MAST602

Lecture 11

Delaware Bay & Continental Shelf

Continental Shelf circulation
Delaware Coastal Current
Longshore flow
Estuarine convective flow
Estuaries
Delaware Bay tides
Subtidal flow
Fronts

MAST 602
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Note: In these lecture notes, references that begin with A, B, or C are keyed to the list at the end of this set of notes.

Continental Shelf oceanography

There's no single type of continental-shelf or offshore oceanography

For example, some areas have broad continental shelves:

- Off US East Coast
- East China Sea
- Off Argentina

Other areas have small or no continental shelves:

- Hawaii
- California
- Peru

Extremes of salinity occur in coastal regions and semi-enclosed seas

- Salinity ~ 40 in the Red Sea
- Salinity ~ 20, even 200km off the mouth of the Amazon

Coastal circulation may be controlled by offshore processes

- Gulf Stream dominates US coastal regions south of Cape Hatteras

In this lecture, we will focus on the US East-Coast continental shelf and the Delaware estuary

US East Coast continental shelf

Definitions by topographic region

Fig 11- 1 Chart of Hudson submarine canyon **Ref. 8, Fig. 2.10**

> In a chart such as this, the differentiation between shelf, slope and rise stands out.

Shelf	~ 1:500 slope;	width ~ 75 km
Slope	~ 7:100 slope;	width ~ 20 km
Rise	< 1:100 slope;	width ~ 100-1000 km

Definitions by physical oceanographic features

Fig 11- 2 Iselin's water-mass subdivisions **Ref. 31, Fig. 2**

> The division into regions based on physics matches surprisingly well with that based on geography. Why might this be so?

Shelf water	$S < 35$ psu
Slope water	$35 < S < 36$ psu
Gulf Stream	$S > 36$ psu
Sargasso Sea	$S > 36$ psu

Other East-coast regions:

- *Middle Atlantic Bight*
  from Cape Hatteras to Cape Cod
- *New York Bight*
  Off New Jersey and Long Island
- *Gulf of Maine*
  from Cape Cod to Nova Scotia

Continental Shelf Circulation

The Continental Shelf over the Mid-Atlantic Bight has a width ~ 100km from shore to shelf break

Surface flow on the Shelf is generally
towards the South and West
with speeds ~ 5 cm/sec (1/10 knot)
except during periods of persistent
adverse wind forcing

Fig 11- 3 Surface circulation map for US East Coast (1913) Ref. A1, Fig. 7.4

> Though done in 1913, this chart catches the essentials of the shelf surface circulation.

📖 **Bumpus & Lauzier Atlas Ref. A6**

> Throwing bottles overboard seems like a comical way to do oceanography. (Especially if you drink the contents first!) The results are serious, though, and the Bumpus and Lauzier *Atlas* is a useful reference.

The flow is shoreward along the bottom
off estuaries, consistent with the inflow
of a salt wedge into the estuary.

Cape Cod (Nantucket Shoals) and
Cape Hatteras (Diamond Shoals)
appear to be natural barriers
limiting alongshore flow

Near Cape Hatteras, the flow turns
offshore, and becomes entrained
into the Gulf Stream

Fig 11- 4 Gulf Stream structure off Cape Hatteras Ref. 33, Fig. 7.16

> The details of the entrainment of shelf water into the Gulf Stream have not been well studied.

Delaware Coastal Current

The Delaware Coastal Current (DCC)
is a flow originating in Delaware Bay
that commonly flows southward
along the inner Continental shelf

The features of the DCC are:

- Width ~ 25-30 Km
- Buoyancy-driven*
- Turns right upon leaving Delaware Bay under the influence of coriolis
- Trapped to the inner shelf by coriolis force
- Length ~ 200 Km
- Conveys materials and biota downstream

* *Buoyancy-driven*:
Water is colder and less saline and hence less dense.
Recall that "light water is on the right looking downstream in the northern hemisphere".

The Delaware Coastal Current is variable:

- Long, narrow, and deep
  under winds producing downwelling
  [such as winter winds from the NW]

- Short, wide, and shallow
  under winds producing upwelling
  [such as summer winds from the SW]

- Winds producing upwelling
  promote rapid mixing

The DCC exits from Delaware Bay on the
right-hand side, looking downstream.

Fig 11- 5 Currents exiting Delaware Bay **Ref. A8, Figs. 3 & 4**

Why should the current hug the right-hand side?

Longshore flow

What is the mechanism that drives
the southwestward longshore flow?

A number of hypotheses have been advanced:

1. Does **freshwater runoff** (buoyancy-driven flow)
drive the longshore flow?

- Runoff is fresher than ocean water
and thus is less dense
- This will cause a geostrophic flow
with lighter water to the right of the flow
(in the northern hemisphere)
- So that off our coast the geostrophic flow
induced by freshwater runoff
would be to the south.

Density-induced coastal geostrophic flows
of this kind are ubiquitous throughout the ocean.

Other examples are:

- Norwegian Coastal Current
- Scottish Coastal Current
- East Greenland Current
- Icelandic Coast Current
- Antarctic East Wind Drift

Fig 11- 6 Coastal water from the West Greenland Current **Ref. A7, Fig 6**

Is the flow off Delaware part of a much larger
pattern of the North American east coast?

In all these cases, salinity, rather than
temperature controls density
[This is generally the case in cold water.]

- In the northern hemisphere
the flow is to the right,
looking seaward.

- In the southern hemisphere,
the flow is to the left,
looking seaward.

2. Does **wind stress** drive the longshore flow?
- This would imply a net offshore wind with Ekman transport to the right.
- Such a forcing is not obvious.

3. Does a **downstream pressure gradient** drive the longshore flow?
- Sverdrup, Johnson, & Fleming (Ref. 9) note a 10 cm difference in sea-level between Cape Hatteras and Cape Cod.
- This might drive the longshore flow.
- However, the geodetic levelling has been put in question by later measurements.

Shelf-break front

The *shelf-break front* is a sharp transition between cooler and fresher coastal water and warmer and more saline offshore water.

Fig 11- 7 Shelf-break sections **Ref. B2, Fig. 1**

Can you identify the "break" in physical properties near the shelf break?

The shelf-break front is a characteristic feature of the edge of the Shelf in the mid-Atlantic Bight.

More on estuaries—classification

Type	Example	Ratio of tidal volume/river input
Highly stratified	fjord salt wedge	<1
Partially mixed	James River	$10 - 10^3$
Well mixed	River Severn	$> 10^3$

Fig 11- 8 Estuary types **Knauss, Fig. 11-4**

For Delaware Bay (Pape & Garvine, Ref. C1),
River input = $650\ \mathrm{m^3\ s^{-1}}$
Tidal volume = $1.9 \times 10^5\ \mathrm{m^3\ s^{-1}}$

So the ratio ~ 290

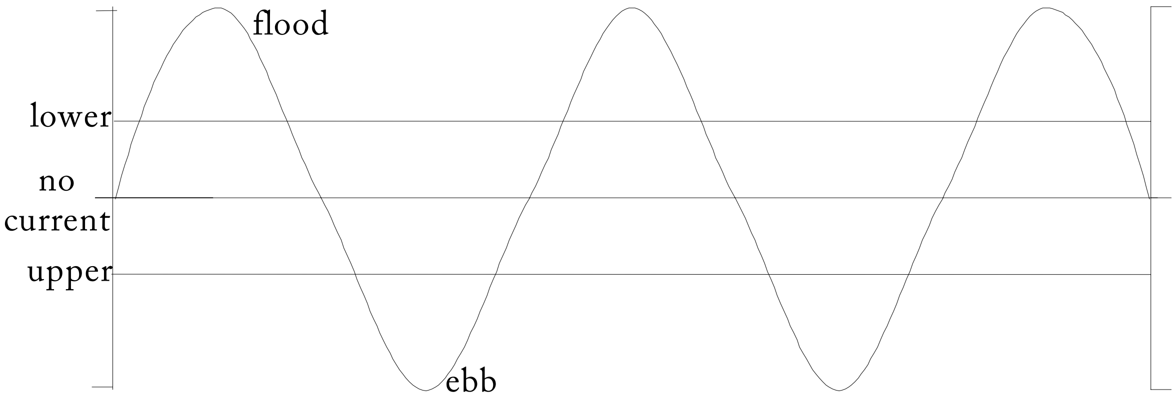
Tidal mixing may nearly eliminate
vertical stratification
(say tide ~ $10^3 \times$ river input)

It's necessary to separate estuarine flow into

- a net flow (which varies with depth)
- an instantaneous flow
(where the ebb and flow of tides dominates)

The depth-varying net flow can modulate
the tidal flow so that the upper and
lower layers can have tidal phases
with different duration and
with different times of ebb and flood.

Layer	Net flow	Tide
Upper layer	seaward	ebb is longer than the flood ebb starts earlier
Lower layer	landward	flood is longer than the ebb ebb starts later



The mean flow in the upper and lower layers can shift tidal phases

Other factors that can vary estuarine flow:

- the wind

  - variations in river runoff
  - the earth's rotation

Note that:

- outflow hugs the right side of the estuary (looking downstream)
- there is a stronger ebb and weaker flood on the right side

Does the outflow in the ocean veer to the right?

Also,
There is often a cross-stream slope to the interface in broad estuaries:

- The lower inflow tends to the right looking up the estuary
- The upper outflow tends to the right looking down the estuary

All the above apply to the Northern Hemisphere, of course. The slope would be reversed in the Southern Hemisphere

Delaware Bay Dimensions:

If we define Delaware Bay as extending from Cape Henlopen/Cape May to Trenton, NJ, (the head of the tide) we get:

Length	132 mi	210 km
width at the Capes	11 mi	18 km
width at widest point	27 mi	43 km
width at Trenton, NJ	1000 ft	0.3 km
mean depth	32 ft	9.6 m
80% of Bay	< 30 ft	< 9 m
Surface area	720 sq mi	1840 km^2
Saline portion	72 mi	120 km

Some other Delaware Bay properties:

- Drainage basin:
  35,000 km^2 in 5 states:
  (Delaware, Pennsylvania, New Jersey,
  New York, and a tiny bit of Maryland)
- Estuary discharge:
  58% from the Delaware River
  15% from the Schuylkill River
  < 1% any other single source
- Average fresh-water residence time:
  ~ 100 days
- Average discharge (at Trenton, NJ):

Annual	320 m^3 s^{-1}
Jun - Oct	195 m^3 s^{-1}
Nov - Feb	334 m^3 s^{-1}
Mar - May	510 m^3 s^{-1}

- Average annual discharge at the mouth of the bay: 550 m^3 s^{-1}

Fig 11- 9 Delaware Estuary drainage basin **Ref. C3, Fig. 1**

The Delaware basin extends into New York State.

Fig 11- 10 Topography **Ref. C3, Fig. 3**

The underwater topography of the Bay is channeled with tongues of deeper water. As you can see, it's not easy to model it simply.

Fig 11- 11 Depth vs. distance **Ref. C2, Fig. 45**

Over much of its length, Delaware Bay has an approximately constant depth.

Fig 11- 12 Width vs. distance **Ref. C2, Fig. 44**

Width approximation:
Much of the Delaware Estuary width can be approximated by:

$$b = b_1 e^{-\frac{x}{l}}$$

x is the distance up the Delaware Estuary from the point of origin
b_1 is width of the estuary at the origin
b is the width of the estuary at position x
l ~ 45.6 km (24.6 n mi)
this is valid for the upper 70% of the estuary

Delaware Bay Tides

The *lunar semi-diurnal tide* (M_2) is dominant in Delaware Bay

i.e., the dominant tide has
a period of 12.42 hours
= 12 hours, 24 minutes

Fig 11- 13 Harmonic tidal constants for Delaware Bay **Ref. C2, Table 3**

Note the dominance of the M_2 tide.

Fig 11- 14 Variation in amplitude of tidal constituents **Ref. C2, Fig. 11**

The tidal components, especially the M_2 increase going up the estuary.

mean range: 1.3 m (4.3 ft)
range increases to 2 m (6.7 ft)
at Trenton NJ, the head of the tide.

Recall: *tidal range* = vertical distance between low and high tide.

High tide arrives at Trenton ~ 8 hours after high tide at Cape Henlopen

Tidal currents are ~ 1 m s^{-1}

Tidal inflow

The Delaware River accounts for
about 51% of the
freshwater inflow
i.e., about 650 $m^3 s^{-1}$

Tidal volume is about
$1.9 \times 10^5 m^3 s^{-1}$.

So that the ratio of tidal volume
to freshwater volume ~ 290

i.e., Delaware Bay is a
partially mixed type of estuary

Do tides increase upstream?

Fig 11- 15 Co-amplitude and co-phase chart for Delaware Bay **Ref. C2, Fig. 4**

Co-amplitude shows contours of equal tidal height.
Co-phase shows contours of equal phase (or arrival time).

Tides are slightly higher
on the eastern shore
of Delaware Bay due to
the coriolis effect.

Fig 11- 16 Tidal ranges in the Delaware Estuary **Ref. C3, Fig. 9**

I believe the later estimates are the more reliable ones. Certainly the tidal range increases up the Bay.

Fig 11- 17 Tidal ranges in Delaware Bay **Ref. C3, Fig. 10**

Note the small but significant difference between the Delaware shore and the Jersey shore.

What is the net tidal flow
at the mouth of Delaware Bay?

Though there in an inflow and outflow,
the residual of the flood and ebb
shows a pattern

Fig 11- 18 Net ebb and flood **Ref. C3, Fig. 30**

This section across the mouth of the Bay shows inflow mostly on the right and near the bottom (looking inward in this figure) and outflow mostly on the left and near the surface. Why this pattern?

Resonance can occur in bays and estuaries,
greatly amplifying the tidal range
(recall the seiche calculations)
though this effect does not occur
appreciably in Delaware Bay

A notable example of resonance
occurs in the Bay of Fundy

In the Minas Basin at the head of
the Bay (in Nova Scotia)

The tidal range reaches 15.4 m
due to a resonance effect
in the Bay of Fundy and
the Gulf of Maine

Subtidal flow in Delaware Bay

Subtidal means that the time scales of the flow are longer than tidal. The frequency is lower than (i.e., “sub”) tidal.

Tidal currents (~ 1 m s^{-1}) are about an order
of magnitude greater than subtidal
currents (0.01 - 0.1 m s^{-1})

If we subtract out the dominant tidal flow, we are left with the residual sub-tidal flow. We find:

- Classic two-layer estuarine flow: surface water moves seaward, from the Bay onto the Shelf.
- Mean subtidal surface outflow ~ 5 cm s^{-1} (Ref. C1)
- Mean inward bottom flow ~ 1 cm s^{-1}
- On the Continental Shelf: bottom water moves landward, from at least as far as 40 km offshore
- In Delaware Bay: Bottom water moves laterally toward the shore, diverging approximately along the deep channels
- Bottom current speeds ~ 5 cm/s
- Surface speeds are ~ order of magnitude greater than bottom speeds
- 2/3 of the variance of the subtidal flow is due to winds
- The Continental Shelf and Delaware Bay are coupled in the subtidal flow
- Continental Shelf: alongshore flow ~ 10 cm/s

Off Delaware Bay, Shelf width ~ 100 km, slope ~ 10^{-3}

- Wind events can generate significant currents in Delaware Bay
- At the mouth of the bay, sea-level fluctuations are forced by wind stress parallel to the shore

It's the classic Ekman transport: a wind along 050°T [SW wind, parallel to the shore] produces a drop in sea level

Within Delaware Bay, estuary-mouth
sea level doesn't account for
all the sub-tidal variability.

At Artificial Island, 1/3 of subtidal
sea-level variance comes from
coupling with upper Chesapeake Bay,
through the C & D Canal

2/3 of subtidal sea level variance comes
from coupling with the Continental
Shelf through the mouth of the Bay

Together, these effects account
for ~ 95% of subtidal variance
(Wong & Garvine, Ref. C4)

Flow is tied to the longshore component of the wind
There also is a cross-shelf Ekman-driven flow:

	North Wind	South Wind
	typical of winter	typical of summer
	may produce downwelling	may produce upwelling
Surface flow	onshore	offshore
Bottom flow	offshore	onshore

Fronts

Fronts are regions of intensified gradients of
properties such as temperature, salinity,
plankton, . . . which may change rapidly,
creating virtual horizontal boundaries

- Large velocities and large velocity gradients are generally associated with fronts
- Convergence in the horizontal flow results in vertical motions and enhanced vertical transfer of momentum and other properties

- Fronts are often viewed as barriers
  but there is extensive mixing along them
- Fronts are important to fisheries
  biology. The horizontal convergence
  can result in a concentration
  of nutrients along fronts
- Fronts are a factor in pollution dispersal;
  there can be a concentration of
  buoyant pollutants in the convergence
  along the front line.

What is the mechanism that creates fronts?

The processes are not well understood.

One theory for fronts has been proposed by Simpson and James (Ref. B5).

Tidal energy leads to mixing.

Solar radiance leads to surface heating, and hence to stratification

Stratification lowers the potential energy of the water column relative to what it would be in a mixed region

On the other hand, mixing can be due to bottom-generated turbulence in shallow waters due to tidal motions

The imbalance between stratification and mixing was characterized by Simpson and James who defined a quantity sometimes called the *stratification index* (s):

$$s = \log_{10}\left[\frac{h}{\left|\vec{U}\right|^3}\right]$$

where h = water depth
and U = depth-mean tidal velocity

Fronts may occur at the boundary between
mixed and stratified regions when $s = 2.7$

Fig 11- 19 The stratification index **Ref. B1, Fig. 3.5**

Fronts may occur along boundaries separating regions of small values of s from regions of large s.

[I find confusion in the literature between

$$s = \log_{10}\left[\frac{h}{\left|\vec{U}\right|^3}\right] \text{ (as above)}$$

and

$$s = \frac{h}{\left|\vec{U}\right|^3}$$

Which is it? I dunno.]

Bottom boundary layers

Friction produces a bottom (or benthic) layer where velocity shear goes from a velocity u, in the fluid to zero at the stationary bottom surface

The bottom stress, τ_b , may be written:

$$\tau_b = \rho\, B_D\, U^2$$

where

B_D is the drag coefficient with typical values of 10^{-3} to 10^{-2}

U is the fluid velocity at the top of the benthic boundary layer

In addition to the frictional benthic layer there can also be a bottom Ekman layer

List of Figures, Lecture 11

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