GLOBAL CHANGE IN THE OCEAN

GREENHOUSE EFFECT

Joseph Fourier

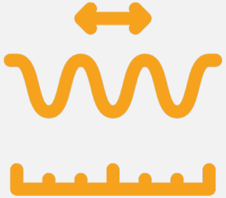
1824

Eunice Foote

1856

John Tyndall

1859



Svante Arrhenius

1896

MILANKOVITCH CYCLE

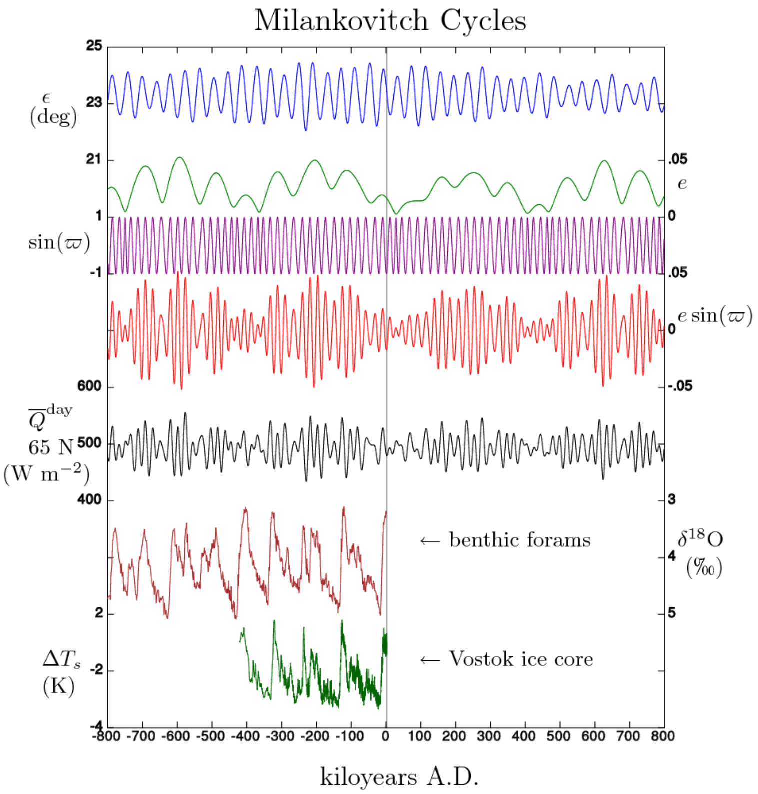
Axial tilt or obliquity

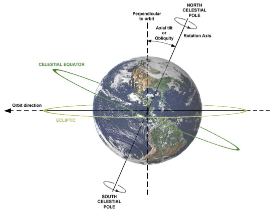
Eccentricity

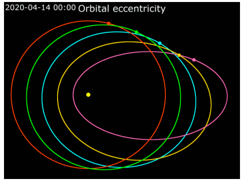
Longitude of perihelion

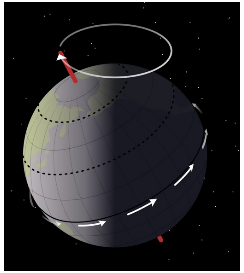
Precession index

Daily-average insolation



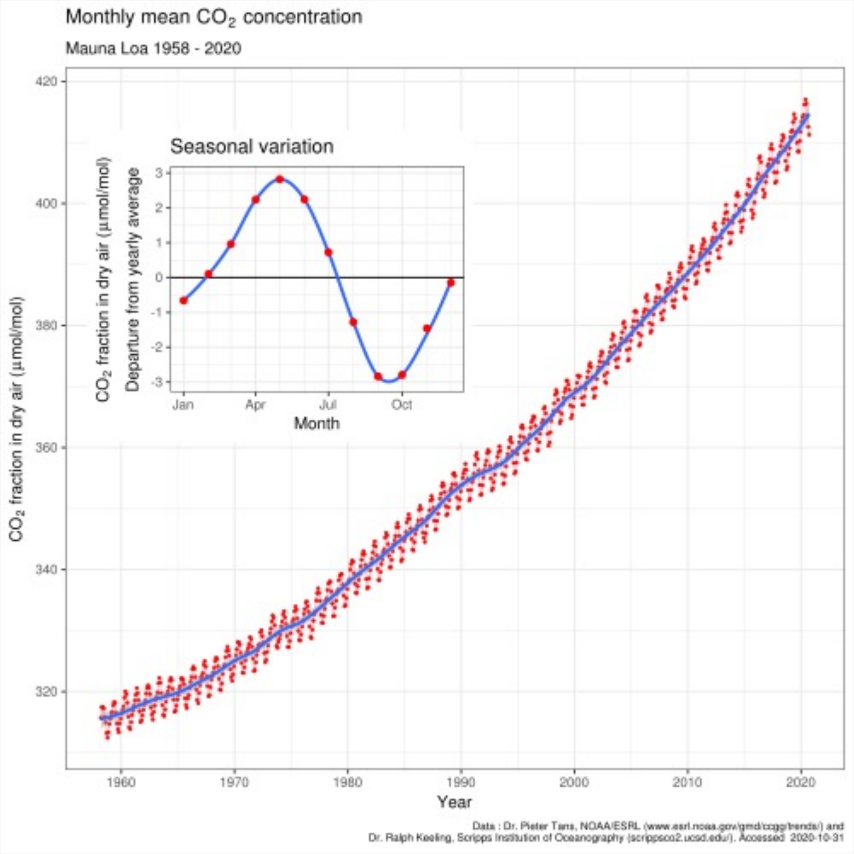






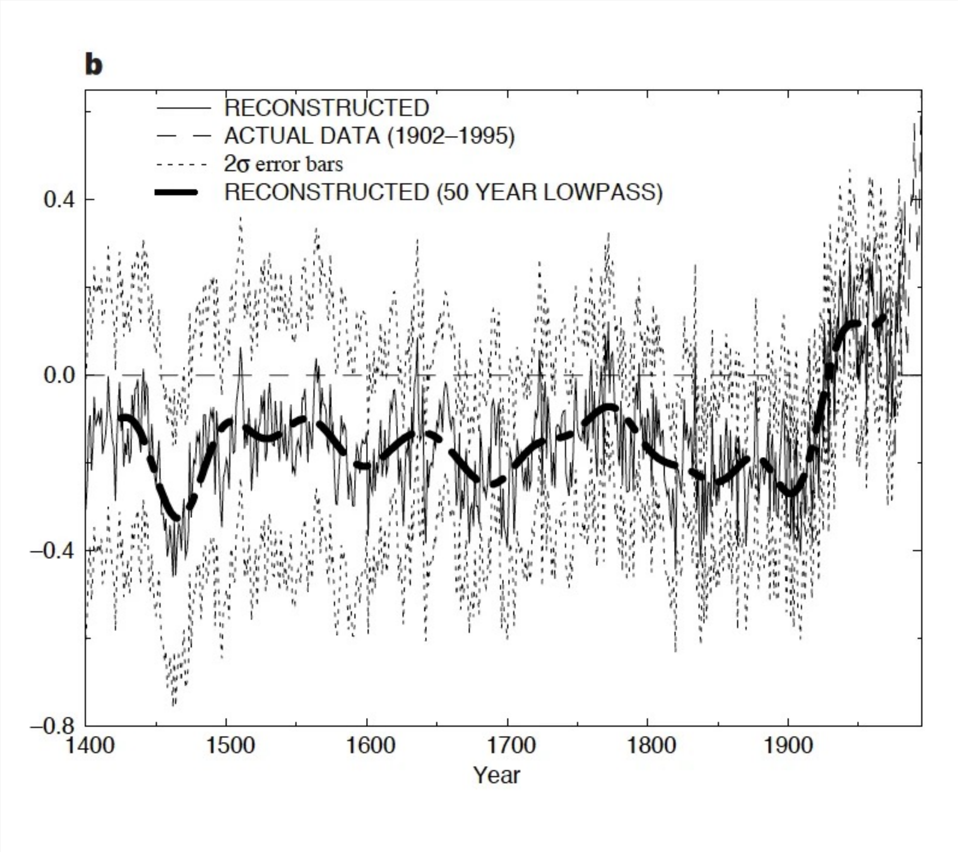
KEELING CURVE

- 1960
- Mauna Loa Observatory, Hawaii
- 1958 to the present day



HOCKEY STICK

- Original "hockey stick" temperature graph in *Nature*, 1998. The Y axis shows the Northern hemisphere mean temperature, in degrees Celsius; the zero line corresponds to the 1902 – 1980 mean.



"Global-scale Temperature Patterns and Climate Forcing over the Past Six Centuries," by Michael E. Mann et al. [in *Nature*], Vol. 392, April 23, 1998

HISTORIC TEMPERATURE RECORDS

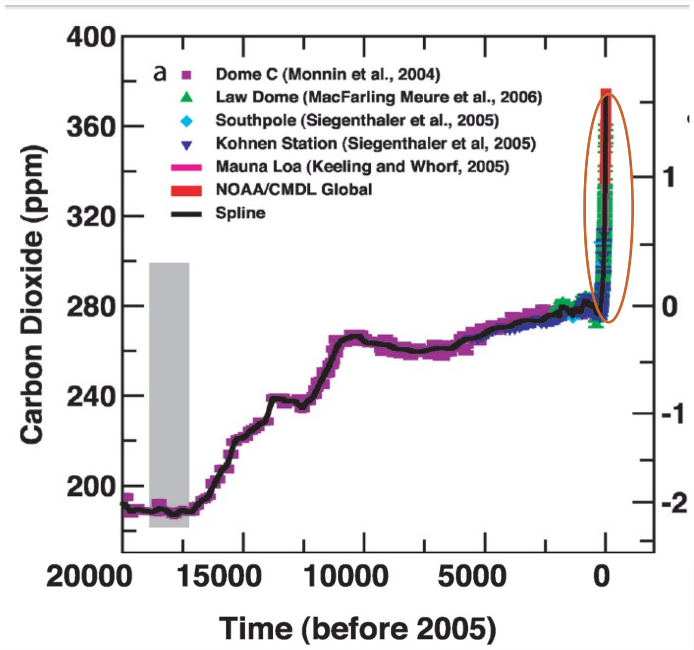
Temperature

1978 - PRESENT DAY	satellite	global
1880 - PRESENT DAY	Thermometers Lake and ocean sediments, ice cores, stalagmites	global
2,000 YEARS AGO - 1880	Sediment and Ice cores tree-rings series	global
20,000 - 2,000 YEARS AGO	Ocean margin sediment cores lake and ice cores on land.	Global
800,000 - 20,000 YEARS AGO	proxy sea surface temperature records	Global

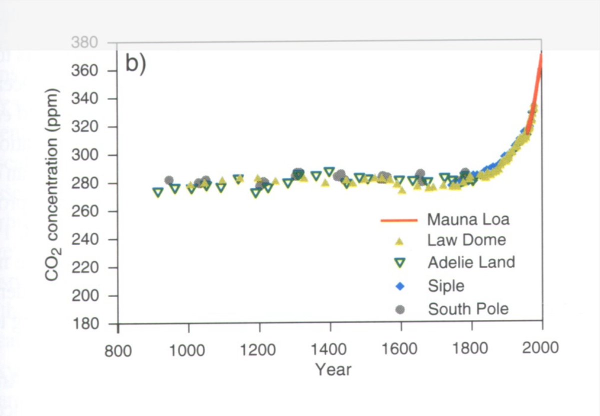
HISTORIC CO_2 CONCENTRATIONS

CO_2		
1958 - PRESENT DAY	in situ air	Mauna Loa, Observatory, Hawaii
1000 YEARS AGO - 1958	Ice cores	Law Dome, Wilkes Land Antarctica
800,000 YEARS AGO - 1000 YEARS AGO	Ice cores	Antarctic Vostok and EPICA Dome C ice

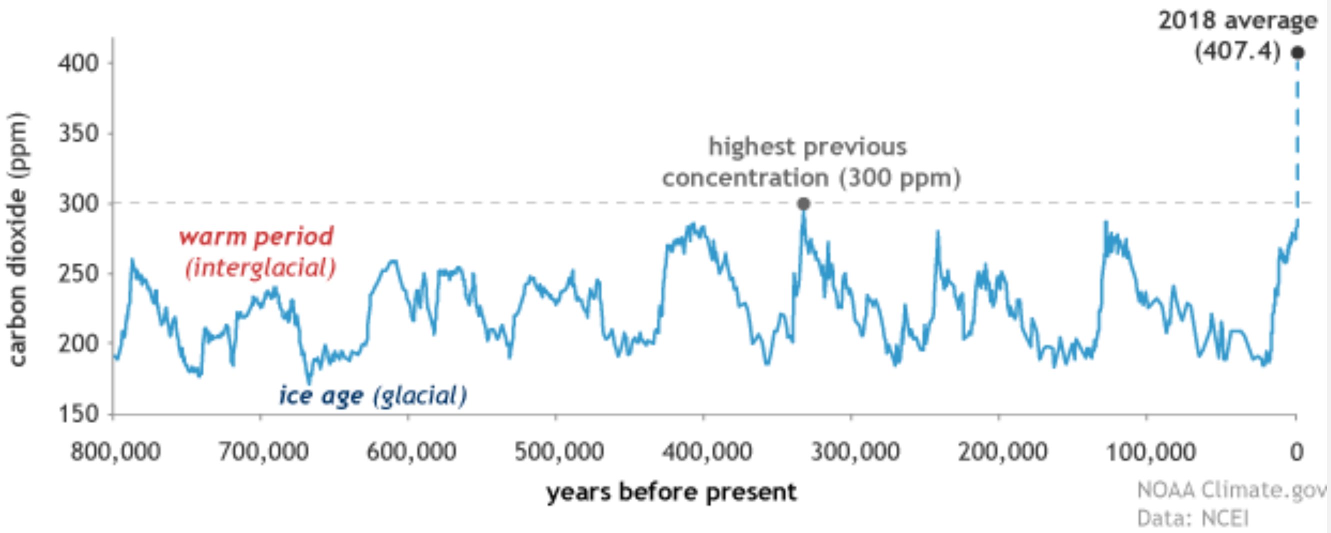
CARBON DIOXIDE IN THE ATMOSPHERE IS INCREASING



- The fastest ↑ of $[CO_2]_{atm}$ ever observed (Zeebe 2012)



CARBON DIOXIDE IN THE ATMOSPHERE IS INCREASING



- The fastest ↑ of $[CO_2]_{atm}$ ever observed (Zeebe 2012)

LOOKING FURTHER BACK

© Beyond Epica (1.5 million years…)

IPCC

1990

IPCC First Assessment Report

1996

IPCC Second Assessment Report

- Special Report on Emissions Scenarios (SRES) , 2000

2001

IPCC Third Assessment Report

2007

IPCC Fourth Assessment Report

2014

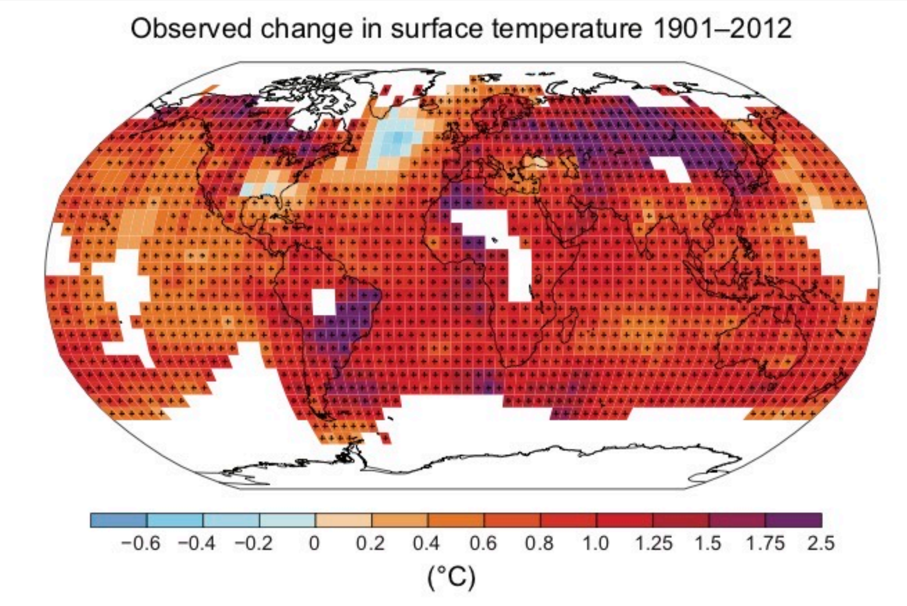
IPCC Fifth Assessment Report

- Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), 2019

2021–2022

Sixth assessment report

Consequences in the atmosphere: Global warming

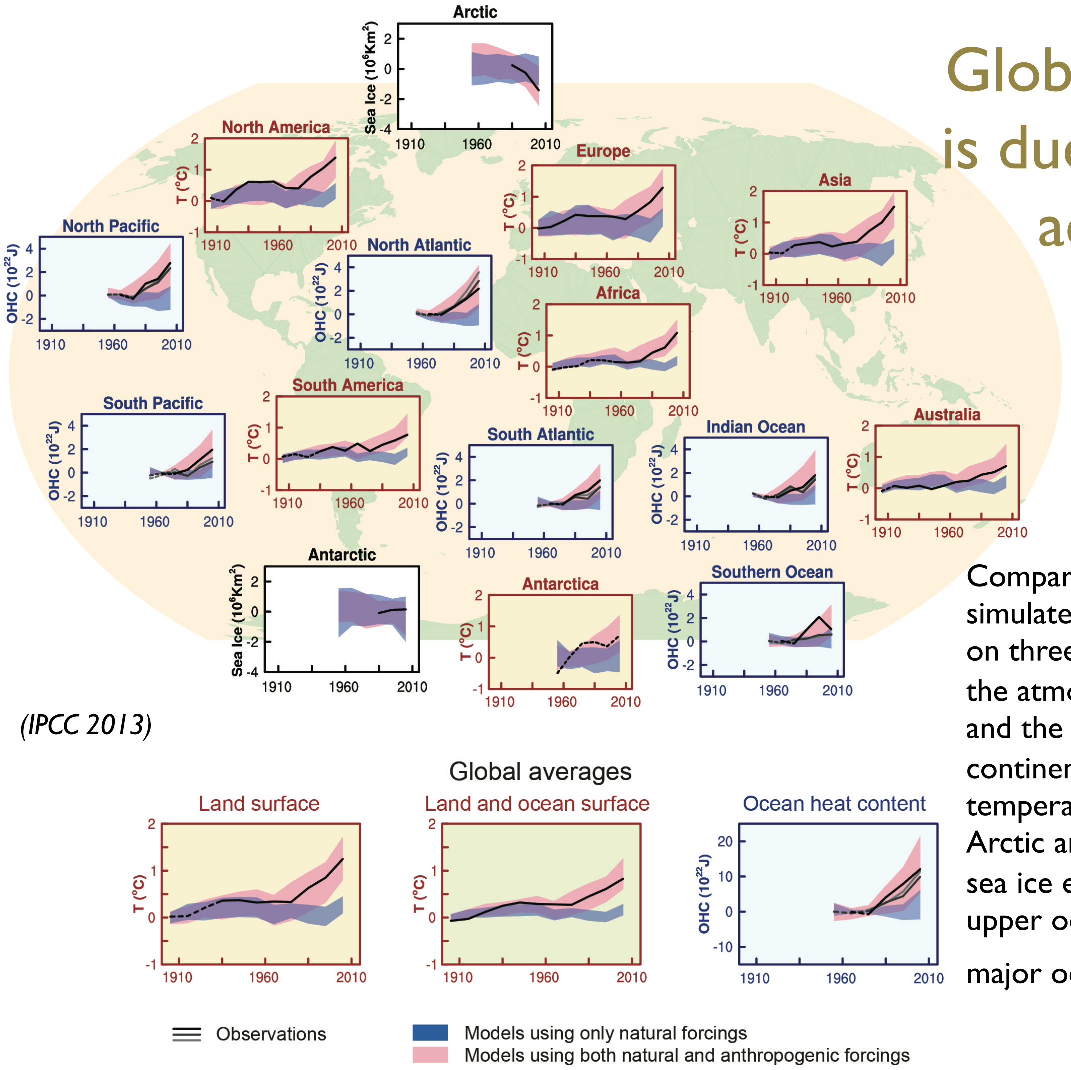


(IPCC 2013)

Global warming of surface atmosphere: 0.65 - 1.06° C

(mean trend)

Global warming is due to human activities



(IPCC 2013)

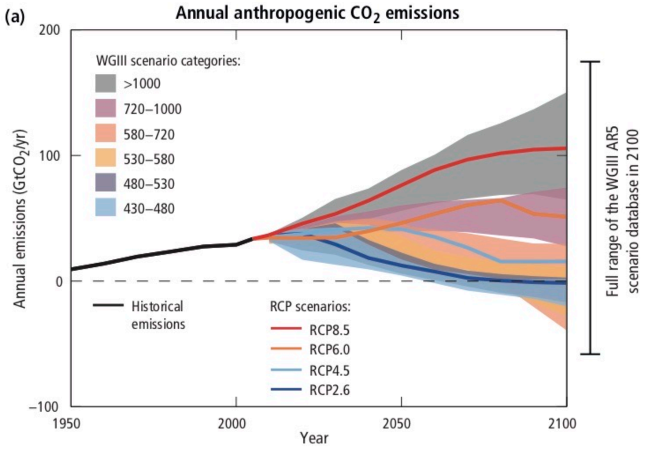
Comparison of observed and simulated climate change based on three large-scale indicators in the atmosphere, the cryosphere and the ocean: change in continental land surface air temperatures (yellow panels), Arctic and Antarctic September sea ice extent (white panels), and upper ocean heat content in the major ocean basins (blue panels)

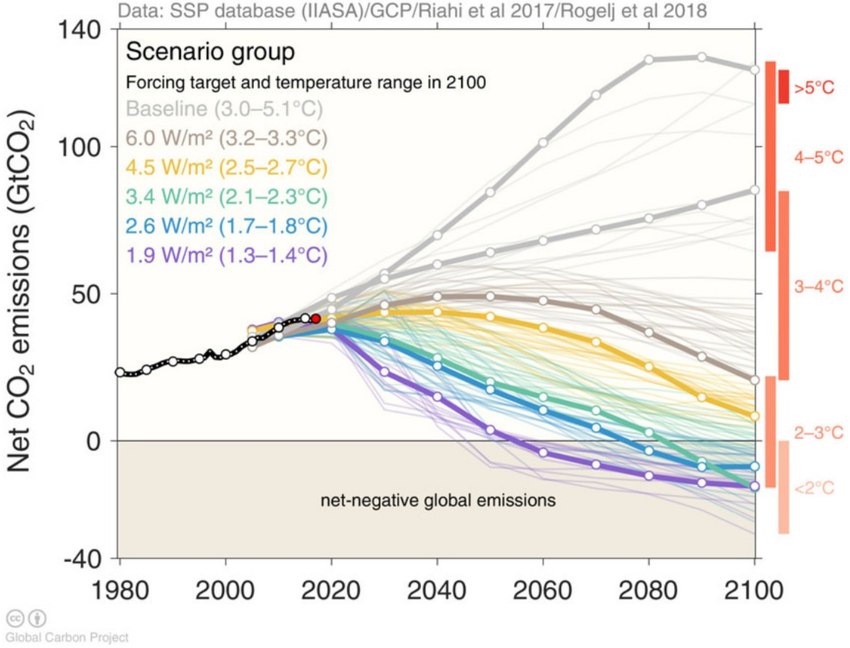
CARBON DIOXIDE IN THE ATMOSPHERE IS INCREASING: FUTURE SCENARIOS

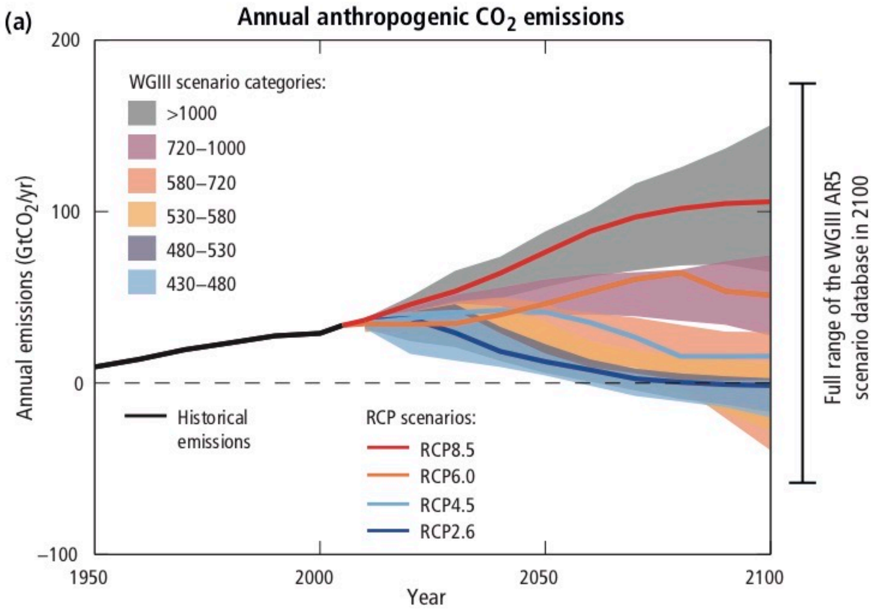
REPRESENTATIVE CONCENTRATION PATHWAYS

Emissions of carbon dioxide (CO_2) alone in the Representative Concentration Pathways (RCPs) (lines) and the associated scenario categories (coloured areas show 5 to 95% range). The scenario categories summarize the wide range of emission scenarios published in the scientific literature and are defined on the basis of CO_2-eq concentration levels (in ppm) in 2100. (IPCC 2013)

- RCP 8.5: ~ business as usual
- RCP 2.6:
  - CO_2 emissions start declining by 2020 and go to zero by 2100.
  - CH_4 emissions go to approximately half the CH_4 levels of 2020
  - SO_2 emissions decline to approximately 10% of those of 1980-1990

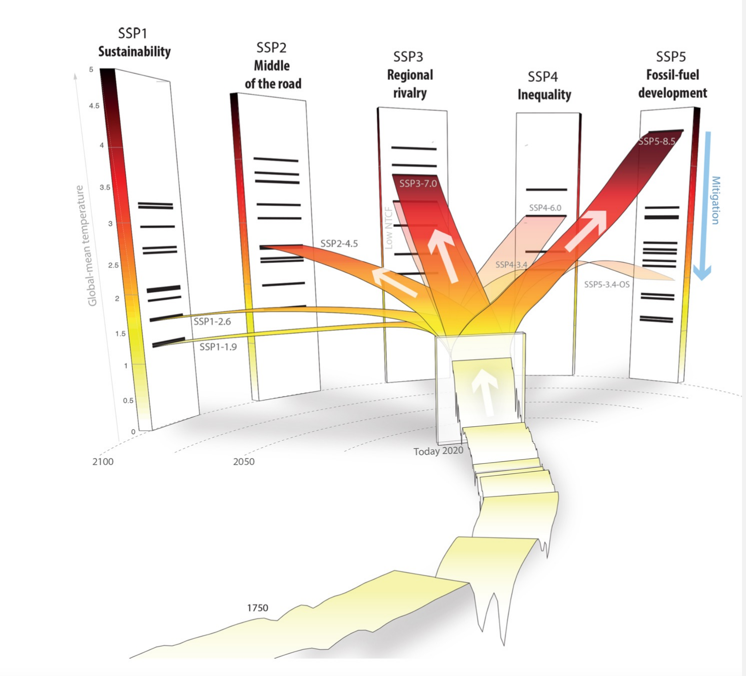




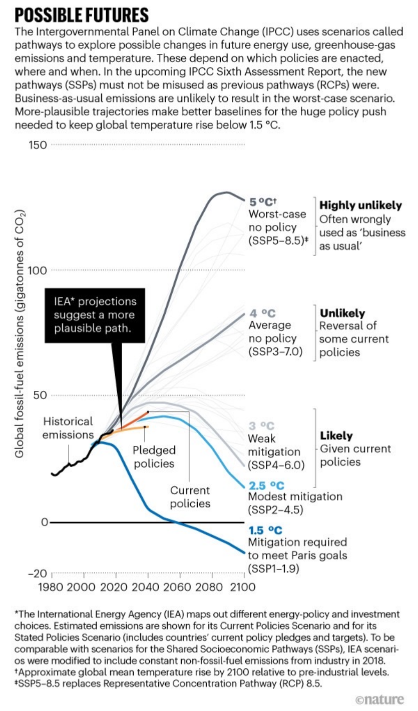


SHARED SOCIOECONOMIC REFERENCE PATHWAY

The SSP scenarios and their five socio-economic SSP families



https://doi.org/10.5194/gmd-13-3571-2020



https://doi.org/10.1038/d41586-020-00177-3

Consequences in the ocean

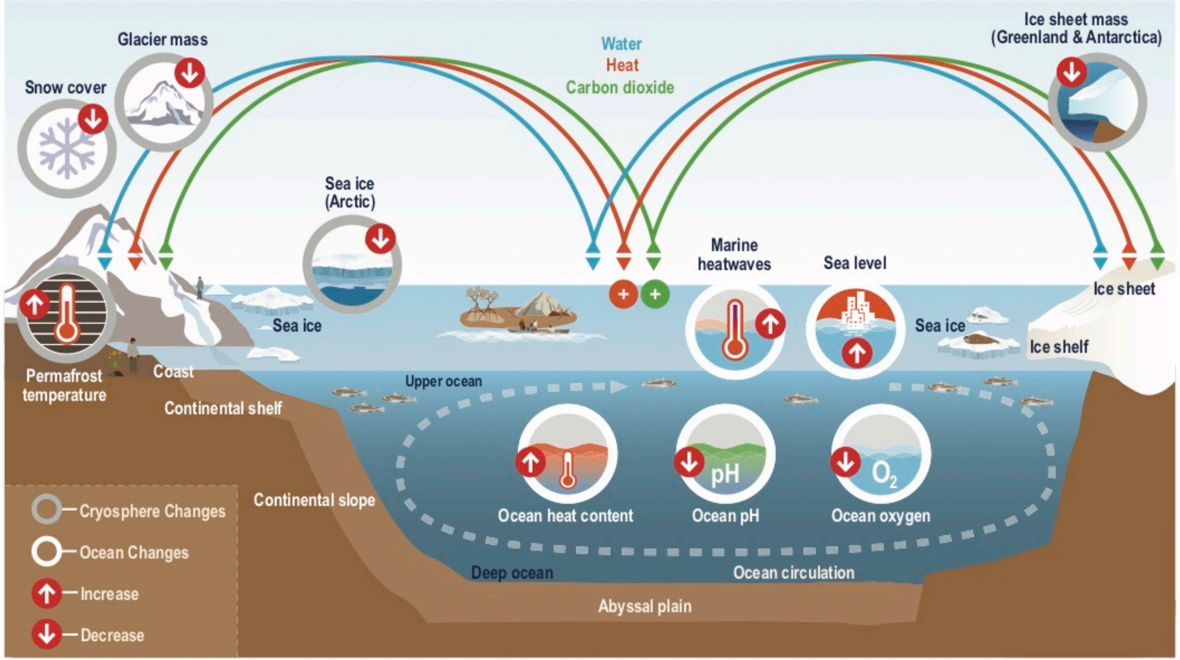
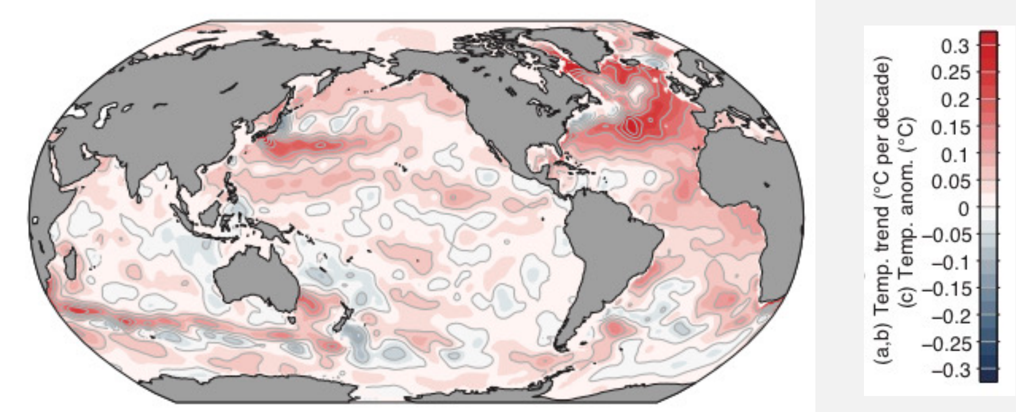


Figure TS.2 | Schematic illustration of key components and changes of the ocean and cryosphere, and their linkages in the Earth system through the global exchange of heat, water, and carbon (Section 1.2). Climate change-related effects (increase/decrease indicated by arrows in pictograms) in the ocean include sea level rise, increasing ocean heat content and marine heat waves, increasing ocean oxygen loss and ocean acidification (Section 1.4.1). Changes in the cryosphere include the decline of Arctic sea ice extent, Antarctic and Greenland ice sheet mass loss, glacier mass loss, permafrost thaw, and decreasing snow cover extent (Section 1.4.2). For illustration purposes, a few examples of where humans directly interact with ocean and cryosphere are shown (for more details see Box 1.1).

IPCC 2013

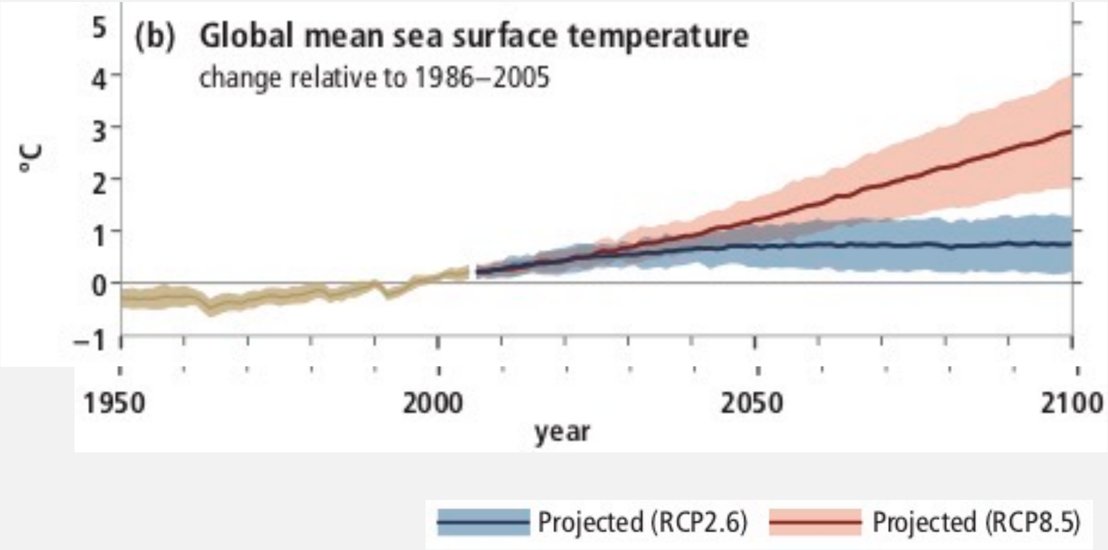
Consequences in the ocean: Ocean warming (OW)



0-700m averaged temperature trend 1971-2010
(IPCC 2013)

The upper 75 m warmed by 0.11 [0.09 to 0.13] ° C <u>per decade</u> over the period 1971 to 2010

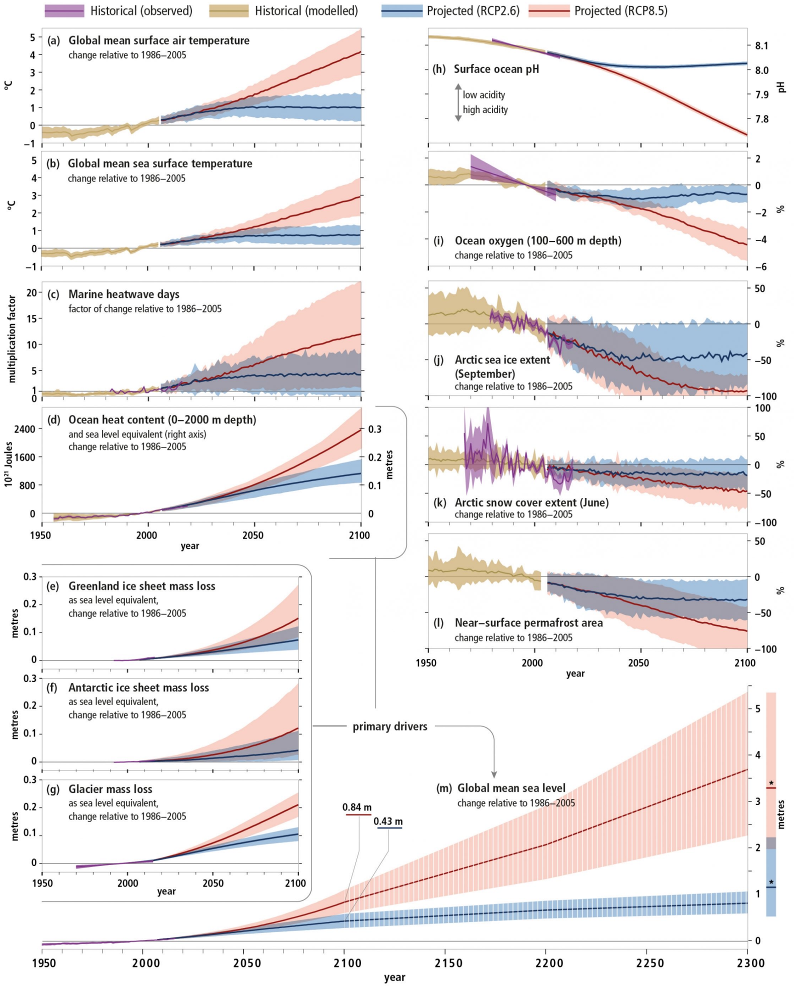
Consequences in the ocean:
Ocean warming future scenarios



IPCC 2013

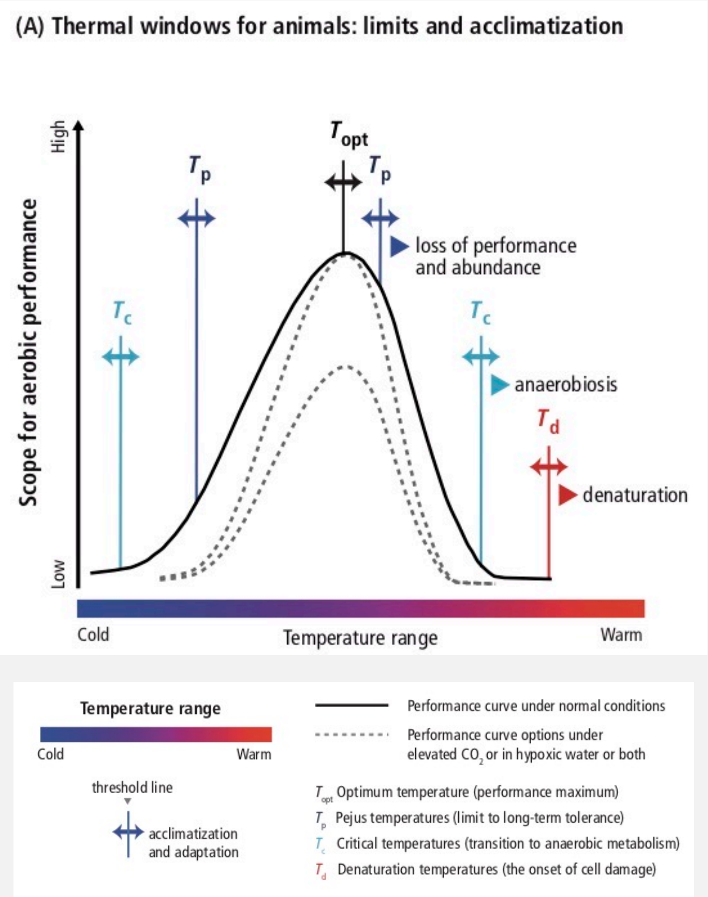
Past and future changes in the ocean and cryosphere

Historical changes (observed and modelled) and projections under RCP2.6 and RCP8.5 for key indicators



OCEAN WARMING
WHY DOES IT MATTER?

IMPACT OF OW EXTINCTIONS AND RANGE SHIFTS



- Most marine organisms do not control their temperature
- Metabolism ↑ with temperature (energetic cost) until a treshold
- Beyond treshold: deleterious effects

→Vulnerability of most marine organisms to warming is set by their physiology, which defines their limited temperature ranges and hence their thermal sensitivity *(IPCC 2013)*

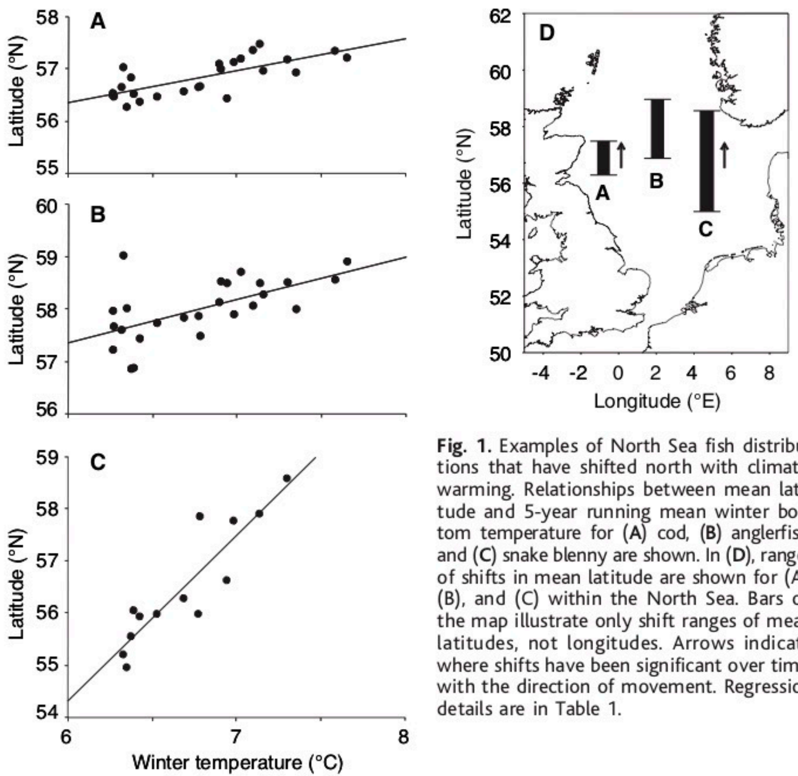


Fig. 1. Examples of North Sea fish distributions that have shifted north with climatic warming. Relationships between mean latitude and 5-year running mean winter bottom temperature for (**A**) cod, (**B**) anglerfish, and (**C**) snake blenny are shown. In (**D**), ranges of shifts in mean latitude are shown for (A), (B), and (C) within the North Sea. Bars on the map illustrate only shift ranges of mean latitudes, not longitudes. Arrows indicate where shifts have been significant over time, with the direction of movement. Regression details are in Table 1.

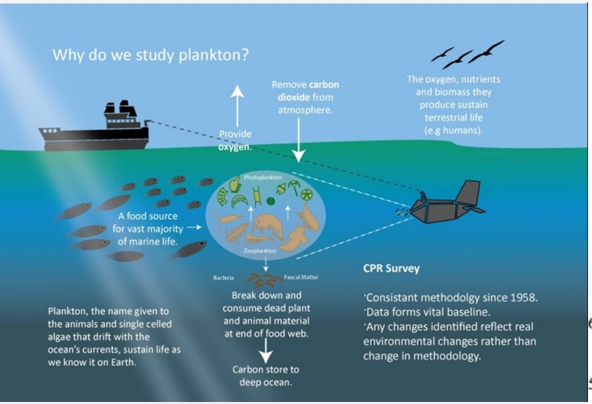
A. Cod

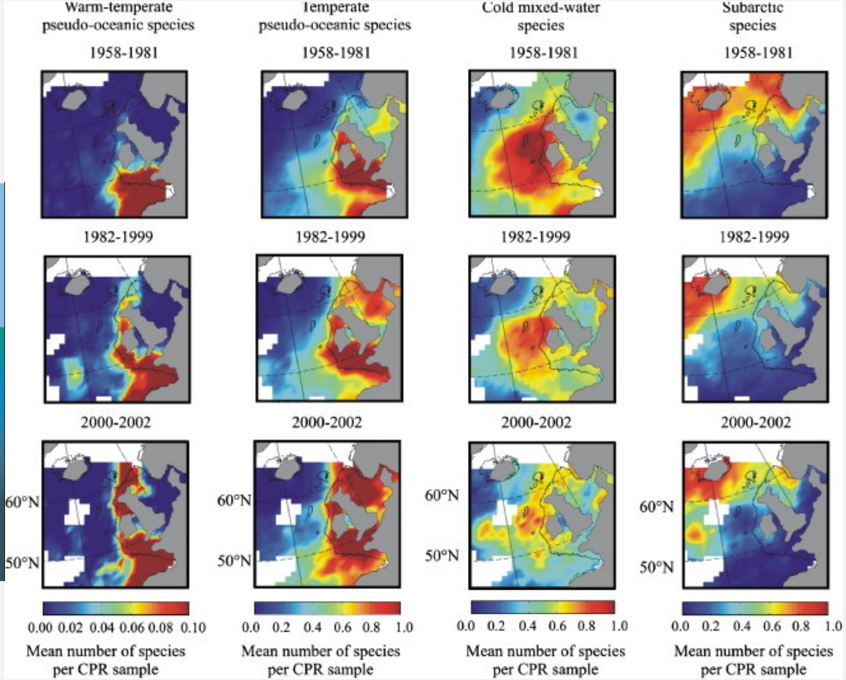
B. Anglerfish

C. Snake Blenny

Shifting temperature means and extremes alter habitat and cause changes in species abundances through local extinctions and latitudinal distribution expansions or shifts of up to hundreds of kilometers per decade (IPCC 2013)

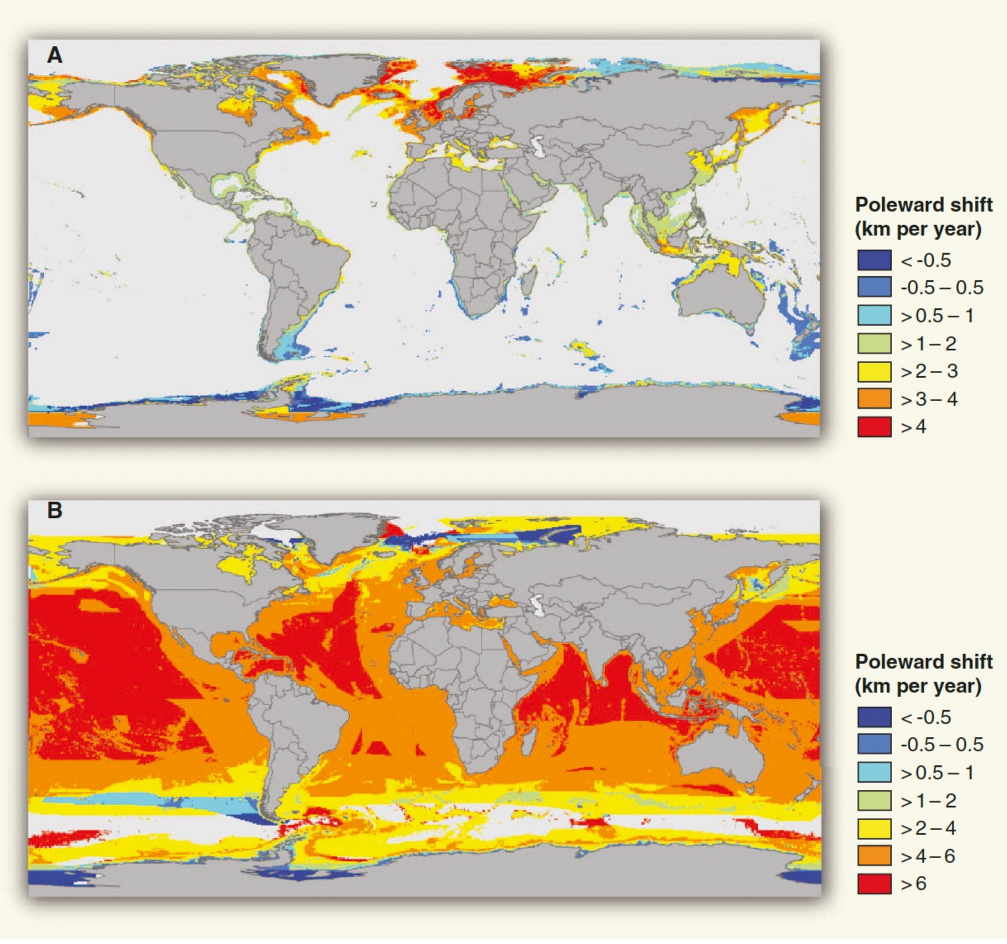
Perry et al 2005





Long-term changes in the mean number of calanoid copepod species per assemblage, 1958–1981, 1982–1999, 2000–2002 (CPR: Continuous Plankton Recorder) (Beaugrand 2005)

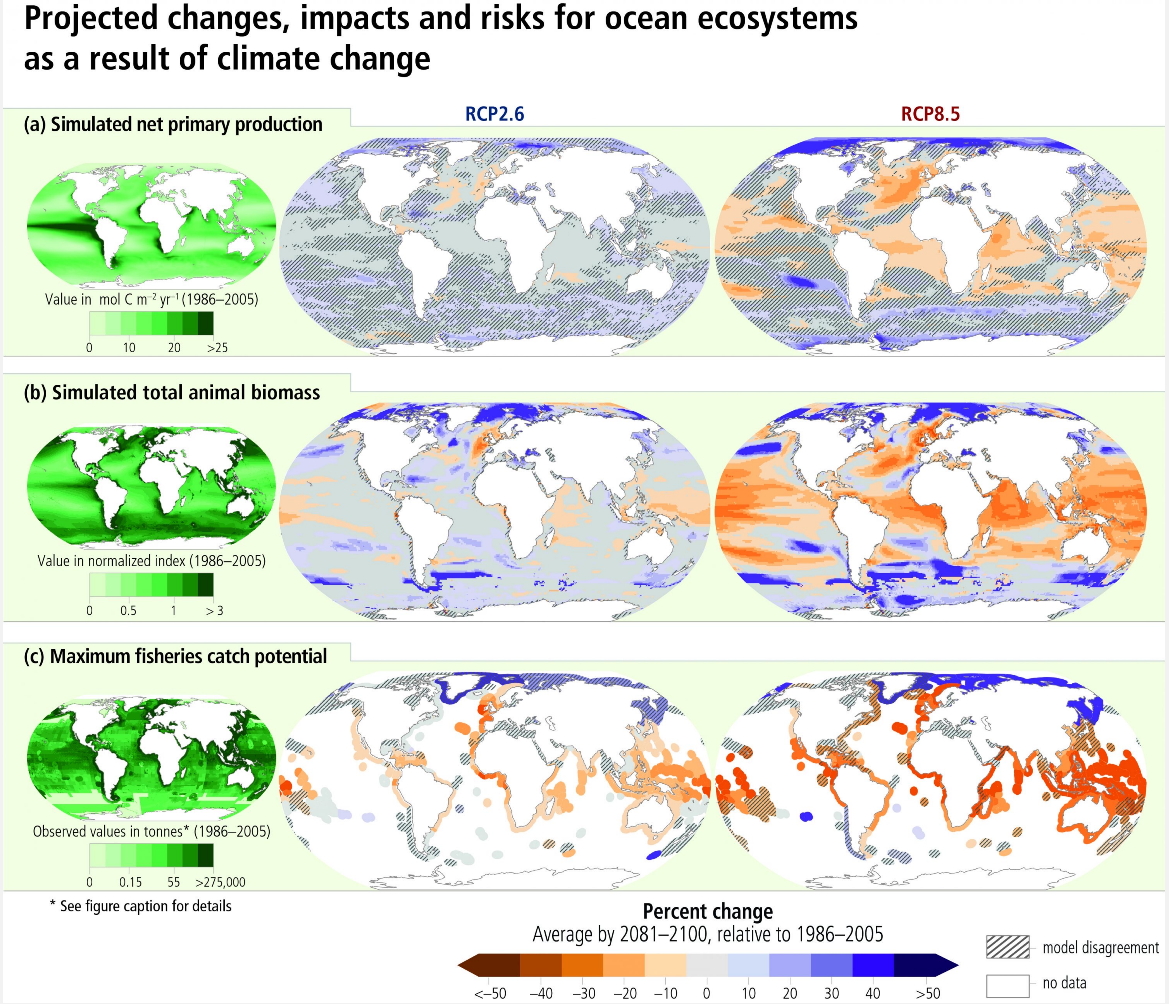
Shifting temperature means and extremes alter habitat and cause changes in species abundances through local extinctions and latitudinal distribution expansions or shifts of up to hundreds of kilometers per decade (IPCC 2013)



demersal species

pelagic species

Scenarios for Global Biodiversity in the 21st Century, Pereira et al. 2010 DOI: 10.1126/science.1196624



Projected changes, impacts and risks for ocean ecosystems as a result of climate change
RCP2.6
RCP8.5
(a) Simulated net primary production
Value in mol C m⁻² yr⁻¹ (1986–2005)
0
10
20
>25
(b) Simulated total animal biomass
Value in normalized index (1986–2005)
0
0.5
1
> 3
(c) Maximum fisheries catch potential
Observed values in tonnes* (1986–2005)
0
0.15
55
>275,000
* See figure caption for details
Percent change
Average by 2081–2100, relative to 1986–2005
<–50
–40
–30
–20
–10
0
10
20
30
40
>50
model disagreement
no data

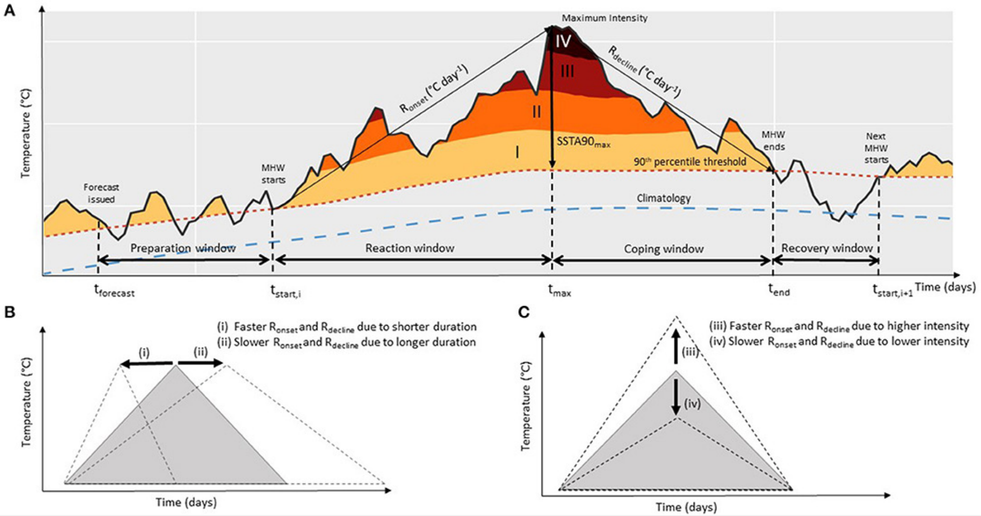
IPCC

MARINE HEATWAVE

- a discrete and prolonged anomalously warm event, lasting at least 5 days (and up to many months) with clear start and end times, and with temperatures in the 90th percentile compared with a 30-year-long baseline of data

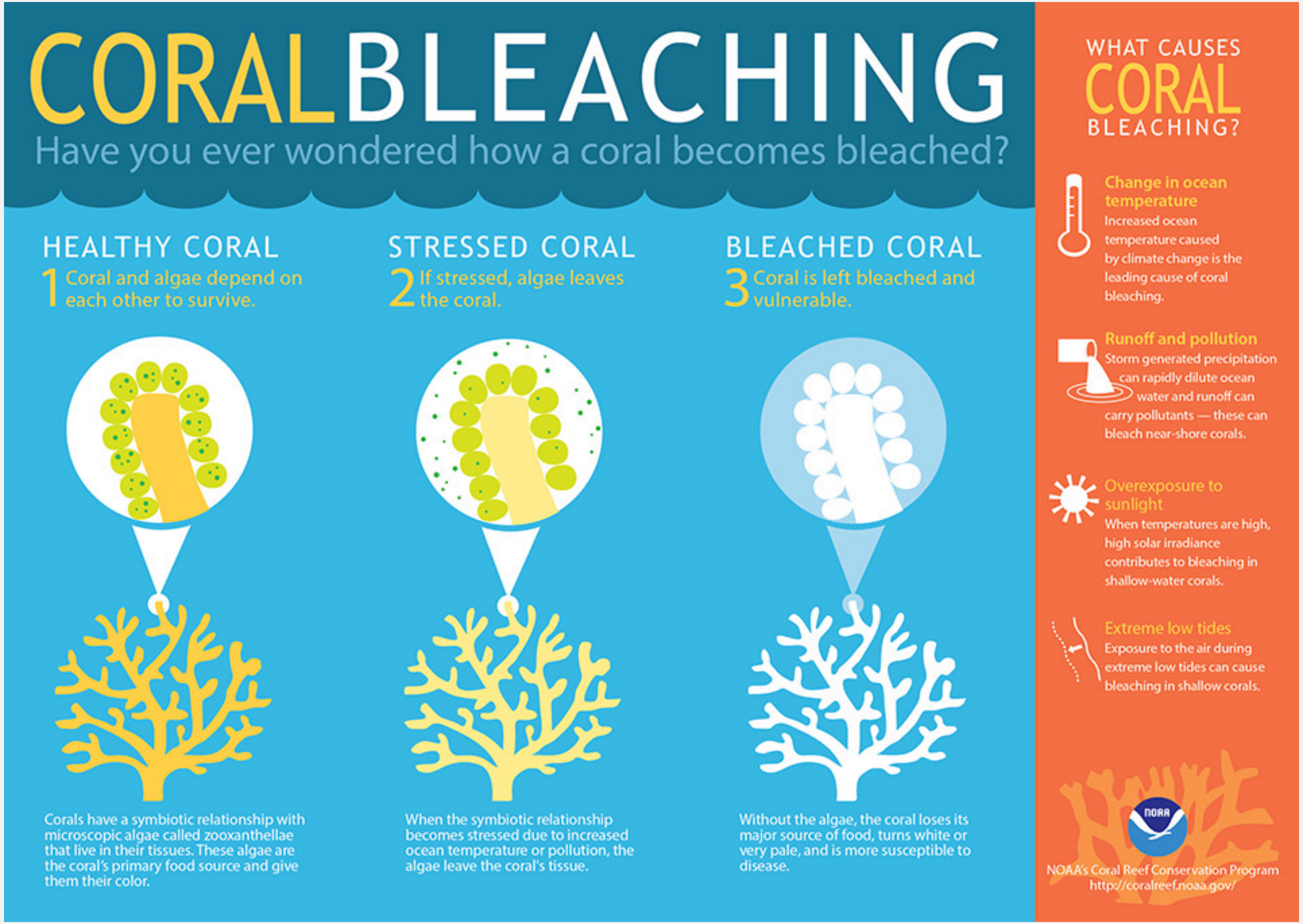
- FIGURE 1. (A) Marine heatwave characteristics, using an observed MHW example. The rate of onset (R_{onset}) is calculated here by dividing the peak exceedance ($SSTA90_{max}$) by the time required to reach it (t_{max}-t_{start}). Similarly, the rate of decline ($R_{decline}$) is calculated here by dividing $SSTA90_{max}$ by the time from peak exceedance to the end of the event (t_{end}-t_{max}). The climatology, 90th percentile threshold, and category (I Moderate, II Strong, III Severe, IV Extreme; [Hobday et al., 2018a]) are also shown. Periods of interest for marine decision-makers include the *preparation window* defined as the time between a forecast issued ($t_{forecast}$) and the start of a MHW (t_{start}), the *reaction window* which is the time from the start of the event to peak exceedance (t_{max}-t_{start}), the *coping window*which is the time from the peak of the event (t_{max}) to the end (t_{end}), and the *recovery window* which begins at t_{end} and ends at the start of the next MHW event. Changes in MHW onset and decline rates can be through (B) changes in duration and/or (C) changes in peak exceedance.

- https://doi.org/10.3389/fclim.2021.801217



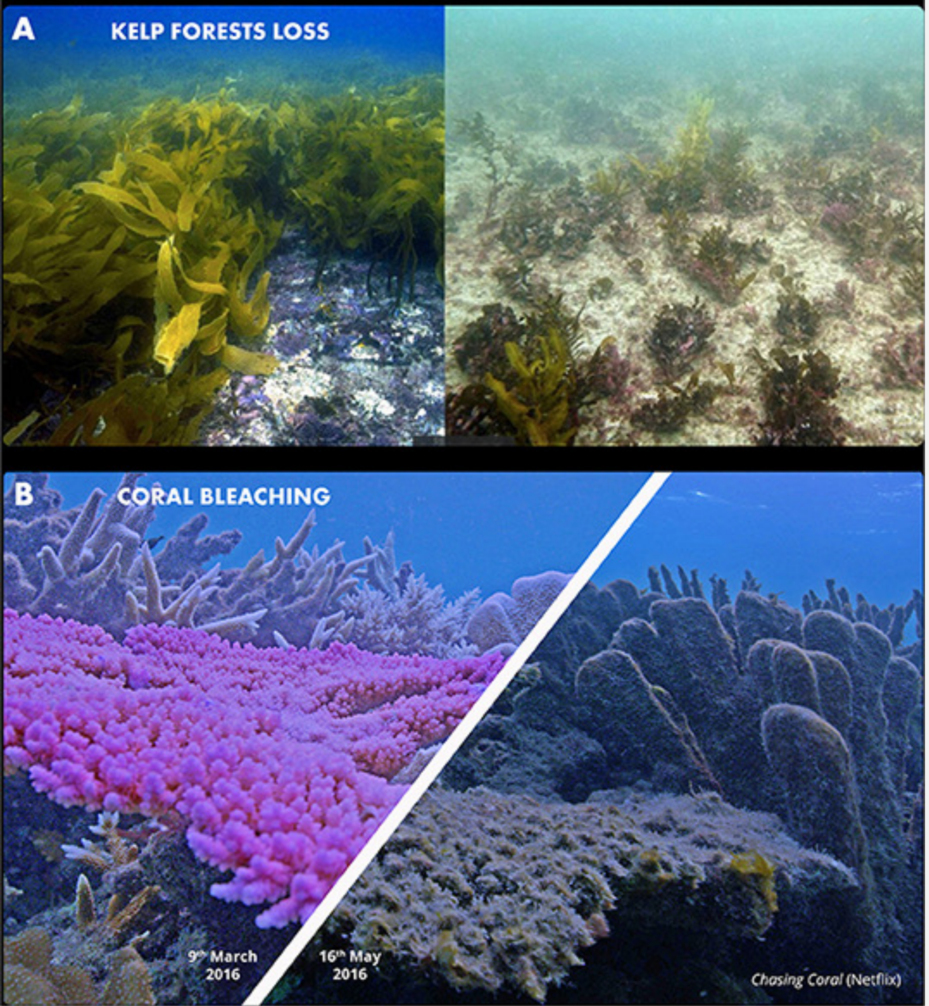
CAUSES

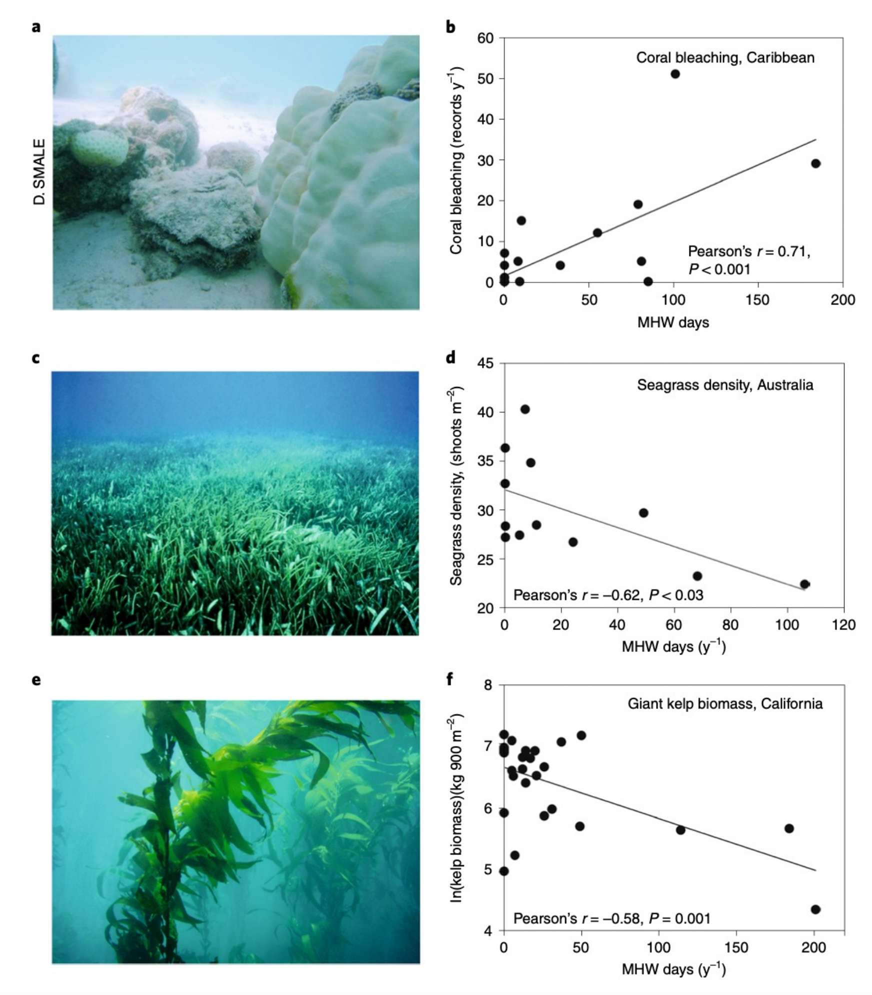
- higher air temperatures
- more intense solar radiation
- less cloud cover
- a thinner mixed layer
- drops in wind speed
- shifts in ocean currents
- presence/absence of large-scale climate phenomena such as the El Niño-Southern Oscillation
- climate change



See lecture on coral reefs

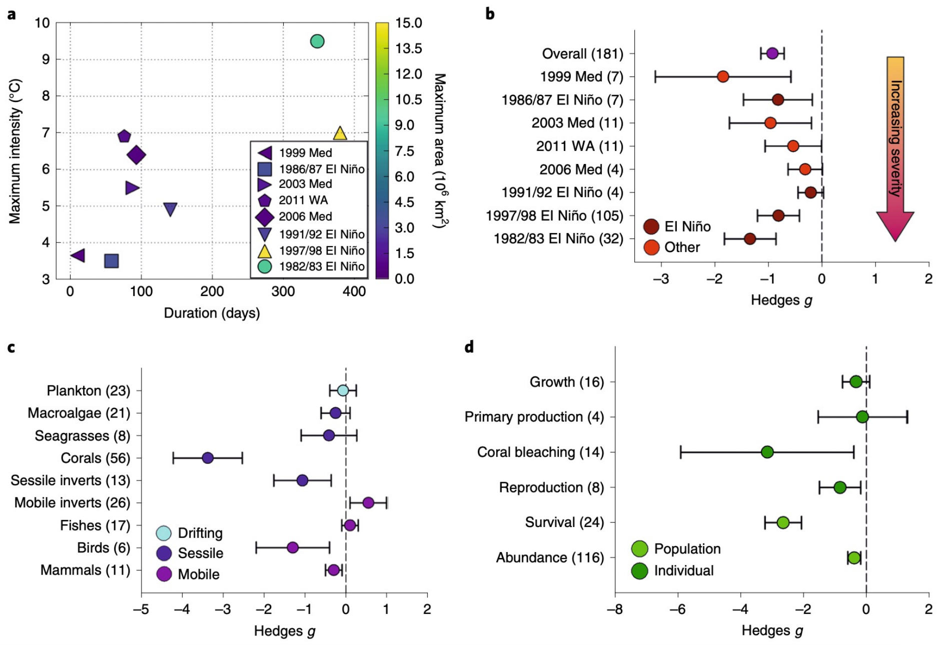
MARINE HEATWAVES AND MARINE LIFE

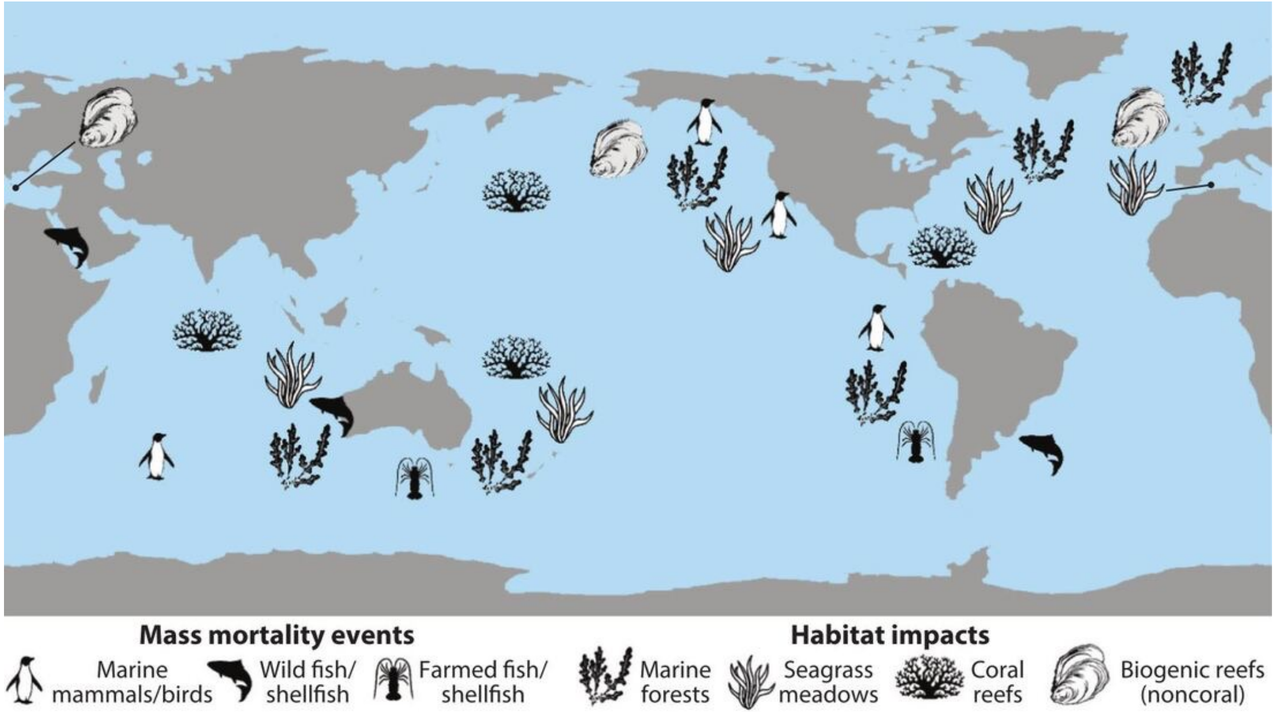




https://doi.org/10.1038/s41558-019-0412-1

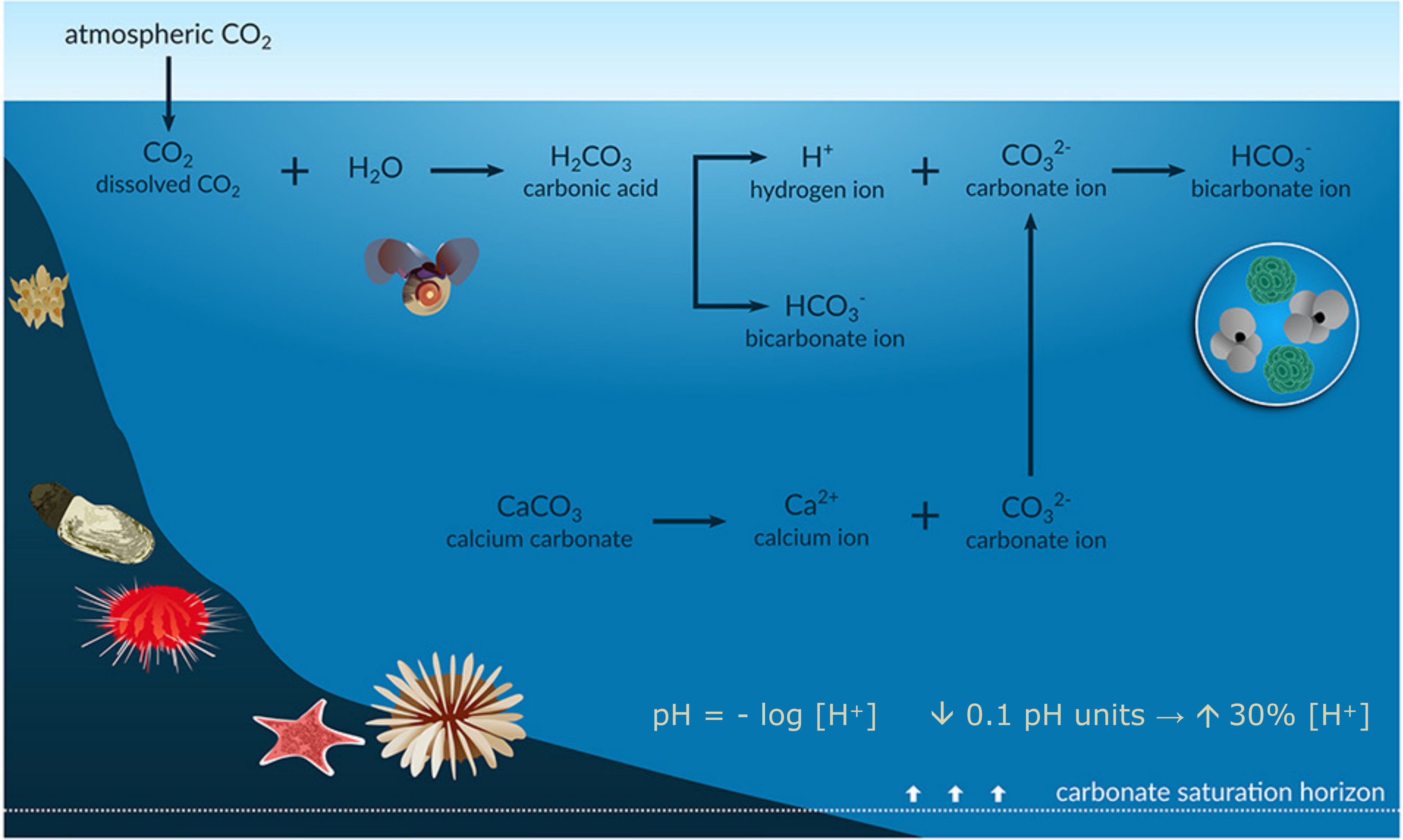
ECOLOGICAL IMPACT



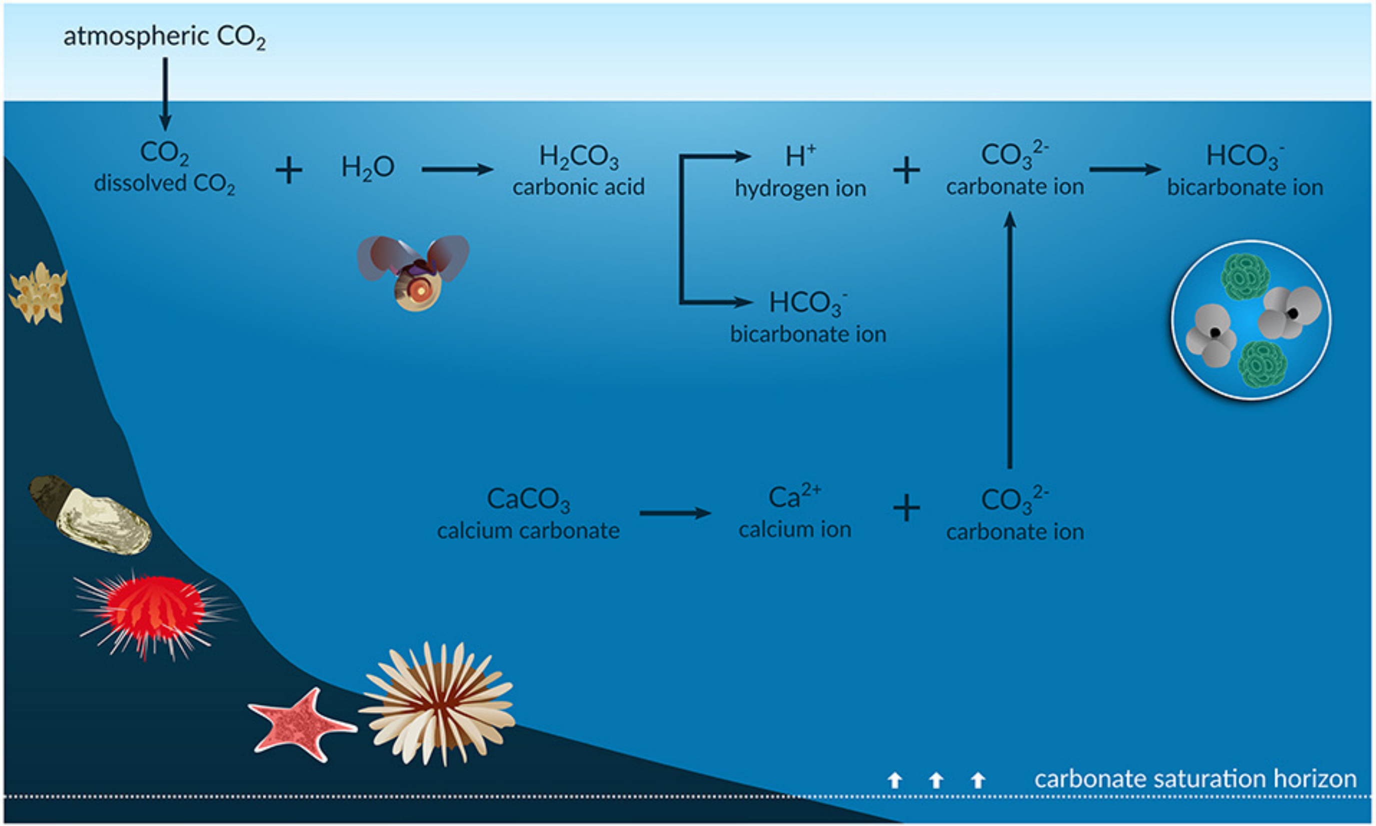


https://doi.org/10.1146/annurev-marine-032122-121437

OCEAN ACIDIFICATION

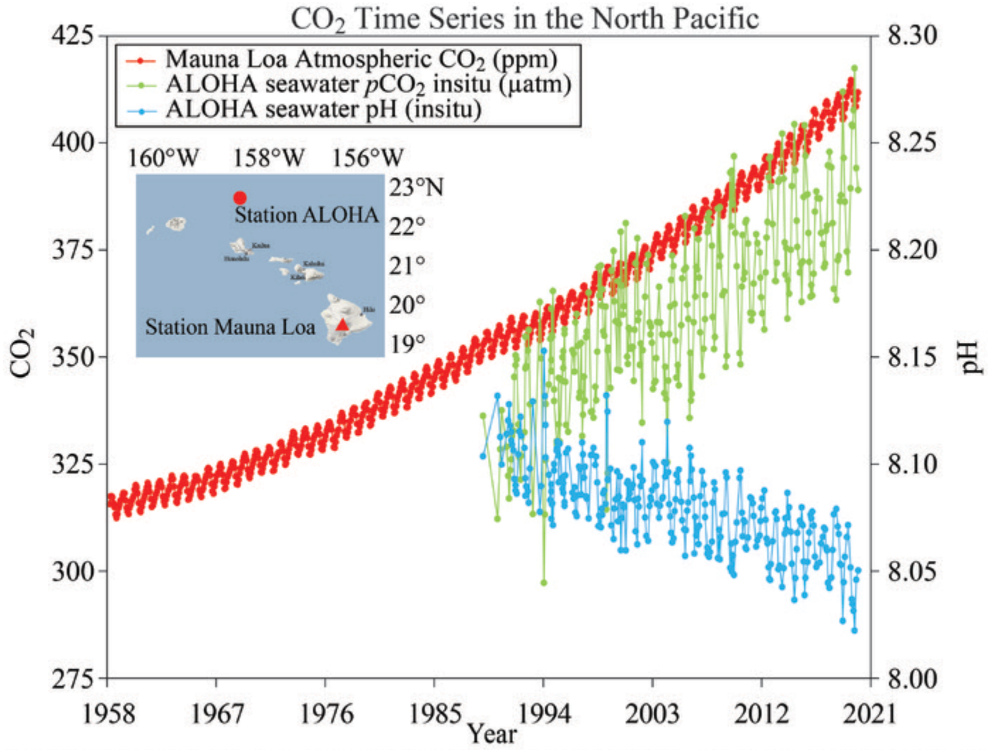


atmospheric CO_2
CO_2
dissolved CO_2
+
H_2O
H_2CO_3
carbonic acid
H^+
hydrogen ion
+
CO_3^{2-}
carbonate ion
HCO_3^-
bicarbonate ion
HCO_3^-
bicarbonate ion
$CaCO_3$
calcium carbonate
Ca^{2+}
calcium ion
+
CO_3^{2-}
carbonate ion
$pH = -\log[H^+]$
$\downarrow$ 0.1 pH units $\rightarrow$ $\uparrow$ 30% $[H^+]$
carbonate saturation horizon



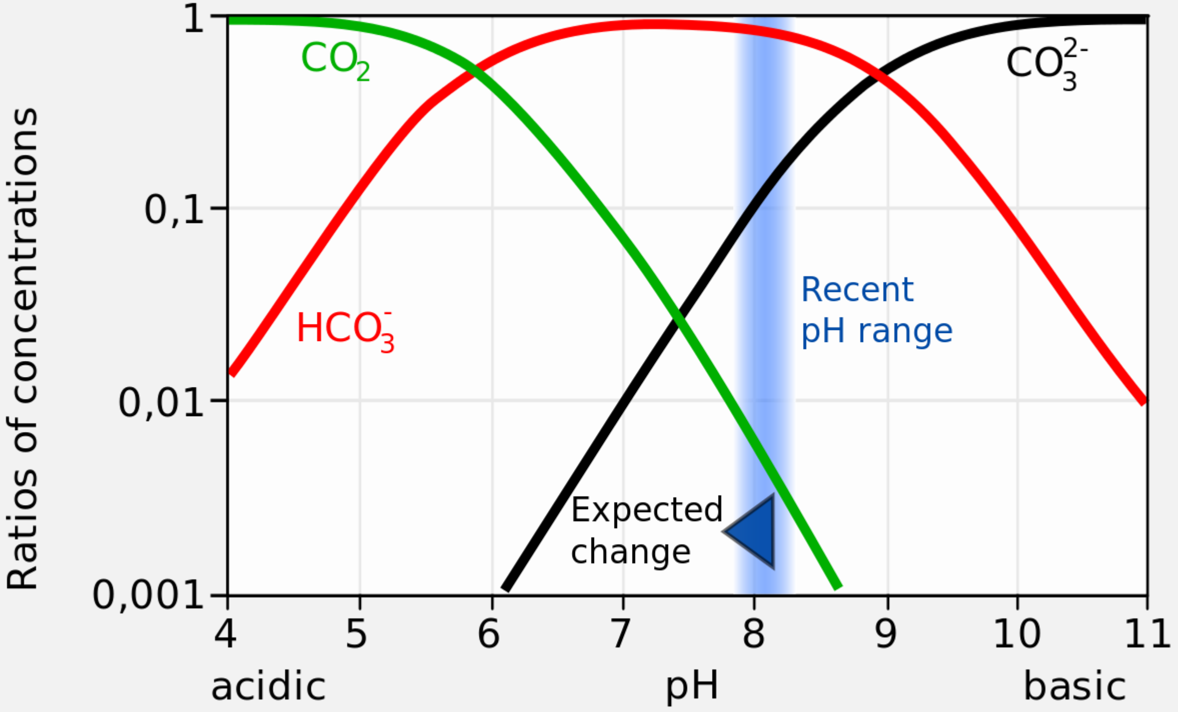
- Fewer carbonate ions
  - Less available for calcification
- Corrosive levels
  - Skeletal parts start to dissolve

OCEAN ACIDIFICATION



Data: Mauna Loa (ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt) ALOHA (http://hahana.soest.hawaii.edu/hot/hot-dogs/bextraction.html)
ALOHA pH & pCO_2 are calculated at in-situ temperature from DIC & TA (measured from samples collected on Hawaii Ocean Times-series (HOT) cruises)
using co2sys (Pelletier, v25b06) with constants: Lueker et al. 2000, KSO4: Dickson, Total boron: Lee et al. 2010, & KF: seacarb

THE CARBONATE SYSTEM



OA= ↓ pH and $[CO_3^{2-}]_{SW}$ + ↑ pCO2 and $[HCO_3^-]_{SW}$

SATURATION STATE OF CALCIUM CARBONATE (Ω)

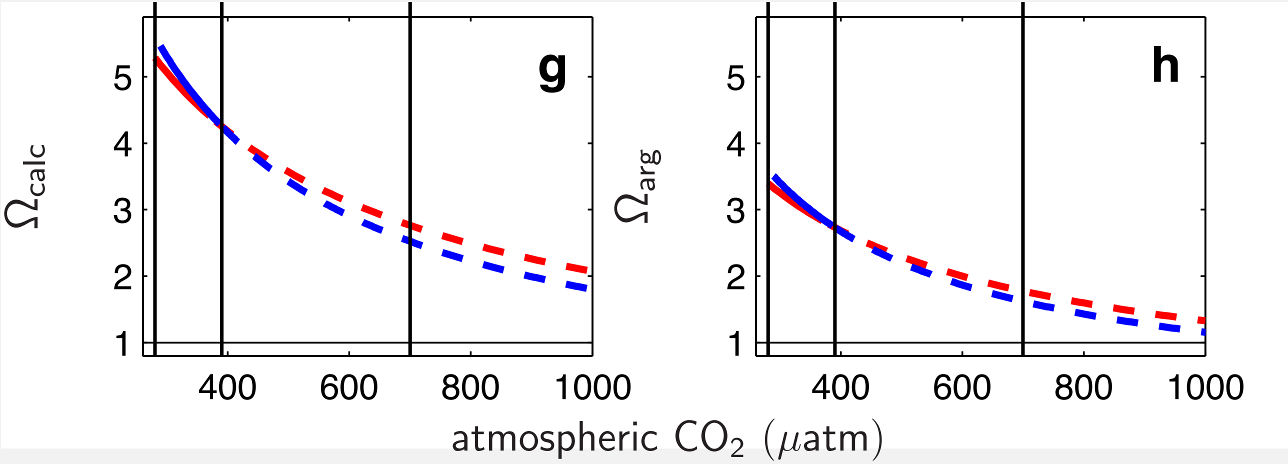
$$\Omega = \frac{[Ca^{2+}]_{SW}\ [CO_3^{2-}]_{SW}}{K^*_{sp}}$$

- K^*_{sp}: apparent solubility constant of the considered $CaCO_3$
- $K^*_{sp} = [Ca^{2+}]_{sat}\ [CO_3^{2-}]_{sat}$
- K^*_{sp} calcite < K^*_{sp} aragonite
- Aragonite is more soluble than calcite: $\Omega_{ar} < \Omega_{cal}$

For inorganic $CaCO_3$, in sea water, if

- $\Omega < 1$: dissolution
- $\Omega = 1$: equilibrium
- $\Omega > 1$: precipitation

SATURATION STATE OF (Ω) CALCIUM CARBONATE AND ATAGONITE

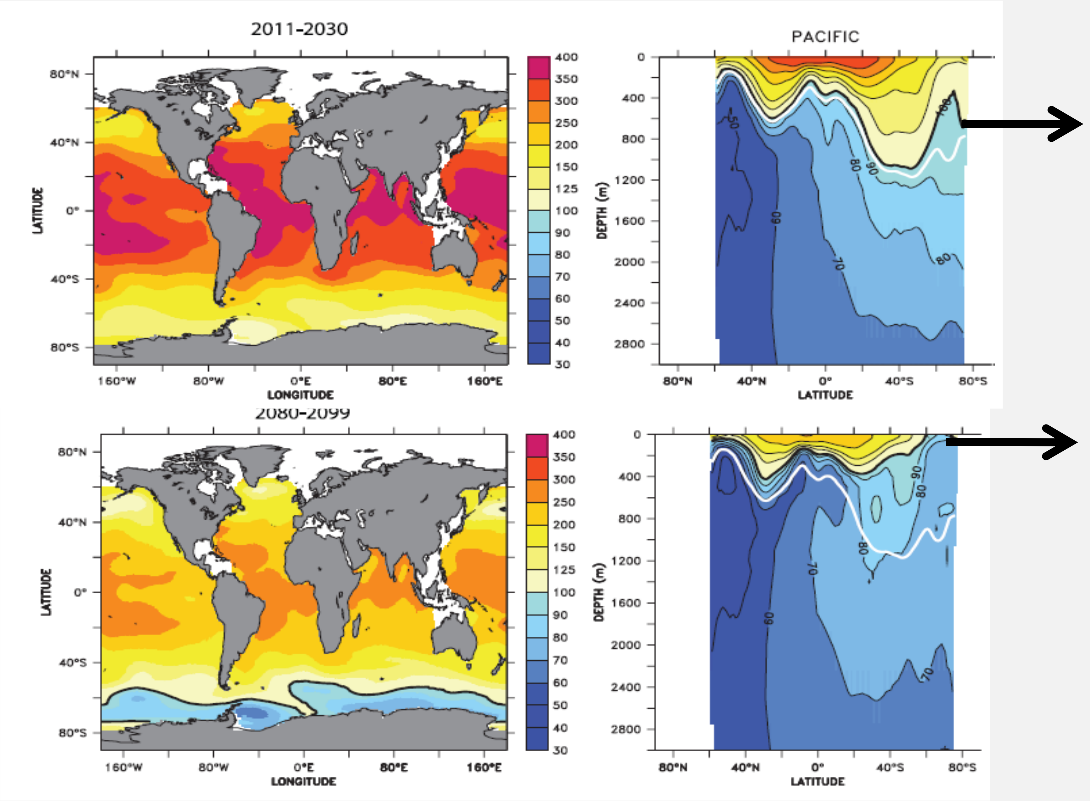


Calcite

Aragonite

(Schulz et al 2009)

Shoaling of the saturation horizon of calcium carbonate



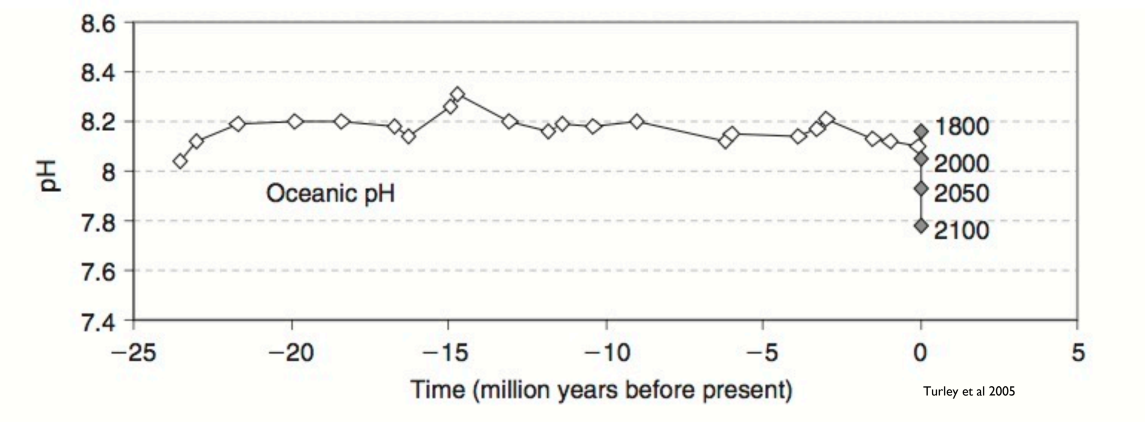
Saturation horizon is the depth at which Ω=1

Saturation horizon is predicted to reach the surface at high latitudes by 2100

Scale: % saturation aragonite

IPCC 2007

- A decrease in pH of 0.3-0.4 units by 2100 and 0.8 units by 2300



Turley et al 2005

The fastest SW pH ⬋ ever observed (Zeebe 2012)

EFFECTS OF ACIDIFICATION

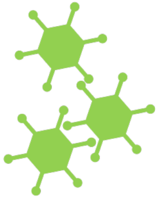
- Hypercapnia (↑CO_2)
- Acidosis (↓pH)
- Limit formation of calcium carbonate
- Erode calcium carbonate

PLANTS

Taxa	Response	Mean Effect
Fleshy algae	Survival	
	Calcification	
	Growth	+22%
	Photosynthesis	
	Abundance	
Seagrasses	Survival	
	Calcification	
	Growth	
	Photosynthesis	
	Abundance	
Diatoms	Survival	
	Calcification	
	Growth	+17%
	Photosynthesis	+12%
	Abundance	

- Not tested or too few studies
- Enhanced <25%
- 95% CI overlaps 0
- Reduced <25%
- Reduced >25%

$$6CO_2 + 6H_20 \longrightarrow C_6H_{12}O_6 + 6O_2$$



Kroeker et al. 2013

PLANTS

Taxa	Response	Mean Effect
 Calcifying algae	Survival	
	Calcification	
	Growth	
	Photosynthesis	–28%
	Abundance	–80%

- Not tested or too few studies
- Enhanced <25%
- 95% CI overlaps 0
- Reduced <25%
- Reduced >25%

Kroeker et al. 2013

Many species of pink coralline algae, which cements coral reefs together, cover a reef surface in the Southern Line Islands. *(Maggie D. Johnson, Scripps Institution of Oceanography)*

IMPACT OF OA ON MARINE ORGANISMS

Acidosis (↓pH)

Hypercapnia (↑CO_2)

Metabolic rates
Physiology
Behavior
Reproduction
Growth
Calcification

Taxa	Response	Mean Effect
Corals	Survival	
	Calcification	−32%
	Growth	
	Photosynthesis	
	Abundance	−47%
Mollusks	Survival	−34%
	Calcification	−40%
	Growth	−17%
	Development	−25%
	Abundance	
Echinoderms	Survival	
	Calcification	
	Growth	−10%
	Development	−11%
	Abundance	
Crustaceans	Survival	
	Calcification	
	Growth	
	Development	
	Abundance	
Fish	Survival	
	Calcification	
	Growth	
	Development	
	Abundance	

- Not tested or too few studies
- Enhanced <25%
- 95% CI overlaps 0
- Reduced <25%
- Reduced >25%

CALCIFIERS

Kroeker et al. 2013

- Most water breathing marine organisms rely on the gradient in pCO_2 between their extracellular inner fluids and sea water to eliminate respiratory CO_2
  - ➔ if SW pCO_2 $\uparrow$, pCO_2 of extracellular fluids $\uparrow$ until the gradient is reestablished (hypercapnia) and, consequently, pH $\downarrow$ (acidosis)
  - ➔ deleterious effects
    - lower enzyme activities,
    - Chemical communication
    - Reproduction
    - Growth

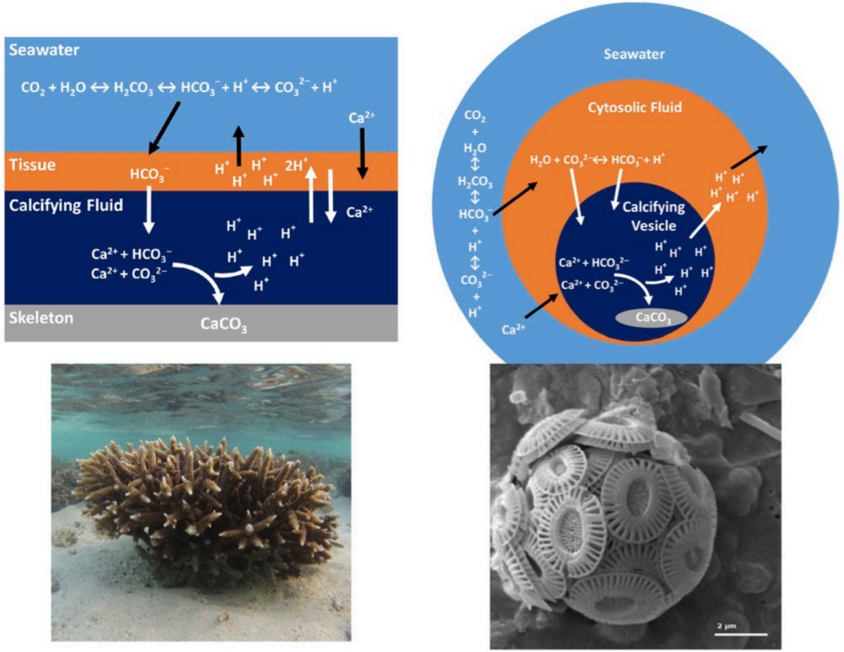


Figure 1. A simplified schematic demonstrating the internal build-up of protons during the calcification process in corals and coccolithophores. Corals (left panel) must dissipate excess protons produced by calcification through a boundary layer and into the water column as proposed by Jokiel (2011b). Internally, corals most likely actively pump HCO_3^- ions into the calcifying fluid where protons build-up as $CaCO_3$ is precipitated. To maintain favourable conditions for precipitation in the calcifying fluid, corals likely actively pump $2H^+$ out and Ca^{+2} in using a Ca^{+2}-ATPase (Allemand *et al.*, 2011). To maintain the pH inside their tissue corals must remove protons, which becomes more energetically demanding when the gradient between the tissue and seawater [H^+] is less pronounced due to ocean acidification. Suffrian *et al.* (2011) demonstrated that internal cellular pH (pH_i) in coccolithophores like *Emiliania huxleyi* (right panel) is directly affected by the surrounding seawater pH. This is most likely because *E. huxleyi* uses passive gated H^+ channels to control cytosolic pH, which are forced to work against a less pronounced H^+ gradient in an acidifying ocean. Black arrows represent fluxes between the organism and external seawater while white arrows represent fluxes occurring within the organism.

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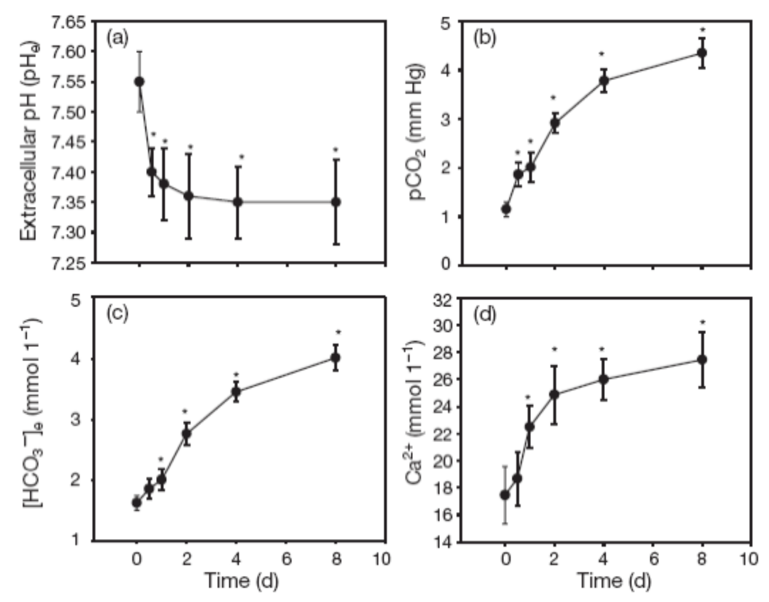
$$\frac{[HCO_3^-]}{[H^+]} = \frac{\Omega_{CaCO_3} K_{sp}^*}{[Ca^{2+}] K_2^*}.$$

Bach 2015

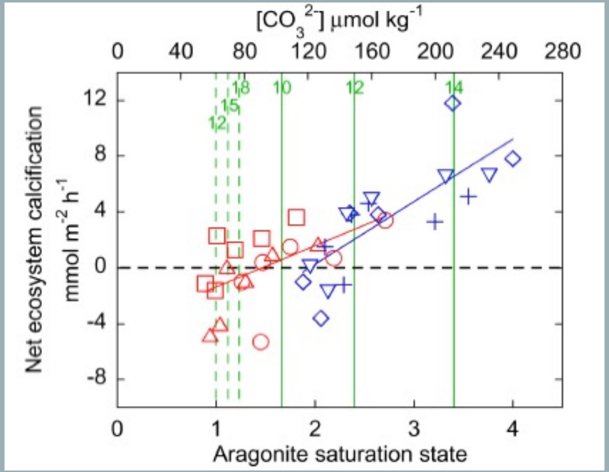
HOW DO ORGANISMS COPE WITH OA?

Mytilus edulis
Michaelidis et al 2005



- Others are not able to compensate their extracellular pH
  - Non-bicarbonate buffering (proteins principally): low concentration
  - No bicarbonate accumulation: bivalves, gastropods (?), sea stars, brittle stars, sea cucumbers etc..

Coral reef ecosystems (**warm waters**) might be particularly at risk



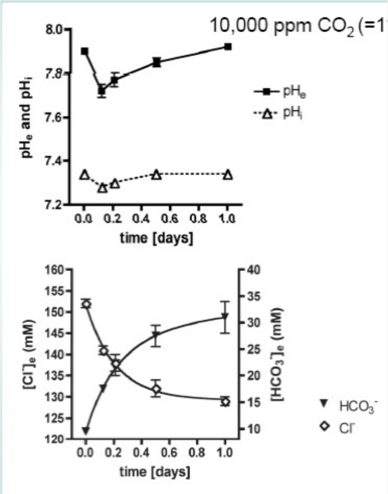
Andersson et al. 2009

Balance of deposition by calcifiers (principally scleractinians, calcareous algae) minus dissolution (chemical and bioerosion) might become negative when $\Omega < 2$, meaning that the coral reefs would loose mass.

EFFECT ON RESPIRATION

HOW DO ORGANISMS COPE WITH OA?

Gadus morhua
Larsen et al. 1997



- Some are able to compensate their extracellular pH
  - Non-bicarbonate buffering (proteins principally): most organisms but very different magnitudes
  - Bicarbonate accumulation: fishes, crustaceans, cephalopods, some sea urchins
- Energetic cost! (active transport: ATPase HCO_3^-/Cl^-)

Effect on respiration differs according to species

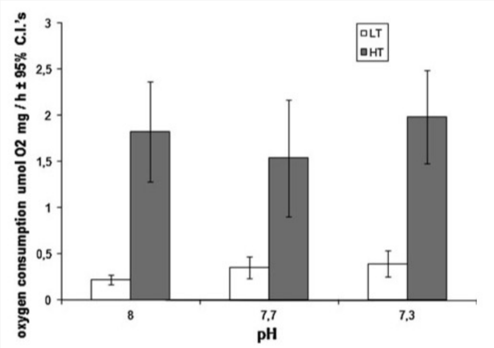


Fig. 1 Mean oxygen uptake rate (μmol O_2 mg/h) standardised by mass, as a proxy of metabolic rate. LT is low temperature (10.5°C), and HT is the high temperature (15°C) exposure. *Error bars* are 95% confidence intervals

Ophiura ophiura, temperate, Wood et al 2010
significant effect of pH

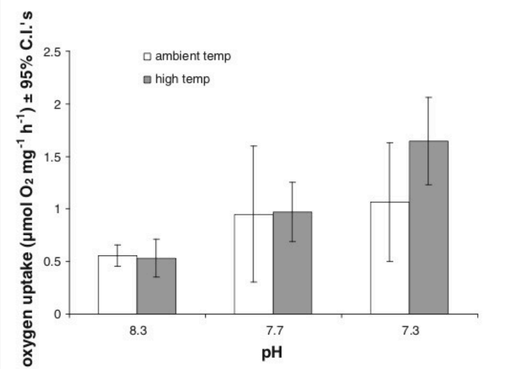
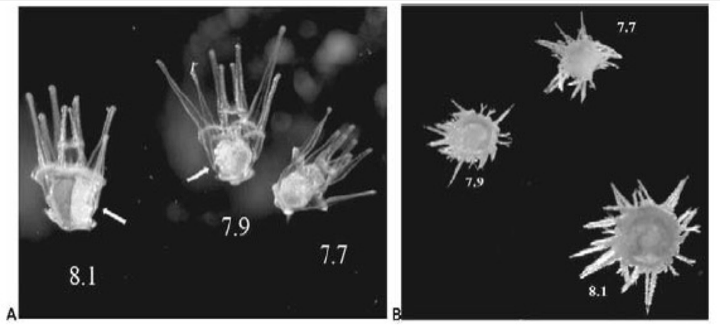


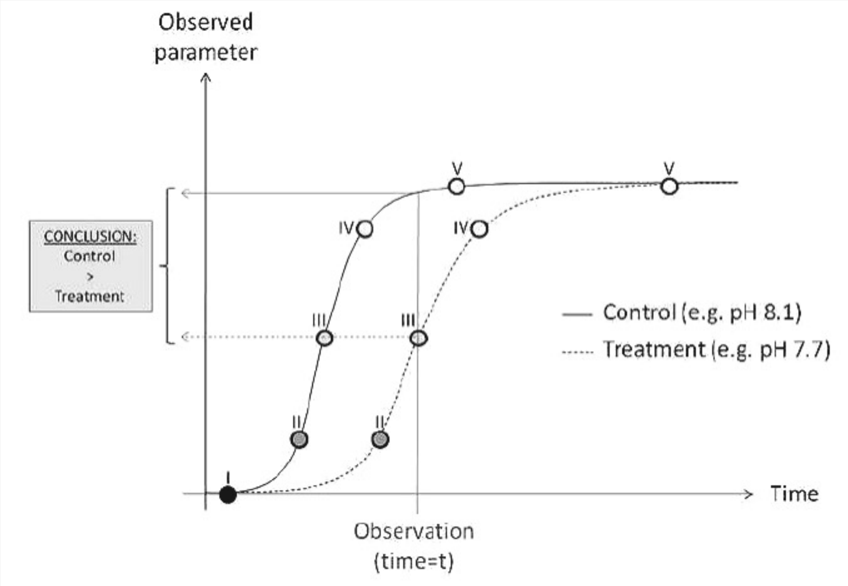
Fig. 1 Mean rates of oxygen uptake of *Ophiocten sericeum* at the three pH and two temperature treatments ±95% confidence intervals. Amputation data pooled as ANOVA showed no significant difference between treatments $N = 30$

Ophiocten sericeum, arctic, Wood et al 2011
No Significant effect

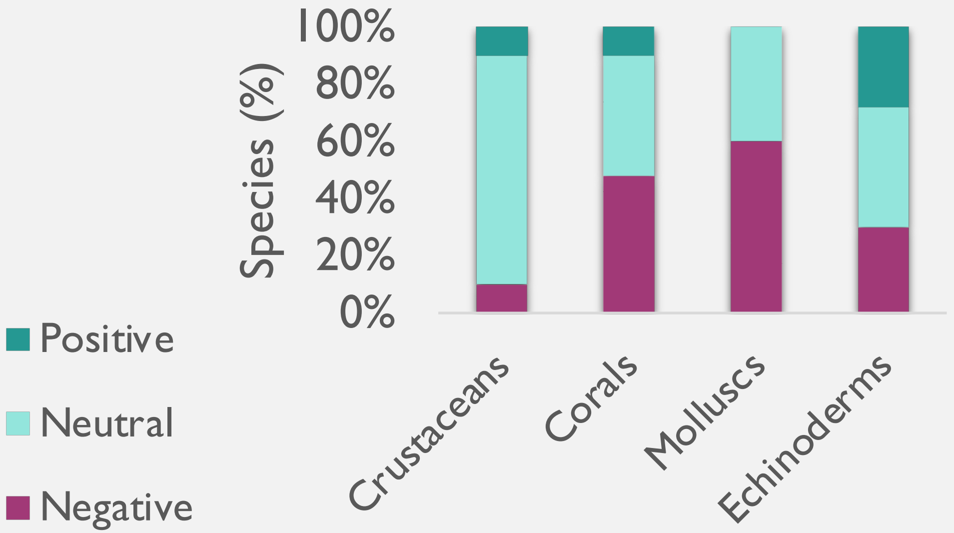


Larvae cultured at different pH (control 8.1, 7.9 and 7.7) show a developmental delay with decreasing pH (Dupont & Thorndyke 2008)

A) Late pluteus larvae - 21 days
B) Juveniles - 50 days



Relation between time and stage of development



Impact differs according to taxon, with species able to compensate their extracellular pH doing better

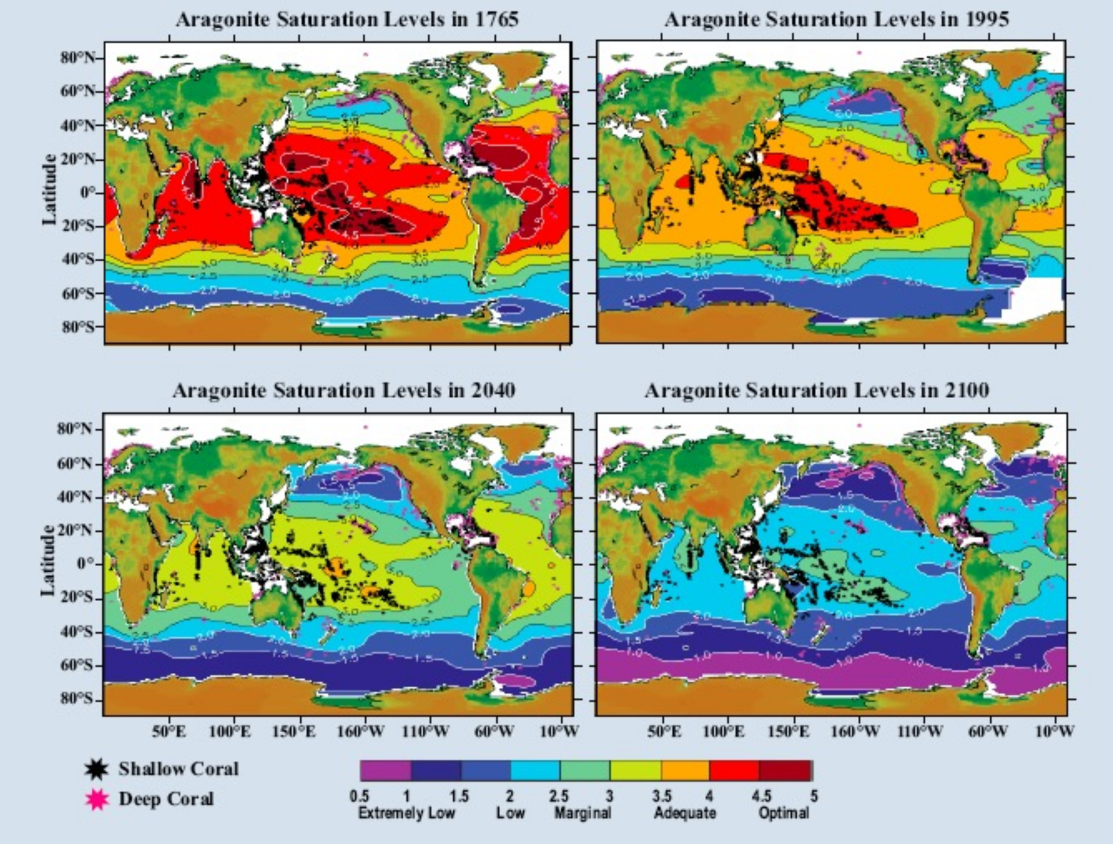
Wittman & Pörtner 2013

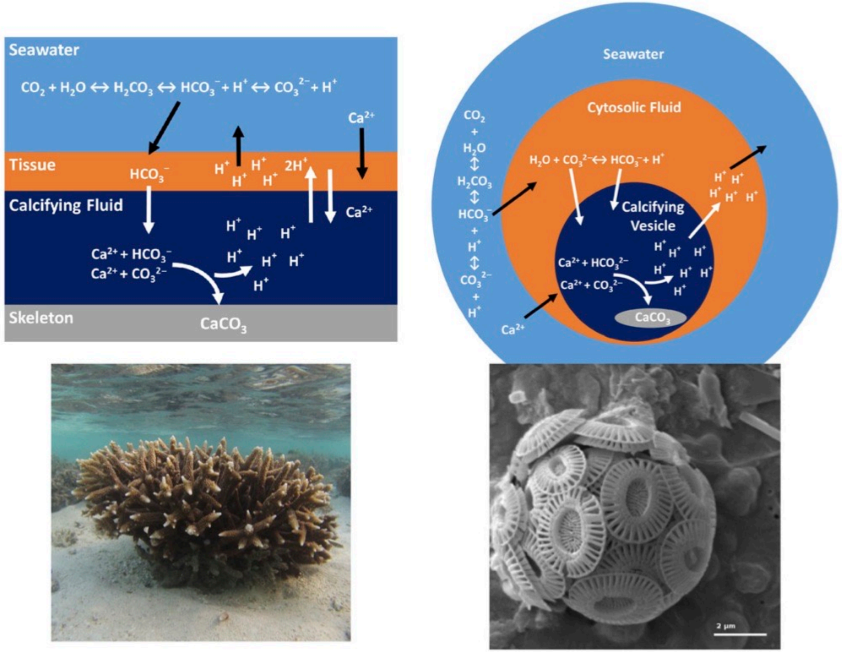
GROWTH AND CALCIFICATION

The main calcifiers in marine environments:

- Coccolithophoridae* (calcite)
- Foraminifera* (Mg-calcite: $Mg_xCa_{1-x}CO_3$; aragonite)
- Corals (aragonite)
- Calcareous algae (aragonite; calcite)
- Pteropods* (aragonite)
- Other molluscs (calcite; aragonite), echinoderms (Mg-calcite), sponges (aragonite; calcite; Mg-calcite), arthropods (calcite; aragonite)

* Produce most of biogenic carbonate precipitated in the open oceans


Aragonite Saturation Levels in 1765
Aragonite Saturation Levels in 1995
Aragonite Saturation Levels in 2040
Aragonite Saturation Levels in 2100
Latitude
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
50°E
100°E
150°E
160°W
110°W
60°W
10°W
Shallow Coral
Deep Coral
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Extremely Low
Low
Marginal
Adequate
Optimal



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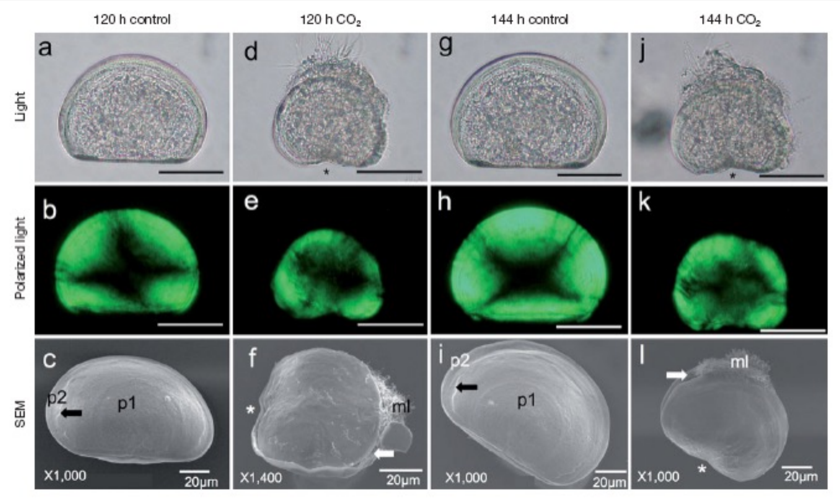
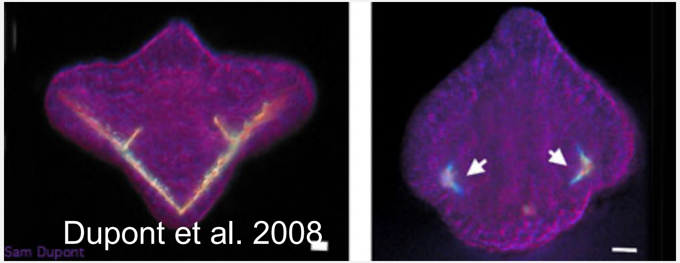
Bach 2015

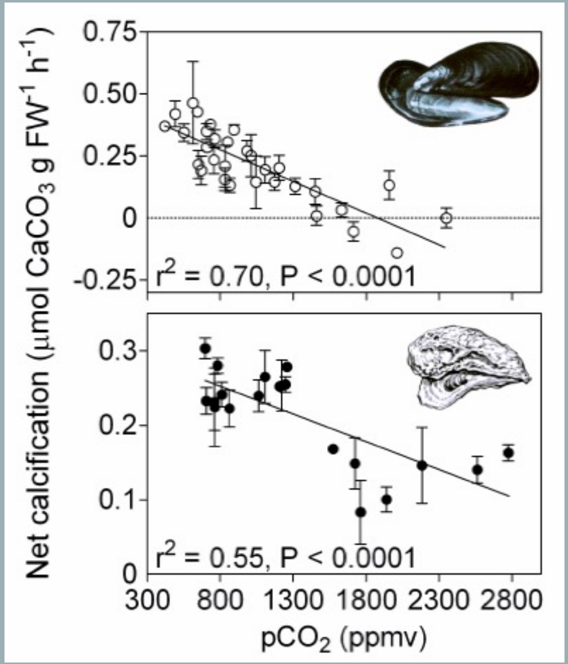
Larval stages are very sensitive to OA:



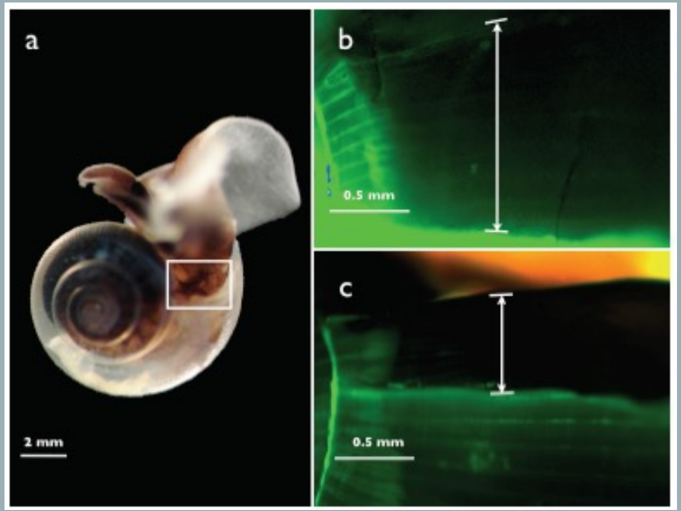
Early development of *Mytilus galloprovincialis.* Morphology of larvae incubated for 120h and 144h control (380ppm; pH=8.13) or in CO_2 seawater (2000ppm; pH=7.42).



Early larvae of the brittlestar *Ophiothrix fragilis* reared in control seawater (pH 8.1, left), and water acidified with CO2 (pH 7.7 right), with a reduced skeleton as an effect.



Gazeau et al. 2007

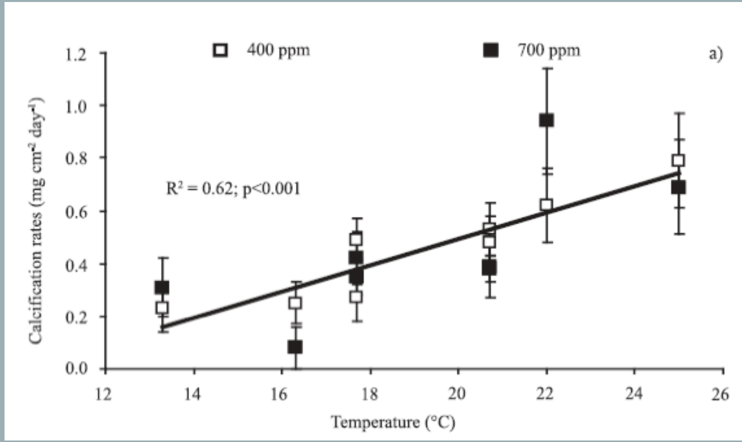


Comeau et al. 2009

Some species show a decrease of their calcification rates when exposed to lower pH seawaters (i.e. higher pCO$_2$ and lower ΩCaCo$_3$).

Decrease of calcification rates of *Mytilus edulis, Crassostrea gigas* and arctic pteropods under high pCO$_2$

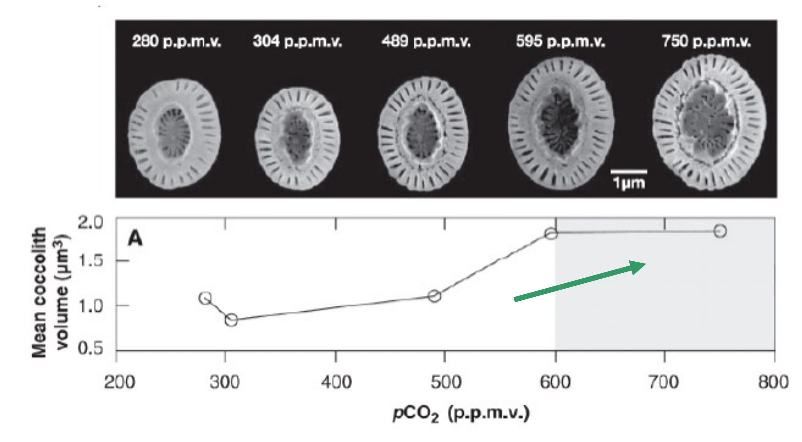
Temperate corals

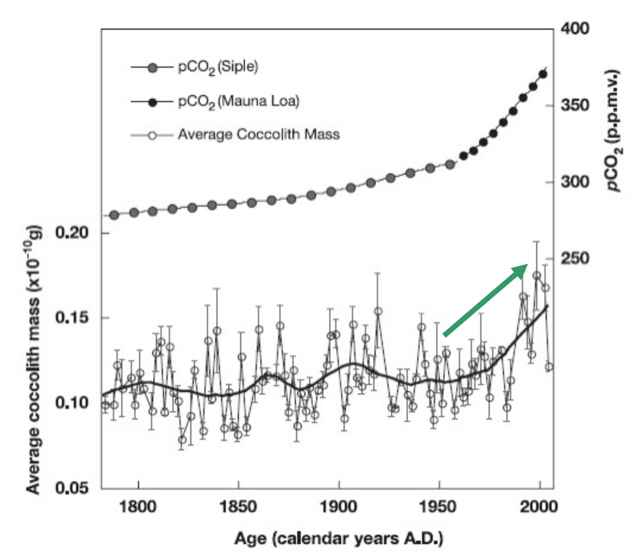


The lack of sensitivity of **temperate corals** to high-pCO2 levels might be due to their **slow growth rates**, which seem to be more dependent on temperature than on the saturation state of calcium carbonate (in the range predicted for the end of the century)

Rodolfo-Metalpa et al. 2009

Coccolithophores





Calcification increment of *Emiliania huxleyi* at higher CO_2 conditions over longer duration

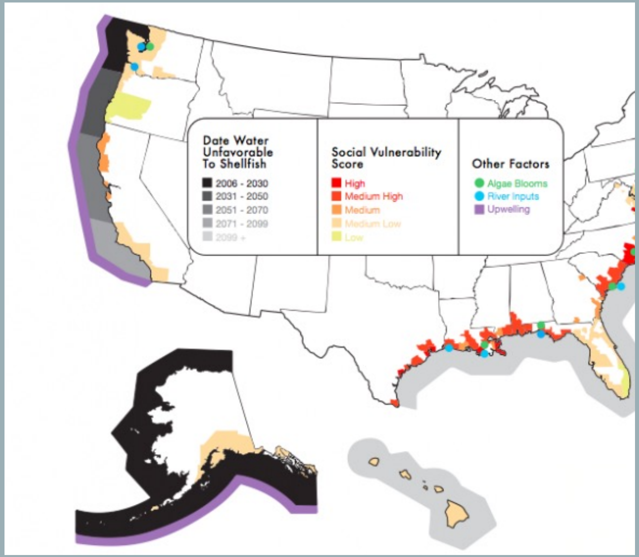
Related with the fact that coccolitophores are autotrophic and their calcification is intracellular?

Calcifiers present different responses toward OA because:

- the organisms are autotrophic or heterotrophic
- biocalcification mechanisms differ (extracellular, intracellular, intercellular)
- metabolic strategies differ
- of acid base regulation abilities differ

IMPACT OF OA: FISHERIES

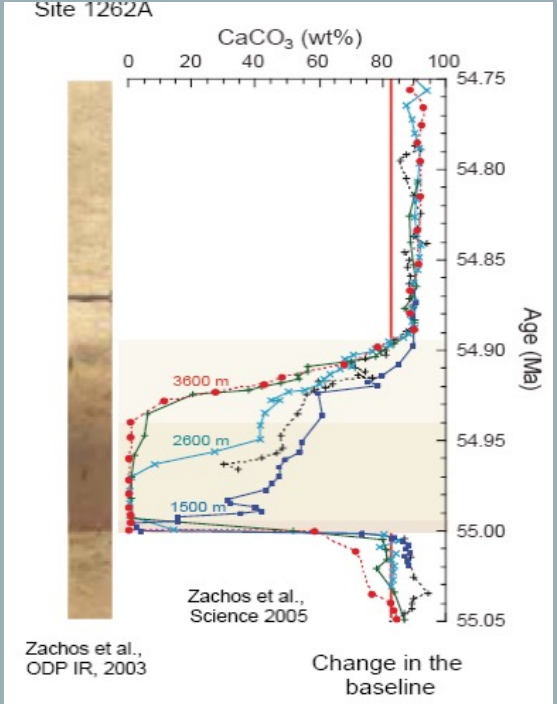
OA can also have social and economic consequences, as, for example, fishery stocks might be affected



Impacts of OA and climate change on fisheries can be indirect as a species loss causes great instability on the ecosystem.
Furthermore, some species of seafood (shellfish) might be at direct risk.

LESSONS FROM THE PAST

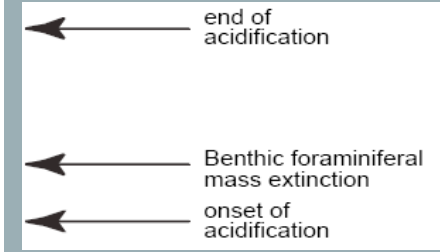
The Paleocene-Eocene Thermal Maximum (PETM)



Adapted from Turley 2008

- Mass extinctions linked to much slower than present OA events

- It took millions of years to recover



% of $CaCO_3$ in the sediment is used as a proxy of foraminifera density

Impact of OA: summary

- Reduced calcification rates, growth, production and life span of adults, juveniles and larvae
- Reduced tolerance to other environmental fluctuations
- Combined impacts of OA and temperature increase
- Changes in fitness and survival
- Changes in species biodiversity, biogeography and food webs
- Shifts in ecosystems: some species will "win" and some will "loose"

Impact of global change in the ocean

Will organisms be able to **acclimate** and/or **adapt** to these changes?

Impact of OA

Acclimation - the progressive adjustments of an organism to any change in the environment that subjects it to physiological stress. It occurs in a **short period of time (days/weeks-months) and within one organism lifetime**

≠

Adaptation - structural, physiological or behavioural characteristics of a population that allows it to be better suited for a certain environment. This process takes place over **many generations through natural selection**

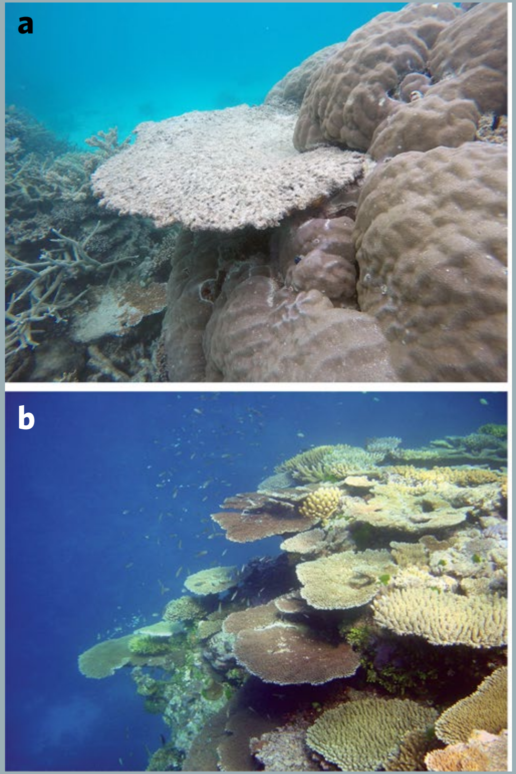
Impact of global change in the ocean: Acclimation and adaptation

- Only preliminary evidence
- Past history of a population may have selected resistant/resilient genotypes
- Recent experimental work has shown that range-limiting traits can evolve rapidly over decadal time-scales *(Diamond 2018)*
- Surely not for all species (loosers and winners) → community changes/shifts

Impact of global change in the ocean: Further readings

- IPCC reports: https://www.ipcc.ch/reports/
- In particular for the ocean https://www.ipcc.ch/srocc/

Impact of global change in the ocean: Acclimation and adaptation



Legacy effects of multiple disturbance.

a, Disproportionate loss of abundant, susceptible tabular and branching *Acropora* corals on northern reefs in 2016, compared with more resistant mound-shaped *Porites*, increased community resistance to recurrent bleaching in 2017.

b, Corals in the southern Great Barrier Reef remained unbleached and dominated by *Acropora* in 2017, despite higher levels of heat exposure than in 2016.

(Hughes et al 2019)