Learning objectives: How are the waters moving/circulating in each ocean?

1. Observed upper ocean circulation: wind driven
2. Thermohaline circulation – extending to deep ocean;
3. Water masses & T-S diagram (to know)
Dynamic height: 0-1000db

Satellite altimetry (oct 1992-present):
sea surface height -
derive geostrophic current;

Ocean Surface Current Analyses
Real-time (OSCAR) surface current: geostrophic + Ekman
1. Observed Ocean circulation: Wind-driven gyres

The Pacific

Subtropical Gyre (STG)

Subpolar Gyre (SPG)

ACC

STG

SPG
The Pacific

ITF (Indonesian Throughflow)

Eastern Pacific (home of El Nino)

S. Pacific current
Normal Pacific EQ currents: 3-D view

EUC: ~200km wide, and ~100m deep
The Atlantic Surface current
North Atlantic current transport

Sketch of the major surface currents in the North Atlantic. Values are transport in units of $10^6 \text{m}^3/\text{s}$. From Sverdrup, Johnson, and Fleming (1942 fig. 187). *Westward intensification is clear!*
Atlantic: 100/700db – based on geostrophic method

SPG: weak; essentially missing

Why??
The Indian Ocean

(a) Southwest Monsoon (July-Aug.)

(b) Northeast Monsoon (Jan.-Feb.)
The Indian Ocean

Spring                                                        Fall

Ship-drift Surface currents and salinity
Mar-Apr EQ Jet Spring Wyrtki Jet(WJ)

Sep-Oct: Fall WJ
Plate 1. Bimonthly plots of SSS [Levitus and Boyer, 1994] and ship drift currents [Mariano et al., 1995].
The Arctic Ocean

Mediterranean seas: a part of the world ocean, which has only limited communication with the major ocean basins (Pacific, Atlantic, Indian) and where the circulation is dominated by thermohaline forcing.

Recent studies show that: Wind-driven effect is also important for driving the exchange circulation.

The Mediterranean Sea in N. Atlantic;
The Red Sea and Persian Gulf in N. Indian Ocean

Thermo (thermal) temperature change (heat flux forcing)
Haline: salinity change (freshwater flux forcing)
Circulation induced by T & S change under buoyancy forcing - thermohaline circulation
Evaporation (E); Precipitation (P)

E-P >0 \[ \text{O}_2 \]

- Marine life
- Salinity increases: concentration basin

E-P <0

- Marine life
- Devoid below Pycnocline
- Dilution basin

(The Arctic Ocean)
The Arctic Ocean: Dilution basin

River: 0.2Sv

$1 \times 10^6 m^3/s$
2. Thermohaline circulation

Wind-driven circulation: STG, SPG, etc in the Pacific, Atlantic, & Indian Ocean; Down to 2000m; Arctic Ocean: Also possesses Thermohaline circulation.
Thermohaline circulation is the movement of water when its density is changed by a change of temperature or salinity.

Examples:

Changes of salinity: Arctic Ocean; The Mediterranean Sea; Red Sea and Persian Gulf.

Changes of temperature: N. Atlantic.
3. Water masses

3a) Atlantic water masses
Water mass: A large body of water with a common formation history, having its origin in a physical region of the ocean

**Atlantic water masses:**

(I) Abyssal water masses: Formed by thermohaline process.

Sources (simplified) of abyssal water masses:
- AntArctic Intermediate Water (AAIW);
- Antarctic Bottom Water (AABW);

Mediterranean Overflow Water (MOW);
- Labrador Sea Water (LSW);
- Nordic Sea Overflow Water (NSOW).
CTD data: y-z, 25W Atlantic

Blue: low salinity; Red: high salinity
AAIW and AABW

AAIW: core depth 500-1000m;
salinity minimum;
source: sea surface near the tip of South America;

AABW: Ocean bottom (in fact they are deep water: same as Circumpolar Deep Water in the Pacific & Indian Ocean).
Below 4000m;
Cold, low salinity, from ACC region.
MOW, LSW, and NSOW => NADW (North Atlantic Deep Water)
1000m-4000m;

Transport: 15-20 Sverdrup (Sv)
1 Sv = 1 \times 10^6 m^3/s

These three are northern sources for abyssal water mass.

AAIW and AABW: Southern Sources for Abyssal water mass.
The NADW is in the middle of AAIW and AABW.
MOW, LSW, and NSOW $\Rightarrow$ form NADW

MOW: upper NADW; LSW: middle NADW; NSOW (GIN seas): Bottom NADW.

GIN (Greenland, Iceland, Norwegian)
Atlantic thermohaline circulation process

(i) Waters from S. Hemisphere into N. Atlantic (surface warm water, AAIW, AABW);
(ii) Modification and convection in N. Atlantic & adjacent seas;
(iii) Outflow in a thick deep layer - NADW. (high salinity) => NADW flows to other oceans, affecting global circulation, heat transport, => climate.

A very simplified figure:
Global thermohaline circulation
3b) Other Water Masses
(reading materials, section 2.3 of notes)

Subpolar Mode Water (SPMW)

Cooling: creates mixed layers in N. Atlan. The thick layers are called SPMW.

SPMW: 14C (N. Atlan. Current), 8C enters Norwegian Sea, 4C enters the Labrador Sea.
Concept: ventilation of the STG or thermocline
T (y,z) Atlantic, 25W
Subtropical Mode Water (STMW)

Also called 18C water in Atlantic.

Immediately south of the Gulf Stream, winter Convection in isopycnal bowl, and then spreads. (Mode: large volume)
Central water and subtropical underwater

Subduction in Ekman convergence region of the STG moves water from sea Surface southward into the subsurface of The STG. Central water is the general name for the whole thermocline. [LPS solution, 1983]

Subtropical underwater: Central STG, center of atmospheric subtropical high. Low Precipitation => increases evaporation=> increase salinity. When it subducts, flows Southward, creates salinity maximum.
Similar to the Atlantic: water masses created by subduction are **Central Water & Subtropical Underwater**.

**STMW:** Western subtropical N. Pacific-Pycnostad, where T,S. and density gradients are weak. Typical for major subtropical WBC recirculation region. Immediately south of Kuroshio extension (16C-19C).
Pacific: Ventilation of SPG

Sea ice formation in the Okhotsk increases salinity, density, and thus ventilates the upper portion of the intermediate density layer of the N. Pacific.

Mixing: extends the layer downward.

Ventilated water of Western SPG enters the STG via WB. Salinity minimum in STG. The intermediate layer is called North Pacific Intermediate Water (NPIW).
Pacific: Deep waters

Below the NPIW lies nearly homogeneous deep water layer 2000-4000m.

The Indian Ocean

Abyssal water mass. AABW or circumpolar water below 3800m. [In the Atlantic we call it AABW.]

1500-2000m to 3800m, Indian Deep Water. It is a transition (due to mixing & diffusion) of the circumpolar water.

Red Sea and Persian Gulf waters:
Red Sea: 400-700m; Persian Gulf: 200-300m. High salinity, high temperature.
Indian Ocean

Water masses of thermocline and surface: Indian Central Water. Surface: Arabian Sea water (salty), Bay of Bengal water (fresh), etc.
b. T-S diagram

Water masses: form at the surface;

Below the surface forcing region, salinity and Temperature - conserved: changes via advection & diffusion. Thus, water masses (say Red Sea water) can be identified using T&S diagram.
An example of a T-S diagram for observations at depths from 150 m to 5,000 m at 9°S latitude in the Atlantic Ocean. Dots represent individual seawater samples; numbers indicate depths in hundreds of meters. Red boxes represent the major subsurface Atlantic water masses. **AABW** = Antarctic Bottom Water; **NADW** = North Atlantic Deep Water; **AAIW** = Antarctic Intermediate Water.