MAST602

Lecture 6

Ocean currents

General circulation
Western boundary currents: Gulf Stream, Kuroshio
Equatorial currents
Indian Ocean (monsoon) currents
Antarctic circumpolar currents
Arctic currents

MAST 602

Lecture 6
Ocean Currents

Large-scale surface circulation

Ocean circulation is driven by the sun's energy.

There are two principal driving mechanisms:

1. *Thermohaline circulation*
   (driven by heating, cooling, evaporation)

   - The ocean is heated and cooled at the surface
   - Cooling may also cause sinking
   - Evaporation may cause sinking,
     though the density increase
     from evaporation
     can be offset by the density decrease
     from heating.

2. *Wind-driven circulation*

   - Large-scale torque of the
     wind stress generates
     ocean-basin-gyre circulation
   - Usually associated with central-gyre
     Ekman pumping, with convergence
     in the center of the gyre

It's generally not possible
to identify specific ocean currents
with one or the other of these
two driving mechanisms.

In reality, ocean currents may be
driven by some combination
of the two processes

Gross features of the general circulation:

Fig 7- 1 General circulation of the world ocean¾ July (Tchernia 1980), Plate 1

Do you expect to be able to go out and find the currents as depicted on this map? If not, what kind of a map is it?

- *Gyres*—anticyclonic circulation in mid-ocean basins

Fig 7- 2 Atlantic circulation¾ February (Tchernia 1980), Plate 7

Notice the asymmetry in the major clockwise circulation of the Atlantic: currents seem to be strong [thick arrows] on the western but not the eastern side of the ocean. Where else are they strong?

- Western boundary currents:
  Gulf Stream, Kuroshio,
- Cold flows:
  Oyashio, Labrador, . . .
- Zonal currents:
  Antarctic Circumpolar Current
  Equatorial currents

Fig 7- 3 Indian & Pacific Oceans ¾ February (Tchernia 1980), Plate 13

Compare this figure with the next one. Notice the differences in the circulation pattern off north-east Africa.

Fig 7- 4 Indian & Pacific Oceans ¾ August (Tchernia 1980), Plate 14

The patterns of ocean currents off the Horn of Africa change seasonally in response to monsoon winds. This is the only place this phenomenon is found.

These examples are average or typical patterns, the instantaneous pattern of currents varies greatly.

Western boundary currents (e.g., Gulf Stream, Kuroshio)

The two strongest western boundary currents are the Gulf Stream, in the North Atlantic, and the Kuroshio, in the North Pacific

Fig 7- 5 Gulf Stream and Kuroshio paths **(Kawai 1972), Fig. 1a & b**

What similarities can you find between these two western boundary currents? What differences?

We will first look at the characteristics of the Gulf Stream in some detail, then briefly review the similarities and differences of the Kuroshio

The Gulf Stream

What we call the “Gulf Steam” is sometimes called:

- Florida Current
  from the Straits of Florida
  up to Cape Hatteras
- Gulf Stream
  from Cape Hatteras
  up to the Grand Banks
- North Atlantic Current
  beyond the Grand Banks

The Gulf Stream is narrow and strong

Fig 7- 6 Surface current profiles **(Knauss 1969), Fig. 1**

Do you think Benjamin Franklin was justified in calling the Gulf Stream “a river in the ocean”?

Gulf Steam characteristics:

Width: ~ 100 km
Speeds: ~ 2 m s^{-1} maximum
Left edge: generally sharp

Though narrow, the Gulf Stream
has meanders and loops
that broaden its range of occurrence

Meanders are not fixed; they vary in time
within a broad envelope

Fig 7- 7 Path Trajectories **(Knauss 1969), Fig. 11**

The paths in this figure were observed over a few years. How would you characterize the envelope of the meanders? The current seems to maintain its narrow identity but wanders around quite unlike a "river".

Gulf Stream currents are time-varying,
even locally reversing; using the raw data
it can be even difficult to sort out the paths

Fig 7- 8 Trajectories of free-drifting buoys **(Richardson 1981), Fig. 1a**

This is sometimes called a "spaghetti diagram." Where is the Gulf Stream?

A filtering procedure can sometimes reveal
the surface current system

Fig 7- 9 Buoy trajectories smoothed **(Richardson 1981), Fig. 1b**

This still doesn't look like a river, does it? At least some kind of larger-scale patterns of flow seem to have emerged.

Meanders and loops can
break off as *rings* north and
south of the Gulf Stream

Ring dimensions are
of the order of ~ 100Km

Fig 7- 10 Gulf Stream ring formation **(Richardson 1980), Fig. 1a**

These rings are cold-core or warm-core. Which is which?

Warm-core rings occur
north of the Stream
= a ring of Sargasso Sea Water
in the Slope Water

Cold-core rings occur
south of the Stream
= a ring of Slope Water
in the Sargasso Sea Water

Fig 7- 11 Ring interaction with the Gulf Stream **(Richardson 1980), Fig. 2a**

Rings are generally spun off from the main current but can also be re-absorbed (coalesce) back into the main Gulf Stream

Rings can be tracked as entities
for up to 18 months

Fig 7- 12 Ring time series **(Lai and Richardson 1977), Fig. 8**

Rings can sometimes be tracked for more than 2 years.

Warm-core rings tend to coalesce with the
Gulf Stream just north of Cape Hatteras

Cold-core rings may coalesce with the
Gulf Stream near Florida

Fig 7- 13 Ring trajectories **(Lai and Richardson 1977), Fig. 7**

A few cold-core rings apparently end up somewhere in the Sargasso Sea

Because of its complexity, with meanders
and rings, it has proven difficult
to model the Gulf Stream realistically

Though some recent numerical models,
run on supercomputers are, beginning
to give encouraging results

Model of Gulf Stream

This "movie" is from the World Wide Web:
http://www.psc.edu/science/OKeefe/OKeefe.html#one
This Gulf Stream, with its meanders and rings, is remarkably similar to what is found. Look, for example at the figures in the 2nd-floor hallway in Lewes.

Gulf Stream structure

The Gulf Stream can be considered
as a dynamic boundary between
the warmer (and less dense) Sargasso Sea
and the cooler (and denser) Slope Water

Fig 7- 14 Temperature section, Chesapeake Bay - Bermuda (Iselin 1936), Fig. 7

Notice that the horizontal gradients in temperature associated with the Gulf Stream extend to great depth.

Fig 7- 15 Salinity section, Chesapeake Bay - Bermuda (Iselin 1936), Fig. 8

Salinities are higher in the upper layers of the Sargasso Sea.
Notice that the water on the seaward side of the Gulf Stream can be identified by its temperature and salinity characteristics.

The Gulf Stream system is not just
a surface phenomenon;
it extends to the bottom

Fig 7- 16 Gulf Stream velocity section Knauss, Fig. 7.4

The currents can be calculated from the density field based on the distribution of temperature and salinity.
Notice the deep counter-current on both sides of a relatively narrow Gulf Stream above the ocean bottom.

Gulf Stream transport

30×10^6 m^3 s^{-1}
off Florida

> 150×10^6 m^3 s^{-1}
just beyond Cape Hatteras

(10^6 m^3 s^{-1} = 1 Sverdrup [Sv])

Kuroshio

Unlike the Gulf Stream,
the Kuroshio may be under
some topographic influence.

It crosses a line of seamounts off Japan
(The Izu-Ogasawara Ridge)

Fig 7- 17 Composite Kuroshio paths **(Taft 1972), Figs. 3 & 4**

The Kuroshio has a bi-stable path off Japan.
Is this due to topographic control?
(The Gulf Stream does not cross a similar ridge, though the meanders increase in amplitude in the region of the New England Seamounts.)

Eastern-side ocean currents

Currents on the eastern side of oceans
are generally weak

- California Current
- Peru Current (Humboldt Current)
- Benguela Current
- Canary Current

Coastal upwelling, related to
Ekman transport, is often found
on the eastern side of ocean basins
(but not exclusively!)

- Morocco
- Peru
- California

Equatorial ocean currents

Surface equatorial currents are related to the pattern of winds

Equatorial winds:

westerlies	⇉	drive subtropical gyre
NE trades	⇇	drive equatorial currents
doldrums	(*weak*)	ITC: climatic equator, 3-10° N
SE trades	⇇	drive equatorial currents
westerlies	⇉	drive subtropical gyre

[ITC = Intertropical Convergence Zone]

3 major equatorial surface currents:

	Currents	winds
⇐	① North Equatorial Current (NEC)	
		↙ NE trade winds
⇒	② North Equatorial Counter Current (NECC)	doldrums
	______________________________ equator	
		↖ SE trade winds
⇐	③ South Equatorial Current (SEC)	

In addition, one major current occurs just below the surface *on* the equator:

⇒ ④ The Equatorial Undercurrent (EUC)

Fig 7- 18 North & South Equatorial Currents **Knauss, Fig. 7.12**

> We've seen this figure before; note the alternating zonal currents as evidenced by the sloping isotherms.
> Is the structure consistent with the sketch shown above in these notes?

Equatorial Undercurrent

Sometimes called the *Cromwell Current*
Discovered about 40 years ago

It flows eastward on the equator

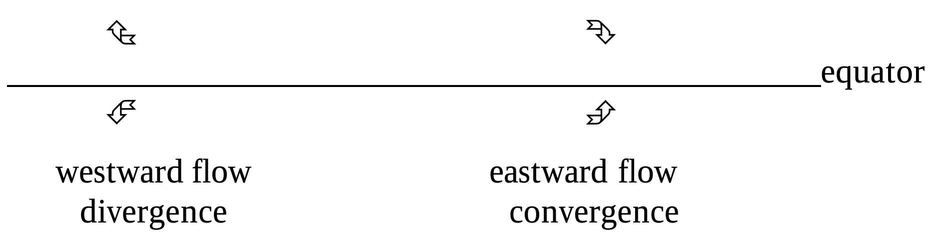
- Width about 1° - 2° of latitude
- Core about 150 m deep
- Maximum speeds about 1 ms^{-1}

Fig 7- 19 Equatorial undercurrent **Knauss, Fig. 7.13**

> The Equatorial Undercurrent is most evident in the oxygen (it's fresher). Though the current is on the equator, is the temperature field the one you'd expect from geostrophy?

Stability of eastward equatorial flow

Westward equatorial flow is unstable,
Eastward equatorial flow converges,
linked to change in sign of
coriolis force at the equator



Indian Ocean currents

The reversing *Somali Current*
in the North-East Indian Ocean
is driven by monsoon winds

The surface circulation is dominated
by the seasonally reversing
monsoon wind field

Monsoon winds blow toward:

- the warm Asian continent in summer
  SW monsoon May ⇒ Sept
- the warm Indian Ocean in winter
  NE monsoon Nov ⇒ Mar

Fig 7- 20 Monsoon winds, January & July **Knauss, Fig. 7.20**

> Notice the reversing winds over the northern Indian Ocean. What processes account for this reversal?

Fig 7- 21 Surface currents, February & August **Knauss, Fig. 7.21**

> The currents off the coast of Africa and in the Arabian Sea reverse seasonally in response to the wind field.

Antarctic Circumpolar Current (ACC)

The ACC, a *zonal* current, is driven by prevailing eastward winds (westerlies)
It's not blocked by any continent

It's probably the largest ocean current in terms of volume transport

The ACC has been studied extensively in the Drake Passage:
dimensions are 500 km × 3000 m

Transport through the Drake Passage is variable:
$29 \Rightarrow 290 \times 10^6\ m^3\ s^{-1}$

Fig 7- 22 Streamlines of Southern Ocean flow **(Tchernia 1980), Fig. 4.20**

> The ACC is the only ocean current that completely encircles Earth.

Fig 7- 23 Regime of surface currents in Southern Ocean (Tchernia 1980), Fig. 4.7

Be careful of the scale on this diagram: it covers an enormous area. For example, what is the corresponding latitude of Delaware on this map?
Though the ACC flows eastward, notice the *westward* flowing current inshore along Antarctica.

North from Antarctica, the surface temperature increases gradually until at some latitude, a rapid increase in temperature occurs

South of this latitude, surface water moves northward, sinking when it reaches the region
This region is known as the *Antarctic Convergence* or the *Antarctic Polar Front*

Further north, another region of rapid temperature rise is known as the *Subtropical Convergence*

Fig 7- 24 Temperature, salinity, & oxygen on S.O. section (Tchernia 1980), Fig. 4.12

AC = Antarctic Convergence
STC = Subtropical Convergence
What are the physical characteristics that define these convergence regions?

East Wind Drift

The *East-Wind Drift* is a surface current, flowing westward off the Antarctic coast

It can be explained by fresh melt water flowing off the Antarctic continent
Fresher water is lighter, thus producing westward geostrophic flow

Arctic ocean circulation

Interior Arctic Ocean:
A clockwise gyre

- Bering Straits:
  Shallow, less than 100 m;
  little significant flow-through
- East Greenland Current:
  Major outflow *from* the Arctic
- West Spitzbergen Current:
  Major inflow *to* the Arctic

Fig 7- 25 Arctic Sea exchanges **(Tchernia 1980), Fig. 5.20**

Is the gyral circulation under the ice in the central Arctic Ocean consistent with the pattern of winds?

List of Figures, Lecture 6

References

Iselin, Columbus O'Donnell (1936). A study of the circulation of the western North Atlantic. *Papers in Physical Oceanography and Meteorology, MIT, Cambridge, MA* **4**(4).

Kawai, Hideo (1972). Hydrography of the Kuroshio extension. *Kuroshio*. H. Stommel and K. Yoshida. Tokyo, Univ of Tokyo Press: 235-352.

Knauss, John (1969). The transport of the Gulf Stream. *Morning Review Lectures of the second International Oceanographic Congress, Moscow, 1966*. Paris, UNESCO: 67-82.

Lai, David & Philip Richardson (1977). Distribution and movement of Gulf Stream rings. *Jour. Phys. Ocean.* **7**(5): 670-683.

Richardson, P.L. (1980). Gulf Stream ring trajectories. *Jour. Phys. Ocean.* **10**(1): 90-104.

Richardson, P.L. (1981). Gulf Stream trajectories measured with free-drifting buoys. *Jour. Phys. Ocean.* **11**(7): 999-1010.

Taft, Bruce (1972). Characteristics of the flow of the Kuroshio south of Japan. *Kuroshio*. H. Sommel and K. Yoshida. Tokyo, Univ of Tokyo Press: 165-216.

Tchernia, Paul (1980). *Descriptive regional oceanography*, Pergamon, Oxford, 253 pp.