MAST602

Lecture 7

Deep currents & general ocean circulation

Thermohaline circulation
Water masses
Bottom topographic effects
Microstructure, double diffusion
Mesoscale eddies
Langmuir circulation

MAST 602

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Thermohaline circulation

Thermohaline = driven by heating, cooling, evaporation)

The density distribution drives the circulation

Density is a function of T (thermo)
and S (haline)

But the role of wind stress is not clear:
wind stress can drive the density field
e.g., surface horizontal convergence
occurs in the subtropical ocean-basin gyres
due to Ekman transport of warm surface water.

$$\underbrace{\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}<0}_{\text{convergence}} \qquad \underbrace{\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}>0}_{\text{divergence}}$$

$$\underbrace{\frac{\partial w}{\partial z}>0}_{\text{downwelling}} \qquad \underbrace{\frac{\partial w}{\partial z}<0}_{\text{upwelling}}$$

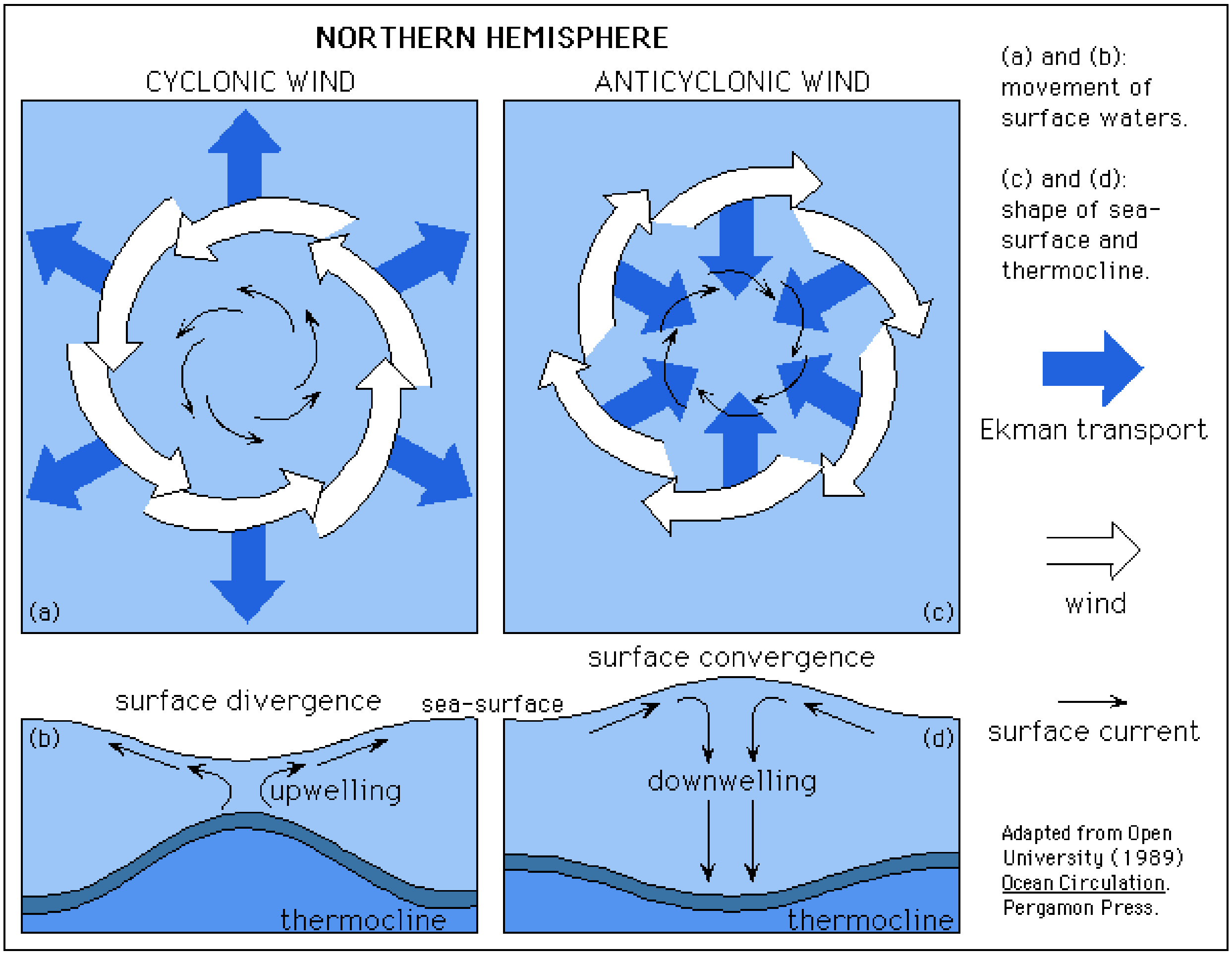


Fig 8- 1 Ekman pumping effects **(Brown, Colling et al. 1989), Fig 3.23**

The convergence of warm water in the center of a subtropical gyre may be difficult to distinguish from the effects of surface warming.

The effects of Ekman pumping on the subtropical gyre can be seen in the dynamic topography of the sea surface.

The warmer, lighter water in the center of the gyre has a higher elevation than the cooler, denser water on the outside.

Fig 8- 2 Mean annual dynamic topography of the Pacific (Wyrtki 1975), Fig. 2

This map is relative to 1000m What does that mean?

How do you think this map, calculated from hydrostation data would compare with the sea-surface topography measured by satellite?

In addition to defining the density distribution, *T* and *S* can be used to track the deep circulation

Iselin: the vertical distribution of *T* & *S* in the central north Atlantic is similar to the north-south distribution of *T* & *S* at the surface.

Does this mean that there is a “flow” along the lines of constant density?

(The “flow” here could be intermittent and irregular; the pattern doesn't allow us to see flow rates or mechanisms.)

The process whereby ocean surface characteristics are transmitted to deeper layers is known as *ventilation*

Fig 8- 3 Meridional distributions of *T, S,* and presumed flow (Tolmazin 1985), Fig. 7.2

Can you see how the temperature and salinity are consistent with deep flow? Deep flow may be tracked by following the *T/S* characteristics of the water.

Water-mass tracking

We can track water movement with the temperature and salinity distribution

Let's look at a few examples from Worthington & Wright's *Atlas*:

North Atlantic Ocean Atlas **(Worthington and Wright 1970)**

- Example: Mediterranean outflow into the central north Atlantic

Fig 8- 4 Mediterranean outflow **Knauss Fig. 8.1**

⇒ Med water S ~ 38

⇒ It's denser than North Atlantic water

⇒ It sinks and spreads from the Straits of Gibraltar

⇒ It sinks to about 1100 m, with a core of high-salinity water

⇒ It mixes with colder, less saline water of the North Atlantic

⇒ It can be followed (because of its high salinity) with sections radiating from Gibraltar

⇒ It's easy to track

- Example: Norwegian Sea water

⇒ Probably the major source of North Atlantic Deep Water

⇒ It flows out through the Denmark Strait into the N. Atlantic through gaps in ridges (e.g., Faroe-Shetland Ridge)

- Example: Labrador Sea Water

⇒ Another source of North Atlantic Deep Water

- Example: Antarctic Bottom Water

⇒ Found at the bottom on the western side of the North Atlantic

Tracking ocean flow by following temperature and salinity along constant density surfaces is sometimes called *core analysis* (*kernschicht*)

Water masses

T and *S* are conservative

Suppose water is "formed" at the surface,
i.e., by heating and cooling (for *T*)
or by evaporation and precipitation (for *S*)

After leaving the surface,
only mixing can modify *T* & *S*

(Deep water can be modified by the flow
of heat from the interior of the earth.)

So perhaps *T* & *S* can be used to
identify water masses and track
their movement in the deep ocean/

Fig 8- 5 Tritium section from geosecs **Knauss, Fig. 8.11**

Soviet H-bomb tests in the 60's can be used as a one-time tracer. The isotope H^3 (tritium) can be used to follow the injection in high latitudes. Note the narrowness of the sinking region.

Is the densest water in the ocean the coldest?
No, it's the saltiest. =high evaporation
Red Sea, Mediterranean, Bahama Banks

Antarctic Ocean:
Water at the freezing point is the densest
Freezing increases density (like distillation)
Water at "formation" is $q \sim -1.9$°C,
$S \sim 34.6$ Weddell Sea
It sinks to become Antarctic Bottom Water,
$q \sim -0.3$°C, $S \sim 34.66$
This water can be traced along the bottom
to the western North Atlantic

North Pacific:
There's no deep or bottom water formation
(the water is not saline enough)

There's no significant transport through
the Bering Straits

Deep western boundary currents:
There's significant flow in the deep water
along the western boundaries
in the N. Atlantic, S. Atlantic, S. Pacific

The flow is equatorward;
strong flow is often measured on the bottom

Let's look more closely at the North Atlantic,
to see how our understanding of the
large-scale circulation has evolved

Fig 8- 6 Circulation diagrams of the North Atlantic (Worthington 1976), Fig. 17

A number of ideas of the North Atlantic circulation have evolved over the years, such as those of Sverdrup (1942), Iselin (1936), & Stommel (1958)

Fig 8- 7 Worthington's North Atlantic circulation diagram (Worthington 1976), Fig. 47

Yet another model of the North Atlantic, that of Worthington, (1976)

Fig 8- 8 Worthington's North Atlantic sections (Worthington 1976), Fig. 1

Worthington occupied a number of hydrographic station sections to trace the North Atlantic circulation.

Fig 8- 9 Transports for the North Atlantic sections (Worthington 1976), Table 3

Here are the values Worthington obtained, broken down by temperature layers.

Schmitz and McCartney (Ref 36)
have updated Worthington's description

Their circulation patterns, based on
more results, are more complex.

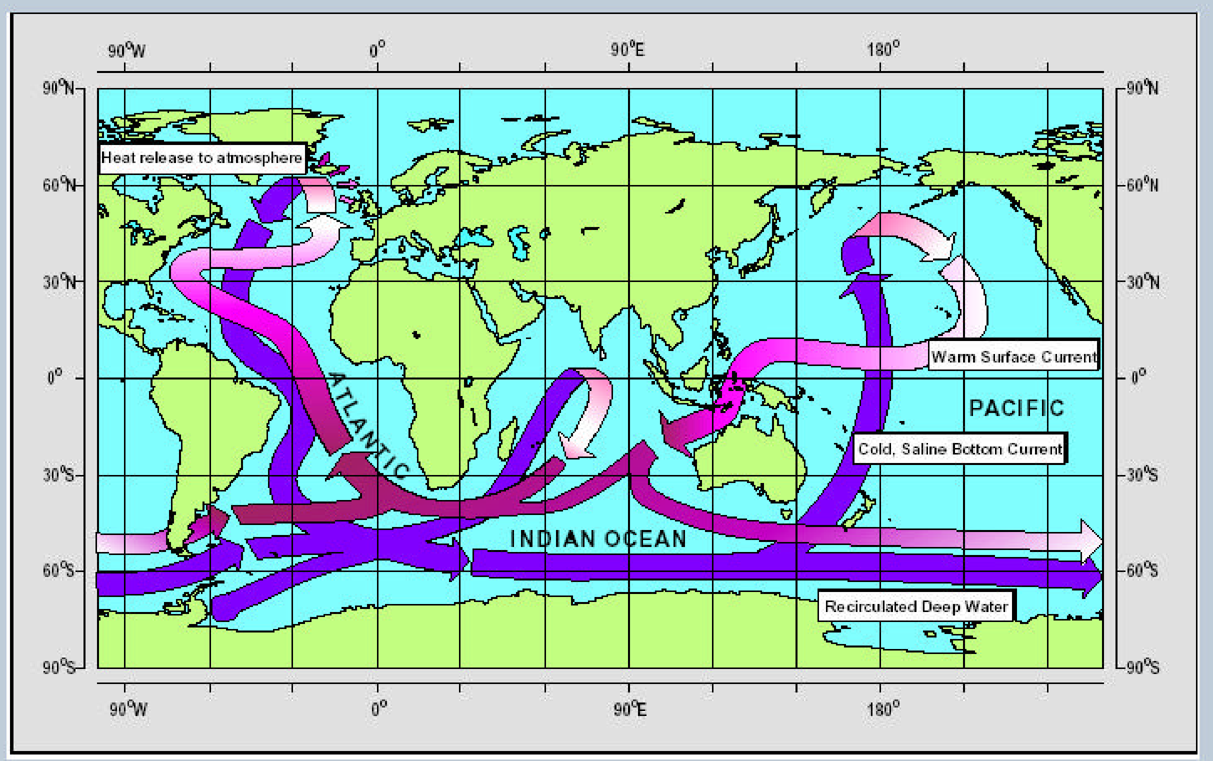
Fig 8- 10 Circulation at temperatures above 7°C (Schmitz and McCartney 1993), Fig. 8

The model of upper-level North Atlantic circulation, by Schmitz and McCartney (1993); it's getting more complex, isn't it?

Fig 8- 11 Circulation features at temperatures below 7°C (Schmitz and McCartney 1993), Fig 10

This model of the deeper-level circulation was proposed by Schmitz and McCartney. Can you match this up with the previous figure?

Broecker (1991) has proposed a speculative *Great Ocean Conveyer Belt* that attempts to bring in the large-scale circulation of the entire world ocean



Schematic diagram of the global ocean circulation pathways, the 'conveyer' belt (after W. Broecker, modified by E. Maier-Reimer).

Broecker's ideas have attracted considerable attention in the popular scientific press. But they have also attracted critical review

For example, Broecker's model is not consistent with the Schmitz & McCartney circulation.

Furthermore, flow in the ocean is neither steady nor laminar; it is *not really* a conveyor belt.

In spite of the extensive work done in this ocean basin, our knowledge of even the North Atlantic is not complete.

According to Schmitz and McCartney: "While the North Atlantic is the most completely observed ocean, there are still significant gaps in our knowledge of its circulation."

Imagine how little we know of the circulation of the more remote ocean basins!

Water-mass types

A commonly used basis for identifying water-mass types is the *temperature-salinity (T-S) diagram.*

The plot of the data often has a characteristic shape that can be used to identify *water masses*

Example: North Atlantic *T-S* curves

Fig 8- 12 Iselin's Sargasso Sea *T-S* curve **(Iselin 1936), Fig. 53**

Notice how tightly the points define a curve, even though they were collected over several years and over a wide extent of the western North Atlantic.

Fig 8- 13 Example of *T-S* "scatter plot" for a 10° square (Pickard and Emery 1990), Figs. 7.15, 7.16

Note the distribution of *T-S* over this North Pacific 10°-square. *T-S* can serve as a sort of "fingerprint" for the water-mass type.

The variation among the 10° squares gives some idea of the evolution of water-mass properties due to mixing and flow.

Fig 8- 14 T-S curves for the world ocean **Knauss, Fig. 8.8**

What are the principal differences between the *T-S* curves for the North Pacific and South Pacific?

What is the biggest difference between the Atlantic and Indian Ocean *T-S* curves and those for the Pacific in the previous figure?

Water-mass census

Where is, what is . . .the water in the ocean?
= volumetric census

Worthington attempted to be quantitative about the distribution of T-S in the ocean.

Fig 8- 15 Contoured *T-S-V* diagram **(Worthington 1981), Fig. 2.8, Fig. 2.9**

T-S-V = Temperature-Salinity-Volume

It's striking how the distribution of most of the water in the world ocean clusters around a few deep, cold values. We can see this more clearly in the figure that follows.

Fig 8- 16 Most abundant fine-scale bivariate classes(Worthington 1981), Fig. 2.6

> The bivariate classes (of T = 0.1 °C and S = 0.01) shown in this Figure contain 50% of the water in the world ocean.
> What is the T and S of the single most common bivariate class?

🕮 ***The water masses of the North Atlantic Ocean*** **(Wright and Worthington 1970)**

🕮 ***The Evolution of Physical Oceanography*** **(Warren and Wunsch 1981)**

Fig 8- 17 Three-dimensional *T-S* diagrams (Worthington 1981), Fig. 2.3 - 2.5

> Notice how narrow, yet distinctive, each ocean region is.

Bottom topographic effects

Bottom topography has an influence on deep flow.

The Mediterranean, Red Sea, Arctic Ocean are isolated; they have distinguishing T-S characteristics

- Example: the Drake Passage blocks Weddell Sea water from the Pacific
- Example: The Romanche Trench

Fig 8- 18 Mid-Atlantic Ridge & Walvis Ridge Knauss, Fig. 8.5

> Water from the western basin flows through the Romanche Trench, across the Mid-Atlantic Ridge.
> Water is blocked in the East by the Walvis Ridge

In deep trenches, q can be constant. E.g., the Cariaco Trench.

Fig 8- 19 Potential temperature in trenches Knauss, Fig. 8.6

> Kinda makes you believe there might be something to this adiabatic thing, after all.

Microstructure

Microstructure: small-scale steps in T & S

- a few hundredths of a °C
- a few meters vertically
- a few hundredths of a psu

Microstructure is widespread
it can be missed with bottle samples

It's found in the Mediterranean outflow,
where warm, saline water flows out
above cooler, less saline Atlantic water

In spite of the structure in T and S,
density is generally not discontinuous

Fig 8- 20 Temp, salinity, density profiles **Knauss, Fig. 8.19**

Notice that the stepped structure in S and q is generally absent in s_q . Why might this be so?

Double diffusion (Salt fingers)

On the small scale, (no greater than a few centimeters) molecular diffusion may be important.

Double diffusion occurs because
diffusion of heat >> diffusion of salt
(~10^{-4} Kg m^{-1} s^{-1}) (~10^{-6} Kg m^{-1} s^{-1})

Thus in a parcel of water
heat diffuses away faster
than salt thereby modifying
the density of the parcel

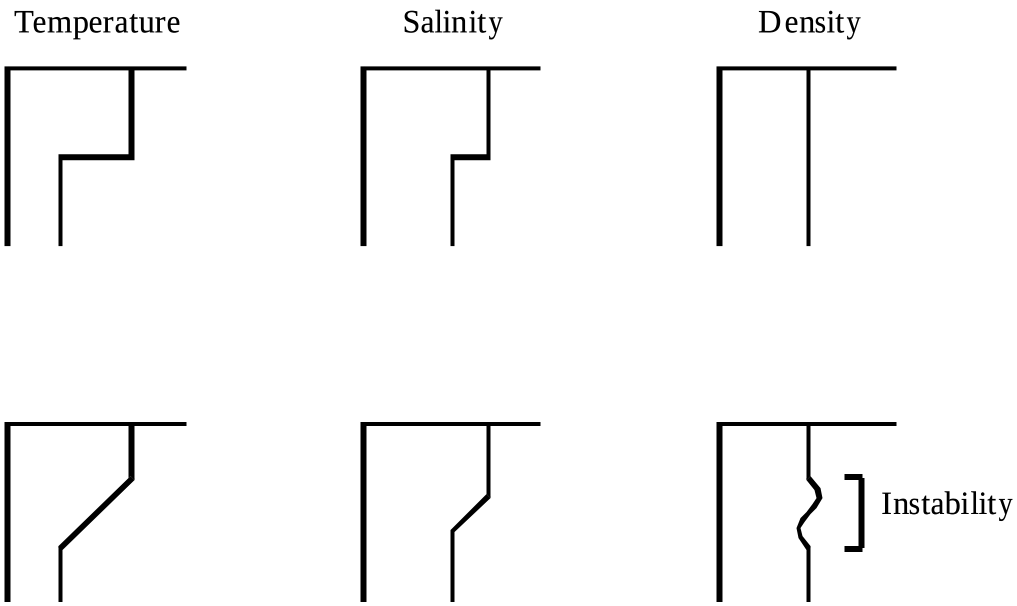
Small columns of water sink,
forming *salt fingers*

Salt-finger characteristics:

- 20 - 30 cm.
- T ~ 0.1 °C or less
- spacing ~ 1 cm.

Detecting salt fingers is difficult!

Lateral mixing may produce microstructure steps of the kind observed.



Mesoscale eddies

microscale	smaller than m.
mesoscale	~ 100 Km.
macroscale	~ ocean basin (10^4 Km.)

Fig 8- 21 Spaghetti diagram - free-drifting buoys (Richardson 1981), Fig. 1a

(We saw this Figure before when discussing the Gulf Stream.)
Note the scale of the loops and whorls in the paths of the drifting objects.

This diagram is intriguing

The dominant space scale may be ~ 100 Km

A number of questions arise:

- Do these tracks show preferred scales of motion?
- Are these mesoscale eddies?
- Do they influence ocean dynamics?

polymode Experiment
- Took place in central W Atlantic
- Tracked mesoscale eddies
- Confirmed the importance of these eddies

Fig 8- 22 Evolution of mesoscale eddy field (Grachev, Koshlyakov et al. 1979), Fig. 4

> The evolution of these oceanic mesoscale eddies may be analogous to the patterns of evolution seen in atmospheric processes
> Are they analogous?

The time scale of the mesoscale eddies is of the order of a few months

Mesoscale eddies may contain 90% of the ocean's kinetic energy

Energy estimates are determined from moored current meter measurements or from following drifting buoys

Fig 8- 23 Frequency spectrum of mesoscale motions (Schmitz 1978), Fig. 4

> A spectrum analysis of this kind is difficult to obtain because of the long time series of observations needed to determine it.

Ocean current measurements

Two ways to describe fluid flow:

Eulerian states velocity at every point in the fluid

Lagrangian states the path of a fluid particle as a function of time

- Lagrangian methods measure velocity by following a particle of water
  Example: sofar floats, acoustically tracked
- Eulerian methods measure velocity by determining the flow of water past a point
  Example: current meters suspended below buoyant floats

These methods have their pros and cons:

Eulerian	**Lagrangian**
Relatively easy to analyze	Difficult to analyze
Susceptible to small-scale processes in space and time that can mask larger-scale events of interest	Imposes a natural filter on small-scale processes, at least in the time domain
Best suited to small-scale velocity studies	Used more for large-scale circulation studies

There is a wide variety of Lagrangian sensors:

- Ship drift
  used extensively in the last century
- Swallow floats (sofar)
  ballasted to float at a predetermined depth
- Satellite-tracked "holey-sock" surface drifters
- Woodhead bottom drifters
- Pollutant concentration

Eulerian sensors

- Generally use some type of sensor
  that measures flow past the instrument
- Are usually "fixed" on a moored line
  which of course wanders under the influence
  of changing ocean currents
  (It's difficult to interpret measurements
    made from a ship
    because of ship movements)
- Moorings may have surface or
  subsurface buoys
- Can be left in place for as long as two years
- Many types of sensors have been used:
  - Moving element
    (Savonius rotor)
  - Fixed element
    (hot-wire anemometer)
  - Electromagnetic
    (GEK = Geomagnetic Electokinetograph)
  - Acoustic Doppler
    (ocean acoustic tomography)

The use of the geostrophic method
  to measure currents is widespread

However, using either Eulerian or Lagrangian
  techniques to determine a reference velocity
  can present problems

The scale of geostrophic measurement
  is often not commensurate
  with direct measurements

The geostrophic method automatically
  provides a large-scale measure of velocity

But current meters measure velocity
  only at a point, not over a large area

Drifting floats follow a particle of fluid,
  that may not represent the flow over a large area

Langmuir Circulation

Wind-generated surface phenomenon
  Roll structures, horizontal vortices
  Flotsam (seaweed, critters) collect in
    convergence rows - *windrows*

Fig 8- 24 Langmuir cells **Knauss, Fig. 8.21**

Long, helically rotating cells in the upper
  mixed layer, whose axes are aligned with
  the wind.

Horizontal spacing of Langmuir Cells: (crude)
  $B \sim 5W$
    where W is wind speed in units s^{-1}.
    and B is windrow spacing in units.

Vertical scale:
  Apparently limited by mixed-layer depth

Downwelling velocity (again, crude):
  ~ 1% of W

List of Figures, Lecture 7

Fig 8- 1	Ekman pumping effects	(Brown, Colling et al. 1989), Fig 3.23
Fig 8- 2	Mean annual dynamic topography of the Pacific	(Wyrtki 1975), Fig. 2
Fig 8- 3	Meridional distributions of *T*, *S*, and presumed flow	(Tolmazin 1985), Fig. 7.2
📖	*North Atlantic Ocean Atlas*	(Worthington and Wright 1970)
Fig 8- 4	Mediterranean outflow	Knauss Fig. 8.1
Fig 8- 5	Tritium section from geosecs	Knauss, Fig. 8.11
Fig 8- 6	Circulation diagrams of the North Atlantic	(Worthington 1976), Fig. 17
Fig 8- 7	Worthington's North Atlantic circulation diagram	(Worthington 1976), Fig. 47
Fig 8- 8	Worthington's North Atlantic sections	(Worthington 1976), Fig. 1
Fig 8- 9	Transports for the North Atlantic sections	(Worthington 1976), Table 3
Fig 8- 10	Circulation at temperatures above 7°C	(Schmitz and McCartney 1993), Fig. 8
Fig 8- 11	Circulation features at temperatures below 7°C	(Schmitz and McCartney 1993), Fig 10
Fig 8- 12	The *Great Ocean Conveyer Belt*	
Fig 8- 13	Iselin's Sargasso Sea *T*-*S* curve	(Iselin 1936), Fig. 53
Fig 8- 14	Example of *T*-*S* “scatter plot” for a 10° square	(Pickard and Emery 1990), Figs. 7.15, 7.16
Fig 8- 15	T-S curves for the world ocean	Knauss, Fig. 8.8
Fig 8- 16	Contoured *T*-*S*-*V* diagram	(Worthington 1981), Fig. 2.8, Fig. 2.9
Fig 8- 17	Most abundant fine-scale bivariate classes	(Worthington 1981), Fig. 2.6
📖	*The water masses of the North Atlantic Ocean*.	(Wright and Worthington 1970)
📖	*The Evolution of Physical Oceanography*	Warren and Wunsch 1981)
Fig 8- 18	Three-dimensional *T*-*S* diagrams	(Worthington 1981), Fig. 2.3 - 2.5
Fig 8- 19	Mid-Atlantic Ridge & Walvis Ridge	Knauss, Fig. 8.5
Fig 8- 20	Potential temperature in trenches	Knauss, Fig. 8.6
Fig 8- 21	Temp, salinity, density profiles	Knauss, Fig. 8.19
Fig 8- 22	Spaghetti diagram - free-drifting buoys	(Richardson 1981), Fig. 1a
Fig 8- 23	Evolution of mesoscale eddy field	(Grachev, Koshlyakov et al. 1979), Fig. 4
Fig 8- 24	Frequency spectrum of mesoscale motions	(Schmitz 1978), Fig. 4
Fig 8- 25	Langmuir cells	Knauss, Fig. 8.21

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