ATMOS 1020 Climate Change

13. The Oceans

Thomas Reichler, Dept. of Atmospheric Sciences, April 5, 2022

1

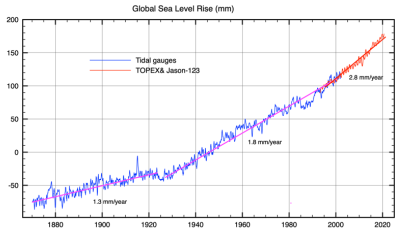
Today: The Oceans

- Measuring sea level
- Sea level rise
- Monitoring the interior of the ocean
- Coral reefs at risk
- Ocean acidification
- Ocean circulation changes

2

20th Century Sea Level Rise

- Sea level rise is probably the most alarming climate change prediction
- Many major cities are located on coasts



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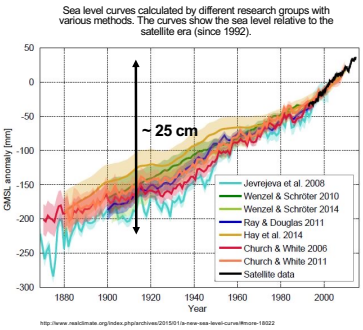
20th Century Sea Level Rise

- Many studies on this topic
- Differences are in the details
- Big picture:
  - sea level rise since 1870 has been around **25 cm** (8")
  - current rates of rise (**3.3 mm/year**) are the highest since the record began



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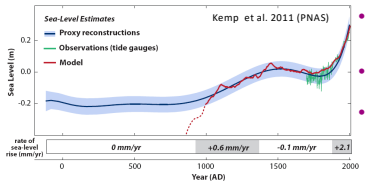
Sea Level Change: Past 2000 yrs



- blue: sea level evolution in North Carolina from proxy data; local land subsidence removed
- green: measurements from a nearby tide gauge
- red: from a simple model connecting global temperature with sea level

- Current sea levels are the highest since the past 2000 years

5

What Causes Sea Level Rise?

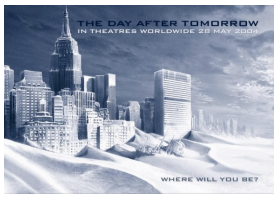
- These **don't**:
  - sea ice
  - ice shelves (these are connected to ice sheets but floating on ocean)
- These **do**:
  - thermal expansion of sea water
    - this is the **main contributor** so far
  - ice sheets (Greenland and Antarctica)
  - mountain glaciers

- Only a **tiny** amount:
  - permafrost
  - snow cover

6

The Day After Tomorrow

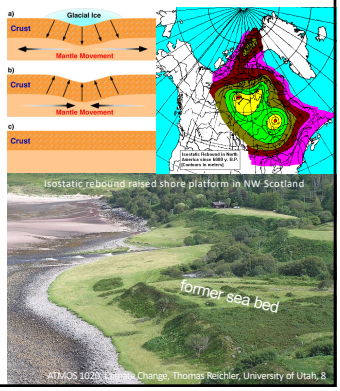
- They had it wrong: a disintegrating floating ice shelf has no effect on sea level
- And the cooling that followed should have caused sea level to drop!



7

Natural Influences on Sea Level

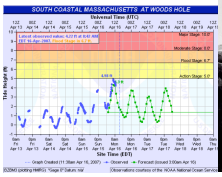
- Tides
- Ocean currents
- Winds/storms
- Tectonic activity
  - some locations are rising/falling
  - isostatic rebound; recovery from last ice age leads to rising land (falling sea level)
- These influences + spotty data means it's been hard to track global sea level accurately!

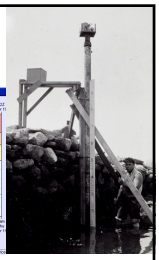


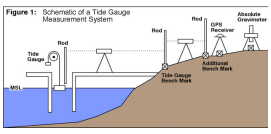
8

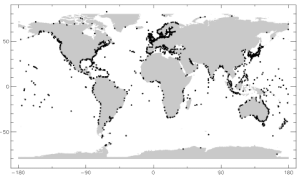
Measuring Sea Level

- Tide gauges are measuring sticks or sometimes float in wells
- Always coastal
- Few long records





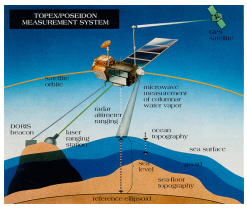


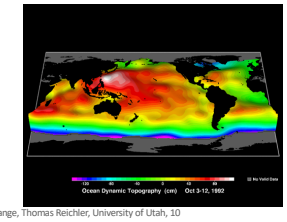


9

Satellite Altimetry

- Radar Altimetry (TOPEX-Poseidon, Jason)
  - instruments emit a short radar flash and measure the time-of-flight of its reflection from Earth. 1,000 times per second.
  - measures **sea level** and **ice sheet height**

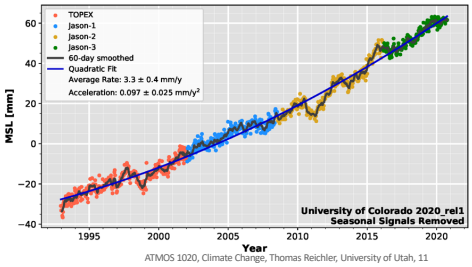




10

Satellite Altimetry

- Most accurate satellite measurements
  - **8.5 cm** rise in last **25 years**
  - **3.3 mm/year**



https://d32ogoqmya1dw8.cloudfront.net/images/getsi/teaching_materials/ice_sealevel/global_sea_level_graph.v2.png

11

Contributions to Sea Level Rise

- Paper by Nerem et al. 2018

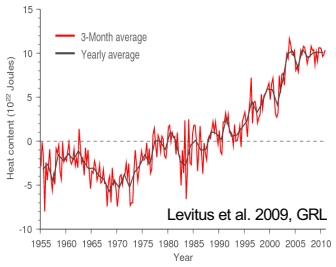
Component	Period	Rate mm/yr	Percent	Acceleration mm/yr^2
Greenland	2002-2017	0.66	22	0.02
Antarctica	2002-2017	0.19	6	0.03
Glaciers & ice caps	2002-2017	0.51	17	0.01
Thermal expansion	1993-2016	1.65	55	0.01
Total		3.01	100	0.07

- Mostly **thermal expansion** so far
- But ice sheet melt is accelerating

12

Thermal Expansion

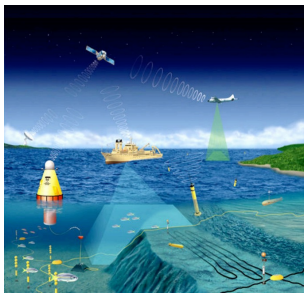
- Thermal expansion is **primary contribution** to sea level rise (~55%)
- Due to ocean temperature increases
  - water expands as it warms
- Ocean heat content (= temperature of the ocean interior) has been steadily increasing in recent decades
- How do we know this?



13

Monitoring the Ocean

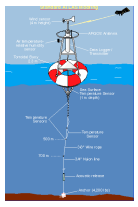
- A multitude of instruments is used to measure the oceans
  - TAO array
  - ARGO floats
  - Ship measurements

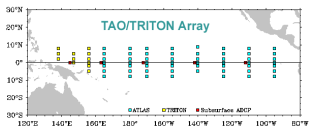


14

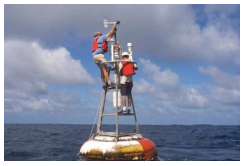
TAO Array

- Tropical Atmosphere-Ocean Array
- ~70 moorings in the tropical Pacific
- Mostly to study ENSO
- Since 1990s
- Operated by US, France, & Japan



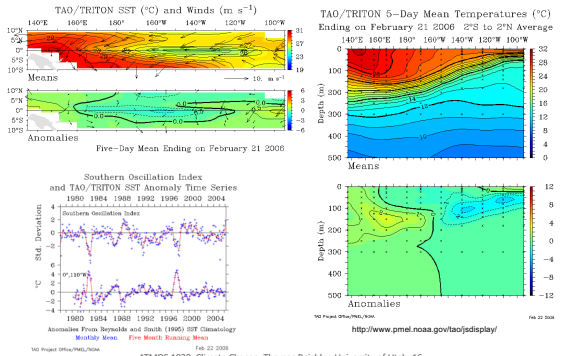


http://www.pmel.noaa.gov/tao/kaimi/



15

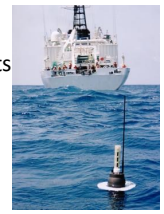
TAO Array Data

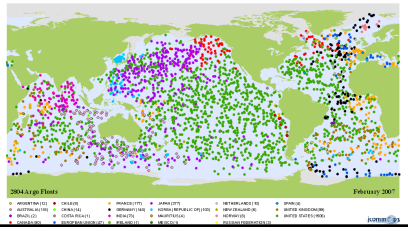


16

ARGO Floats

- Multinational project
- Global array of free drifting profiling floats
- Since ~2000s
- Measure to 2,000 m depth
- Mar 2022: >3993 floats



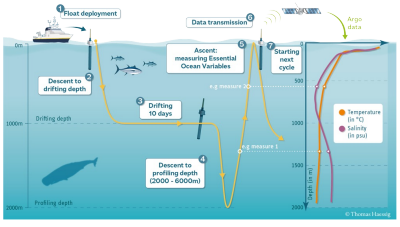


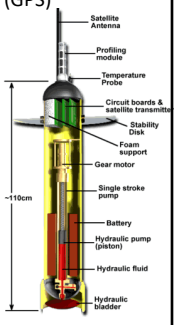
http://www.argo.ucsd.edu
http://wo.jcommops.org/cgi-bin/WebObjects/Argo.woa/1/wo/5WPcueKmsKQFr6MCXXgKkw/19.0.0.3.1

17

How Does ARGO Work?

- Passive drifters/floats
- Measure temperature, salinity, and currents (GPS)
- "Radiosondes" of the oceans



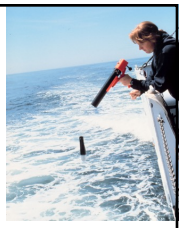


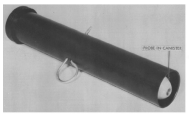
http://www.argo.ucsd.edu/

18

Ship Measurements

- Expendable Bathythermograph (XBT)
- Ocean temperature down to 1,500 m
- About 70 voluntary ships toss them overboard
- 14,000 each year
- In use since 1962





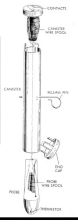


Fig. 1: XBT diagrams: Bathythermograph (probe) and exploded view.

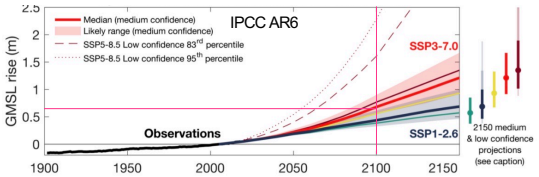
19

Ice Contributions to Sea Level Rise

- 2018 numbers:
  - Melting **mountain glaciers** contribute **17%** to rising sea levels
  - **Greenland + Antarctica** contribute **28%**

20

Future Sea Level Predictions

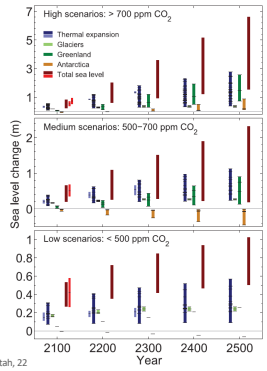


- What will sea level be by the end of the 21st century?
- Best estimate: **+0.7 m** relative to 2014
  - from AR6: 6th assessment report of the IPCC (2021)

21

AR5 Projections Beyond 2100

- Up to 7 m in 2500
- This is HUGE
- Mostly from thermal expansion and Greenland ice melt
- Lot's of uncertainties



22

Speed of Sea Level Rise

- Sea level rise is a **very slow** process
  - takes an extremely long time to melt Greenland/ Antarctica
- In the long term, ice sheets will be the main problem, but this **will take centuries** to happen
- We're closely monitoring for any surprises (extra ice breaking off)
- What places are most vulnerable to sea level rise?
  - low lying coastal zones

23

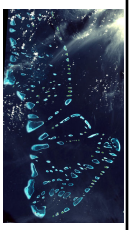
Population Distribution

- About half of the world's population live within 200 km of a coastline
- "1 person in 10 lives in an "at-risk zone" for flooding and storms, exacerbated by climate change" (New Scientist)

24

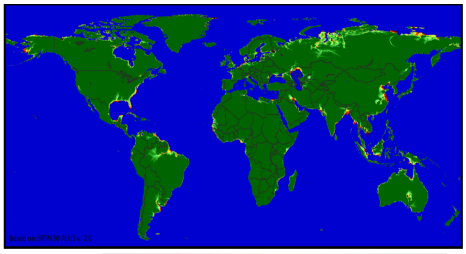
Low Lying Island Nations

- **Tuvalu** (Pacific)
  - highest point is 4.5 m above sea level
- **Maldives** (Indian Oc.)
  - max. elev = 2.5 m
  - average elev = 1.5 m
- Some **Caribbean** nations are also quite vulnerable
  - Bahamas: 80% within 1.5 m of sea level
- These nations could disappear!

25

Vulnerable Regions



26

Countries Most at Risk

- 2014 study finds that about 200 million people live on land that will be below sea level by the end of this century
- Mostly in China

By Total

Country	Population Exposed (thousands)	Percent of National Population Exposed
1. China	50,465	4%
2. Vietnam	23,407	26%
3. Japan	12,751	10%
4. India	12,643	1%
5. Bangladesh	10,230	7%
6. Indonesia	10,157	4%
7. Thailand	8,176	12%
8. Netherlands	7,793	47%
9. Philippines	6,205	7%
10. Myanmar	4,742	9%
11. United States	3,687	1%
12. United Kingdom	2,574	4%
13. Brazil	1,737	1%
14. Germany	1,665	2%
15. France	1,256	2%
16. Malaysia	1,171	4%
17. Taiwan, Province of China	1,032	4%
18. Korea, Republic of	1,028	2%
19. Nigeria	848	1%
20. Italy	842	1%

27

Costs of Sea Level Rise

- Main problems will likely be from **large storm surges** (e.g., tropical storms and other extreme events) on top of the sea level rise
- Costs
  - wetland loss
  - salinization of aquifers/crops
  - constructing barriers
  - relocation

28

Other Impacts on the Ocean

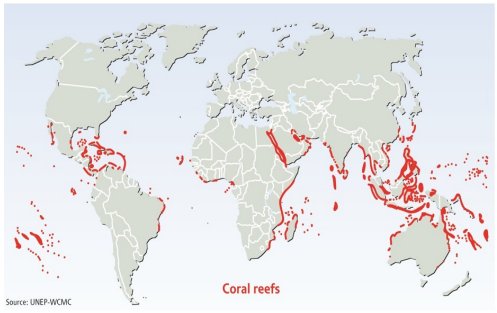
- We'll next discuss:
  - coral reef loss
  - ocean acidification
  - ocean circulation and ENSO

29

30

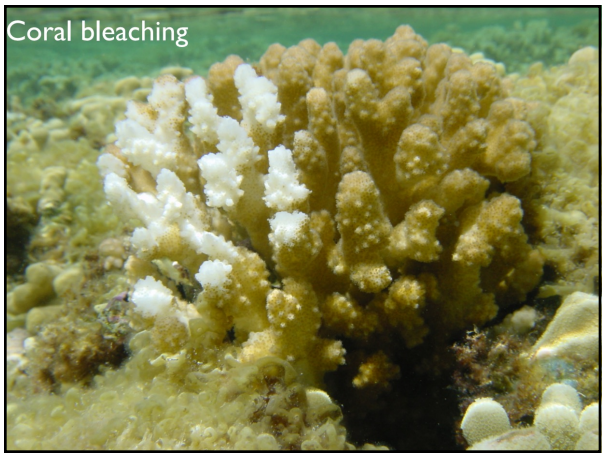
Coral Reefs

- Coral reefs are found in warm, shallow, and clear waters of the tropical oceans



31

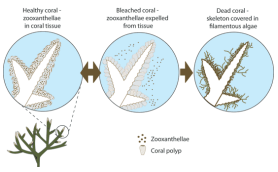
Coral bleaching



32

Coral Bleaching

- Corals depend on phytoplankton algae (zooxanthellae) that provides nutrients
  - algae leaves when temperatures exceed **~24°C**, so color of reef reflects color of underlying coral (white)
- Corals bleach if ocean temperatures rise
  - increases of 1.5–2°C lasting for 6-8 weeks are enough to trigger bleaching
  - when these temperatures persist for more than 8 weeks, corals begin to die



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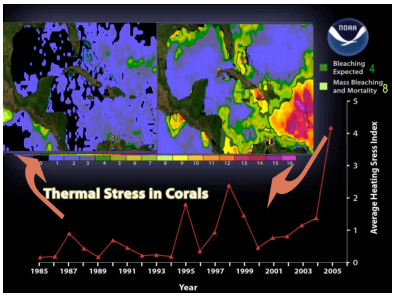
33

Coral Bleaching

- Coral bleach in El Niño years and with global warming



https://www.gbrmpa.gov.au/the-reef/reef-health/coral-bleaching-101

34

The 1997/98 El Niño

- 16% of all coral were damaged in 1997/98 El Niño alone. Some bounced back.
- "Corals could become rare on tropical and subtropical reefs by 2050 due to the combined effects of increasing CO_2 and increasing frequency of bleaching events" (IPCC 2007 WG2)

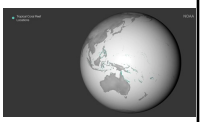
Coral in normal conditions

Coral in acidified conditions

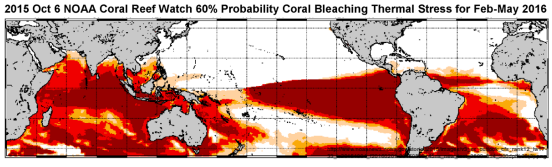
35

The 2015/16 El Niño

- NOOA declares third global coral bleaching event ever
  - "We are losing huge areas of coral across the U.S., as well as internationally"
- From climate change and El Niño
- Corals recover from mild bleaching, but severe bleaching is often lethal



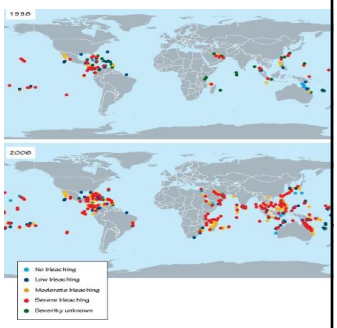
2015 Oct 6 NOAA Coral Reef Watch 60% Probability Coral Bleaching Thermal Stress for Feb-May 2016



36

Severe Coral Bleaching

- Incidence of mass coral bleaching increased dramatically in the last few decades
- "By 2030 or 2050, bleaching thresholds will be exceeded annually or bi-annually at the majority of reefs worldwide"



37

Summary: Coral Reefs At Risk

- Rising ocean temperatures threat coral reefs
- In particular the combination of global warming and interannual El Niño-related warm events
  - 1982/83 El Niño: first observed mass coral bleaching
  - 1997/98 and 2010 El Niño: more severe, global scale bleaching
  - 2014-2017: most destructive global bleaching
- Interval between events is becoming too short for a full recovery
- Will have dramatic effects on future coral reef growth

38

More Warming Related Ocean Changes

- Increased **disease** in fish
- **Poleward movement** of some species
  - tuna, marlin, cod, …
- Increased **mortality** of winter flounder eggs and larvae
- Marine mammals, birds, seals, sea lions and walruses:
  - feed mainly on plankton, fish, and squid
  - vulnerable to changes in prey in response to climatic factors

- Nesting of sea turtles is strongly affected by temperature
- Source: IPCC 2007 WG2

39

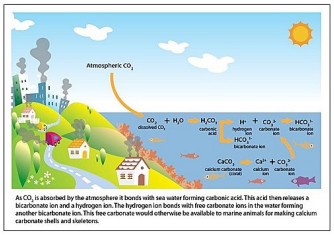
Ocean Acidification

- Another risk for coral
- Carbon dioxide can dissolve in water
- Carbonated drinks: pressurized CO_2 is dissolved in water
  - when opened at normal pressure, it releases CO_2 bubbles
  - higher atmospheric CO_2 levels means more CO_2 dissolves in seawater

40

Chemistry of Ocean Acidification

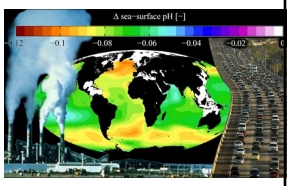
- When CO_2 is dissolved in water, some **carbonic acid** is formed (**H_2CO_3**)
  - water becomes **more acidic**
    - mineral water tastes sour
  - pH of the ocean has been decreasing as CO_2 levels have risen

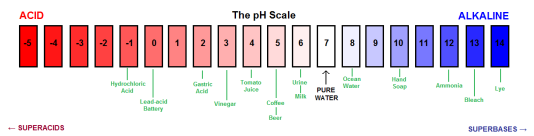


41

Ocean Acidification

- pH
  - pre-industrial (1700s) 8.25
  - recent past (2000s) 8.10
  - 2050 (2×CO2 = 560 ppm) 7.95
  - 2100 (IS92a) 7.82

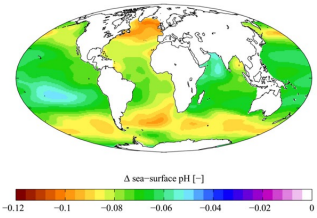




42

How Much More Acidic?

- pH is a logarithmic scale, so the observed drop in pH corresponds to a **30%** increase in hydrogen ions (H^+)
- Who cares about a more acidic ocean?



Change in sea surface pH caused by anthropogenic CO2 emissions between the 1700s and 1990s. http://scienceprogress.org/2008/06/our-dying-oceans/

43

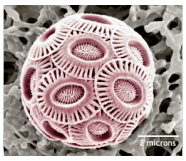
Acids

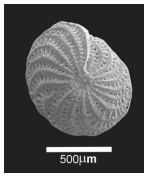
- What kinds of things react with acids?
- TUMS, of course …
- Tums has calcium: **calcium carbonate** ($CaCO_3$)
- This is actually **relevant to the ocean**: calcium carbonate is what marine organisms of all types use to **build shells, skeletons**, etc.
- Higher ocean acidity means less free carbonate (CO_3^{2-}) for building shells and skeletons

44

Ocean Acidification

- Just as the Tums react with acid, creatures with shells also react …
  - not just clams & lobsters
  - even low on the food chain organisms like phytoplankton are affected
- Phytoplankton are responsible for 1/3 of all photosynthesis on the planet and feed the marine food web



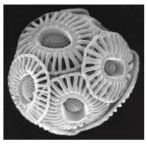


45

Ocean Acidification

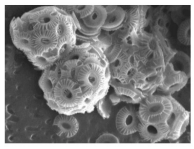
- Ocean acidification is likely to **impair shell formation** in oceanic calcifying organisms like **plankton** and **corals**

normal coccolithophorid



10-30 microns

coccolithophorids in acidified conditions



46

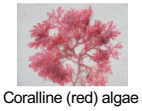
Ocean Acidification

- Increasing the acidity of the ocean has a negative impact on many types of biology

Pteropods (small molusks)

Coccolithophore (single-celled algae, protists and phytoplankton)

Shellfish



Coralline (red) algae

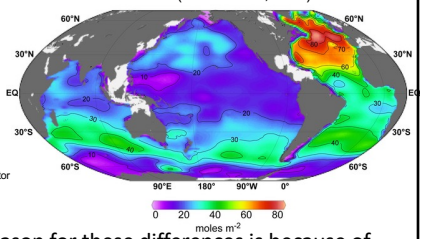
47

Human Carbon in the Ocean

- Human carbon is not evenly distributed
- More than 23% is in the North Atlantic

http://www.pmel.noaa.gov/co2/story/Ocean+Carbon+Storage

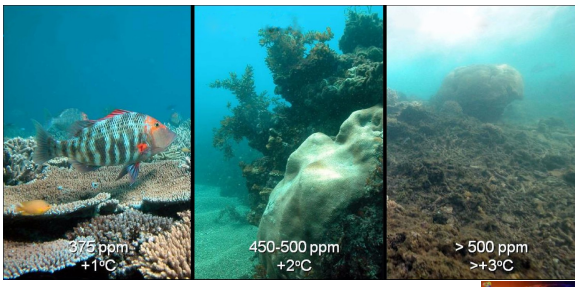
Column inventory of anthropogenic CO2 in 1994 (Sabine et al., 2004)



- The primary reason for these differences is because of the slow mixing time in the ocean interior and the fact that waters only move into the deep ocean in a few locations

48

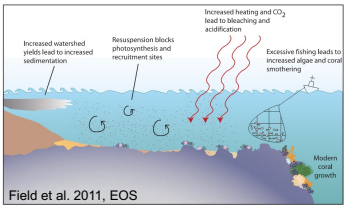
Ocean Acidification



49

Corals: More Risk Factors

1. Increasing sea surface temperatures and coral bleaching
2. Ocean acidification
3. Sea level rise
   - increased erosion
4. Enhanced sedimentation
5. Fisheries



Field et al. 2011, EOS

Beach erosion due to rising sea levels

50

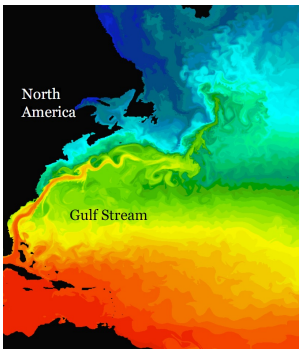
Ocean Circulation Change?

- Will currents change?
  - we'll discuss the **thermohaline circulation**
    - and why claims of **Europe freezing** over with global warming are **overblown**

51

The Gulf Stream

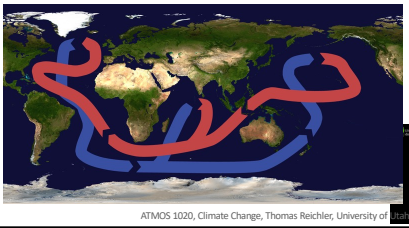
- AVHRR satellite: colors show temperature
- The Gulf Stream transports **heat northward**
- This surface current is **driven by winds** and is **not subject to stopping**



52

Thermohaline Circulation

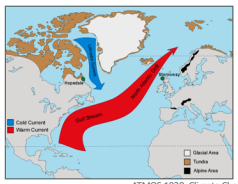
- AKA: ocean conveyor belt
- Driven by **heavy water sinking slowly**
  - also transports heat northward
  - takes ~1000 years for one cycle
- This **could slow down even further** with global warming

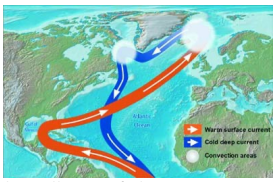


53

North Atlantic Drift

- **Part of thermohaline circulation driven by sinking** near Greenland
- Circulation **could slow** as water gets warmer and fresher (more rain & melting ice) at high latitudes
- Warmer and fresher water is **less dense** and does not sink as readily
- If this weakened it **would cause Europe to cool**

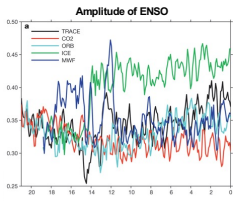




54

ENSO

- Climate change may affect ENSO
  - frequency and intensity of individual events
  - lot's of uncertainty here, but ENSO is very important for our climate
- Recent study by Liu et al. 2014 (Nature)
  - running climate model several times with different forcings
  - El Niño is fairly sensitive to forcings, but the picture is messy



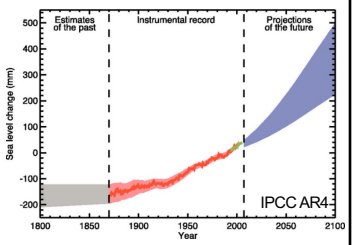
55

Extra Slides

56

AR4 Sea Level Predictions

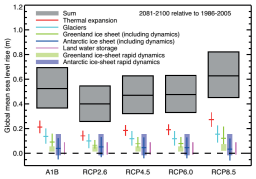
- AR4: 4th assessment report of the IPCC (2007)
- What will sea level be by the end of the 21st century?
- Estimate from AR4 IPCC Report: **0.2 – 0.5 m** (8-20")
- But model predictions did not consider changes in Greenland and Antarctic ice sheets!



57

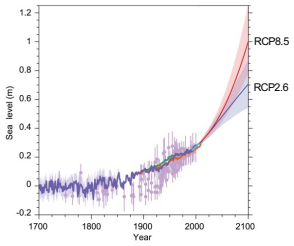
AR5 Sea Level Predictions

- AR5: 5th assessment report of the IPCC (2013)
- Process-based models:



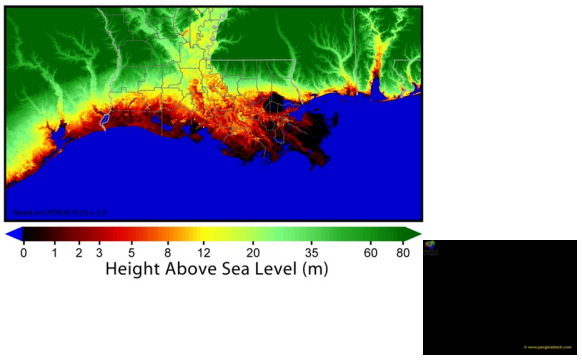
http://www.ipcc.ch/report/ar5/wg1/

- Paleo data, tide gauge data, and climate models combined: **0.7 – 1.2 m**



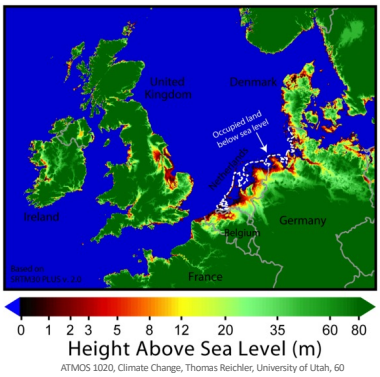
58

Sea Level Risk: Louisiana



59

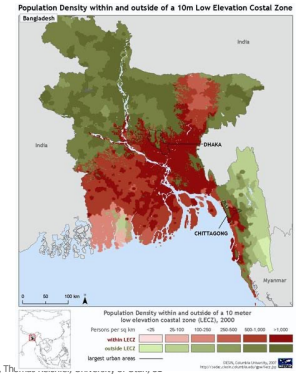
Sea Level Risk: North Sea



60

Bangladesh

- Most of Bangladesh is at high risk from flooding, sea-level rises, and stronger storms due to climate change
- Areas in **red are 10 m or less** above sea-level, areas in green are higher, and darker colors indicate denser populations (Image: CIESIN)



61