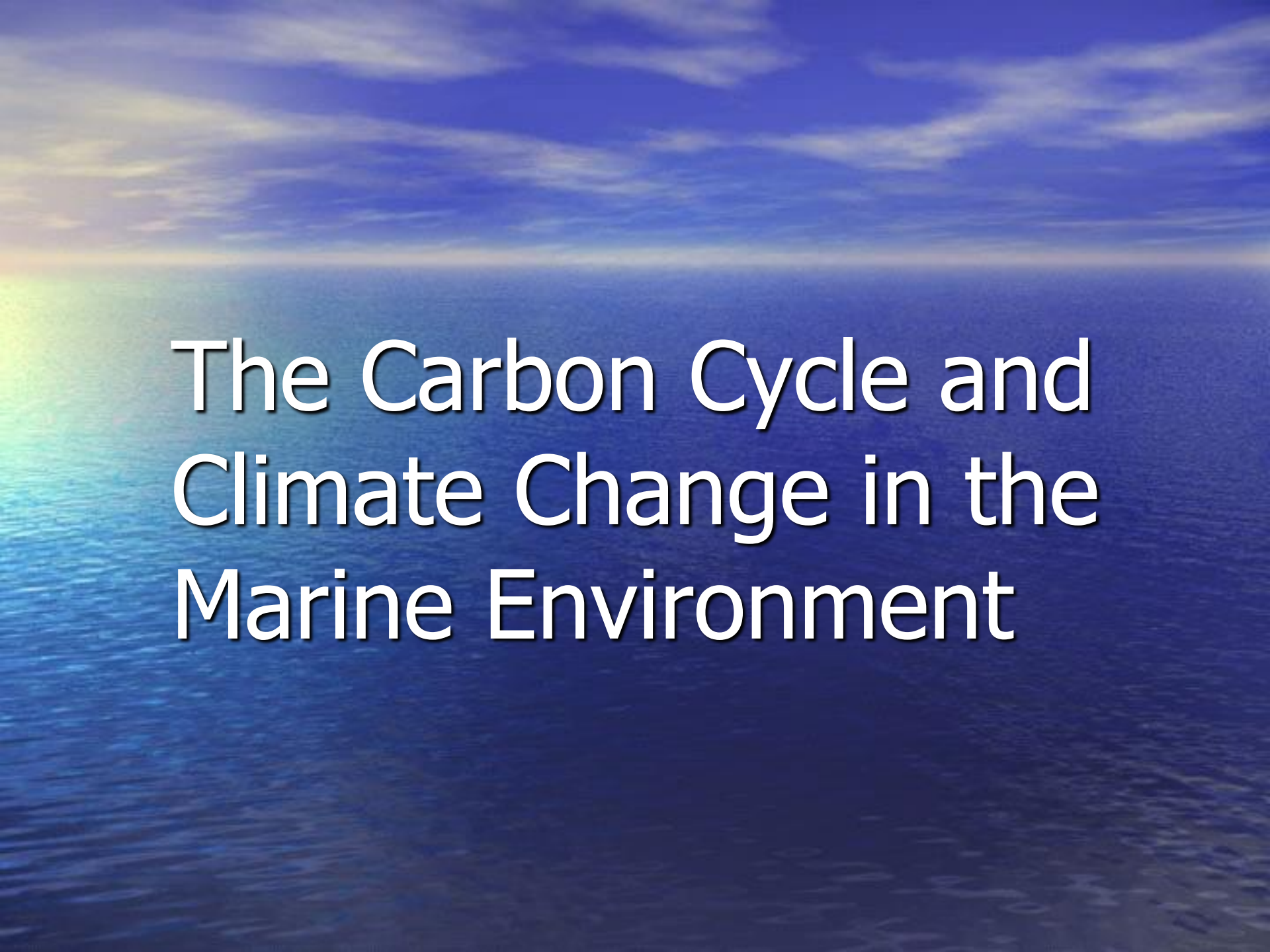


The background of the slide is a photograph of a vast, deep blue ocean stretching to the horizon. Above the horizon, the sky is a lighter blue with wispy white clouds. On the far left side, a portion of a rainbow is visible, showing colors from yellow to blue. The text is centered in the middle of the image.

The Carbon Cycle and Climate Change in the Marine Environment

Carbon Dioxide

- Greenhouse gas
- Flux between ocean, land and the atmosphere:
 - Land – living biota; decaying organic material
 - Ocean – dissolved CO₂; small creatures
- Deep ocean largest reservoir:
 - 40,000 Gt C cf. 2,000 Gt C on land, 1,000 Gt C in upper ocean and 750Gt C in atmosphere

Global Carbon Cycle

1. Terrestrial Cycle

- Photosynthesis
- Soil carbon – respiration
- Varying carbon sinks
- Human activity effects
- 1950's – fossil fuel emissions exceed land use change



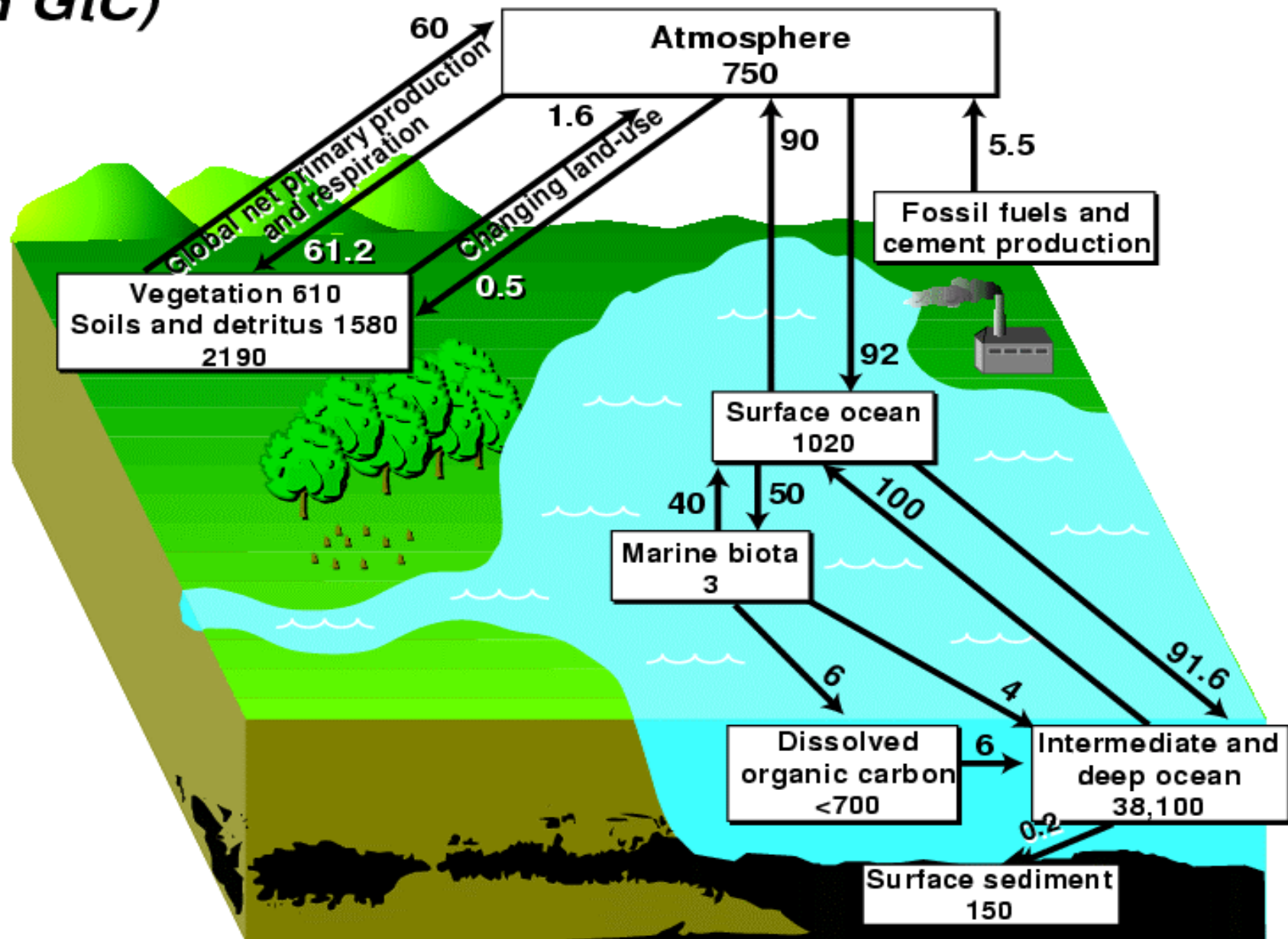
Global Carbon Cycle

2. Oceanic Cycle

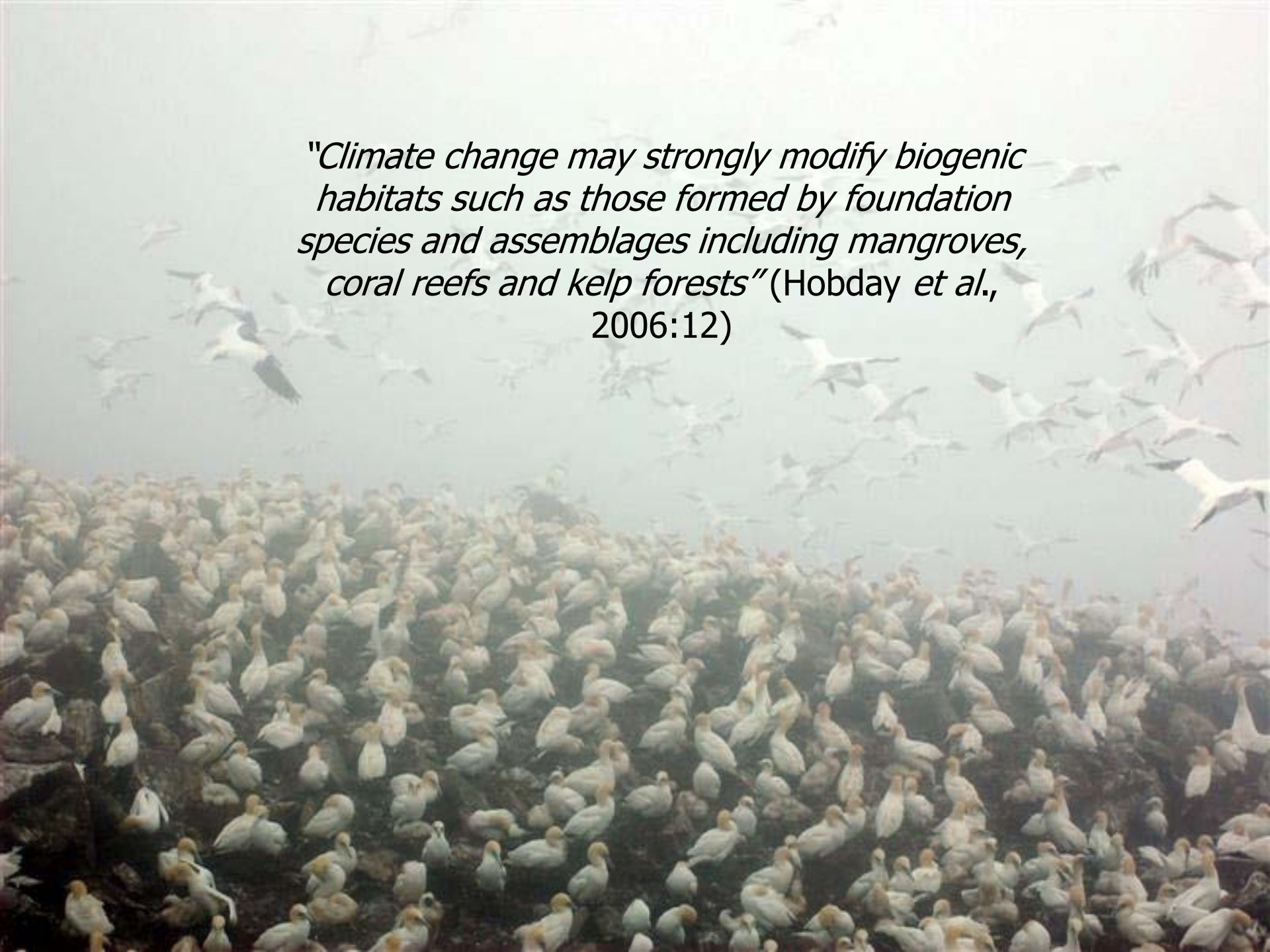
- Dissolved Inorganic Carbon (DIC)
- Solubility Pump
- Biological Pump
- Carbonate Pump



Global Carbon Cycle (in GtC)

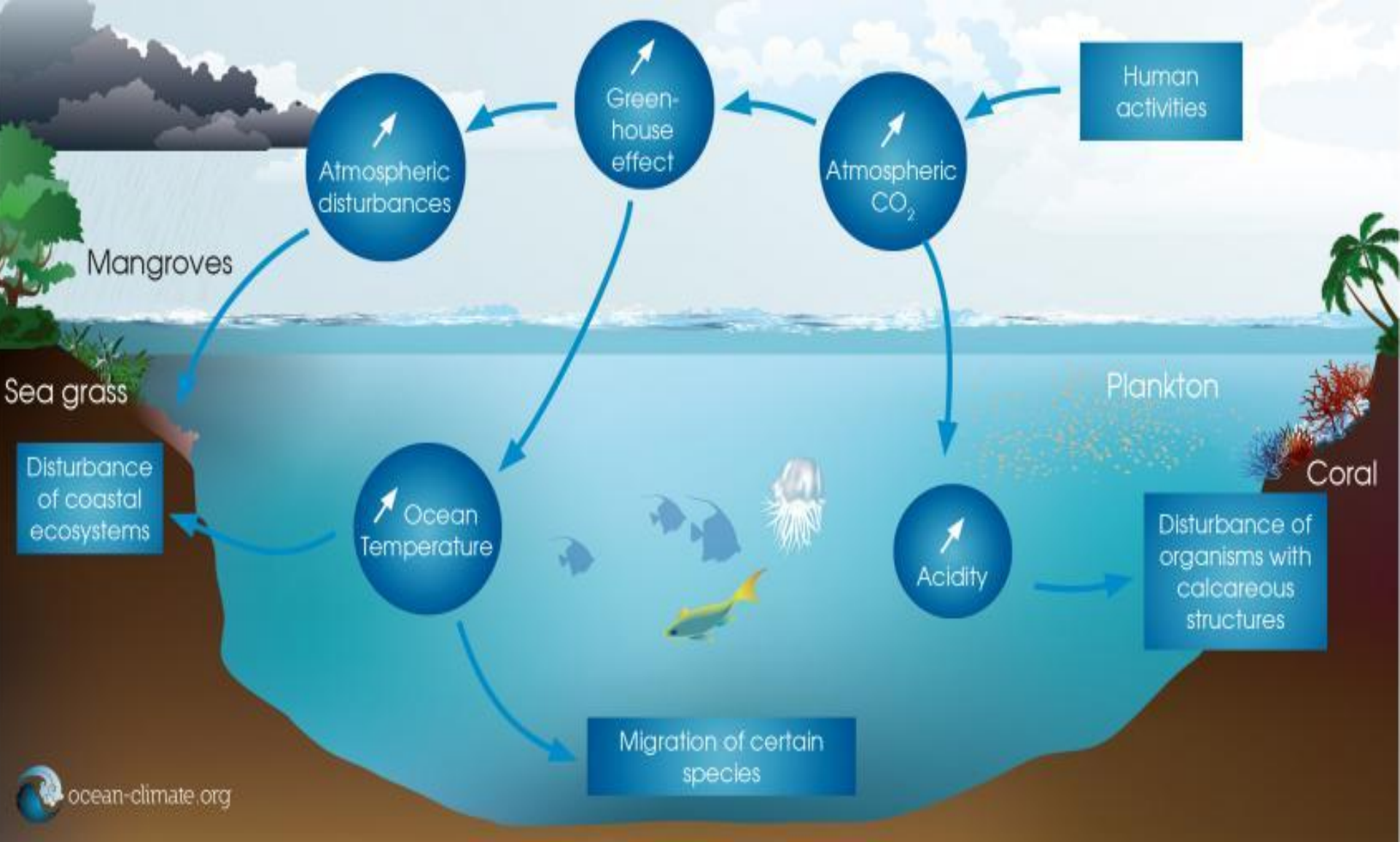


"Climate change may strongly modify biogenic habitats such as those formed by foundation species and assemblages including mangroves, coral reefs and kelp forests" (Hobday et al., 2006:12)



Impacts of Climate Change

- Physical and Chemical Effects of Climate Change
- Physical Effects of Ozone depletion and enhanced UV radiation
- Effects on biodiversity
- Effects on important ecosystems
- Deep ocean circulation patterns
- Wind patterns
- Ocean stratification
- Chemical composition
- ENSO and NAO
- Stratospheric ozone levels
- Plankton
- Fish
- Seabirds
- Mammals
- Polar Regions
- Deep Sea



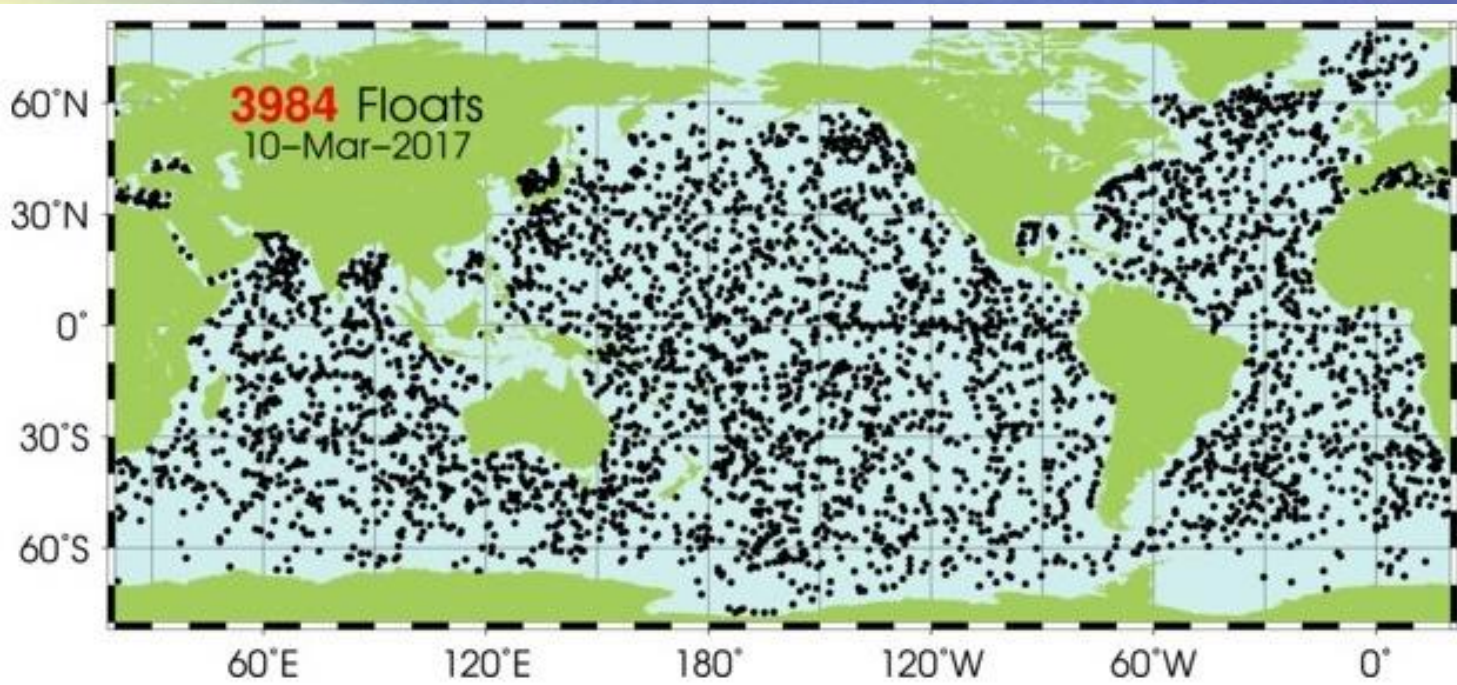
Broad Summary of Effects now being measured (IUCN, 2020)

Changing Oceans: Physical and Chemical Changes

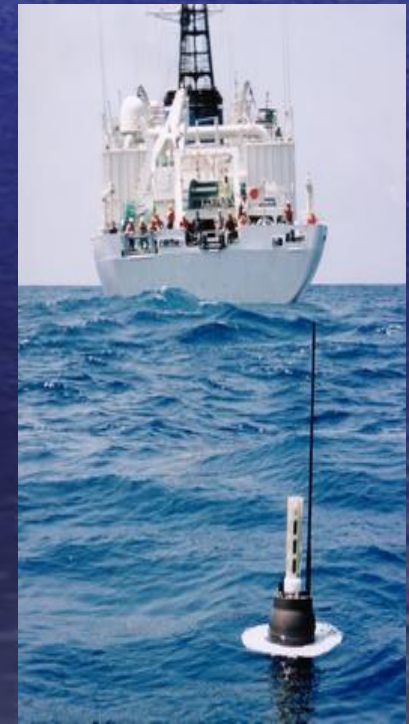
- 1-3°C increase in 50 yrs
- 1.4 - 5.8 °C by the end of the century (IPCC, 2015)
- Translated into warmer seas
- Changes not uniform
- Some cooling may be experienced
- loss of 0.5–3.3% DO between 1970–2010 from the ocean surface to 1000 m (IPCC, 2019)



Argo network of ocean sensors

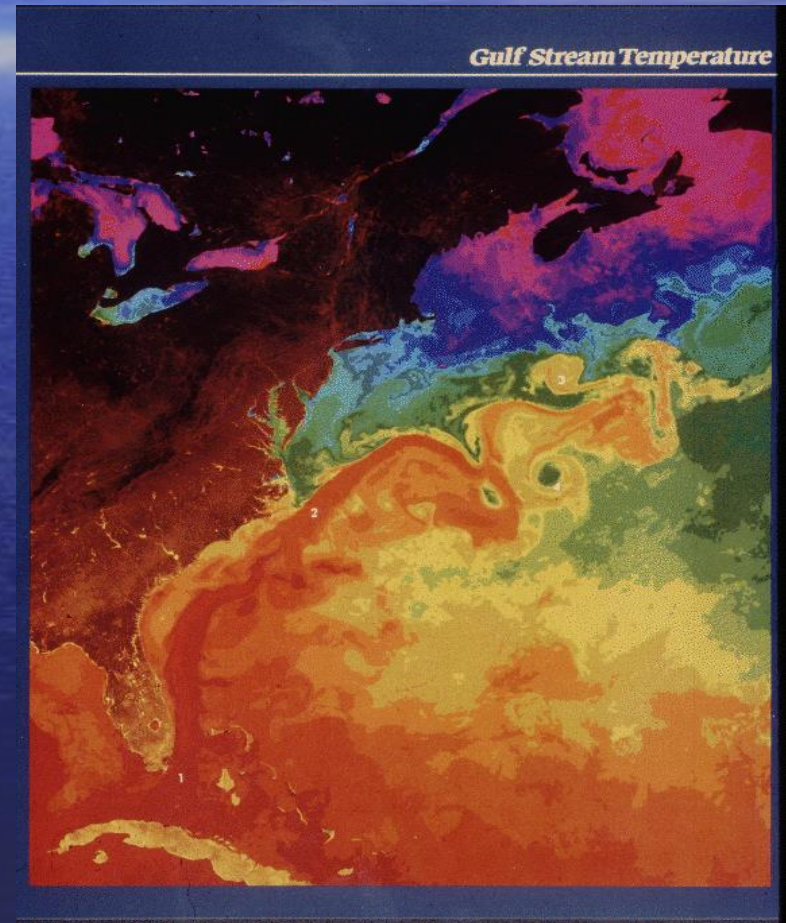


Argo deployments began in 2000



Changing Oceans: deep ocean circulation patterns

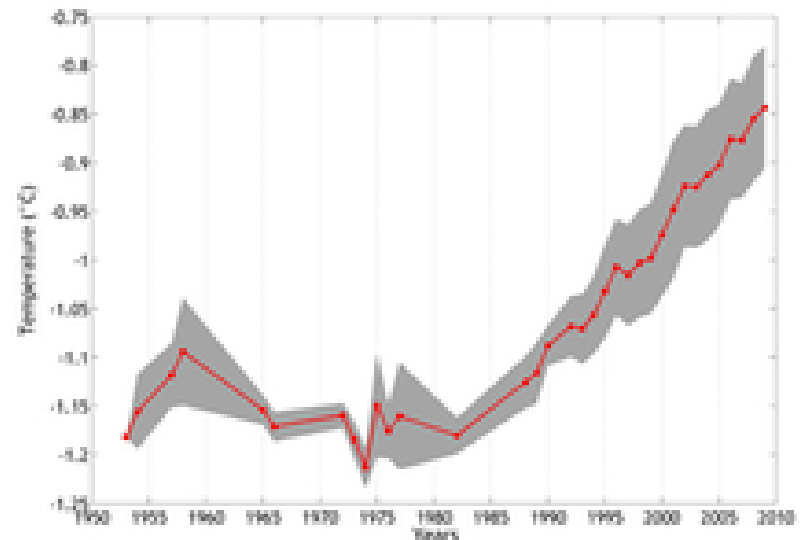
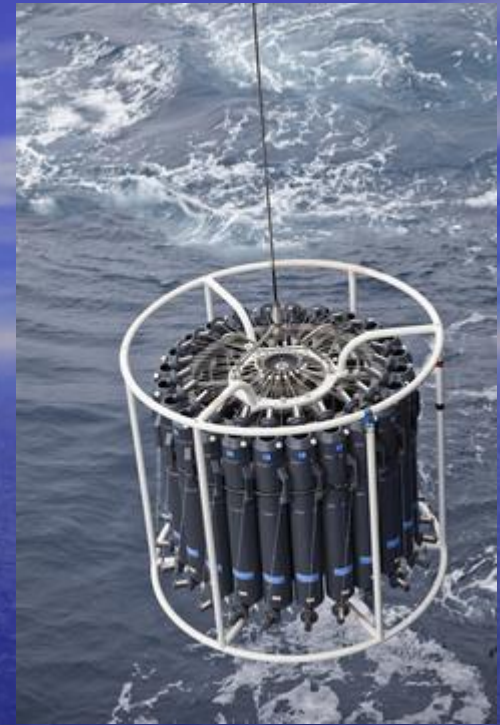
- ❖ Glacial melt – reduces salinity
- ❖ Density reduced - reduces strength of thermohaline circulation
- ❖ Limits transport heat around ocean
- ❖ Warmer waters in Tropics – less dissolved CO_2 – positive feedback
- ❖ In Sea of Japan, waters are absorbing half as much carbon as they were during 1990s (Bingham, 2019)



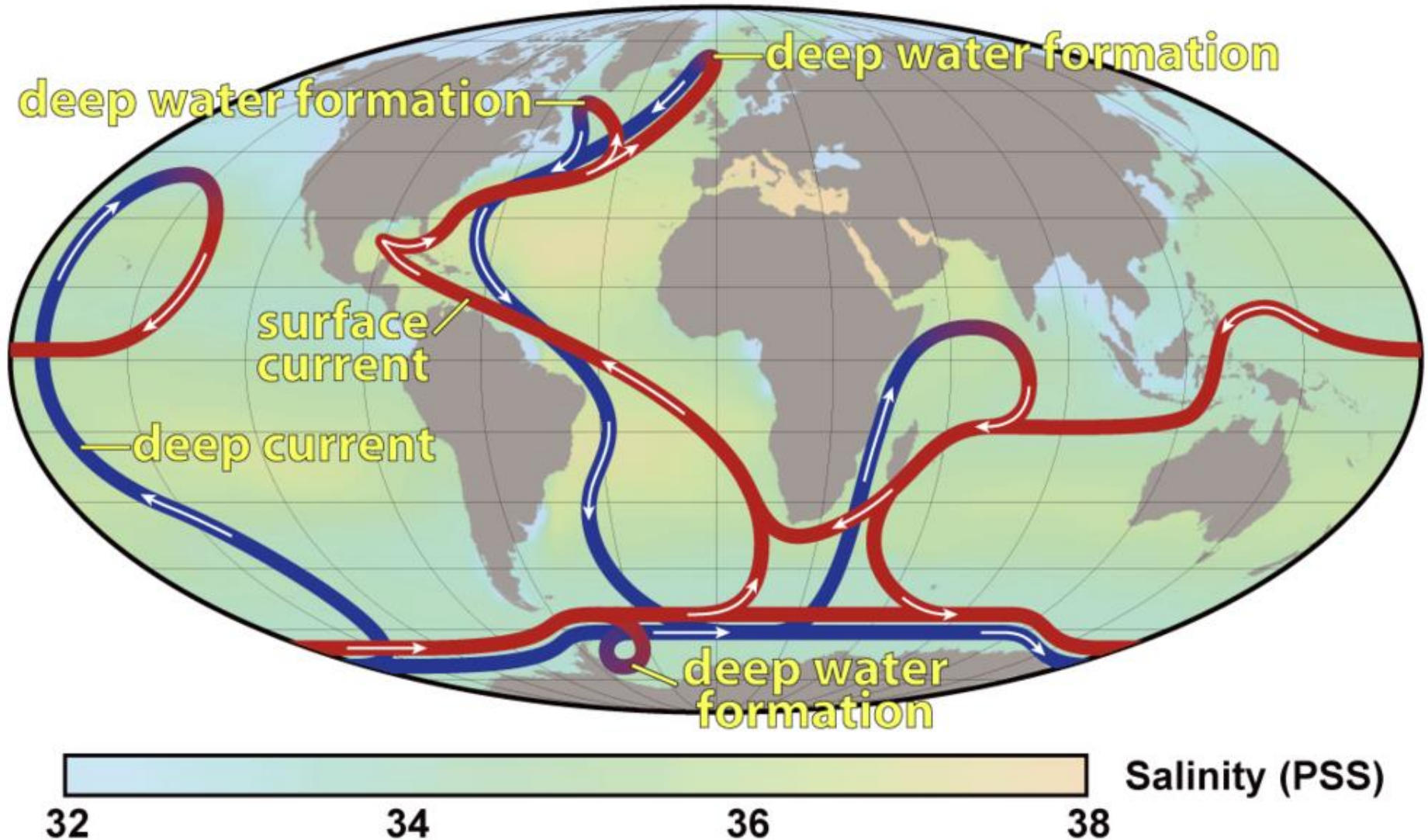
The system of circulating water currents that moderates northern Europe's weather is 30 percent slower than it was nearly 50 years ago (Bryden, 2005)

Greenland Sea deep water is warming ten times as fast as the rest of the global ocean (Alfred-Wegener Institut, 2013)

Over the last 30 years, water between 2000m and the sea floor has risen by 0.3°C



Thermohaline Circulation



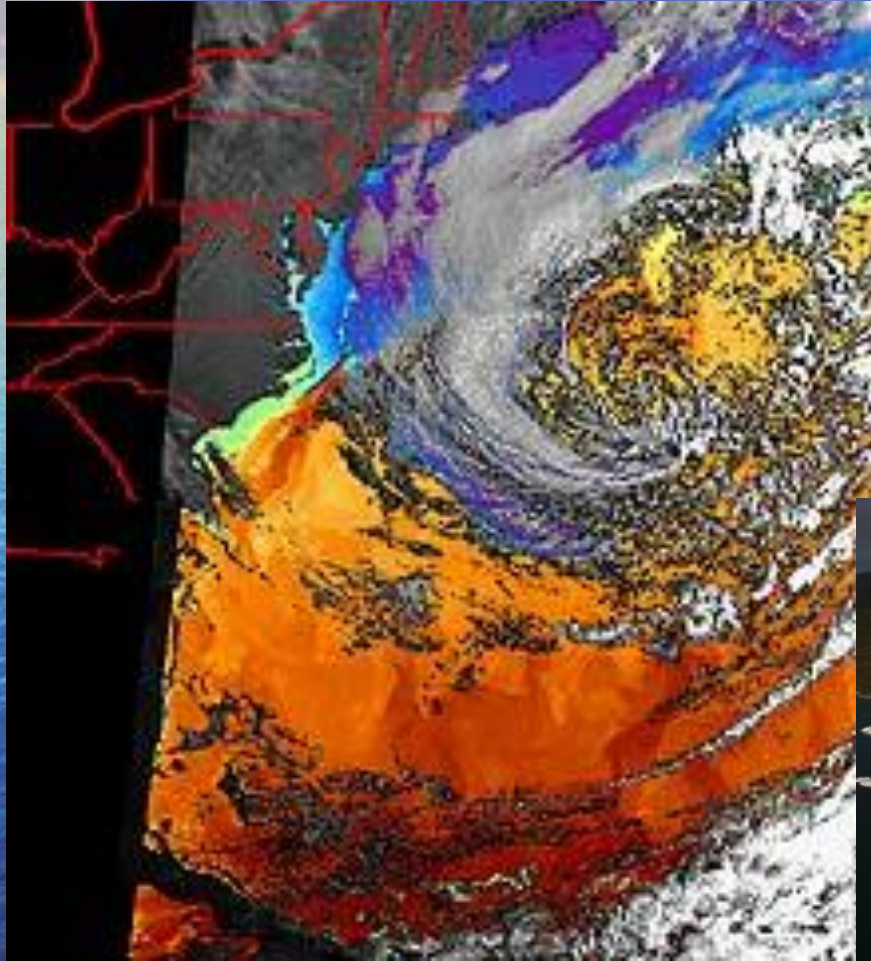
The entire circulation pattern takes 2,000 years to complete (Gaworeki, 2016)



From 2009 to 2010, the average strength of key ocean currents in the North Atlantic dropped by about 30 percent, causing warmer waters to remain in the tropics rather than being carried northward.

"The consequences included an unusually harsh European winter, a strong Atlantic Basin hurricane season, and an extreme sea level rise of nearly 13 cm along the North American coast north of New York City," (Hand, 2017: p.1)

Gulf Stream slowing



(Simms *et al.* , 2004)

15-20% in last 100 years, (Rahmstorf, 2015) - Potsdam Institute for Climate Impact Research in Germany.



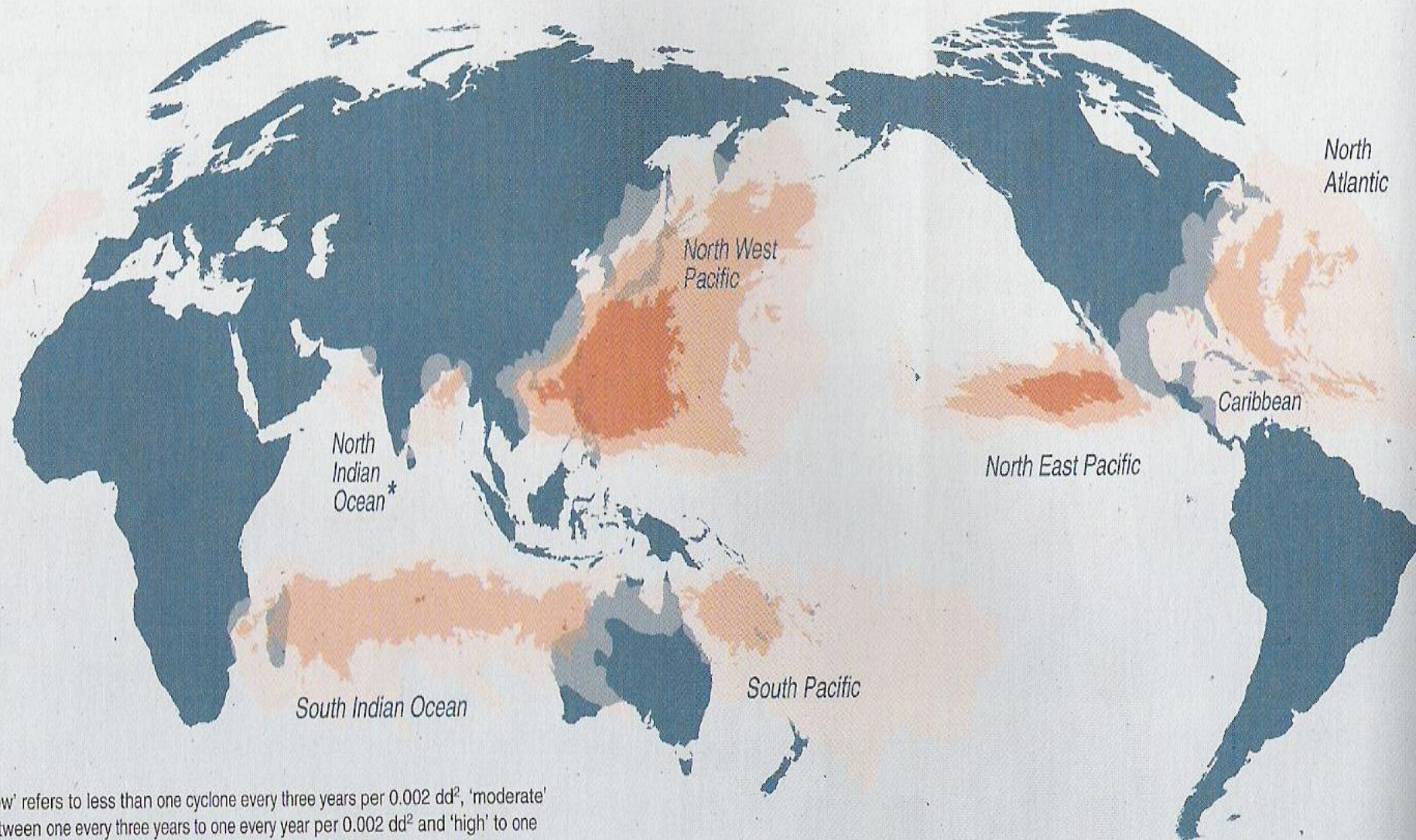
Changing oceans: wind patterns

- Sea surface temp affects patterns in atmospheric pressure – wind generation
- Stronger winds in some areas
- Frequency of extreme events
- Tropical storms – sea temp above 27°C
- Alteration to upwelling patterns



Average number of cyclones:
(1980-2000)

low moderate high



'Low' refers to less than one cyclone every three years per 0.002 dd², 'moderate' between one every three years to one every year per 0.002 dd² and 'high' to one to three cyclones per year per 0.002 dd². The unit '0.002 square decimal degree (dd²)' is equivalent to 25 km² on the equator, diminishing as latitude gets higher.

* average based on eight years only.

Sources: PREVIEW Global Cyclone Asymmetric Windspeed Profile, UNEP/GRID-Europe.

2020 Atlantic Hurricane Season

A satellite image of a hurricane over the Atlantic Ocean. The hurricane has a well-defined eye and a dense, swirling cloud structure. The surrounding ocean is dark blue, and some landmasses are visible in the background.

- 2020 Atlantic hurricane season has spawned 30 tropical storms
- 2005 of 28 named storms.
- A typical season only produces 12 named storms, so 2020 has already seen two and a half times more than average.

Coastal Vulnerability in UK

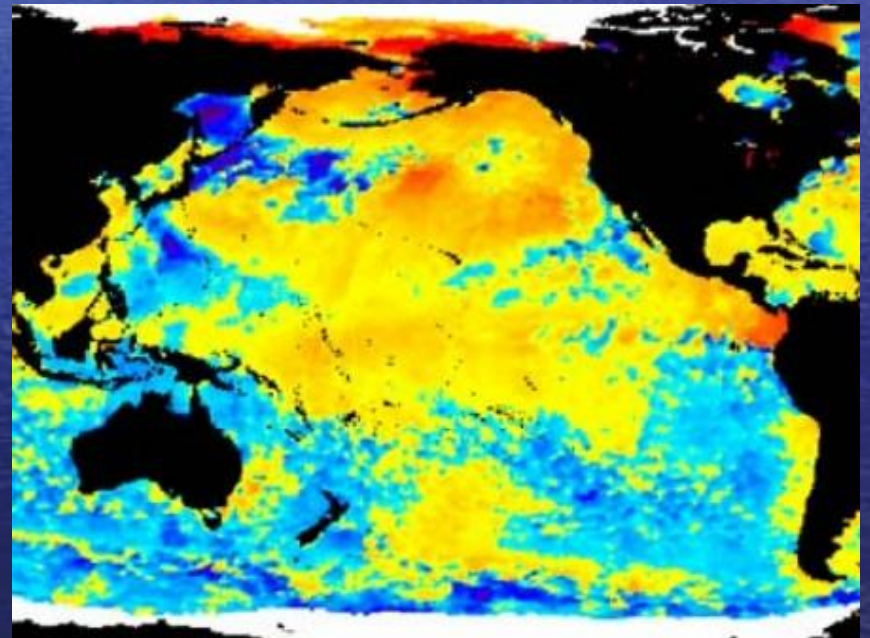
Coastal Damage during flooding in Feb 2014
at Dawlish, England



Source: Met office, 2014

Changing Oceans: ENSO/NAO

- El Nino Southern Oscillation – naturally occurring fluctuation of atmospheric pressure in Pacific which weakens Trade Winds
- 2-8 year cycle – frequency and duration appear to have increased recently
- North Atlantic Oscillation – positive and negative phases
- Currently positive phase – stronger winter storms



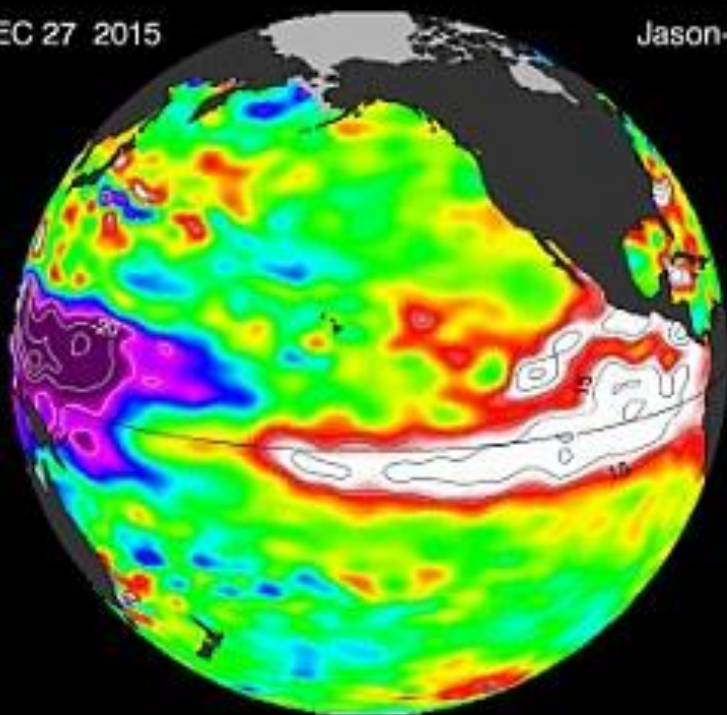


- The clearest sign that an El Niño event is underway is the appearance of unusually warmer water (up to 5°C) between the date line and coasts of Ecuador and Peru

El Nino Comparison 2015 cf 1997

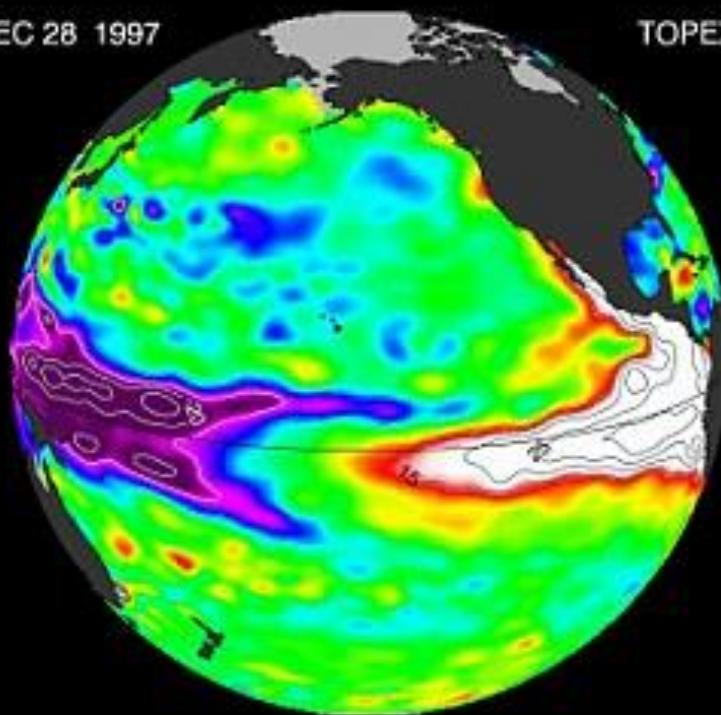
DEC 27 2015

Jason-2

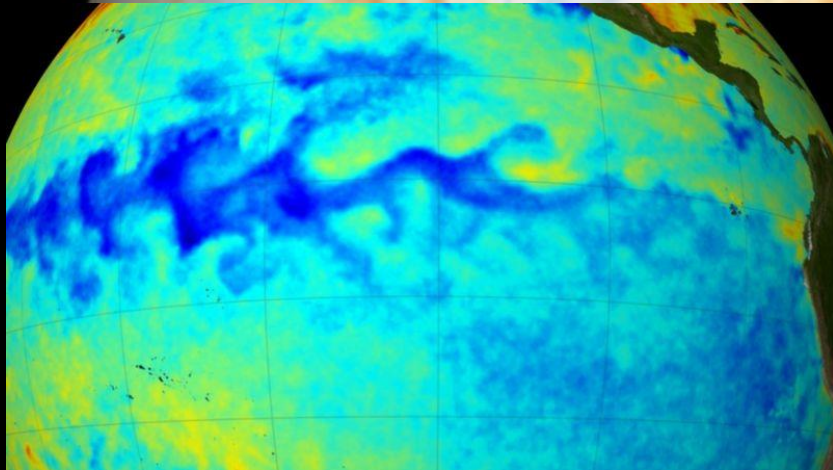


DEC 28 1997

TOPEX/POS



satellite sea surface temperature imagery for the month of October 2015, where orange-red colors are above normal temperatures and are indicative of El Niño. (NOAA, 2015)



“El Nino can bring more than just floods” (New Scientist, 2014:1)

- Stunted growth of children affected by 1997 El Nino
- Affected crops – cut of roads – malnutrition, diarrhoea from polluted water – lack of access to healthcare
- 16 times more rainfall in coastal areas



Changing oceans - stratification

- Warm, calm conditions – stratification intensified
- Resistance to mixing
- Winter winds may be less able to mix layers
- Increased 2.18-2.42% since 1970s (IPCC, 2019)



Changing oceans: chemical composition

- Naturally alkaline – pH 8.2
- Warmer water – reduced concentration dissolved gases
- Exacerbate temperature rise
- However, less saline water can hold more CO_2 – glacial melt
- Aragonite reduction

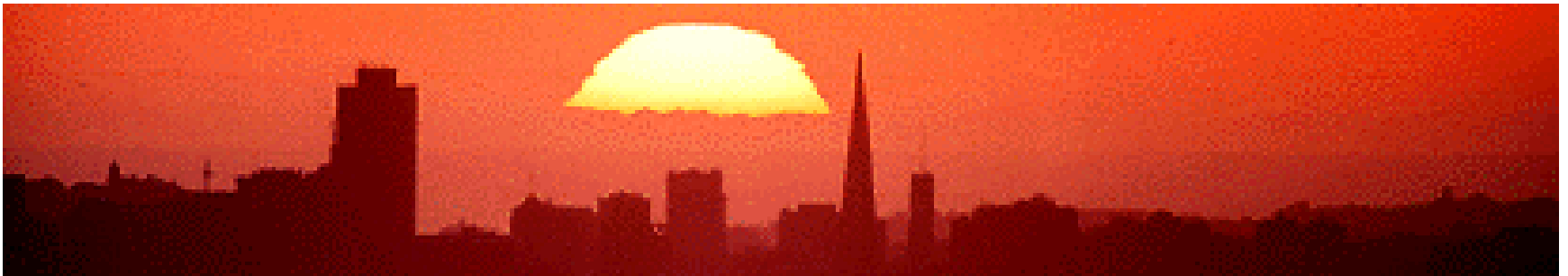
Ocean Acidification



- Under saturated with calcium carbonate
- Coccolithospores – basis marine food chain
- 2100, 75% cold water corals
- Changes could develop in decades not centuries (Orr *et al.*, 2005)
- 0.5 change in average pH by 2100
- The open ocean surface water pH is observed to be declining - range of 0.017–0.027 pH units per decade since the late 1980s (IPCC, 2019)

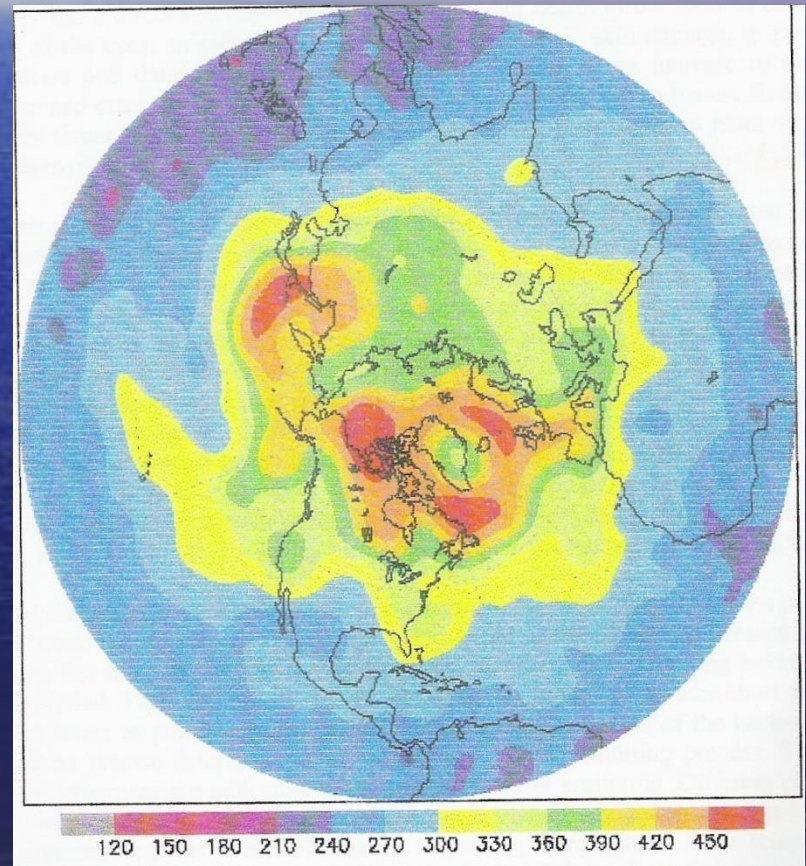
Ozone Depletion: UV radiation

- 90% ozone found in stratosphere
- 10% troposphere
- Filter mechanism
- Secondary pollutant – low level ozone
- Stratospheric O₃ – lowest levels since measurements began
- CFC's
- Ozone hole may have peaked



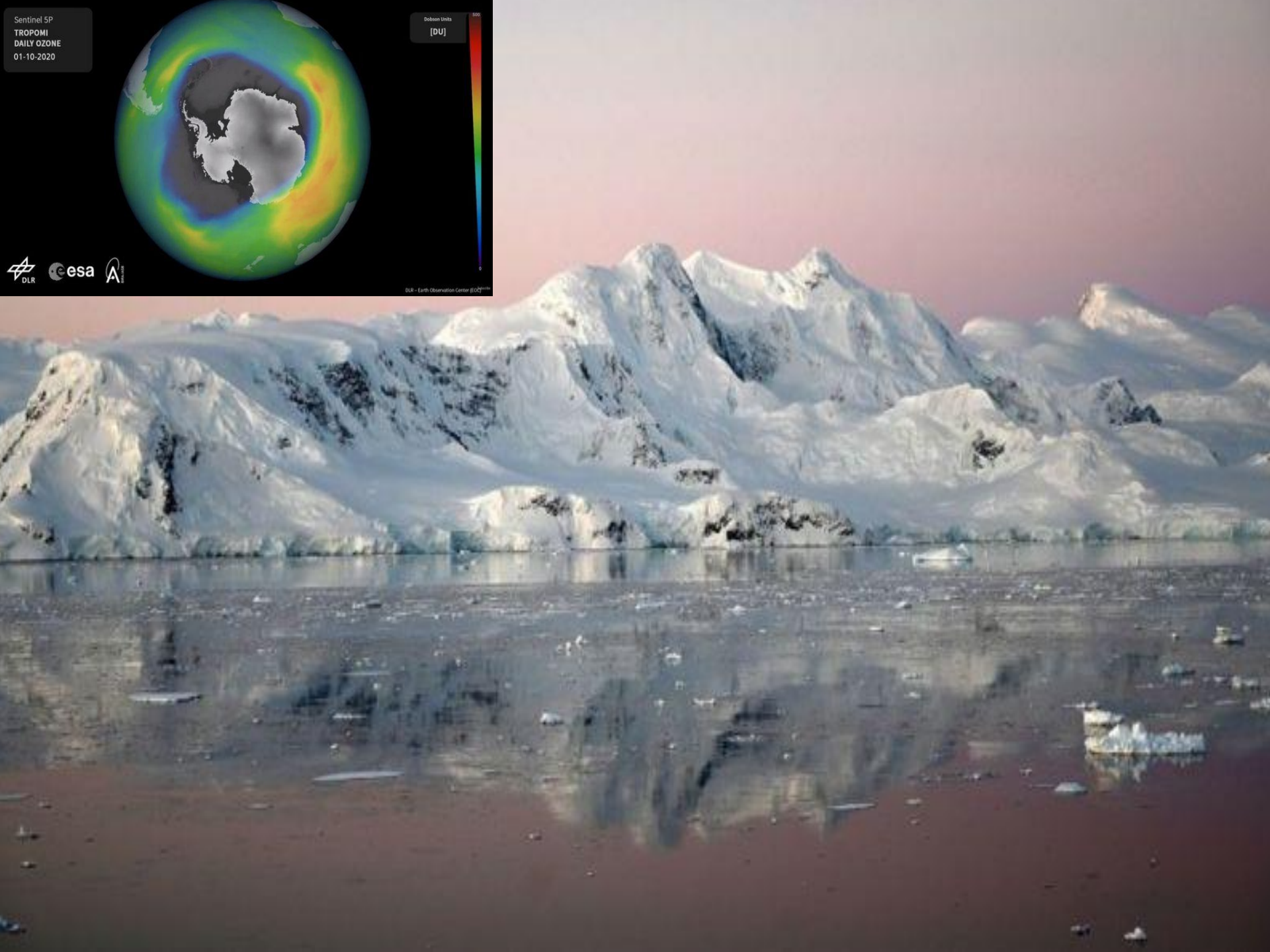
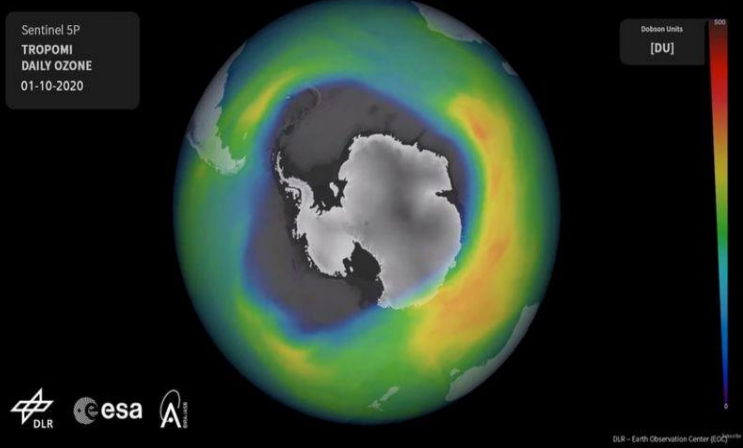
Ozone Depletion: UV radiation

- A beam of UV radiation can travel up to one and a half kilometres through pure water before all the harmful rays are completely absorbed.
- Dissolved oxygen – degree of shielding
- 1987 Montreal Protocol on Substances that Deplete the Ozone Layer
- Long-term effects



The ozone hole has shrunk by 1.5 million square miles (four million square kilometres) -- an area nearly about the size of India -- since 2000.





Impacts of Climate Change

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- Polar Regions
- Deep Sea

Geographical Shifts

- UK – significant biogeographical transition (Warm – Med/Atlantic species in south west) and Boreo-Arctic species in north & east
- Most varied coasts in Europe – rocky outcrops (wave-exposed) in West to deep sea lochs & muddy estuaries
- >10,000 species identified (Howson & Picton, 1997)

Climate Change – Biodiversity

- Warming seawater
 - Warming air temperature (* intertidal species)
 - ↑ & stronger stratification
 - ↑ acidification
 - ↑ sea level rise – coastal squeeze
 - ↑ storminess
 - Slowing of ocean currents
- (MarLIN, 2005)



Consequences of warming air and sea water

- Increase sea temp of 2°C by 2050 (UK Climate Impact Programme 2002)
 - Species distributional changes
 - Trophic mismatches
 - Exotic species
 - Increases in abundance
 - Changes to structural habitat



Species distributional changes

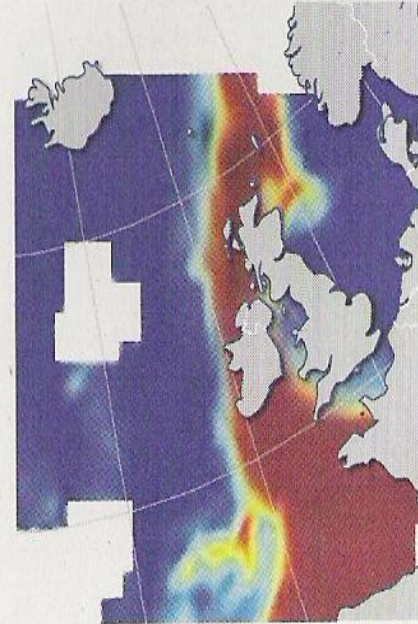
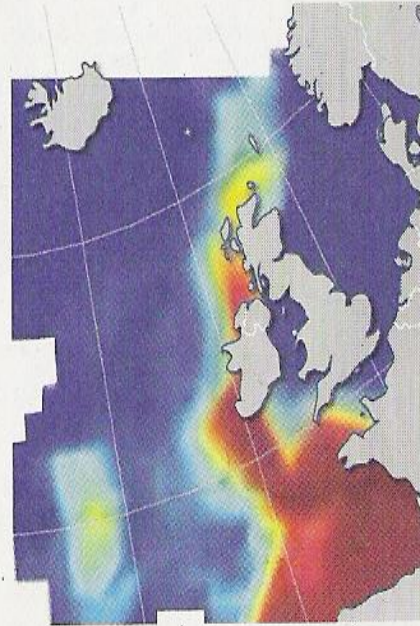
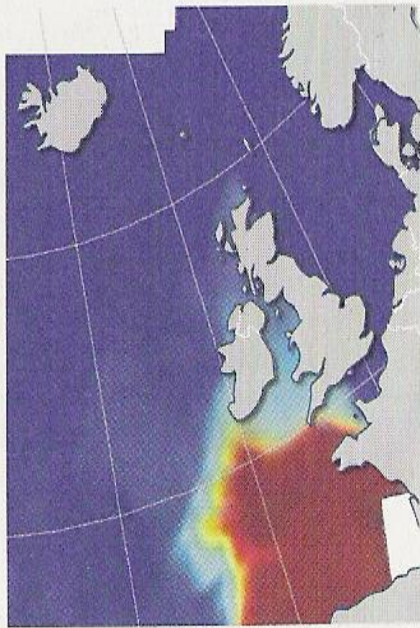
- Most noticeable – living in water column
- Northwards shift 10° of latitude southern species copepod (Beaugrand *et al.*, 2002)
- Trophic mismatch - affects larval cod



1958–1981

1982–1999

2000–2002

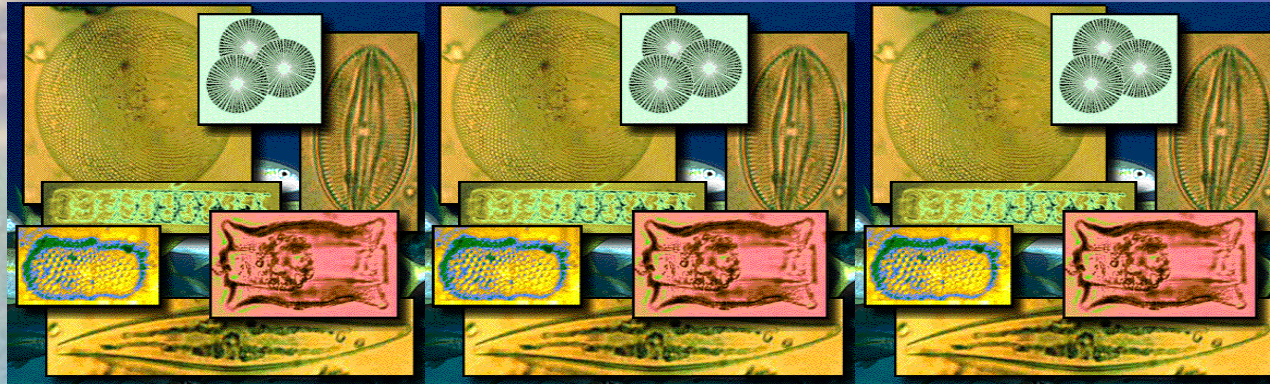


Mean number of species per CPR sample



- Poleward movement of warm water species of plankton, fish and intertidal organisms in last 60 yrs
- Continuous Plankton Recorder (CPR) survey
- Copepods (crustacean) moved northwards by 10° Latitude (~ 1000km) in 40 yrs (up to 1999) – trend continues

Biodiversity: Plankton



- Changes to phytoplankton composition
- Carbon absorption varies per species
- Affect on food chain → Californian zooplankton
- UV radiation – affects photosynthesis, growth, reproduction and enzyme functioning
- HABs – harmful algal blooms

- Some plankton, such as diatoms, grow better at cooler temperatures. Warming may cause other, less palatable, species to replace them, depriving zooplankton of their primary food source.
- Increases in carbon dioxide (CO_2) affect the growth of certain species, but not all species are impacted the same. Some algae, such as Cyanobacteria, are favoured under higher temperatures and CO_2 concentrations. Cyanobacteria can form noxious blooms



HABs

- Scottish waters – PSP (Paralytic shellfish poisoning) toxicity of blue mussels has increased – caused by dinoflagellate *Alexandrium spp.*
 - ↑Stratification, nutrient availability & cloud cover
 - ↑sea temp – extend geographical range species not currently here – PSP associated dinoflagellate *Gymnodium catenatum*
- (MCCIP, 2011)



A new study finds that unusually warm Pacific Ocean temperatures helped cause a massive toxic algae bloom that closed lucrative fisheries from California to British Columbia and disrupted marine life from seabirds to sea lions, Sept. 29, 2016. Scientists linked the patch of warm ocean water, nicknamed the "blob," to the vast ribbon of toxic algae that flourished in 2015 (Harvey, 2017)



Zooplankton

- Alterations to species composition
- Changes to recruitment timing – succession patterns in communities
- Decoupling with lower trophic levels and fish yields
- Shell integrity of some species compromised
- Jellyfish swarms



Trophic mismatch

- Cold water copepods bloom early in year – when larval cod need food of a certain size
- Warmer water copepods bloom later in the summer - young cod require large food by then



Tropical Corals

- **Globally – between 1 and 9 million species**
- **Economic, and habitat relevance**
- **Bleaching – 1°C large scale & regular mortality**
- **Acidification**
- **Distributional change**

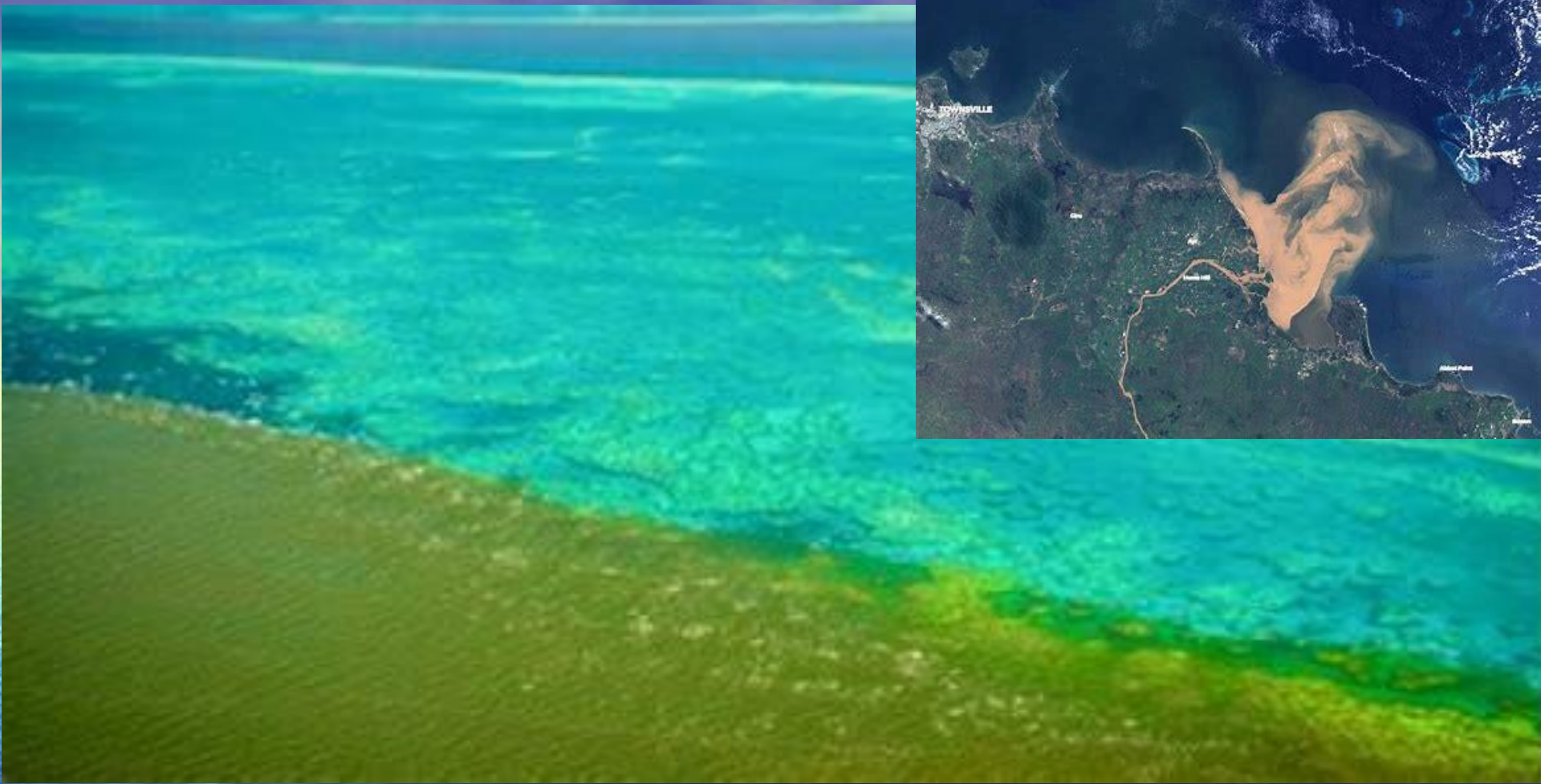








“For the second year in a row, the Great Barrier Reef is experiencing a mass bleaching event” (Raphael, 2017:1)



January 2019 – massive pollution in North Queensland
caused by unusually high rainfall and flooding (The Guardian,
2019)



In some places coral transplants are having to be introduced to save this valuable ecosystem.



Cold water corals

- Seamounts and continental rise
- Hotspots of biodiversity
- Slow growing
- Depth of aragonite saturation horizon
- 70% affected by 2100



Species distributional changes: Fish

- Exotic species in northern North Sea - Red Mullet *Mullus surmuletus*; anchovy *Engraulidae spp.* (Beare *et al.*, 2003)
- Atlantic bluefin tuna *Thunnus thynnus* returning to south-west England (Carrell, 2012)
- Southern species - snakelocks anemone *Anemonia viridis* moving north; Topshell *Gibbula umbilicalis*
- Seabed species – not such dramatic changes:
 - Northern stone crab *Lithodes maia* moving north
 - Common Tortoiseshell limpet *Tectura testudinalis* reduced recruitment rate

Species distributional changes

- Abundance:

- Pacific oyster *Crassostrea gigas* – a non native. Population increasing
- ↓ Mussel production by 50% (1°C ↑ in temp NI and Scotland (Carrell, 2012))

- Structural changes:

- Horse mussel *Modiolus modiolus*. Large bed forming – complex habitat with diverse fauna

Fish yields



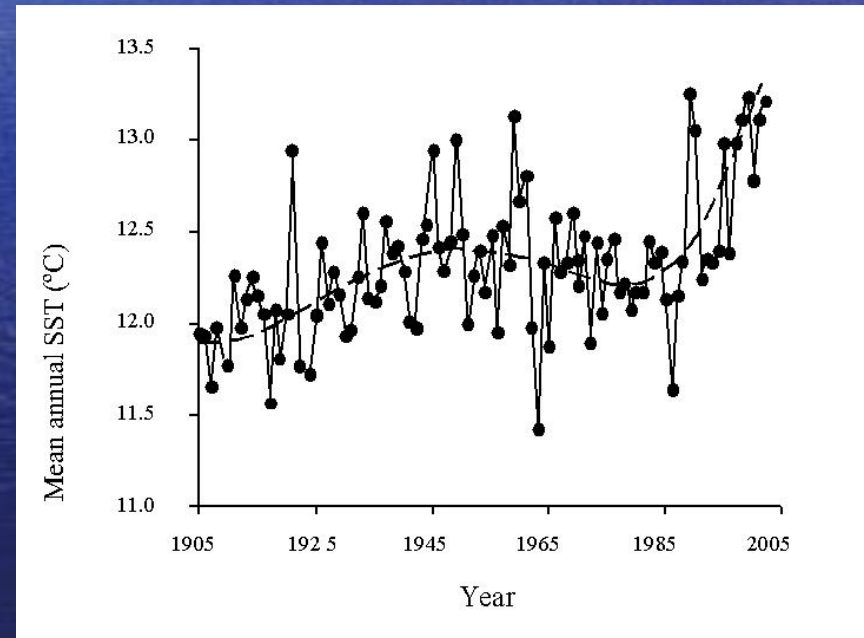
1963 – North Sea



2001 – North Sea

Response to climate change: Fisheries

- Trawls between 1913 and 2002
- Correlation between climate-linked temperature shifts and species composition and abundance
- Poor cod *Trisopterus minutus*, Butterfly blenny *Blenius ocellaris* responded positively to warming
- Southern species such as skate and rays have declined steadily



African fisheries

- **2.6 billion people – 40% world's population – fish make up a fifth of their protein intake**
- **In Pacific El Nino conditions could become near permanent**
- **Badly managed – Nigeria, Senegal, Vietnam, Angola**
(Pearce, 2009)



Atlantic Cod *Gadus morhua*

Marine Turtles

- **Slow growth rate**
- **Changes to critical habitats**
- **Life history characteristics**
- **Skewing of sex ratio**
- **Wave energy and storminess**
- **Food chain benefits - jellyfish**
- **Alteration to timing of egg laying – Florida; Loggerheads**



Seabirds

- **Bio-indicators - distributional changes**
- **Altered reproductive success**
- **Nesting timing**
- **Loss habitat**
- **Current alteration – migration and foraging**
- **9% ↓ number breeding birds in UK 2000-2008 (MCCIP, 2011)**



Biodiversity: Seabirds

- Starvation – Alaskan shearwaters
- Not a simple cause effect relationship – Leach's storm petrel
- Shift in prey preference
- Reproductive success – Cassin's auklets
- Increased storm activity
- Mobility



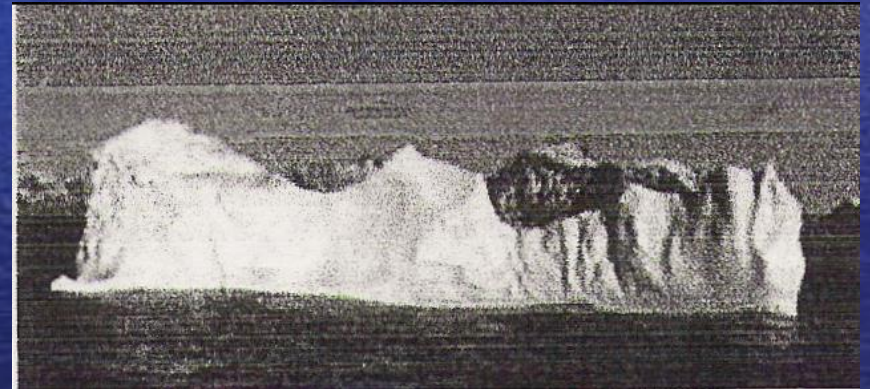
Biodiversity: Mammals

- Reduction in abundance of prey
- Energy expenditure – seals and seal lions
- Open water species thriving
- Polar species suffering consequence of diminishing ice sheets
- Cetaceans – changes in distribution
- Collisions and noise pollution!

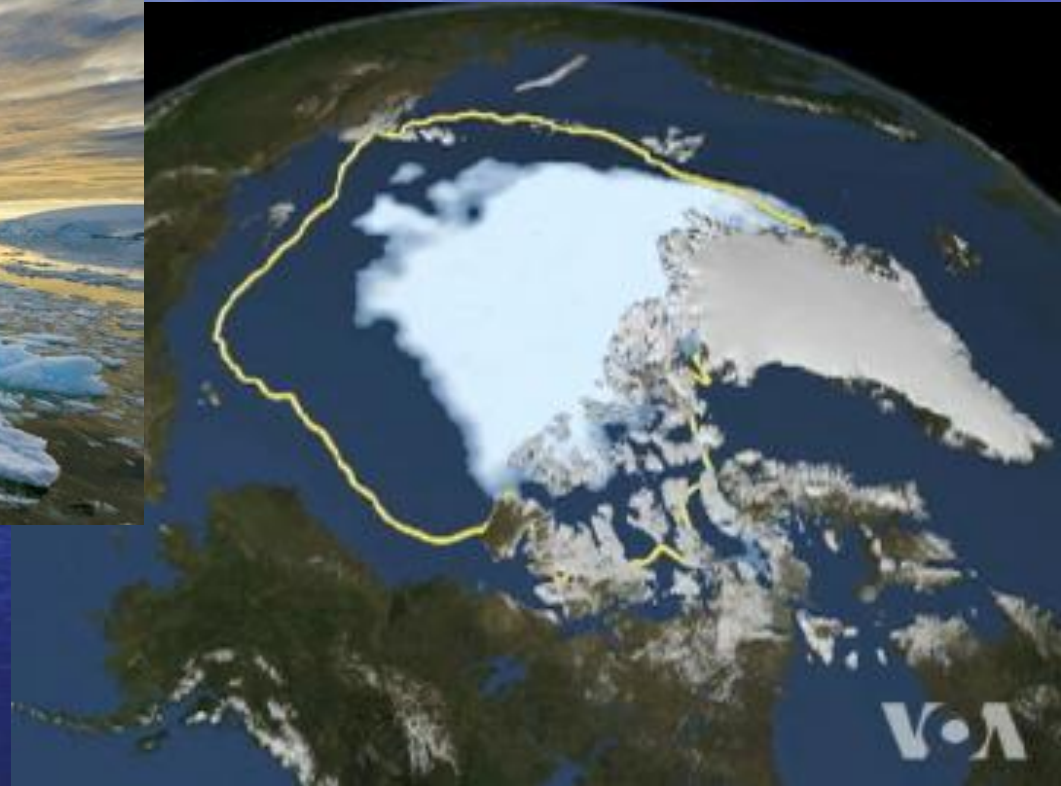


Ecosystems : Polar Regions

- Greatest overall temperature changes
- Decrease in coverage and thickness Arctic sea-ice
- Bloom of coccolithophores – Bering Sea



Arctic Sea ice



While Arctic sea ice reaches a record low, Antarctic sea ice reaches a new maximum!

Nasa warns 'iceberg twice the size of MANHATTAN' to break away from Antarctica (Keach, 2019)



150km iceberg from Larsen C Ice shelf Heading for South Georgia (Nov 2020)

Salt marshes/mangroves



- Coral reefs, mangroves and salt marshes vulnerable
- In England, 40-100 hectares saltmarsh lost annually (Eccleston, 2008)
- Vertical accretion rates and space for horizontal migration
- Ecosystem resilience reduced where there are also human influences

Research in 2018 paints a grim outlook for saltmarshes

Marshlands in south-east England could start to vanish in about 20 years due to rising sea levels; rest of UK by 2100

Salt marshes protect coastal areas from erosion by acting as a buffer against waves and reducing flooding by slowing and absorbing rainwater.



Seagrasses

- **Vital role in carbon and nutrient cycling**
- **Buffer**
- **Biodiversity – crustaceans, fish**



- **Increase in productivity**
- **Temperature & UV radiation**
- **Storm regimes**
- **Flowering timing**

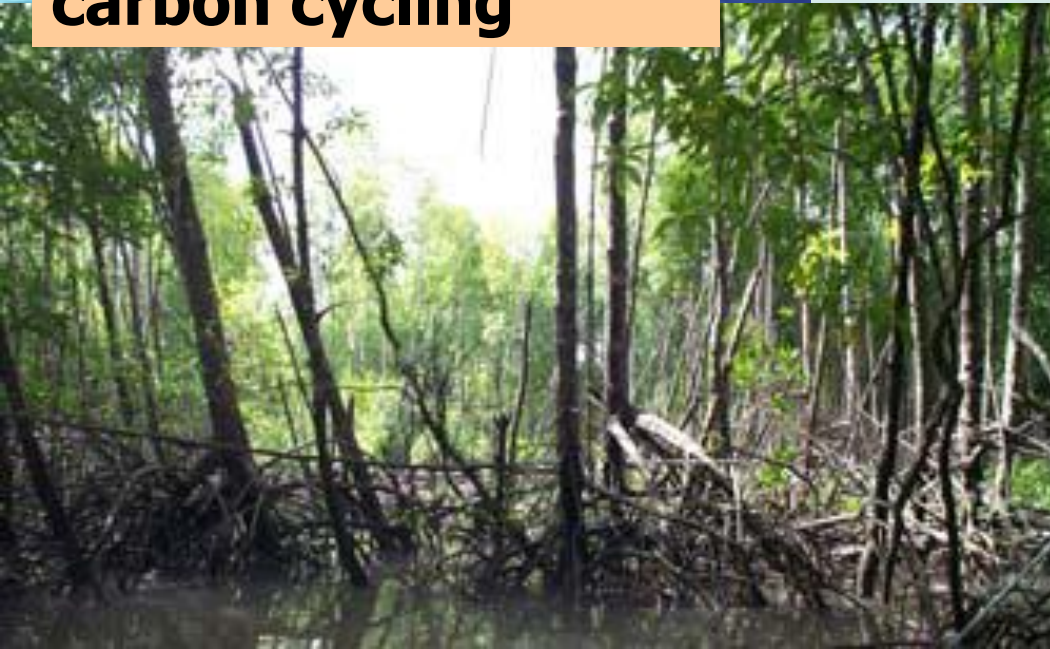
Project Seagrass

The background of the slide is a photograph of seagrass underwater. The seagrass is green and has long, thin leaves. It is growing on a sandy seabed. The water is clear and blue.

- 92% seagrasses have died in the UK over the last century (Kings College, London)
- *If we want to provide our fisheries and our coastlines with the potential to adapt to a rapidly changing climate we need to restore the habitats and biodiversity that support their productivity.* (Dr Richard Unsworth, Swansea University, 2020)

Mangroves

- **Buffer**
- **Sediment**
- **Filtering**
- **Habitat –fish, crabs, prawns, birds**
- **Nutrient and carbon cycling**



- **Increase productivity**
- **Threat of sea level rise**
- **Shift in distribution**
- **Growth rate changes**

Kelp Forests

- **Shifts in distribution and decline**
- **Storminess**
- **Changes in rainfall**
- **Species compositional change – herbivores**



Rocky Shores

- **Species distributional movements**
- **Changes to abundance and community composition**
- **Alteration to timing of reproduction and larval or spore release**



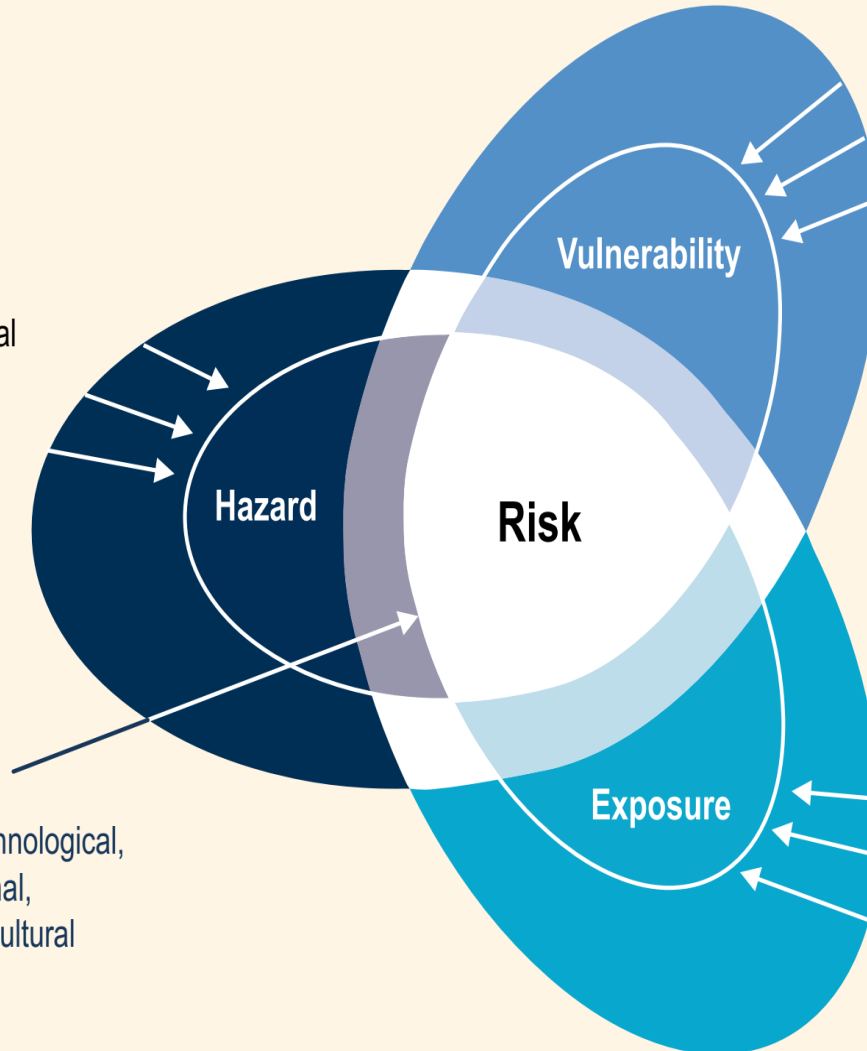
Actions to reduce Hazards

Examples include:

- Ecosystem-based measures to reduce coastal flooding
- Mangroves to alleviate coastal storm energy
- Water reservoirs to buffer low-flows and water scarcity

Limits to Adaptation

- E.g. physical, ecological, technological, economic, political, institutional, psychological, and/or socio-cultural



Actions to reduce Vulnerability

Examples include:

- Social protection
- Livelihood diversification
- Insurance solutions
- Hazard-proof housing and infrastructure

Actions to reduce Exposure

Examples include:

- Coastal retreat and resettlement
- Risk sensitive land use planning
- Early warning systems and evacuations

Figure TS.4 | There are options for risk reduction through adaptation. Adaptation can reduce risk by addressing one or more of the three risk factors: vulnerability, exposure, and/or hazard. The reduction of vulnerability, exposure, and/or hazard potential can be achieved through different policy and action choices over time until limits to adaptation might be reached. The figure builds on the conceptual framework of risk used in AR5 (for more details see Cross-Chapter Box 2 in Chapter 1).