Student's Handbook Guide to EAS 212 Oceans

A student's guide to the complex nature of the world Ocean

An introduction to the physics and chemistry of the oceans. Topics covered include ocean currents, the ocean floor, origins and buffering of the chemistry of the oceans. The role of the oceans in determining past and present climates is introduced.

By mastering the complex nature of the oceans will lead you to a heroic victory against the machination of the professor. By defeating his midterm champion(s) and ending the final themselves. The heroic legacy of your achievement will be remembered on your academic transcript.

Disclaimer: The following information does not provide any knowledge on what to do if a Kraken, Tiamat, Great White Shark, Amanar, or any other fictional or non-fictional creature attacks you in the ocean. You are on your own (and most likely fucked).

Contents

Part I

Week 1

1-7-2019: Introduction

What is Oceanography

- Ocean Graphy (Seas descriptive science)
- The studying of the processes of the ocean
- **Physical Oceanography**: systems like wave dynamics, currents, atmosphere interaction, etc
- **Chemical Oceanography**: systems like dissolved solids and gasses in the ocean, composition of water.

Themes regarding the oceans

- The oceans as a source of food
- We use the oceans
- Oceans influence weather and climate

Themes influences

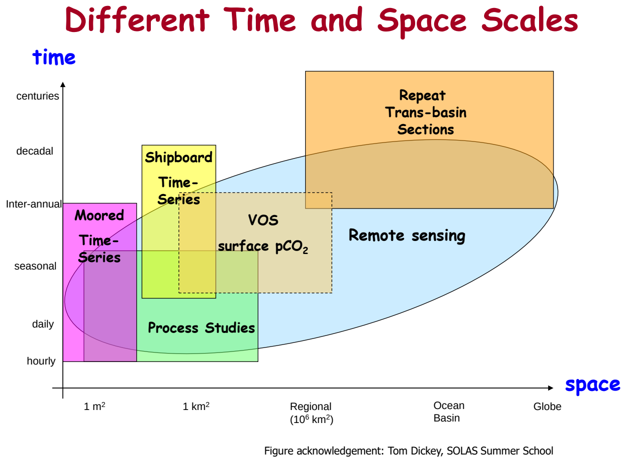
- What we measure
- How measurements are made
- Geographical areas of interest
- Interest in different process of different scale

What processes are important?

- Heat storage and transport in the oceans
- The exchange of heat with the atmosphere and the rile of the ocean in climate
- Wind and thermal forcing of the surface mixed layer
- The wind-driven circulation
- The dynamics of ocean currents
- The formation of water types and masses
- The deep circulation
- Equatorial dynamics and El Nino
- Waves in the ocean, both surface and internal
- Waves in shallow water and coastal processes

The Domains of Measurement

- Time and Space

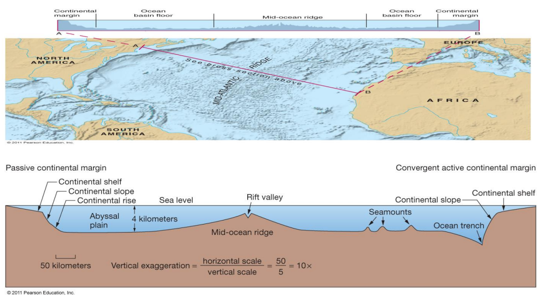


1-9-2019: Studying the Ocean and Bathymetry

The oceans are less well studied than the land. In fact more know less about our oceans than some planets in our solar system. This is because studying the ocean is very difficult.

The Ocean Bottom Topography:

Ocean vertical scale often exaggerated on plots



Problems with Studying the Oceans

Seeing through Ocean Water

Depending on the material or composition (algae, salt water, ocean life, etc), sea state, etc can affect light penetration of the ocean. Radar and other instruments have their limitations as well. Moreover, water is an excellent absorber of EM radiation making LIDAR measurements difficult as well.

Inaccessibility

Humans cannot breath underwater as well as the overwhelming majority of the earth's surface is covered with water. Moreover, the terrain difference is more drastic underwater than on land (i.e. most of the ocean is as remote from the sea surface as the top of the mountains on land).

Cost

Running a research ship can cost at minimum 40,000 dollars per day. Moreover, ships are slow at most 20 km/h, and the time required to step up an observation take hours.

Pressure

Water is more dense then air. Approximately 1 atm/10 m of depth. Deep ocean surveying requires highly specialized equipment and transportation which further increase the cost of exploration and surveying.

Conduction/Corrosion/Fouling

Seawater conduct electricity and increases corrosion on sensors and equipment. Marine life can foul equipment as well causing inaccurate data.

Wave Dynamics

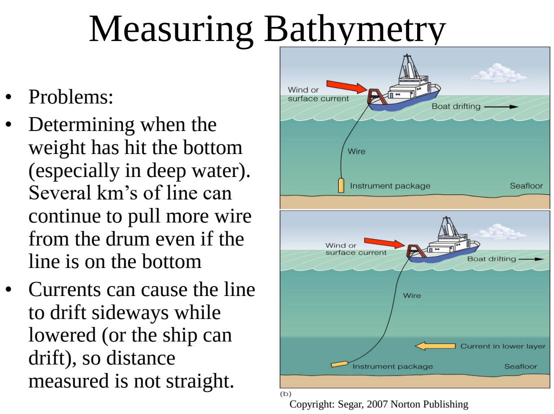
Heavy sea states and poor ocean conditions can cause sea sickness, OHSA hazards with heavy equipment, and potential damages.

Measuring Bathymetry

Bathymetry is the measurement of depth from the surface of the ocean to the ocean floor.

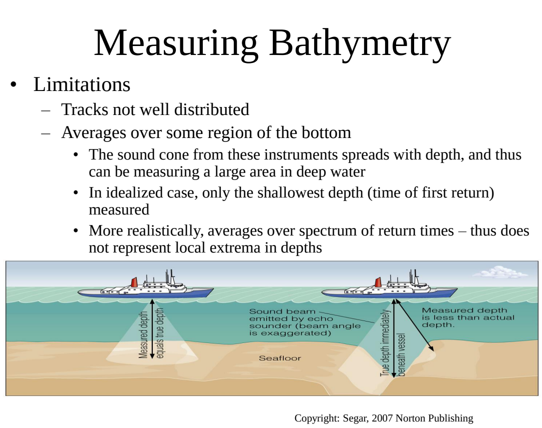
Old way

The old way involved a weight at the end of the rope with knots at specific intervals to measure the depth. This method can (and often) overestimate the depth as underwater currents and movement of the ship can cause inaccurate measurements.



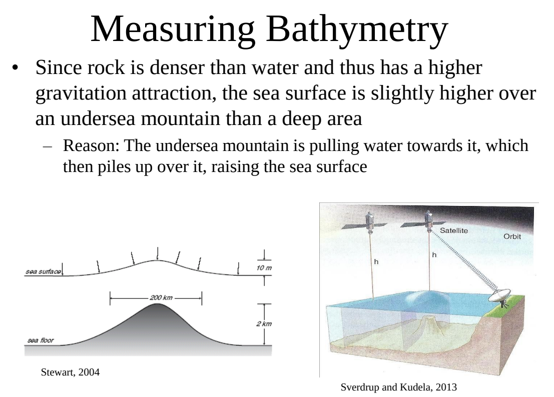
Echo Sounders

Modern methods use echo sounders or SONAR to measure the depth but only works well on a flat surface, highly varied surfaces may not be represented as the depth is averaged from a cone. It may also be affected by marine life.

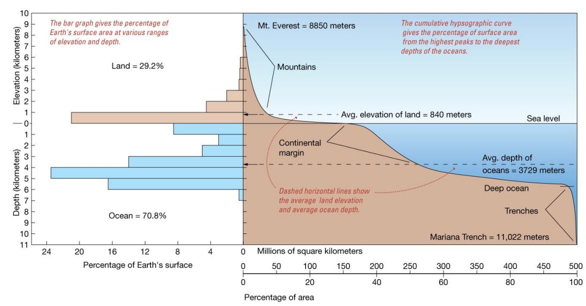


Satellites

Measure the surface variation of the ocean as EM radiation does not penetrate well in water. The surface variation can tell the use the contour of the ocean floor which can be useful with other types of measurements.



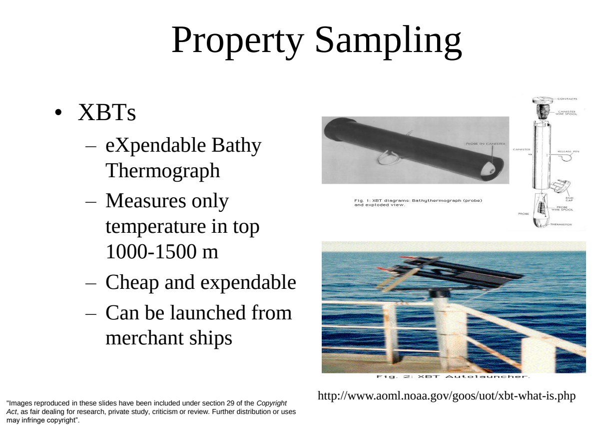
Summary



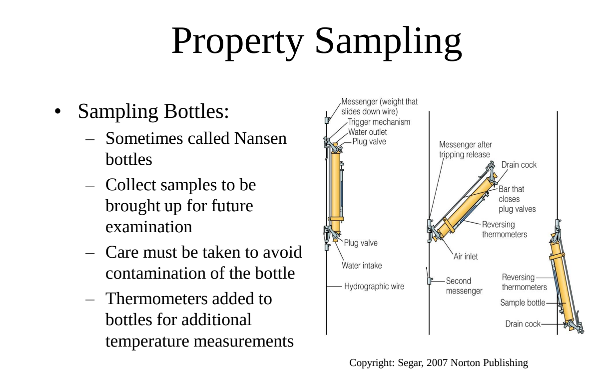
As you can 70 percent of the earth is covered by oceans, most of which is 4 km under water.

1-11-2019: Observing the Ocean

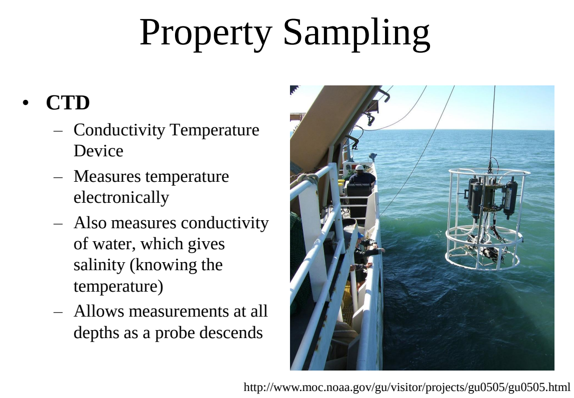
Observing different properties of the ocean.

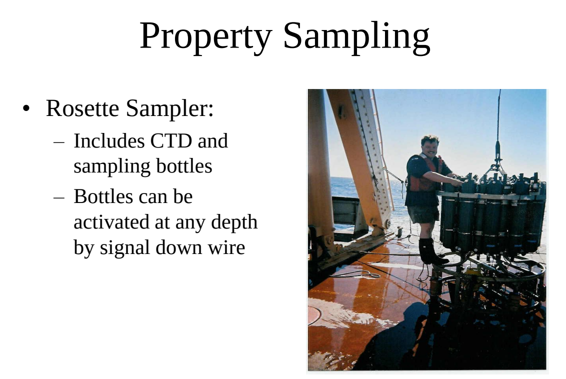


We can also use satellites to measure the surface temperature of the ocean. However, they can only measure the surface, not hundreds of meters below. XBT uses electrical signals to measure the temperature during it descent, taking temperature data frequently creating a dataset.

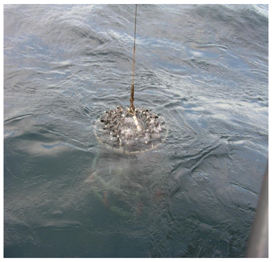


Uses a messenger (a weight) to trigger the sampling bottle to prevent contamination. Each time the bottle is triggered it releases another message to trigger the next sample bottle.





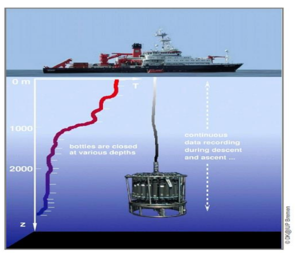
Property Sampling



Queen Charlotte’s, Summer

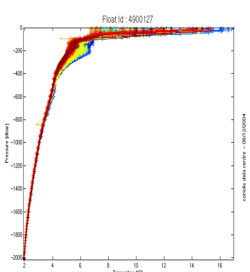
Property Sampling

C: conductivity (→ salinity)
T: temperature
D: pressure (~depth)
O: oxygen

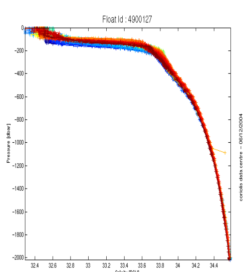


Today we use a combination of CTD and sampling bottles electronically to measure the temperature, salinity, and take water samples.

TS Profile



Temperature

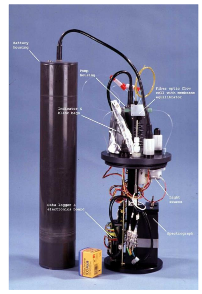


Salinity

International Argo Program - http://www.argo.ucsd.edu/index.html

The vertical axis is pressure which is correlated to depth, and the horizontal axis is temperature and salinity for the two graphs. For salinity, leftward is less salty, rightward is more salty.
Notice the trend of the graphs. There are wide changes near the surface of the ocean, while at lower depths the differences are less pronounced. This is because changes are more localized near deeper parts of the oceans.

Property Sampling



CO_2 Sensor

Oxygen Sensor

Compliments of WOCE

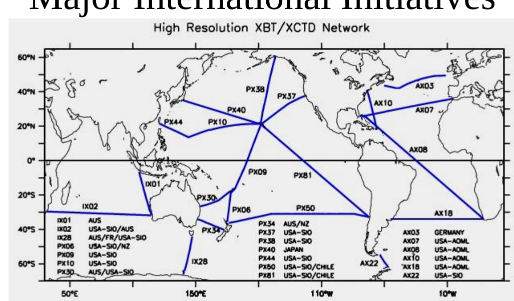
Other sensors used to gather useful information.

Ocean Research Missions

- Cruise Plan must be generated
- Must focus on the scientific objectives
- Identify stations where observations to be made
- Important to make measurements thru a region to understand spatial structure

Mission plans are tailor made depending on the scientific objectives.
You first decide on an objective then make decisions on measurements, methods, location(s), etc.

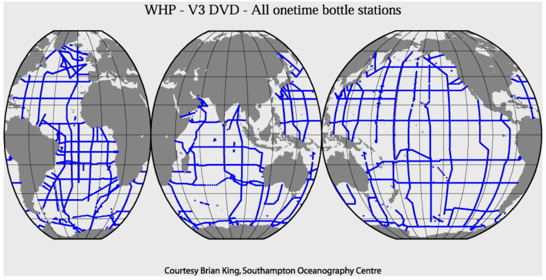
Major International Initiatives



Voluntary Observing Ship (VOS) Program:

http://www.vos.noaa.gov/

World Ocean Circulation Experiment (WOCE)

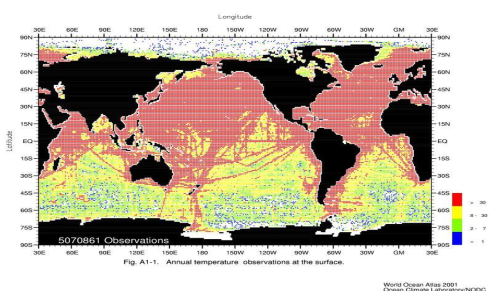


Some studies are done by many ships, by many countries, over a huge timeline.

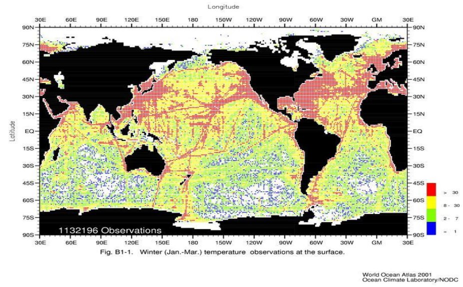
Ocean Observations

- With all the missions launched over the last century, one might think that there are enough observations to give a good description of the oceans
  - Yet, NO, much of the ocean's are poorly explored

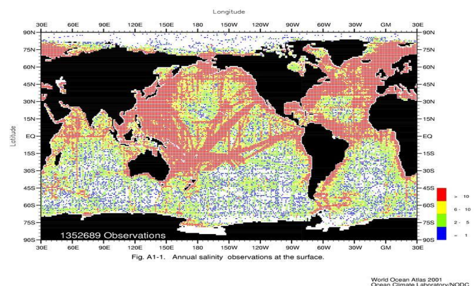
Annual Surface Temperature



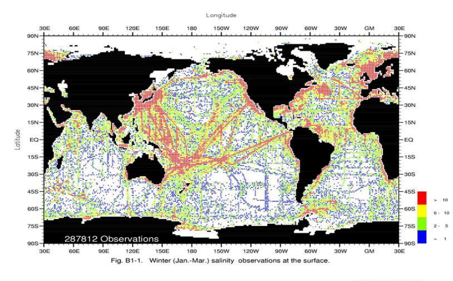
Winter Surface Temperature



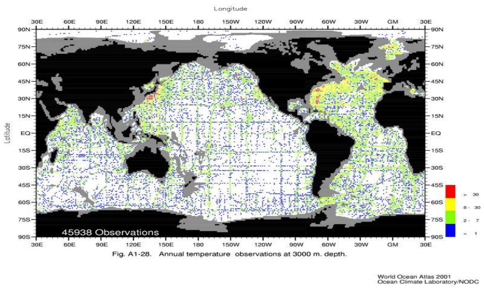
Annual Surface Salinity



Winter Surface Salinity



Annual 3000 m Temperature



Depending on the season, depth, and types of data required there are inconsistencies in the coverage of the samples.

Current Measurements

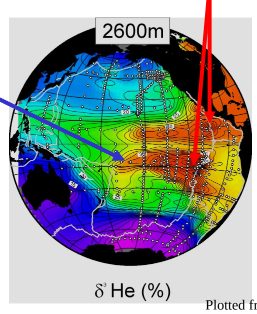
- We also want to know how the oceans are moving, both at an instant and over time
- Two main ways to determine ocean currents
- 1) Direct Methods: Directly determine speed and direction of ocean motion
  - Two types: Passive and Active
- 2) Indirect Methods: Infer motion from other types of measurements

Flows must be from high concentration to low concentration

Current Measurements

Source Region: Vents – East Pacific Rise

- Indirect Measurements:
  - Infer motion from other types of measurements
  - Useful for motions over larger areas and longer time scales
  - Most commonly based upon ocean tracer measurements
  - Note the issue of data density in some regions



Deep Ocean Helium

Plotted from WOCE data

The white dots are sample locations.

Current Measurements

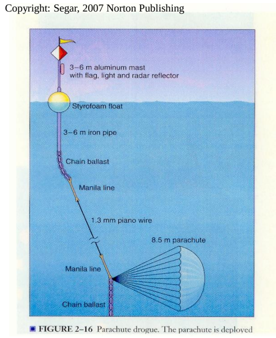
- Passive (Direct) Measurements:
  - Basically involve placing an item in the water, letting it flow and following it
  - Simplest ones are unplanned based on objects that end up in the water

Passive vs Active measurements of current:
- Passive: we don't control where we are going, let nature currents of the ocean do that for you.
- Active: we control where we are going and measure current at a specific location. Modern, more scientific methods.

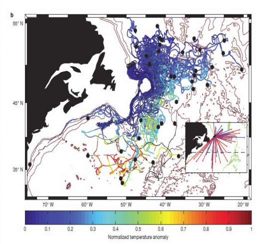
These are passive systems: These sensors follows the flow of current.

Current Measurements

Copyright: Segar, 2007 Norton Publishing



Standard Surface Float

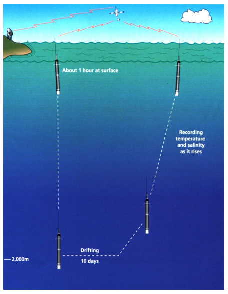


Bower et al., Nature, Vol 459| 14 May 2009| doi:10.1038/nature07979

'Spaghetti Diagram' of float trajectories

Current Measurements

- Subsurface floats:
  - Can be set to float at a given depth
  - Can also be specified to float within a given density surface to follow a water mass
  - Return to surface at intervals to send information

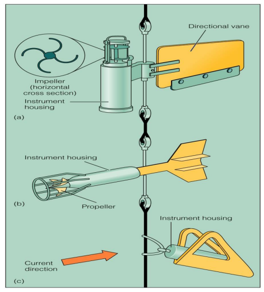


International Argo Program - http://www.argo.ucsd.edu/index.html

Active system: These sensors are locked into place usually anchored to the ocean floor.

Current Measurements

- Current Meters
  - Determine current speed by counting rotations of an impeller or propeller
  - A vane records direction
- Moorings:
  - Sets of current meters at different depths



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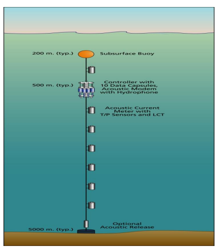
Current Measurements

- Acoustic Current Meters:
  - Send out sound pulses and measure the return
  - Return comes from particles and other objects travelling with the current
  - Current speed and direction given by changes in the frequency of the sound (I.e. the Doppler Shift)
    - If the current is approaching, the frequency increases
    - If the current is moving away, the frequency decreases
  - These devices can measure currents at all depths within range of the beam

Sonar, basically.

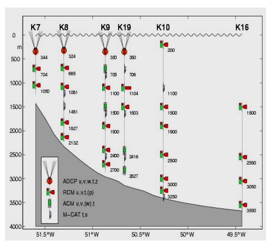
Current Measurements

Copyright: Segar, 2004 Norton Publishing



Mooring provides information at different depths

Fischer and Schott, 2004, Journal of Physical Oceanography



Mooring Array allows flows to be observed across a current(s)

Example of Currents from Mooring Array

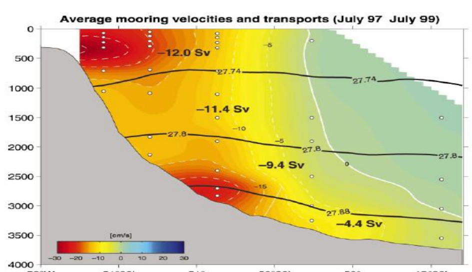


FIG. 11. Mean alongshore flow (cm s^{-1}) for the period Aug 1997–Jul 1999 with currents color coded, water mass boundaries by isopycnals (black lines), and transports in Sverdrups (Sv) for layers labeled.

Fischer and Schott, 2004, Journal of Physical Oceanography

Labrador Sea: 53N – 1997/99

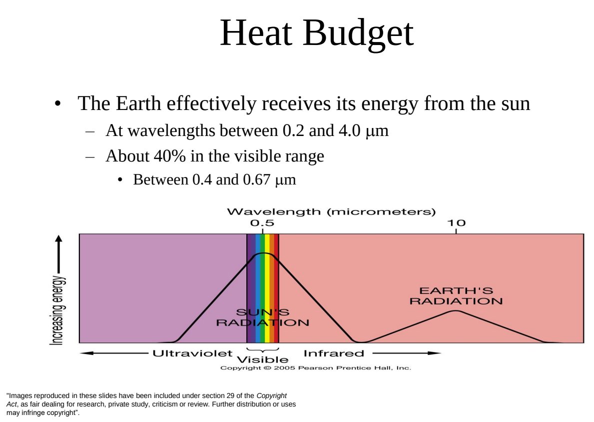
Part II

Week 2

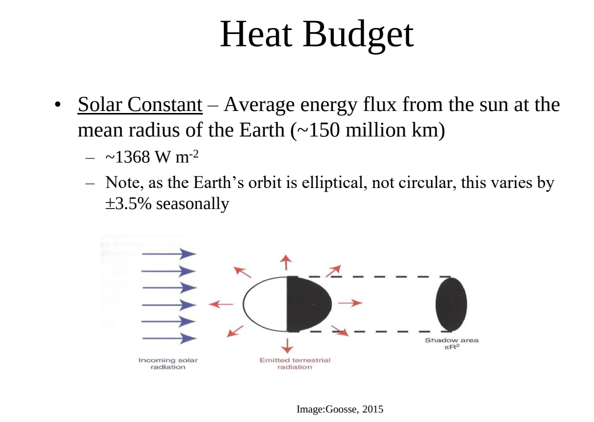
1-14-2019: Heat Budget

Talks about the earth's energy budget. How some places are hotter then others.

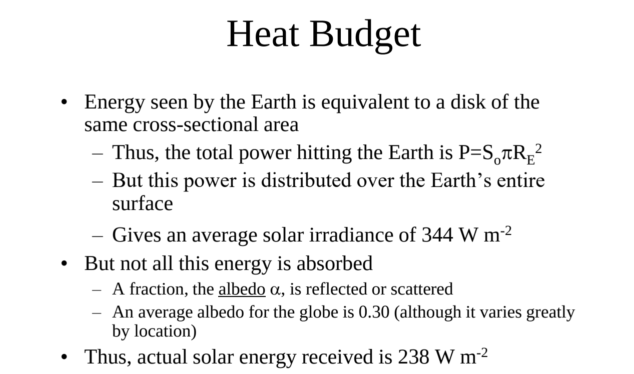
Heat Budget



Most of earth's energy is from the sun. The wavelength is very short.
The Earth's outbounding radiation are much longer.

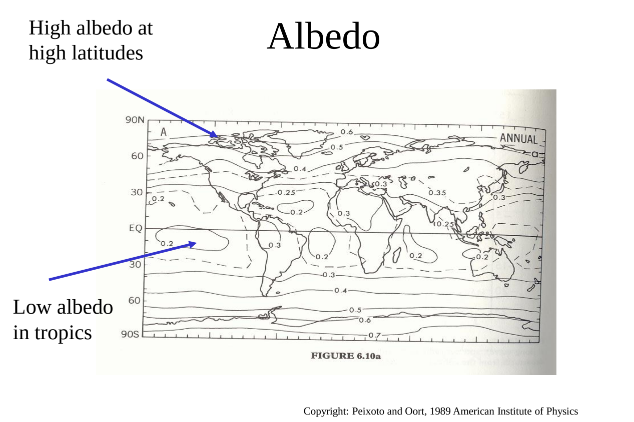


$1368\frac{W}{m^2}$ is the average amount of solar energy at 150 million km from the sun.



This energy is distributed over a sphere so the total solar energy is divided by 4 because math and physics. Therefore the average solar irradiance at the top of the atmosphere is $344\frac{W}{m^2}$.
Some of the solar energy are reflected back into space so in the end, on average the actual solar energy received is $238\frac{W}{m^2}$

Albedo



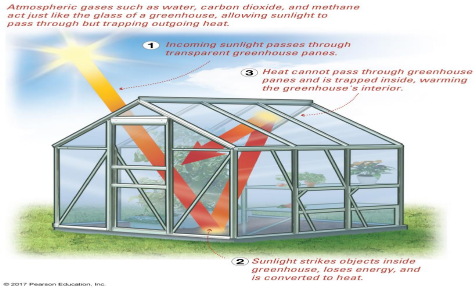
Snow near the polar regions of the earth are great at reflecting sunlight back into space (High albedo).
Dark forested region like Central America are great at absorbing energy (Low albedo) due to their dark colour. Water is also a great absorber of solar energy as well.
In general: Lighter surfaces increases albedo while darker surfaces decreases albedo.

Greenhouse Effect

Greenhouse Effect

- Stefan-Boltzmann Law: $I = \sigma T^4$ with $\sigma = 5.670 \times 10^{-8}$ W m^{-2} K^{-4}
  - Thus, the flux density (energy per unit area per unit time) emitted by a black body is proportional to the 4th power of the absolute temperature
  - Using our solar constant calculations, we can find a T_{earth} of 255K or –18C
  - But, we know the average surface temperature is 288K or 15C
  - The difference is caused by radiation absorbed and trapped in the atmosphere
    - Incoming energy is short wave radiation
    - Outgoing radiation is long wave (infrared)
    - This is termed the greenhouse effect
    - The main greenhouse gas is water vapour

Greenhouse Effect



Heat Budget

Web Link: http://goo.gl/imdsCN

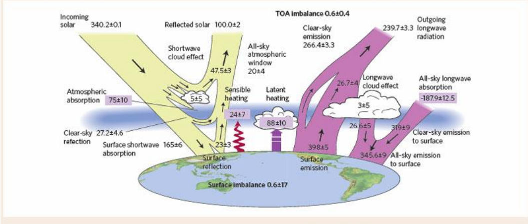


Figure B1 | The global annual mean energy budget of Earth for the approximate period 2000–2010. All fluxes are in Wm^{-2}. Solar fluxes are in yellow and infrared fluxes in pink. The four flux quantities in purple-shaded boxes represent the principal components of the atmospheric energy balance.

Stephens et al., 2012, Nature Geoscience

Here is the overall flow of energy to and from the earth.

Heat Fluxes

Heat Fluxes

- Net Heat Flux = SW + LW + Sensible + Latent
- SW – incoming net short wave radiation
- LW – outgoing long wave radiation
- Sensible – Flux of heat due to conduction
  - Direct physical contact between the atmosphere and the ocean leads to energy exchange by conduction
  - Energy is transferred to the cooler (and thus slower) molecules by molecular collisions
  - Thus it depends on the local air-sea (or land) temperature difference and wind-speed

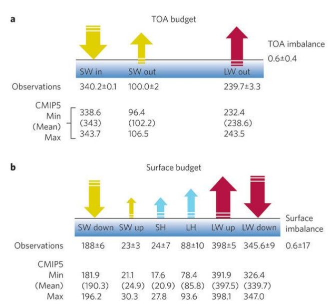
Transferring energy from direct conduction. The contact between water and air. Energy transfer due to a gradient difference between hot and cold air/water mass. etc.

Heat Fluxes

- Latent – latent heat exchange
  - When water is evaporated, energy is supplied to the molecules to free them from the strong bonds in liquid water
  - When the molecules condense to form droplets, usually in clouds, energy is released to heat the surrounding air
  - This process is very temperature dependent
    - The higher the temperature, the more moisture air can hold and therefore the greater potential for latent heat release upon condensation

Changing the phase or state of the water to transfer the energy around. It takes energy to heat up or vaporize water. Removing energy will cool down water.

Heat Fluxes



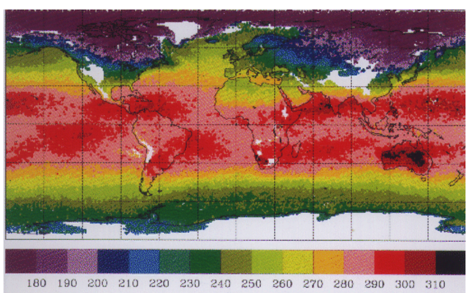
Stephens et al., 2012, Nature Geoscience

Heat Properties of Water

Heat Properties of Water

- Water's very high heat capacity and latent heat has tremendous impacts on the ocean's storage and transport of heat, as well as climate
- In polar regions, most heat exchange is latent (cooling in winter, warming in summer)
  - This means that the ocean temperatures change very little over the course of the year
- The high latent heat of vapourization is also important for atmospheric heat transport
  - Heat is added in the tropics, which warms the water and leads to evaporation. This heat is then stored in the water vapour molecules, which are blown to higher latitudes, where they condense as rain
  - Thus the heat in those water molecules is released to the atmosphere, warming the higher latitudes

Heat Budget



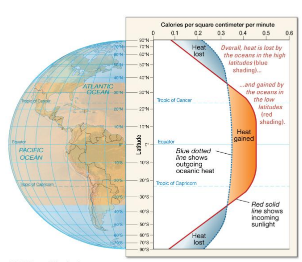
Net Radiation Received, W m^{-2}

Copyright: Peixoto and Oort, 1989 American Institute of Physics

Near the equator the amount of heat is around 300 W per m^2. This decreases as you move away from the equator.

Heat Budget

- Incoming solar radiation is not evenly divided over the earth
- Net surplus of radiation in tropics and deficit at high-latitudes
- This leads to a transport of heat by the oceans and atmosphere from the equatorial regions to the poles
- This need to redistribute heat is the main driving force the oceanic and atmospheric circulation



This redistribution of heat allows winds to be produced on earth.

Heat Budget

- Reasons for the distribution of incoming solar radiation:
- 1) Angle of impact of solar radiation

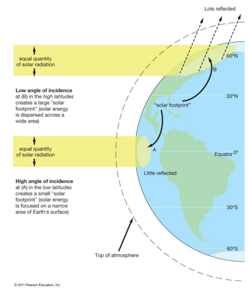


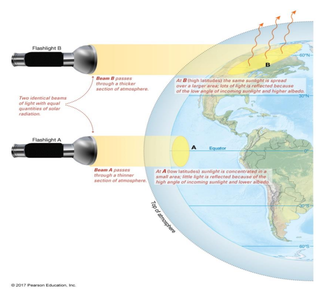
TABLE 6.1 REFLECTION AND ABSORPTION OF SOLAR ENERGY RELATIVE TO THE ANGLE OF INCIDENCE ON A FLAT SEA

Elevation of the Sun above the horizon	90°	60°	30°	15°	5°
Reflected radiation (%)	2	3	6	20	40
Absorbed radiation (%)	98	97	94	80	60

The lower the angle of incidence, the higher amount of energy being reflected.

Heat Budget

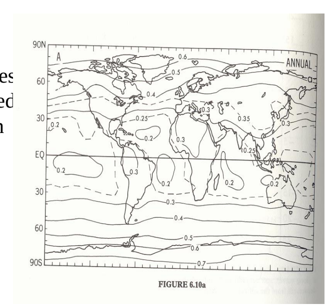
- 2) Earth's surface area
- 3) Atmospheric path length



At higher latitude, solar energy is being spread out more than at the equator. It also has a longer path to travel losing some energy along the way.

Heat Budget

- 4) Albedo
  - This value measures the ratio of reflected incoming radiation



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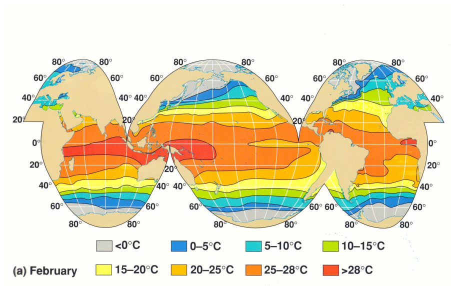
As stated before, higher albedo areas reflect more solar energy away from the earth while lower albdeo areas absorb more.

Ocean Surface Water Properties

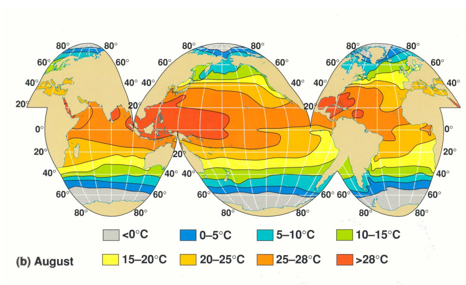
Ocean Surface Water Properties

- Mainly controlled by:
  - Solar radiation
  - Transfer of heat and water with the atmosphere
  - Ocean currents
  - Vertical mixing
  - Runoff

February Surface Temperatures



August Surface Temperatures



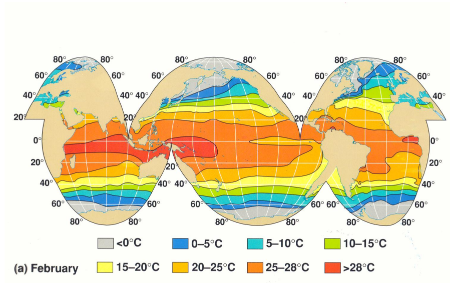
The bands are mostly running east-west due to earth's heat budget (mostly).

1-18-2019: Temperature and Salinity

Formally defined in terms of degrees Kelvin but generally measured in degrees Celsius.

Commonly measured using:
- Mercury thermometers
- Thermistors
- Bucket temperatures
- Ship injection temperatures
- Advanced Very High Resolution Radiometery

February Surface Temperatures



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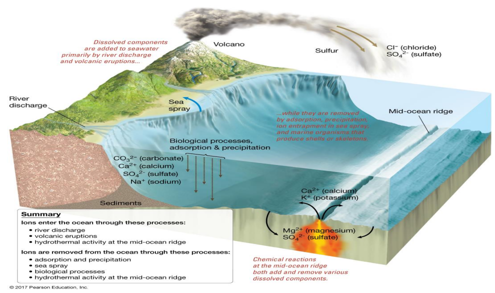
In the figure above, regions of similar temperature are in horizontal bands decreasing in temperature away from the equator.

Biogeochemical Cycles

Seawater is a solution of many different chemical compounds. Most of these chemicals are from the **weathering and erosion** of continental rocks, that are then transported to the ocean. The timeline of this cycle is slow, millions of years slow.

Wind, gravity, glaciers, and streams as well as the geography of these mechanism all affect the composition of the earth's oceans.

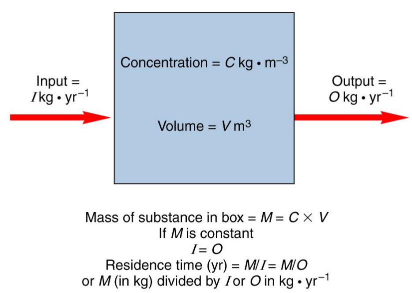
Biogeochemical Cycles



The concentration of each element is determined by the rate it enters the oceans and the rate it is removed from the oceans. If the rate of input is higher than the rate of output then the concentration of that element increases and vice versa. This process takes hundreds of millions of years but they have been occurring for billions of years.

Thus, we assume the oceans are in **steady-state** i.e. the rate of input is the same as the rate of output.

Biogeochemical Cycles



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The actual concentrations do depend on the **residence time**. It's effectively the time taken to replace all of the given substance in the water with 'new material' of that substance from other sources.

Salinity

At the simplest level, is the amount of dissolved material in grams in 1 kg of water. The variability of dissolved salt is small, thus it needs to be determined accurately.

Salinity

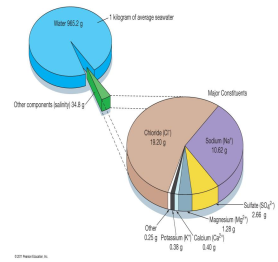
- Originally expressed as
  - grams of dissolved salts / kilogram of seawater

  And sometimes given in parts per thousand ‰

Ocean seawater has ~35 grams of salt for each kilogram of water → 35 ‰
- Salinities sometimes reported in PSU (Practical Salinity Units)
  - 35 ‰ = 35 psu
- But really it is a dimensionless quantity

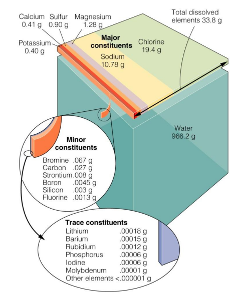
Major Constituents

- Chlorine
- Sodium
- Sulfate
- Magnesium
- Calcium
- Potassium
- Together make up 99.28 % of all salts in seawater



Minor Constituents

- Bromine
- Carbon
- Strontium
- Boron
- Silicon
- Fluorine
- Concentrations from 1-100 parts per million
- Some (e.g. carbon, silicon) very important for biological process



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Dissolved Chemicals

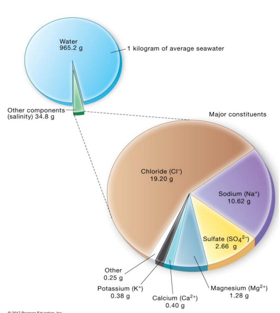
There are a variety of elements and compounds in seawater including most elements, as well as radioactive and organic compounds.

They generally appears as compound ions like Phosphate rather than actual raw elements.

They are designated as **major, minor, or trace** according to their concentration.

Dissolved Chemicals

- Measured in:
- 1) Parts per million (mg kg^{-1})
  - 1 teaspoonfull in 5000 litres of water
- 2) Parts per billion (µg kg^{-1})
  - 1 teaspoonfull in 5,000,000 litres of water (~5 Olympic size swimming pools)



- The main process to remove major constituents is the precipitation of salt deposits, which mainly occurs in marginal seas with high evaporation (e.g. the Mediterranean)
- The residence times for major constituents are very long and the associated river /erosion inputs are very slow, thus the concentrations of these ions very little from place to place in the open ocean
- Since the concentrations from minor and trace constituents are so slow, and the sources are often localized, the concentrations of trace elements can very significantly in different parts of the ocean.

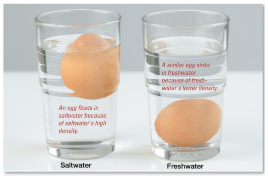
The amount of Tritium is very small, so small that its a trace element in our ocean.

Freshwater vs Saltwater

Freshwater vs Saltwater

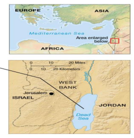
TABLE 5.4 COMPARISON OF MAJOR DISSOLVED COMPONENTS IN STREAMS WITH THOSE IN SEAWATER

Constituent	Concentration in streams (parts per million by weight)	Concentration in seawater (parts per million by weight)
Bicarbonate ion (HCO_3^-)	58.4	trace
Calcium ion (Ca^{2+})	15.0	400
Silicate (SiO_2)	13.1	3
Sulfate ion (SO_4^{2-})	11.2	2700
Chloride ion (Cl^-)	7.8	19,200
Sodium ion (Na^+)	6.3	10,600
Magnesium ion (Mg^{2+})	4.1	1300
Potassium ion (K^+)	2.3	380
Total (parts per million)	119.2 ppm	34,793 ppm
Total (‰)	0.1192‰	34.8‰



SMARTTABLE 5.2 COMPARISON OF SELECTED PROPERTIES OF PURE WATER AND SEAWATER

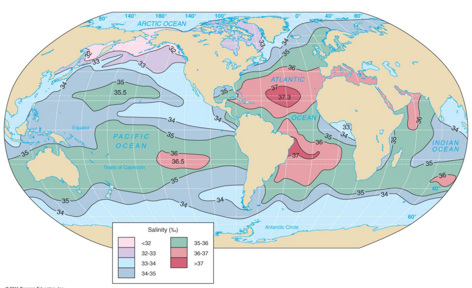
Property		Pure water	35‰ seawater
Color (light transmission)	Small quantities of water	Clear (high transparency)	Same as for pure water
	Large quantities of water	Blue-green because water molecules scatter blue and green wavelengths best	Same as for pure water
Odor		Odorless	Distinctly marine
Taste		Tasteless	Distinctly salty
pH		7.0 (neutral)	Surface waters, range = 8.0–8.3; average = 8.1 (slightly alkaline)
Freezing point		0°C (32°F)	−1.9°C (28.6°F)
Boiling point		100°C (212°F)	100.6°C (213.1°F)
Density at 4°C (39°F)		1.000 g/cm³	1.028 g/cm³



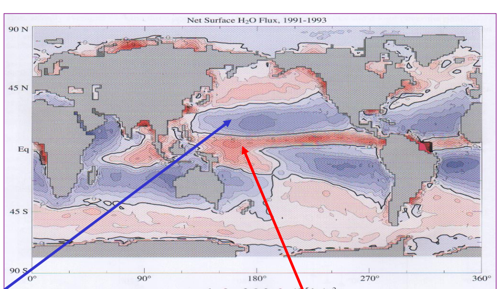
Buoyancy due to extreme salinity – Dead Sea: S~ 330

Salt water is more buoyant as the density of saltwater is higher than freshwater due to the addition of salt.

Sea Surface Salinity (SSS)



Evaporation minus Precipitation



Blue Regions: Excess Evaporation

Red Regions: Excess Precipitation

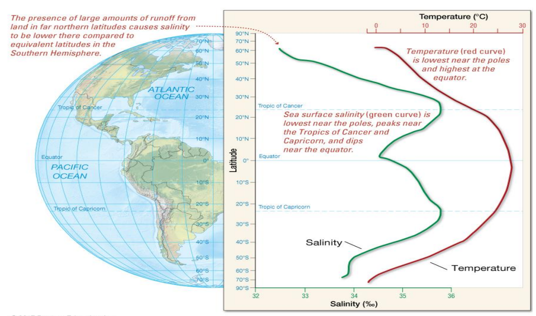
In areas where there is excess evaporation the level of salinity is higher then areas of excess precipitation. This is because salt does not evaporate and its concentration is increased as there is less water due to evaporation.

Sea Surface Salinity (SSS)

- Pattern is more complex than temperature because Evaporation and Precipitation have a complex pattern
- SSS generally highest in sub-tropical regions
- SSS generally lower at the equator and in high-latitude regions
- SSS differences in some regions due to runoff and/or ice melt
- North Atlantic's salinity is higher than the Pacific because of the circulation
- Salinity very high in marginal seas (E.g. Mediterranean, Red Sea) where Evaporation dominates

TABLE 5.3 PROCESSES AFFECTING SEAWATER SALINITY

Process	How accomplished	Adds or removes	Effect on salt in seawater	Effect on H_2O in seawater	Salinity increase or decrease?	Source of freshwater from the sea?
Precipitation	Rain, sleet, hail, or snow falls directly on the ocean	Adds very fresh water	None	More H_2O	Decrease	N/A
Runoff	Streams carry water to the ocean	Adds mostly fresh water	Negligible addition of salt	More H_2O	Decrease	N/A
Icebergs melting	Glacial ice calves into the ocean and melts	Adds very fresh water	None	More H_2O	Decrease	Yes, icebergs from Antarctic have been towed to South America
Sea ice melting	Sea ice melts in the ocean	Adds mostly fresh water and some salt	Adds a small amount of salt	More H_2O	Decrease	Yes, sea ice can be melted and is better than drinking seawater
Sea ice forming	Seawater freezes in cold ocean areas	Removes mostly fresh water	30% of salts in seawater are retained in ice	Less H_2O	Increase	Yes, through multiple freezings, called *freeze separation*
Evaporation	Seawater evaporates in hot climates	Removes very pure water	None (essentially all salts are left behind)	Less H_2O	Increase	Yes, through evaporation of seawater and condensation of water vapor, called *distillation*



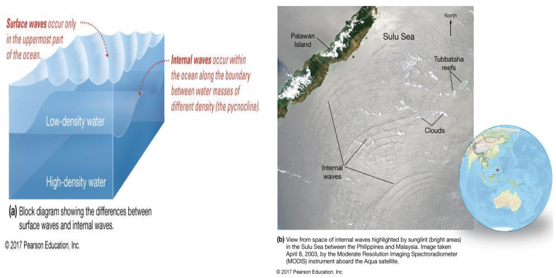
Part III

Week 3

1-21-2019: Waves in the Ocean

How are Waves generated:
Waves created by winds, also associated with pycnocline, caused by tides, turbidity currents, winds, ships.

Internal Waves



(a) Block diagram showing the differences between surface waves and internal waves.
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(b) View from space of internal waves highlighted by sunglint (bright areas) in the Sulu Sea between the Philippines and Malaysia. Image taken April 8, 2003, by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Aqua satellite.
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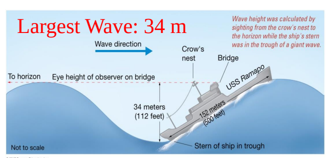
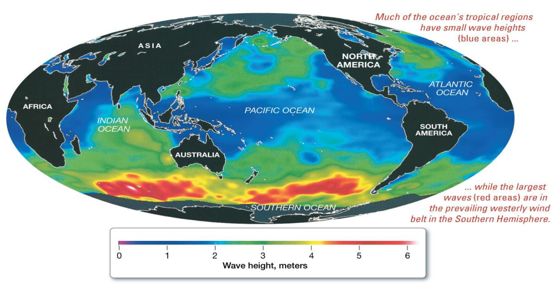
Global Wave Heights





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Waves

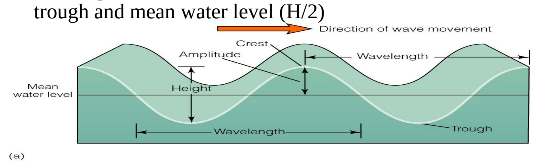
- Waves are energy transmitted through matter.
- The medium does not travel as the energy passes through, but constituent particles oscillate in place as the energy passes through them
  - Consider hitting a table – the energy passes through and the vibrations can be felt at the far end but the table does not move
- Waves move through matter in 3 dimensions
- Progressive waves are those where the waveform can be observed travelling through the medium

Waves

- Waves generated by two competing forces
  - A disturbing force that modifies a 'un-disturbed' medium to create the wave
    - Most common such force is the wind that blows over the surface and transfers energy to the ocean
  - A restoring force that tends to bring a system to its undisturbed state
    - For waves along liquid surfaces, the restoring force is gravity

Waves

- The point of highest elevation of a wave is the crest
- Between each pair of crests is a depression or trough
- The distance between each successive pair of crests or troughs is the wavelength, represented as λ (Lambda)
- The vertical distance between crest and trough is the height, represented as H
- The amplitude is the vertical distance between the crest or trough and mean water level (H/2)



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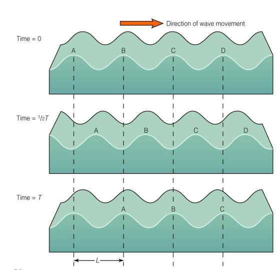
Crest: The point of highest elevation of a wave
Trough: Between each pair of crests
Wavelength: The distance between each successive pair of crests or troughs
Wave Height (H): The vertical distance between crest and trough
Amplitude (H/2): Half wave height.

Waves

- The wave period (represented T) is the time it takes for the wave to move a distance equal to one wavelength
  - Equivalently, it is the time between the arrival of two successive crests or troughs at a given location
- Wave frequency (represented f) is the number of crests (or troughs) that pass a point in a fixed unit of time
- Period and frequency are directly related: T = 1/f



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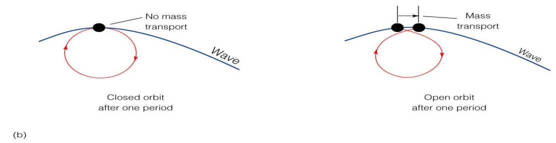
Waves

- Wave speed (represented C) is related to the speed of ‘movement’ of the wave crest
  - $C = \lambda/T$
  - The wave speed is the rate the wave form moves at, not the water
- Wave steepness is the ratio of the wave height to the wavelength (H/λ)
- Note: For the ocean, since waves are typically very long (I.e. less than 1 crest or trough passes a point in a ‘time unit’), we focus more on period than frequency

Wave Motion

- There is some net forward motion of the water as a wave passes
- This is because the particle speed decreases with depth
  - I.e. the forward speed at the crest is slightly larger than the backwards speed at the base of the trough
  - So molecules will move slightly farther forward at the crest than they move back in the trough
- This type of motion is called Stokes Drift

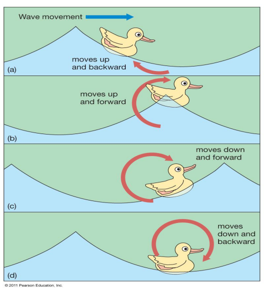


There is a net force in the direction of the wave, so the duck does move forward a little bit.

Wave Motion

Web Link: https://goo.gl/zvZ6Mf

- When a wave moves across the ocean without breaking, there is almost no net forward motion of the water itself
- Only the energy and the waveform associated with the wave moves

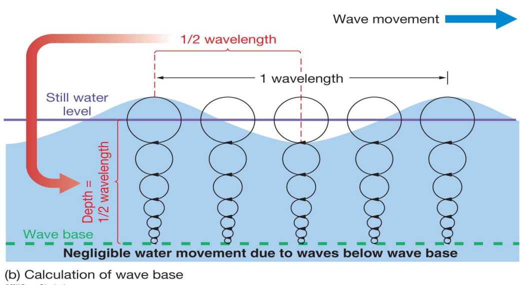


The duck doesn’t move really but the wave energy does.

Creating Waves

- Wave are created by a number of processes
  - 1) Interactions of winds with the ocean surface
  - 2) Impacts on the ocean
  - 3) Tidal interactions
  - 4) Passage of vessel or marine mammals
- Waves can also be created on density interfaces within the ocean, as well as the surface (internal waves)

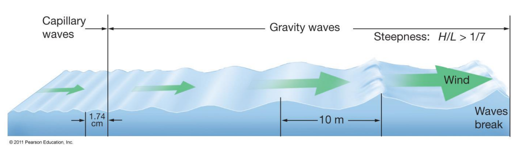
Wave Motion



(b) Calculation of wave base

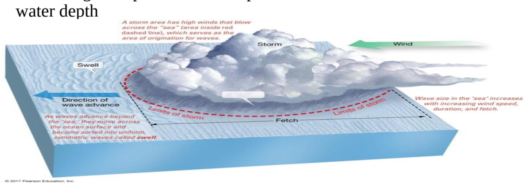
Creating Waves

- Over time, waves shift from a more regular sinusoidal form to one of trochoidal shape (pointed crests and rounded troughs)
- When waves get too steep ($H:\lambda$ 1:7), they break
  - Here the energy input by the wind is released
  - Waves can break in the open ocean



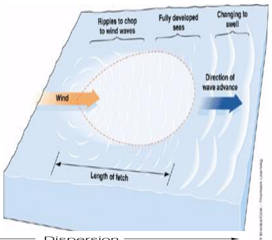
Creating Waves

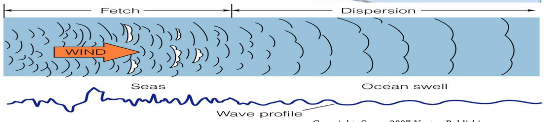
- Winds never blow uniformly over the ocean surface, thus we gets waves of many heights, wavelengths, periods, direction, etc.
  - This confused state is known by mariners as “Sea”
- Swell is where waves are generally smooth, from the same direction and have the same wavelength
- Wave heights depends on wind speed, wind fetch, wind duration and water depth



Wave Dispersion

- In the open ocean, longer waves travel faster than shorter waves
  - This is wave dispersion
  - Thus the swell outruns the storm that generates it and arrives first
  - As the storm approaches, the wavelength and period of the approaching swell will decrease





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Wave Interactions

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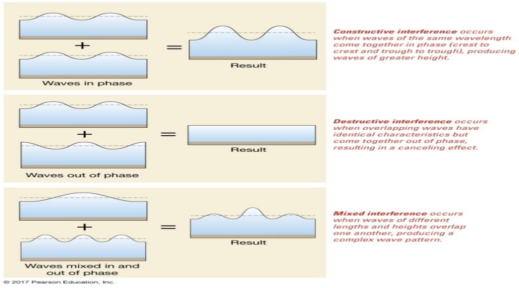

Physics of wave interactions.

Wave Interactions

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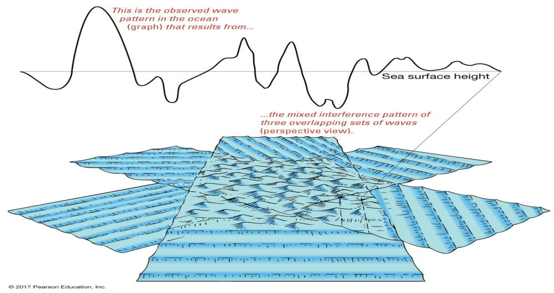
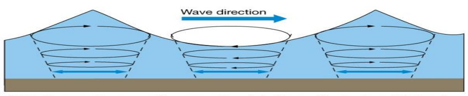


1-23-2019: Shallow Water Waves and Tsunamis

Shallow Water Waves

Shallow Water Waves

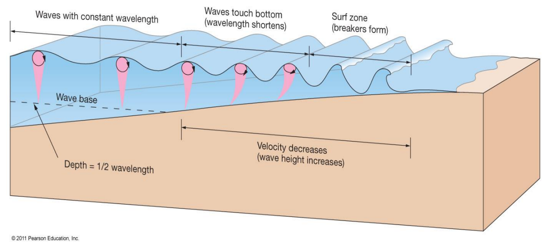
- When waves enter shallow water, they interact with the seafloor
  – This includes the seafloor preventing water particles from moving in circular orbits (as molecules at the seafloor can only move back and forth)
  – This distorts the orbits of molecules into elongated ellipses
  – This compression, combined with friction, slows the forward motion of the wave



(c) Shallow-water wave: The ocean floor interferes with circular orbital motion, causing the orbits to become progressively flattened. Water depth is less than $^1/_{20}$ wavelength.

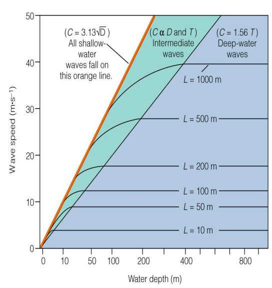
Shallow Water Waves

Web Link
http://goo.gl/55FMau



Shallow Water Waves

- As the water depth decreases, so does the wave speed
  – This leads to intermediate and then <u>shallow</u> water waves (depth less than λ/20)
  – Speed is $\sqrt{gH}$
  – Thus, all waves in shallow water travel at the same speed in the same depth water, regardless of period

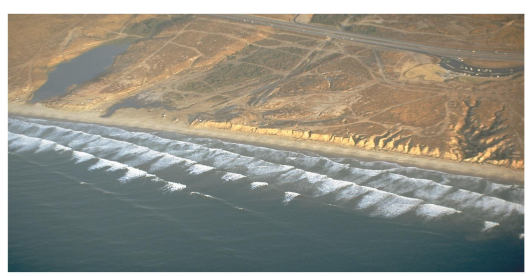


Shallow Water Waves

- As waves enter shallow water and are slowed, their period does not change
  – Since C=λ/T and the period does not change, the wavelength must decrease
  – This makes sense if we consider a wave approaching shore and slowing – This means the next wave can come closer to it as it is deeper water, thus reducing the distance between crests
  – As the waves continue towards the shore, the leading wave is normally always in shallower water and thus moving slower, allowing the trailing wave to catch up even more
  – The height thus increases as kinetic energy is converted to potential energy
  – The decrease in wavelength means there is also an increase in steepness

Because the speed is determined by $\sqrt{gH}$ all waves in shallow water travel at the same speed in the same depth of water.

Shallow Water Waves

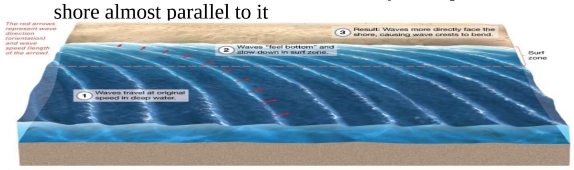


(a)

Shallow Water Waves

Web Link: https://goo.gl/mJrwgb

- Waves usually approach the shore at an angle
- This usually means one part of the wave is in shallow water, while the rest is in deeper water
  - The wave is thus refracted or bent
- This continues such that waves normally end up reach the shore almost parallel to it



(a) Aerial view of wave refraction along a straight shoreline.
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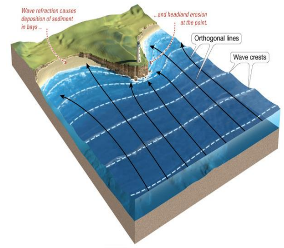
Shallow Water Waves

- In the end, we get the wave breaking almost parallel to the coast, as usual
- As the wave is refracted in the bay, the total length of the crest in increased, lowering its height
- Thus the wave energy is spread along the beach, with gentler waves
- This process also transports sand towards the shore where in builds the beach



(b) Perspective view of wave refraction along an irregular shoreline.
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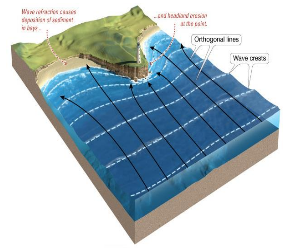
Because some areas of the waves are at different speeds the wave refracts when it gets close to the shore.

Shallow Water Waves

- At the headland, refraction reduces the length of the wave crest, increasing the height
- Thus one will generally see more energetic and higher waves breaking in these areas
- The same wave can also hit the headland from both sides at once
- This focusing of the wave energy leads to lots of erosion and the carrying away of sand



(b) Perspective view of wave refraction along an irregular shoreline.
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Shallow Water Waves

(c)

(c) Photo of wave refraction at Rincon Point, California (looking west).
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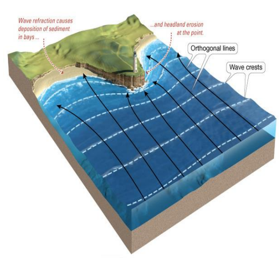
Shallow Water Waves

- Wave refraction can be as complicated as the seafloor topography (which is often an extension of what is seen on land)
- If a wave approaches a bay flanked by headlands, normally it is shallow in front of the headlands
  - This first slows the wave in these areas, while it is last slowed over the deeper water in the centre of the bay



(b) Perspective view of wave refraction along an irregular shoreline.
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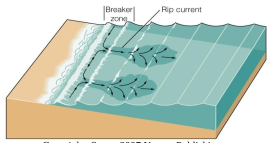
Rip Currents

Rip Currents

- Water dumped nearshore by breakers must return offshore
  - First moves parallel to beach as a longshore current
  - Then turns and flows offshore in a narrow swift rip current
  - The rips are usually spaced hundreds of metres apart



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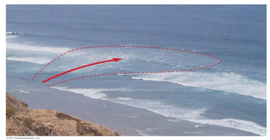

Shallow Water Waves

Breaking Waves

- Wave steepness increases until the wave becomes unstable and breaks.
- The area offshore within which waves are breaking is called the **surf** zone.

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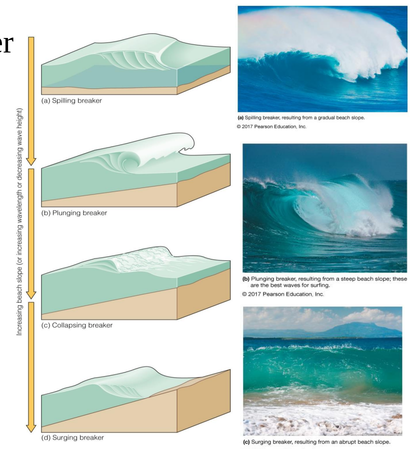

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Shallow Water Waves

- Surfers position their board so they are on the upward moving part of the wave orbit, where this upward movement can balance the effect of gravity.

Surfing Waves

Surfing Waves

- Why are wave conditions for surfing generally better on the west coast than the east coast of North America
  - Pacific bigger than Atlantic, so greater fetch, so bigger waves can develop
  - Beech slopes generally steeper on Pacific coasts, creating plunging breakers
  - Winds generally onshore (westerlies), enhancing waves on west coast and weakening them on the east coast

Defining Coastal Regions

Definitons of Coastal Regions

Shore: The zone that lies between the low tide line and the highest area on land affected by storm waves.

Coast: extends inland as far as ocean related features are found.

Coastline: Boundary between shore and coast.

Backshore: Part of shore above high tide shoreline.

Foreshore: Part of the shore exposed at low tide and submerged at high tide.

Shoreline: Water's edge that migrates with the tide.

Nearshore: Extends seaward from low tide shoreline to low tide breaker line.

Offshore: Zone beyond low tide breakers.

Beach: Wave-worked sediment deposit of the shore area.

Wave-cut Bench: Flat, wave-eroded surface.

Berm: Dry, gently sloping, elevated beach margin at the foot of coastal cliffs or sand dunes.

Beach face: Wet, sloping surface extending from berm to shoreline.

Longshore trough: Separates longshore bar from beach face.

Composition of Beaches

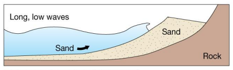
- Formed from locally available material
- May be coarse or fine grained sediment
  - Boulders from local cliffs
  - Sand from rivers
  - Mud from rivers
- Significant biologic material on tropical beaches
- Material is always in transit along the shoreline.

Sand Movement Along Beach

- Perpendicular to shoreline (toward and away)
  - **Swash** – water rushes up the beach
  - **Backwash** – water drains back to the ocean
- Parallel to shoreline (up-coast or down-coast)
  - **Longshore current** – transports sand along the beach

Summertime Beach

- Light wave activity
  - Wide, sandy berm
  - Steep beach face
  - Swash dominates
- Longshore bars not present
- Generally milder storms

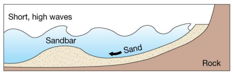


(a) Summertime beach (fair weather)

Web Link:
http://goo.gl/XsoVZk

Wintertime Beach

- Heavy wave activity
  - Backwash dominates
  - Sediment moved away from shore
  - Narrower beach
  - Flattened beach face
- Longshore bars are present
- Stormy weather



(b) Wintertime beach (storm)

Tsunami

Underwater displacement from the sea floor.
Tsunamis are not the same as tidal waves.
These are fast shallow-water waves.
These waves are usually generated by earthquakes.
However, not all earthquakes produce Tsunami.
Earthquakes below subduction zones have large vertical movement (reverse fault) that generates Tsunami. While earthquakes on strike-slip faults have mostly horizontal movement and tend not to generate Tsunami.

Tsunami

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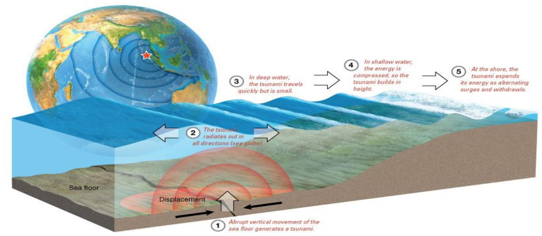

(a) How a tsunami is generated, propagated, and surges to extreme heights at the shore.
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Tsunamis in the Open Ocean

- Earthquake generated tsunami:
  - Wavelengths often greater 200 km
  - Wavelength greater than the depth of the ocean
- Tsunami are **Shallow Water Waves**
  - all properties, including refraction, apply

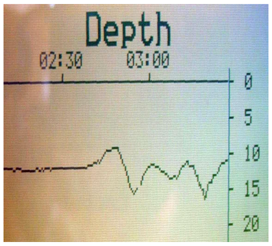
$$C = \sqrt{gH}$$

- Pacific Ocean depth ~4,600 m gives speed of:
  - C = 212 m/s (~760 km/hr)
- Amplitude small in the open ocean.
- The rate of energy loss is inversely related to its wavelength. A tsunami can travel transoceanic distances with only limited energy loss.

Tsunamis and the Coast

Tsunamis and the Coast

- When the tsunami approaches the coastline:
  - its speed decreases (as the water depth decreases)
  - its amplitude increases as energy is converted from kinetic into potential
  - Waves can easily reach 10+ m in amplitude



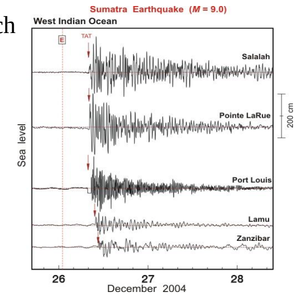
Magnitude

Tsunami Magnitude

- The size of a tsunami depends partly on the size of an earthquake
  - usually given as a Richter Scale magnitude
  - Magnitude is a measure of the strength of an earthquake or strain energy released by it,
  - An increase of one unit of magnitude (for example, from 8.1 to 9.1) represents
    - a 10-fold increase in wave amplitude on a seismogram or
    - approximately a 30-fold increase in the energy released.

Tsunamis and the Coast

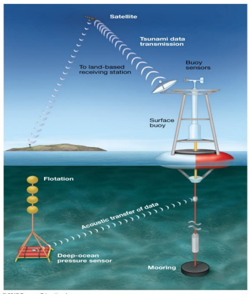
- The first wave to reach the coast is often not the highest



Courtesy of Fisheries and Oceans Canada

Tsunami Warning Systems

- Warning Network
  - 1) Earthquake reported by global seismic network
  - 2) Offshore buoys/satellites measure wave heights
  - 3) Models predict size of waves and timing when reach coast
  - 4) Local Emergency Response units contacted
- B.C. Tsunami Alert Plan
  - https://www2.gov.bc.ca/gov/content/safety/emergency-preparedness-response-recovery/preparedbc/high-ground-hike



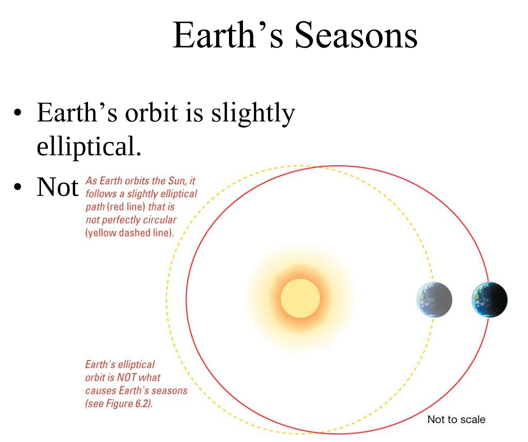
Tsunami

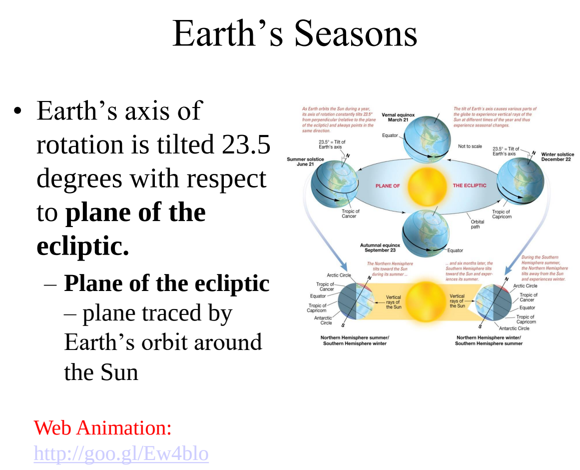
- For a tsunami, if the crest arrives first (associated with upward crustal motion during original seismic event), wave will arrive first
- If the original event had downward crustal motion, the trough will proceed the crest
- This causes the water along the shore to receed by up to 3-4 m over 2-3 minutes

1-25-2019: Introduction to the Atmosphere and the Coriolis Effect

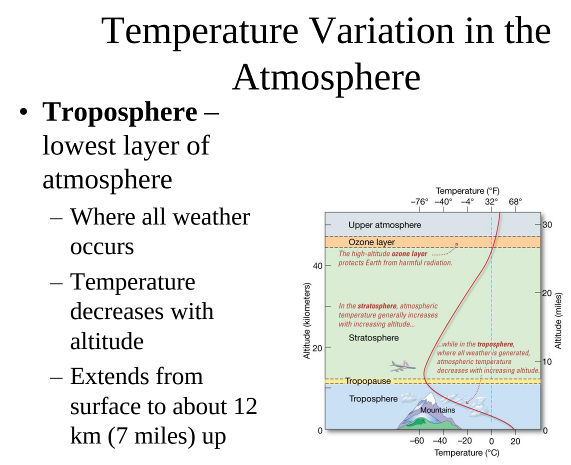
There is an interaction between the ocean and the air it is in contact with. To understand this interaction one must understand how large-scale atmospheric circulation works.

Earth's Season



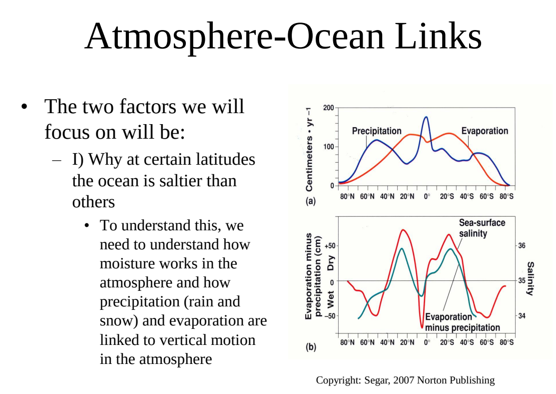


Temperature Variation in the Atmosphere



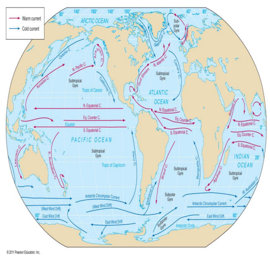
Atmosphere-Ocean Links

There are two main factors that are involved in the interaction between the air and ocean.



Atmosphere-Ocean Links

- II) Why the pattern of large scale upper ocean currents is setup the way it is, with circular patterns (gyres) within all oceans (except around Antarctica)
  - To understand this, we need to know how the large scale pattern of atmospheric surface winds is set-up

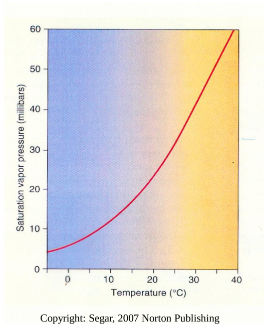


Atmosphere-Ocean Links

- We will start by considering how water vapour behaves in the atmosphere
- This will lead us to the idea of pressure gradients
- Then, because the Earth is rotating we will need to consider what is known as the Coriolis Effect
- Finally we all will put this together to arrive at the large scale atmospheric circulation
- Note that we are considering long-term average patterns here and not the short term variability associated with 'weather'

Water Vapour

- Water vapour within the atmosphere behaves somewhat like sugar in water
  - It dissolves, but there is a maximum amount that can be held
  - Thus for air, it holds water vapour, up to a maximum amount, with the amount that can be held increasing with temperature
- The maximum amount of water that can be held as vapour in air is the saturation vapour pressure



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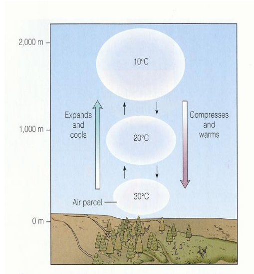
Atmosphere

- As water evaporates, water molecules, which are lighter than air molecules are added to the atmosphere
  - This means moist air is less dense than dry air
  - Moist air thus tends to rise until it reaches an equilibrium level
  - If the water is removed, the air gets more dense and sinks back to its new equilibrium level

Atmosphere

- Additionally, as the air rises, the pressure decreases, causing the air to expand and to cool by adiabatic expansion
  - This decreases the saturation vapour pressure
- When the saturation vapour pressure becomes less than the actual vapour pressure, the air can no longer hold the moisture it presently contains and liquid vapour forms
  - This can lead to cloud formation and rain



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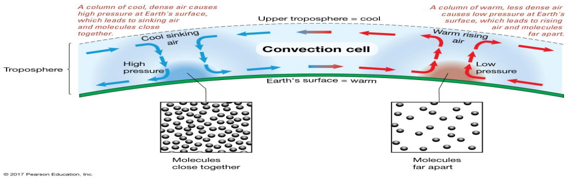
Atmosphere

- As well, when water vapour condenses to form liquid water, this releases heat (more on this process later in the course) to the surrounding air
  - This warms the air, which reduces the density, causing the air to rise some more, which leads to more adiabatic cooling and thus condensation, …
  - This process can lead to the strong rising plumes associated with thunderstorms, for example

Pressure



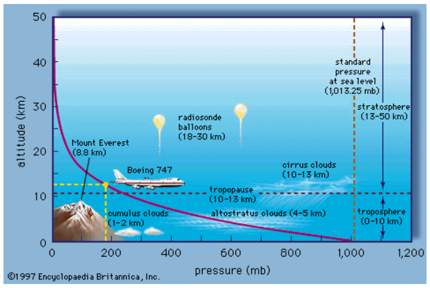
Pressure

Pressure

Atmospheric pressure depends on the weight of overlying air.

This is why pressure decreases with altitude:

- higher up there is less air above you, so less weight/area pushing upon you.



Pressure

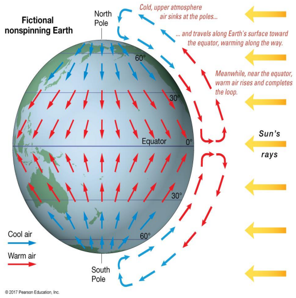
- The thicker or more dense the column of air, the higher the pressure
  - A column of cool dense air is associated with high pressure at the surface and sinking
  - A column of warm, less dense air is associated with low pressure at the surface and rising
- Pressure Gradient: Given a difference in pressure between locations, pressure exerts a force from HIGH to LOW pressure

13

Fictional Non-rotating earth

Fictional Non-Rotating Earth

- Solar heating causes air to rise at the equator and then spread towards the poles
- Rising air also creates low pressure at the surface, so the surface winds flow towards the equator
- Surface Convergence at the equator
- Surface Divergence at the poles



Air near the equator gain solar heat more than air near the poles. This causes the air to expand and rise where they are carried in the upper atmosphere to the poles where they cool down and fall. This cool, dense, high pressure air then spreads out filling the low pressure void at the equator.

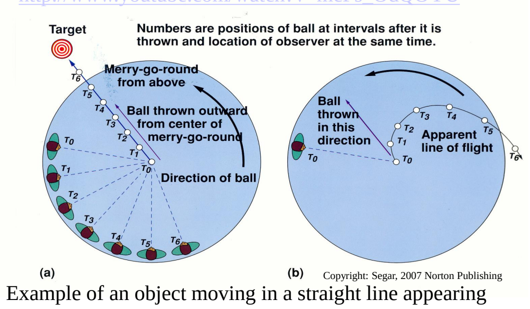
Coriolis Effect

Coriolis Effect

- The **Coriolis Effect** changes the intended path of a moving body and is named after the French Engineer Gaspard Gustave de Coriolis (1835)
- Causes objects moving on the Earth to follow **Curved Paths**
- Acts on all moving objects but most pronounced on objects travelling long distances
- This effect is generated because of the Earth's rotation to the East
- Objects actually travel in straight lines (as per Newton's Laws of Motion) but since the Earth rotates underneath them, the objects appear to follow curved paths

Coriolis Effect

- http://www.youtube.com/watch?v=mcPs_OdQOYU



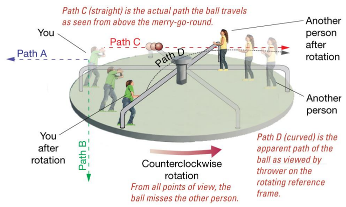
Example of an object moving in a straight line appearing curved to an observer

The ball's trajectory is straight but the movement of the target make it look like it's curving.

The Coriolis Effect

- Deflects path of moving object from viewer's perspective
  - To right in Northern Hemisphere
  - To left in Southern Hemisphere
- Due to Earth's rotation

Web Animation:
https://goo.gl/UE3t03

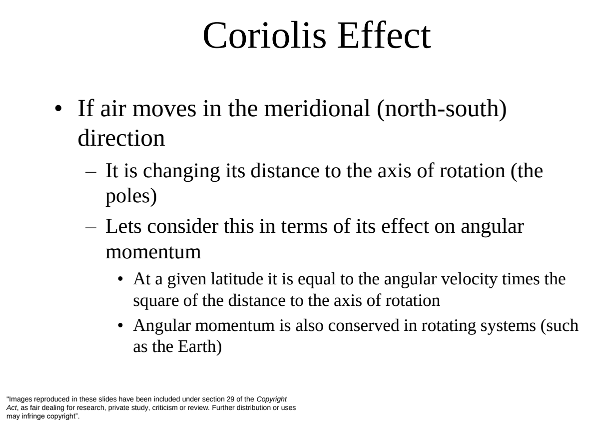


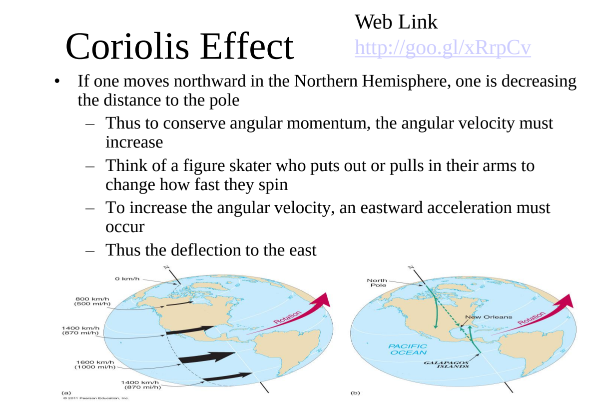
In the northern hemisphere, an object will follow a path to the **right** of its intended direction.
In the Southern hemisphere, an object will follow a path to the **left** of its intended direction.
The direction of the deflection are with respect to the viewer's perspective looking in the direction which the object is traveling.

Part IV

Week 4

1-28-2019: Large Scale Atmospheric Circulation

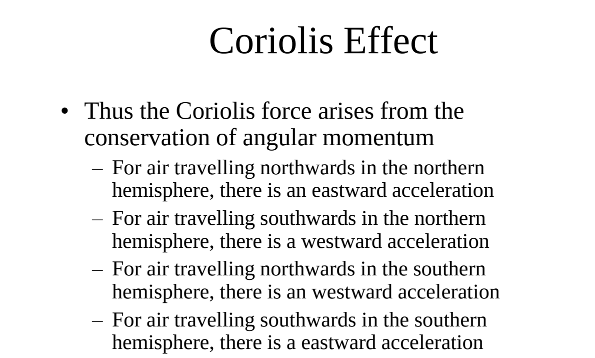


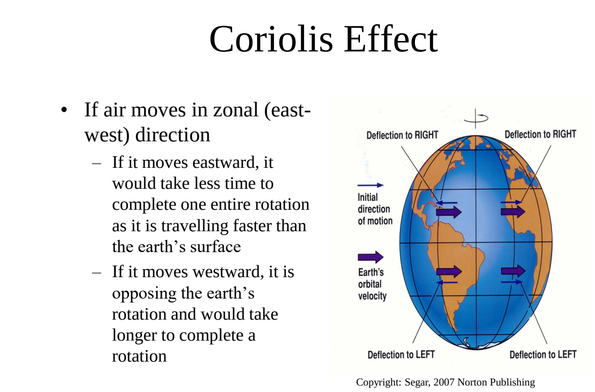


The direction of rotation is from west to east. As you move further away from the equator the speed decreases. Note: angular speed is constant but the distance decreases with the increase in latitude so the "speed" decrease when you move away from the equator.

In the Northern Hemisphere, if a fluid is move away from the equator then in order to maintain momentum in the slower moving latitude the fluid gains an eastwardly acceleration that moves the fluid up and to the right. If the fluid is moving towards the equator then in order to maintain momentum in the faster moving latitude the fluid gains a westwardly acceleration that moves the fluid down and left. In both situations the fluid is moving rightward in their perspective.

In the Southern Hemisphere this process is the opposite.





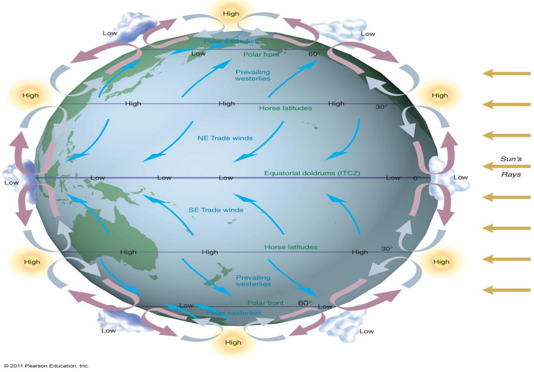
If the angular velocity increases then the excess energy want to go towards the equator, right in the north, left in the south in perspective with the flow. If the angular velocity decrease then the excess energy want to go away from the equator. The equator has the highest level of angular velocity ignoring external forces.

Coriolis Effect

- Eastward motion in the northern hemisphere leads to a southward acceleration
- Westward motion in the northern hemisphere leads to a northward acceleration
- Results are opposite in the southern hemisphere
  - Eastward motion in the southern hemisphere leads to a northward acceleration
  - Westward motion in the southern hemisphere leads to a southward acceleration

Large-Scale Atmospheric Circulation

- We can thus link our basic ideas of vertical motion in the atmosphere with the effects of the Coriolis Force to
  - Gives us a simplified picture of the average north-south overturning circulation into 3 cells (Hadley, Ferrel and Polar)
  - The surface winds produced by these cells are then deflected by the Coriolis Force to drive east-west winds above the surface of the ocean



Hadley Cell

Warm, moist air rises at the equator, it then flows poleward (and is deflected to the right due to the Coriolis effect where it cools and sink in subtropic regions where it then returns as surface flow.

Ferrel Cell

Poleward surface flow, rising in mid-latitudes. Returns equatorward at height and sinks in subtropic regions.

Drives northeasterly TRADES in sub-tropics. Drives Westerlies in mid-latitudes.

Climatic Winds

- Since rising air is often moist and since air cools as it rises, that moisture can't held, producing clouds and precipitation
  - Intertropical Convergence Zone
- Sinking air can hold more moisture (as it is warming as descending), which normally means dry, clear conditions
  - Thus, downwelling in the sub-tropical divergence zone means dry conditions and deserts

Idealized Three-Cell Model

- More complex in reality due to
  - Tilt of Earth's axis and seasons
  - Lower heat capacity of continental rock vs. seawater
  - Uneven distribution of land and ocean
  - http://goo.gl/zVaUTq

1-30-2019: Properties of Water

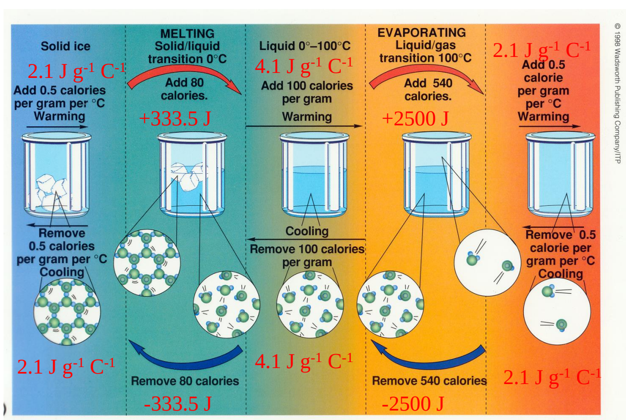
Heat Properties of Water

- **Heat Capacity**: The amount of heat needed to heat 1 g of a substance 1˚C
  - For ice 2.1 J g^{-1} ˚C^{-1}
    - Note: A calorie is an older unit of energy
    - 1 calorie = 4.19 J
  - This occurs until the ice reaches the melting point
  - At that point, adding more energy (heat) does not change the temperature. Instead, once 333.5 J per gram of ice have been added, the substance melts
  - For ice/water, the Latent Heat of Melting is 333.5 J g^{-1}

Heat Properties of Water

Sensible Heat: Heat that raises or lowers the temperature of an object but does not change its phase.

Latent Heat: Heat added or removed that does not change the temperature of the substance but leads to a change of phase.



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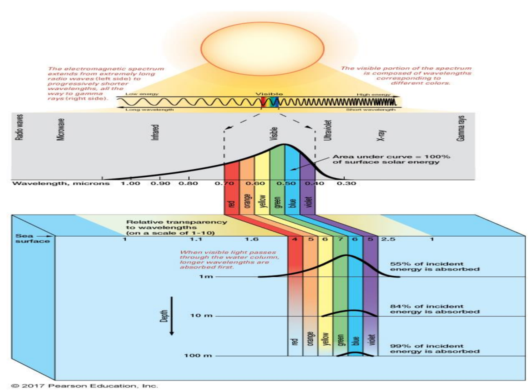
Liquid vs other phases of water

Note that the sensible heat for liquid water is twice that of water vapour, and ice.

Transmission of light

Transmission of Light

- **Absorption:** Water absorbs electromagnetic (EM) radiation, with the depth of penetration depending on the wavelength
  - Most EM radiation can penetrate only a few cm's, or m's at the most
  - Light has enhanced penetration, although the distance still depends on the wavelength
    - On average, light penetrates to about 100 m depth, where about 1% of the initial energy remains
    - This depth is defined as the Photic Zone and is where photosynthesis occurs



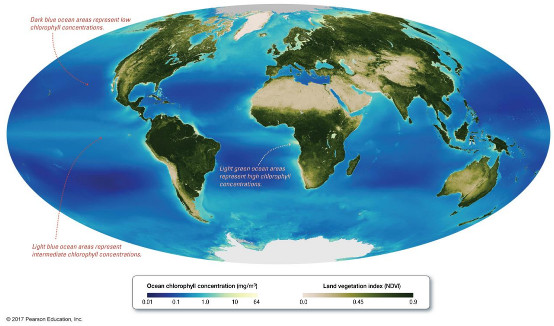
Web Link: https://goo.gl/Dvl14o

Light penetration is reduced in coastal and estuarine waters where there are a lot of suspended sediments, thus reducing the amount of light penetration. In general this is the primary reason why radar and lasers cannot be used to study the ocean interior.

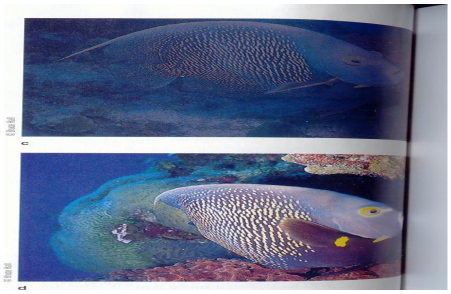
Transmission of Light

- **Scattering and Reflection:** Light is scattered when photons bounce off water molecules and/or suspended sediments
- In general, scattering occurs in all directions
- Since blue light penetrates the ocean the farthest, it has the greatest chance of being scattered
  - Hence, clear ocean waters have a deep blue colour
  - In turbid waters, all light is scattered, giving a greenish or brownish-blue shade from the mixing of light
- Particles also reflect light, with the colour of an object given by the wavelength it reflects
  - Ocean colour can thus be used to determine the location of phytoplankton, sediments, etc.

Ocean Chlorophyll



Transmission of Light



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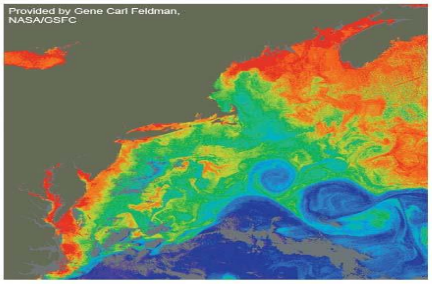
Ocean Colour



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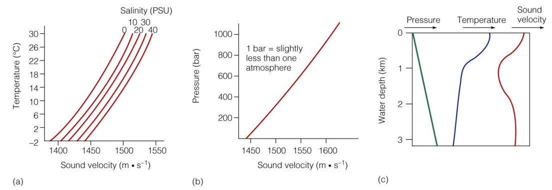
Sound Transmission

Sound is transferred by the vibration of adjacent molecules (and thus can't travel in a vacuum). Moreover, sound waves are produced by pressure changes between molecules.

Unlike light, sound is less affected by water and thus have good penetration properties. The speed of sound in water is about 4 times greater than in air, and the speed is proportional with salinity, temperature and pressure.

Sound Transmission



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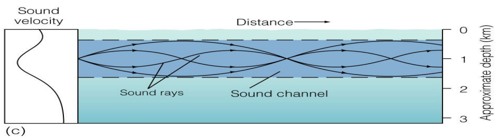
Sound Transmission

- Sound that travels vertically is little effected by refraction
  - Sound waves at other angles are often significantly deflected as they hit sloping density layers
- Shadow Zone: A region where sound pulses can't reach
- Sound Channel: A region associated with the sound speed minimum where sound waves that entered are trapped. This allows them to travel great distances with little loss of energy

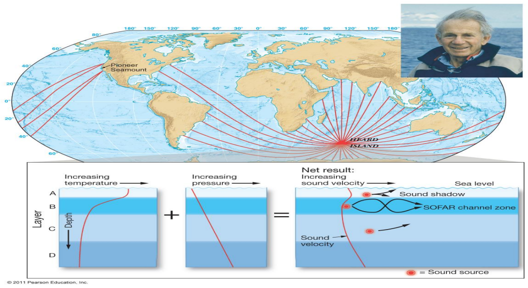


ACOUSTIC THERMOGRAPHY

This is a technique to precisely determine travel times in water over large distances by noting how the speed of sound changes with temperature.

- Presently being used to help detect climate warming.
- Involves a low frequency sound produced in the sound channel. This sound travels around the world, with the time taken for it to arrive at different stations measured precisely.
- Since the speed of sound increases with temperature, if the oceans are warming, the signal will take less time to arrive at its destination.

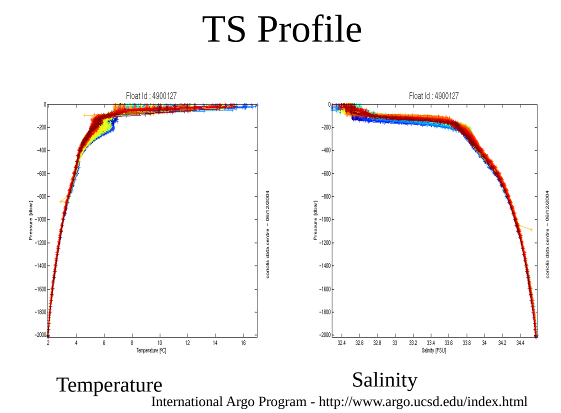
Sound Transmission

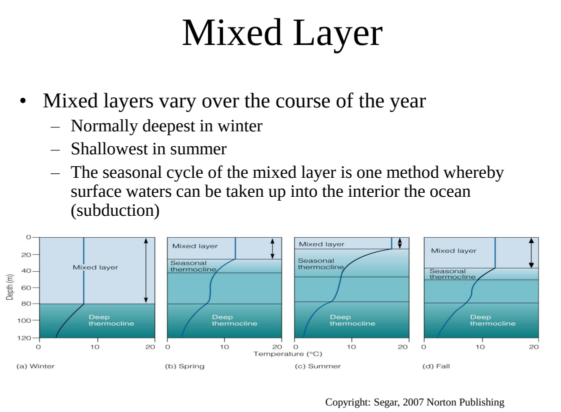


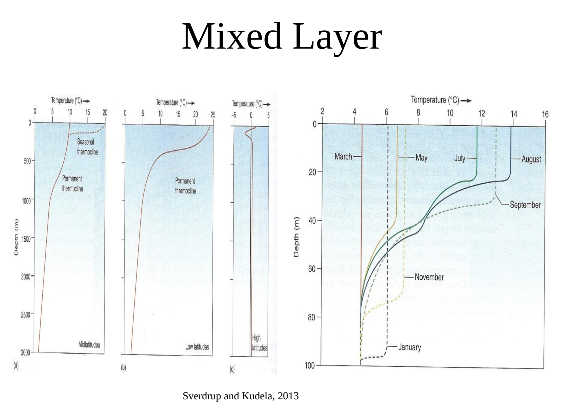
2-1-2019: Water Density

Mixed Layer

A homogeneous layer at the surface of the ocean within which oceanic properties specifically temperature or salinity changes very little.

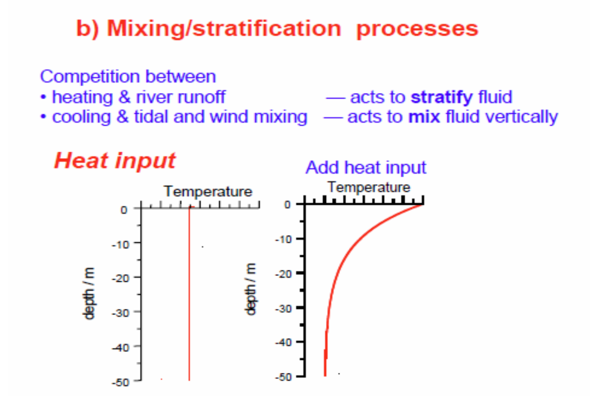


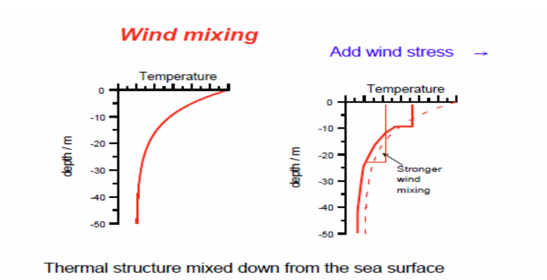


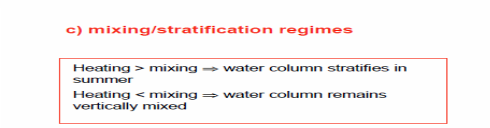


Factors that control mixed layer depth includes:

- Wind driven mixing
- Stability of the underlying water
- Surface buoyancy changes like surface heating or cooling, or provision of freshwater to the ocean's surface
- Large scale ocean circulation







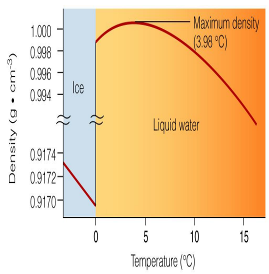
Water Density

The density of sea water depends on temperature, salinity and pressure

Pressure: Water is pretty much incompressible as the molecules are fairly close together. In the deep ocean, where pressures are over 1000 times that of the surface atmospheric pressure, water density increases by about 2% (for the same temperature and salinity)

Water Density

- **Temperature:** In general, for both water and ice, density decreases as the temperature increases
- Note: An exception is for pure water, where the density increases as the temperature increases from 0 degrees to 3.98 degrees
- Note: The density decreases that occurs when water freezes to ice



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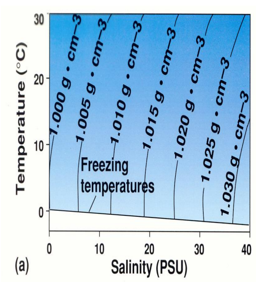
Water Density

- **Salinity**: Increasing salinity (more dissolved salts) means an increasing density
- **Density:** The interplay of temperature and salinity (TS effects) determines sea water density



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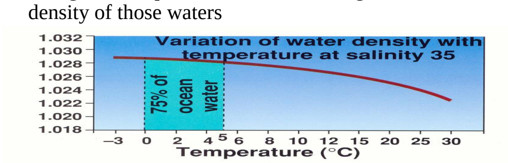
Water Density

- In general, temperature changes are more important in the tropics as the slope of the density line in the figure below is greater for large temperature
- Note that most of the ocean's water is cold and thus changes in temperature do not have large effect on the density of those waters



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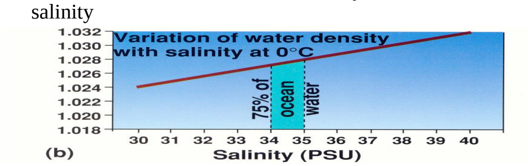
Water Density

- In general, salinity changes are more important at high latitudes, where the slope of the density line is greater for salinity than for temperature (comparing the figure on this page with the one on the previous)
- Note that most of the ocean has a fairly intermediate salinity



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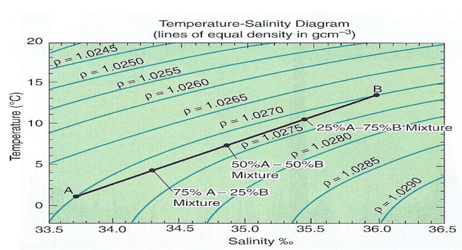
Water Density

- **Equation of State:** A complicated equation describes how ocean density depends on temperature and salinity (and also pressure)

$$
\begin{aligned}
\rho(s,t,o) = \; & +999.842\,594 && +6.793\,952 \times 10^{-2} \times T \\
& - 9.095\,290 \times 10^{-3} \times T^2 && +1.001\,685 \times 10^{-4} \times T^3 \\
& - 1.120\,083 \times 10^{-6} \times T^4 && +6.536\,332 \times 10^{-9} \times T^5 \\
& + 8.244\,93 \times 10^{-1} \times S && -4.089\,9 \times 10^{-3} \times T \times S \\
& + 7.643\,8 \times 10^{-5} \times T^2 \times S && -8.246\,7 \times 10^{-7} \times T^3 \times S \\
& + 5.387\,5 \times 10^{-9} \times T^4 \times S && -5.724\,66 \times 10^{-3} \times S^{3/2} \\
& + 1.022\,7 \times 10^{-4} \times T \times S^{3/2} && -1.654.6 \times 10^{-6} \times T^2 \times S^{3/2} \\
& + 4.831\,4 \times 10^{-4} \times S^2.
\end{aligned}
$$

This version is for surface density

Effect of Non-Linear Equation of State



Sverdrup and Kudela, 2013

Density

- In general, density is not measured but calculated from observational (in-situ) measurements of temperature, salinity, pressure
  - Thus, we define ρ (S, T, p)
  - Can be done with an accuracy of parts per million
  - A typical surface density is 1026 kg m^{-3}
  - Thus, we typically use the density anomaly in practice
    - σ (S, T, p) = ρ (S, T, p) – 1000 kg m^{-3}
  - If we are studying the surface of the ocean, we can ignore compressibility
    - σ_t = σ (S, T, 0)

Ocean Vertical Structure

Thermocline

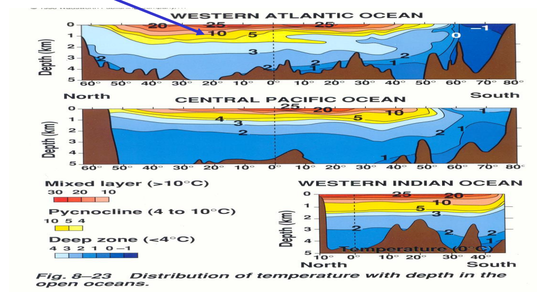
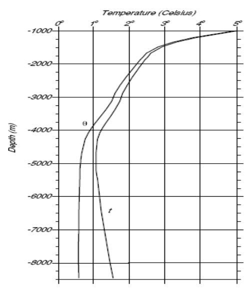


Fig. 8—23 Distribution of temperature with depth in the open oceans.

Potential Temperature

- In the interior, the T and S of a water parcel will only change by mixing with other waters
  - Thus the properties can be used to trace the water parcel's motion
  - To do this, we need to eliminate the effect of compressibility
- Potential Temperature (Θ): The temperature a parcel of sea water would have if lifted adiabatically to the sea surface
  - Adiabatically means no heat exchange with the surroundings

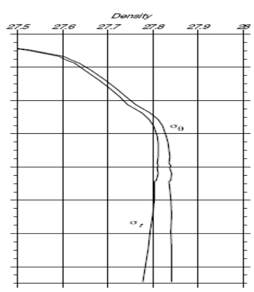


Stewart, 2004

Pycnocline

Potential Density

- Potential density (ρ_θ) is the density a parcel of water would have if it was raised adiabatically to the surface without a change in salinity
  - ρ_θ = σ (S, Θ, 0)
  - It is a conserved thermodynamic property

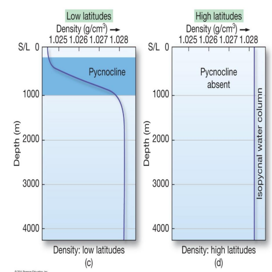


Stewart, 2004

Pycnocline

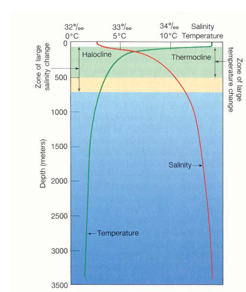
Web Animation: https://goo.gl/1zC18l

- In most of the ocean, there is a depth range where the density changes very rapidly in the vertical – this is the pycnocline
- Normally present at depths of 100-500 m
  - Below the mixed layer



Pycnocline

- If the rapid density changes are associated with temperature, we get a thermocline
  - Thermoclines often develop in spring and summer due to solar hearing
- If the rapid density changes are associated with salinity, we get a halocline
  - Haloclines often associated with freshwater input (rivers, ice melt, etc.)



Part V

Week 5

2-6-2019: Ekman Circulation

Wind-Driven Currents

Friction from the wind causes energy to be transferred into the ocean. This energy causes the surface layer in motion and generates currents and waves. The actual transfer process is complex and depends on many factors including: the wind speed, and the surface tension and roughness of the water. Generally about 1-3% of the wind energy is converted to ocean kinetic energy. Most direct wind-driven currents only reach 100-200 meters deep.

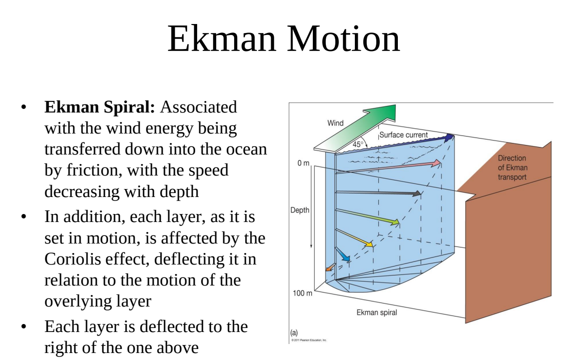
Once a current is set in motion, it will continue after the wind stops blowing because the water has momentum. Moreover, the friction between ocean layers is small, thus the momentum slowly dissipates. Additionally, by blowing/pushing the surface in a given direction, the wind causes the sea surface to become sloped.

Although these height changes are only a few cm's (or 10's of cm's) across the entire ocean, they are still enough to create pressure gradients. This means that flow is generated from high to low pressure, as the water tries to attempt to flatten out the surface. Effectively, the flow is going 'down the hill'

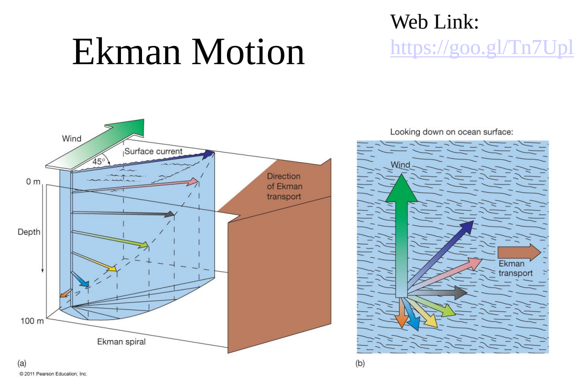
Factors that affect the Ekman Circulation

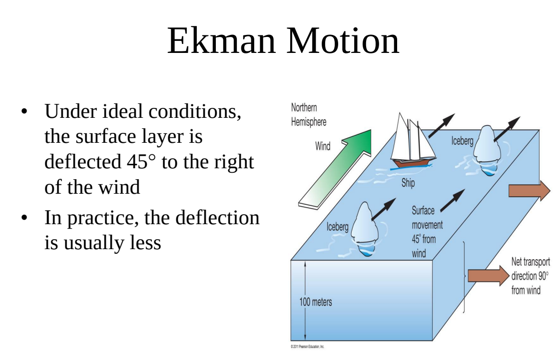
Once currents are set in motion, they are then affected by other factors: One being the Coriolis effect and the second being the coasts.

Ekman Motion



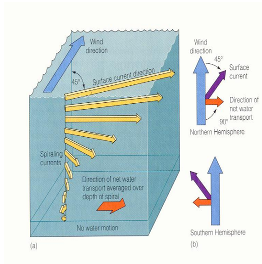
In the Northern Hemisphere, each layer is defected to the right from the wind blowing on the surface. The opposite is true in the Southern Hemisphere.



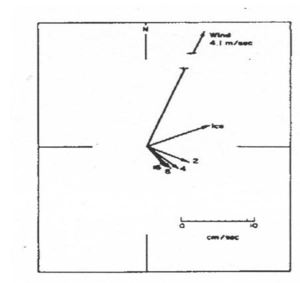


Ekman Motion

- Note that since the speed decreases with depth, so does the deflection
- The depth where the current is opposite to the wind is the Depth of Frictional Influence, where the speed is about 4% of that at the surface



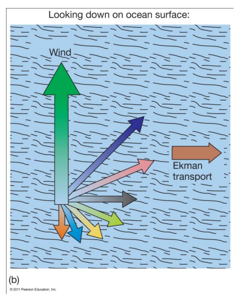
Observations of Ekman Layers



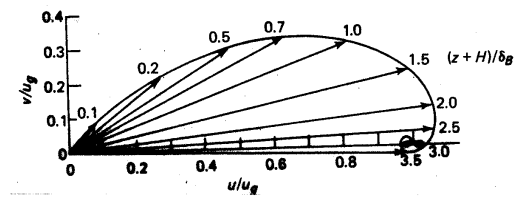
Ekman spiral under Arctic ice (from Hunkins, 1974)

Ekman Motion

- Averaging all these currents (at the different depths), we find that the total transport of the water is 90° (in theory) to the right of the wind
- This motion is called the **Ekman Transport**



The Ekman spiral at the seafloor (N. Hemisphere)



Stewart, 2003

Other conditions must hold for the Ekman motion associated with the Ekman spiral to be set up.

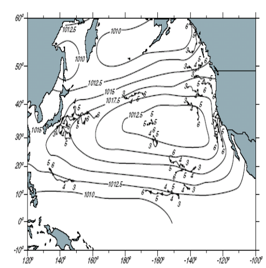
- The water column must be nearly uniform in density over the spiral
- The winds must blow at a constant speed for at least 1-2 days
- If the water is too shallow, friction with the bottom stop the establishment of the Ekman spiral.

Interactions with the bottom and friction set up another Ekman spiral at the bottom of the oceans.

Near the sea floor the direction of the Ekman spiral is opposite than at the top. i.e. Counter-clockwise vs clockwise on the surface.

Link to Winds above the Boundary Layer

- Winds at surface 45 degrees to left of those aloft
- Surface currents 45 degrees to the right of surface winds
  - Thus currents are nearly in the direction of the winds above the planetary boundary layer
  - Thus almost parallel to the atmospheric pressure gradient



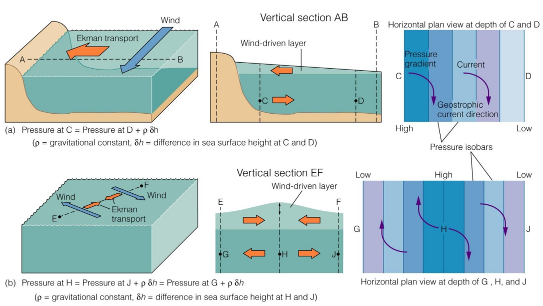
Stewart, 2003

2-8-2019: Geostrophic Currents

Geostrophic Currents

Ekman transport of surface water can lead to it "pilling up" or "being removed" from an area, this is known as convergence or divergence.
Even if the winds blew continuously, we do not have a continual pile-up or removal of water.
Other motions tend to try to restore the sea surface towards a 'flat' state.

Pressure gradient forces move water from high to low pressure regions. This high pressure is created by the elevated sea surface created by the Ekman transport. Unlike Ekman motion, pressure gradient transfer occurs at all depths where a pressure gradient may be found. This means that the mean flow in deeper layers may oppose Ekman transport at the surface. This will also produce vertical motion, such as upwelling or downwelling which we will discuss later in this book.



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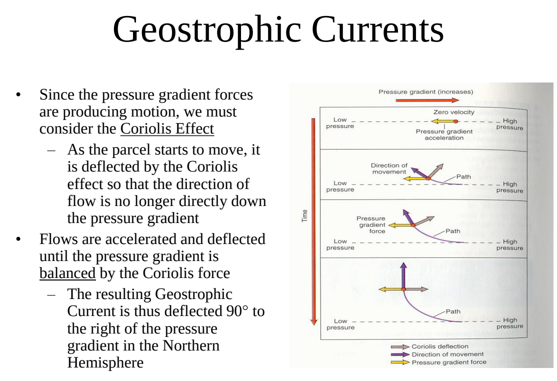
As you can see areas with more water creates a higher pressure which pushes the water underneath to areas of lower pressure. Therefore the flow below the wind driven layer is opposite to that of the wind driven layer.



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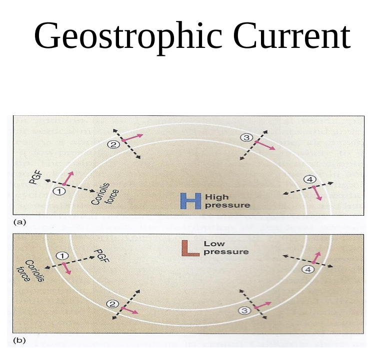
Geostrophic Current

A current that is produced by the balance between the pressure gradient force and the Coriolis force with the direction of flow is 90 degrees to the right of the pressure gradient in the Northern Hemisphere. In the Southern Hemisphere the direction is opposite.

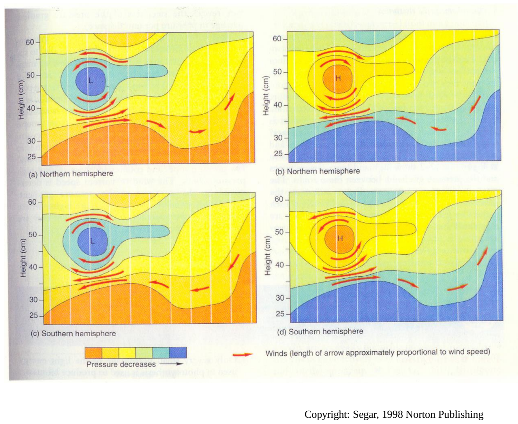
Note

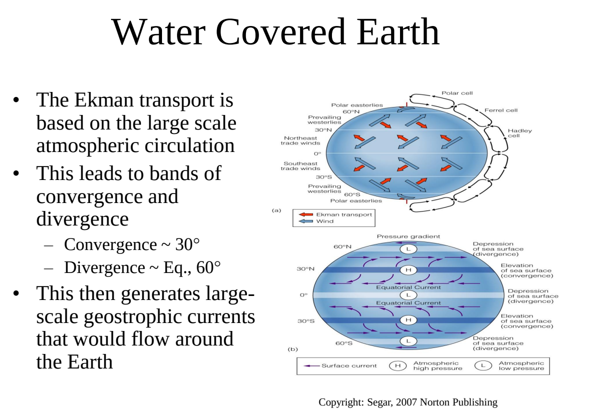
In reality flow are never perfectly geostropic as friction and other effects come into play.



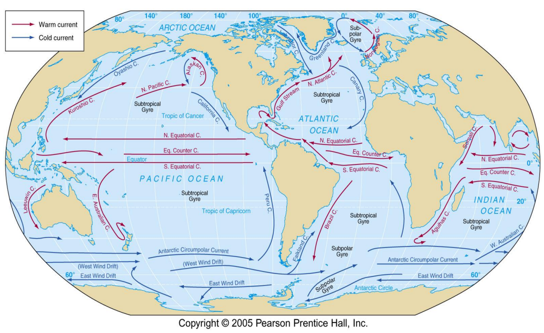
Aguado and Burt, 2013

As the flow moves away from the areas of high pressure or towards areas of low pressure it is deflected to the right in the northern hemisphere.





This is what would happen if the entire earth is covered in water.



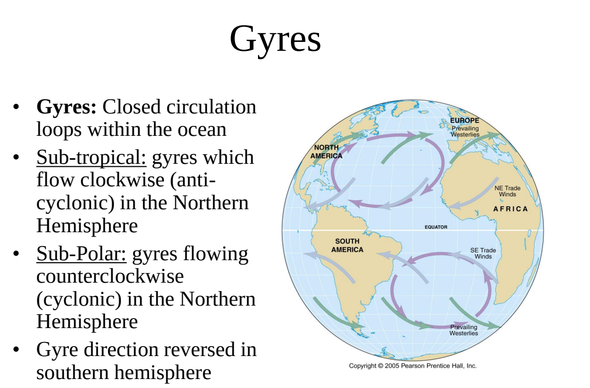
Gyres

Are circulation patterns that are modified due to the presence of land. Only in the south can a current flow all the way around the world (Antarctic Circumpolar Current).

At most latitudes, we get zonal currents within each ocean. The currents are deflected north and south by land to form western and eastern boundary currents.

Open ocean Surface Currents

Surface currents initiated by Ekman transport, which is then maintained as Geostrophic Currents Generally reach a few hundred meters deep, although some can reach 2000 meters.
One typical ocean unit of volume transport is the **Sverdrup (Sv)** or $1,000,000\frac{m^3}{s}$



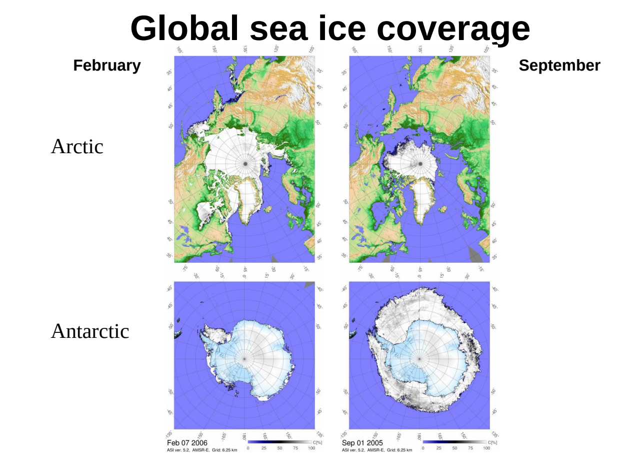
A way to remember the direction of sub tropical and sub polar gyre direction is that these two types of gyres spin in opposite direction. So all you need is to know one and derive the other. In the northern hemisphere is spins clockwise therefore its polar siblings spins counter-clockwise.

Part VI

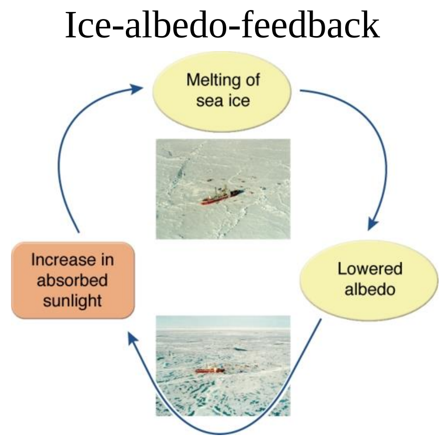
Week 6

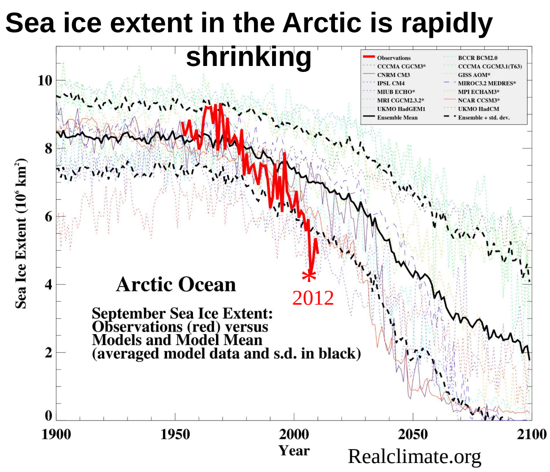
2-11-2019: Sea Ice and Icebergs

Sea Ice

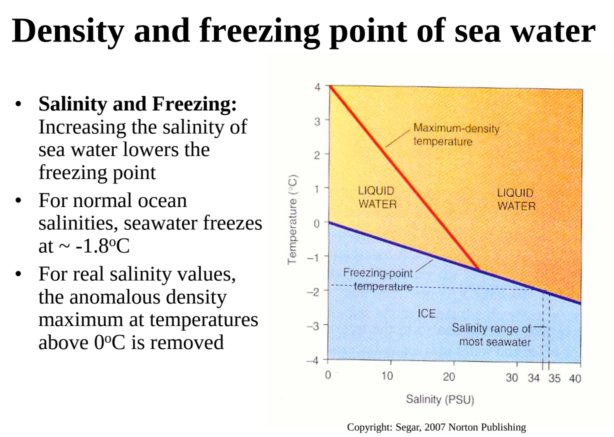


More ice in the winter, less in the summer.

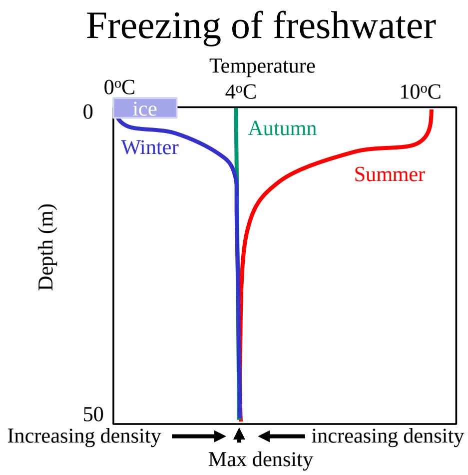




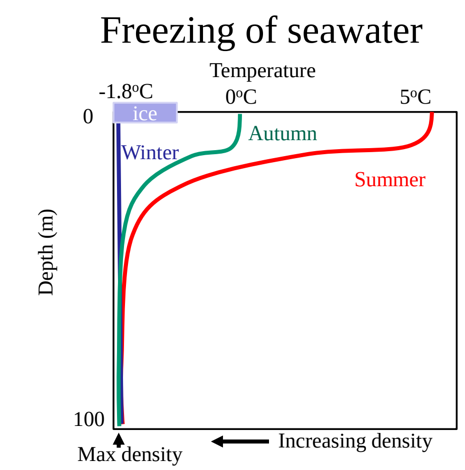
Density and Freezing Point



Normal sea water freezes at -1.8°C



Water below the ice is warmer than the ice itself. When water cools towards zero degrees it floats to the top as its less dense and freezes growing downward.

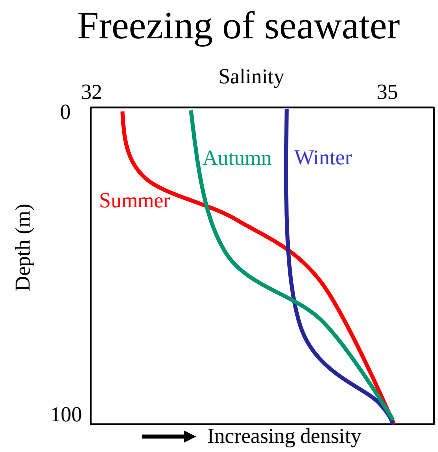


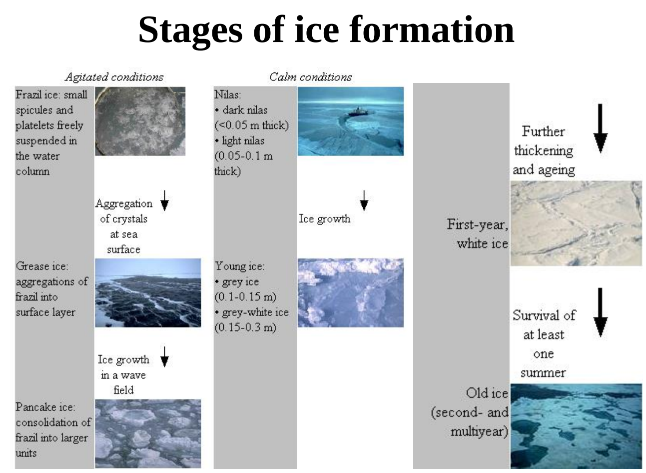
Seawater needs to lose a lot more heat before they can freeze. Salinity affect the freezing point of water a lot.

Brine rejection

- When sea water freezes, it squeezes salt out into the water underneath. This process is called <u>Brine Rejection</u>.
  - This leads to a higher salinity and thus density for the water underneath the newly formed ice, leading to this water sinking and mixing with the water masses below it
  - Also, as the salinity increases, the freezing point is lowered, making it even harder to freeze this water below the ice

Freezing salt water will cause some of the salt being rejected increasing the salinity below the ice.





Different sea conditions affect how the ice is formed.

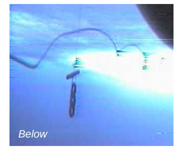
Different types of ice

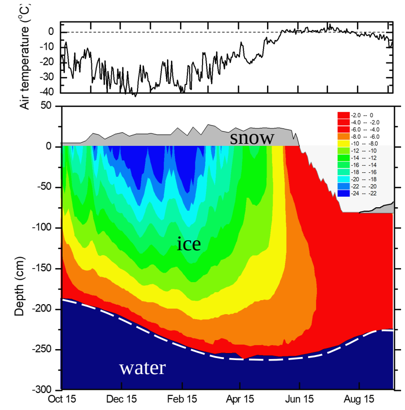
- **Grease Ice**:
  - A later stage of freezing than frazil ice when the crystals have coagulated to form a soupy layer on the surface.
  - Grease ice reflects little light, giving the surface a matt appearance.
  - Grease ice behaves in a viscous fluid-like manner, and does not form distinct ice floes

- **Pancake Ice**:
  - Predominantly circular pieces of ice from 30 cm - 3 m in diameter, and up to 10 cm in thickness with raised rims due to the pieces striking against one another.

The mass balance of sea ice

- Simple concept
  - snow accumulation
  - snow melt
  - ice growth
  - surface melt
  - bottom melt





Mass balance: 1 way to grow, 4 to melt

Grow on bottom: Melt on top, bottom, internal, lateral

Sea-Ice Growth

Sea-Ice Growth

Once a sheet of ice has formed, it can **increase in thickness by the freezing of water on its lower surface**.

- This means that heat must be removed from the water
- When the air above the ice is colder than the water below the ice, heat is removed by conduction through the ice from the water to the air above

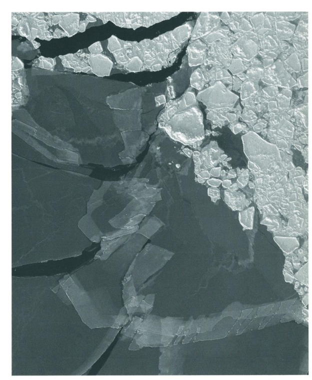
In general ice can be around 1.5 to 2 meters over the course of the winter.

The rate at which heat flows from the water is proportional to the temperature difference between the air and water. It is inversely proportional to the thickness of the ice layer and the snow cover on top of the ice. Snow cover acts as a blanket, slowing down the flow of heat from the water.

Sea-Ice Age

Young Ice

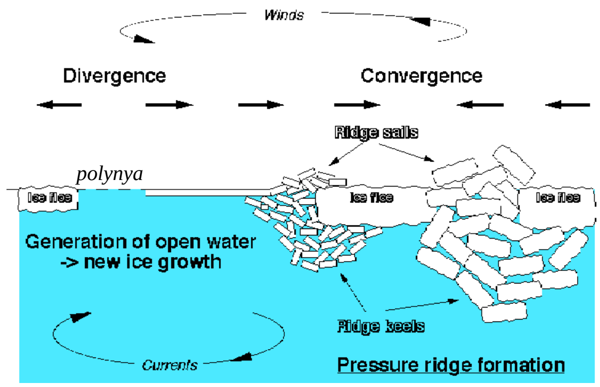
- Forms under quiet conditions
- Dark nilas: < 5 cm thick
- Light nilas: 5-10 cm thick
- Grey ice: 10-15 cm thick
- Prominent “finger rafting“



First Year Ice

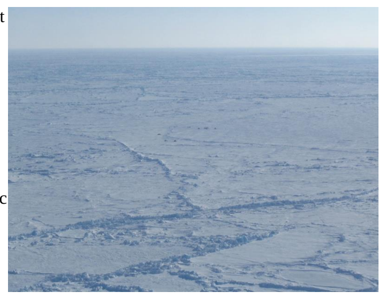
- > 30 cm thick
- Can be up to 2.0 m thick (and occasionally thicker)
- Associated with not more than 1 winter's growth
- Gaps between ice floes called *fractures* or *leads*

Processes changing the ice thickness distribution



Multi-Year Ice

- Old ice that has survived at least 1 summer's melt
- The older the ice gets, the smaller the salt concentration within it
- As thicker and less dense, stands higher out of the ocean
- Most common in the Arctic and rarer in the Antarctic
- Can reach 6-7+ m thick

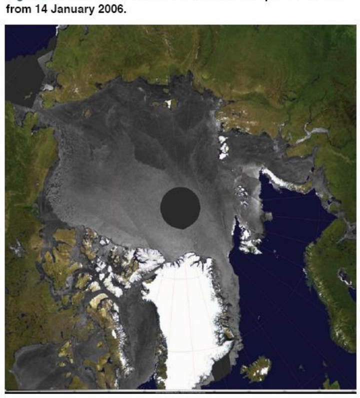


The older the ice, its salinity falls as the salt falls out of the ice.

Multi-Year Ice

- Due to its lower salinity, has higher radar backscatter and lower microwave emissivity
- Can be well distinguished from first-year ice by satellites
- Satellite data show a strong reduction of MYI area, representative of overall thinning

Fig. 4.2. Envisat ASAR and visible (MERIS) composite mosaic from 14 January 2006.

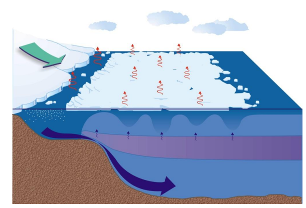


(Courtesy of Microsoft Vexcel UK, ESA PolarView Consortium)

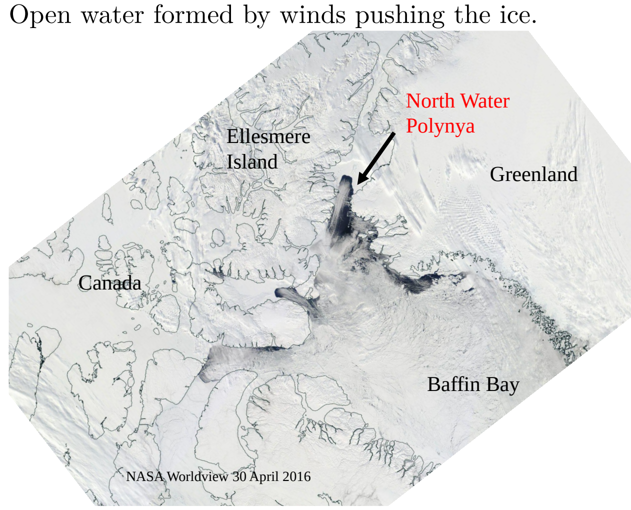
Polynyas

Polynyas

- A polynya forms when winds push the ice away from the coast or fast ice, resulting in the recurrent presence of open water even during winter.
- Strong, recurrent ice production with formation of "deep" water
- Very important for marine life in polar regions



Open water formed by winds pushing the ice.

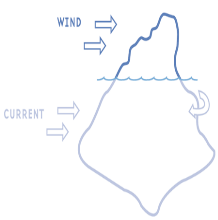


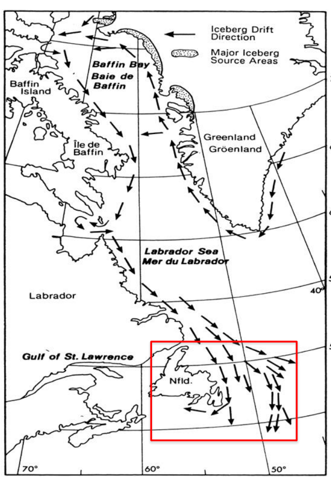
Icebergs

- An **Iceberg** is a massive piece of ice of greatly varying shape, which has broken away from a glacier or ice shelf and which may be afloat or aground
- Since they come from glacial ice, i.e. snow, they are **fresh**
- About 90% of all icebergs encountered in Canadian waters are calved from the glaciers of Western Greenland
  - 10,000 to 40,000 annually

Iceberg drift

- Large icebergs are controlled mainly by water currents
  - Winds become more important to icebergs having high sail to draft ratio or high ratio between the above water to below water portion
  - The drift of an iceberg from its place of origin on the west coast of Greenland to the Grand Banks of Newfoundland takes an average of 2 to 3 years

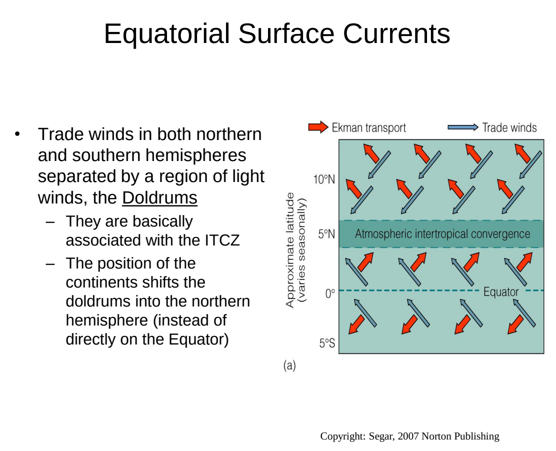


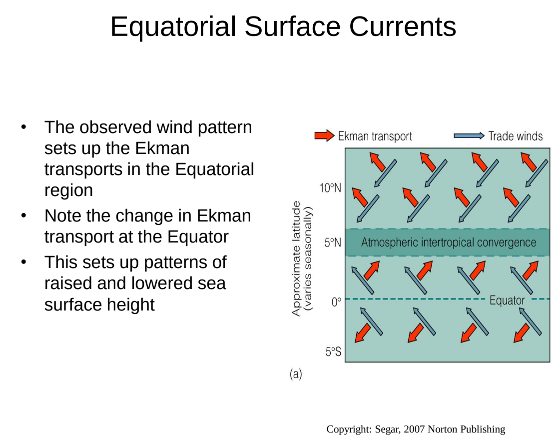


www.ec.g

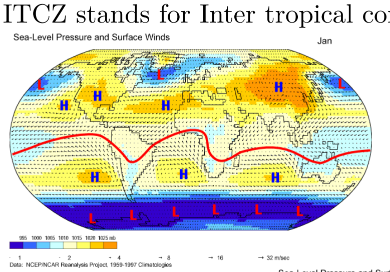
2-13-2019: Pacific and Indian Ocean Circulation

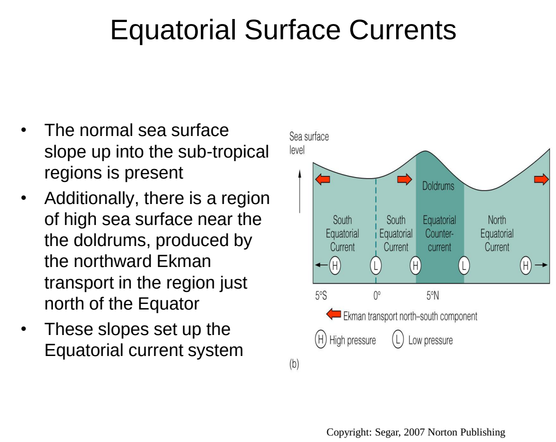
Equatorial Surface Currents

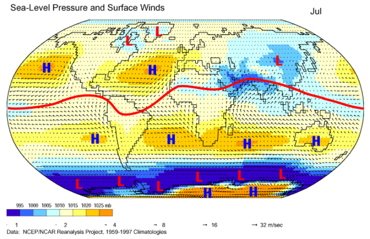


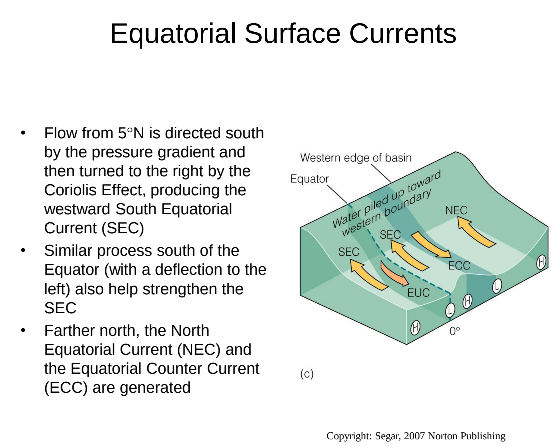


ITCZ stands for Inter tropical convergence zone

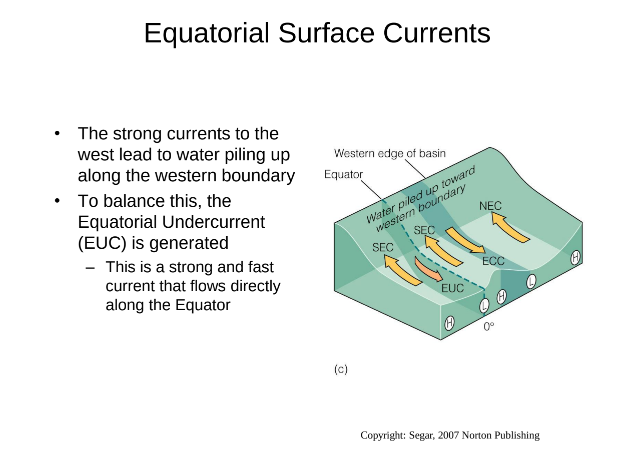


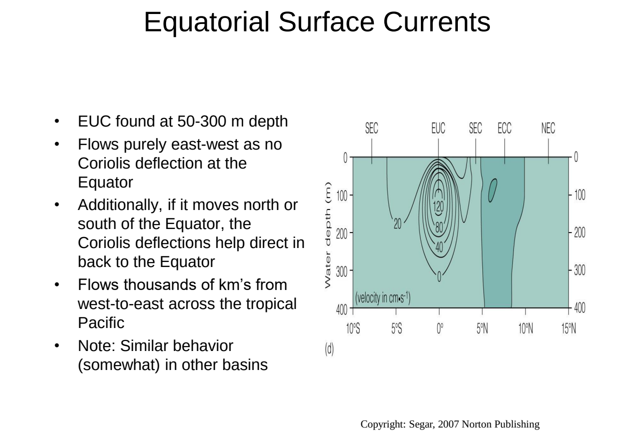


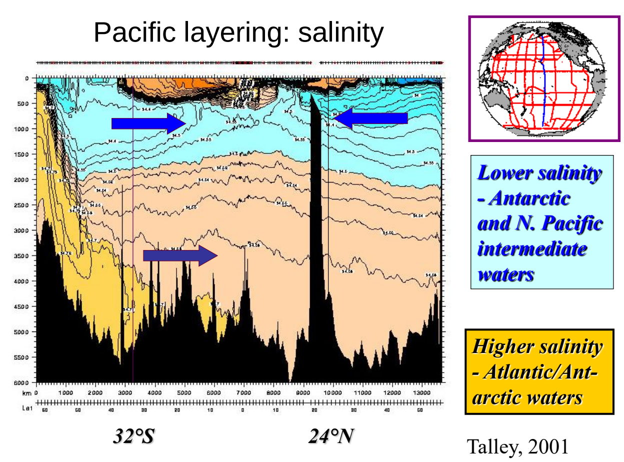




The top-left figure is the ITCZ in January while the other is the ITCZ in July

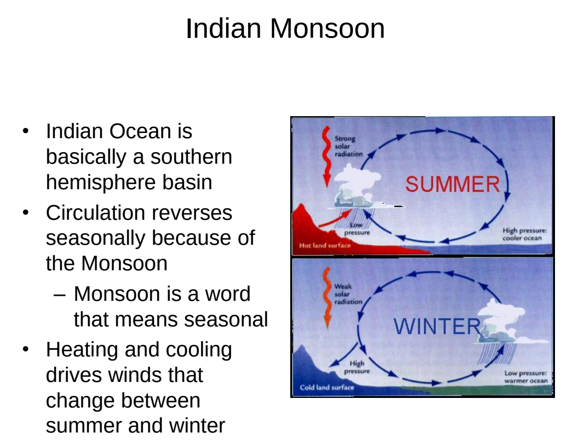






High salinity at the Atlantic and antarctic waters
Low salinity at the N pacific intermediate, and Antarctic

Indian Monsoon



Summer

Strong heating warms the land mass faster than the ocean. Which creates a low atmospheric pressure, rising motion precipitation, and onshore winds.

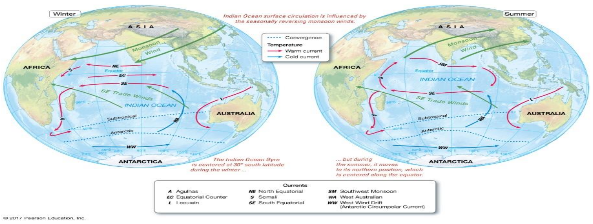
Winter

Air over land rapidly cools, creating higher pressure. This drives offshore flow from land to ocean and have dry conditions over land.

Ocean Response

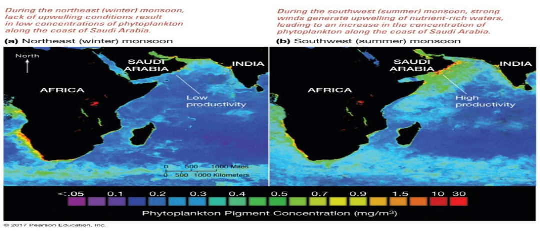
Ocean Response

- Reversing seasonal winds cause major currents to switch direction
  - Only place in the world this happens
  - Changed winds change directions of Ekman transport and resulting geostrophic currents



Ocean Response

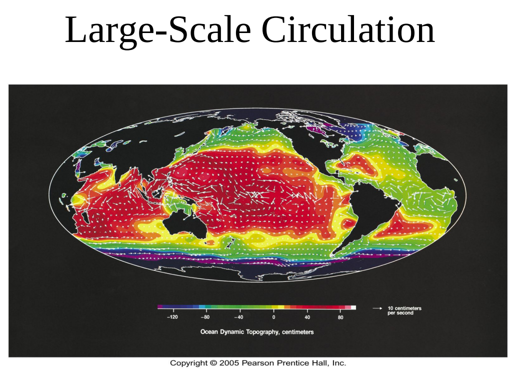
- Reversing seasonal winds and currents have major biogeochemical implications
  - Locations of higher ocean productivity switch between seasons

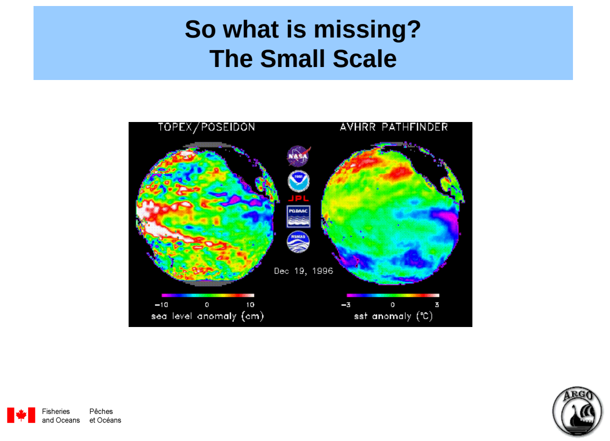


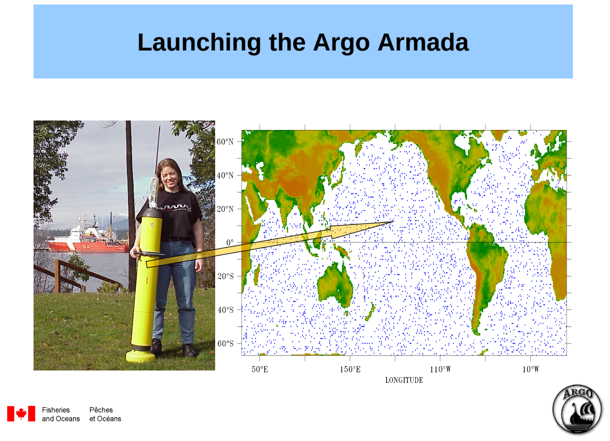
Higher productivity near the shore in the summer as the incoming summer heat blow wind towards the shore, lower productivity in the winter as the wind is blowing away from the shore.

2-15-2019: ARGO

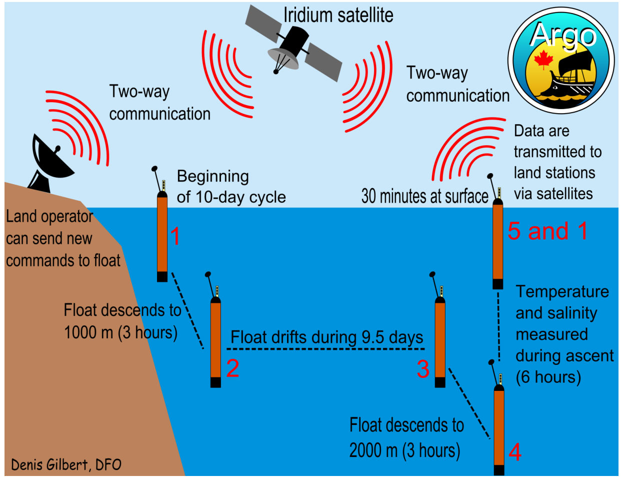
A case study into a large-scale circulation program.

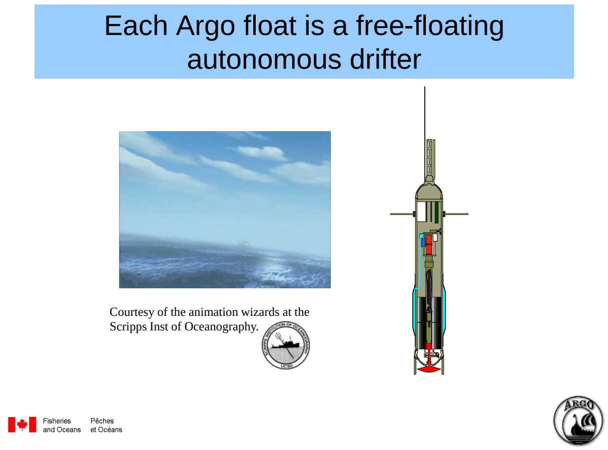


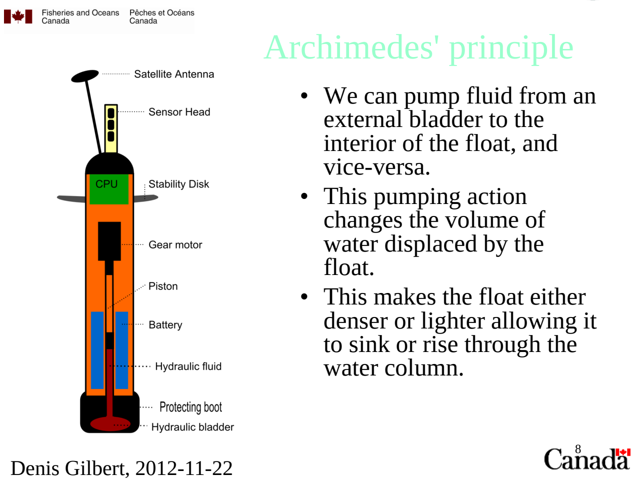




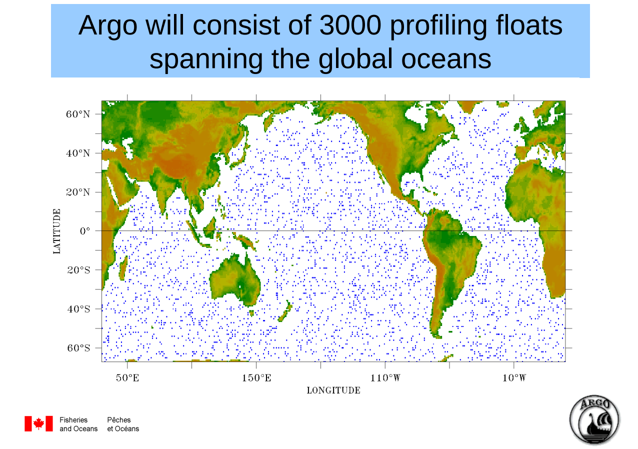
How it works

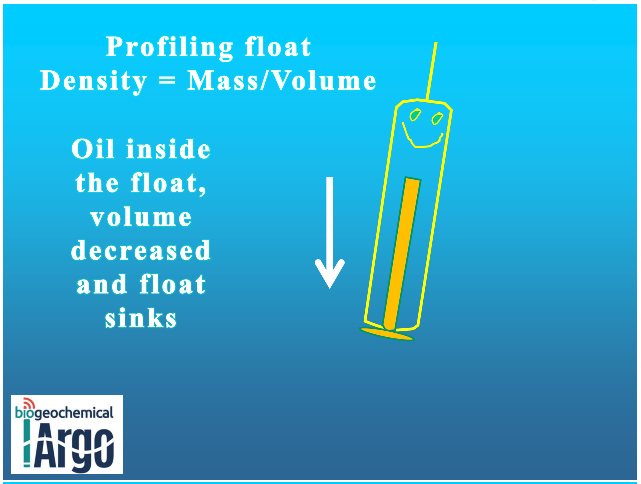


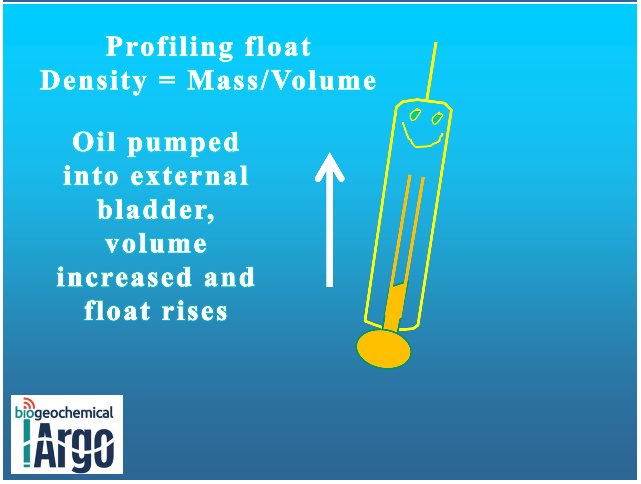


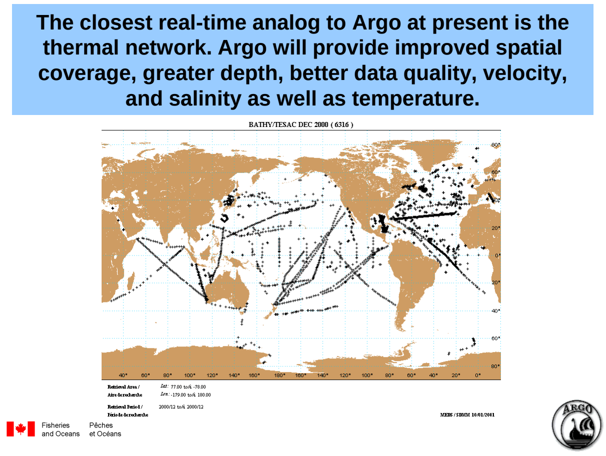


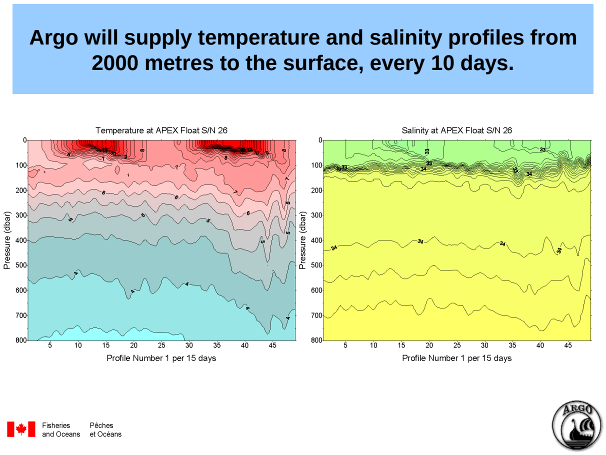
Data Collection

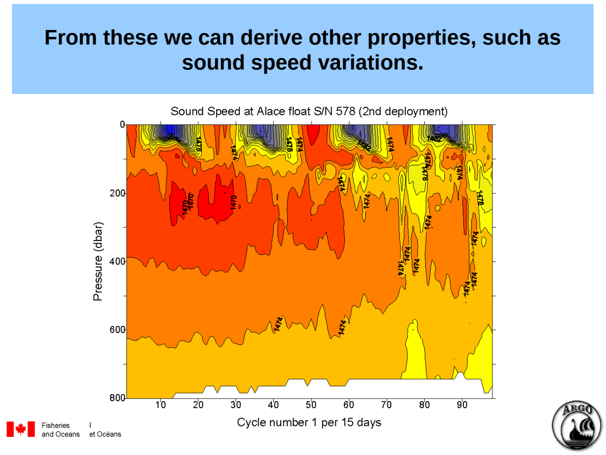




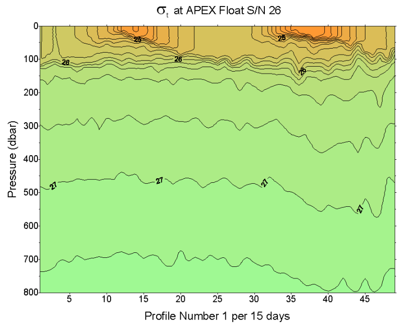






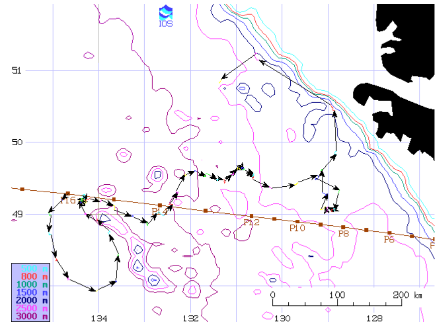


…and density variations, which leads us to dynamics.



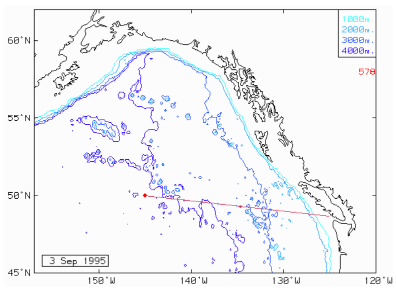
Fisheries and Oceans Pêches et Océans

Velocity information can be separated into deep and shallow drifts.



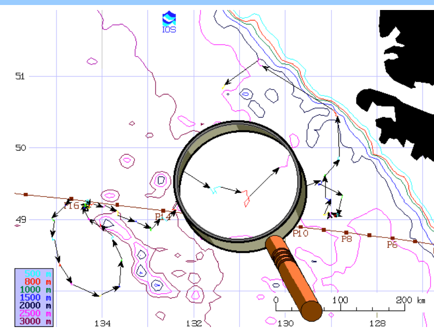
Fisheries and Oceans Pêches et Océans

Argo will supply drift information, hence velocity.



Fisheries and Oceans Pêches et Océans

Velocity information can be separated into deep and shallow drifts.



Fisheries and Oceans Pêches et Océans

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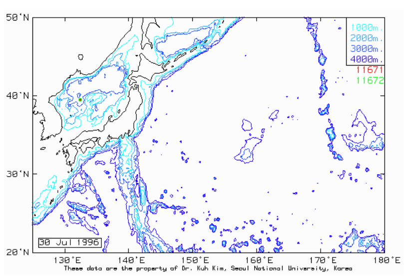


Fisheries and Oceans Pêches et Océans

Argo will supply the following properties, globally, in real-time, and without protection.

- Deep velocity field (i.e. a level of known motion)
- Drift velocities in the surface Ekman layer.
- Temperature and salinity from the deep level to the surface, hence, dynamic height fluctuations.
- Hence sufficient to determine the time-varying circulation of the global ocean, minus eddies.

Fisheries and Oceans Pêches et Océans

Application of Argo

Argo will have many applications.

The primary motivations for Argo are:

- **Understanding the present climate and the ocean's role in the coupled climate system (storage and transport of heat, mass and salt).**
- **Improved seasonal-to-interannual climate prediction. Global profiles of temperature and salinity will increase the accuracy and realism of data assimilation modeling.**
- **Interpreting global sea level observations from Jason altimetric data.**

Fisheries and Oceans Pêches et Océans

Fisheries and Oceans Canada Pêches et Océans Canada

Golden fleece story from Greek mythology

JASON + ARGO

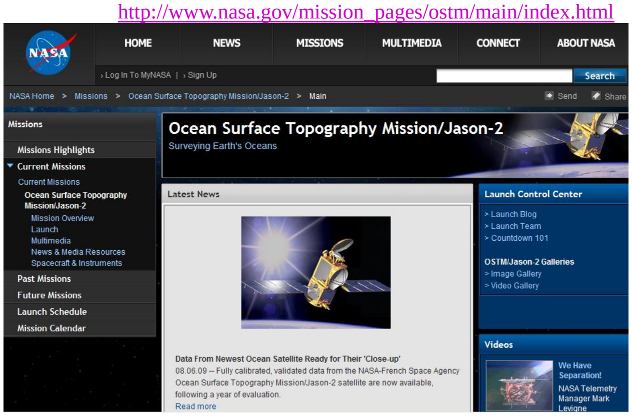
Surface currents estimated from sea surface slope

Vertical shear of currents estimated from vertical profiles of temperature, salinity and density

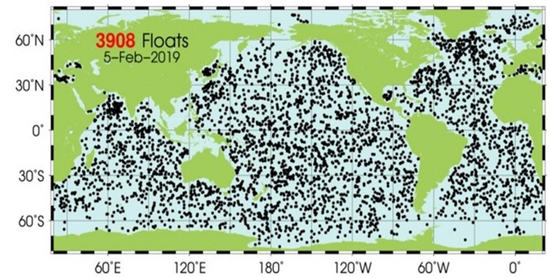
Denis Gilbert, IML, 2012-11-22 Canada

Jason-2 satellite altimeter

http://www.nasa.gov/mission_pages/ostm/main/index.html

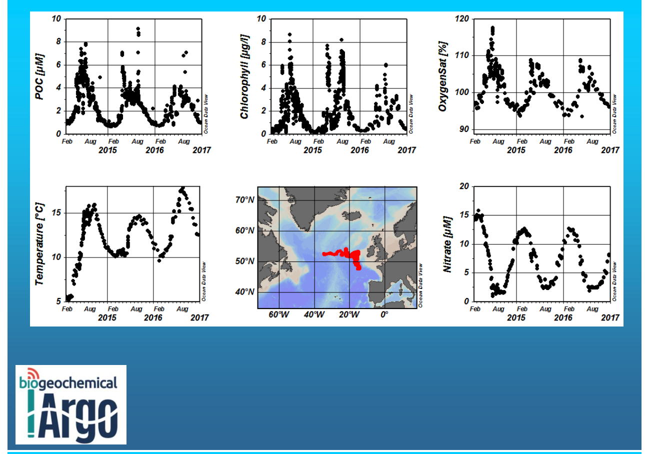


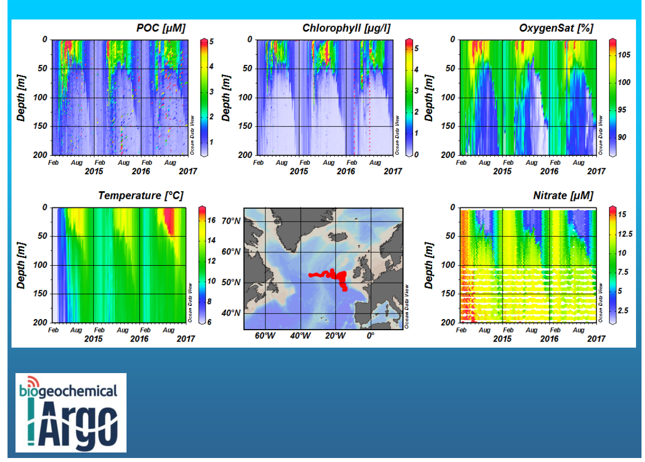
International Commitments for Argo Floats



3908 Active Floats – February 5, 2019

Fisheries and Oceans Pêches et Océans





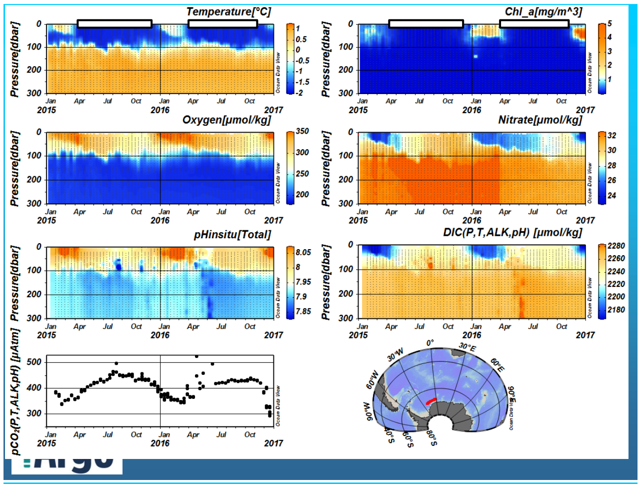


Table 2. Biogeochemical-Argo system costs (USD)*		
Item	Capital cost	Total cost (capital + data transmission + data processing and QC).
Core Argo T/S float	$22,000	$33,000
Add O_2 to Argo	$7,000	$10,200
Add nitrate	$24,000	$31,000
Add biooptics (Chl, BB, Ed)	$17,000	$20,200
Add pH	$10,000	$13,200
Cost per float	$80,000	$107,600
	Floats/year	Program Cost/year
US share (1/2)	125	$13,450,000
Complete array	250	$26,900,000

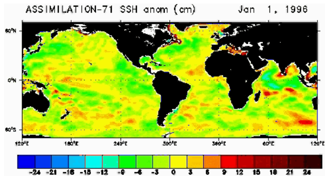
* Capital costs of components are estimates of current market price. Total cost for a core Argo float was estimated as US Argo budget of $10,000,000/year/300 floats/year. Operating costs for additional sensors were estimated from Gruber et al. (2007) for O_2, and a similar cost was applied to biooptics and pH. Nitrate is more complex and its operating cost was doubled, relative to oxygen.

biogeochemical Argo

Though deployed along lines floats will quickly disperse to populate an ocean basin
(these are non-profiling floats in the Indian Ocean)

Fisheries and Oceans Pêches et Océans

So where is all of this going?

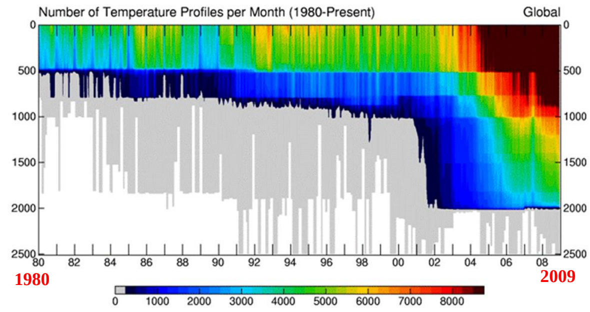


GODAE
(The Global Ocean Data Assimilation Experiment)

Images courtesy of Dr. Detleff Stammer, Scripps Inst. of Oceanography

Fisheries and Oceans Pêches et Océans

Global number of ocean temperature profiles



Where does the improved sampling come from? Argo

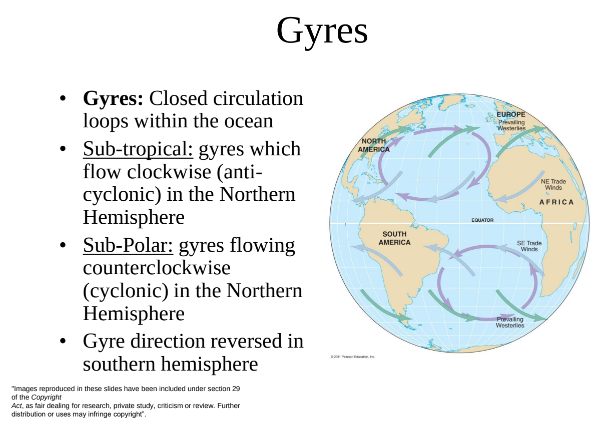
31

Part VII

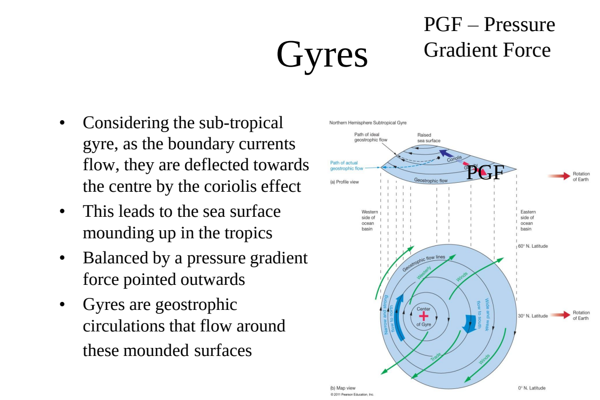
Week 7

2-25-2019: Western Boundary Currents

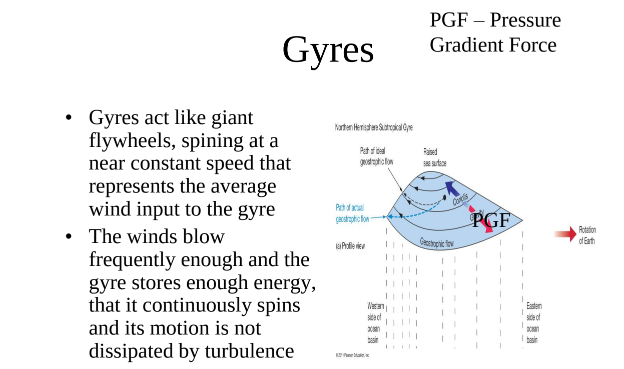
Gyres again



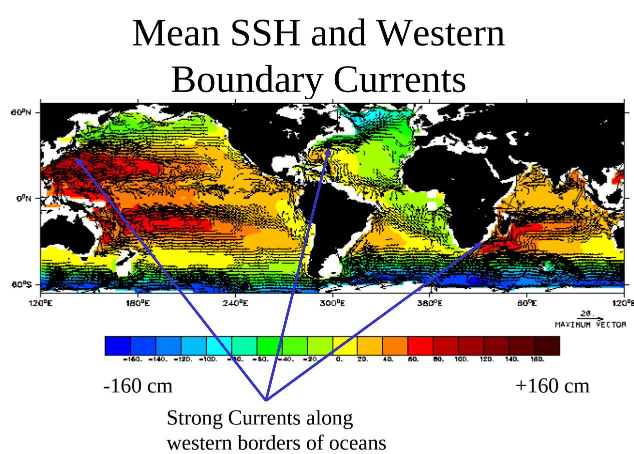
The black arrows shows the direction of circulation

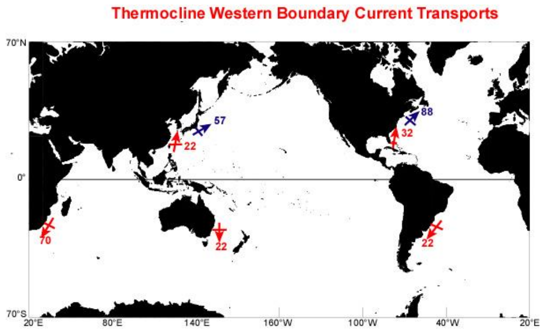


The water is pushed into the gyre as the Coriolis effect push the circular current towards the center. They are also self maintaining.



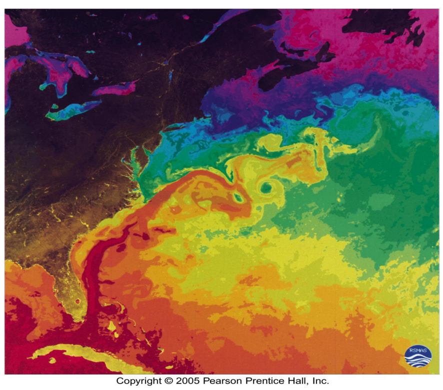
The increase amount of water at the center of the gyre produce a pressure gradient force away from the gyre.
Sub-polar gyres flows in opposite direction to sub-Tropical gyres. Therefore, the Coriolis effect causes the currents to be deflected outwards from the gyre centre. This leads to the sea surface being depressed in the center, thus the pressure gradient points inwards. The same processes also produce western boundary currents for these gyres.





Strongest Currents along western boundaries: Are measured in a unit called Sv – 10^6 m^3 s^{-1}

Bryden, 2001

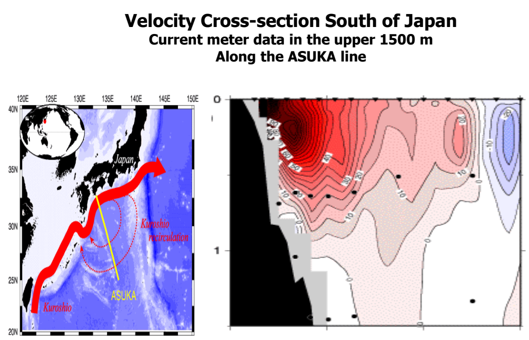


Gulf Stream

Heat Transport

~1.3 PW

AVHRR Snapshot of SST



Imawaki, 2001

	Western Boundary Currents	Eastern Boundary Currents
Examples	Gulf Stream, Kuroshio, Brazil Current	California, Canary, Peru Currents
Width	Narrow (<100 km)	Broad (~1000 km)
Depth	Deep (to 2 km)	Shallow (< 500 m)
Speed	Fast (>100 km/day)	Slow (< 50 km/day)
Volume Transport	Large (50 Sv)	Small (10-15 Sv)
Boundaries with Coastal Currents	Sharply Defined	Diffuse
Upwelling	Almost none	Frequent
Nutrients	Depleted	Enhanced
Fishery	Usually Poor	Usually Good
Water Temperature	Warm	Cool

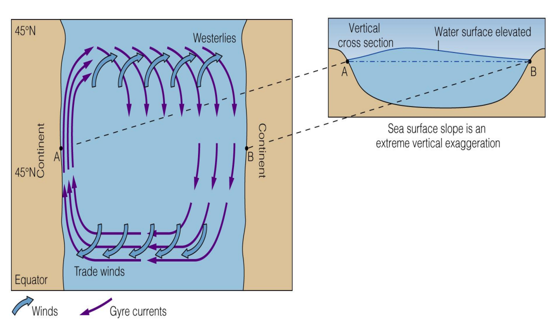
Web Link: https://goo.gl/P2G56w

Western Intensification of Sub-Tropical Gyres

Variation of the Coriolis parameter with latitude

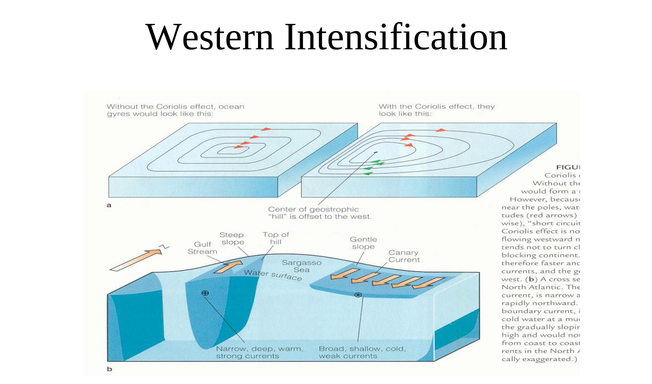
I.e. the increase in Coriolis parameter as one moves poleward. The water moving eastward is deflected more than water moving westward. Thus, in the westerly zone, water is transported towards the gyre centre over the entire ocean width. Meanwhile, in the easterly wind zone, there is little deflection and water can flow across to pile up on the west side of the ocean. This causes the gyre centre to be offset to the wind.

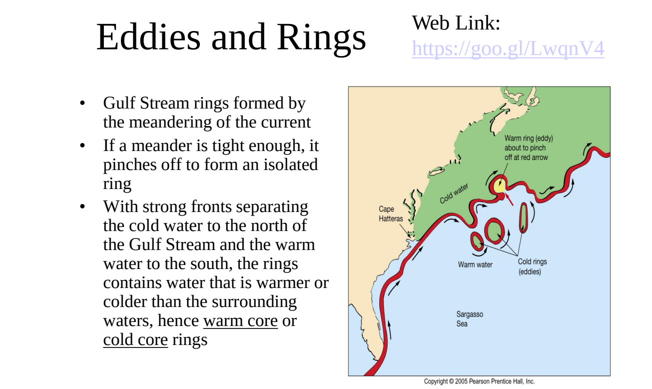
Western Intensification

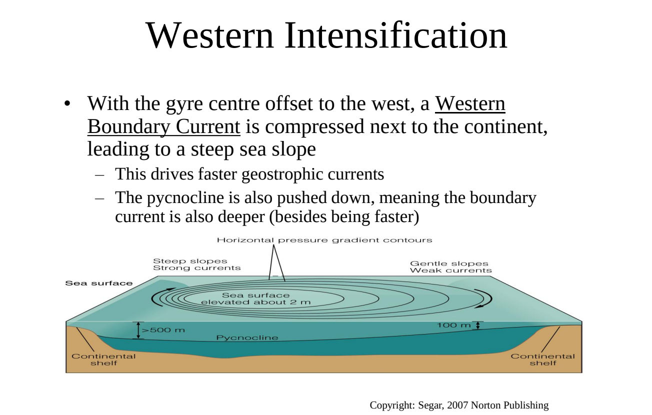


Copyright: Segar, 2007 Norton Publishing

The Western gyres are faster, narrower, and taller. While the Eastern gyres are slower, wider, and not as tall.
The Coriolis effect push the gyre to the left.







Warm vs Cold core rings

Warm core rings spin clockwise or anti-cyclonically while Cold core rings spin counter-clockwise or cyclonically.

Both can reach sizes of 100-300 km in diameter and can reach from the surface to the seafloor.

The rotating currents at their rims can reach speeds of approx. 90 cm/s.

Cold core rings last longer because they are not limited in area (such as for warm core rings, which are limited to move between the Gulf Stream and land).

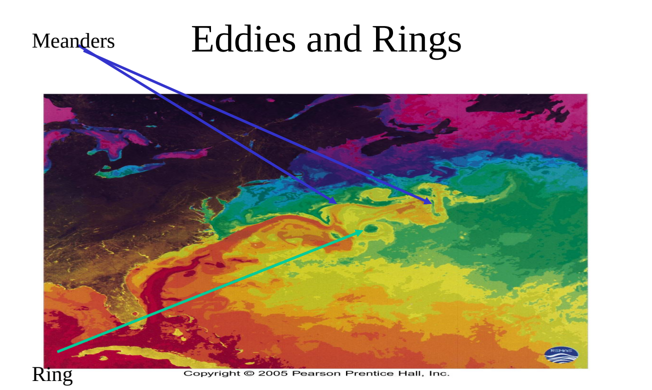
Eddies are important for transporting heat, nutrients and marine organisms around.

Eddies and Rings

Local variations of meandering fronts and swirling motions are called eddies. Since ocean eddies are much smaller than in the atmosphere, they are more numerous, move slower but last longer. They can detected by satellite.

Mesoscale eddies

These eddies exist throughout the oceans, typically 25-200 km across with a rotation current of 10cm/s at the rim.



2-27-2019 and 3-1-2019: Tides

Tides are long period waves, continuously raising and lowering the sea surface. High tides are associated with the wave crest while low tides are associated with wave trough.
The vertical motion can be as much as 10-15 meters, twice a day in some areas.

Tides produce strong currents of up to 5 m/s in coastal waters. They also generate internal waves over seamounts and other topography. Tidal currents play a role in suspending bottom sediments. The elastic Earth's crust bends under the influence of the tidal potential (up to ± 10cm)

Currents are also associated with the tidal processes. Incoming Currents associated with rising tides are called flood currents. While outgoing currents associated with decreasing tides are called ebb currents.

Tides are pretty powerful they slowly change the earth's rotation and length of day, influence the orbits of satellites, and keeps the same face of the moon always facing the earth.

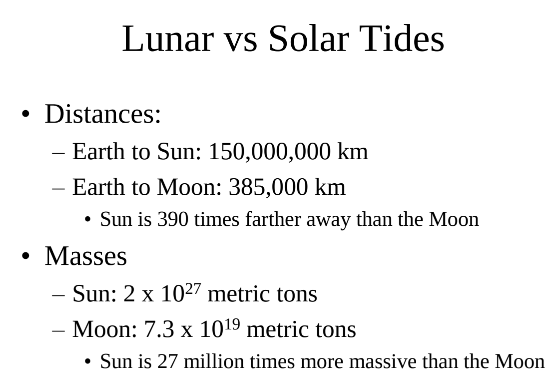
What Causes Tides

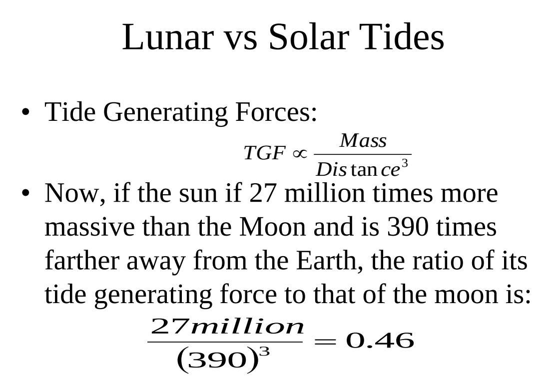
Gravity is the main force that causes tides, specifically two orbiting bodies. The Moon and the Sun.

The strength of the gravitational pull is proportional to their masses and inversely proportional to the square of the distance between the two bodies.

The even though the moon weighs less than the sun its close proximity to earth brings a larger influence to the tides than the sun.

Lunar vs Solar Tides

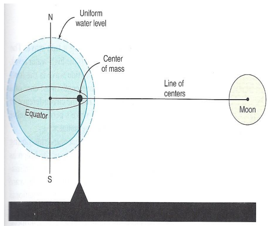




Earth-Moon System

Earth-Moon System

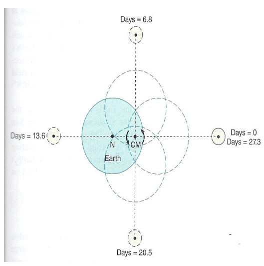
- Simple Assumptions (to start with):
  - Earth is smooth and covered by a single ocean of uniform depth
  - Moon is directly above the Earth's equator
  - The moon is always above the same point on the Earth's surface
- Can then assume this system balances on its centre of mass
  - Centre of mass 1710 km below Earth's surface



Sverdrup and Kudela, 2013

Earth-Moon System

- Earth-Moon system rotates about it centre of mass
  - One complete revolution approximately every month (27.3 days)
- Average distance between Earth and Moon remains constant because of a balance of forces
- Gravity keeps the Earth and Moon in orbital relation to each other
  - But would also tend to move them closer and closer without something to counterbalance

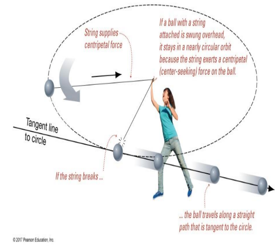


Sverdrup and Kudela, 2013

Balance of Forces

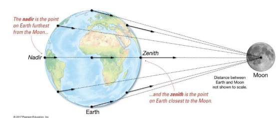
Balance of Forces

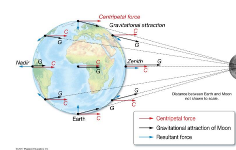
- Inertia (in the form of the Centrifugal Force) also plays a major role in tide generation
  - Acts as the force to counterbalance gravity
  - Can be considered as the tendency of moving objects to continue moving in a straight line
  - Without gravity the Earth and Moon would fly apart into deep space
- Gravity and the Centrifugal Force lead to the creation of tidal bulges



Balance of Forces

- Top Panel
  - Relative gravitational forces on Earth due to the moon
    - Is a function of distance and is stronger where moon is 'closer'
- Bottom Panel
  - Centripetal forces required to keep identical sized fluid elements in identical sized orbits due to rotation of Earth-Moon system
    - Same for every point on the Earth

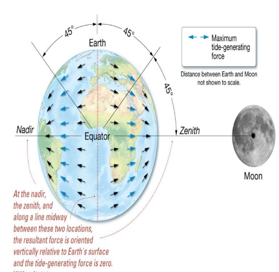




Balance of Forces

Web Link: http://goo.gl/eBCMYZ

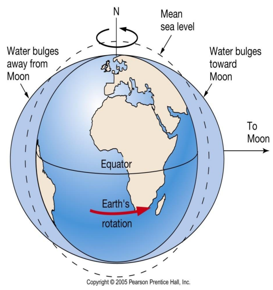
- Thus there is an overall force balance only for the Earth-Moon system as a whole
  - Gravitational forces are an 'Excess' closer to the moon
  - Gravitational forces weaker on the 'far' side and thus there is an 'excess' of the centrifugal force



Gravity, Inertia and Tidal Bulges

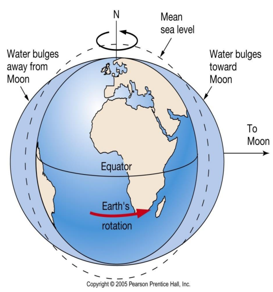
Gravity, Inertia and Tidal Bulges

- Gravitation attraction strongest on side facing the moon
  - Causes water on near side of earth to be pulled towards the moon
  - Inertial forces try to keep the water in place, but the gravitational force is larger and a bulge appears facing the moon



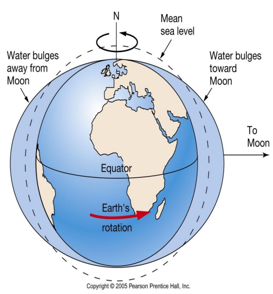
Gravity, Inertia and Tidal Bulges

- On the opposite side of the earth, gravitational attraction is weaker
  - Hence the inertial (Centrigufal) forces exceed the gravitational force
  - Thus the water moves away from the moon, forming another bulge



Gravity, Inertia and Tidal Bulges

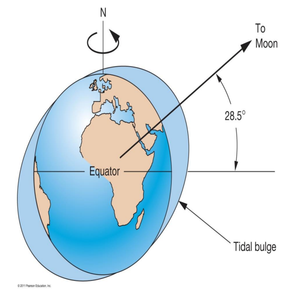
- Thus we get 2 bulges, under and opposite to the moon
- As water is a fluid, the bulges stay aligned with the moon as it rotates
- Interaction with the sun modifies the tidal bulges



Declination Effect

Declination Effects

- The Earth's tidal bulges track the positions of the moon
- As the moon revolves around the Earth, its angle increases and decreases in relation to the equator
  - This is called the lunar declination
  - The two tidal bulges track the changes in lunar declination, also increasing or decreasing their angles to the equator



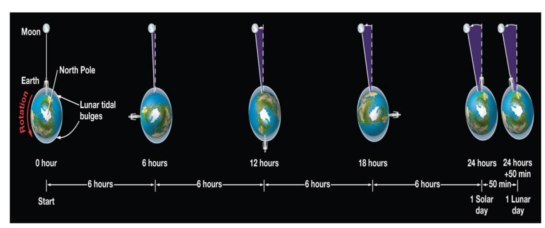
The Earth, Moon, + Sun System

Frequency of Tides

- **Many locations experience two high tides and two low tides each solar day**
  - **Solar day: Time for a specific point on the earth to rotate from an exact point under the sun back to that same exact point (24 hours)**
  - **Lunar Day: Time it takes for a specific site on the Earth to rotate from an exact point under the moon to the same point under the moon**
  - **24 hours and 50 minutes long**
    - **Extra length is because moon revolves around the earth in the same direction as the earth rotates around its axis, needing the extra 50 minutes to "catch up"**
  - **Earth rotates through 2 bulges each lunar day, thus giving two high tides**

Lunar Day

Web Link: https://goo.gl/bbYGx0



Spring and Neap Tides

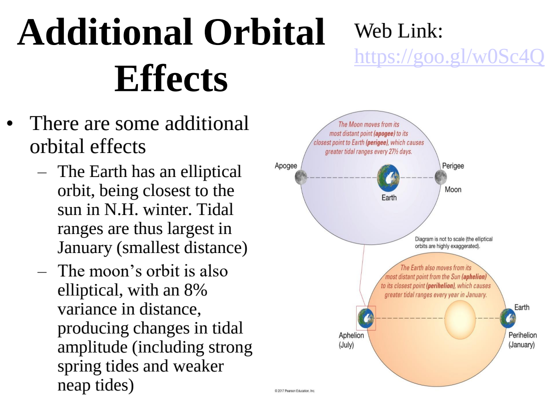
Although smaller than the moon, the sun does exert a significant tidal force. Normally expressed as a variation of the lunar pattern.

> **Spring tide**
> When the sun and moon are aligned, the solar bulge has an additive effect on the lunar bulge, creating extra high and very low tides

> **Neap tides**
> When the sun and moon are at right angles to each other, their bulges partially cancel out, producing more moderate tides

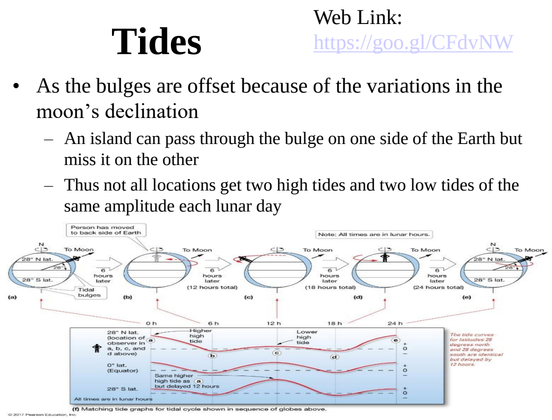
Spring and Neap tides occur alternatively around every 7 days

Additional Orbital Effects

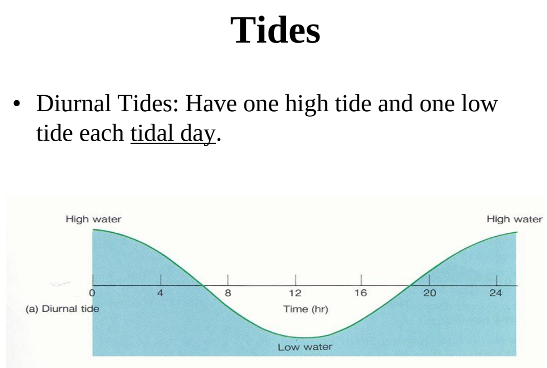


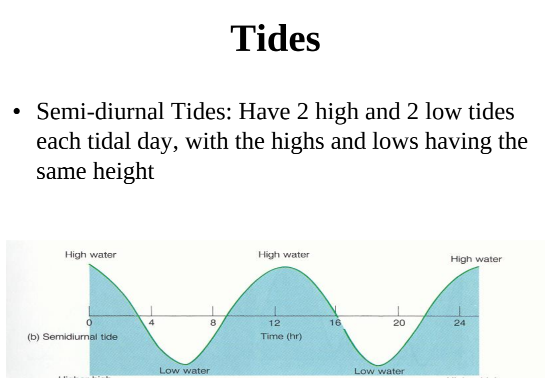
The earth and the moon both have an elliptical orbit. Thus winter the in northern hemisphere have the largest tidal range as the earth is closest to the sun in January.
Same with the moon but it happens every 27 and a half days.

Tides



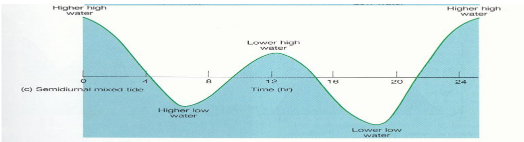
Because the earth is at an angle there are some regions that will get bulges on one side of the earth but miss it on the other.
Thus not all locations get two high tides and two low tides of the same amplitude each lunar day. This is why we have mixed tides.



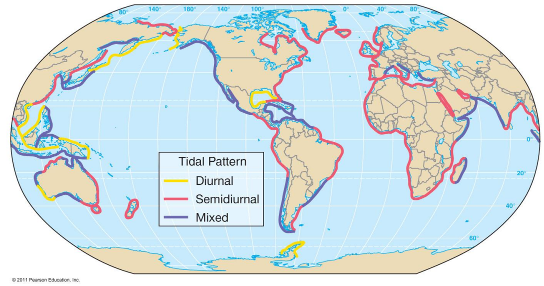


Tides

- Mixed Tides: Have 2 high tides and 2 low tides each day
  - But the heights of the 2 high tides and/or the 2 low tides are different

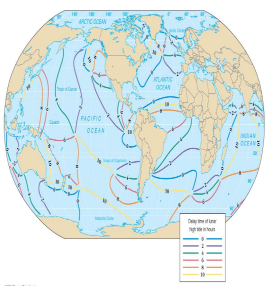


Distribution of Tide Types



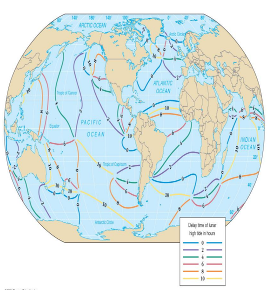
Real Ocean Tides

- If bulges with wave crests of half the world's circumference, they would travel at 1600 km/hr
- But this wavelength makes them shallower water waves, with speed based on the water depth, about 700 km/hr
- Thus the tidal bulges can't keep up with Earth's rotation
- Instead they break up into large circulation units called cells



Real Ocean Tides

- In the ocean, the crests and troughs rotate around a point near the centre of each cell
  - The Amphidromic Point – here there is basically no tidal range
  - From it radiate co-tidal lines, that connect all points with a high tide at the same time for that cell
  - Waves must complete 1 rotation in half a lunar day
  - Tidal wave rotates counterclockwise in the northern hemisphere
  - Tidal wave rotates clockwise in the southern hemisphere



Part VIII

Week 8

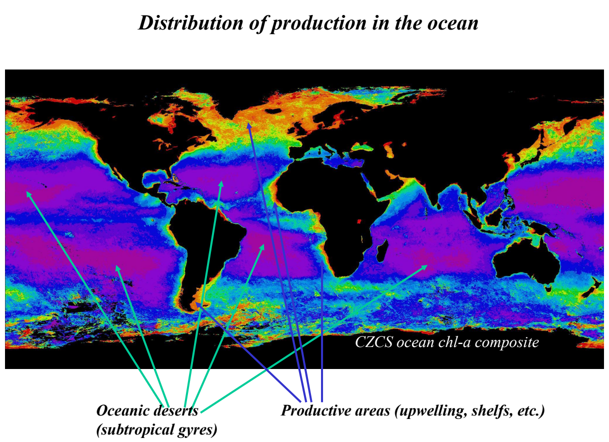
Ocean Vertical Structure and Deep Water Formation

Upwelling and Downwelling

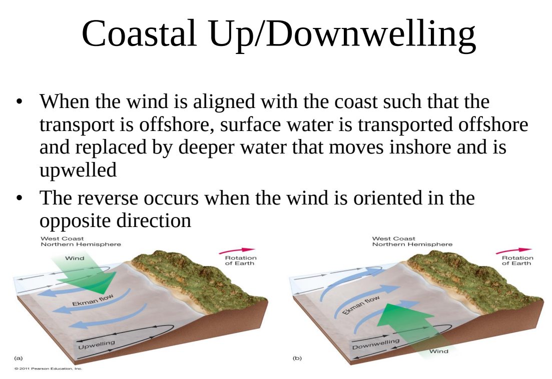
How the wind can drive vertical motion

When the wind blows away from an area, we get divergence, which causes water to upwell from below. This Upwelling is important because it brings cold water, rich in nutrients up from below the pycnocline. Areas with high amount of upwelling are rich in biological life because of this mechanism.

Winds blowing towards an area lead to the convergence of ocean currents. This causes water to be forced down, producing downwelling also called subduction which means that there is a thicker layer of warm water above the pycnocline. This also means that these bodies of water have very little nutrients thus having poor conditions for biological life.



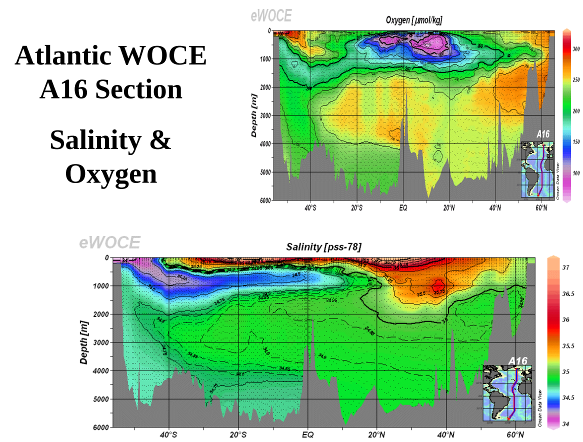
Coastal Up/Downwelling



Boundary Current and Upwelling

Western vs Eastern Boundary Currents

- **Western Boundary Currents:** Often have a very deep pycnoline, with lots of warm water making it difficult to bring cold, nutrient rich water needed for rich biological life.
- **Eastern Boundary Currents:** Are shallow, such that even weak offshore Ekman transport will to upwelling of cold nutrient rich water



Ocean Vertical Structure

Ocean Vertical Structure

- Temperatures high in the tropics due to solar heating
- Salinity high in lower latitudes due to high evaporation (with lower salinity at the Equator because of the ITCZ)
- Although the equatorial surface waters have high salinity, their high temperatures keep the density low and prevent those waters from sinking

Ocean Vertical Structure

- When the pycnocline is sharp, there is little motion across it, as large amounts of energy are needed to move water across strong density gradients
  - Thus water masses trend to flow mainly horizontal
  - Deep waters are effectively isolated from the surface

Ocean Vertical Structure

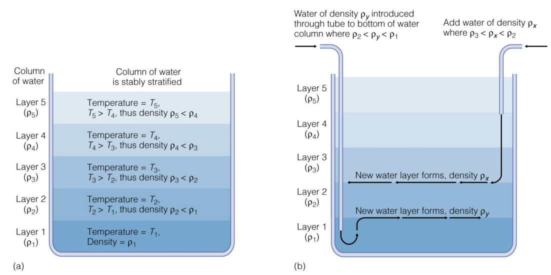
- At high latitudes, there is generally no pycnocline because of strong heat loss to the cold atmosphere above the ocean
  - This leads to the surface waters having a high density, causing them to sink and form intermediate and deep waters
- Since other than this sinking, motion is mainly horizontal, we can determine where water originates from in the ocean by tracing contour of salinity and temperature back to where that water last was in contact with the atmosphere

Ocean Vertical Structure

- When water sinks, the water above it has lower density and the water below it has higher density
  - This keeps each layer in the ocean separate, defining each as a separate water mass
  - Temperature, salinity and density only vary slightly in a water mass as it moves away from the source
    - The main changes to T and S are by vertical mixing

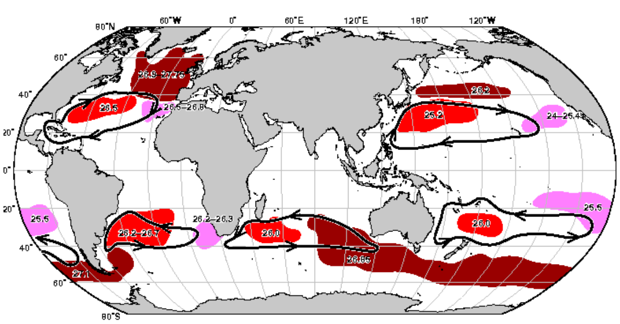
Density Layering

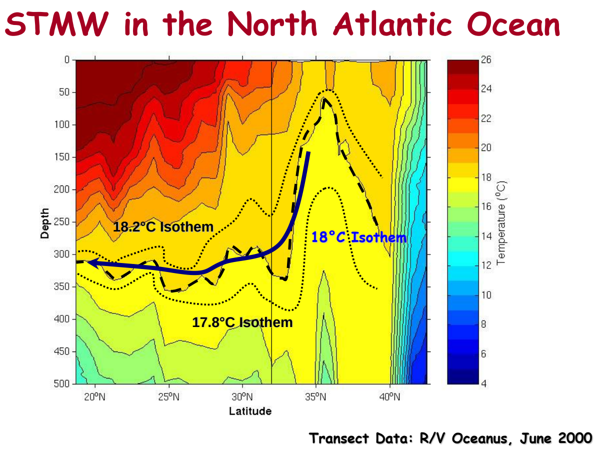
Density Layering



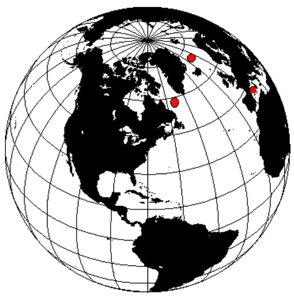
Cold Temp and high salinity will cause some vertical motion down to the lowest depth of the ocean

Upper Ocean Intermediate Waters (Mode Waters)





Northern Hemisphere Deep Water Formation Locations



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Off the North-eastern coast of Canada, the East coast of Greenland and Western coast of Norway are the only places where the density is high enough for the water to sink down to the deep ocean.

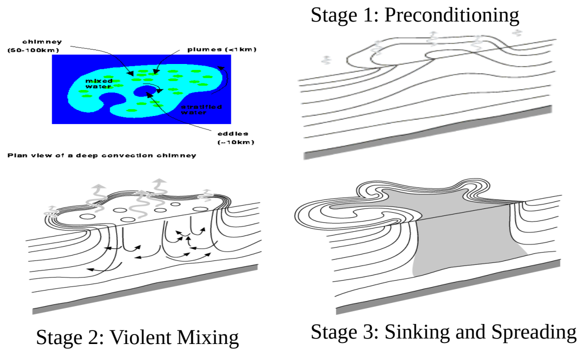
Convection

CONVECTION

Actual deep water formation process often called *convection*. These are small scale process that occur on the scales of km's to tens of km's. There are three factors that determine the locations of convection sites

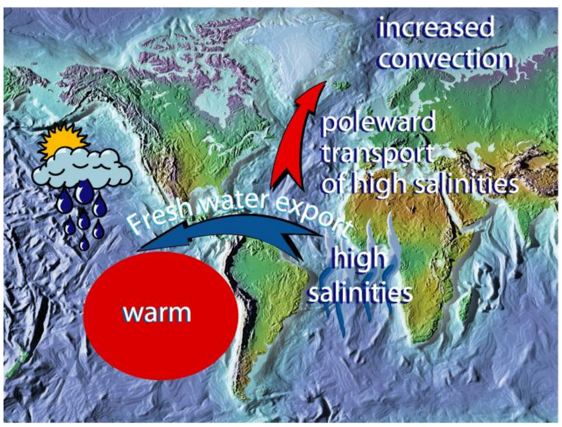
- strong wintertime heat loss
- strong winds that drive deep mixing of the mixed layer
- cyclonic ocean circulation, leading to doming of the isopycnals and 'pre-conditioning'

Deep Convection



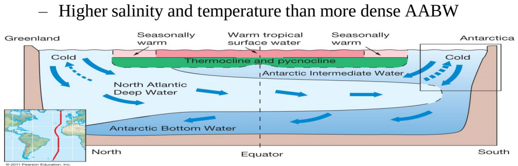
Deep Water Formation

- Indian Ocean:
  - does not reach high latitudes → no deep water formation
- North Pacific:
  - Isolated from polar regions by land, island chains and shallow water
  - High precipitation means low salinity
  - → No Pacific Deep Water formation



Deep Water Formation

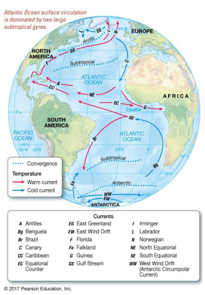
- North Atlantic: Intense cooling occurs in the Labrador, Greenland and Norwegian Seas
  - Forms North Atlantic Deep Water (NADW)
  - Then sinks and flows south filling the world's oceans (most voluminous water mass in the world)
  - Higher salinity and temperature than more dense AABW



Atlantic and Southern Oceans

Atlantic Ocean Circulation

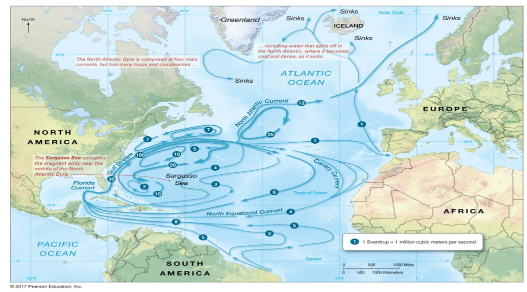
Atlantic Ocean Circulation



- Contains large scale wind driven gyre circulation
- But also location of active deep water formation
  - Generates major sub-surface water masses
- Headwaters of Atlantic overturning circulation

North Atlantic Circulation

North Atlantic Circulation



Thermohaline Circulation

Thermohaline

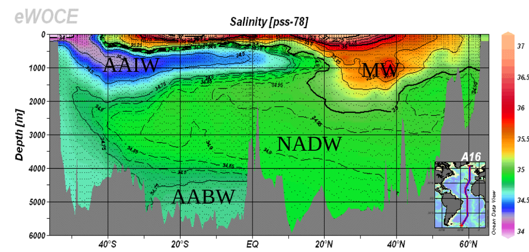
Below the pycnocline, currents are driven by the density difference between water masses. These differences allow water masses to sink or rise to their appropriate level.

- Where water masses sink, this processes changes the density distribution with depth
- This will then change pressure distribution and thus horizontal pressure gradient, generating currents
- Therefore, once a water mass has found the appropriate level, it then flows horizontally, driven by pressure gradients.

Because seawater density is mainly set by temperature and salinity, this motion is called Thermohaline Circulation

Atlantic Vertical Structure

Atlantic Vertical Structure



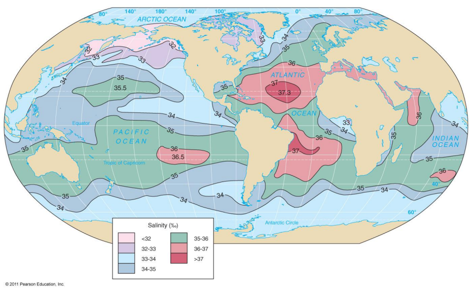
Atlantic Water Masses

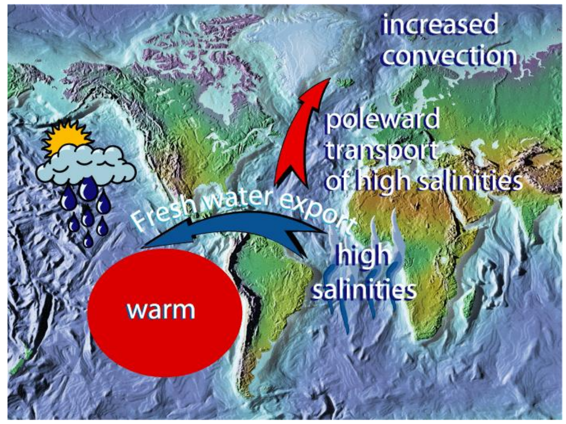
Atlantic Water Masses

- MW - Mediterranean Water
- AAIW - Antarctic Intermediate Water
- NADW - North Atlantic Deep Water
- AABW - Antarctic Bottom Water

Sea Surface Salinity (SSS)

Sea Surface Salinity (SSS)



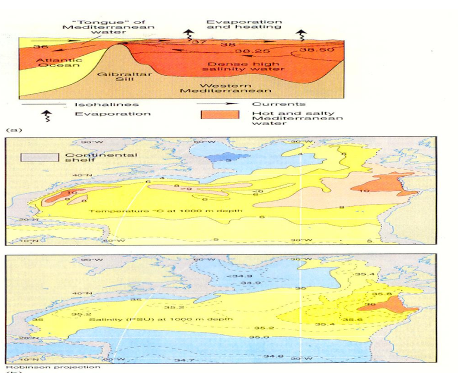


Highest in the Mid Atlantic Ocean, lowest near the Arctic ocean.

Atlantic vs Pacific

The Atlantic is significantly saltier than the Pacific for a few reasons

- Presence of the thermohaline circulation
- Atmospheric circulation
- Mediterranean inflow



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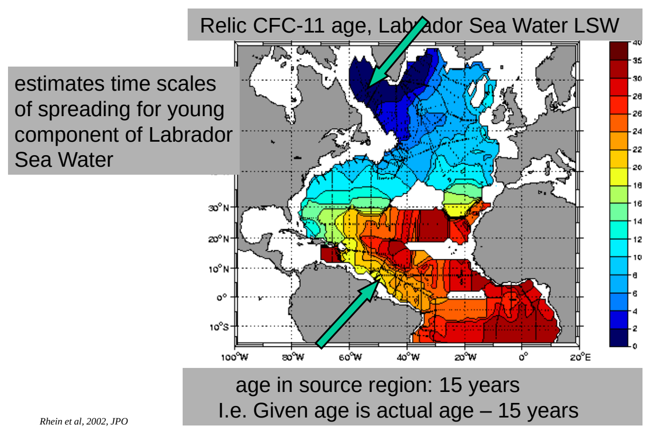
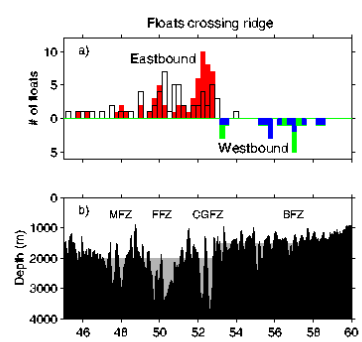
Deep Water Dispersal

Deep water currents are also affected by the Coriolis effect. This leads to the intensification along western boundaries, the formation of Deep Western Boundary Currents, and it ciruclate in gyre like patterns. Moreover, it's significantly affected by topography.



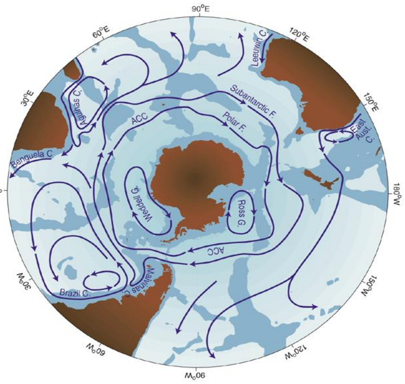
Rhein et al, 2002, JPO

Influence of Mid-Atlantic Ridge on float trajectories



Bower et al, 2002, Nature

Main Currents of the Southern Ocean



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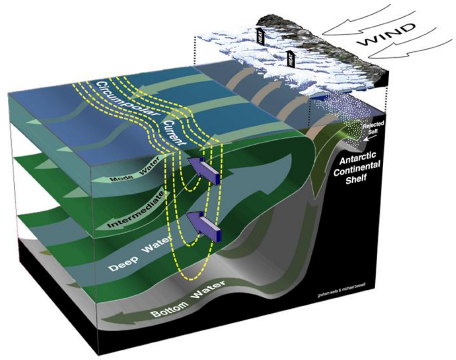

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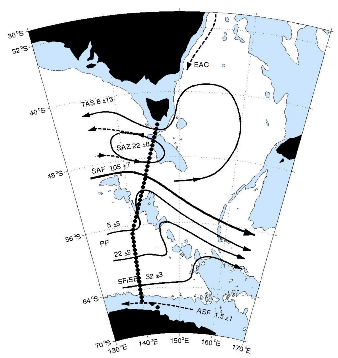
ACC Transport



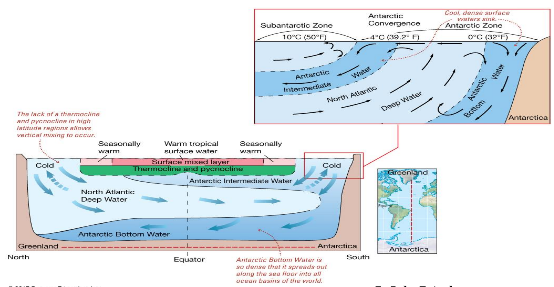
Rintoul and Sokolov, JGR, 2001

Transport concentrated in narrow bands (jets)

Bands focussed along fronts

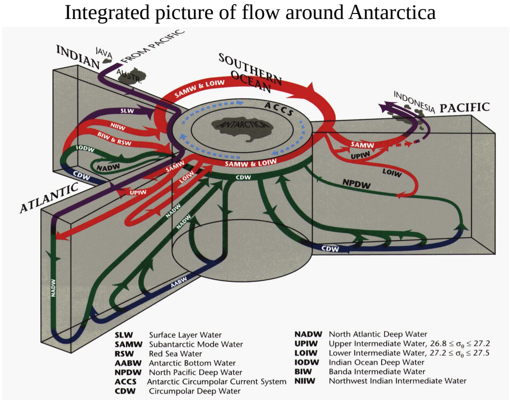
In regions, countercurrents (currents flowing opposite direction exist) but simple maps based on net flow

Atlantic/Antarctic Sub-Surface Water Masses

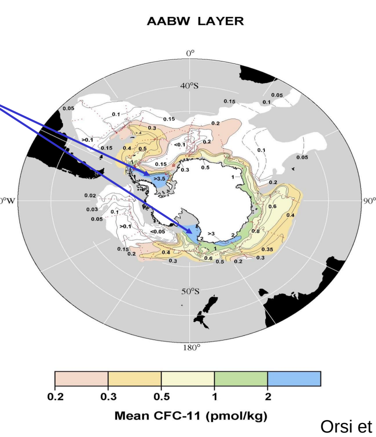


Web Link:
https://goo.gl/ow7wr6

Integrated picture of flow around Antarctica



Schmitz (1996)

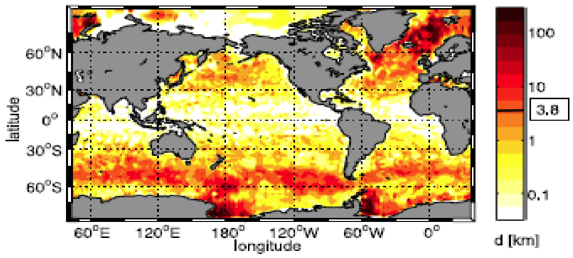


Formation Locations

Of AABW

Orsi et al., 1999

Origins of Water Masses



Gebbie and Huybers, 2011, GRL

Part IX

Week 9

3-15-2019 and 3-18-2019 Arctic Ocean and Global Thermohaline Circulation

Global Ocean Circulation

In a simple way the world's ocean can be likened to a giant conveyor belt.

1. Water is cooled near the poles, where it sinks

2. It is transported in the deep ocean where it mixes with other waters

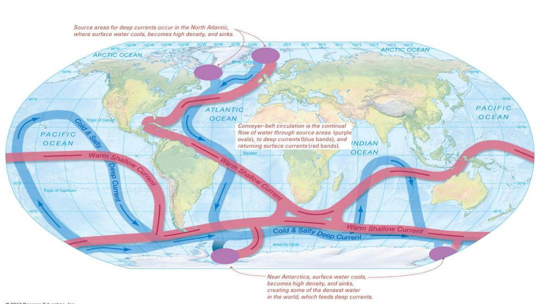
3. It returns to the surface far from where it sank

4. It is then transported back on the surface to high latitudes, where it cooled to start the cycle again.

This is important as:

- it carries the heat and dissolved chemicals around the planet including nutrients,
- transport properties between the surface and deep ocean
- by transporting heat, it is important in regulating climate and can cause climate variability.

Conveyor Belt Schematic



North Atlantic Deep Water Conveyor

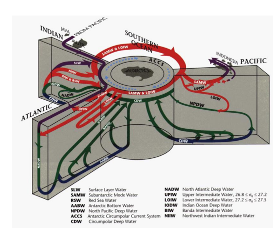
The Global Thermohaline circulation also called the theromohaline circulation (THC), meridional circulation (MOC), Atlantic meridional circulation (AMOC). The complete circuit takes about 1000 years, although no individual water parcel will ever do the complete circuit. It transport a huge amount of water an order 20 Sv.

Mechanism

It starts in Labrador and in the Nordic Seas. The warm salty water is cooled in the winder by cold winds from the Arctic. Thus increasing the density of the surface water and causes it to sink, forming the North Atlantic Deep Water (NADW). Once it sinks to depth, the NADW flows south through the deep Atlantic, mainly in deep western boundary currents. As it nears Antarctica, it encounters the AABW (Antarctic Bottom Water), which it flows over.

NADW Conveyor

- Once it reaches the ACC, the water flows around (Antarctica) one or more times
- Then it travels north into the Pacific and Indian Oceans at depth



Rintoul, 2004

As the deep water flows into the Pacific and Indian Oceans, it mixes and upwells back towards the surface. Some upwelling also occurs around Antarctica. How? we don't know. Our best answer now is above rough topography due to waves and tides.

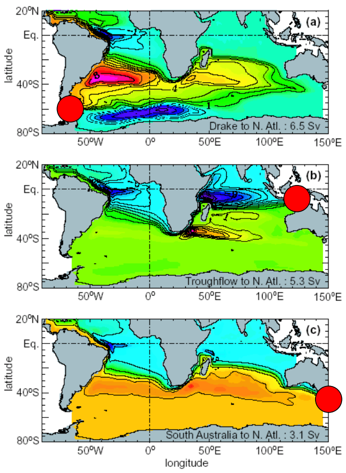
There are 2 to 3 routes back to the Atlantic via the surface.

1. Warm water route: through the Indonesian Straits and then around Africa (as eddies/rings) (about 5.3 Sv)

2. Cold water route: South through the Pacific, through Drake Passage and north into the Atlantic (about 6.5 Sv)

3. Also an intermediate 'cool' route (Tasman Leakage south of Australia) (about 3.1 Sv)

As the water comes north through the sub-tropics, it is exposed to lots of evaporation, giving it a high salinity by the time it reaches the northern regions.



Upper branch of the global OTC

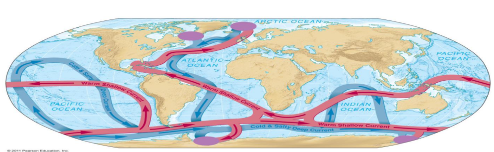
"cold" = 6.5 Sv

"warm" = 5.3 Sv

"cool" = 3.1 Sv

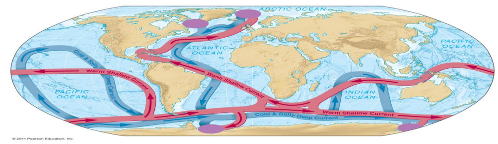
Speich et al., GRL, 2001

THC Cartoon has limitations



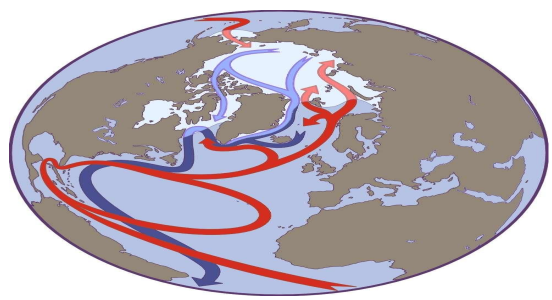
- Advantages
  - Gives simplified picture all can understand
  - Boils down the complicated large-scale ocean circulation to a few key ideas

THC Cartoon has limitations



- Disadvantages
  - Boils down the complicated large-scale ocean circulation to a few key ideas
  - No water parcel ever flows the complete circuit
  - Misses processes
  - Potentially implies we know completely how the ocean (and especially the deep ocean) works
  - Missed high latitude processes

AMOC - Arctic



Holloway, 2002

Part X

Week 10

3-18-2019: Marine Pollution

Pollution

Any harmful substance or energy put into the ocean by humans

Human touch

The human touch have no boundaries on the planet with regards to pollution. A large fraction (41%) is strongly affected by multiple drivers

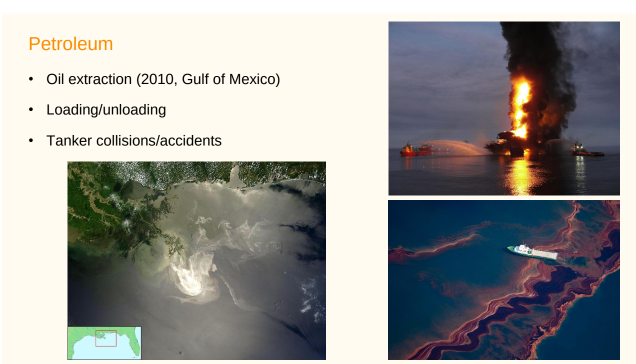
- Pollutants (organic, inorganic, fertilizer)
- Oil rigs
- Population Density
- Invasive species
- Overfishing
- Ocean certification
- Climate Change

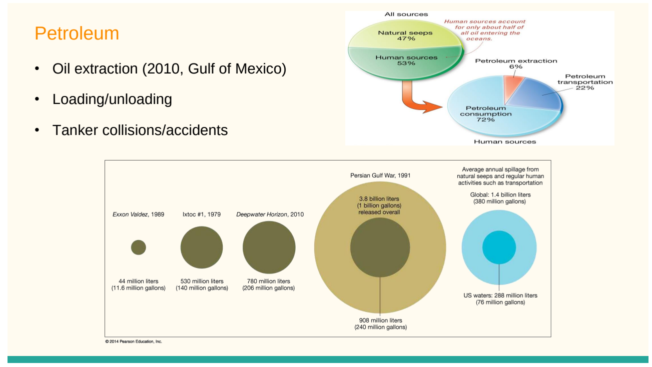
Pollutants

Any harmful substance (introduced by men)

- Petroleum
- Waste water
- DDT and PCBs
- Mercury
- Garbage especially plastic

Petroleum



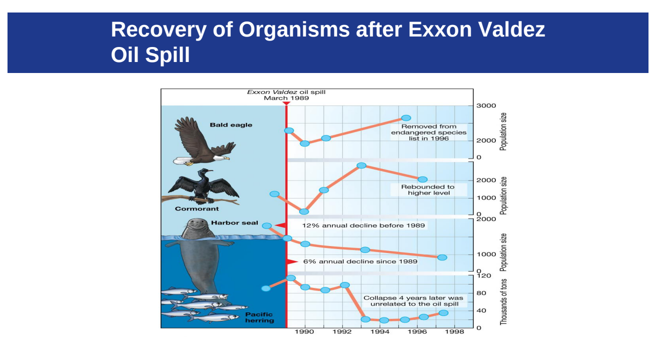


Petroleum itself is biodegradable. But has the impact of toxic compounds and destroys the insulating ability of fur and water repellency of bird's feathers.

Cleaning oil spills

There are many ways to clean oil spills

- **Skimming** booms rise about 1m above the water level, and are attached to a skirt that hangs underwater, from the surface skimmers suck or scoop the oil into containment tanks.
- in-situ burning
- chemical dispersion
- bioremediation



Waste Water

Includes

- Sewage: most is untreated, even done in developed countries
- Water from showers, laundry, dishes
- Runoff from roads
- Waste water from factories

These waters includes viruses, bacteria, parasites, chemicals from pharmaceuticals and personal care products, microbeads, garbage.

DDT and PCBs

These chemicals are toxic, persistent, and tend to accumulate in the food chain. Even Antarctic marine organism contain measurable quantities. Can cause cancer and birth defects. PCBs can also affect animal reproduction, DDT thin eggshells, These chemicals are banned in the mid 80s and 90s in Canada.

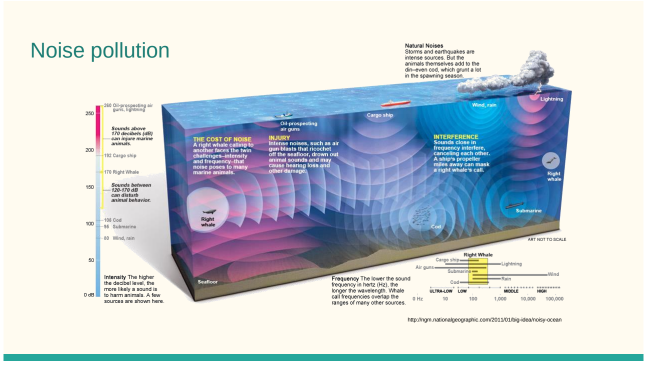
Bio-accumulation and magnification

- **Bio-accumulation** organisms concentrate pollutant from seawater
- **Bio-magnification** organisms gain more pollutant by eating other contaminated organisms

Mercury

Consumed by bacterial and converted to organic form. Toxic for most living things. In 1938 there was the Minamata Bay incident, degenerative neurological disorder.

Noise Pollution



Some species communicate and navigate using sound (SONAR), but non-natural sources like propellers, air guns, etc effect these species ability to navigate.

Invasive Species

Lack predators and other natural control. These leads to the domination of the native population. This also includes the introduction of new parasites and diseases. Ballast water can also introduce invasive species as ships from one location can introduce new organism to another location.

Garbage

Trash washed down storm drains, dumped into ocean or beaches. Road oil and improperly disposed oil each year is equivalent to 1.5 times the amount of the Deepwater Horizon oil spill. Glass, metal, rags, and food (far from the shore) -> sink or biodegrade.

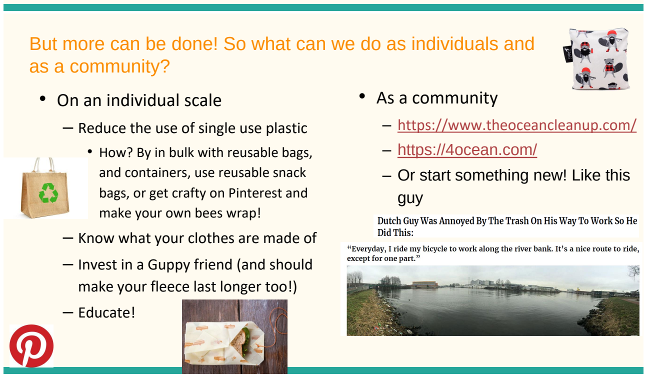
Plastics

Can remain in the marine environment almost indefinitely. Leads to entanglement and ingestion by species. Affinity for non-water-soluble toxic compounds. Collects in main ocean gyres. Population and plastic production have been increasing.

Microplastic

Super small pieces of plastic (< 5 mm). Things like beads, fibers, film. They come from the break down of larger plastic pieces. Shampoo, soap, toothpaste, glitter, clothing.

What to do?



3-20-2019: Computer Modelling

Definition

- A usually miniature representation of something.
- A system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs.

What is an ocean model?

What is an ocean model?

A representation in the form of equations or computer code describing physical processes of our understanding of how the ocean works.

Most models are differential equations. These models then involve solving the equations either analytically or numerically. Due to the natures of computers being discrete timing are done in time slices.

There are many different types of ocean models, designed to describe different processes like climate change, conceptual or process models, etc.

Main elements of a Model

Elements of a model

- Governing equation(s)
- Initial conditions
- Boundary conditions like external forcing: transport, radiation.

Example

The Ocean General Circulation Models, is based on a series of coupled partial differential equations that includes parameters for temperature, salinity, density, u,v,w velocities, and sea surface height. The domain of these parameters are discretized into a 3-D grid. Therefore the parameterizations and results depend on the grid resolution.

Boundary Conditions

- Basin Geometry
- Bottom Topography
- Atmosphere above

Initial Conditions

- Temperature, Salinity and Velocity fields
- Maybe from climatology, data, a previous spun-up run, . . .

Forcing fields

- Heat: Shortwave radiation, long wave radiation (up and down welling), sensible and latent heat at the surface.
- Evaporation and precipitation at the surface
- Land surface runoff at the margins
- winds
- tides

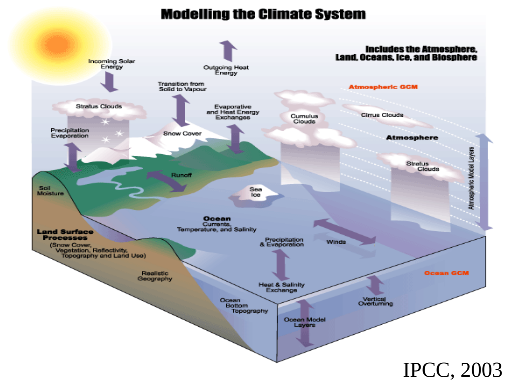
Discretization

Because computers do not have infinite precision we have to discretize or gather data in integer like unit. This is applied to both the time and space domain.

More definitions

Parameterization: is a model within a model. Example: decay has been parameterized as a first-order process, λ[CO]. In this case λ is used as a *parameter* a constant used within a parameterization.

Calibration: adjustment of independent variable in order to match dependent variable with observations.



IPCC, 2003

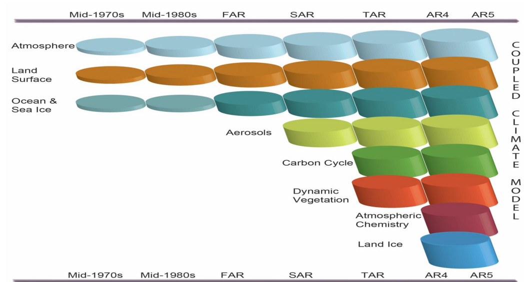
Parameterizations

Processes need to be parameterized for two main reasons

- We don't want to spend the computational resources to directly treat or resolve them as they are too small or complex.
- We don't completely understand the process.

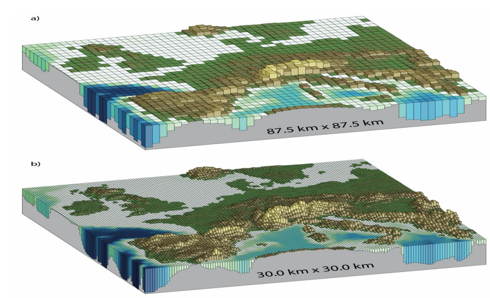
The main issue with low resolution models are meso-scale eddies.
The main issues with high resolution models are sub-mesoscale, internal wave mixing, flow-topography interaction.

Processes Considered in Climate Models



IPCC, 2013

Improvements in Model Resolution



IPCC, 2013

Validation

A valid model is one that is internally consistent. One that:

- contain no coding errors
- have sound numerics
- give the same results on different computers
- agree with analytic solutions (if available)

Uses of Models

- Hypothesis testing
- Sensitivity analysis
- "What-if" scenarios
- Estimation of hard-to-measure quantities
- Extrapolation

3-22-2019: Hurricanes

Earth's Seasons

The earth's axis of rotation is tilted at 23.5 degrees with respect to the ecliptic - plane traced by Earth's solar orbit. Seasonal changes and Earth's rotation cause unequal solar heating of the Earth's surface.

The tilt is responsible for our seasons.

- vernal (spring) equinox
- Summer solstice
- Autumnal equinox
- Winter solstice

Winds

Cyclonic vs Anticyclonic flow

Cyclonic flow: Counterclockwise around a low in the Northern Hemisphere, clockwise in the Southern Hemisphere.

Anticyclonic flow: Clockwise around a high in the Northern Hemisphere, counterclockwise in the Southern Hemisphere.

Sea and land breezes

These breezes are caused by differential solar heating due to the different heat capacities of land and water.

Sea breeze: is wind from the ocean to land.
Land breeze: is wind from the land to the ocean.

Tropical Cyclones (Hurricanes)

Are large rotating masses of low pressure air. Have strong winds and torrential rain resulting in storm surges, the increase in shoreline sea level. They are classified by the maximum wind speed sustained. Hurricane season is June 1 – November 30. About 100 worldwide per year. They have different names Typhoons or Cyclones.

Hurricanes, arguably, are the most powerful storms in the world. They transform the quiet stored energy of warm, moist tropical oceans into vicious winds, raging seas, torrential rains, and widespread flooding.The heat-energy released by conversion of invisible water vapour to water droplets is immense. A hurricane's one-day energy release could supply enough electrical energy to meet Canada's needs for years.

Origins

These are the conditions for a hurricane to form.

1. Coriolis Effect
2. Large-scale, low level convergence and low surface pressure
3. Warm, moist tropical atmosphere conducive to overturning when the air becomes saturated,
4. Sea surface temperature greater than 26 degrees C
5. Greater than 5 degrees away from the equator
6. Low vertical wind shear
7. High pressure situated above the tropical cyclone
8. Winds feed water vapor - latent heat of condensation.
9. Air rises, low pressure deepens

Stage of development

1. **TROPICAL DISTURBANCE** When a moving area of thunderstorms in the tropics maintains its identity for 24 hours or more, the NHC classifies the weather system as a tropical disturbance
2. **TROPICAL DEPRESSION** If the area of thunderstorms becomes organized such that a rotation develops and winds become strong (20 knots or 37 km/h), the system is upgraded to a tropical depression.
3. **TROPICAL STORM** If the winds continue to increase, reaching sustained gale strength (34 knots or 63 km/h) the NHC upgrades the system to a tropical storm. While the winds may be tame in comparison with a hurricane, rainfalls of 100-200 mm are not uncommon. The storm is now given a name.
4. **HURRICANE** Should the winds reach 64 knots (119 km/h) or more, a hurricane is born. There are 5 categories of hurricanes

Levels of intensity

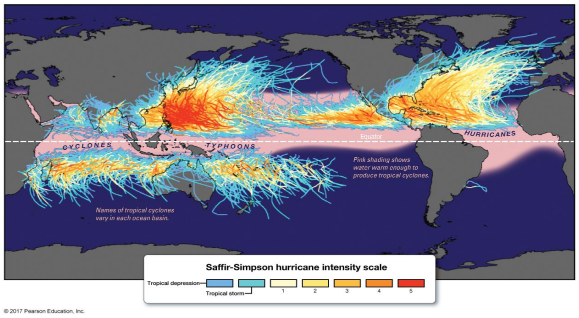
Hurricane Intensity

Web Link:
https://goo.gl/FICvaJ

TABLE 6.3 THE SAFFIR-SIMPSON SCALE OF HURRICANE INTENSITY

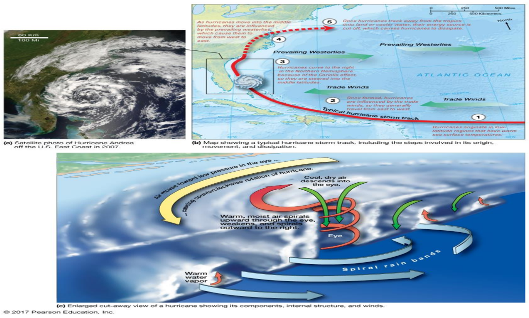
	Wind speed		Typical storm surge (sea level height above normal)		
Category	(km/hr)	(mi/hr)	(meters)	(feet)	Damage
1	120–153	74–95	1.2–1.5	4–5	Minimal: Minor damage to buildings
2	154–177	96–110	1.8–2.4	6–8	Moderate: Some roofing material, door, and window damage; some trees blown down
3	178–209	111–130	2.7–3.7	9–12	Extensive: Some structural damage and wall failures; foliage blown off trees and large trees blown down
4	210–249	131–155	4.0–5.5	13–18	Extreme: More extensive structural damage and wall failures; most shrubs, trees, and signs blown down
5	>250	>155	>5.8	>19	Catastrophic: Complete roof failures and entire building failures common; all shrubs, trees, and signs blown down; flooding of lower floors of coastal structures

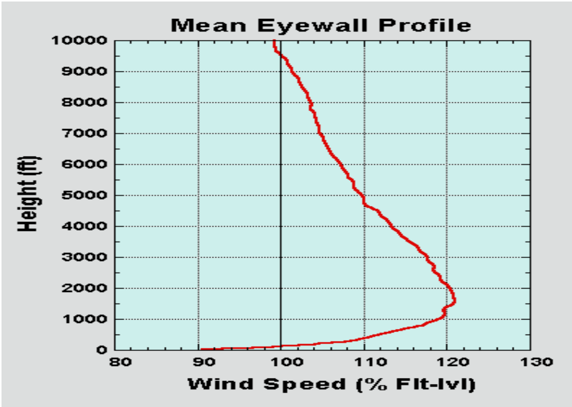
Historical Storm Tracks



Hurricane Anatomy and Movement

Web Links:
https://goo.gl/DcEaEV
https://goo.gl/99HYop





Maintenance

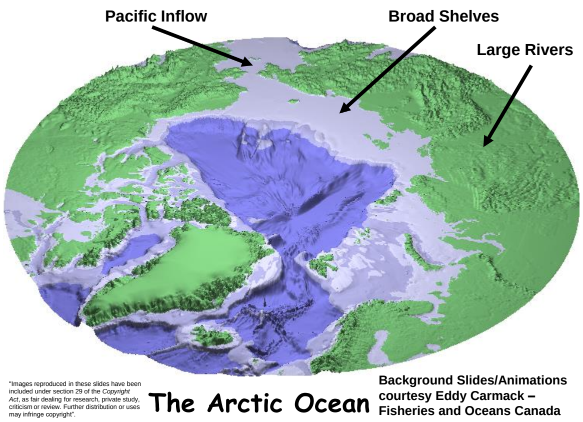
A hurricane will Not weaken until:

- It's source of heat / moisture is removed (passage over land / cold water)
- It encounters vertical wind shear
- Dry, cool air, which doesn't develop deep convection, is imported into it
- The high pressure aloft is replaced by a low

Part XI

Week 11

3-25-2019: Arctic Ocean 2

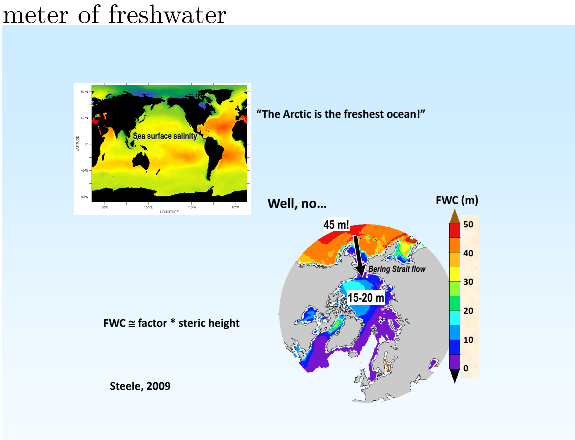


Beaufort Gyre

Is the largest freshwater reservoir in the Arctic Ocean

> **What is Freshwater**
>
> Freshwater stands for the amount of zero-salinity water contained in a volume of water with a given salinity relative to a reference salinity.

For example: If you have one cubic meter of water with a salinity of 18 and that is made up with 0.52 cubic meter of water at a salinity of 34.8 which is the reference and 0.48 cubic meter of water with zero salinity then that body of water contains 0.48 cubic meter of freshwater



Water from the arctic ocean goes to the Atlantic.

Arctic passages

Bering strait

Bering sea water (Green)

- nutrient-rich anadyr water (Green)
- Low-nutrient Bering shelf water (light green)

Alaskan Coastal Current (Red)

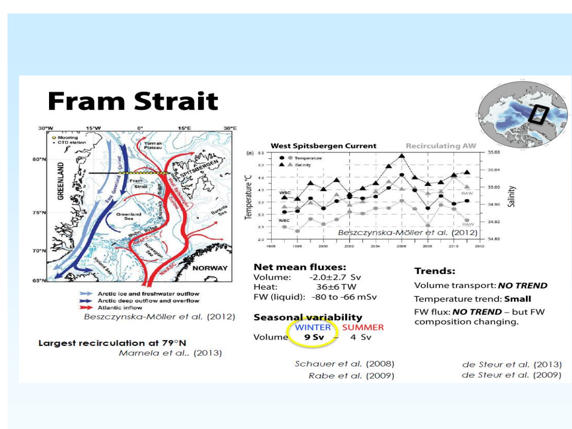
- fresh and warm
- present summer to late fall
- loses water to central Chukchi

Siberian Coastal Current (Purple)

- Fresh, cold
- Present some summers
- May reach Bering Strait or may exit into central Chukchi

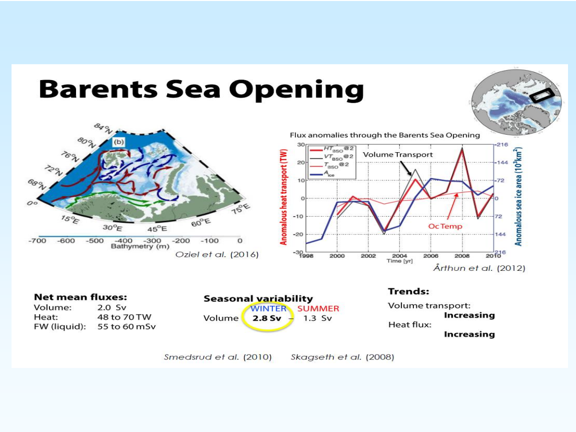
More water -> more heat -> more FW flux
It moves about 1.2 Sv in the summer and 0.4 Sv in the winter.

Fram Strait



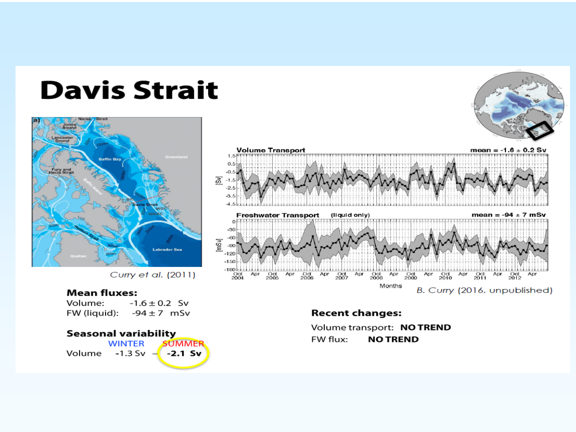
Moves more water in the winter

Barents Sea Opening

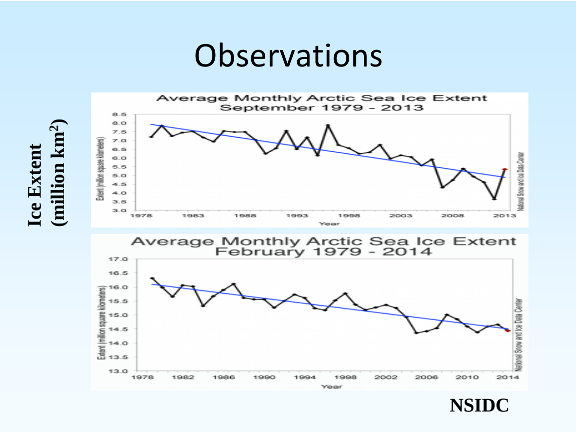


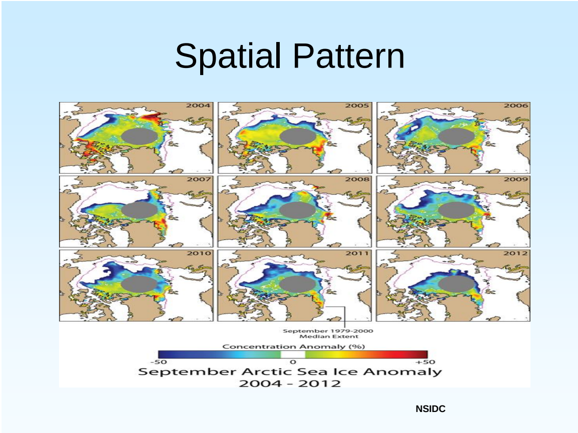
Moves more water in the winter. The arctic is receiving more water of different properties

Davis Strait

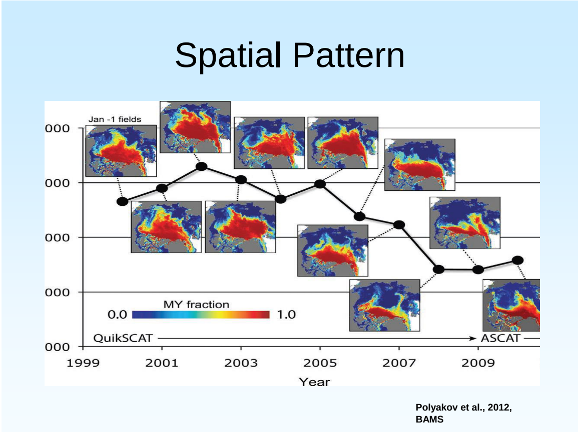


The arctic itself is getting fresher, yet fluxes at Arctic gateways seem relatively stable.

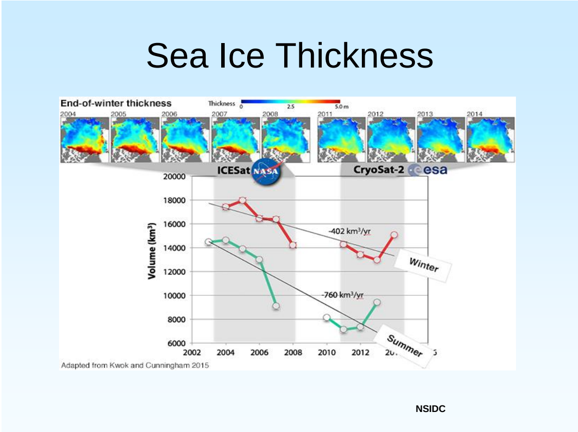




The ice is getting smaller. The ice is being pushed to Iceland and Greenland

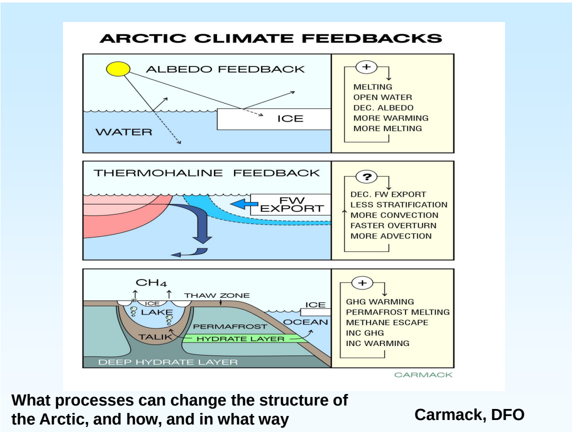


The ice is getting thinner over time as well

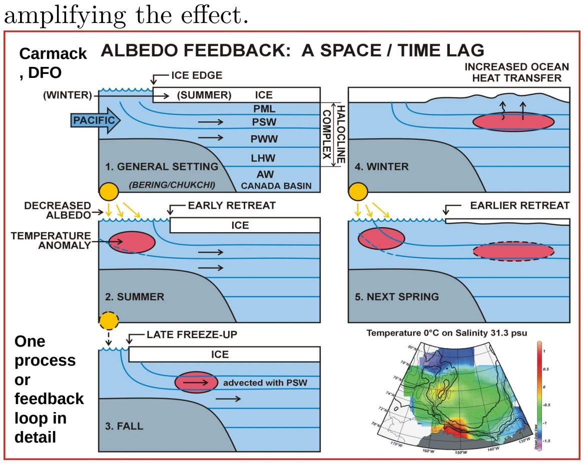


We are also getting less older ice over time.

Why are we getting less sea ice?



Feedback loops - negative is a response to go back to normal, positive feedback is a response that is amplifying the effect.



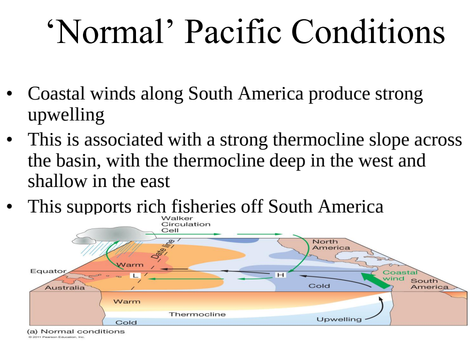
When the ice is in early retreat is creates a temperature pocket that is carried underneath the ice via the ocean current. This increases the temperature of the ice which decrease it volume/area. This effect is magnified when there is less ice to reflect the sun light.

3-27-2019: Modes of Climate Variability

Normal Pacific Conditions

Walker Circulation. East-West Atmospheric Cell.

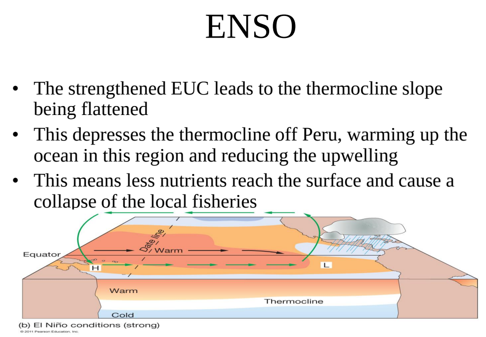
- high pressure and shrinking in east Pacific
- Low pressure and rising (and precipitation) in west Pacific
- Easterlies help drive SEC to the west, causing warm water to pile up in the western Pacific (Pacific Warm Pool)

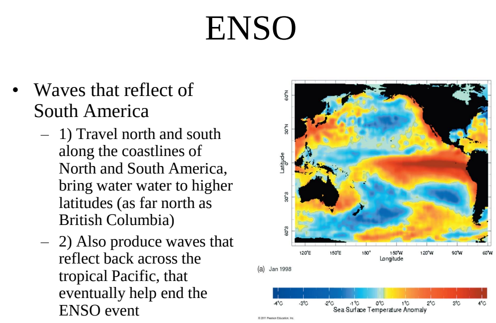


ENSO

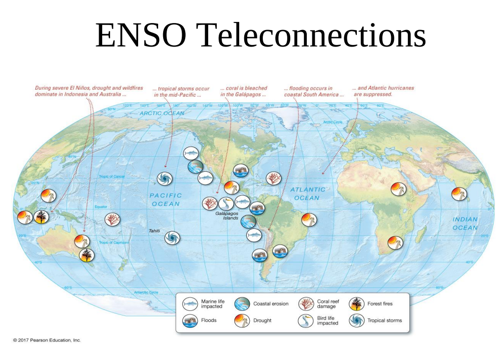
Is an abbreviation for El-Nino-Southern Oscillation. The name indicates that this phenomenon is related to coupled atmospheric-ocean process, the atmospheric Southern Oscillation and the oceanic El Nino process. This process starts happening in September in most years when it occurs and reaches the Peruvian coast by December.

Atmospheric processes can cause bursts of westerly winds to occur at times along the equator. This weakens (or even reverses) the Walker circulation. With weakened or lack of trade winds, the warm pool is no longer held against the western side of the basin and ’sloshes’ back to the Pacific. This also initiate Kelvin waves, that travels eastwards across the tropical Pacific. These Kelvin waves strength the EUC.





Is associated with world wide natural damages.

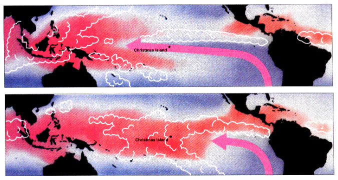


El Niño /La Niña

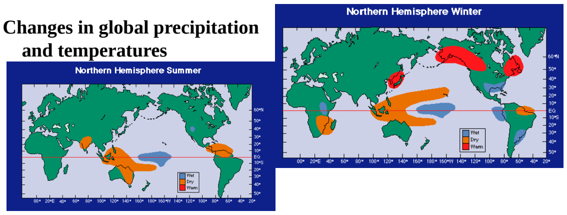
Changes in SST→

Convective displacement →

Changes in high level winds →



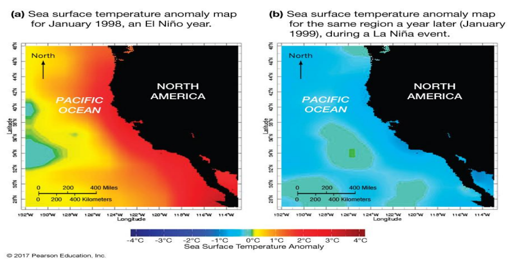
Changes in global precipitation and temperatures



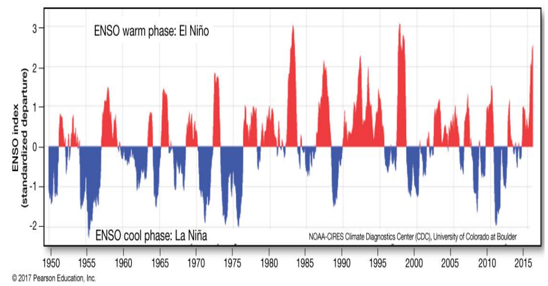
ENSO Frequency

- Historical SST records shows El Nino's have been occurring from hundred of years, but the frequency may be increasing
  - On average they occur every 2-10 years
  - Over the last 30 years, maybe every 2-5 years
- Variability represented by the ENSO index
  - Positive → El Nino conditions
  - Negative → La Nina conditions

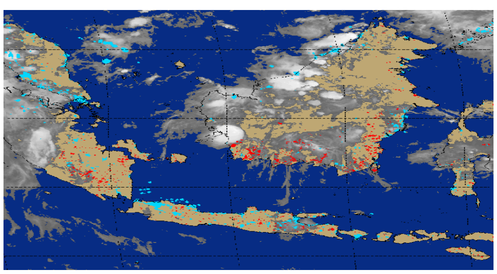
Sea Surface Temperatures off Western North America



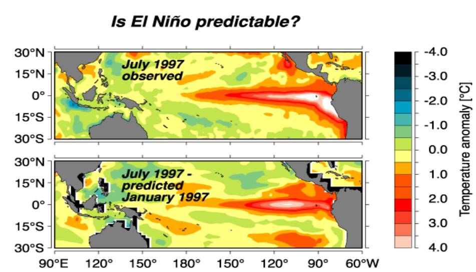
ENSO Time series



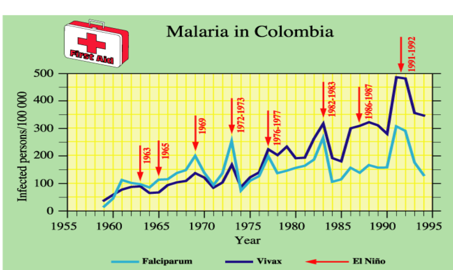
Indonesia Fires due to ENSO, 1997



ENSO Predictability

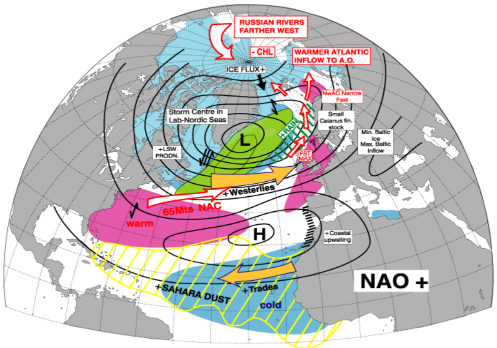


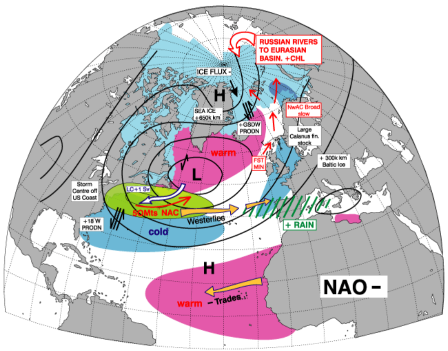
Malaria and ENSO



North Atlantic Oscillation (NAO)

The NAO, a component of the Arctic Oscillation (AO), is the sea level pressure difference between Ponta Delgada, Azores and Stykkishholmur. It measures aspects of variability in the Atlantic.

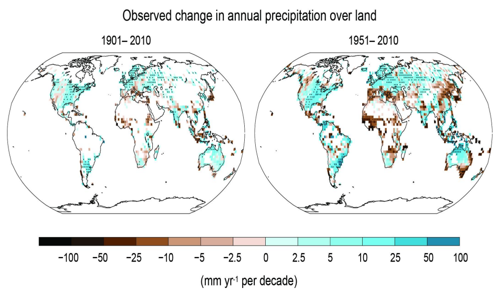

RUSSIAN RIVERS FARTHER WEST
- CHL
WARMER ATLANTIC INFLOW TO A.O.
ICE FLUX+
NwAC Narrow Fast
Storm Centre in Lab-Nordic Seas
Small Calanus fin. stock
Min. Baltic Ice Max. Baltic Inflow
L
+RAIN
+LSW PRODN.
FST MAX
+Westerlies
65Mts NAC
warm
H
+Coastal upwelling
+SAHARA DUST
+Trades
cold
NAO +


RUSSIAN RIVERS TO EURASIAN BASIN. +CHL
ICE FLUX -
H
NwAC Broad slow
SEA ICE +650k km
+GSDW PRODN
Large Calanus fin. stock
warm
FST MIN
+ 300k km Baltic Ice
L
Storm Centre off US Coast
LC+1 Sv
50Mts NAC
Westerlies
+ RAIN
+18 W PRODN
cold
H
NAO –
warm
– Trades

3-29-2019: Introduction to Climate Change

IPCC Process

- IPCC – Intergovernmental Panel on Climate Change
  - The role of the IPCC is to **assess** on a **comprehensive, objective**, open and transparent basis the **scientific**, **technical** and socio-economic information relevant to understanding the **scientific basis** of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation. **Review** by experts and governments is an essential part of the IPCC process. The Panel does not conduct new research, monitor climate-related data or recommend policies. It is open to all member countries.
  - The latest report is the 2013 5th Assessment on Climate Change
  - Based only on peer-reviewed scientific literature
  - www.ipcc.ch (source for slides presented in this lecture)



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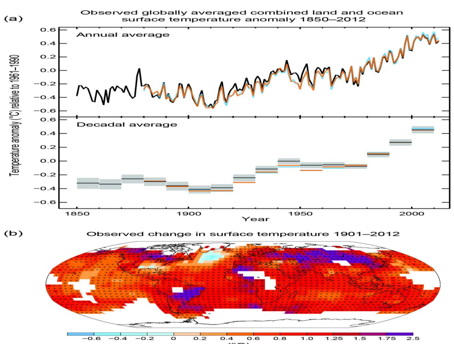

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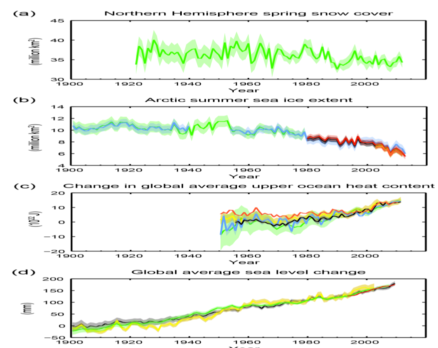

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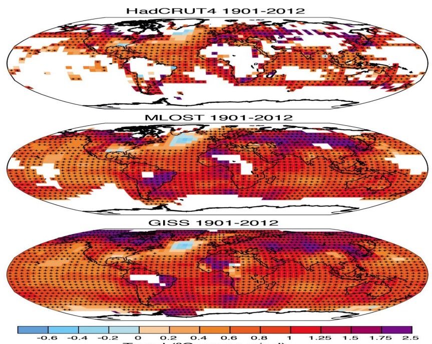

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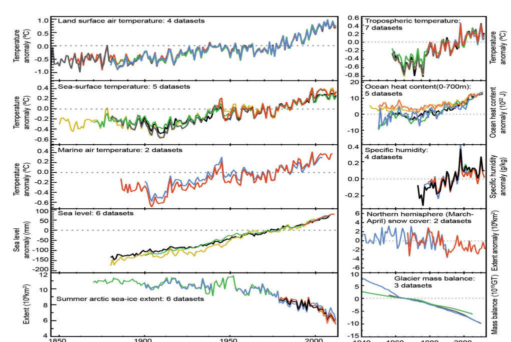

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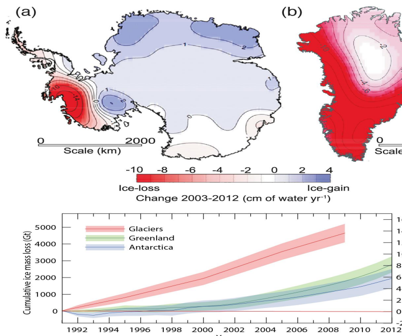

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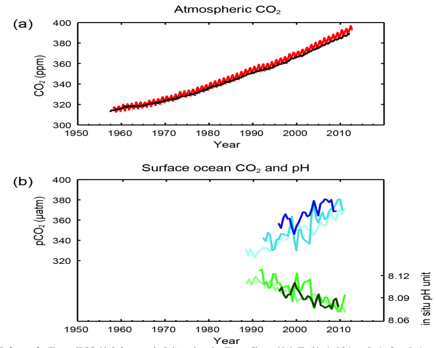

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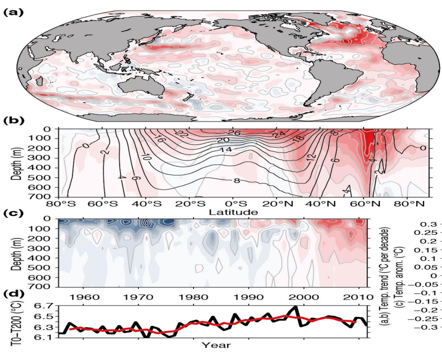

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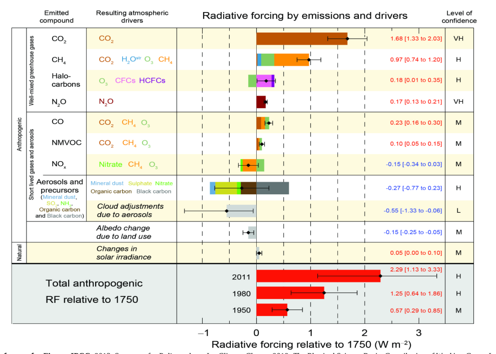

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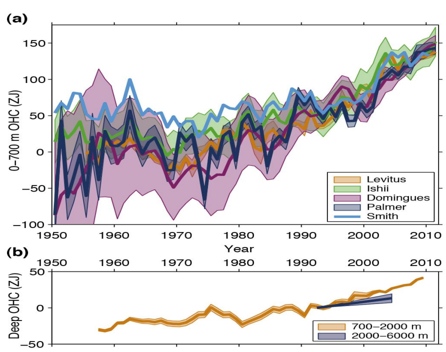

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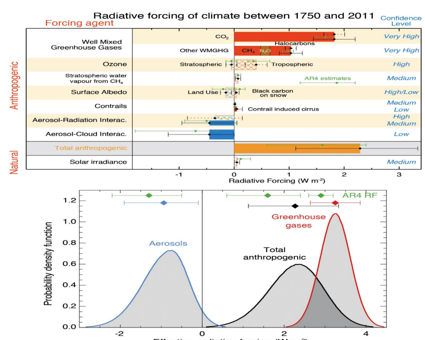

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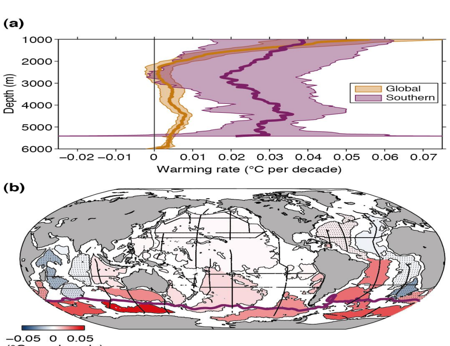

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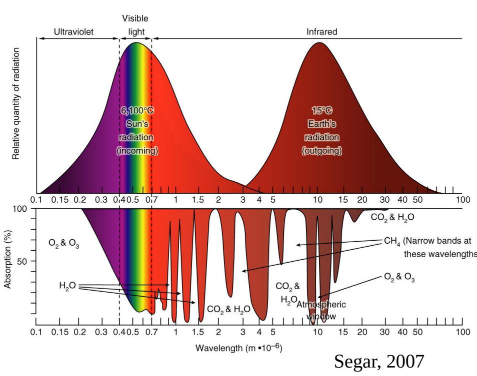
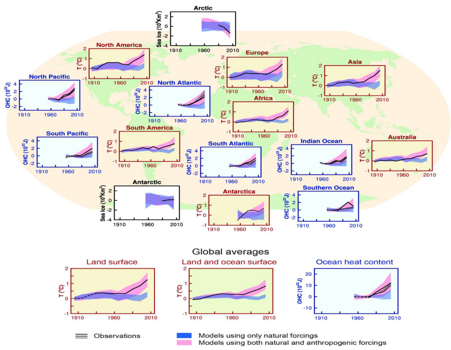


Segar, 2007



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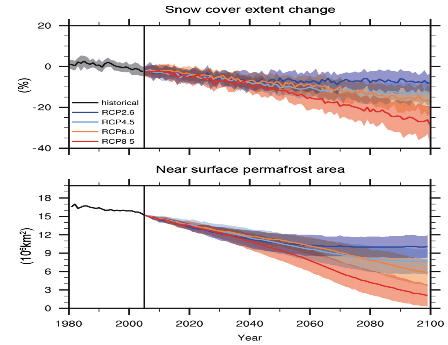

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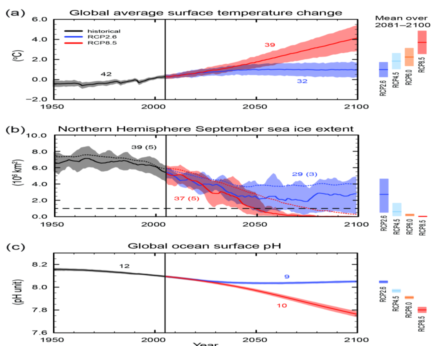

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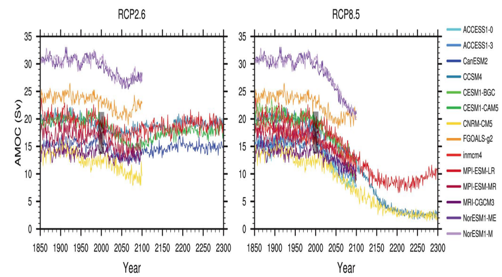

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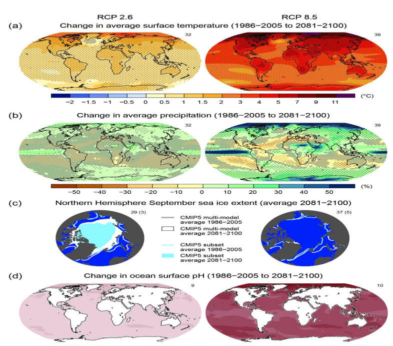

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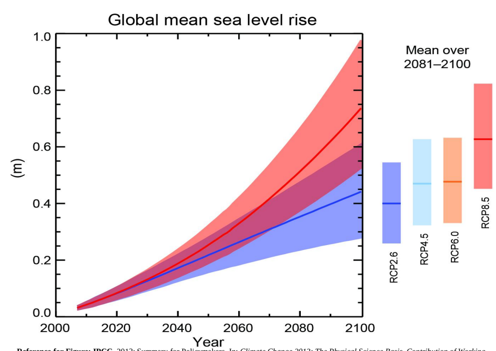

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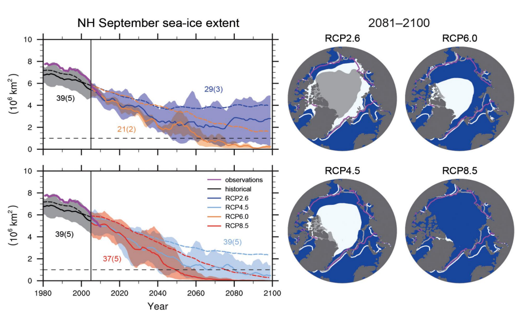

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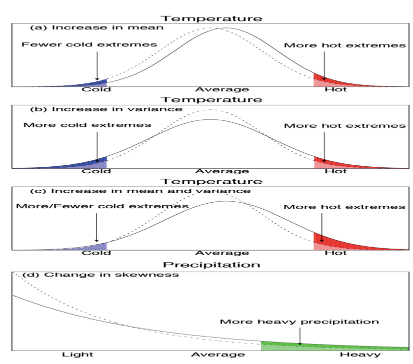

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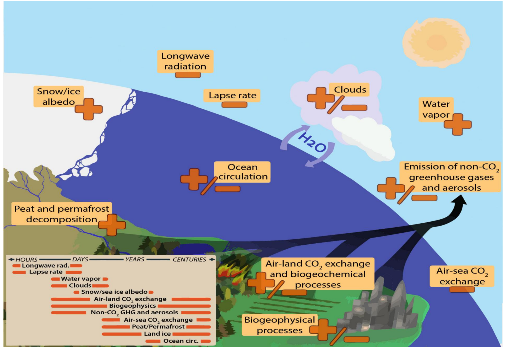

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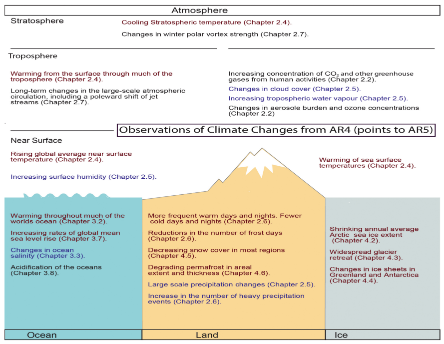

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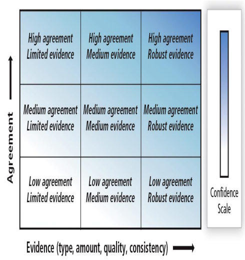
Definitions



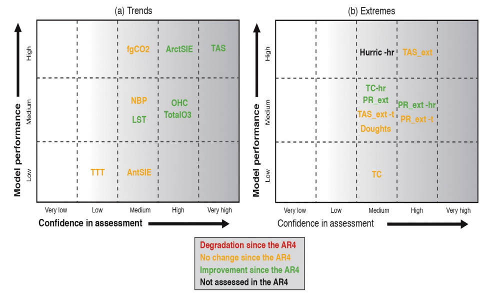
Term	Likelihood of the Outcome
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

Notes:
Additional terms that were used in limited circumstances in the AR4 (*extremely likely* = 95–100% probability, *more likely than not* = >50–100% probability, and *extremely unlikely* = 0–5% probability) may also be used in the AR5 when appropriate.

Reference for Figure: IPCC, 2013: Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald and J.-G. Winther, 2013: Introduction. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Changes in Phenomenon	Uncertainty in observed changes (since about the mid-20th century)			Uncertainty in projected changes (up to 2100)		
IPCC Assessment Report	TAR	AR4	SREX	TAR	AR4	SREX
Higher maximum temperatures and more hot days	*Likely* over nearly all land areas	*Very Likely* over most land areas	*Very Likely* at a global scale	*Very Likely* over nearly all land areas	*Virtually Certain* over most land areas	*Virtually Certain* at a global scale
Higher minimum temperatures, fewer cold days	*Very Likely* over nearly all land areas	*Very Likely* over most land areas	*Very Likely* at a global scale	*Very Likely* over nearly all land areas	*Virtually Certain* over most land areas	*Virtually Certain* at a global scale
Warm spells/heat waves. frequency, length or intensity increases	-	*Likely* over most land areas	*Medium Confidence* in many regions	-	*Very Likely* over most land areas	*Very Likely* over most land areas
Precipitation extremes	*Likely*[1], over many Northern Hemisphere mid- to high latitude land areas	*Likely*[2] over most areas	*Likely*[3]	*Very Likely*[1] over many areas	*Very Likely*[2]	*Likely*[2,4] in many land areas of the globe
Droughts or dryness	*Likely*[5], in a few areas	*Likely*[6], in many regions since 1970s	*Medium Confidence* in more intense and longer droughts in some regions , but some opposite trend exists	*Likely*[5], over most mid-latitude continental interiors (Lack of consistent projections in other areas)	*Likely*[6]	*Medium Confidence*[7] that droughts will intensify in some seasons and areas; Overall *low confidence* elsewhere
Changes in tropical cyclone activity (i.e. intensity, frequency, duration)	Not Observed[8], in the few analyses available	*Likely*[9], in some regions since 1970	*Low confidence*[10]	*Likely*[8], over some areas	*Likely*[9]	*Likely*[11]
Increase in extreme sea level (excludes tsunamis)	-	*Likely*	*Likely*[12]	-	*Likely*	*Very Likely*[13]

Reference for Figure: IPCC, 2013: Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald and J.-G. Winther, 2013: Introduction. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.



Reference for Figure: IPCC, 2013: Stocker, T.F., D. Qin, G.-K. Plattner, L.V. Alexander, S.K. Allen, N.L. Bindoff, F.-M. Bréon, J.A. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J.M. Gregory, D.L. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. Krishna Kumar, P. Lemke, J. Marotzke, V. Masson-Delmotte, G.A. Meehl, I.I. Mokhov, S. Piao, V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L.D. Talley, D.G. Vaughan and S.-P. Xie, 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G. K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Part XII

Week 12

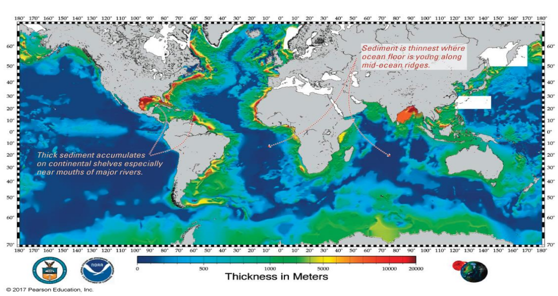
4-1-2019: Past Sea Level Change

Ocean Sediments

Ocean Sediments
are the accumulation of innumerable solid particles of many different types of materials that are deposited on the seafloor, by a process called sedimentation. These particles ranges in the size from 0.001 mm to 10 cm (with most in the lower end of the range)

Sediments cover all of the world ocean's seafloor except where fast currents have swept them clear. Accumulation rate very from 1mm/1000 years to 1m/year.

Global Sediment Thickness



Since sediments accumulate continuously, the newer material falls on top of and covers older material. Thus preserves a record of what happened at a location over time.

Differences in sediment structure, content, deposition rate can all tell us about past climates. We note though that this approach must assume that the sediments are unchanged over time)whether by bioturbation, erosion, seismic events)

- One key factor in examining the sediment record is considering fossils preserved in the sediments
- The temperature range that a species exists in at present may give a temperature range for the water at the time if the fossil's death
- Isotopic examination of calcareous sediments may provide further information

Oxygen Isotope Studies
The two most common isotopes of oxygen are O_{16} and the heavier O_{18}. Since lighter water is easier to evaporate than heavier water, water vapour is enriched in O_{16}.

When the Earth **cools**, water vapour condenses as snow and then ice into the polar ice caps, rather than being returned to the ocean. Thus, O_{16} is transferred to the glacier (meaning there is less of it in the oceans) and thus the oceanic ratio of O_{16}/O_{18} gets **smaller**.

When the Earth **warms**, the ice caps melt and lose some of their water, releasing the previously trapped O_{16} back to the atmosphere/ocean, increasing the amount of O_{16} in the ocean and thus the O_{16}/O_{18} ratio gets **larger**.

Heavy, O_{18} rich water condenses over mid-latitudes while they decrease rapidly over the poles.

We can examine the past oxygen isotope record in several ways:

- Gas bubbles in ice cores taken from glaciers can

show the atmospheric composition of each isotope at the time the air was trapped
- Organisms that live in the oceans incorporate both isotopes of oxygen into their shells as they grow (with the ratio depending on the temperature of the water where they lived)
  - When the organisms die, their shell material falls to the seafloor and is incorporated into the sediments. By examining the isotopic changes in cores recovered from the sediments, we can examine past climate changes

Sea Level Change and Climate

The Earth's temperature has varied over its lifetime

- $\approx$ 0.5 C over the last 1000 years
- 2-3 C over the last 10,000 years
- 10 C over the last 2-3 million years

The period of large cooling is known as the Ice Ages, as the polar ice sheets extended to much lower latitudes.

The reason for changes in climate are many, varied and complex. They can produce significant changes in the oceans and their interactions with the land. We are also not considering continental drift.

Eustatic Sea Level Change

- When a climate cools, the oceans cool and contract and polar ice sheets expand as water is transferred to the land as snow and ice.
- Conversely, in warm periods, the oceans expand as heating melts the ice and snow, which then flows to the ocean, rising sea level.
- Such changes are called Eustatic and occur synchronously throughout the world.

Weight of overlying ice sheets can press down the continental crust underneath. Why?

The continents float on the Earth's Asthenosphere, a fluid level below the earth's crust, such that adding more weight causes the object to be pressed down, as if weight is added to a log floating in water

When the ice melts, the continent begins to rise. These processes thus change sea level.

Note
Only affects the continent in question, not the entire globe, it is also a very slow process very slow and may take millions of years.

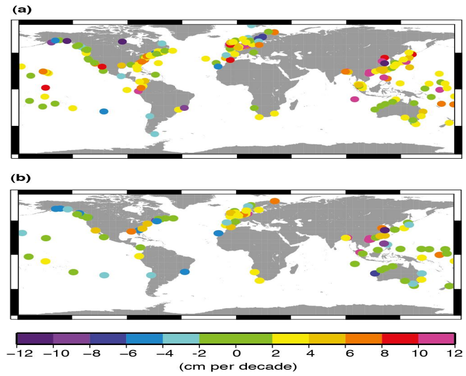
Steric Sea Level Change

- As the ocean temperature changes, so does the density
  - Warming leads to a decrease in density
  - With a constant mass, a density decrease leads to a volume increase
- Thus steric sea level rise is the change in sea level due to changes in ocean volume (from temperature changes)
- This steric sea level rise occurs at all ocean temperatures and is one of the major contributors to sea level changes during the 20th and 21st centuries.
- Water as higher temperatures or under greater pressure (i.e., at greater depth) expands more for a given heat input, so the global average expansion is affected by the distribution of heat within the ocean.
- Salinity changes within the ocean also have a significant impact on the local density and thus local sea level, but have little effect on global average sea level change.

4-3-2019: Waterworld - Potential Future Sea Level Change

In the movie Waterworld, melting of all the ice in the glaciers and the polar ice caps caused the oceans to expand and cover all the land surface on the Earth except a few small islands. Is this possible?

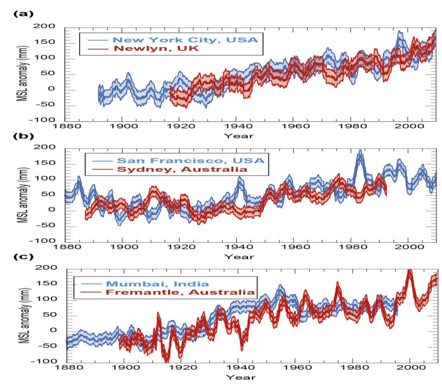
In short, No. If all the ice melted then it would increase the sea level by about 62.2 m. The mean land elevation is 840 m.



Reference for Figure: IPCC, 2013: Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley and F. Wang, 2013: Observations: Ocean. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Sea level and climate change

- Antropogenic warming will cause sea level to rise as ice melts.
- Rate of sea level rise is between 1.5 mm/year to 3.5 mm/year
  - Unless the ice caps melt (presently though unlikely in the near term), sea level will be in the 10's of cm's (to 1 meter) over the next century.



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Tide gauges

These were the tide gauges for the global mean sea level

TIDE GAUGE-BASED
SEA LEVEL RISE
FOR THE 20th CENTURY
Global

- **1.5 +/- 0.5 mm/yr (IPCC, 2001)**
- **1.71 +/- 0.55 mm/yr (Douglas, 2001; 27 sites)**
- **1.84 +/- 0.35 mm/yr (Peltier, 2001; 27 sites)**
- **1.5 +/- 0.4 mm/yr (Tamaseia et al., 2001; 23 sites)**

Pros.

- Historical information (back to 1900)
- Useful for calibrating onboard altimetry systems

Cons.

- Heterogeneous and limited coverage
- gaps in data records
- land motion contamination
- data sensitive to local perturbations

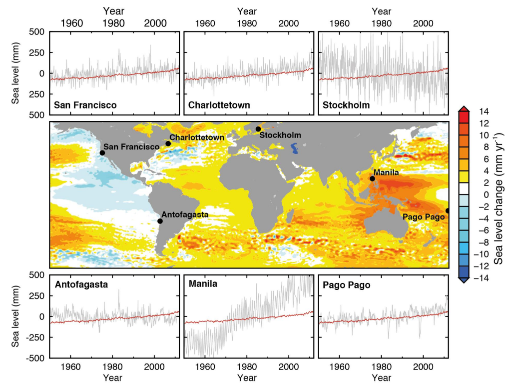
Satellite Altimetry

Pros.

- High-precision
- High spatio-temporal resolution
- global coverage
- absolute measurements

Cons.

- time series still short (20 years)
- no coverage of high-latitude oceans



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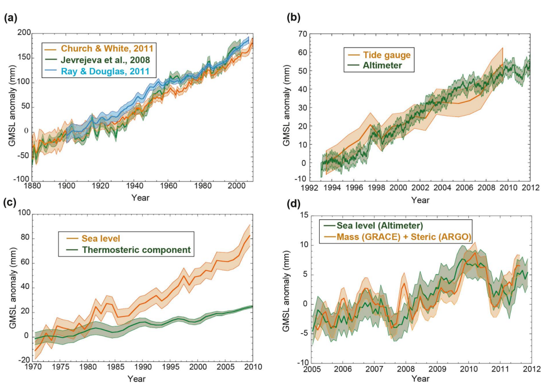

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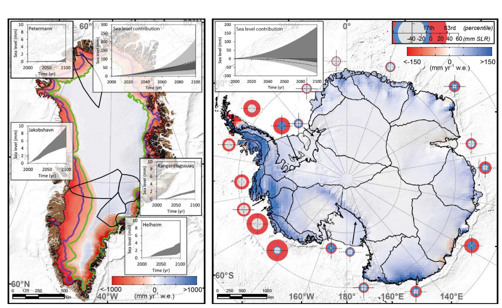
Eustatic Changes from Ice Sheets



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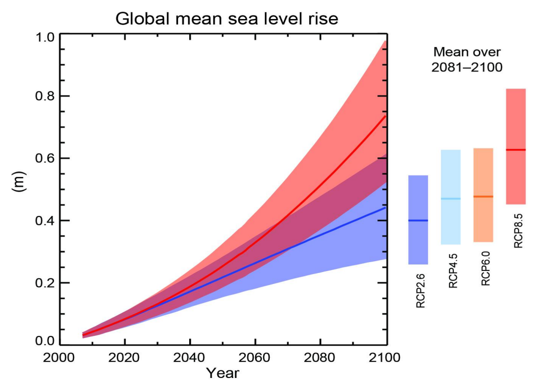

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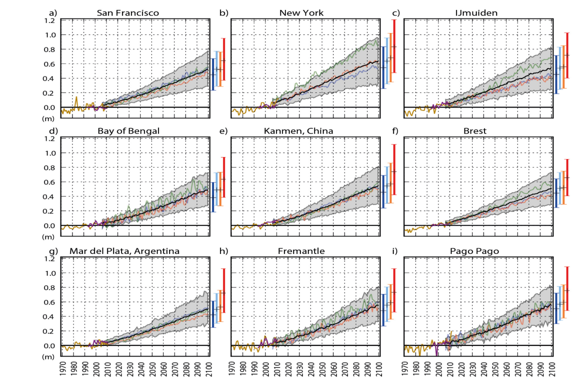

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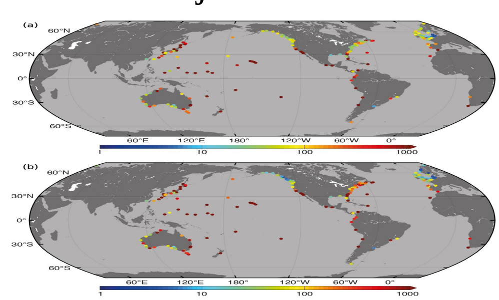
Enhanced Flooding Risk During Major Events



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Basically if this keeps on happening the coast lines are fucked.

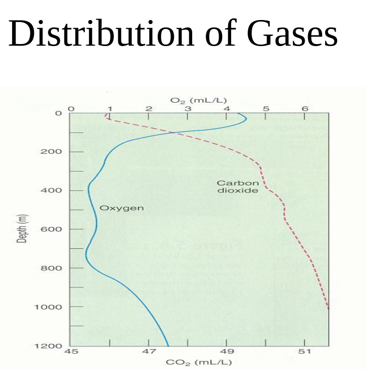
4-5-2019: Dissolved Gases and Oceanic CO2 Uptake

Dissolved Gases

- Gases freely move between the ocean and the atmosphere at the sea surface (and only at the sea surface)
- Direction of exchange governed by the saturation solubility and the concentration of the gas in seawater
- **Saturation Solubility**: The maximum amount of gas that can be dissolved in water at a given temperature, salinity and pressure.
  - If the seawater is under-saturated then transfer is from the atmosphere to the ocean
  - If the seawater is over-saturated then transfer is from the ocean to the atmosphere

Solubility increases with

- Decreasing temperature
- Decreasing salinity
- Increasing pressure



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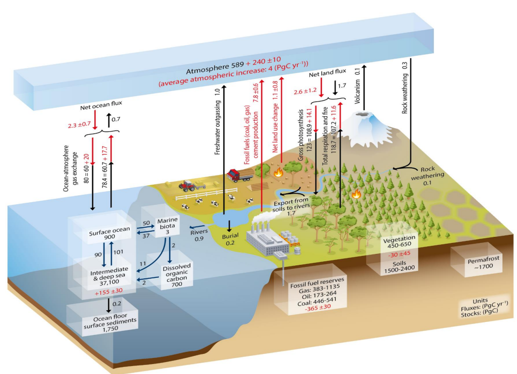
In the ocean proportions of dissolved gases primarily changed by biogeochemcial processes.

- In the photic zone (the region of teh ocean penetrated by light), CO2 is consumed and O2 produced by photosynthesis
- In the deep ocean, oxygen is used by respiration and decomposition, with these processes producing excess CO2 as a by-product.

Implications

- Low CO2 near the surface means that the ocean can take more CO2 from the atmosphere
- Meanwhile, high CO2 in the deep ocean is far from the sea surface and thus trapped, unable to escape back to the atmosphere. These two facts are important climate implications, as the ocean can store away CO2 for a period of time.
- Deep oceans can also hold more CO2 as saturation solubility increases with increasing pressure and decreasing temperature.
- The fact that saturation solubility increases with decreasing temperature also has an effect on oxygen supply within the oceans
- O2 concentrations are high in polar water and thus those regions are often rich in life
- O2 concentrations are often low in tropical waters, leaving those regions vulnerable to processes that consume oxygen



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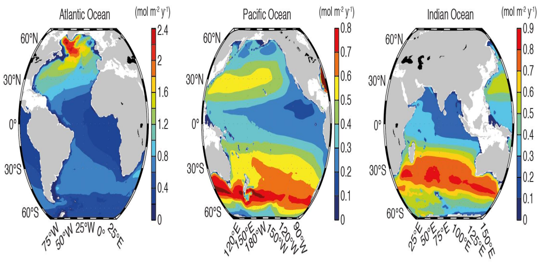
Anthropogenic Carbon Fluxes



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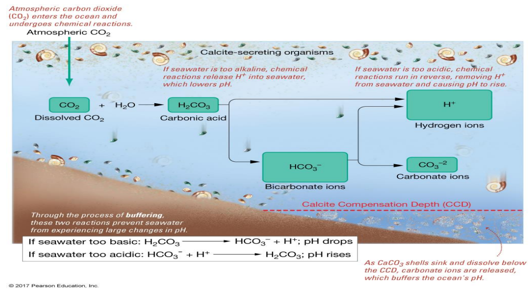
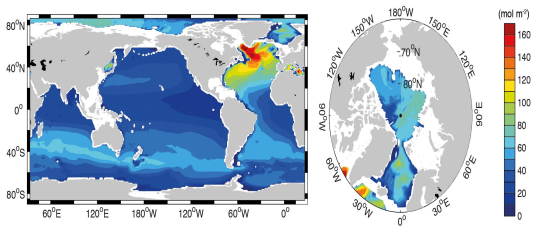
Carbonate Buffering System

https://goo.gl/ZsCngq



Column Inventories of CO_2



Reference for Figure: **IPCC**, 2013: Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley and F. Wang, 2013: Observations: Ocean. In:*Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

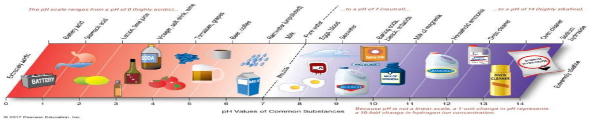
Impacts of Ocean Acidification

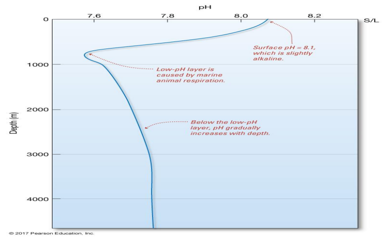
Ocean acidification

When CO2 is combined with water is creates carbonic acid. As it is an acid it decreases the PH in the ocean which affect coral rifts and shellfish. As CO2 in the water increases it decreases the PH.

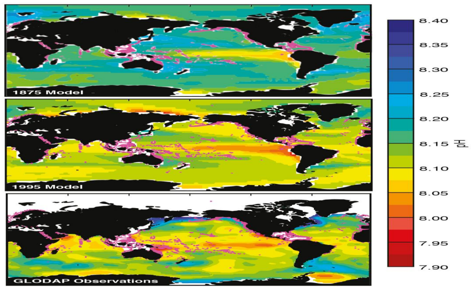
PH and the Ocean

Web Link: https://goo.gl/58UuLh





Ocean PH Changes



Reference for Figure: **IPCC**, 2013: Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley and F. Wang, 2013: Observations: Ocean. In:*Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

It takes about 1-10 years for the carbon to be cycled from the atmosphere to the ocean surface. 100-2000 years from deep sea.

Around 1-100 years from vegetation and 10-500 years from the soil.

Part XIII

Week 13

4-8-2019: Day After Tomorrow Scenarios

Premises

Global warming leads to abrupt climate change occurring over several days/weeks

- Leads to start of new ice age and ice sheets covering much of North America
- Giant hurricanes descend from the Arctic freezing people with −150F temperatures

Massive snow storms batter tropical parts of the world (New Delhi India in the movie)

- 40 foot storm surge strikes New York
- tornadoes and other extreme weather strikes places not normally exposed to them

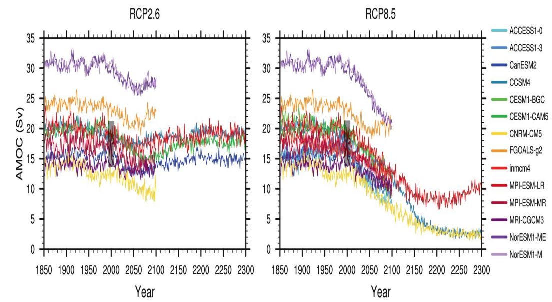
Antarctic ice sheet breaking off causes sea level to rise

Changes to the Conveyor

Can the conveyor be shutdown? No! But it can be weakened. Reason: As the last ice age ended and climate warmed, the ice cap started to melt. This formed a large freshwater lake, Lage Agassiz, around where the Great Lakes presently are.

One Scenario for the Younger Dryas

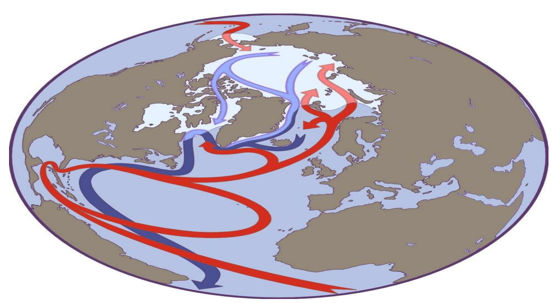
- As Lake Agassiz began to drain, water initially flowed out via the Mississippi
- As the ice retreated, water could retreat through the St. Lawrence valley
- This pumped large amounts of freshwater out in to the North Atlantic
- The surface water density thus decreases
- This meant no deep sinking and a weakening of the conveyor
- With the conveyor weakened, the return flow of water to the north (and thus heat) was weakened
- This continued until all the freshwater was mixed in and cold temperatures allowed convection to start again



Atlantic MOC variability from models

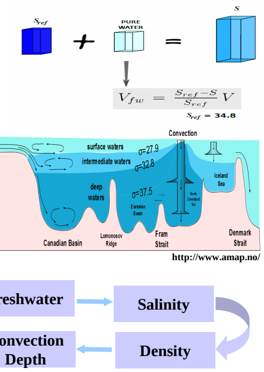
Reference for Figure: IPCC, 2013: Stocker, T.F., D. Qin, G.-K. Plattner, L.V. Alexander, S.K. Allen, N.L. Bindoff, F.-M. Bréon, J.A. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J.M. Gregory, D.L. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. Krishna Kumar, P. Lemke, J. Marotzke, V. Masson-Delmotte, G.A. Meehl, I.I. Mokhov, S. Piao, V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L.D. Talley, D.G. Vaughan and S.-P. Xie, 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G. K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

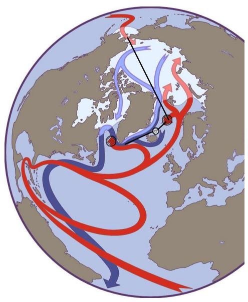
AMOC and Arctic



Holloway, 2002

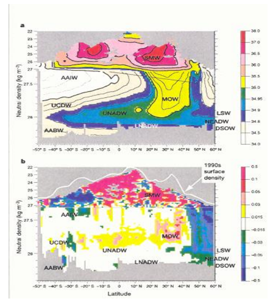
Arctic-Atlantic Links



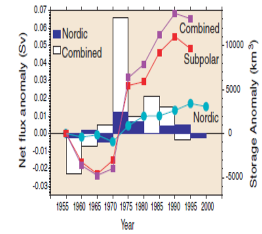


Holloway and Proshutinsky 2007

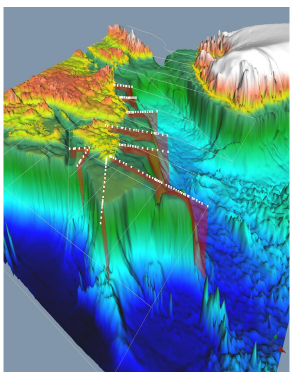
Meridional Atlantic Salinity Changes

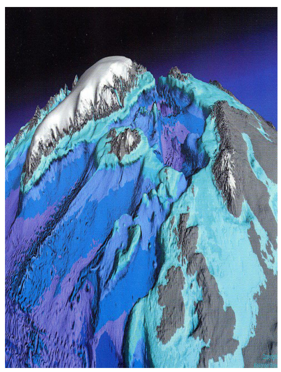


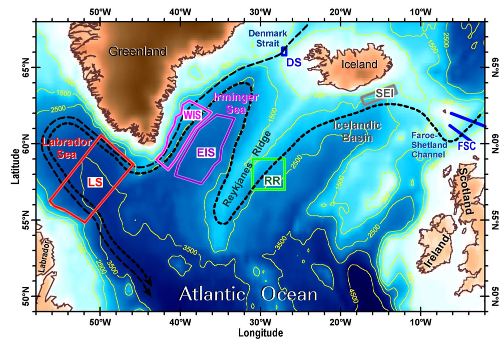
Curry et al., 2003



Curry and Mauritzen, 2005

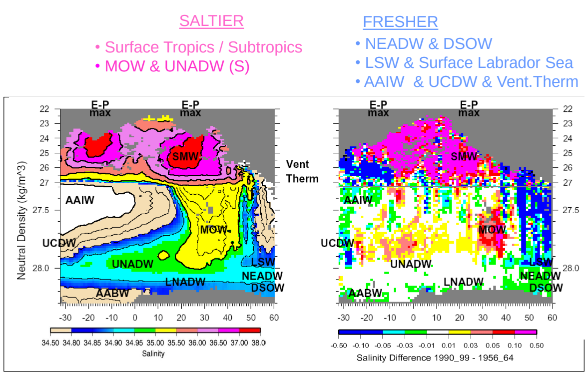




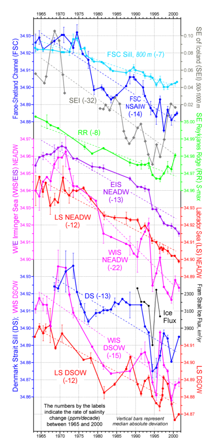


…so that if we construct salinity time series at intervals along the spreading pathways of both overflows from their sills to the deep Labrador Sea…

ATLANTIC WATER MASSES 1990-99 minus 1956-64



Curry, Dickson & Yashayaev, 2006

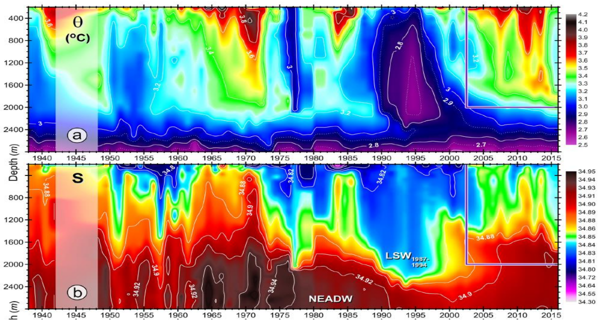


… we find that the entire system of overflow and entrainment that ventilates the deep Atlantic has undergone a remarkably rapid and remarkably steady freshening over the past four decades.

A change in the ocean-climate of sub-arctic seas has thus been transferred to the deep and abyssal ocean at the headwaters of the "Great Conveyor"

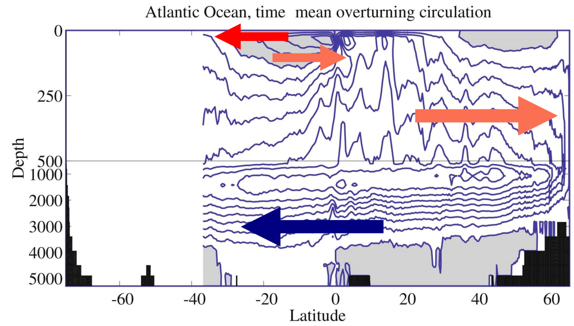
Dickson et al 2002

Labrador Sea Evolution



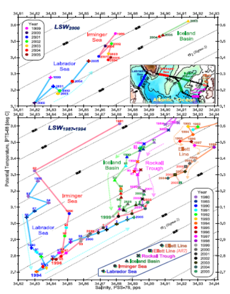
Yashayaev and Loder, 2016

Meridional Overturning Circulation (MOC)

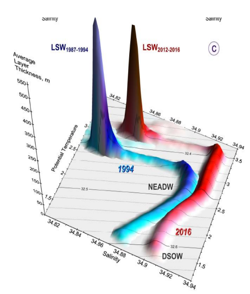


Jayne & Marotzke 2001

LSW Properties



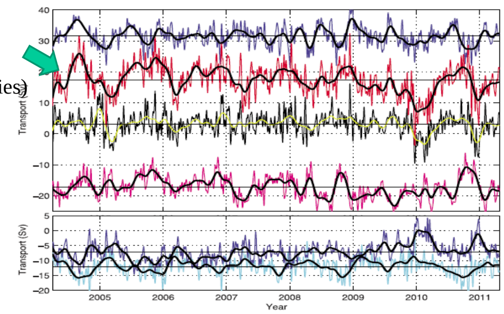
Yashayaev et al., 2007



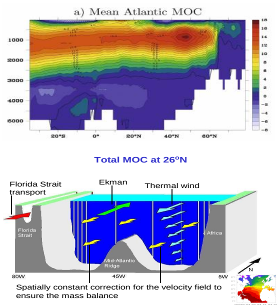
Yashayaev and Loder, 2016

Temporal Variability of the Atlantic Meridional Overturning Circulation at 26.5°N

AMOC (red timeseries)

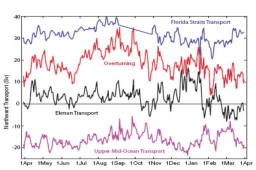


MOC Strength



Rapid Array – from Hirschi et al., 2006

Kohl and Stammer, 2008 – ECCO Reanalysis



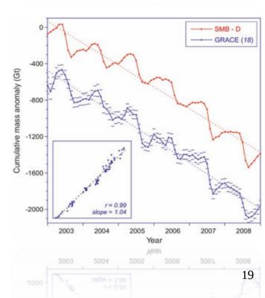
Cunningham et al., 2007 – Rapid Array, March 04 to March 05 – Overturning: 18.7 ± 5.6 Sv

Observations show Greenland ice sheet is melting.

- Mass loss trend:
  (Straneo and Heimbach 2013. Science)
  - 1992-2001 (+50 km^3/yr)
  - 2002-2011 (+211 km^3/yr)
  - 2003-2008 (+237 km^3/yr)

Estimated mean mass loss ~ 550km^3/yr
(Dickson et al. 2007)

Cumulative mass loss 2003-2008



van den Broeke et al. 2009, Science

19

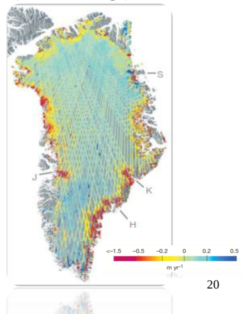
Observations show Greenland ice sheet is melting.

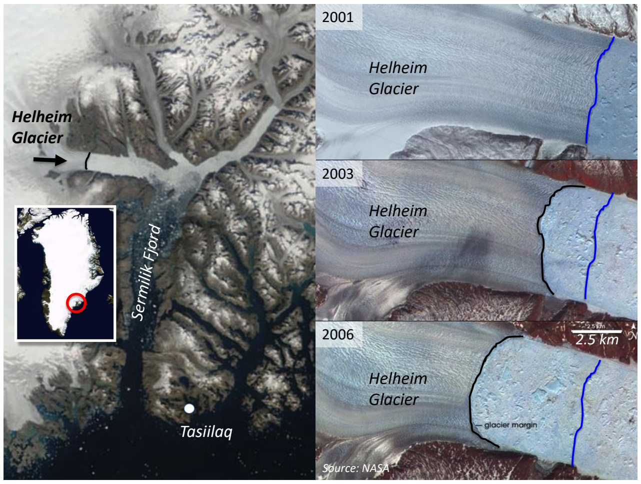
– Prominent thinning

–

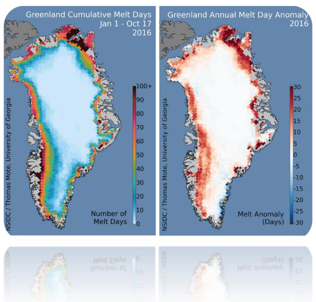
- Northwest and
- Southeast ice-sheet margins
-
- Rate of change on red areas is -0.8 to -0.2 m/yr

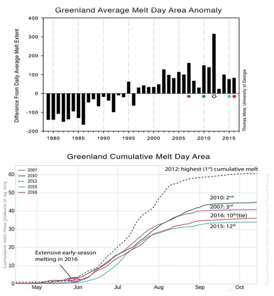
Surface elevation (rate of change)





Melting Enhanced on Greenland Ice Sheet (GrIS)

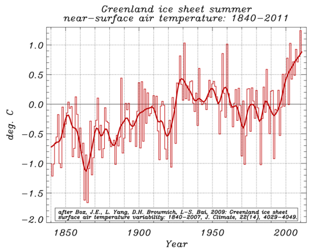


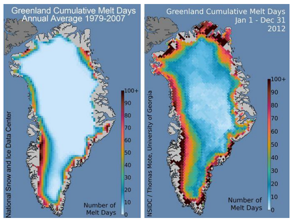


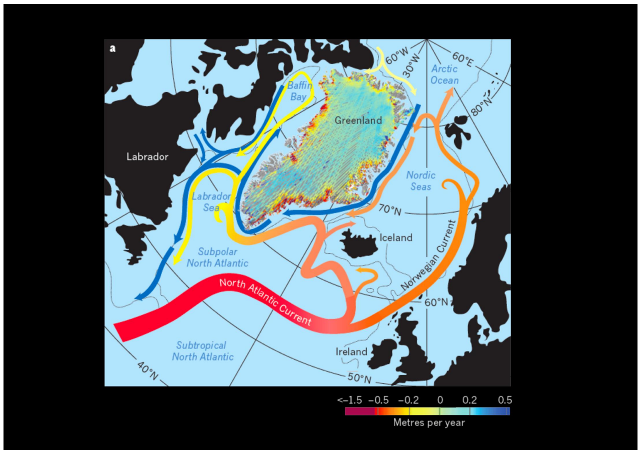
Examples of Oceanic Variability Impacting Greenland Glaciers

1. Sub-Polar Gyre Circulation impacted by the North Atlantic Oscillation
2. Changes transport of warm salty water within gyre, to west coast of Greenland
3. Changed winds also drive this water onshore, into Greenland Fjords
4. Added heat in deep waters of fjord impacts and leads to rapid glacier melt

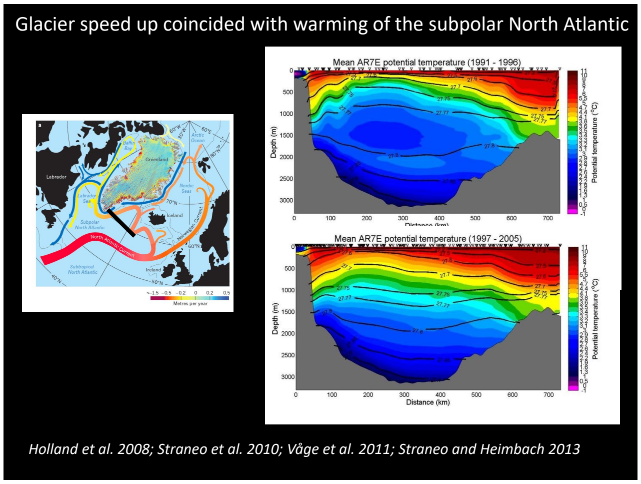
Increased surface melt from rising air temperatures ~½ of loss

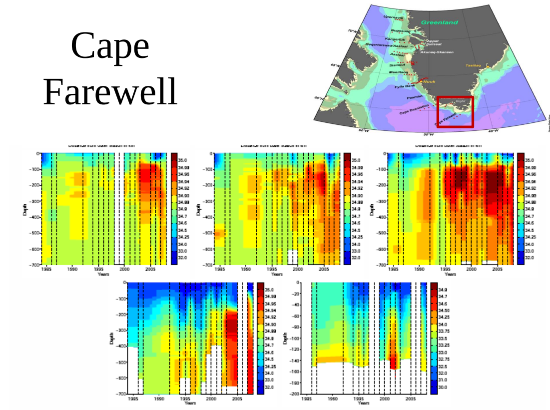




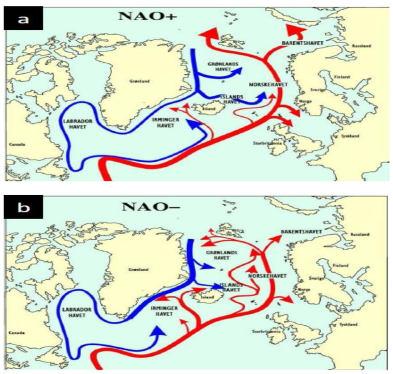


(Pritchard et al. 2009; Straneo & Heimbach 2013)

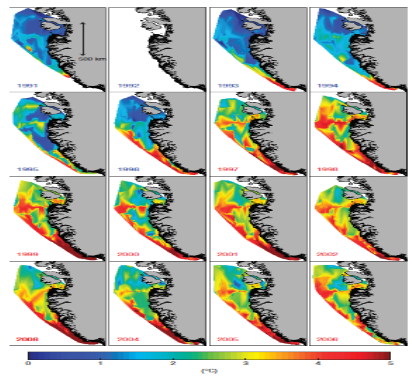




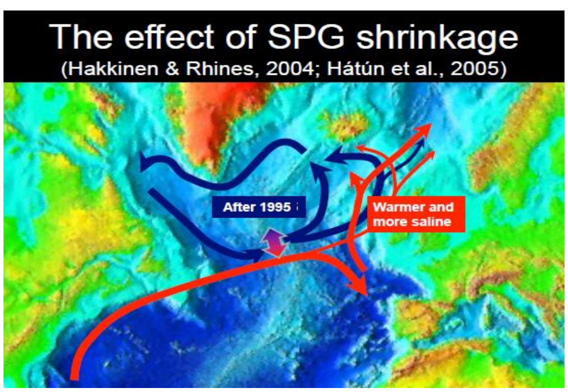
Myers et al., 2009, Progress in Oceanography



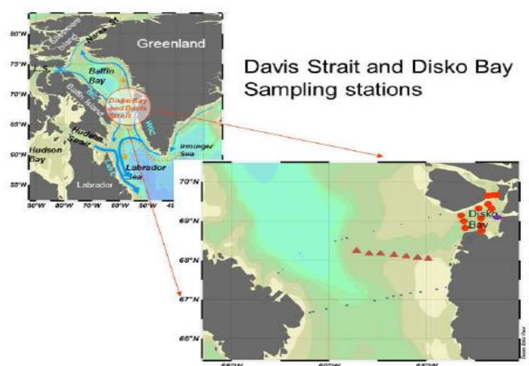
Holland et al., 2008, Nature Geoscience



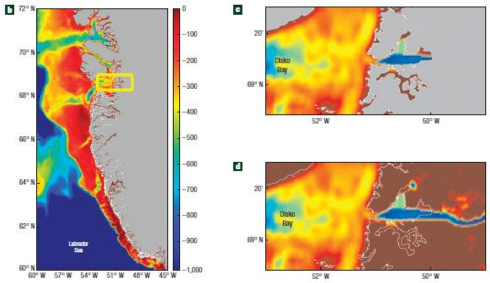
Holland et al., 2008, Nature Geoscience



Hansen, 2013

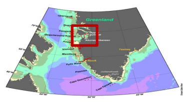


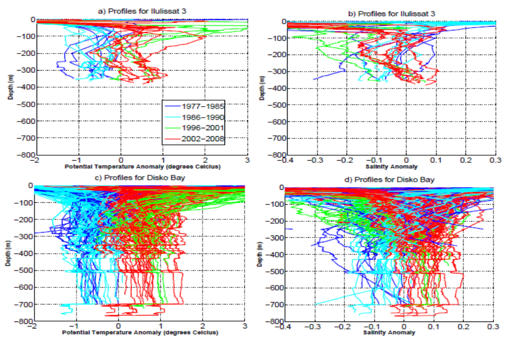
Myers and Ribergaard, 2013, JPO



Holland et al., 2008, Nature Geoscience

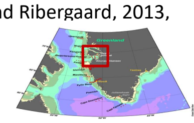
Disko Bay Profiles

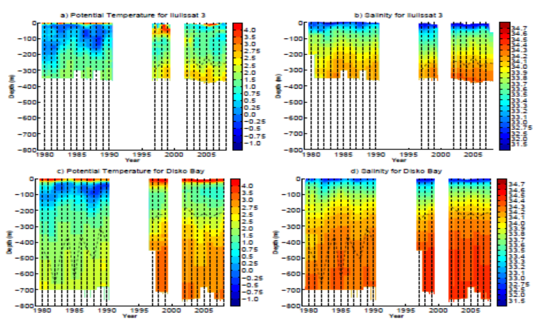




Myers and Ribergaard, 2013,

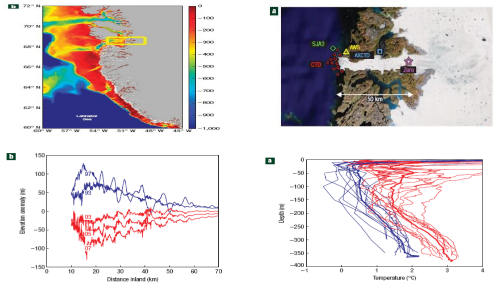
Disko Bay Temperature and Salinity



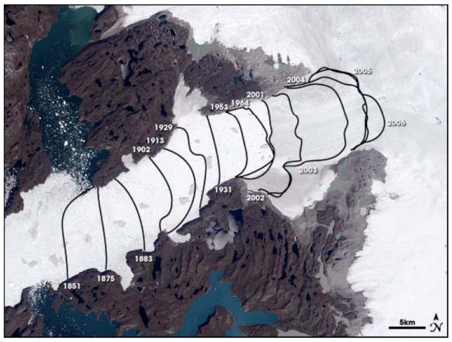


Myers and Ribergaard, 2013,

Irminger Water and Glacier Melt



All Figures: Holland et al, 2008: Nature Geoscience



Holland et al., 2008, Nature Geoscience

Review

1-9-2019

- difficulties in studying the ocean
- techniques for measuring bathymetry and how they work i.e., soundings, stat altimetry

1-11-2019

- Techniques for property sampling
- current measurements, indirect and direct -> active vs passive

1-14-2019

- earth's heat budget -> concept of albedo, greenhouse effect
- heat fluxes
- distribution of incoming radiation
- ocean surface water properties

1-18-2019

- Sea surface temp
- basic biogeochemical cycle ideas
- salinity definition
- dissolved chemicals
- sea surface salinities

1-21-2019

- Waves

1-23-2019

- Shallow water Waves
- tsunamis

1-25-2019

- atmosphere-ocean links
- basics on the Coriolis effect

1-28-2019

- further details on the Coriolis effect
- Large scale atmospheric circulation

1-30-2019

- Heat properties of water
- Transmission of light
- Sound transmission

2-1-2019

- Mixed layer, density and the pycnocline

2-6-2019

- Wind-driven currents

2-8-2019

- Geostrophic Currents

2-11-2019

- Ice

2-13-2019

- Basic ideas of Pacific circulation
- Equatorial surface circulation
- Indian ocean monsoon

2-15-2019

- International ARGO Program
- Applications

2-25-2019

- Gyres
- Western Boundary Currents
- Eddies and Rings

2-27-2019 to 3-1-2019

- Tides

3-6-2019

- Upwelling and downwelling
- Ocean vertical structure
- Water formation

3-8-2019

- Definitions of thermohaline circulation basic structure of Atlantic ocean including main water masses and their abbreviations
- reasons why Atlantic is saltier than Pacific
- deep water dispersal
- structure of ACC
- Antarctic water formation

3-13-2019 to 3-25-2019

- Basic structure of the arctic ocean
- freshwater in the northern ocean system
- ice/albedo feedback

3-15-2019

- Ocean circulation and climate
- Thermohaline circulation

3-18-2019

- Marine pollution

3-20-2019

- computer modeling

3-22-2019

- Hurricanes

3-27-2019

- ENSO
- North Atlantic Oscillation

3-29-2019

- Basic ideas and observations associated with global warming
- what processes are important
- impact of climate changes on distributions of properties and changes in the likelihood of extreme events

4-1-2019

- Sediment records
- sea level

4-3-2019

- Waterworld - can we cover the world with sea-ice if we melt all land ice -> short answer no
- present sea level changes
- tide gauge vs sat measurements

4-5-2019

- How dissolved gases taken up by the ocean
- factors that affect dissolved gas concentrations in the ocean

4-8-2019

- Thermohaline conveyor stability
- Large-scale oceanic climate variability
- Ocean impacts on glaciers and ice shelves

Professor's Villains

First Midterm Champion

Large paper psychic, neutral evil

Armor Class 20
Hit Points 35
Speed 50 minutes

STR	DEX	CON	INT	WIS	CHA
23 (+6)	14 (+2)	21 (+5)	16 (+3)	13 (+1)	20 (+5)

Senses —
Languages Oceans, physics
Challenge 8 (3,900 XP)

Coverage

This will only cover content from Chapters 1-7-2019 to 2-1-2019.

Composition

Multiple Choice. There are 25 MC question on the midterm.

Short Answer. There are 4 short answer question on the midterm.

Second Midterm Champion

Large paper psychic, neutral evil

Armor Class 20
Hit Points 35
Speed 50 minutes

STR	DEX	CON	INT	WIS	CHA
23 (+6)	14 (+2)	21 (+5)	16 (+3)	13 (+1)	20 (+5)

Senses —
Languages Oceans, physics
Challenge 8 (3,900 XP)

Coverage

This will only cover content from Chapters 2-6-2019 to 3-8-2019.

Composition

Multiple Choice. There are 25 MC question on the midterm.

Short Answer. There is 3 short answer question on the midterm. Total: 10 marks

Final Foe

Gargantuan paper psychic, neutral evil

Armor Class 60
Hit Points ?
Speed 120 minutes

STR	DEX	CON	INT	WIS	CHA
30 (+10)	14 (+2)	29 (+9)	18 (+4)	17 (+3)	28 (+9)

Senses —
Languages Oceans
Challenge 23 (50,000 XP)

Coverage

Everything

Composition

?

Legend

Armor Class is the weight as a percentage of the final grade.

Hit Points is the amount of marks.

Speed is the duration of the exam/assignment.

Credits

General

- Created by u\DnD_Notes, March 2019
- Typesetting engine: LaTeX
- Dungeon and Dragon (5e) LaTeX Template

Art

- Kraken for the cover art is from D&D Beyond
- Andy the D&D Ampersand is from Dungeon and Dragons
- Cover art formatting: Photoshop CC 2019

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