"On my honour as a member of the Democratic Order of Pirates International (D.O.P.I), I promise to be greedy, tricky, mean and icky. . . "

"The Pirates Pledge"
from the cartoon
"'The Adventures of Dr.Doolittle" (1970)

(Watch Dr. Doolitle on YouTube)

– Basic Ocean Navigation –

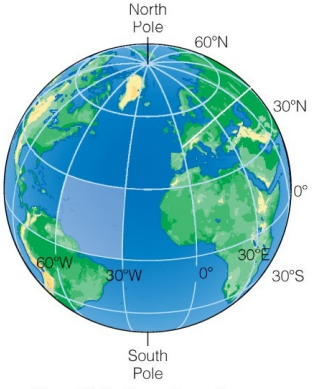
For Aspiring Pirates, Privateers and other Adventures. . .

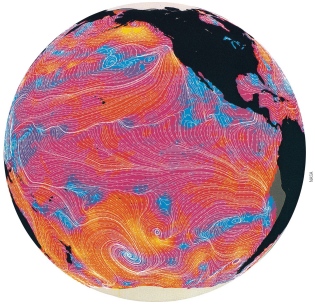
Chammika Udalagama
Department of Physics
Special Programme in Science

October 9, 2017
@ LT09

Please visit: http://physics.nus.edu.sg/how/piracy/

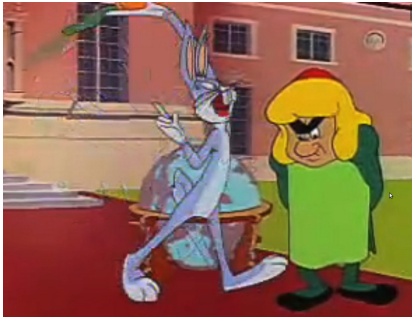
Lecture Objectives. . .





- Add a scientific context to what you are learning in GEK2049/GEH1013.
- Give you an appreciation of how challenging it was to be out in the ocean.
- After this lecture you should:
  - be able to use Polaris to determine your latitude.
  - be able to use the sun and a watch to determine longitude.
  - explain why maps are never perfect.
  - explain how the trade winds and monsoons are formed.
  - explain how ocean currents are formed.

The world, she is flat. . .



Video 1: Bugs Bunny proves the world is round.
(Watch YouTube The World She is a flat...)

Figure 1: Terry Practhett's 'Discworld'.

A Quick Question

On an adventure trip you come across a people that know nothing of satellites (remember 1959 is not that long ago). How will you convince them that the Earth is not flat like 'Discworld'? (Perhaps not the way Bugs does. . . ☺)

Did you know that the Earth is Spherical?

Figure 2: A ship 'disappearing' over the horizon.

Figure 3: Photos of Earth's Shadow by Anthony Ayiomamitis.

A Quick Question

Can you think of a way to estimate the size of the Earth?

Home

Figure 4: 'The Blue Marble' - By the crew of Apollo 17 (1972)

Figure 5: 'The Blue Marble' - Using the satellite MODIS (2002)

- First satellite image of Earth in 1959!
- Have a play with Google Earth.

Home

A Lunar Perspective. . .

Figure 6: Image of the Earth taken from the moon by crew of Apollo 11 (1969).

Eratosthenes

- Eratosthenes of Cyrene (276 BC - 194 BC) was the second librarian of the great Library of Alexandria.
- Eratosthenes figured out that the Earth was spherical and estimated the circumference to within 8%, over 2000 years ago!!!

Figure 7: Portrait of Eratosthenes

Watch ERATOSTHENES on YouTube.

The Size of the Earth

- Eratosthenes used a deep well, a long pole, some simple geometry and a lot of ingenuity and powers of observation to figure out the circumference of the earth.

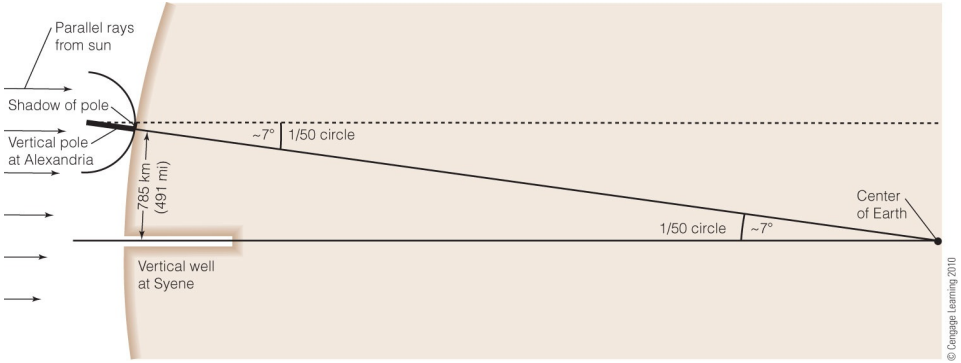


Figure 8: The idea behind Eratosthenes' method to determine the circumference of the Earth.

A Quick Question

If Eratosthenes had been in Singapore (☺), how well do you think would have his method worked?

Some Features of our Home

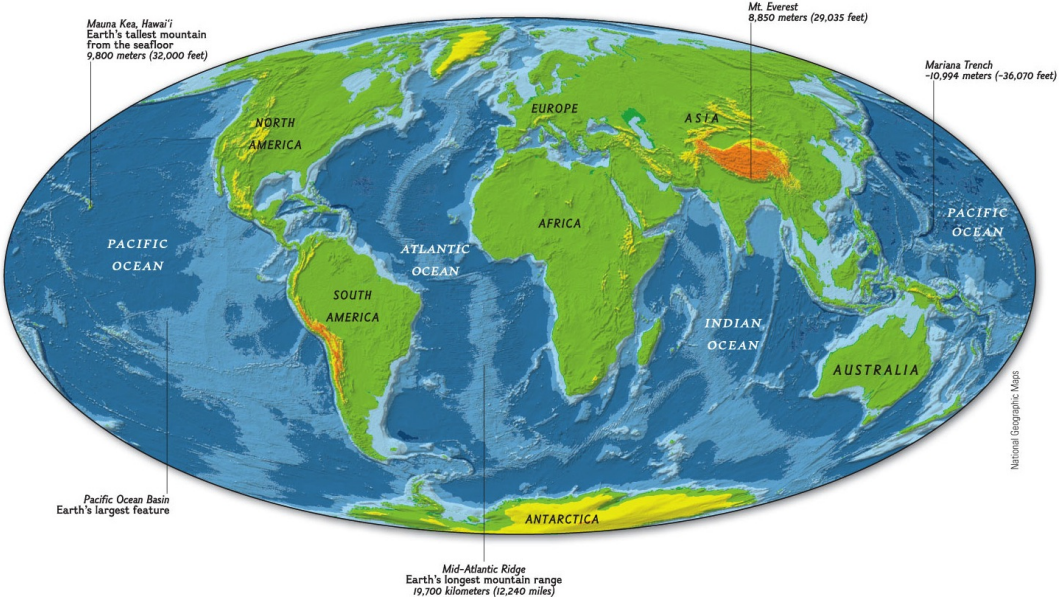


Figure 9: Locations of some significant features of our home.

Some features. . . the xkcd way

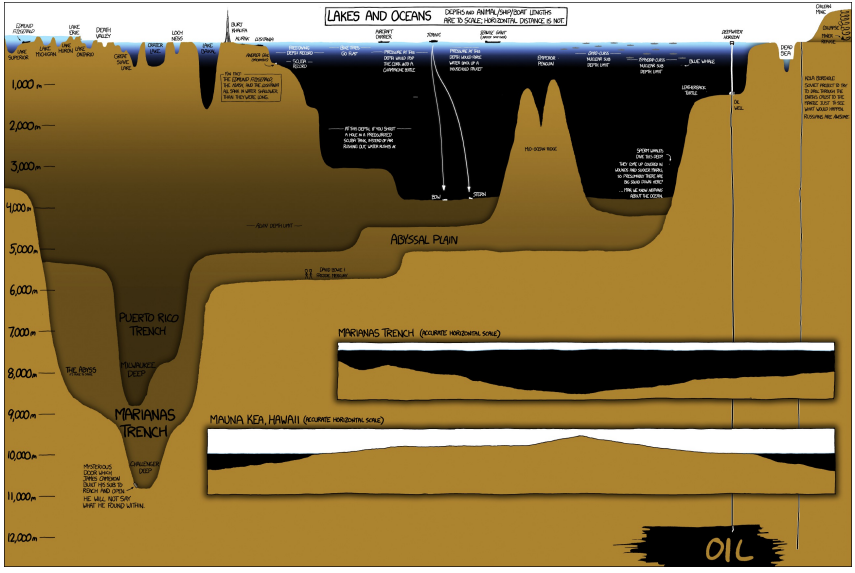


Figure 10: ☺

The Ocean at a Glance

Ocean	Avg. Depth(m)	Max. Depth(m)	Area (sq. km)	Boundary	Features
Arctic	990	5,669 (Molly Deep)	8,676,520	66 N to 90 N Circumpolar	3%, 50,000 icebergs/year, Polar bears, Northwest passage
Southern	3,239	7,412 (South Sandwich Trench)	20,973,318	60 S to 85 S Circumpolar	6.5%, -89 C, largest ocean current, permanent ice
Indian	3,897	7,125 (Java Trench)	67,469,539	25 N to 60 S 20 E to 145 E	20%, Ninetyeast ridge, Growing, Red sea, hydrothermal vents, Y shaped ridge
Atlantic	3,408 (North) 3,967 (South)	8605 (Puerto Rico Trench)	41,258,837 (North) 40,446,560 (South)	60 S to 60 N 98 W to 2 W 70 W to 20 E	25%, Mid-Atlantic Ridge, Mediterrenean, Lost City, Bay of Fundy, Chicxulub Crater, Caribbean, Growing
Pacific	4,573 (North) 3,935 (South)	10,920 (Challenger Deep)	68,907,910 (North) 83,709,249 (South)	60 S to 64 N 130 E to 30 W 145 E to 70 W	46% , Black smokers, Shrinking, Panthalassa, Half subducted, Ring of Fire, Mauna kea

Table 1: Borders, depths and other details of the five oceans.

How deep is your. . . home

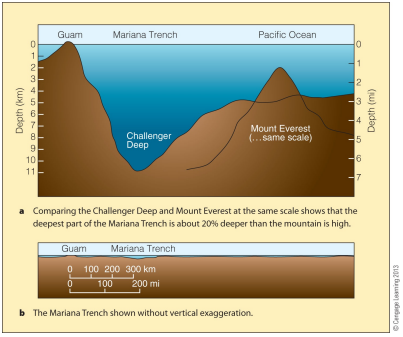


Figure 11: Comparing the highest and the deepest.

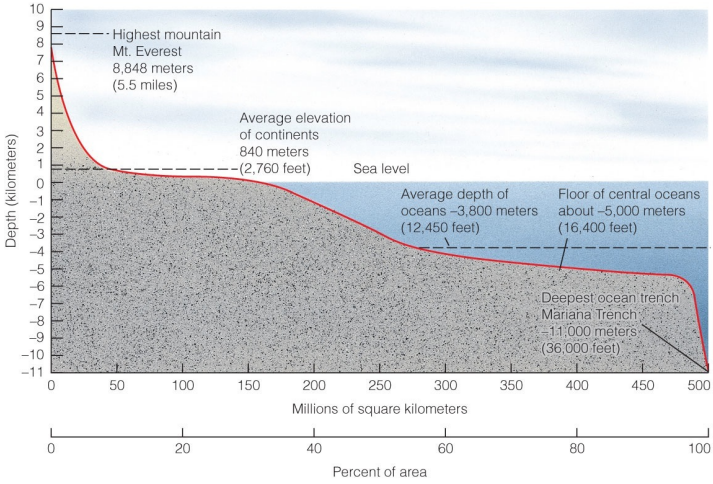
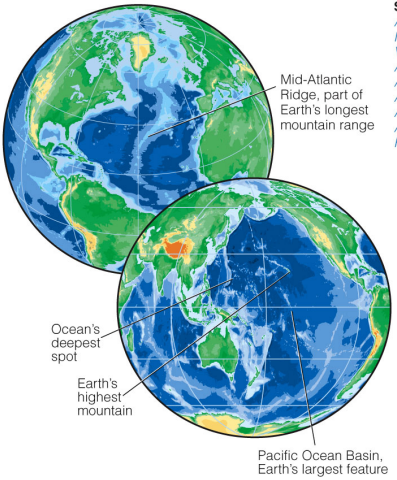


Figure 12: How the area of the Earth is distributed in elevation/depth.
Notice that more that 50% of our planet is under more than 3 km of water!

Water: Not a little, Not a lot, Certainly Not 71%?



Some Statistics for the World Ocean

Area: 361,100,000 square kilometers (139,400,000 square miles)
Mass: 1.41 billion billion metric tons (1.55 billion billion tons)
Volume: 1.33 billion cubic kilometers (329 million cubic miles)
Average depth: 3,682 meters (12,081 feet)
Average temperature: 3.9° (39.0°F)
Average salinity: 34,482 grams per kilogram (0.56 ounce per pound), 3.4%
Average land elevation: 840 meters (2,772 feet)
Age: About 4 billion years
Future: Uncertain

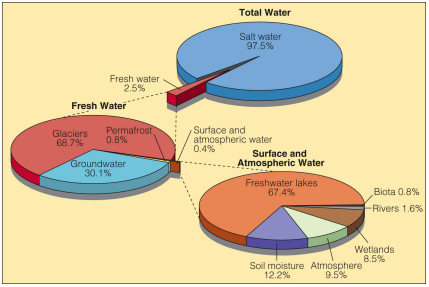


Figure 13: Some water statistics.

A Point to Ponder

Where do you think all this water came from? Does the Earth lose water?

I live here...! Here?

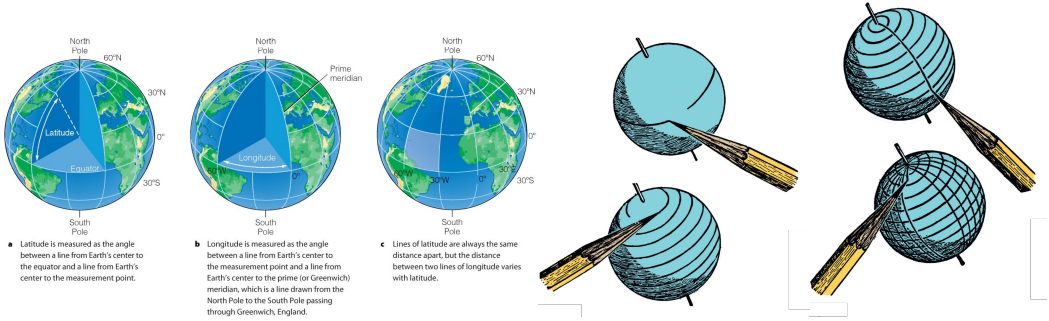


Figure 14: 'axes' and 'coordinates' to specify where we are on a globe...

- The Earth, being a ball, has no boundaries, so specifying location is not obvious.
- So we (actually Eratosthenes) draw a graticule to help us pin-point places.
- These are the **latitudes** (parallels) & **longitudes** (meridians).
- In this scheme the Earth is split into 360 parallels & meridians.

Where is Zero?

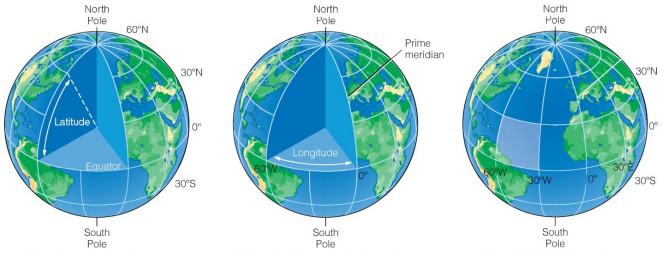


Figure 1: 'axes' and 'coordinates' to specify where we are on a globe...

- An obvious choice for zero latitude (parallel) is the equator.
- There is no such obvious choice of zero for the longitudes (meridians).
- It is agreed that the **prime meridian** (i.e. zero longitude) is that meridian passing through Greenwich, England (This was not always the case).
- Read Dave Sobel's (fantastic) *Longitude...* [Sob95] for more (juicy) information.

A Point to Ponder

Do you think a simple (x, y) Cartesian system of coordinates will work?

Where in the World Are We?!

- The North Star (Polaris), can be used to determine latitude of a location in the northern hemisphere.

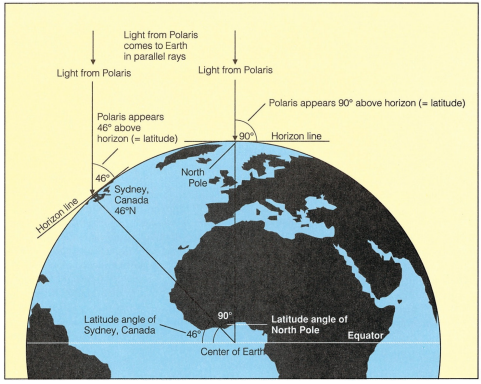


Figure 15: The North Star can be used to determine latitude.

Figure 16: The Earth's axis of rotation points at the North Star.

Using the North Star for Latitude

Its all in the angles. . .

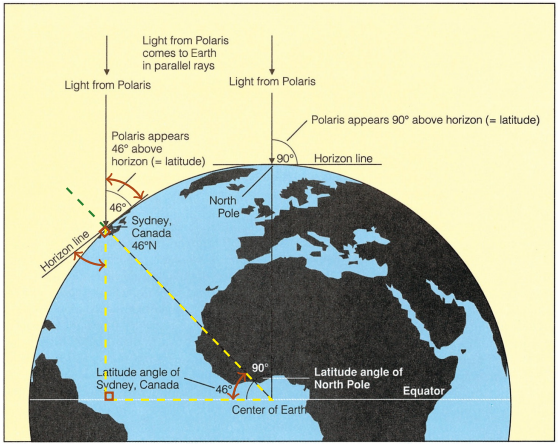


Figure 2: How to determine latitude using Polaris

A Point to Ponder

What do we do in the southern hemisphere? Is there a 'South' star?

Parallels & Meridians

- Latitudes and longitudes are given in degrees and by referring to **N** or **S** and **E** or **W**.
- E.g. Singapore is approximately at:
  1°N 103° E
- Further refinement is obtained by using minutes (′) and seconds (″).
- $1° = 60'$ and $1' = 60''$
- E.g. Singapore is 'exactly' at:
  1°17'N 103°50'E

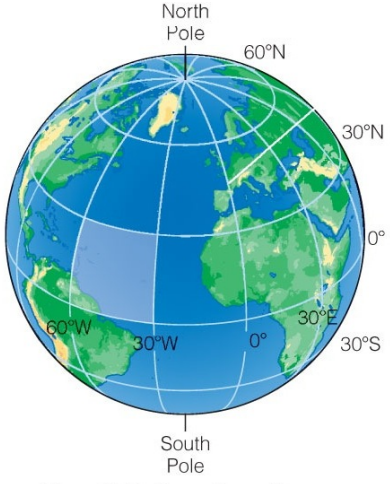


Figure 17: Location can be specified using angles.

This Minute is Not the Same as that Minute. . .

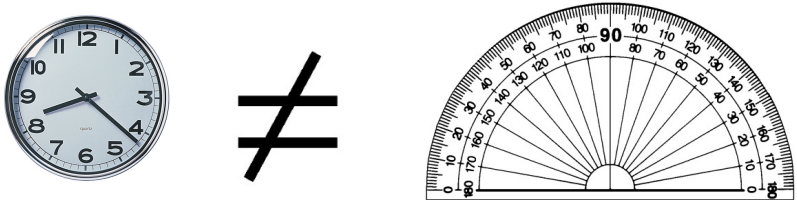


Figure 18: Minutes (′) and Seconds (″) are measures of angles, not time!

- Degrees (°), Minutes (′) and Seconds (″) measure **angles**.
- If we used the more familiar decimal system:

$$1' = \left(\frac{1}{60}\right)^\circ = 0.017^\circ$$

$$1'' = \left(\frac{1}{60}\right)' = \left(\frac{1}{60} \times \frac{1}{60}\right)^\circ = \left(\frac{1}{3,600}\right)^\circ = 0.00028^\circ$$

$$10^\circ 30' = 10.5^\circ$$

- The use of degrees, minutes and seconds is retained for historical reasons.

Importance of Longitude

- Even if you knew north/south and latitude, travelling the ocean without knowing your longitude is dangerous.

> *"For lack of a practical method of determining longitude, every great captain in the Age of Exploration became lost at sea despite the best available charts and compasses. From Vasco da Gama to Vasco Núñez de Balboa, from Ferdinand Magellan to Sir Francis Drake—they all got where they were going willy-nilly, by forces attributed to good luck or the grace of God."*
>
> From Dave Sobel's 'Longitude...' [Sob95]

- A storm or current can easily make you lose your bearing.
- The 'longitude problem' cost governments lots of lives and money that in 1714 the British government passed an act of parliament that offered a (staggering) prize of £20,000 for an accurate solution.

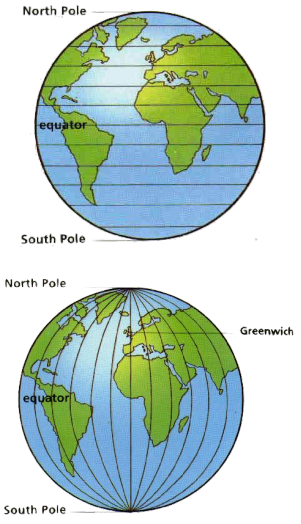


Figure 19: The heavenly bodies can help with latitude but not with longitude.

Longitude in the Days Past

- When you are at sea, you can use a compass and the stars to determine your latitude, but not longitude.
- Complicated methods involving the the Sun, the Moon and the stars were proposed and even used.
- The most dependable method was to use 'noon' at the present location, along with an accurate clock.
- The problem was producing a clock that can withstand the vicissitudes of ocean travel.

Figure 20: Using a 'Jacob's Staff' to determine the position of the Sun. Lots of people ended up blind in one eye with this instrument.

H-4

- John Harrison's fantastic chronometer, that won him the £20,000 prize in 1773.
- This is the fourth and the most accurate that Harrison manufactured.

> *"I think I may make bold to say, that there is neither any other Mechanical or Mathematical thing in the World that is more beautiful or curious in texture than this my watch or Timekeeper for the Longitude . . . and I heartily thank Almighty God that I have lived so long, as in some measure to complete it."*
>
> – John Harrison [Sob95]

- There is a very rich historical backstory to this topic involving a lot of great names such as Galileo, Euler, Newton, Halley. . .
  (Again: see 'Longtude' [Sob95] for more details).

National Maritime Museum, London/The Image Works

Figure 21: Harrison's fourth timepiece: H-4.

Noon is Not Just Only for Lunch. . .

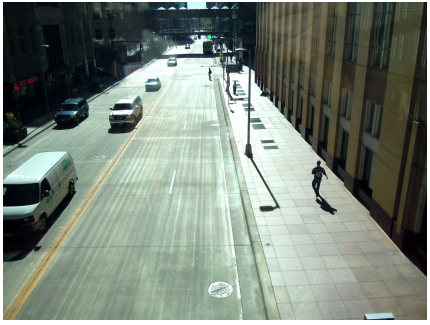


Figure 22: The position of the Sun when it casts the shortest shadow signifies 'noon'.

- Noon marks the point when the Sun is at its peak, for that day.
- Noon is when the shadow cast by the Sun is the shortest (not necessarily zero).
- This unique position of the Sun can be used to standardize what time is.

A Point to Ponder

Can 'sunrise' or 'sunset' be used for time-keeping?

Time & Longitude

- Since there are 360 meridians and the Earth rotates through all these meridians in 24 hours:

  Time for the Sun 'to go' from one meridian to the next
  $= \frac{24\ \text{h}}{360} = \frac{24 \times 60\ \text{min}}{360} = 4\ \text{min}$

- So, if we know the time at our location, we can figure out the time at another location if we know its longitude.
- If we know the times at two locations, then we can figure out the difference in longitude between these two locations.

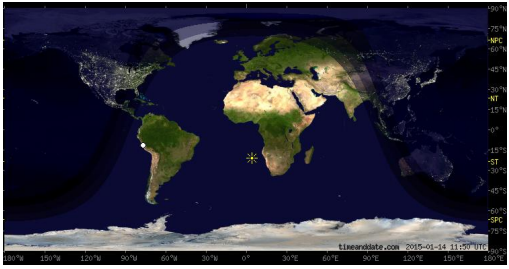


Figure 23: The time of day (usually) depends on the position of the Sun. Look here to see where the Sun is now!

Living on a Ball. . . is Different

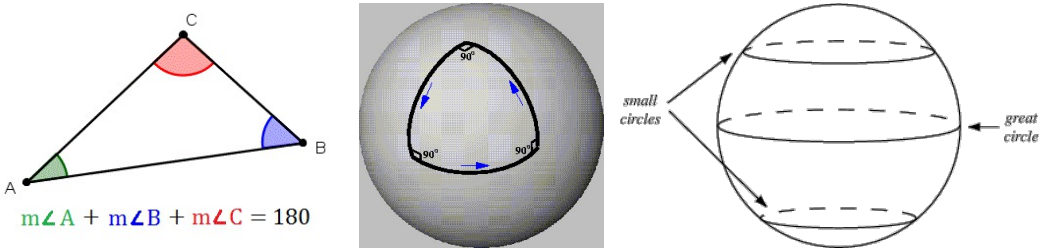


Figure 24: The usual rules of geometry does not seem to work on spheres!

- Triangles are different, 'parallel' is different & the shortest distance is not straight.
- The shortest distance between two points is along a 'great circle'.
  (Check out: Shortest Path Between Two Points On A Sphere).
- A 'great circle' shares the centre of the sphere.
- This is partly why planes seem to fly 'funny'.
  (Check out: Great Circles On Mercators Chart).

A Point to Ponder

If all this is true, why don't we notice these weird things in everyday life?

What is the 'Real' Shape of the Earth

xkcd version

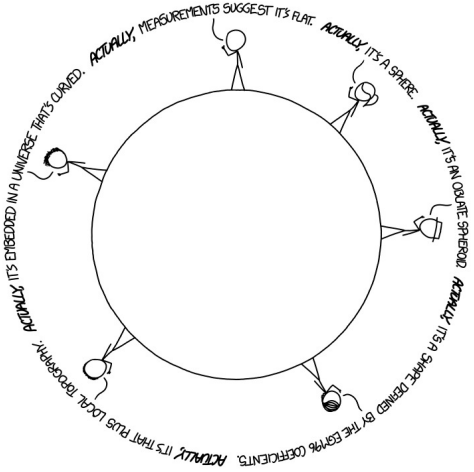


Figure 25: The shape of the Earth according to xkcd

Map worth $10,000,000!

Figure 26: The Waldseemüller map (1507). (See Wikipedia for more information.)

Projections & Distortions

- No projection of a sphere on to a plane is ever perfect.
- Each projection is optimised for a specific use (e.g. navigation or surveying).
  (Check out: World Map Projections).

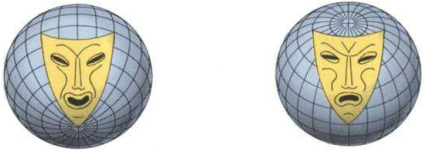


Figure 27: Two 'faces': comedy (in the S) and tragedy (in the N) for reference.

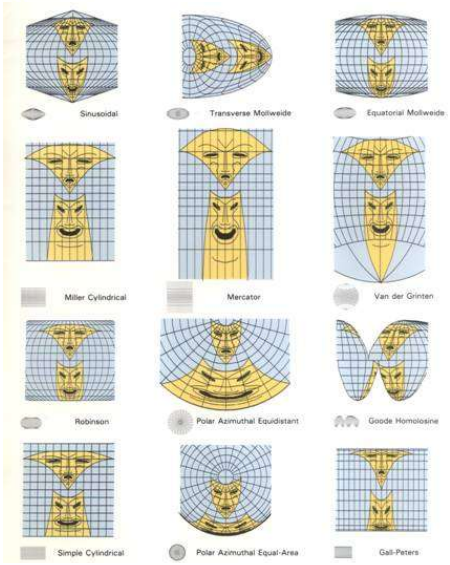


Figure 28: What each projection does to the faces.

How well do you know your World?

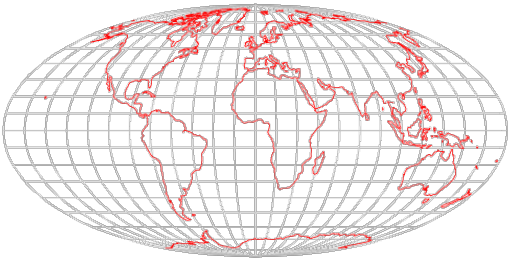


Figure 29: Mollweide Projection

A Quick Question

Which is bigger; Africa or Greenland?

Figure 30: Mercator Projection

Seasons in the Sun

- The position of the Sun in the sky changes throughout the year.
- The Sun is directly over the equator twice a year:
  1. Spring equinox($\approx$ 20$^{\text{th}}$ Mar)
  2. Fall equinox ($\approx$ 20$^{\text{th}}$ Sep.)
- The Sun is over the Tropics of Cancer and Capricorn during the solstices.
  1. Summer Solstice ($\approx$ 20$^{\text{th}}$ Jun.)
  2. Winter Solstice ($\approx$ 20$^{\text{th}}$ Dec.)

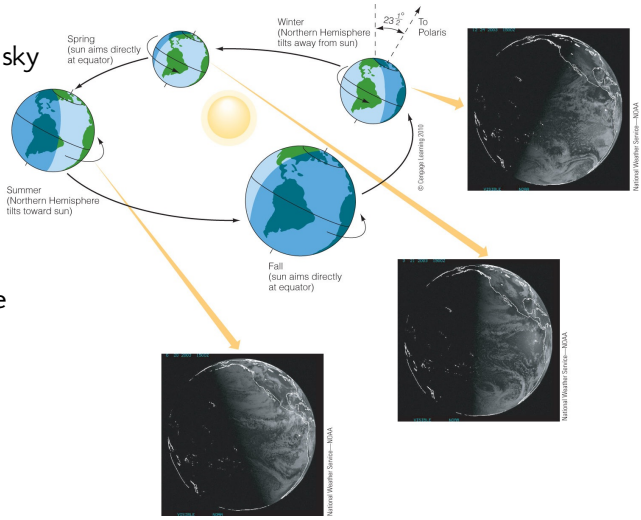


Figure 31: Seasons are caused due to the Earth's $23\frac{1}{2}°$ tilt.

Angles Are Important

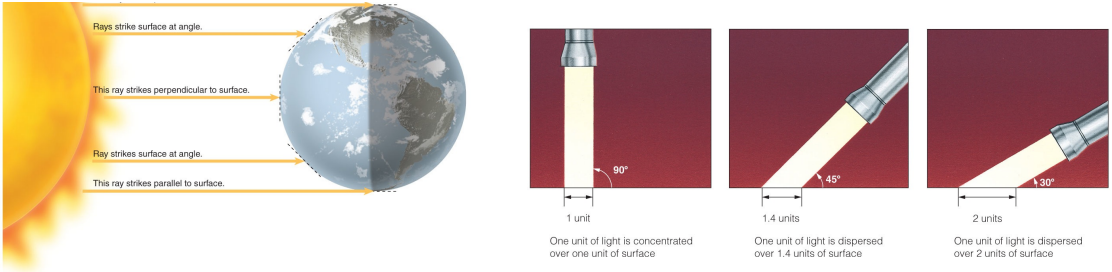
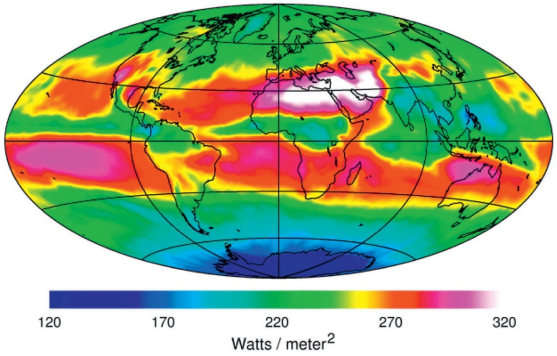


Figure 32: The angle of incidence of sunlight determines how much light is available for absrobtion.

Differential Heating of Earth



Terra satellite data for the month of July 2000 shows areas on Earth where solar heat input exceeds the radiation of heat back into space (red, orange), and areas where the radiation of heat into space exceeds heat input from the sun (blue).

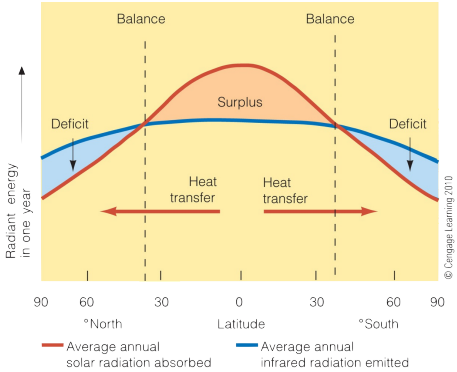


Figure 33: Averaged over a year; the Sun provides different amounts of heat to the different latitudes of the globe.

- This differential heating leads to large scale atmospheric currents that try to redistribute the energy evenly.
- These currents carry $\frac{2}{3}$ (!) of the poleward heat from the tropics and also lead to many other effects.

Some Basics: Which is heavier, Dry or Wet Air?

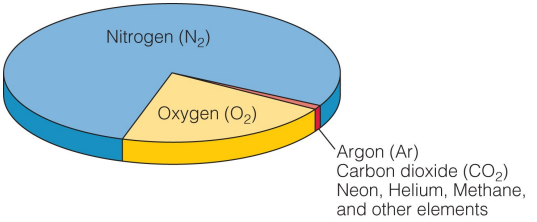


Figure 34: Water vapour is an important component of the atmosphere.

- Air is never dry. There is always some water vapor.
- Water vapor can occupy as much as 4 % of the air volume.
- The residence time for water vapor in the lower atmosphere is 10 days!
- Water vapour is one of the most important (good) greenhouse gases that is responsible for keeping the Earth warm.

Some Basics: Rising & Falling Air

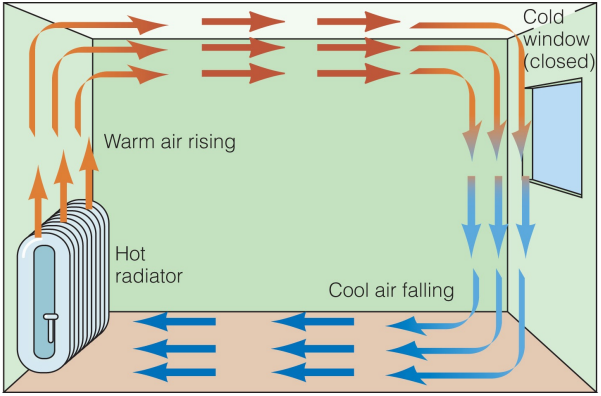


Figure 35: Convection is an important process in atmospheric circulation.

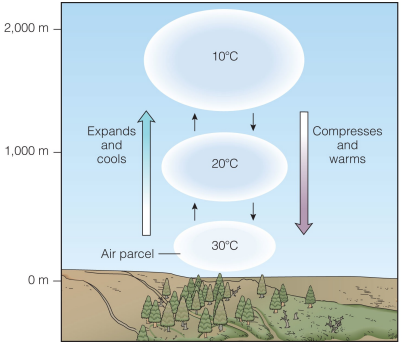


Figure 36: Warm air rises due to its density but cools down due to expansion.

- Rising air expands and cools
- Descending air gets compressed and heats up (recall pumping air into a tire).

Some Basics: Coriolis,

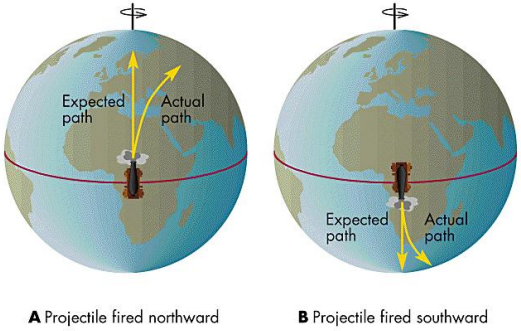


Figure 37: The Coriolis effect is paramount in determining atmospheric circulation.

- Objects moving in the **Northern** hemisphere are deflected to the **right**.
- Objects moving in the **Southern** hemisphere are deflected to the **left**.

Some Basics: Trying to Make Sense of Coriolis

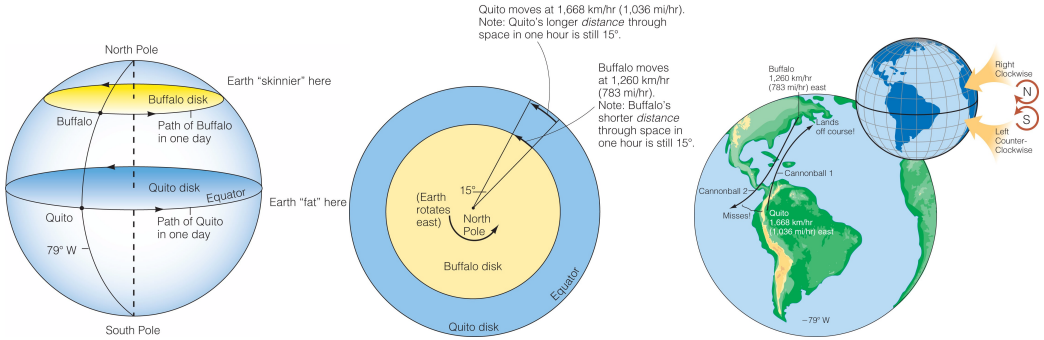


Figure 38: The Coriolis effect arises due to the rotation of the Earth.

- Different locations on the planet travel at different speeds.
- If something moves from one location to another this difference leads to the appearance of the Coriolis force.

Motion of the Atmosphere: A Simplified View

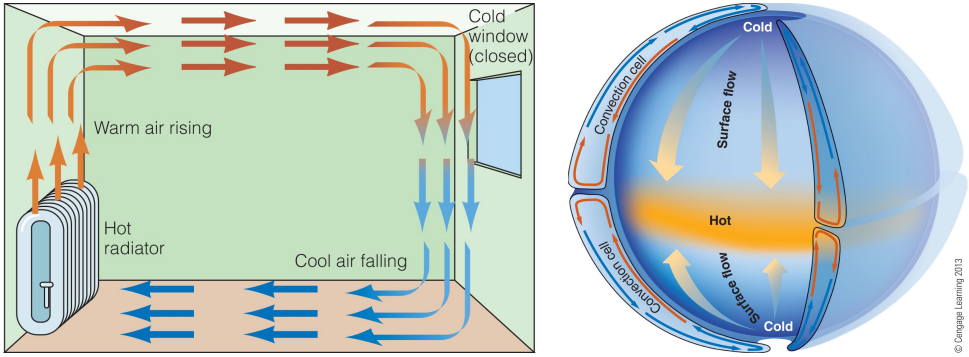


Figure 39: Convection is an important process in atmospheric circulation.

Motion of the Atmosphere: A More Realistic View

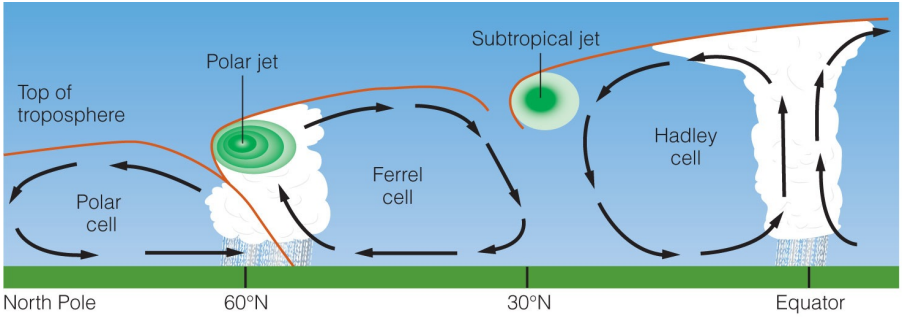


Figure 40: The differential heating of the Earth leads to the creation of atmospheric circulation cells.

- There are three (Hadley, Ferrel, Polar) circulation cells.
- Regions where the air rises are low pressure regions.
- Regions where the air descends are high pressure regions.

Motion of the Atmosphere: An Even More Realistic View

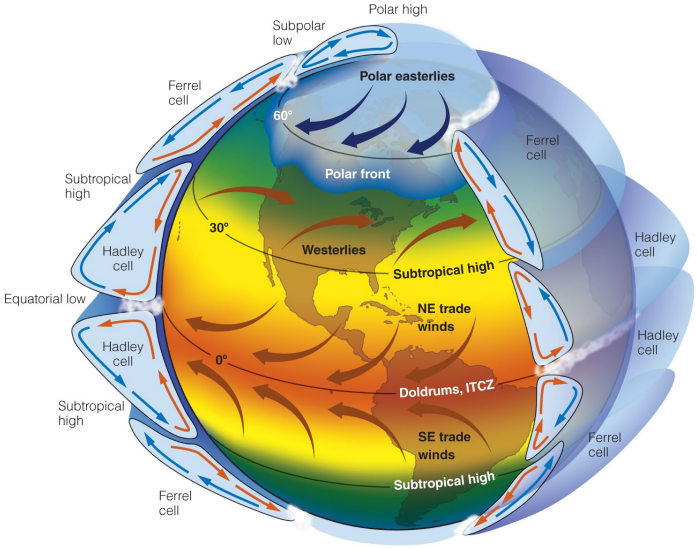


Figure 41: The Coriolis effect causes significant changes to the motion of air.

Motion of the Atmosphere: The Real Deal

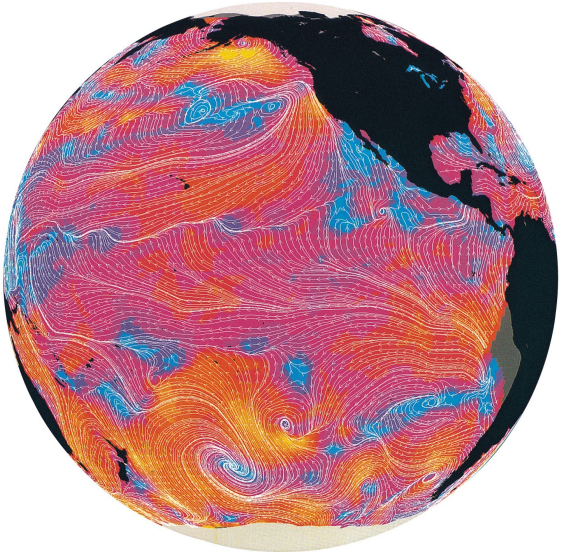


Figure 42: The circulation of the atmosphere is not readily predictable.

The ITCZ

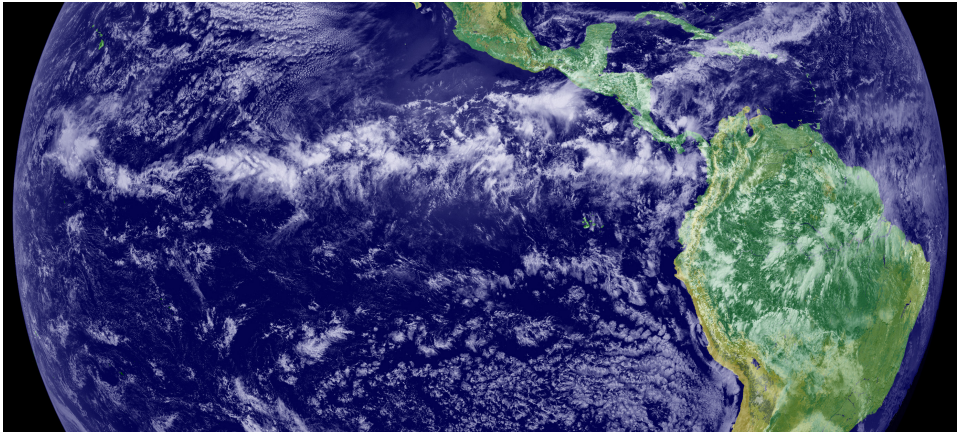


Figure 43: The ITCZ is marked by the formation of clouds above it.

The ITCZ

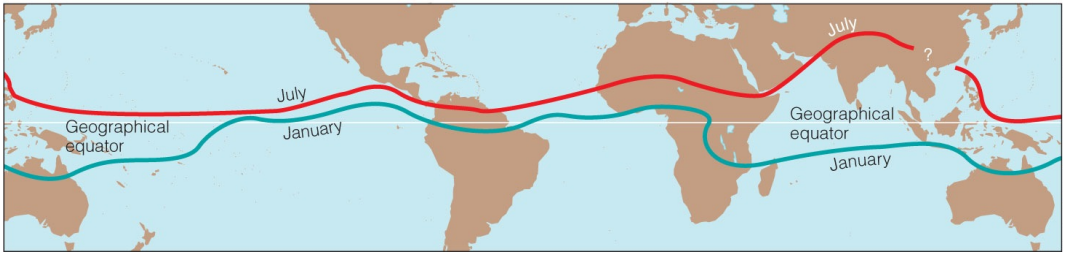


Figure 44: The ITCZ is like the meteorological equator of the planet.

- The Hadley cell does not really start at the equator but at the ITCZ.
- ITCZ (Intertropical Convergent Zone) is like the meteorological equator of the planet.
- ITCZ constantly shifts depending on the motion of the Sun.
- The location of the ITCZ is significantly affected by how the land and ocean is distributed.
- It is the motion of the ITCZ that causes the monsoons in our part of the world.

Sea & Land Breezes

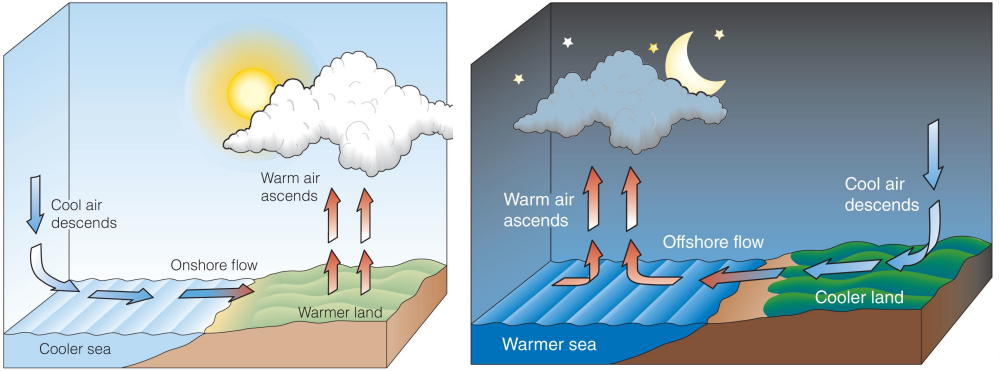


Figure 45: The different heat capacity of land and sea leads to sea and land breezes.

Monsoons

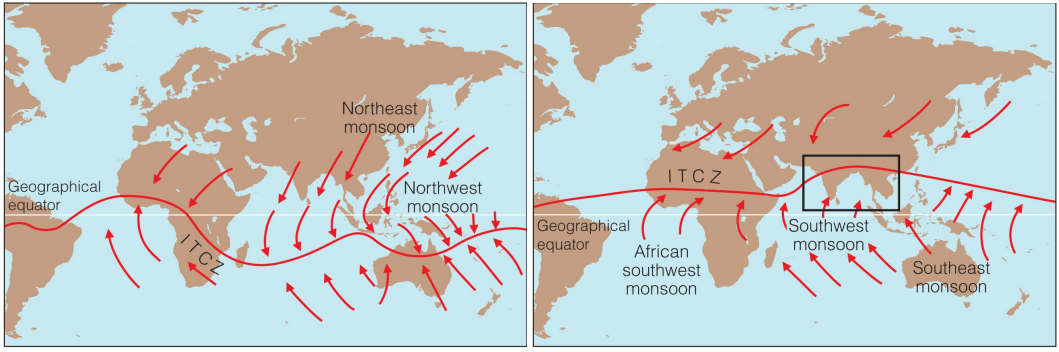


Figure 46: Position of the ITCZ in January (left) and July (right) and the consequent occurrence of the monsoons.

- Monsoons are also created due to the different heat capacities of land/sea.
- Also involved is the north-south movement of the ITCZ.
- Take a loot at this (cool) interactive website.

Riding the EAC

Figure 47: Remember the EAC in 'Finding Nemo'?

The World's Surface Currents

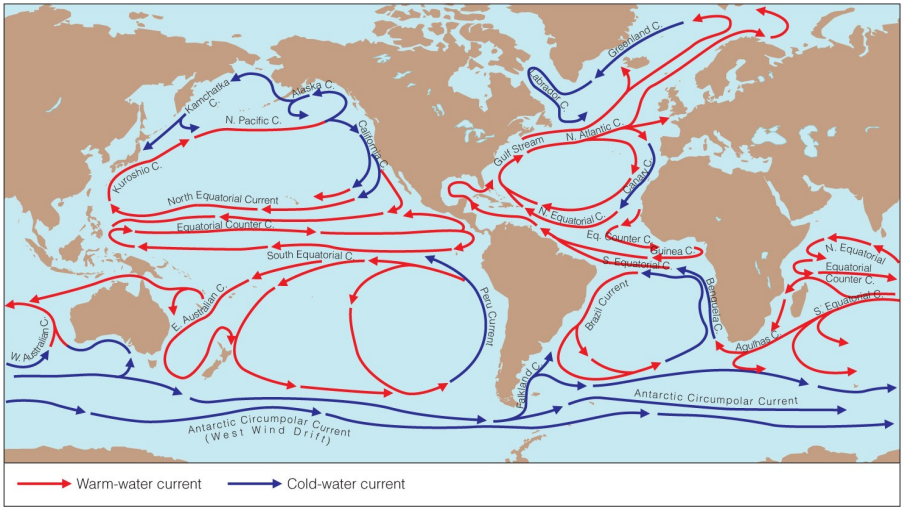


Figure 48: The surface water in certain region of the ocean are constantly flowing; like a river!

Currents

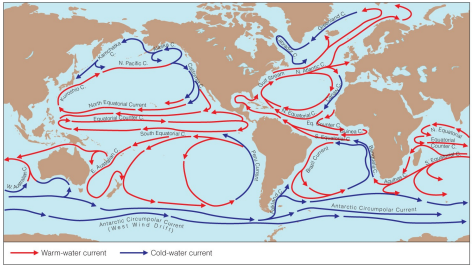


Figure 3: Currents closer to the surface.

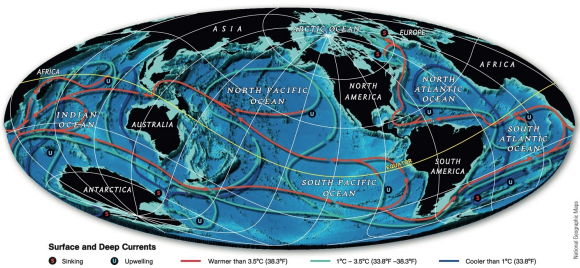


Figure 49: Currents that are in the deep ocean.

- A **current** is a mass flow of water.
- Currents can either be horizontal or vertical, closer to the surface or closer to the bottom.
- **Surface currents** are driven by wind.

Surface Currents

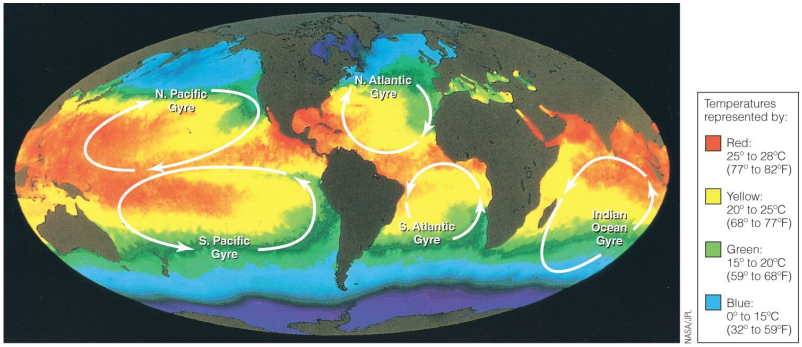


Figure 50: The gyres are responsible for carrying heat polewards.

- Surface currents are created by wind friction and water up to $\approx$ 400 m in depth are involved in surface currents ($\approx$10% of the ocean's water).
- These currents flow along the periphery of the ocean basins and are called **gyres** (There are five great gyres).
- The flow of the gyres are influenced by the location of the continents.

Details of Figures I

Slide 4 → figure 1: Image from www.gopixpic.com
Slide 5 → figure 3: From website of Anthony Ayiomamitis
Slide 6 → figure 4: From Wikipedia.
Slide 6 → figure 5: From NASA
Slide 7 → figure 6: From NASA
Slide 8 → figure 7: From Wikipedia
Slide 9 → figure 8: From [Gar12].
Slide 10 → figure 9: From [Gar12].
Slide 11 → figure 10: From xkcd
Slide 13 → figure 11: From [Gar12].
Slide 13 → figure 12: From [Gar12].
Slide 14 → figure 13: From [Gar12].
Slide 15 → figure 14: From [Gar12].
Slide 17 → figure 15: From [Gar12].
Slide 17 → figure 16: From [Gar12].
Slide 19 → figure 17: From [Gar12].
Slide 22 → figure 20: From Wikipedia: "Jacobstaff" by John Seller (1603-1697) - Scan from the original book Practical navigation (1st edition 1669) p. 200
Slide 23 → figure 21: From [Gar12].
Slide 25 → figure 23: Image from Day and Night World Map
Slide 27 → figure 25: xkcd
Slide 28 → figure 26: From [Gar12].
Slide 31 → figure 31: From [Gar12].
Slide 32 → figure 32: From [Gar12].
Slide 33 → figure 33: From [Gar12].
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Slide 35 → figure 35: From [Gar12].
Slide 35 → figure 36: From [Gar12].
Slide 36 → figure 37: From the website CoPraNet
Slide 37 → figure 38: From [Gar12].
Slide 38 → figure 39: From [Gar12].
Slide 39 → figure 40: From [Gar12].

Details of Figures II

Slide 40 → figure 41: From [Gar12].
Slide 41 → figure 42: From [Gar12].
Slide 42 → figure 43: Image from NASA's Earth Observatory.
Slide 43 → figure 44: From [Gar12].
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Slide 45 → figure 46: From [Gar12].
Slide 47 → figure 48: From [Gar12].
Slide 48 → figure 49: From [Gar12].
Slide 49 → figure 50: From [Gar12].

List of Resources


Tom Garrison, *Essentials of oceanography*, 6th ed., Brooks/Cole, Cengage Learning, Belmont, CA, 2012.


Dava Sobel, *Longitude: the true story of a lone genius who solved the greatest scientific problem of his time*, Walker, New York, 1995.