Global change in the ocean

1

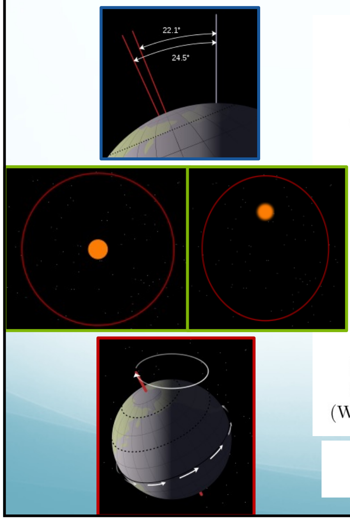
Greenhouse effect

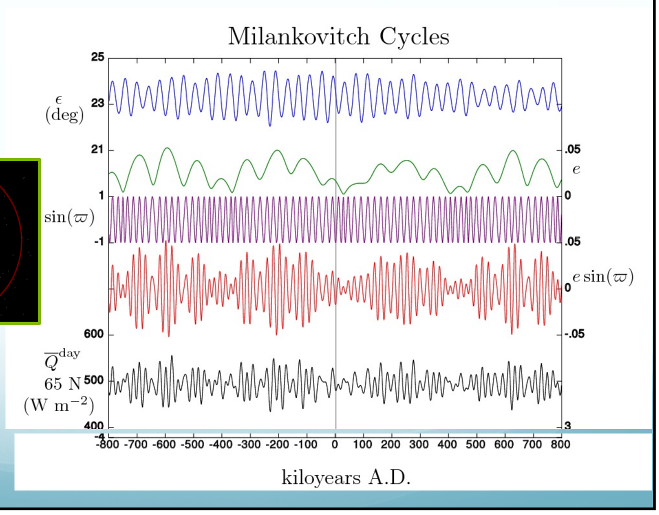
- 1824 Joseph Fourier
- 1856 Eunice Foote
- 1859, John Tyndall
- 1896 Svante Arrhenius

2

Milankovitch cycle

- 1920s

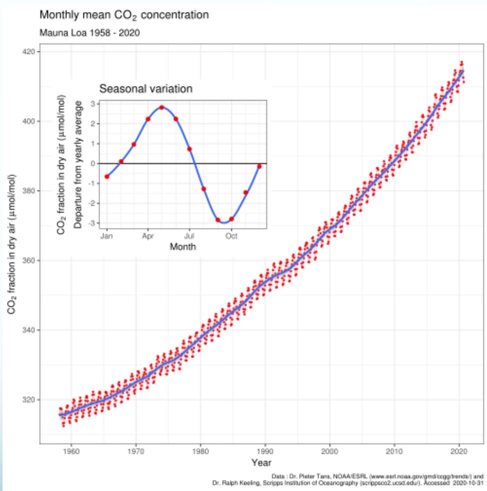




3

Keeling Curve

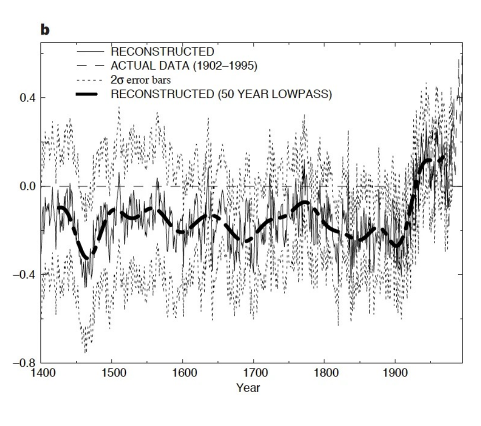
- 1960
- Mauna Loa Observatory, Hawaii
- 1958 to the present day



4

hockey stick

- Original "hockey stick" temperature graph in *Nature*, 1998. The Y ax 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

5

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

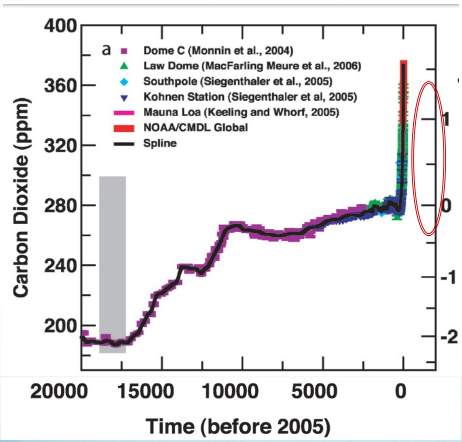
6

Historic CO_2 concentrations

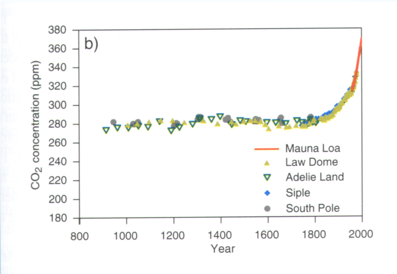
CO_2		
1958 - PRESENT DAY	in situ air	Mauna Loa, Observatory, Hawaii
1000 YEARS AGO - 1958	Ice cores	Law Dome, Wilkes Land Antarctica
800,000 YEARS AGO - 1000 YEARS AGO	Ice cores	Antarctic Vostok and EPICA Dome C ice

7

Carbon dioxide in the atmosphere is increasing

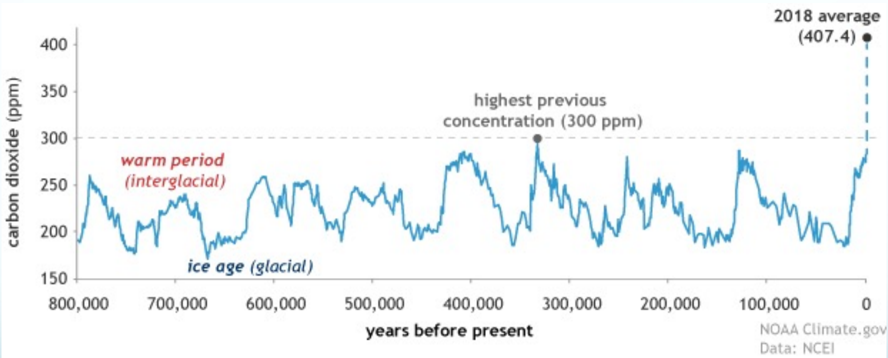


- The fastest ↑ of $[CO_2]_{atm}$ ever observed (Zeebe 2012)



8

Carbon dioxide in the atmosphere is increasing



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

9

Looking Further back

December 2021

© Beyond Epica (1.5 million years…)

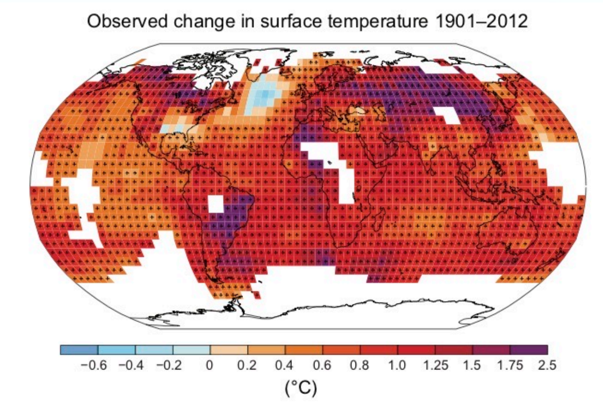
10

IPCC

- IPCC First Assessment Report, 1990
- IPCC Second Assessment Report, 1996
    - Special Report on Emissions Scenarios (SRES) , 2000
- IPCC Third Assessment Report, 2001
- IPCC Fourth Assessment Report, 2007
- IPCC Fifth Assessment Report, 2014
    - Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), 2019
- Sixth assessment report (2021/2022)

11

Consequences in the atmosphere: Global warming



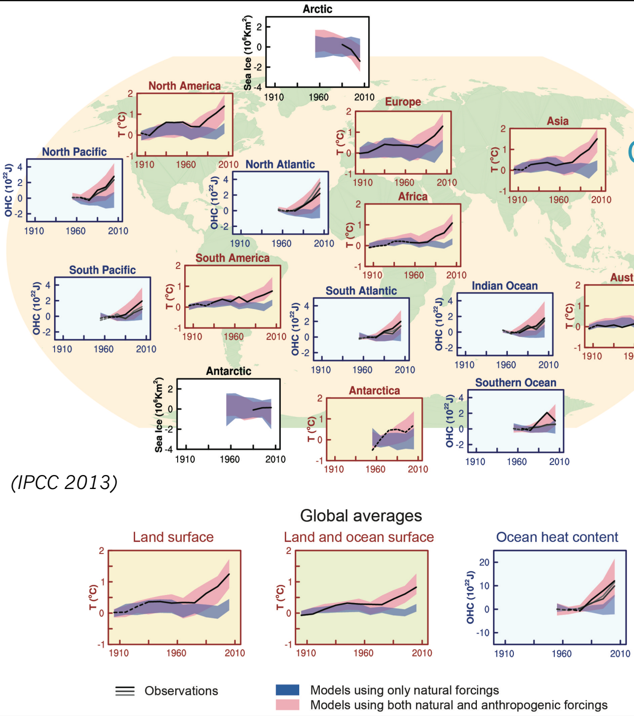
(IPCC 2013)

Global warming of surface atmosphere: 0.65 - 1.06° C

(mean trend)

12

Global warming is due to human activities



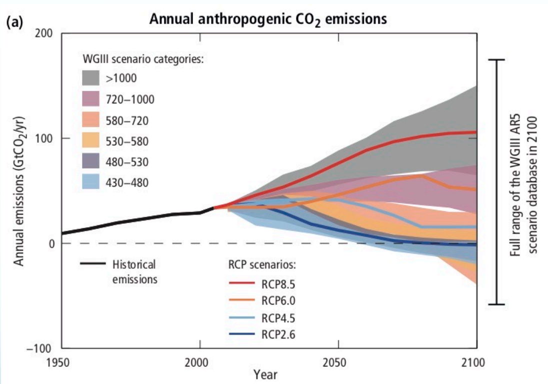
(IPCC 2013)

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)

13

Carbon dioxide in the atmosphere is increasing: future scenarios

<u>R</u>epresentative <u>C</u>oncentration <u>P</u>athways

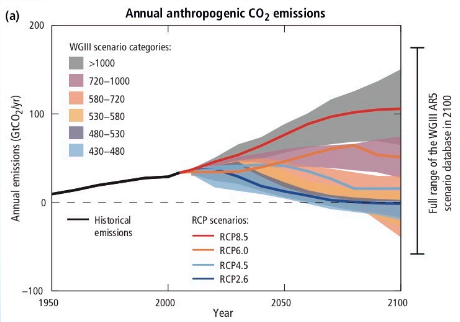


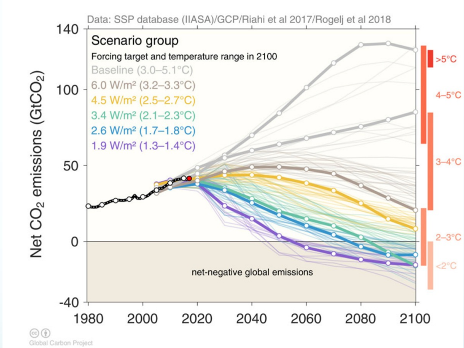
Emissions of carbon dioxide (CO_2) alone in the Representative Concentration Pathways (RCPs) (lines) and the associated scenario categories (coloured areas show 5 to 95% range). The scenario categories summarize the wide range of emission scenarios published in the scientific literature and are defined 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

14

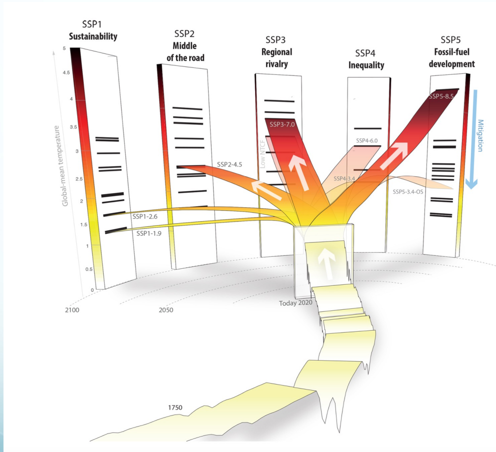
Shared Socioeconomic reference Pathway



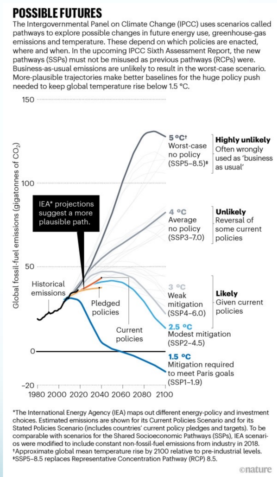


15

The SSP scenarios and their five socio-economic SSP families



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



POSSIBLE FUTURES

The Intergovernmental Panel on Climate Change (IPCC) uses scenarios called pathways to explore possible changes in future energy use, greenhouse-gas emissions and temperature. These depend on which policies are enacted, where and when. In the upcoming IPCC Sixth Assessment Report, the new pathways (SSPs) must not be misused as previous pathways (RCPs) were. Business-as-usual emissions are unlikely to result in the worst-case scenario. More-plausible trajectories make better baselines for the huge policy push needed to keep global temperature rise below 1.5 °C.

*The International Energy Agency (IEA) maps out different energy-policy and investment choices. Estimated emissions are shown for its Current Policies Scenario and for its Stated Policies Scenario (includes countries' current policy pledges and targets). To be comparable with scenarios for the Shared Socioeconomic Pathways (SSPs), IEA scenarios were modified to include constant non-fossil-fuel emissions from industry in 2018.
†Approximate global mean temperature rise by 2100 relative to pre-industrial levels.
‡SSP5–8.5 replaces Representative Concentration Pathway (RCP) 8.5.

©nature

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

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Consequences in the ocean

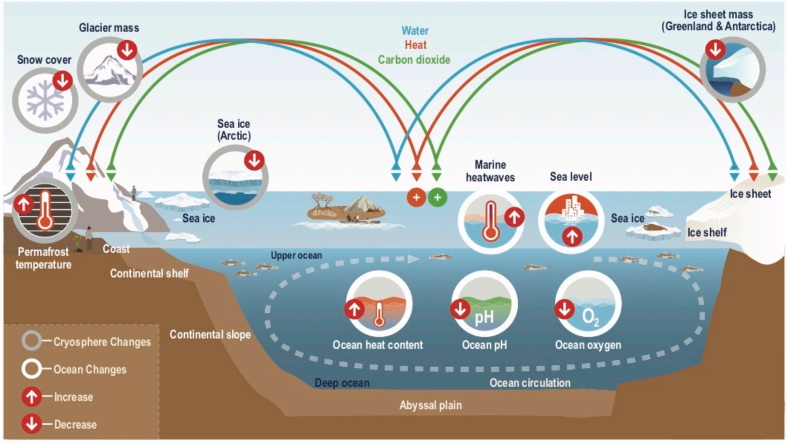
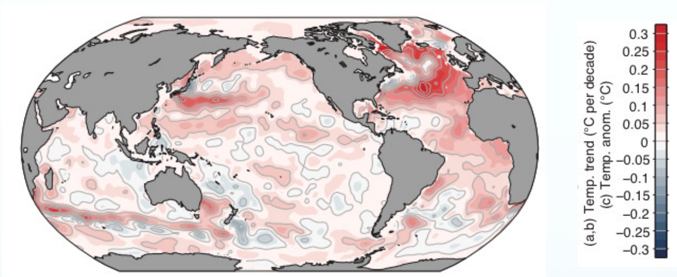


Figure TS.2 | Schematic illustration of key components and changes of the ocean and cryosphere, and their linkages in the Earth system through the global exchange of heat, water, and carbon (Section 1.2). Climate change-related effects (increase/decrease indicated by arrows in pictograms) in the ocean 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

17

Consequences in the ocean: Ocean warming (OW)

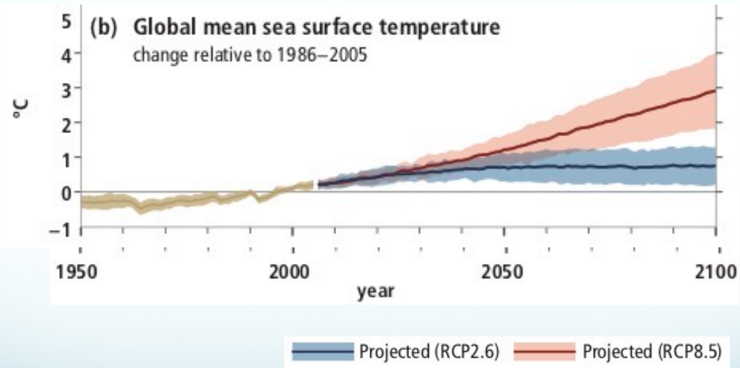


0-700m averaged temperature trend 1971-2010
(IPCC 2013)

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

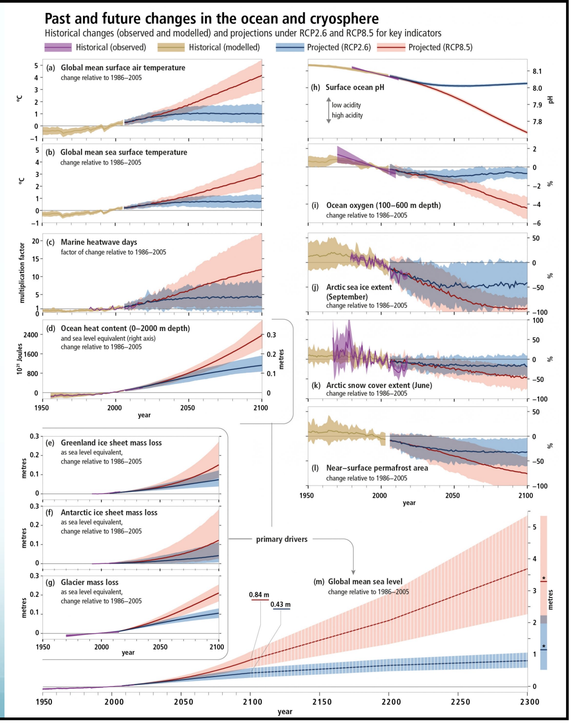
18

Consequences in the ocean: Ocean warming future scenarios



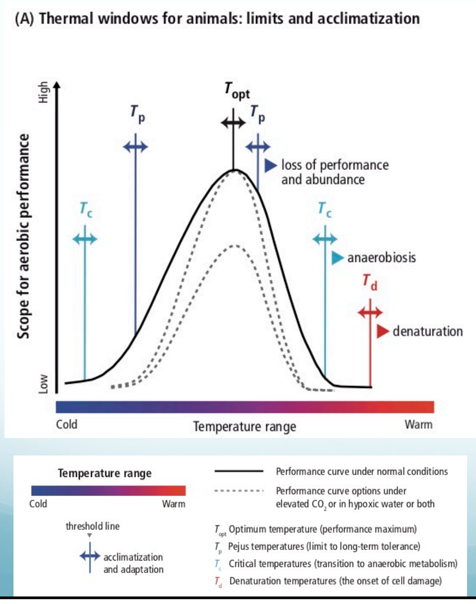
IPCC 2013

19



20

OW: why does it matter?



- 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)*

21

Impact of OW
Extinctions and range shifts

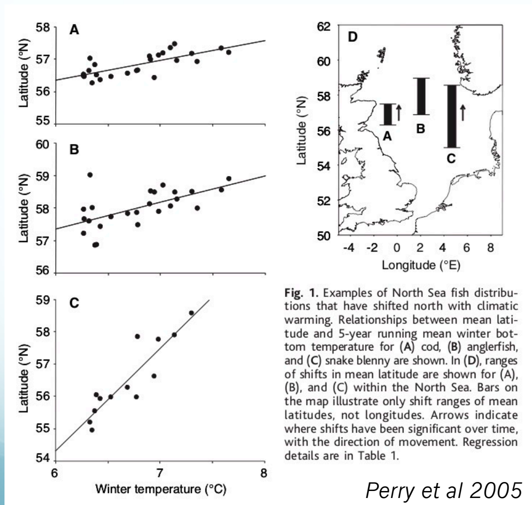


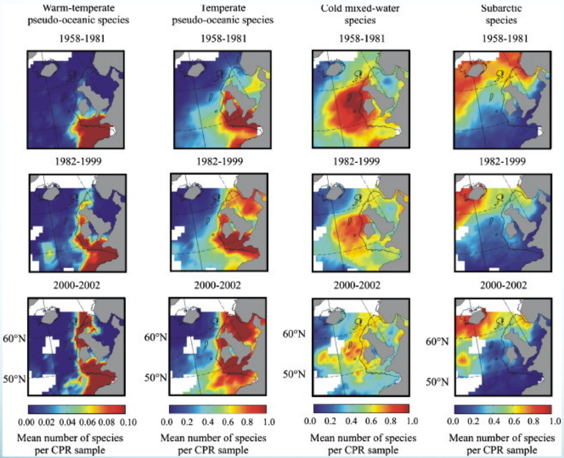
Fig. 1. Examples of North Sea fish distributions that have shifted north with climatic warming. Relationships between mean latitude and 5-year running mean winter bottom temperature for (A) cod, (B) anglerfish, and (C) snake blenny are shown. In (D), ranges of shifts in mean latitude are shown for (A), (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.

Perry et al 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)

22

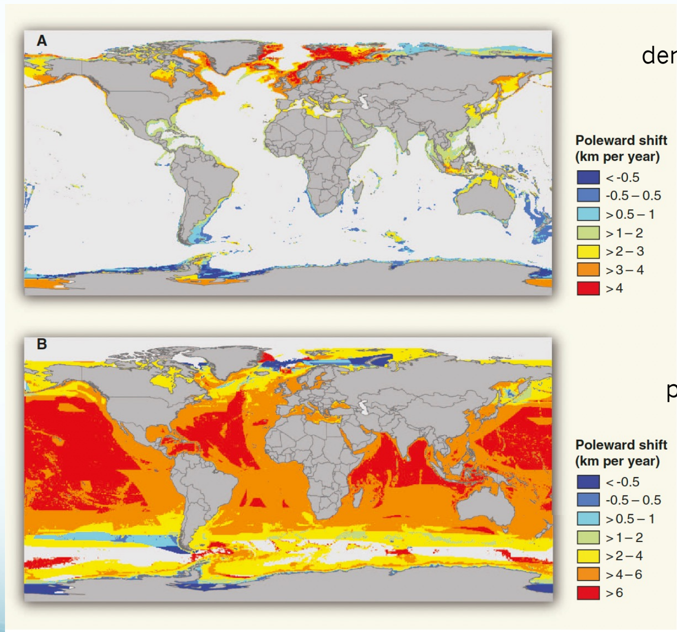
Impact of OW
Extinctions and range shifts



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)

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)

23

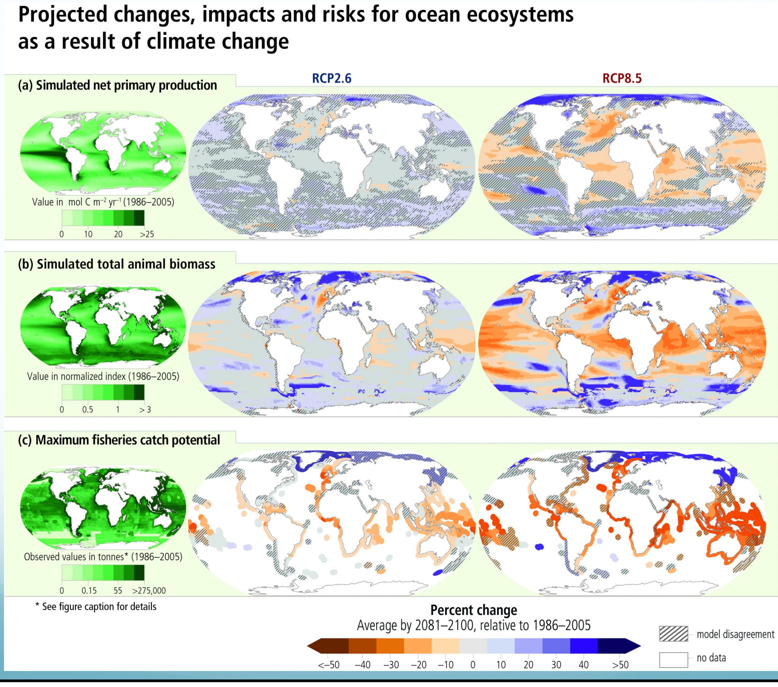


demersal species

pelagic species

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

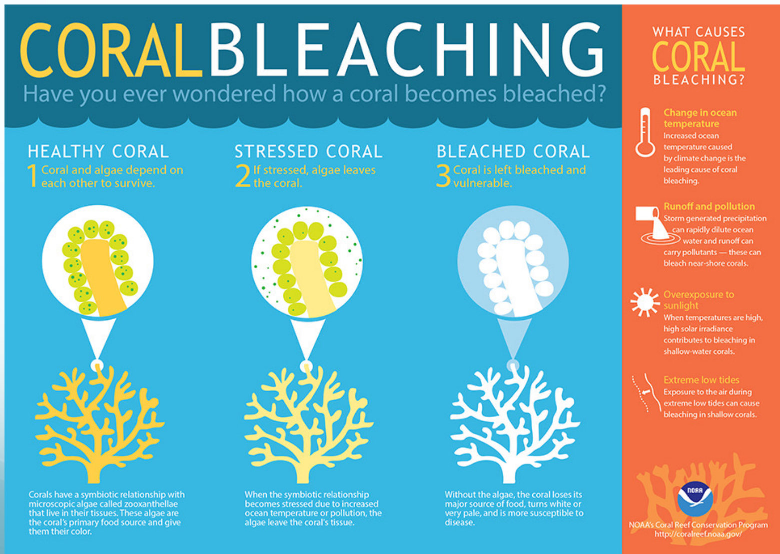
24



IPCC

25

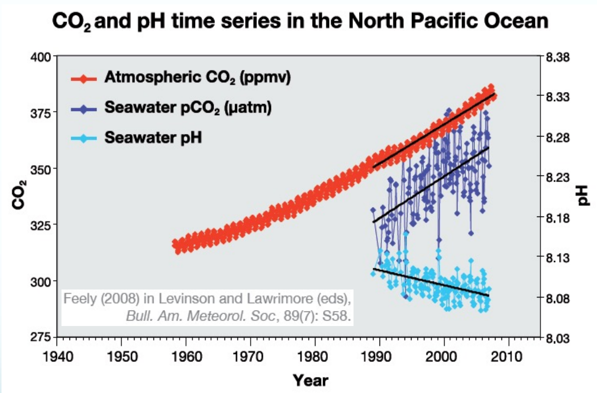
Impact of OW
Extinctions and range shifts



See lecture on coral reefs

26

Consequences in the ocean: Ocean acidification

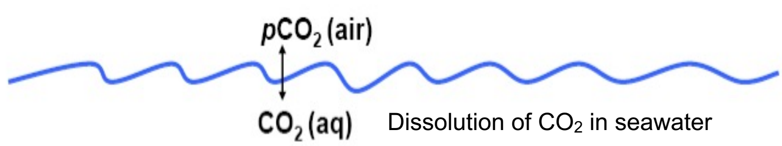


0.1 unit decrease since the Industrial Revolution

27

Ocean acidification (OA): The carbonate system

The ocean has taken up between 20–30% of total anthropogenic CO_2 emissions since the 1980s



Dissolution of CO_2 in seawater

$CO_2(aq) + H_2O \leftrightarrow H_2CO_3$ → Formation of carbonic acid

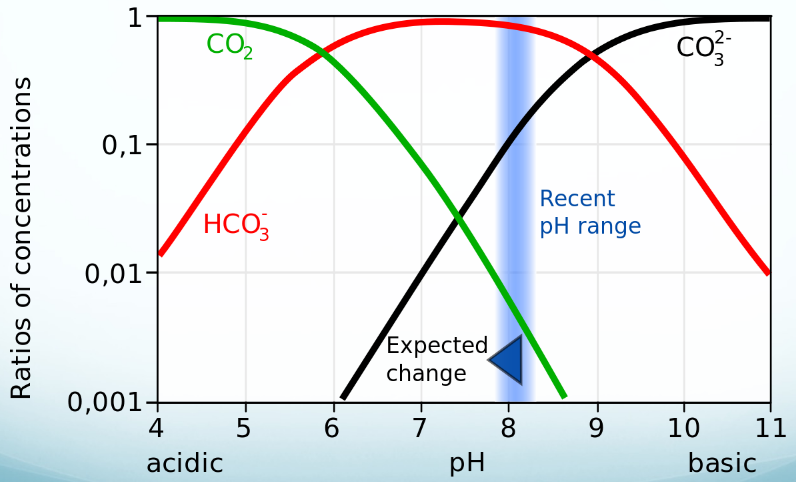
$H_2CO_3 \leftrightarrow HCO_3^- + H^+$ ↑ → Dissociation of carbonic acid

$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$ ↓ ← Decrease of CO_3^{2-} availability

$pH = -\log[H^+]$ ↓ 0.1 pH units → ↑ 30% $[H^+]$

28

Ocean acidification (OA): The carbonate system



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

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Ocean acidification (OA) The carbonate system:

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

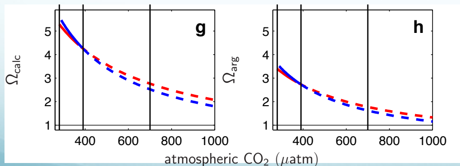
- $\Omega < 1$: dissolution
- $\Omega = 1$: equilibrium
- $\Omega > 1$: precipitation

30

Ocean acidification (OA) The carbonate system:
Saturation state of calcium carbonate (Ω)

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

- OA: $[CO_3^{2-}]_{SW}\downarrow \rightarrow \Omega \downarrow$



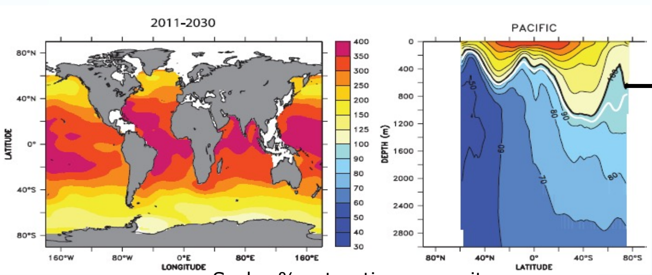
For inorganic $CaCO_3$, in sea water, if

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

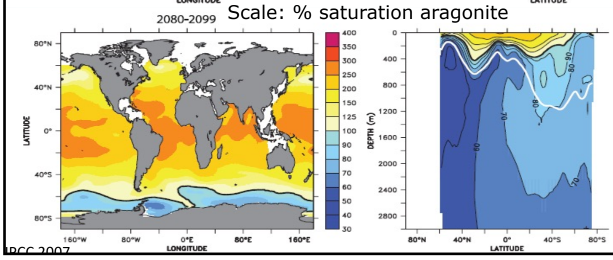
(Schulz et al 2009)

31

Ocean acidification (OA) The carbonate system:
Shoaling of the saturation horizon of calcium carbonate



Scale: % saturation aragonite



Ω=1

Saturation horizon is the depth at which Ω=1

Ω=1

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

IPCC 2007

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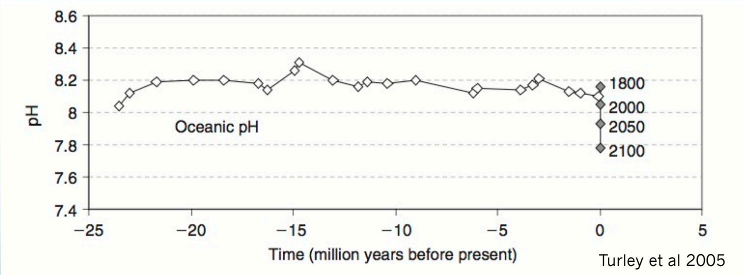
Consequences in the ocean: Ocean acidification

The fastest SW pH ↙ ever observed (Zeebe 2012)



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

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OA: Why does it matter?

- 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 ↑, pCO_2 of extracellular fluids ↑ until the gradient is reestablished (hypercapnia) and, consequently, pH ↓ (acidosis)
  - → deleterious effects, e.g. lower enzyme activities

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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	

CALCIFIERS

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

Kroeker et al. 2013

35

Impact of OA: metabolism

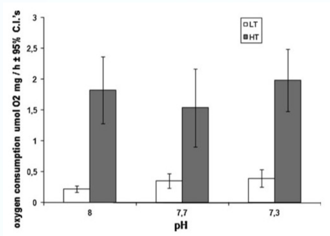

Fig. 1 Mean oxygen uptake rate (μmol O_2 mg/h) standardised by mass, as a proxy of metabolic rate. LT is low temperature (10.5°C), and HT is the high temperature (15°C) exposure. *Error bars* are 95% confidence intervals

Ophiura ophiura, temperate, Wood et al 2010
No significant effect of pH

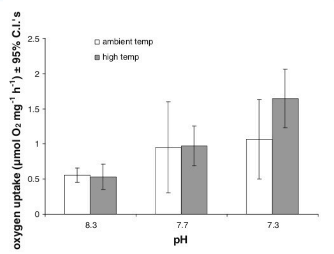

Fig. 1 Mean rates of oxygen uptake of *Ophiocten sericeum* at the three pH and two temperature treatments ±95% confidence intervals. Amputation data pooled as ANOVA showed no significant difference between treatments $N = 30$

Ophiocten sericeum, arctic, Wood et al 2011
Significant effect of pH

Effect on respiration differs according to species

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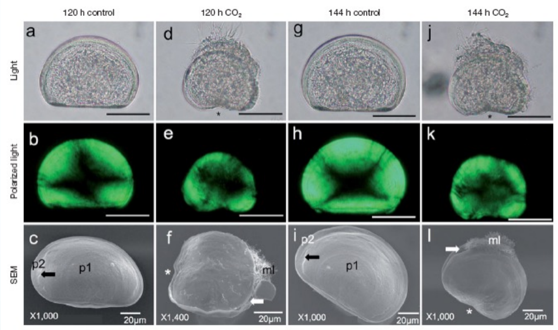
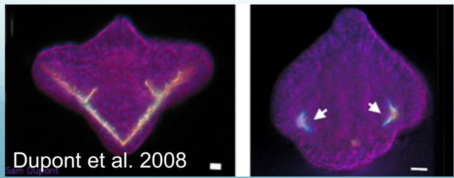
Impact of OA: reproduction

Larval stages are very sensitive to OA:



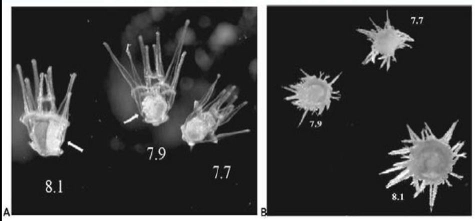
Early development of *Mytilus galloprovincialis.* Morphology of larvae incubated for 120h and 144h control (380ppm; pH=8.13) or in CO_2 seawater (2000ppm; pH=7.42).



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.

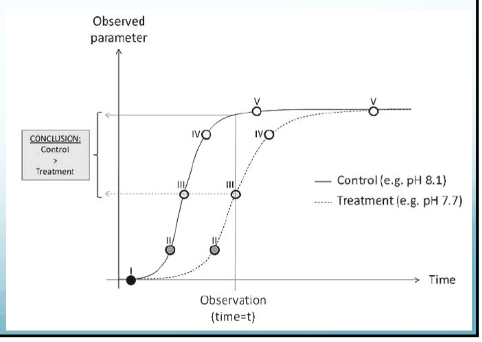
37

Impact of OA: reproduction



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

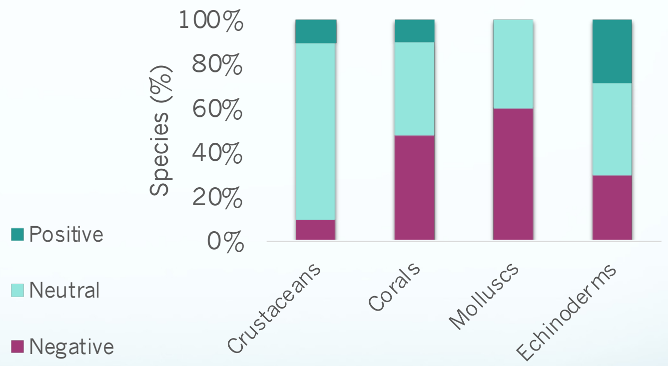
A) Late pluteus larvae - 21 days
B) Juveniles - 50 days



Relation between time and stage of development

38

Impact of OA: growth and calcification



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

Wittman & Pörtner 2013

39

Impact of OA: growth and calcification

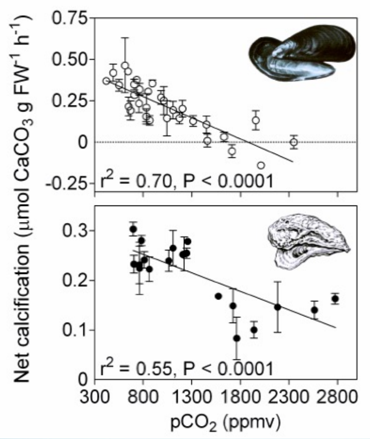
<u>The main calcifiers in marine environments</u>:

- 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)

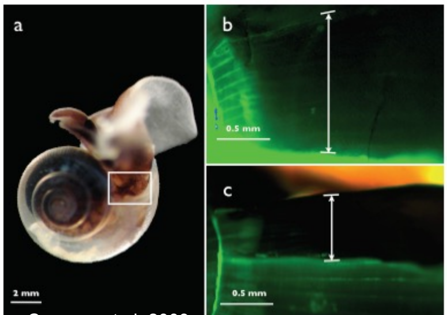
* Produce most of biogenic carbonate precipitated in the open oceans

40

Impact of OA: growth and calcification



Gazeau et al. 2007



Comeau et al. 2009

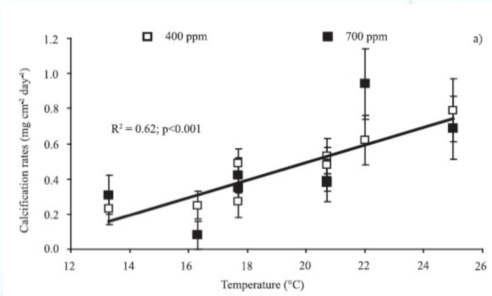
Decrease of calcification rates of *Mytilus edulis, Crassostrea gigas* and arctic pteropods under high pCO_2

Most bivalves and gastropods show a decrease of their calcification rates when exposed to lower pH seawaters (i.e. higher pCO_2 and lower Ω)

Impact of OA: growth and calcification

Temperate corals

Cladocora caespitosa

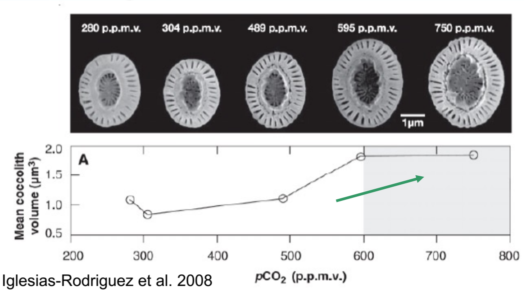


The lack of sensitivity of **temperate corals** to high-pCO2 levels might be due to their **slow growth rates**, which seem to be more dependent on temperature than on the saturation state of calcium carbonate (in the range predicted for the end of the century)

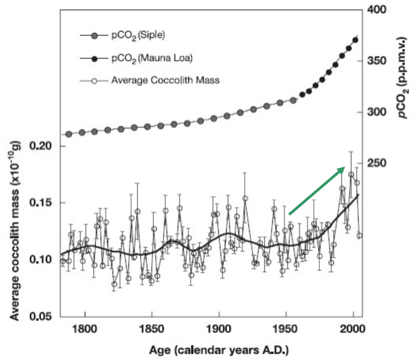
Rodolfo-Metalpa et al. 2009

Impact of OA: growth and calcification

Coccolithophores



Iglesias-Rodriguez et al. 2008



Calcification increment of *Emiliania huxleyi* at higher CO_2 conditions

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

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Impact of OA

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

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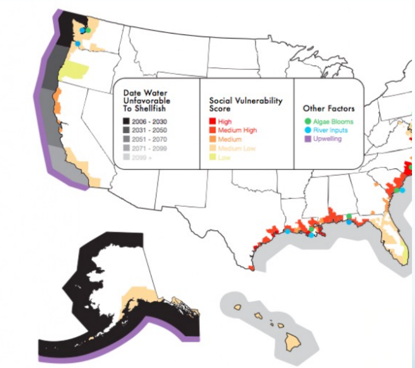
Impact of OA: fisheries

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.

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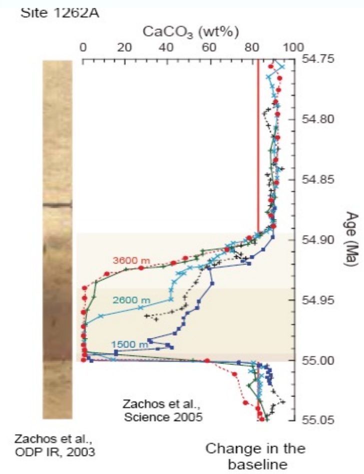
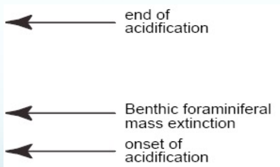
Impact of OA: Lessons from the past

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

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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”

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Impact of global change in the ocean

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

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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**

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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

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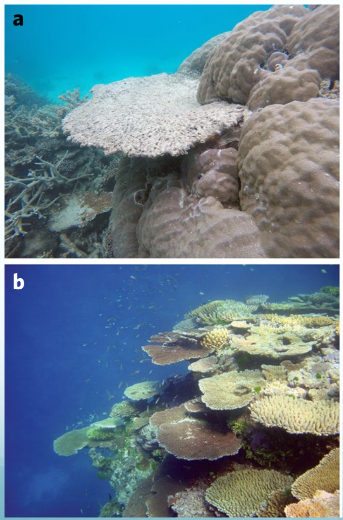
Impact of global change in the ocean: Acclimation and adaptation



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)

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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/

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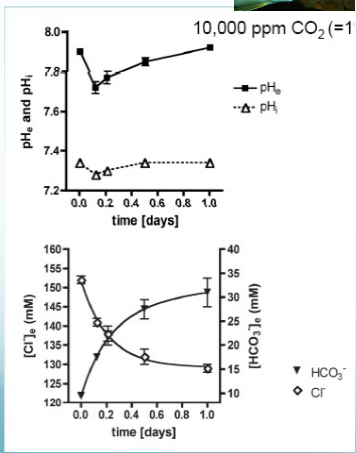
How do organisms cope with OA?

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^-)

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Impact of OA: growth and calcification

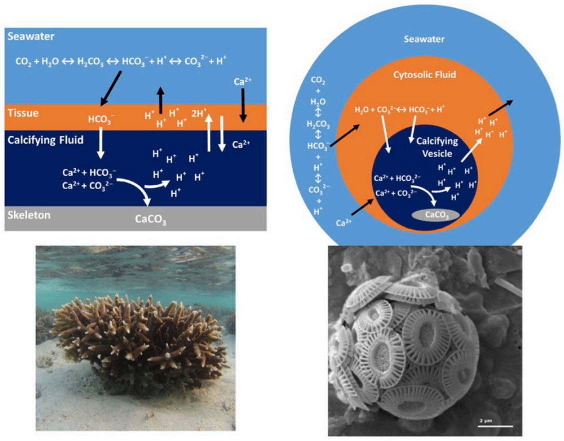

Figure 1. A simplified schematic demonstrating the internal build-up of protons during the calcification process in corals and coccolithophores. Corals (left panel) must dissipate excess protons produced by calcification through a boundary layer and into the water column as proposed by Jokiel (2011b). 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.

Cyronak et al 2015

Ω is not the real problem:

- HCO_3^- is the required ion for calcification (not CO_3^{2-})
- Calcification produces H^+: $Ca^{2+} + HCO_3^- \leftrightarrow CaCO_3 + H^+$
- H^+ has to be removed from the calcifying site ➔ energetic cost
- Ω can be used as a proxy because it is linked to $[H^+]$

$$\frac{[HCO_3^-]}{[H^+]} = \frac{\Omega_{CaCO_3} K^*_{sp}}{[Ca^{2+}]\, K^*_2}.$$

Bach 2015

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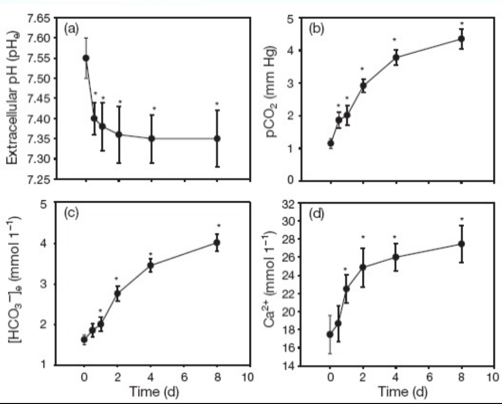
How do organisms cope with OA?

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..

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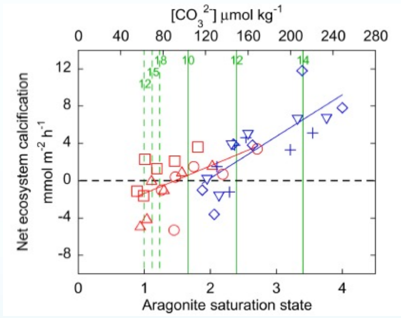
Impact of OA: growth and calcification

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.

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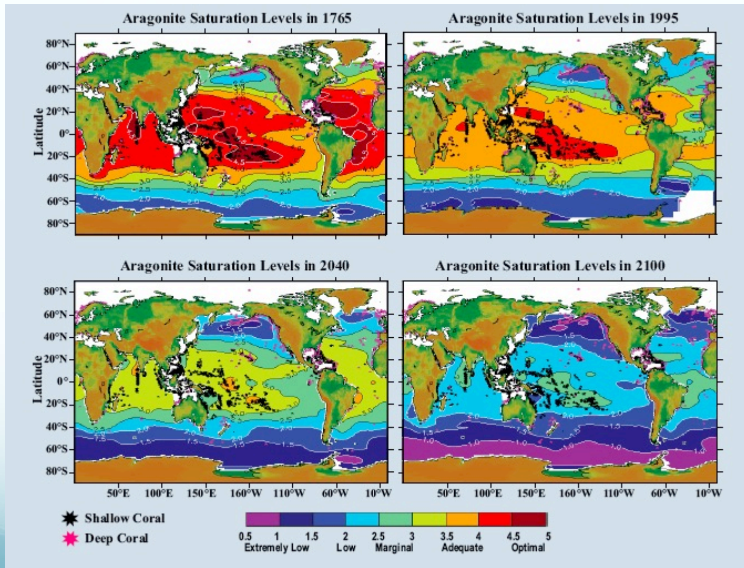
Impact of OA: growth and calcification



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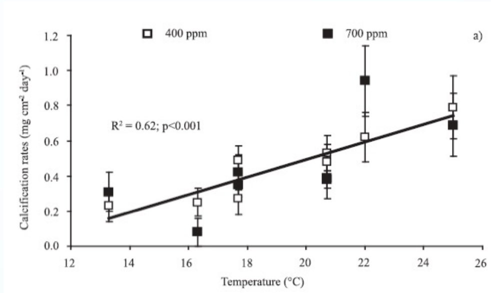
Impact of OA: growth and calcification

Temperate corals



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Rodolfo-Metalpa et al. 2009

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