Introduction to Earth System

Ocean

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Ocean

1. Intro & Ocean structures
2. Ocean circulation
3. Ocean temperature
4. Sea level

2

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The Oceans

- Cover Q?% of the area of the Earth's surface
- Reach an extreme depth of ~ Q?km
- Total volume is equivalent to that of a layer Q? km deep, covering the entire surface of the Earth
- Oceans' mass: ~ Q? times compared to that of the atm.

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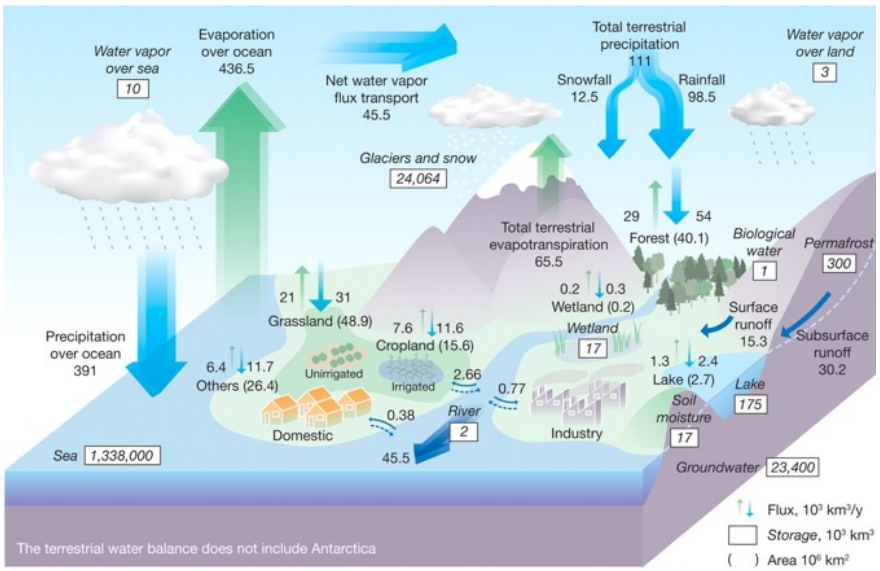
The water cycle



Oki and Kanae, Science, 2006

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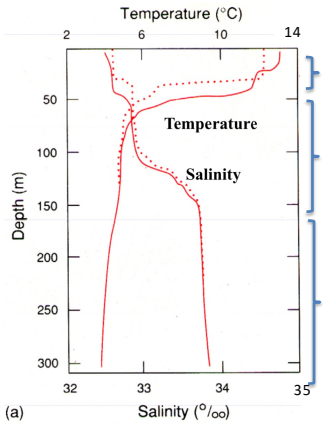
Ocean structures

- **The ocean is mostly stably stratified**
- Upper ocean: shallow (~100m), warm, abundant light, most marine life
- Deep ocean: cold, dark, much nutrients and carbon



(Climate system Modeling)

Mixed layer: T & S well mixed
- Atmosphere affect: heating, wind forcing & freshening (P-E)
- Global average depth ~ 70m
- Heat capacity of mixed layer → ~ 30 times heat capacity of the atmosphere

Thermocline: large gradient of T, S

Deep ocean: T, S ~independent of height

Q: Is mixed layer seasonally dependent?

Q: Is mixed layer geographically dependent?

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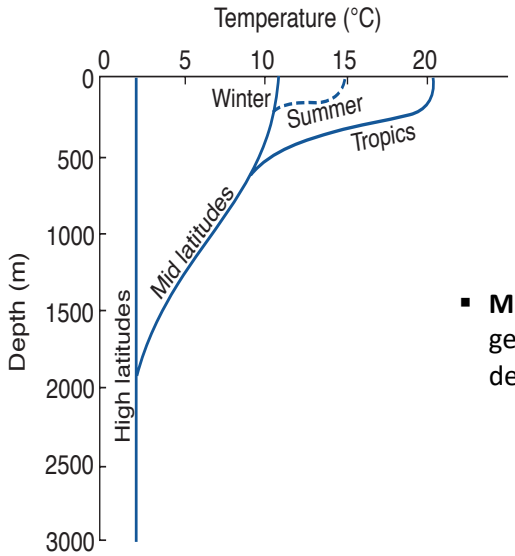
Ocean structures



- **Mixed layer**: seasonal & geographical location dependence

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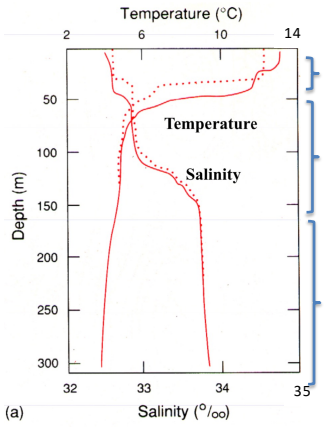
Ocean structures



(Climate system Modeling)

Mixed layer

Thermocline: large gradient of T, S

A thermocline is the transition layer between the warmer mixed water at the surface and the cooler deep water below, where the temperature gradient is greater than that of the warmer layer above and the colder layer below.

Deep ocean

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Ocean circulation

Drivers:

- Wind stress on the surface
- Earth's rotation (Coriolis effect)
- Pressure gradients from density differences
- Buoyancy fluxes (heat, freshwater)

Wind-driven circulation
dominates the surface currents

Thermohaline circulation
density driven component; circulation deeper in the oceans

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Fundamental Equations

1. Momentum (Navier-Stokes in rotating frame)
2. Continuity (mass conservation)
3. Thermodynamics (T, S conservation)
4. Equation of state ($\rho = \rho(T, S, p)$)

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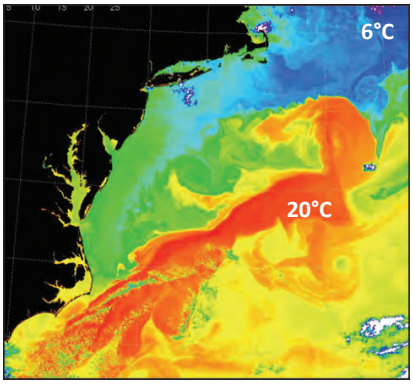
Ocean circulation

Wind-driven circulation:

- **Surface winds** → horizontal momentum from the atm. into the oceans → generating currents
- **Wind-driven currents** are typically on the order of 10 cm/s → a few % of surface wind speed



SST Gulf Stream (Based on NASA Terra/MODIS – Otis Brown)

Gulf stream:

- Speed: 2m/s
- Depth: 450 m
- Width: 70 km

Eddies along the landward edge of the Gulf Stream

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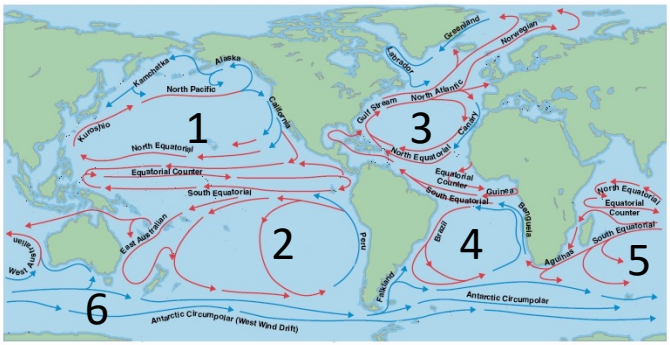
Six largest currents



5 geostrophic gyres:

1. North Pacific Gyre
2. South Pacific Gyre
3. North Atlantic Gyre
4. South Atlantic Gyre
5. Indian Ocean Gyre

&

6. The largest current: Antarctic Circumpolar Current (West wind drift)

Gyres' characteristics: each gyre includes 4 current components

Two boundary currents:
- western: fast, deep, narrow; moves warm water poleward
- eastern: slow, shallow, broad; moves cold water equatorward

Q: Why clockwise (anti-clockwise) gyres in the NH (SH)?

Two transverse currents:
- Trade wind-driven: Moderately shallow & broad westward current
- Westerly-driven: wider & slower eastward current compared to the trade wind-driven current

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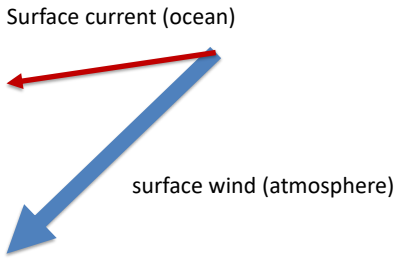
Surface winds & ocean currents

- Starting with a surface wind, e.g. the Northeast trade winds



→ the ocean's surface layer current is:
- more slowly
- to the **right** of the wind

→ Q: Why?

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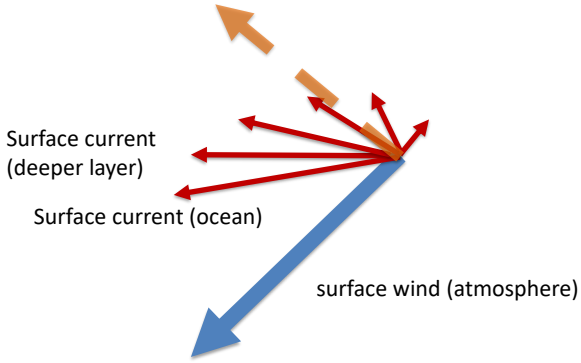
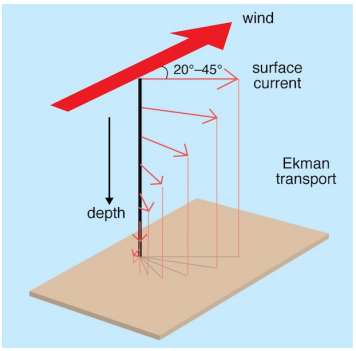
Ekman transport





- Keep going down → the current both slowing and turning clockwise → an **EKMAN SPRIAL**
- Average the current and mass transport → the mean direction is to the right (~90º) of the surface direction → This mass motion is called the **EKMAN TRANSPORT**

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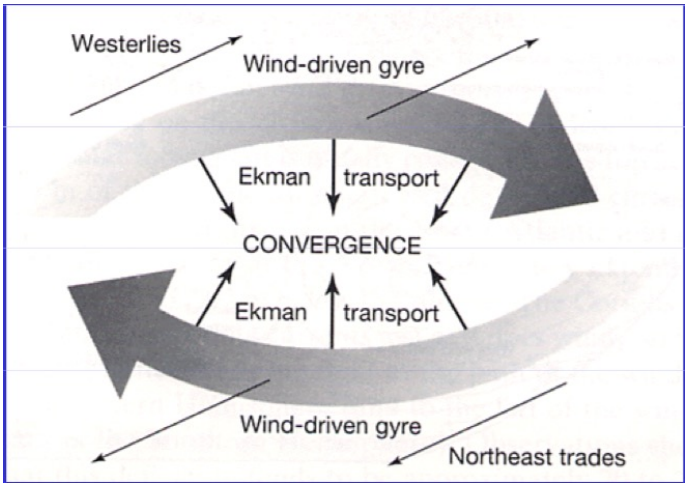
Ekman transport



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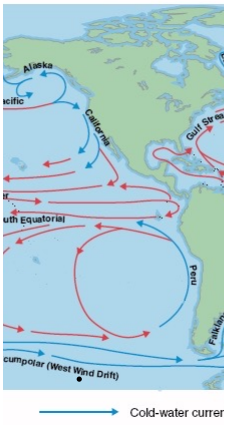
Ekman transport



E.g. west side of the American continent

→average movement of upper ocean water is westward, **AWAY** from shore.
→Push cool water away from the shoreline → colder water from the bottom is brought up → UPWELLING

→UPWELLING → transports nutrients to the surface (& cooler SST) → allowing phytoplankton to prosper

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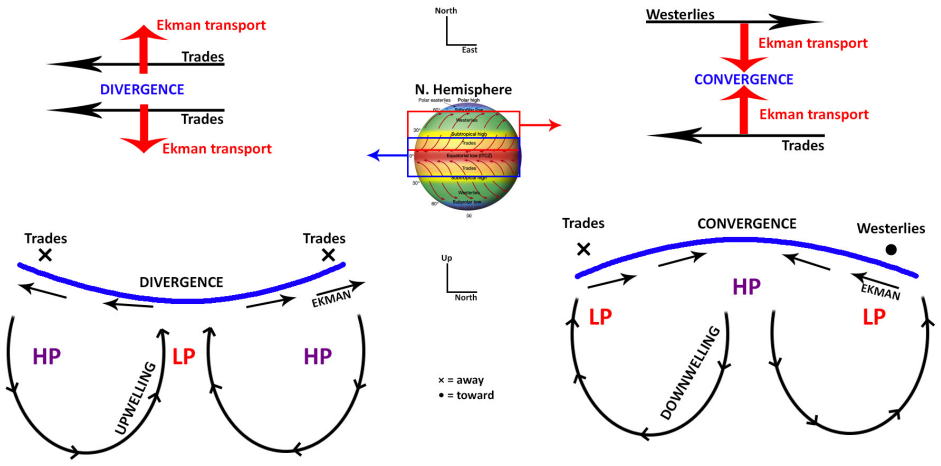
Upwelling & Downwelling



@C. Cameron

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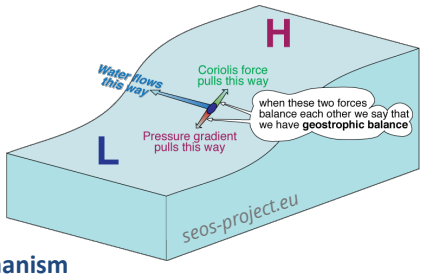
Ekman transport to geostrophic flow



$$-fv + \frac{1}{\rho}\frac{\partial p}{\partial x} = 0$$

$$fu + \frac{1}{\rho}\frac{\partial p}{\partial y} = 0$$

Mechanism

1. **Winds** → **Ekman** transport.
2. → **convergence** (or **divergence**).
3. → **high (low) pressure zones** in deep waters.
4. → **horizontal pressure gradient forces**.
5. → **water to move** horizontally from high to low pressure.
6. This horizontal water movement adjusts until it is 90° to the Coriolis effect and traveling at 90° to the pressure gradient force.

The Coriolis effect and pressure gradient force are equal but opposite → **geostrophic flow**

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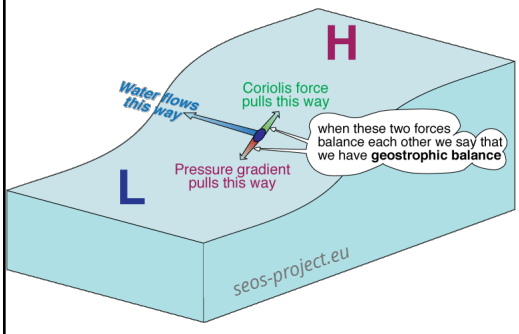
Geostrophic current

- pressure gradient is balanced by the Coriolis force



- → The direction of geostrophic flow is parallel to the isobars
- In NH (SH), the high pressure is on the right (left) of the flow

- In the NH, the Coriolis force acts at right angles to the flow → clockwise gyre

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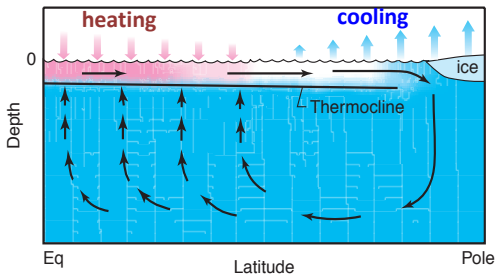
Ocean circulation

The idealized schematic of the thermohaline circulation



- Pink (blue) shading indicates warmer (colder) water
- Rejection of salt when water freezes along the ice edge that makes the **water dense** enough to enable it to sink to the bottom
- Timescale: relatively slow process, ~ hundred years

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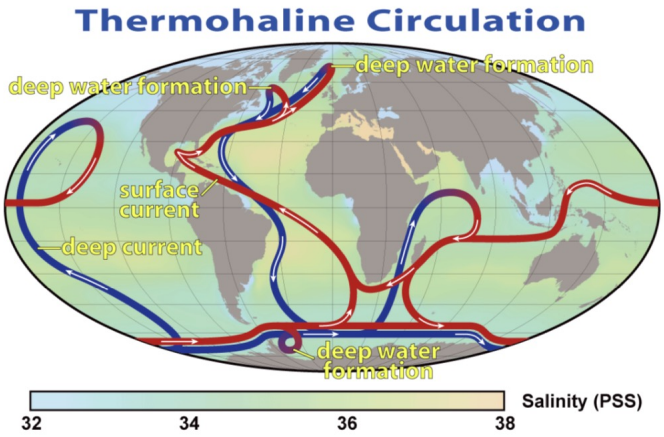
Ocean circulation



- Although slow, a large amount of upper ocean water converted into deep bottom water, ~ **15,000,000 m3/s** in the Atlantic ocean.
- As a comparison, all the rivers in the world combined deliver ~ **1,000,000 m3/s** of fresh water into the ocean.

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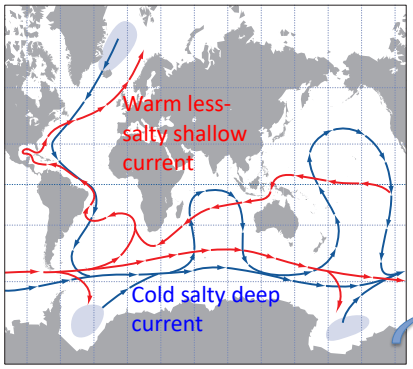
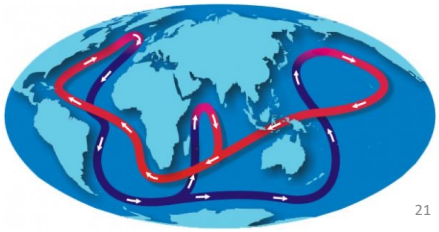
Ocean circulation



Simplified schematic of the thermohaline circulation.

- Shading → regions of downwelling
- Blue arrows: transport of bottom water
- Red arrows: return flow of surface water

A very simplified model: **the Global Conveyor Belt**



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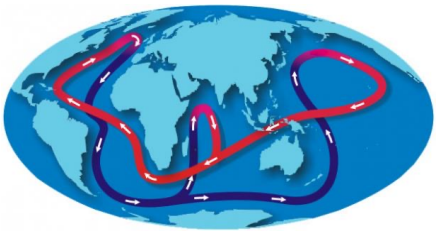
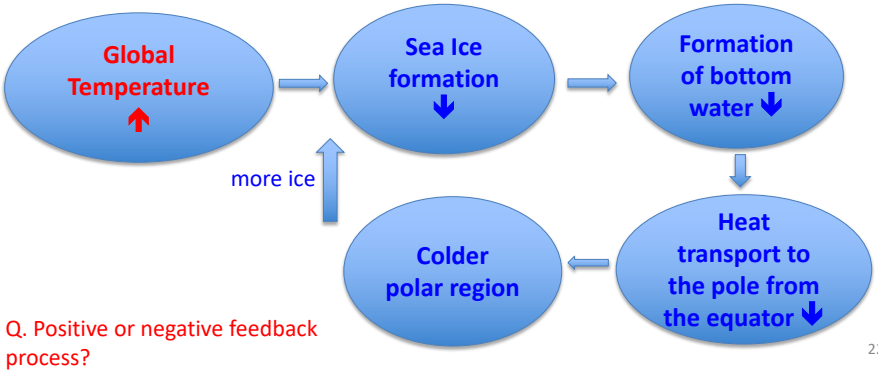
Ocean circulation

Climate Change & Global Thermohaline circulation

- Climate change studies suggest:





Q. Positive or negative feedback process?

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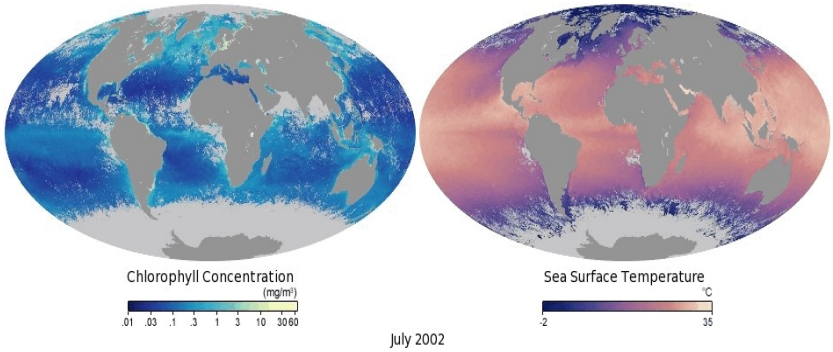
Ocean circulation: Upwelling

- **Upwelling**: the rise of cold water from deeper layers to replace warmer surface water
  - stimulate the growth & reproduction of phytoplankton
  - **~25% of the total global marine fish** catches come from five upwellings that occupy only **5% of the total ocean area**
  - Q: How to identify upwelling?
    - Identified by cool SST & high concentration of chlorophyll



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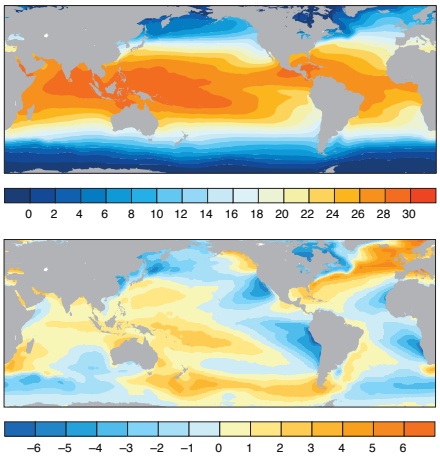
E.g. Sea Surface Temperature (SST)

- Radiative heating (e.g. north-south gradient, top fig.)
- Dynamical factors: (e.g. bottom fig.)
  - Subtropical latitudes
  - Higher latitudes
  - Equatorial regions



Annual mean SST. (Top) The total field (Bottom) Departure of the local SST at each location from the zonal average field

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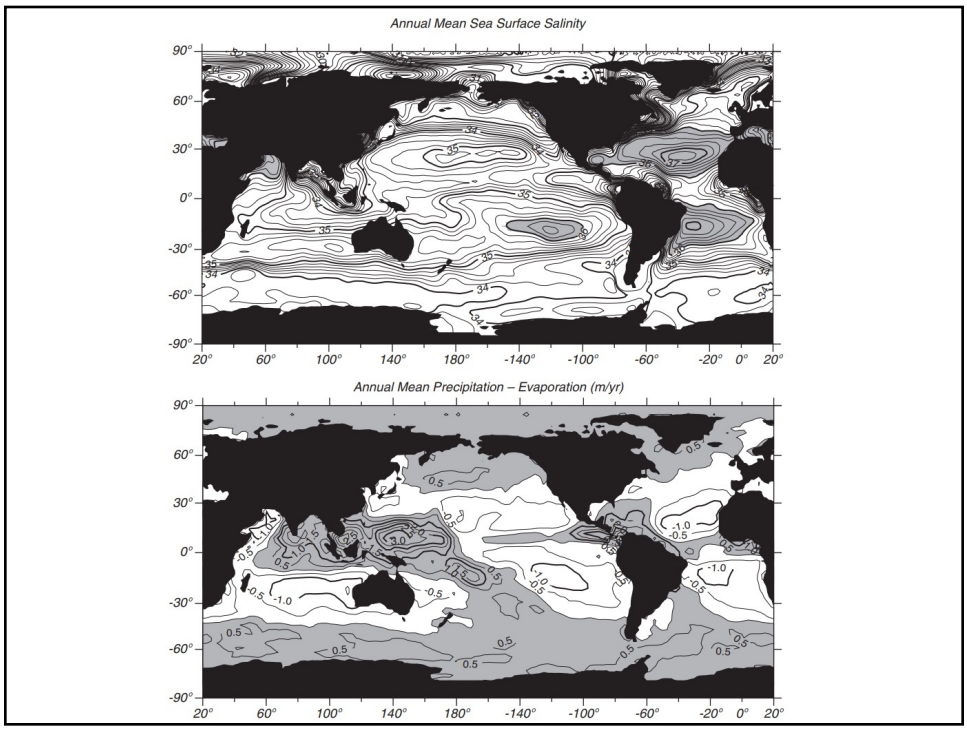

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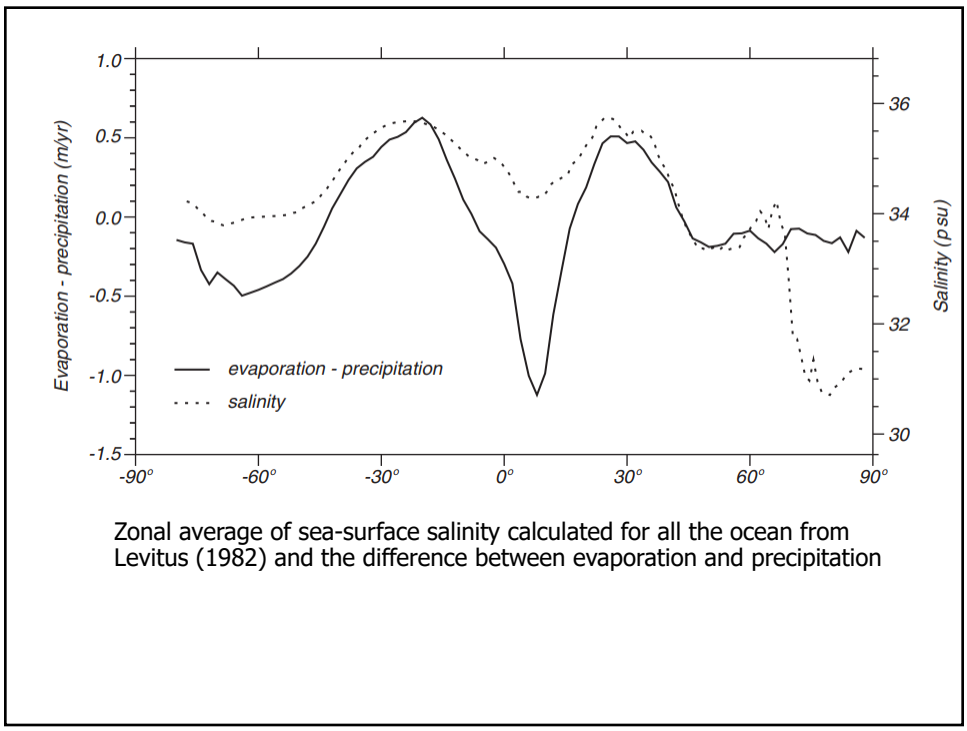

Zonal average of sea-surface salinity calculated for all the ocean from Levitus (1982) and the difference between evaporation and precipitation

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Heat Capacity

- Large heat capacity of the ocean

		Units	Air	Water
Specific Heat Capacity	c_p	J/(g°C)	1	4.2
Density	ρ	kg/m^3	1	1000
Volumetric Heat Capacity	$c_{vol} = c_p\rho$	$J/(m^3°C)$	1000	4,200,000

- Volumetric heat capacity of water is 4200 times that of air
- Top 2 m of the ocean has the same heat capacity as the whole atmosphere.

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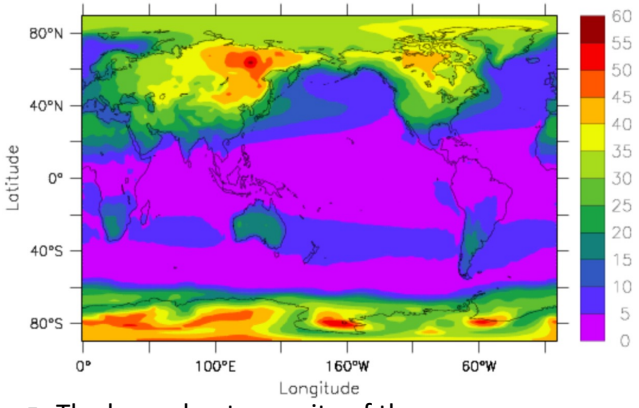
- Land heat capacity << ocean heat capacity

→ temperature change over the ocean is slower than over land

$$\Delta T/\Delta t = \Delta F/C$$

NCEP Reanalysis



Surface Temperature (ºC): *summer minus winter, 1958-1996*

- The larger heat capacity of the ocean

→ dampens temperature variations on other timescales

→ warming is smaller over the ocean than over land

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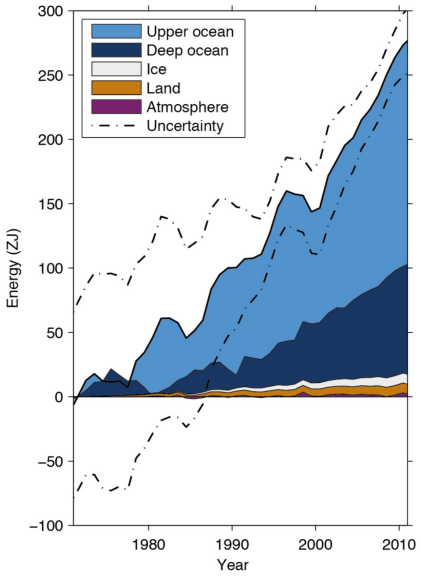
Heat Capacity

- ~90% of the observed increase in Earth's heat content goes into the **ocean**.
- Most of the remaining 10% goes into **ice** and **land**
- The heat gain of the **atmosphere** is very small.



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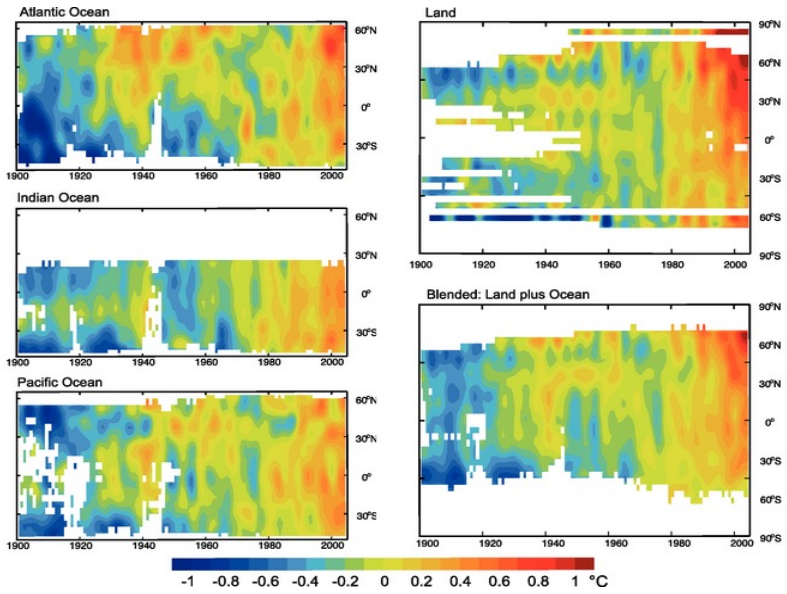

Zonal average of temperature anomaly compared to the period 1961-1990

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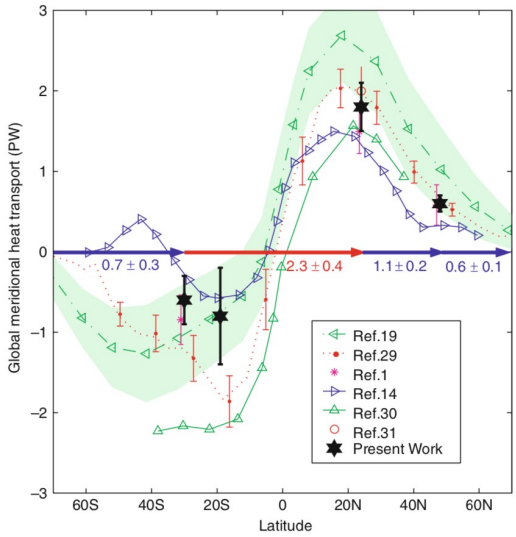
Heat transport in the Ocean



Zonally integrated heat transport in the ocean based on observations and modelling (Ganachaud and Wunsch, 2000)

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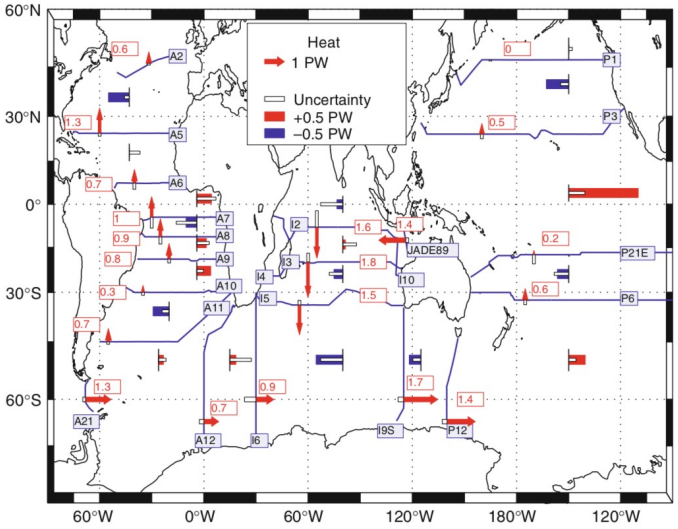
Heat transport in the Ocean



- Atlantic: Northward transports
- Indian Ocean: southward transport
- Pacific: surprisingly small
- Transport in the circumpolar current is largest with about 1.3 – 1.7 PW eastwards.

Meridional and vertical heat transports in the different regions of the world ocean. Numbers in boxes denote the meridional transport in PW. Horizontal bars represent the vertical transport (to the left – downwards) (Ganachaud and Wunsch, 2000)

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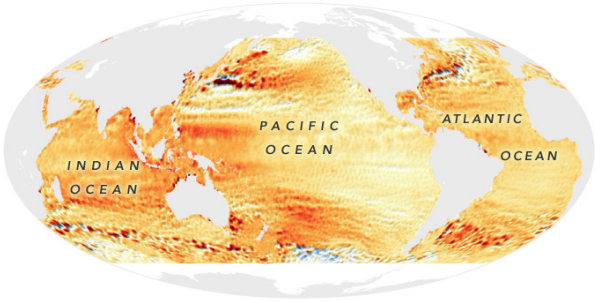
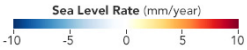
Sea level rise

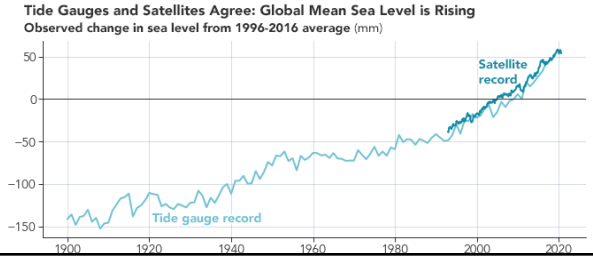


In-situ & satellite observations show that the overall level of the sea has been rising

1993-2018



https://earthobservatory.nasa.gov/



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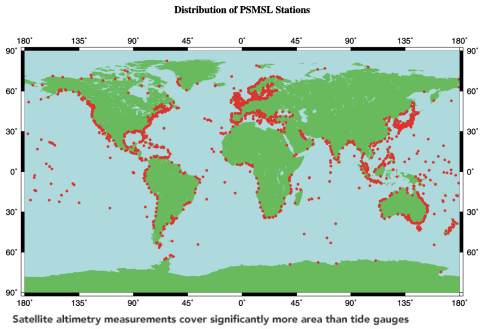
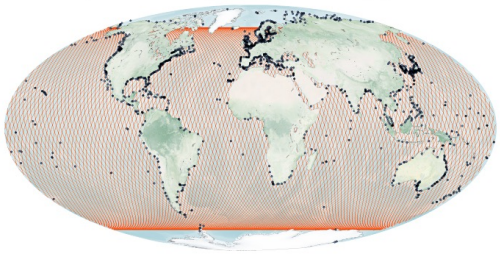
Sea level rise

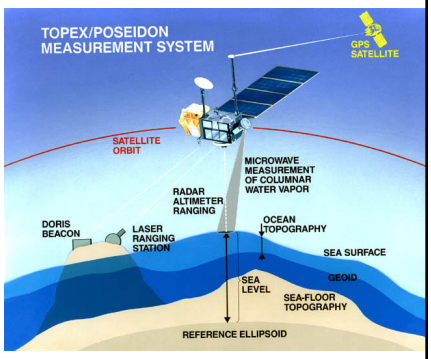


Satellite altimetry measurements cover significantly more area than tide gauges



https://earthobservatory.nasa.gov/

satellite altimetry



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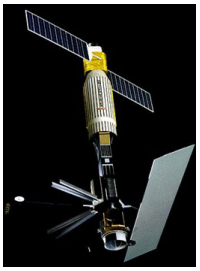
Past and Current altimeter satellites

Satellite	Years	Organisation	Accuracy
• SKYLAB	1972	NASA	20 m
• GEOS-3	1975-1978	NASA	3 m
• SEASAT	1978	NASA	2 m
• GEOSAT	1985-1990	US Navy	30 cm
• ERS-1	1991-1996	ESA	4-10 cm
• ERS-2	1995-2006	ESA	4 cm
• T/P	1992-2005	NASA/CNES	2 .. 3 cm
• GFO	2000-	US Navy	2 .. 5 cm
• JASON	2001-	NASA/CNES	2 .. 3 cm
• ENVISAT	2002-	ESA	2 .. 3 cm



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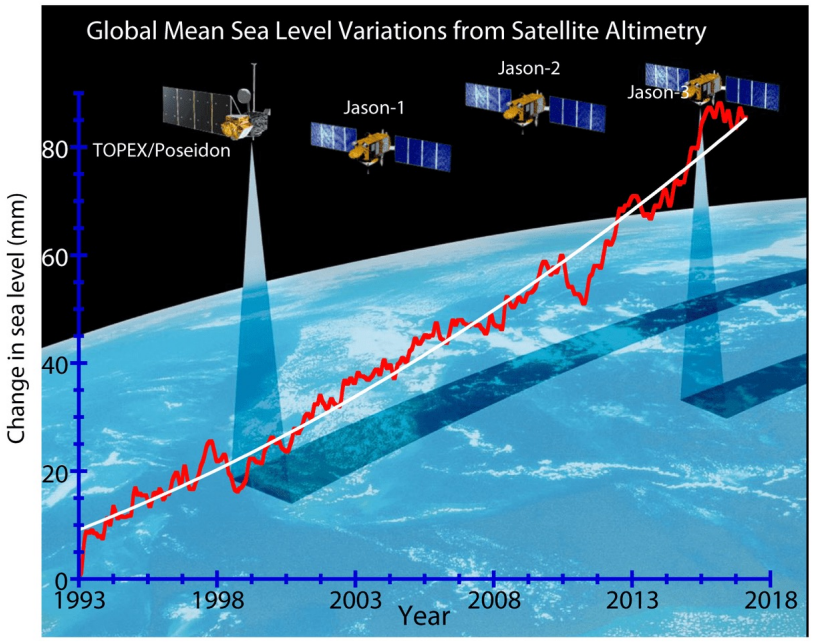

Satellite altimetry data. Illustration: John Fasullo

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Sea level rise

- **Global Causes:**
  - Thermal expansion
  - Mass exchange with other reservoirs (Antarctica, Greenland, underground water in land, river systems, atmosphere, ..)
- **Local causes:**
  - Sinking land (groundwater withdrawal, tectonic plates)
  - Ocean circulation (e.g. the Gulf Stream is slowing, less water is taken from the East Coast of America → causing sea level to rise in places like Florida)

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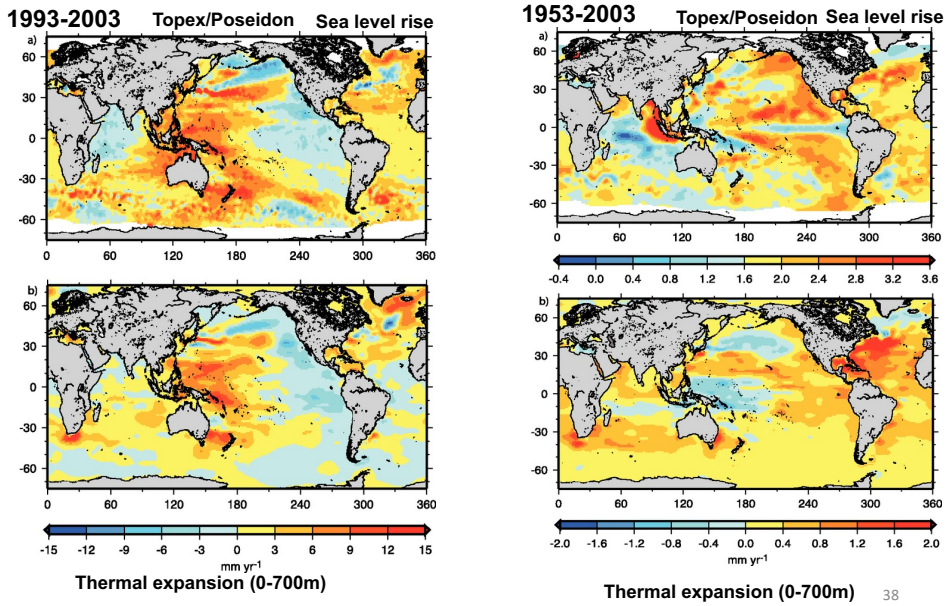
Sea level rise



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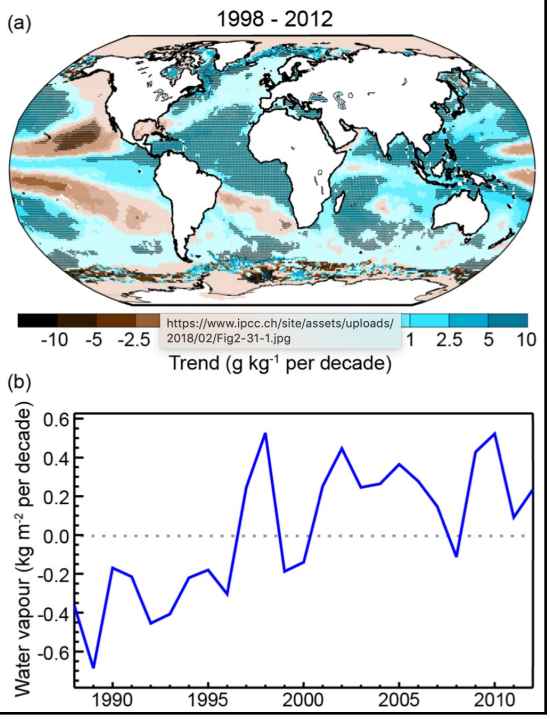
- increases in water vapor content in the atmosphere

← Warmer air can hold more water vapor



(a) Observed changes in surface specific humidity estimated from satellites. Dark shading indicates significant changes.

(b) Changes in globally averaged water vapor content.

From Harmann et al. (2013)

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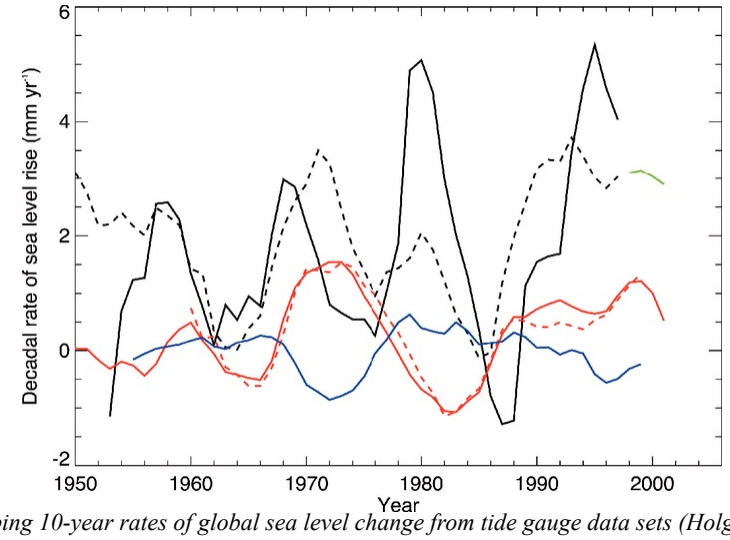

Overlapping 10-year rates of global sea level change from tide gauge data sets (Holgate and Woodworth, 2004, in solid black; Church and White, 2006, in dashed black) and satellite altimetry (updated from Cazenave and Nerem, 2004, in green), and contributions to global sea level change from thermal expansion (Ishii et al., 2006, in solid red; Antonov et al., 2005, in dashed red) and climate-driven land water storage (Ngo-Duc et al., 2005, in blue). Each rate is plotted against the middle of its 10-year period.

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Practice Python #7.1

The CSV format

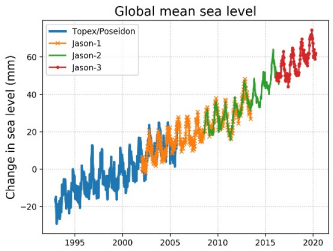
CSV (Comma Separated Values), e.g. sea level rise data from altimetry

Read and plot global mean sea level data observed by multiple altimetry missions

```
#title = mean sea level anomaly global ocean (66S to 66N) (Annual signals retained)
#trend = 2.94 mm/year (no glacial isostatic adjustment correction)
year,TOPEX/Poseidon,Jason-1,Jason-2,Jason-3
1992.9614,-16.24000,,,
1992.9865,-17.94000,,,
1993.0123,-14.84000,,,
1993.0407,-19.84000,,,
1993.0660,-25.24000,,,
1993.0974,-29.34000,,,
1993.1206,-27.64000,,,
1993.1493,-21.84000,,,
1993.1765,-18.94000,,,
1993.2037,-19.44000,,,
1993.2307,-22.94000,,,
1993.2851,-26.24000,,,
1993.3123,-20.04000,,,
1993.3394,-19.84000,,,
```

http://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise.

https://www.star.nesdis.noaa.gov/socd/lsa/SeaLevelRise/slr/slr_sla_gbl_keep_ref_90.csv



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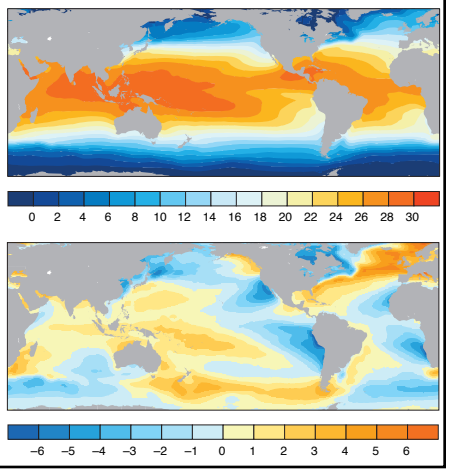
Practice #7.2: Sea Surface Temperature

SST netCDF data

1. Download sst.mnmean.nc from https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html
2. Plot the average SST over the oceans (e.g. upper figure)
3. Plot the SST departures (e.g. lower figure)



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Solution #1

https://www.star.nesdis.noaa.gov/socd/lsa/SeaLevelRise/slr/slr_sla_gbl_keep_ref_90.csv

```
import numpy as np
import matplotlib.pyplot as plt
data=np.genfromtxt("slr_sla_gbl_keep_txj1j2_90.csv",delimiter=',',comments='#')
time=data[:,0]
topex=data[:,1]
jason1=data[:,2]
jason2=data[:,3]
jason3=data[:,4]
plt.plot(time,topex,lw=3,label='Topex/Poseidon')
plt.plot(time,jason1,lw=3,label='Jason-1')
plt.plot(time,jason2,lw=3,label='Jason-2')
plt.plot(time,jason3,lw=3,label='Jason-3')
plt.legend(loc='upper left')
plt.ylabel('Sea level rise (mm)',fontsize=14)
plt.title('Global mean sea level',fontsize=16)
```

```
import pandas as pd
df =pd.read_csv(file,delimiter=',')
```

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Solution #2

```
import numpy as np
import matplotlib.pyplot as plt
data=np.genfromtxt("slr_sla_gbl_keep_txj1j2_90.csv",delimiter=',',comments='#')
time=data[:,0]
topex=data[:,1]
jason1=data[:,2]
jason2=data[:,3]
jason3=data[:,4]
# to deal with NaN values
ttp=np.delete(time,np.argwhere(np.isnan(topex)))
tp=np.delete(topex,np.argwhere(np.isnan(topex)))
tjs1=np.delete(time,np.argwhere(np.isnan(jason1)))
js1=np.delete(jason1,np.argwhere(np.isnan(jason1)))
tjs2=np.delete(time,np.argwhere(np.isnan(jason2)))
js2=np.delete(jason2,np.argwhere(np.isnan(jason2)))
tjs3=np.delete(time,np.argwhere(np.isnan(jason3)))
js3=np.delete(jason3,np.argwhere(np.isnan(jason3)))
plt.plot(ttp,tp,lw=3,label='Topex/Poseidon')
plt.plot(tjs1,js1,lw=3,label='Jason-1')
plt.plot(tjs2,js2,lw=3,label='Jason-2')
plt.plot(tjs3,js3,lw=3,label='Jason-3')
plt.legend(loc='upper left')
plt.ylabel('Sea level rise (mm)',fontsize=14)
plt.title('Global mean sea level',fontsize=16)
```

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Appendix. netCDF

UCAR

- netCDF (network Common Data Form): a set of data formats, programming interfaces, and software libraries that help read and write scientific data files.
- developed and maintained at Unidata, University Corporation for Atmospheric Research (UCAR)

netCDF files

- **self describing** shows you what it contains
- **portable** [machine independent]

http://www.unidata.ucar.edu/software/netcdf/

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Information normally contained in a netCDF file

- Dimensions
  - ✓ name, length
- Variables: named arrays
  - ✓ name, type, shape, attributes, values
  - – **Fixed sized variables**: array of fixed dimensions
  - – **Record variables**: array with its most-significant dimension **UNLIMITED → no limit in size, data can be extended along the unlimited dimension**
  - – **Coordinate variables**: 1-D array with the same name as its dimension
- Attributes - "metadata about the data"
  - ✓ name, type, values, length
  - – Variable attributes
  - – Global attributes

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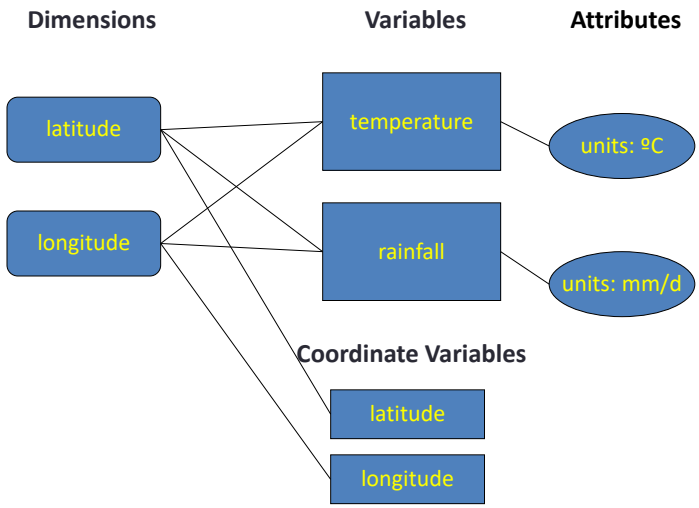
netCDF file



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How to examine a netCDF?

Ncdump, ncgen is Unidata utilities, available when you install netCDF

In Jupyter notebook

- ! ncdump file_name | less
  - dumps the entire contents of a file
- ! ncdump -h file_name | less
  - dumps the header info
- ! ncdump -v t2m file_name | less

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```
import numpy as np
import netCDF4 as nc
from netCDF4 import Dataset
# open a netcdf file
file='sst.mnmean.nc'
fh = Dataset(file, 'r')  # Dataset is the class behavior to open the netCDF file
                    # fh means the file handle of the open netCDF file
# print fh format
print fh.file_format
# print info about dimensions
print fh.dimensions.keys()
print fh.dimensions['time']
 # print info about variables
print fh.variables.keys()
 # print attributes
print fh.Conventions
for attr in fh.ncattrs():
      print attr, '=',getattr(fh,attr)
# Extract fh from NetCDF file
lat = fh.variables['lat'][:]  # extract/copy the fh
lon = fh.variables['lon'][:]
time = fh.variables['time'][:]
d_times=nc.num2date(fh.variables['time'][:],fh.variables['time'].units)
sst = fh.variables['sst'][:]  # shape is time, lat, lon as shown above
sst_units=fh.variables['sst'].units
fh.close()
```

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