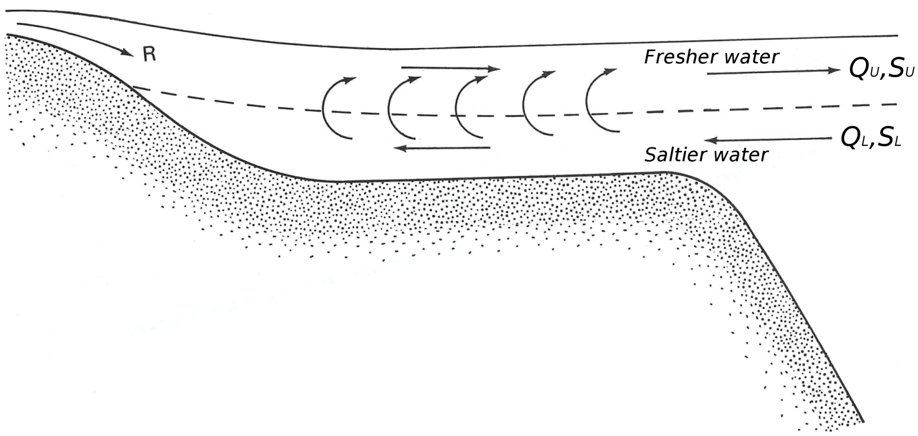


Figure 1

Definition sketch of an idealized partially mixed estuary, showing (*a*) the tidally averaged circulation highlighting the exchange flow and (*b*) isoahalines. Vertical profiles of salinity (*c*) and velocity (*d*) come from the analytical solutions in Equations 8 and 9.

2.5 5). Salt balance

By considering the mass & salt budgets over an esturine basin (where riverine input flows out to fill estuaries before connecting with the sea), we can predict the size of exchange flow at the sill/strait or mouth [Knudsen, 1900].



- R is the riverine input;
- Q_U and Q_L are the transport of mass at the upper (U) and lower (L) layers;
- S_U and S_L are the salinity of the upper and lower layers.

Chalk talk and Discussion: Combine the principles of mass and salt conservation to derive expressions for Q_U and Q_L (Knudsen relations), and discuss the implications for two-layer estuarine exchange circulation. Tips: consider the role of mixing and along-estuary variations

The relations for Q_U and Q_L, known as Knudsen relations, allow us to draw some conclusions about the 2-layer circulation: - For (S_L - S_U) > 0, the lower layer flow has opposite sign to the upper layer; - Mixing reduces (S_L - S_U) and increases ($Q_L + Q_U$) along the estuary. By measuring salinity profiles in different coordinates along the estuarine channel we can quantify the mixing that occurs in the zone between the profiles; - Near the ocean (S_L - S_U) will be smaller and hence the fluxes will be larger; - The along-estuary difference in the inflowing water, Q_L, must equal the amount of water mixed vertically into the upper layer.

3 2. River Plume

River plumes are generated by the flow of buoyant river water into the coastal ocean, where they significantly influence water properties and circulation.

- In the source region, the buoyancy and momentum that initiate a river plume are determined by estuarine processes, which are responsible for the initial transformation of river discharge. The salinity, thickness, and turbulent mixing rates of the near-field river plume are set by the competition between the stratifying influence of river discharge and the mixing provided by tidal energy within the estuary. In strongly forced systems, the estuarine discharge separates from the bottom near the river mouth and forms the buoyant layer. The liftoff point is the location of the bottom attached salt front where the upper layer loses contact with the bottom.

- The river plume accelerates into a jet-like near-field region beginning at liftoff, or at the river mouth if liftoff occurs within the estuary.

- The river plume begins to shoal and widen, leading to deceleration as it enters the mid-field region. This is where the inflowing river water transitions from the inertial near-field jet into a geostrophic or wind-dominated far-field plume. Lateral spreading is arrested, inflow momentum is lost, and plume dynamics become increasingly influenced by Earth's rotation.

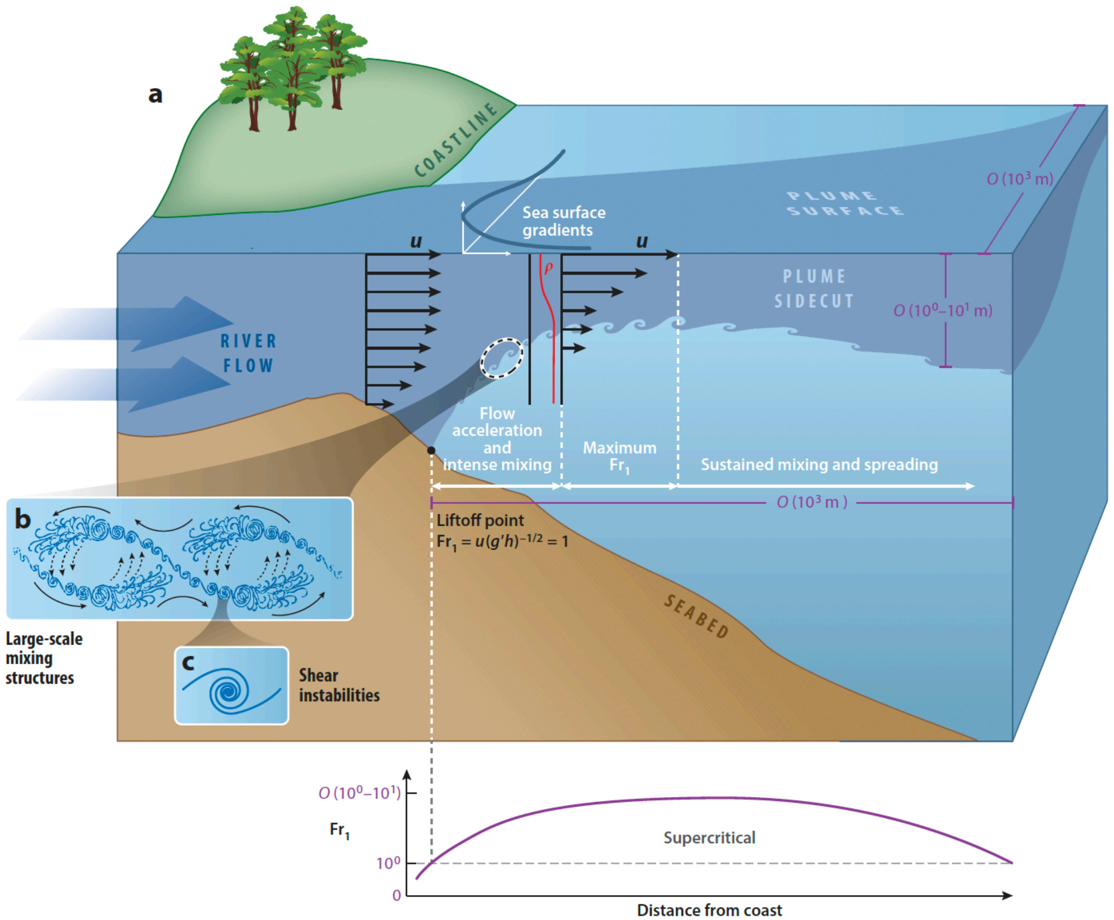


Figure 1

(*a*) Schematic representation of the plume liftoff process and the near-field plume region. (*b*) Large-scale mixing structures in the flow acceleration region. Panel *b* adapted from Geyer et al. (2010). (*c*) Shear instabilities comprising the large-scale mixing structures.

- Finally, the far field is the region beyond the mid-field in which the plume no longer has a memory of the initial momentum of the river discharge, and the dynamics are primarily governed by Earth's rotation, buoyancy, wind stress, and sometimes bottom stress. This region may extend hundreds of kilometers from the mouth. When winds and ambient currents are not sufficient to force the plume offshore, the far-field plume forms a geostrophic coastal current

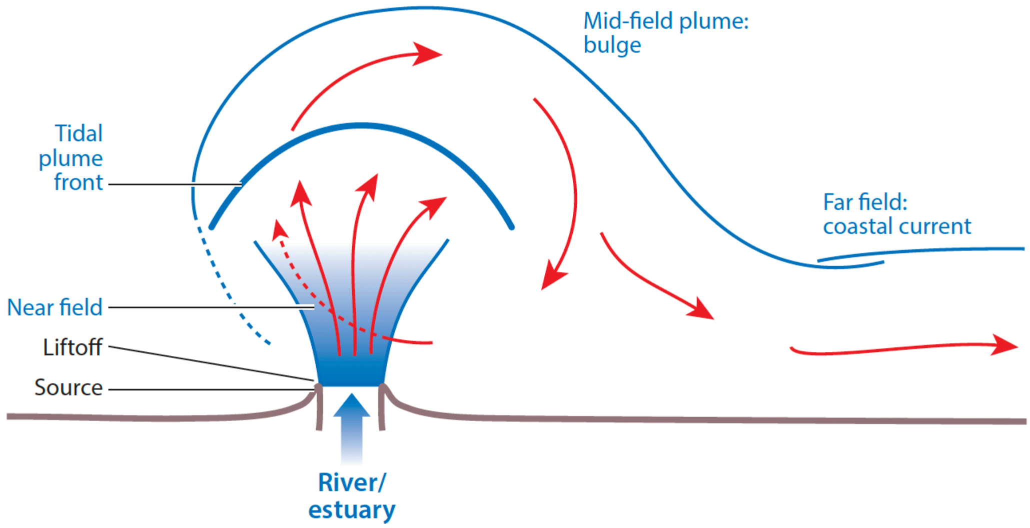


Figure 2

Schematic representation of the prototypical plume comprising all dynamical regions. Other plume morphologies are discussed in Section 5 and shown in **Figure 5**.

The fresh buoyant water that exits the Connecticut River mouth during each ebb tide expands as a plume, and floats above the denser waters of Long Island Sound. Currents in the Sound flow back and forth along the coast each tide, pushing the plume along the shore first to the east and then to the west. The location of the plume boundary (front) goes through a similar cycle almost every tide, initially being held stationary by eastward tidal currents (ebb), then expanding freely around slack tide, and subsequently being aided as it moves to the west by the ambient flow (flood).

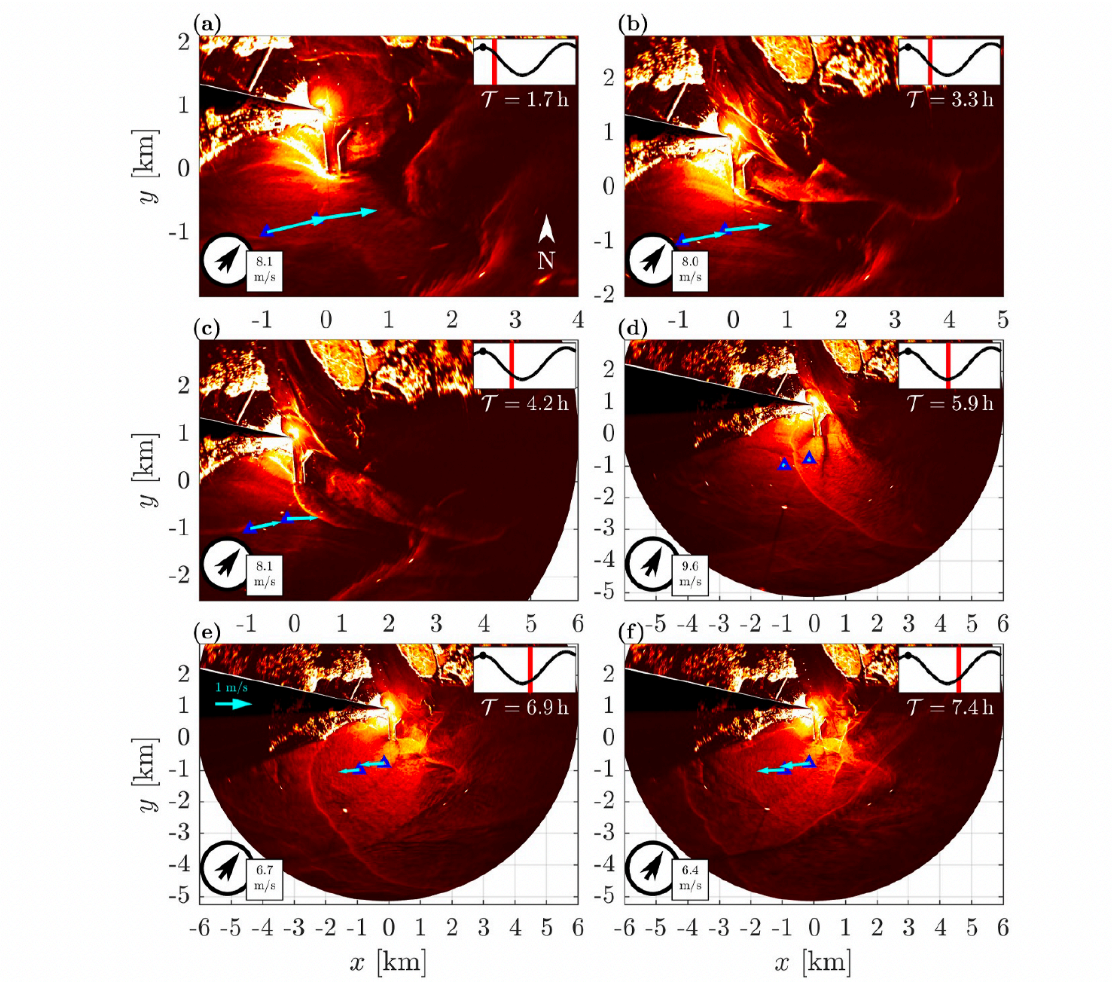


Figure 6. Observed image time series of frontal evolution during 26–27 June 2017, with depth-averaged current vectors (cyan arrows; see scale in panel e) overlain and insets of wind speed and water surface elevation. Hour after high tide (26 June 2023 at 17:25 UTC) is labeled below each surface elevation inset.

4 3. Connectiuct River

The Connecticut River is the largest source of freshwater discharging into Long Island Sound, with a mean discharge of about 500 m^3/s and spring freshet conditions that exceed 2000 m^3/s. The tidal range at the mouth is 1–1.5 m and is predominantly semidiurnal, and tides propagate approximately 100 km up the river to the dam near Thompsonville, CT. The estuary is relatively shallow, with multiple bedrock constrictions of 300–400 m width and thalweg depths of 10–12 m separated by wider (700–1200 m), shallower regions with maximum depths of 4–6 m. The modest cross-sectional area of the estuary leads to relatively strong velocities due to the river discharge, corresponding to 0.16 and 0.7 m/s for the average flow and typical freshet conditions. As a result of the shallow bathymetry and strong river velocities, the salinity intrusion is relatively short, typically extending only 5–15 km from the mouth. By comparison, the Hudson River is the next major drainage basin to the west and has a similar mean annual discharge, but its deeper bathymetry results in a salinity intrusion that extends 30–100 km from the mouth. Under moderate to high discharge conditions, the Connecticut is a tidal salt wedge characterized by strong horizontal salinity gradients and strong stratification that varies tidally with frontal propagation during flood tides and intense mixing during ebbs [Ralston et al., 2010].

4.1 1). Stratification in estuary and tidal effects

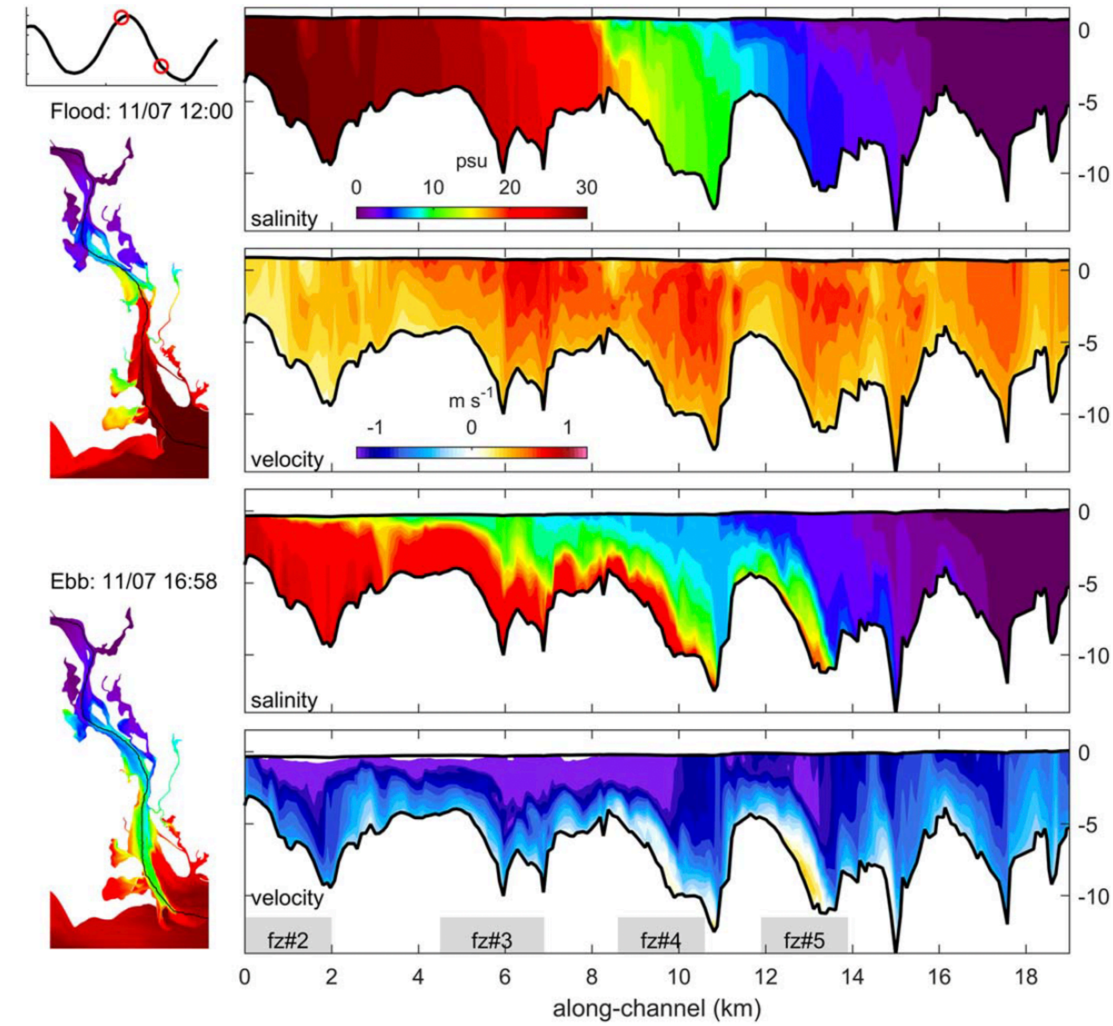
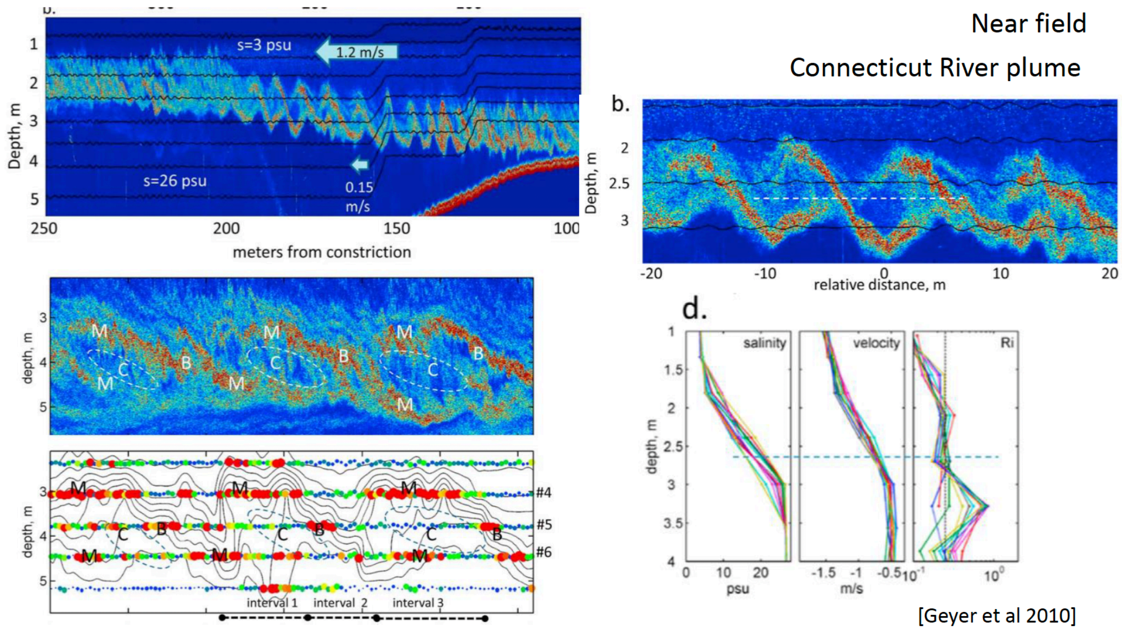


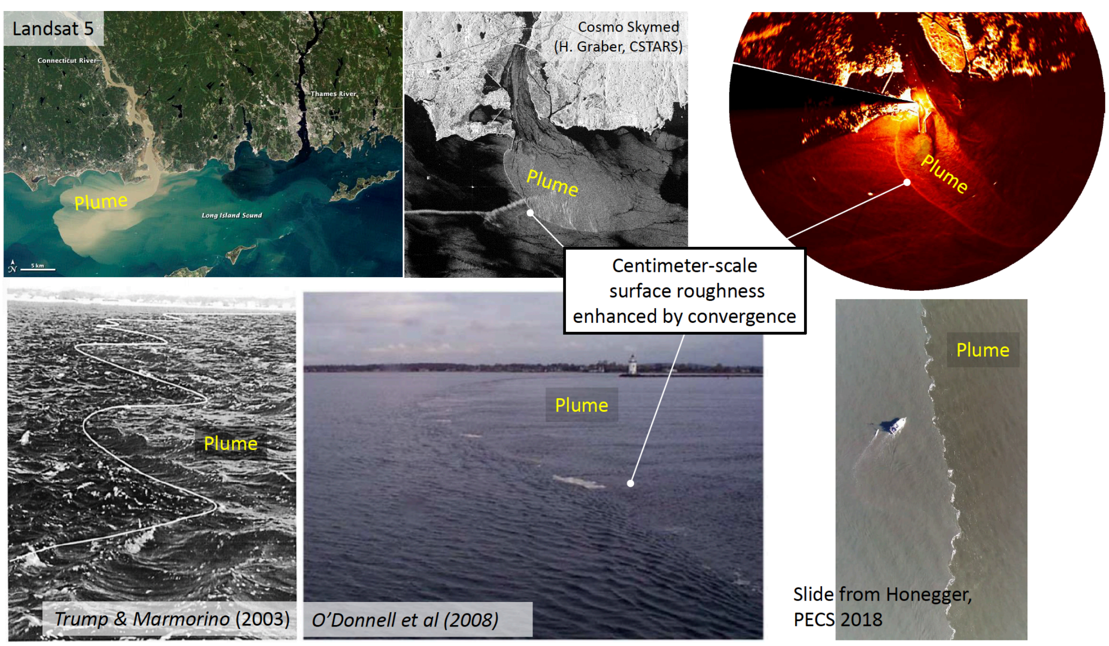
Figure 2. Along-channel sections of salinity and along-channel velocity from the fine grid model during the November 2013 observation period. Top plots are during a flood tide and bottom during an ebb. Corresponding surface salinity maps are to the left, marking the location of the along-channel transect. The water level at the time of the two snapshots is shown at the top left. [Ralston et al. 2017]

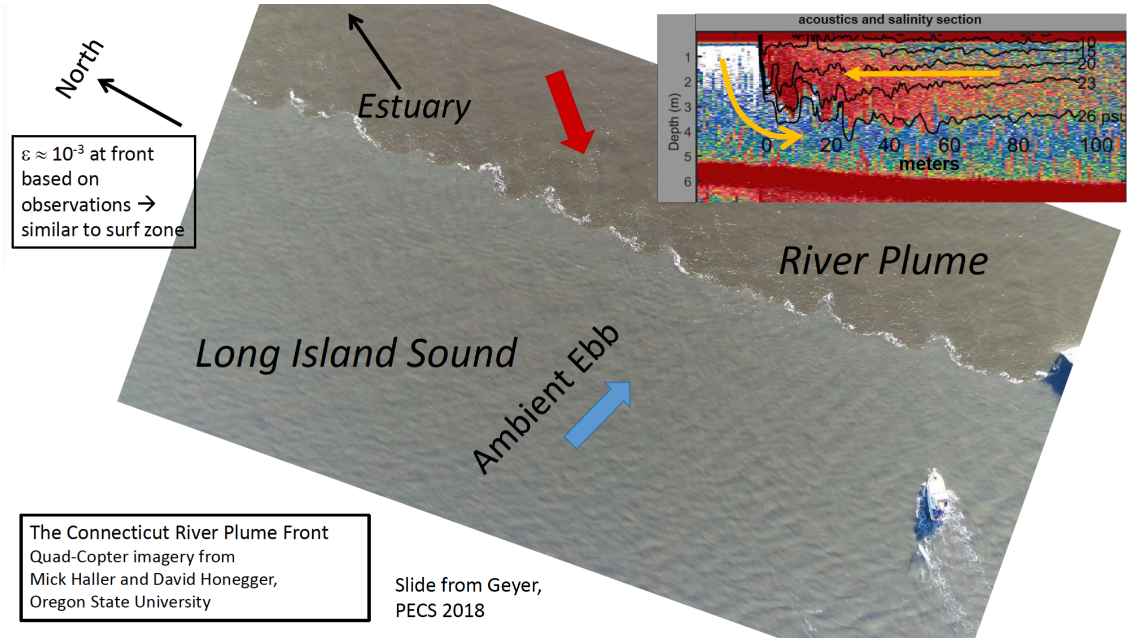
4.2 2). river plume

4.2.1 a. Near field



4.2.2 b. mid field





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