Rechauffement et acidification des océans

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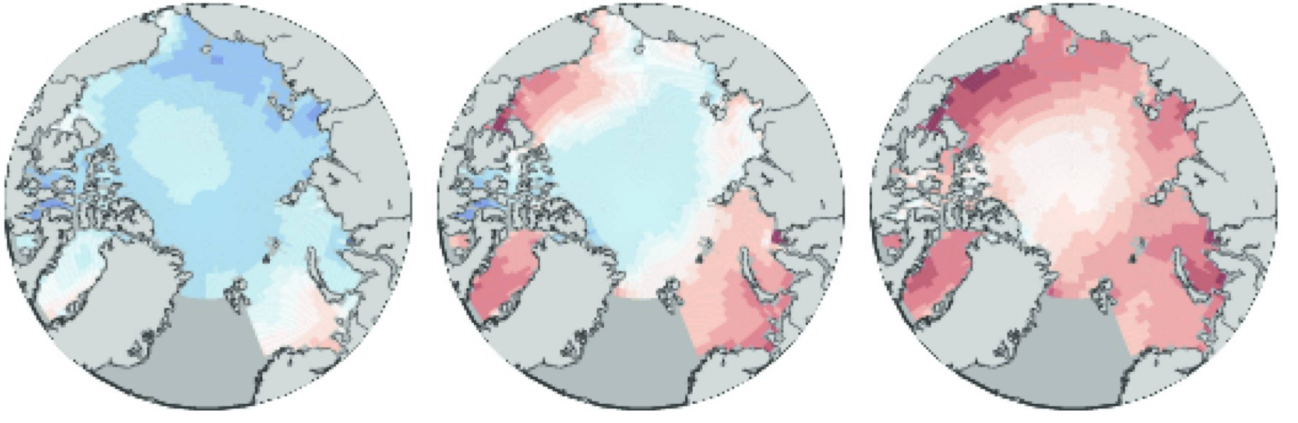
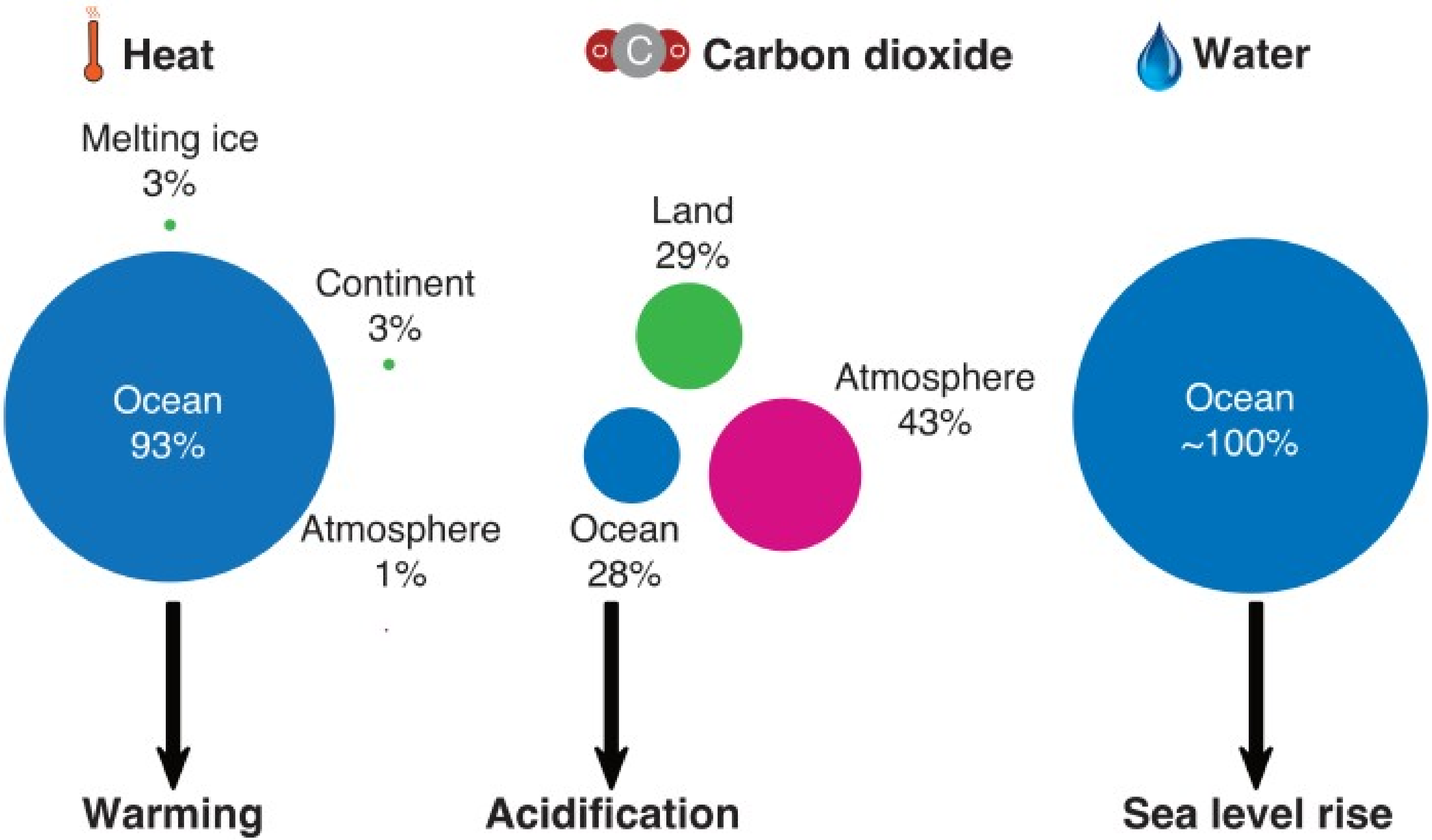
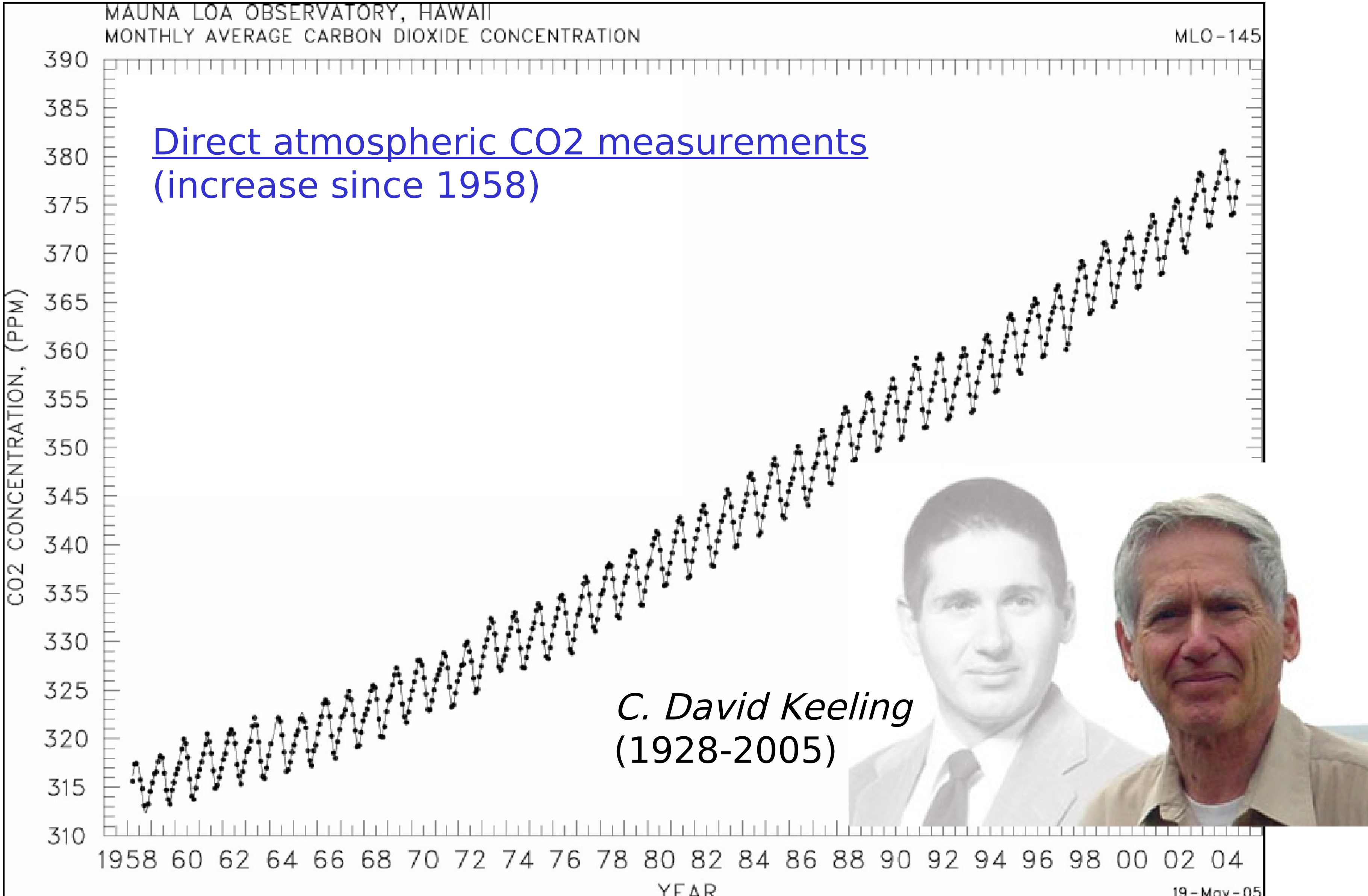


The ocean is influenced by many factors



Gattuso *et al.* 2015

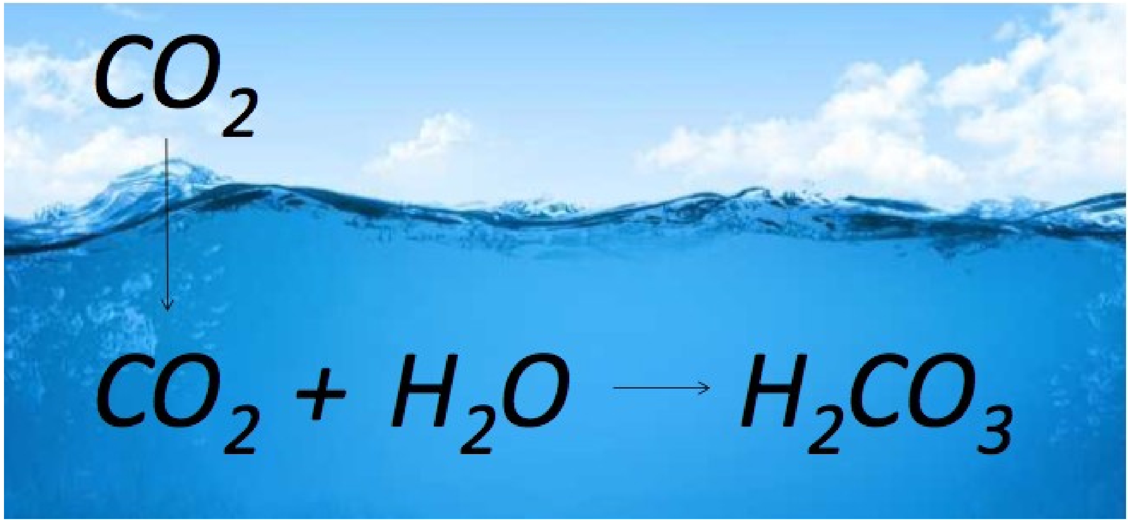
The atmospheric CO_2 increase is well documented



[Direct atmospheric CO2 measurements]
(increase since 1958)

C. David Keeling
(1928-2005)

More atmospheric CO_2 means increased ocean acidity



Schematic: Sam Dupont, University of Gothenburg

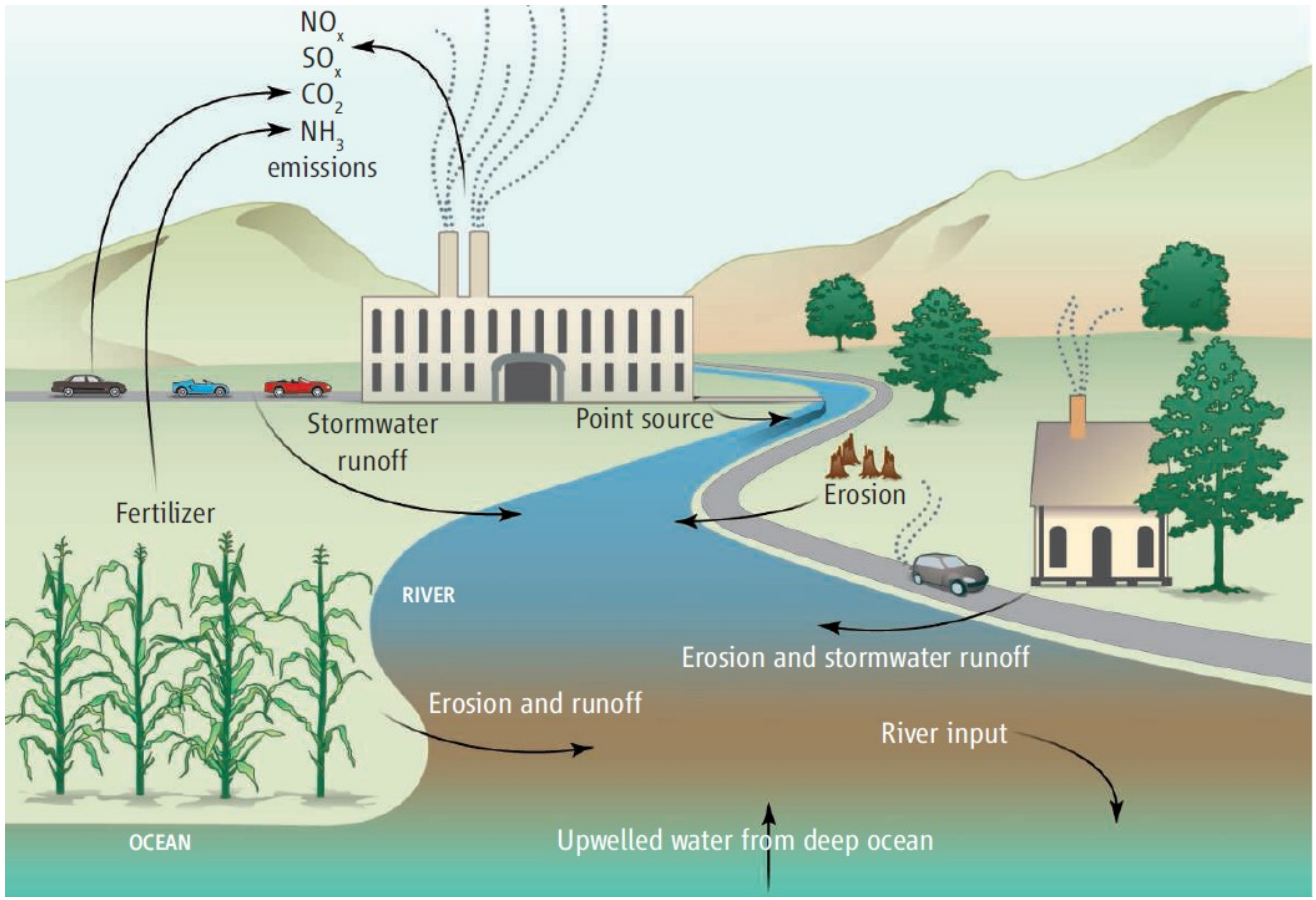
Some numbers:

4 kg CO_2 per day **per person** added to the ocean

+30% acidity in surface ocean since start of industrial era

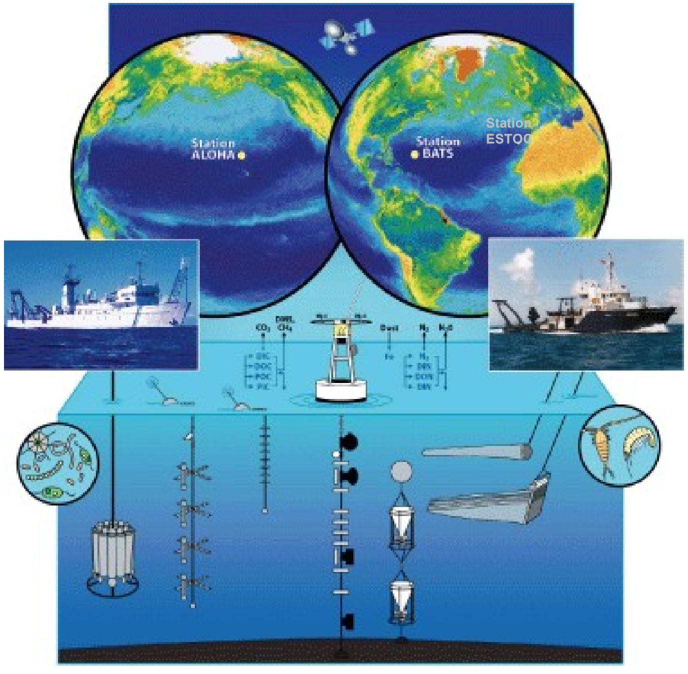
+100 to 200% by 2100

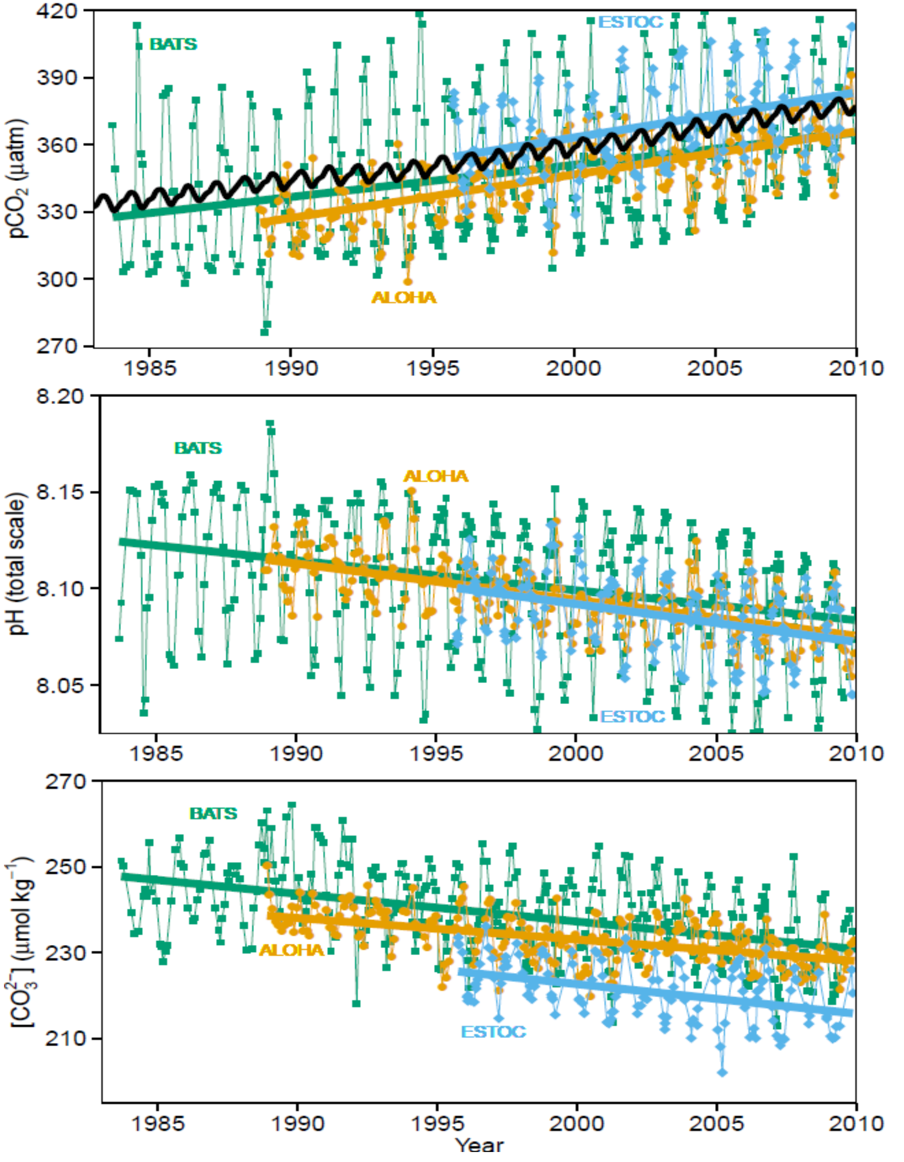
Ocean acidification is largely from atmospheric CO_2 increase but other factors may also affect coastal regions



Kelly et al (2011, Science)

Change in pH from ocean acidification is already measurable



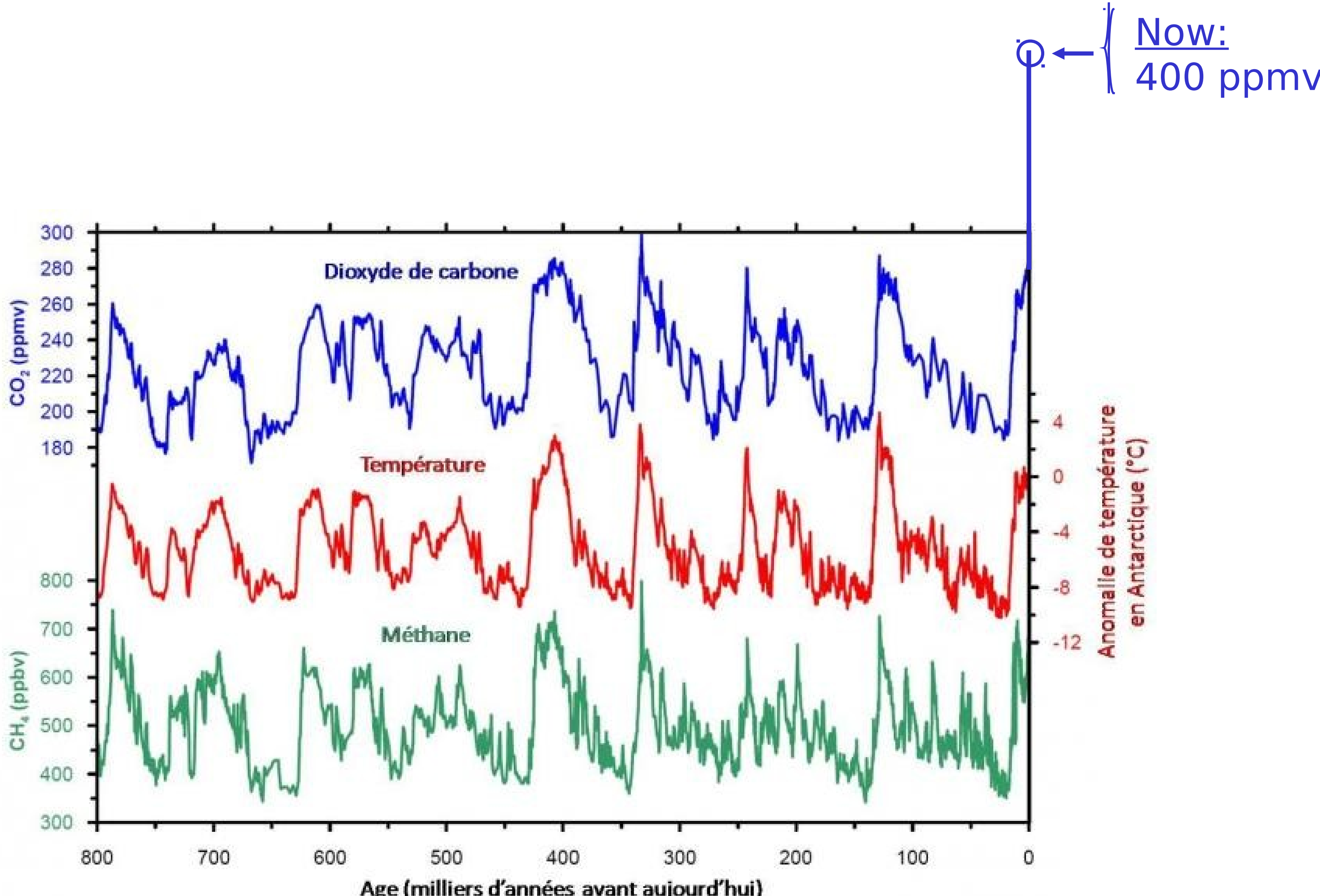


<u>Data</u>:

Bates (2007)
Dore et al. (2009)
Santana-Casiano et al. (2007)
Gonzàles-Dàvila et al. (2010)

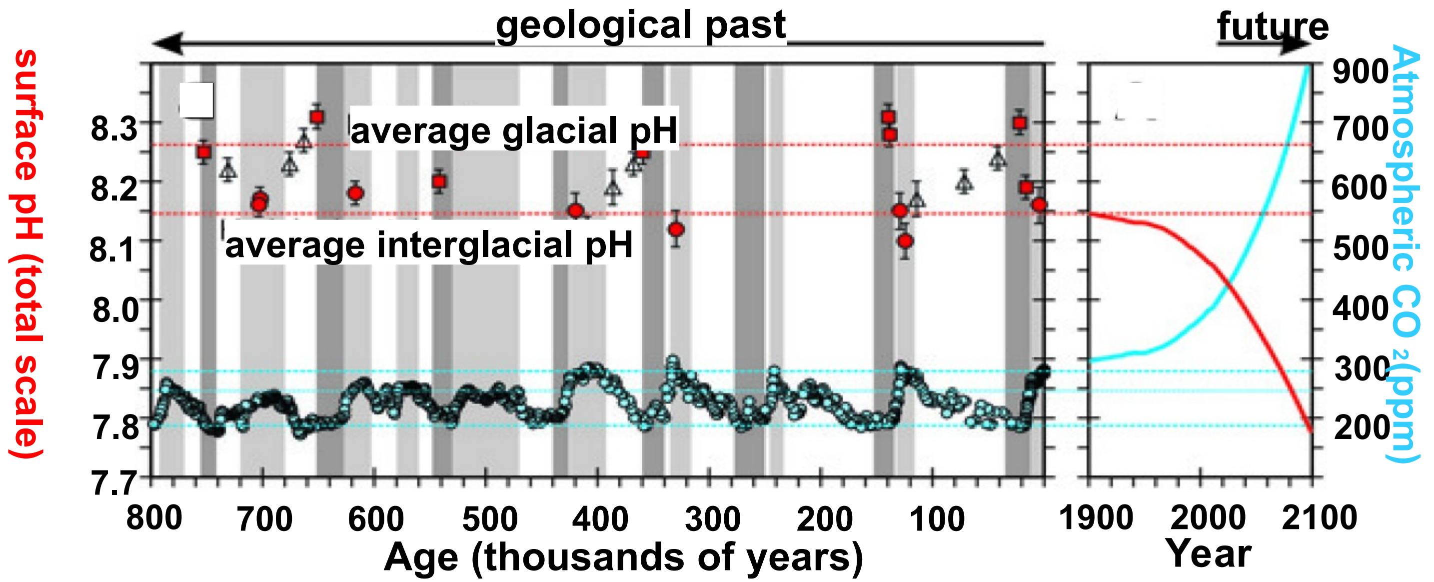
IPCC AR5 WG1 Report (2013)

Today's atmospheric CO_2 level appears as instantaneous spike relative to glacial-interglacial variations



Luthi et al. (2008, Nature)

Today's rate of ocean acidfication is unprecedented

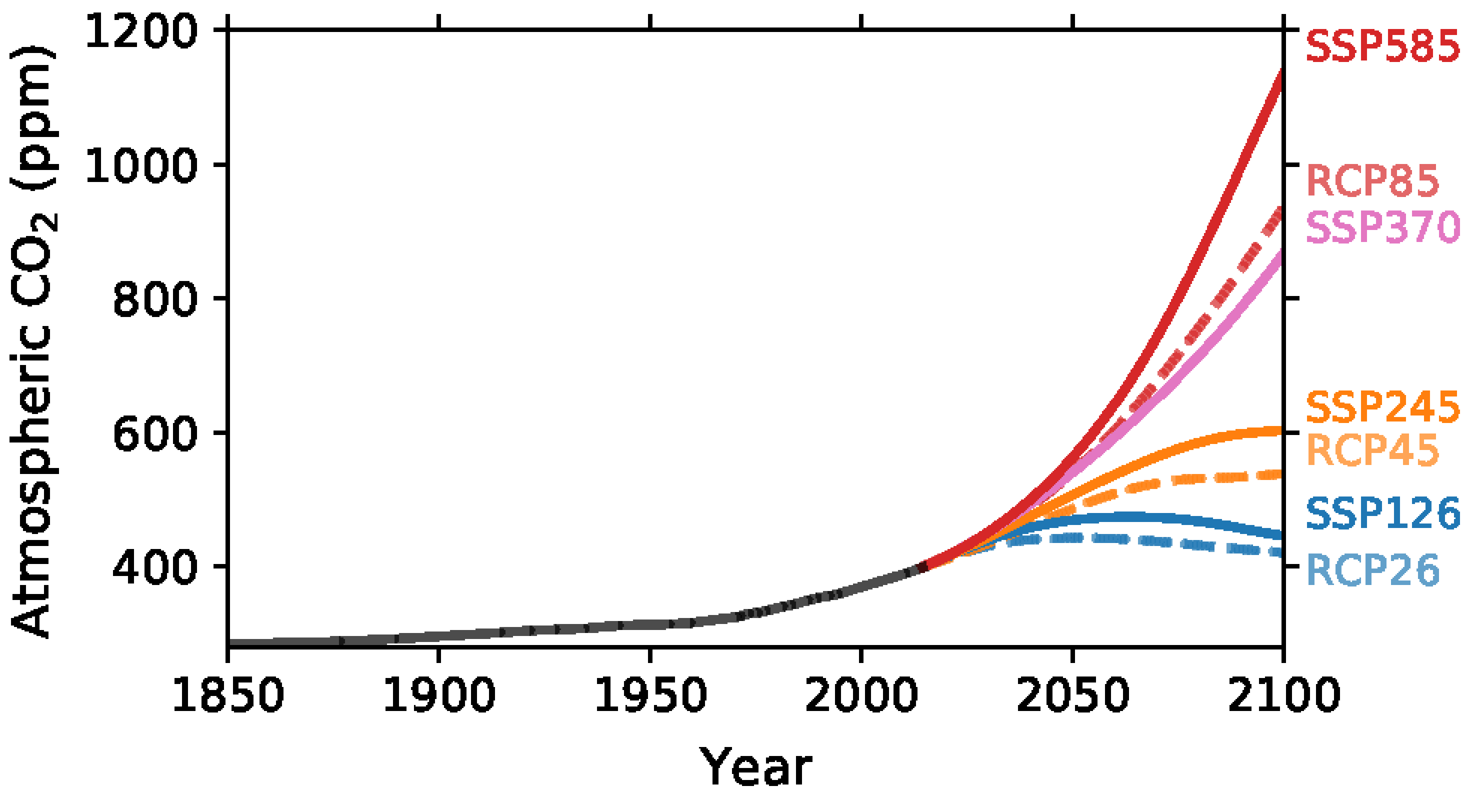


Barker and Ridgwell (2012)

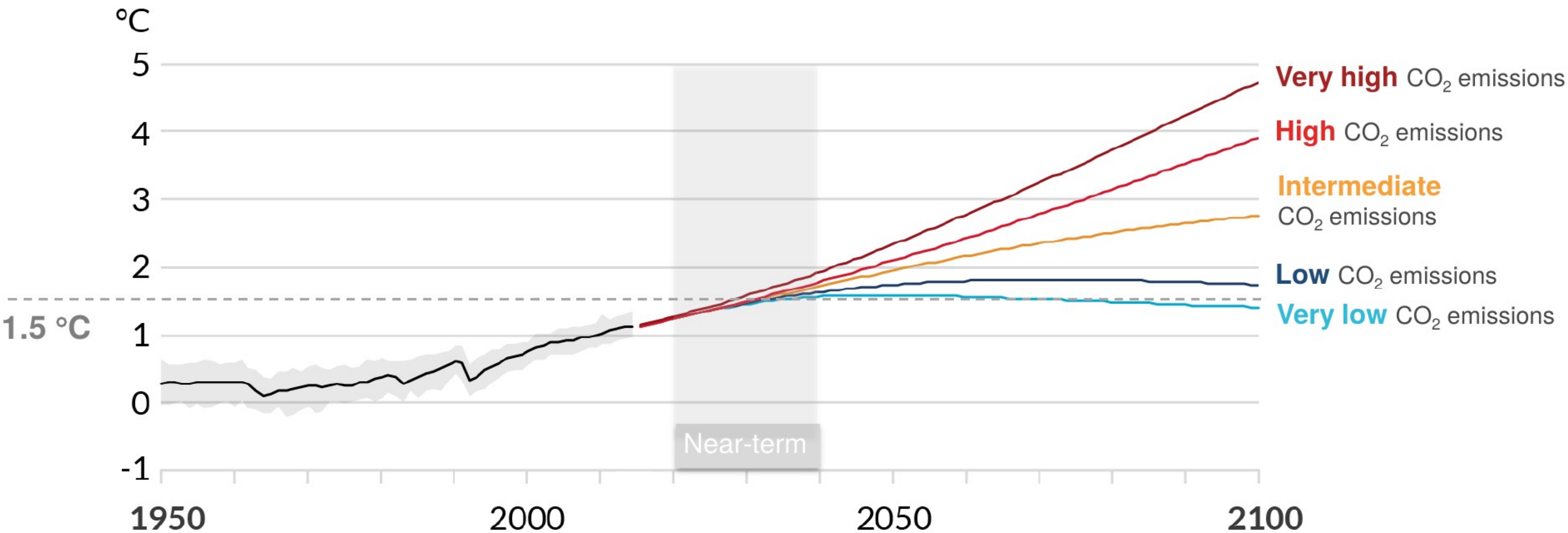
Current change:

- overwhelms natural variations (last 800 000 years)
- 10x faster than natural event (55 million years ago)
- unprecedented (over last 300 million of years)
- 26% increase in acidity (H^+) during industrial era
- 100% increase (or more) projected by 2100

Atmospheric CO_2 scenarios used in projections describe very different possible futures



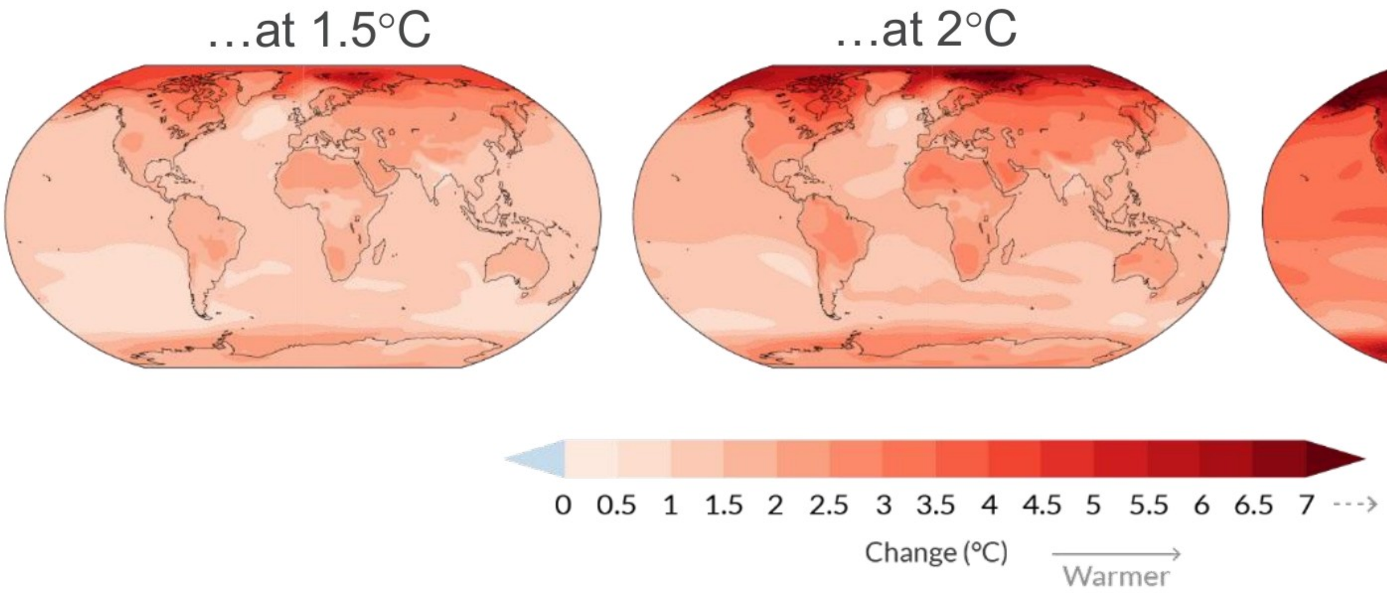
Future emissions cause future additional warming



IPCC AR6 WG1 report

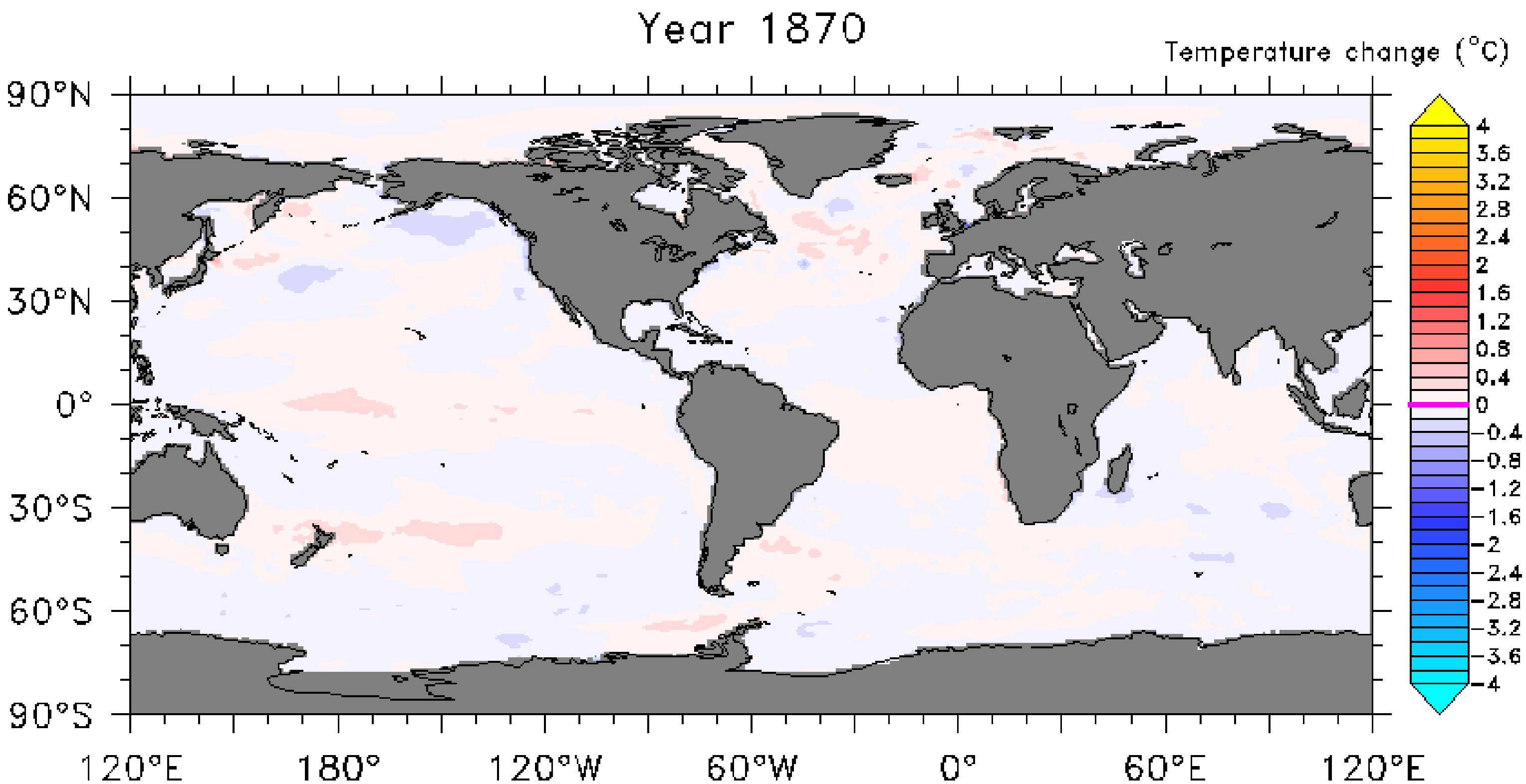
Surface air temperature warms less over the ocean

Simulated changes…



IPCC AR6 WG1 report

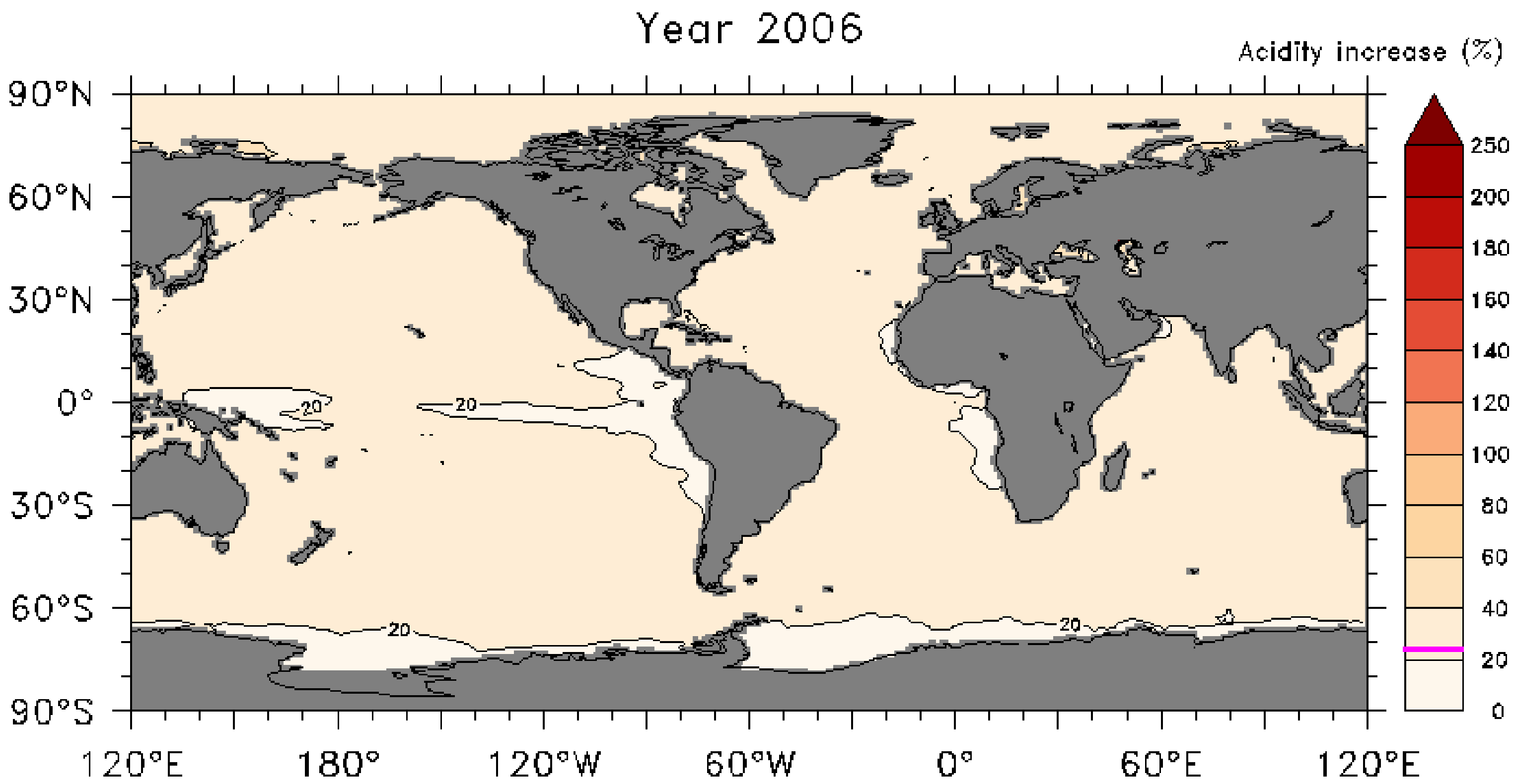
The sea surface warms everywhere



Animation
Copyright: James C. Orr

Projections (IPCC AR5 WG1, 2013)
scenario RCP8.5

Surface ocean acidity increases everywhere

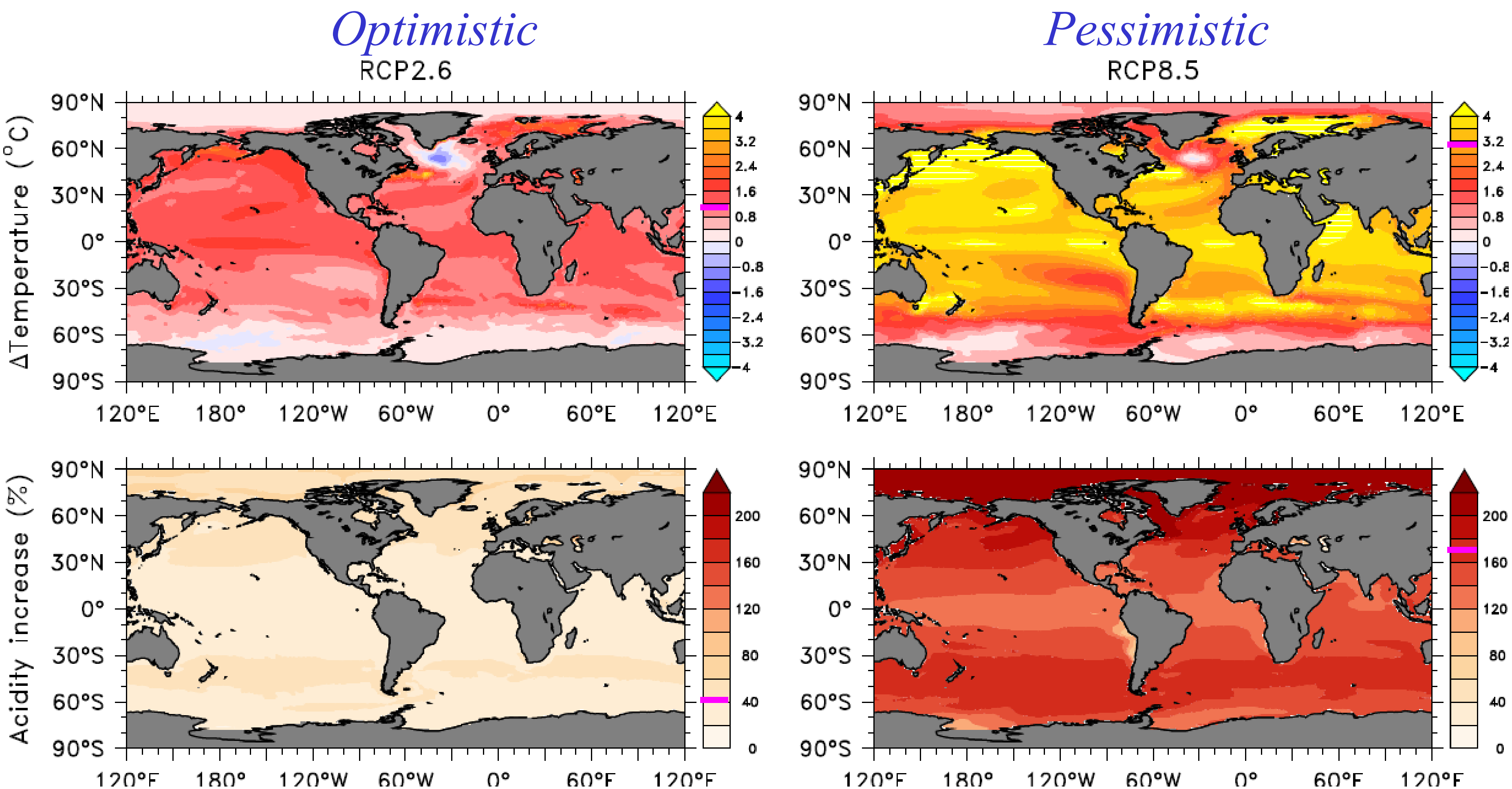


Animation
Copyright: James C. Orr

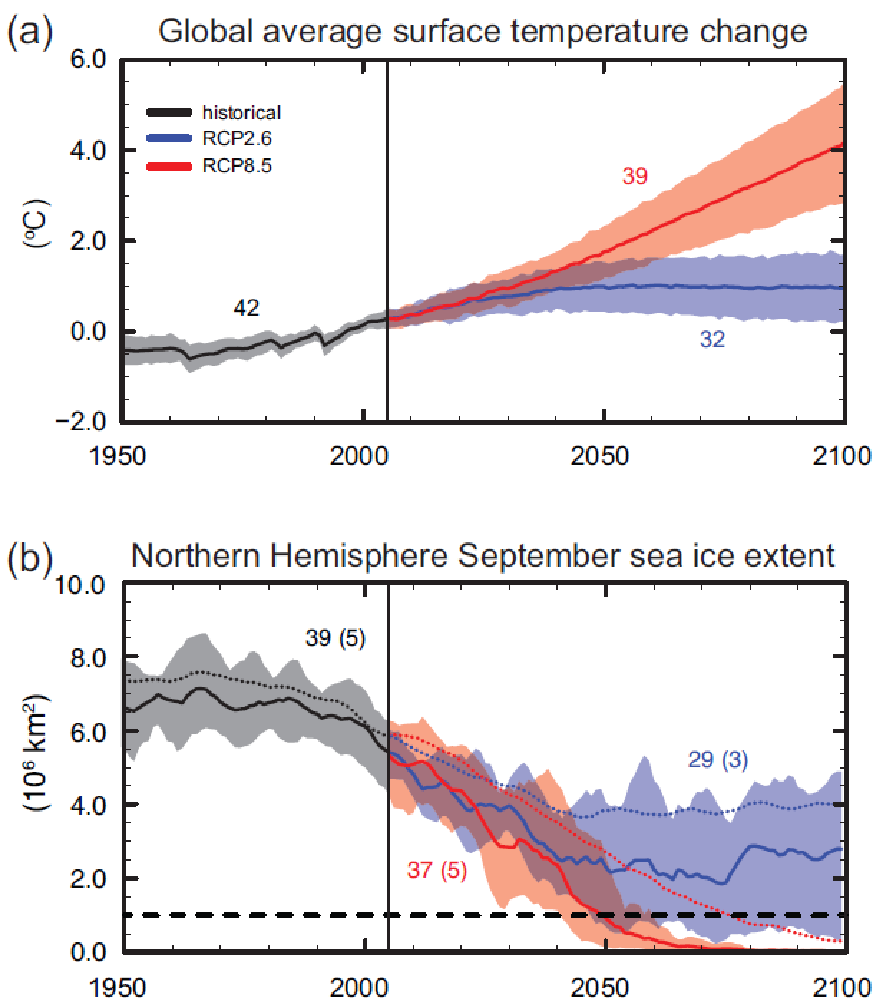
Projections (IPCC, AR5 WG1, 2013)
scenario RCP8.5

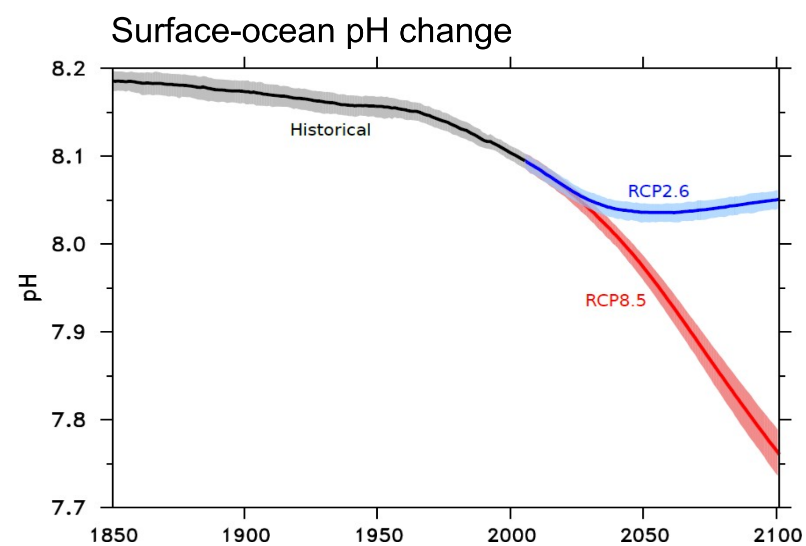
see also Bopp et al. (2013, Biogeosciences)
Kwiatkowski et al. (2013, Biogeosciences)

Large regional differences, but the intensity depends on us



Differences between models is less than between scenarios, especially for pH

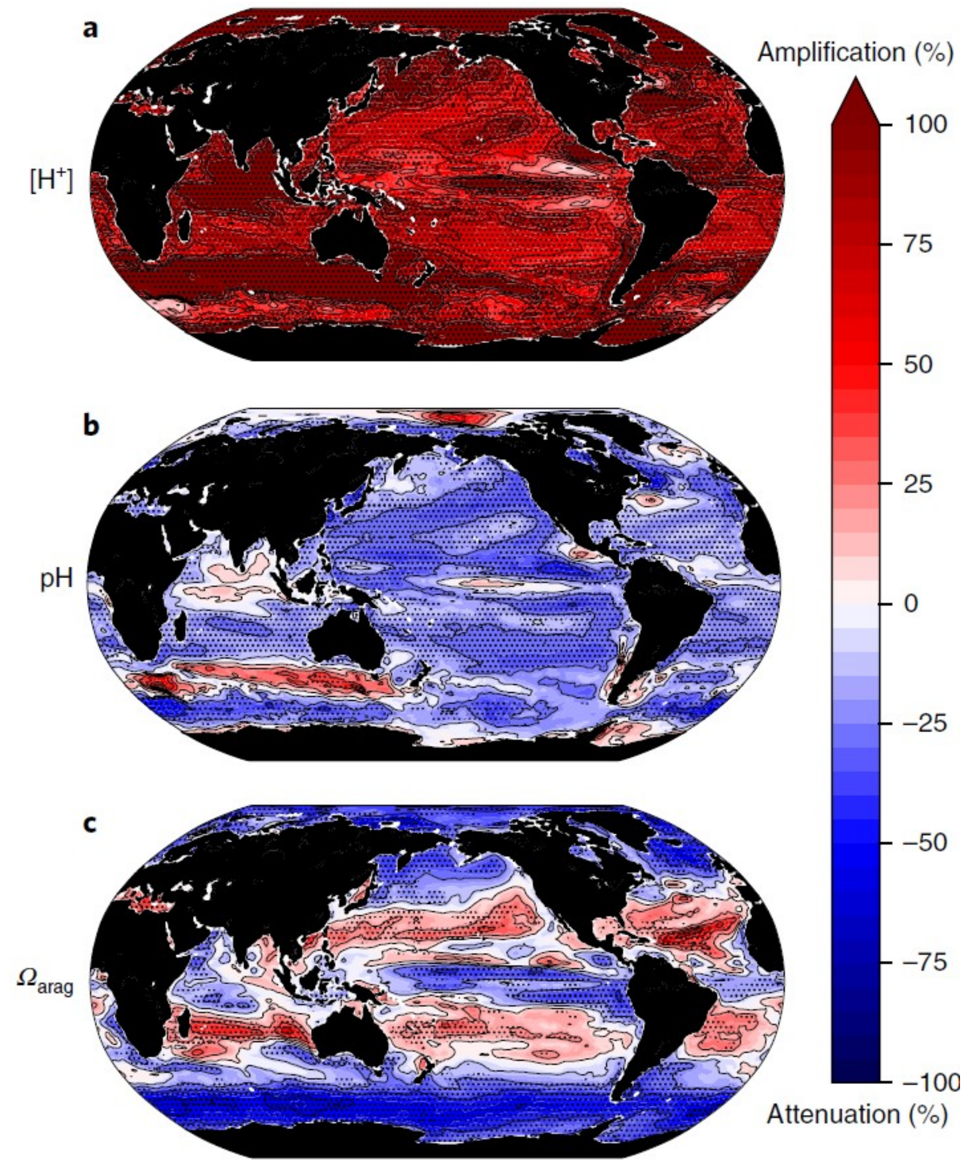




IPCC AR5 WG1 Report (2013)

There is an increase not only in annual average acidity, but also the seasonal amplitude, doubling by 2100

21st century increase
in seasonal amplitude
(summer–winter difference)



Kwiatkowski & Orr (2018, Nat. Clim. Change)

The formation and dissolution of $CaCO_3$ depend on the *saturation state*

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

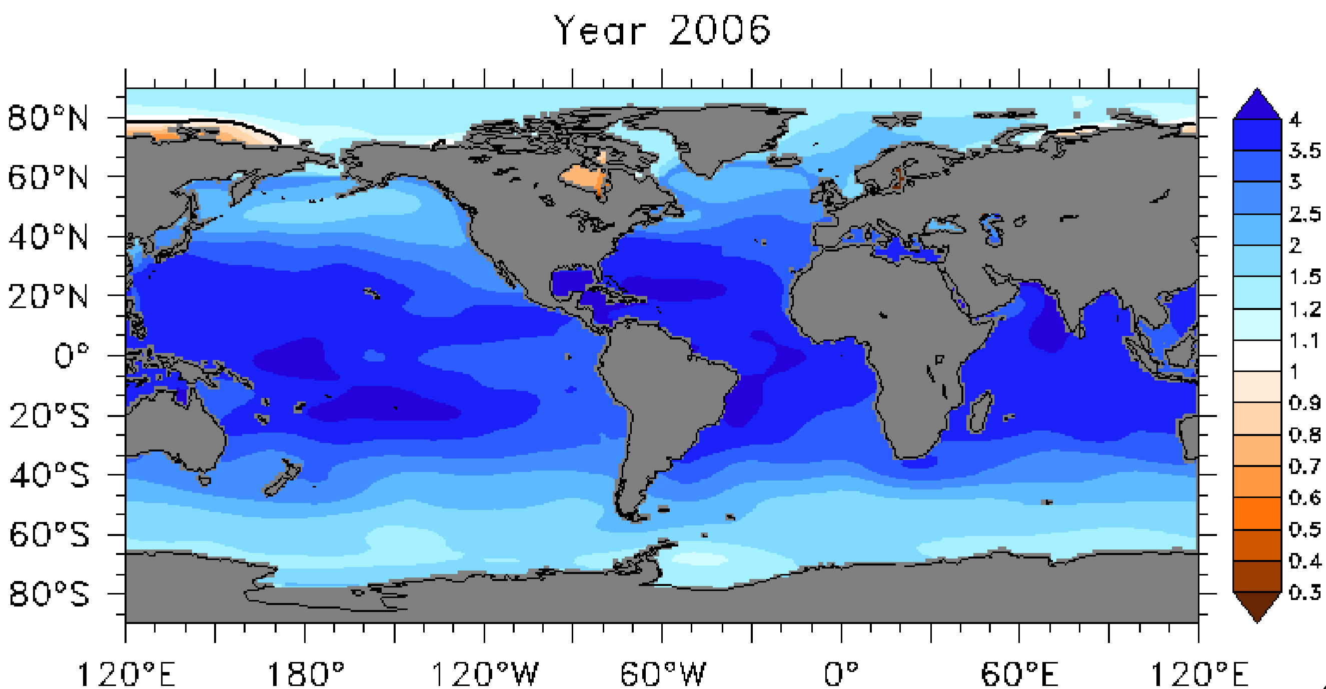
$$\Omega = [Ca^{2+}][CO_3^{2-}] / K_{sp}^{*}$$

$$K_{sp}^{*} = [Ca^{2+}]_{sat}[CO_3^{2-}]_{sat}$$

$$CO_2 + CO_3^{2-} + H_2O \longrightarrow 2\ HCO_3^{-}$$

The *corrosivity* of surface seawater increases this century

Seawater corrosivity to aragonite, a $CaCO_3$ mineral that certain organisms secrete to build their skeletal material (corals, shell builders)



Corrosivity to aragonite (when < 1, l'aragonite dissolves)

Animation Copyright: James C. Orr

Projections summarized for IPCC (AR5 WG1, 2013)

These corrosive conditions dissolve shells of sea butterflies

Movie: Brad Seibel, University of Rhode Island

Sea butterfly shells ($CaCO_3$) exposed to corrosive conditions expected by 2100

Orr et al. (2005)

Fabry et al. (2008)

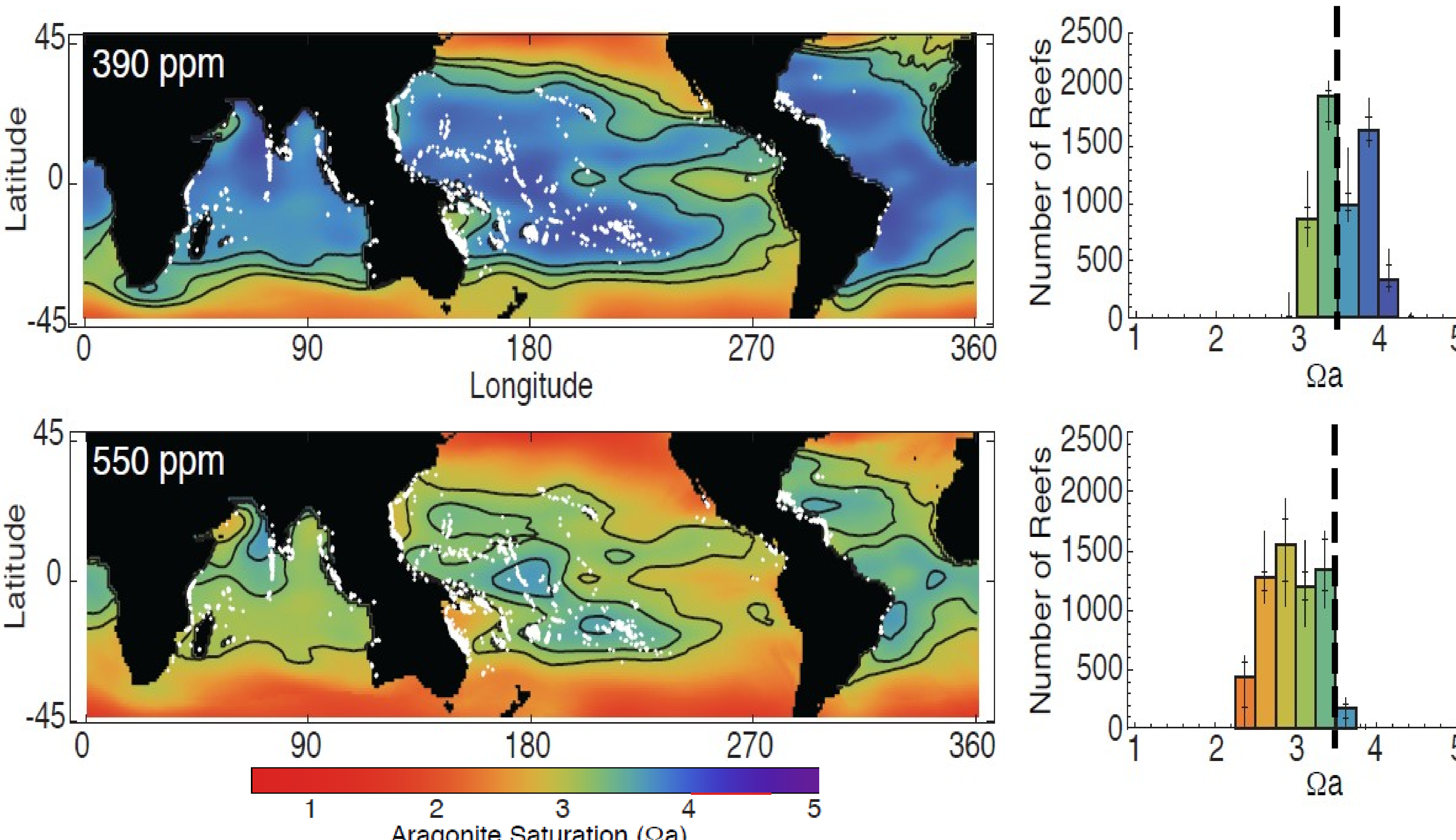
Comeau et al. (2009; 2011; 2012)

Lischka et al. (2011); Lischka & Riebesell (2012)

Bednarsek et al. (2012)

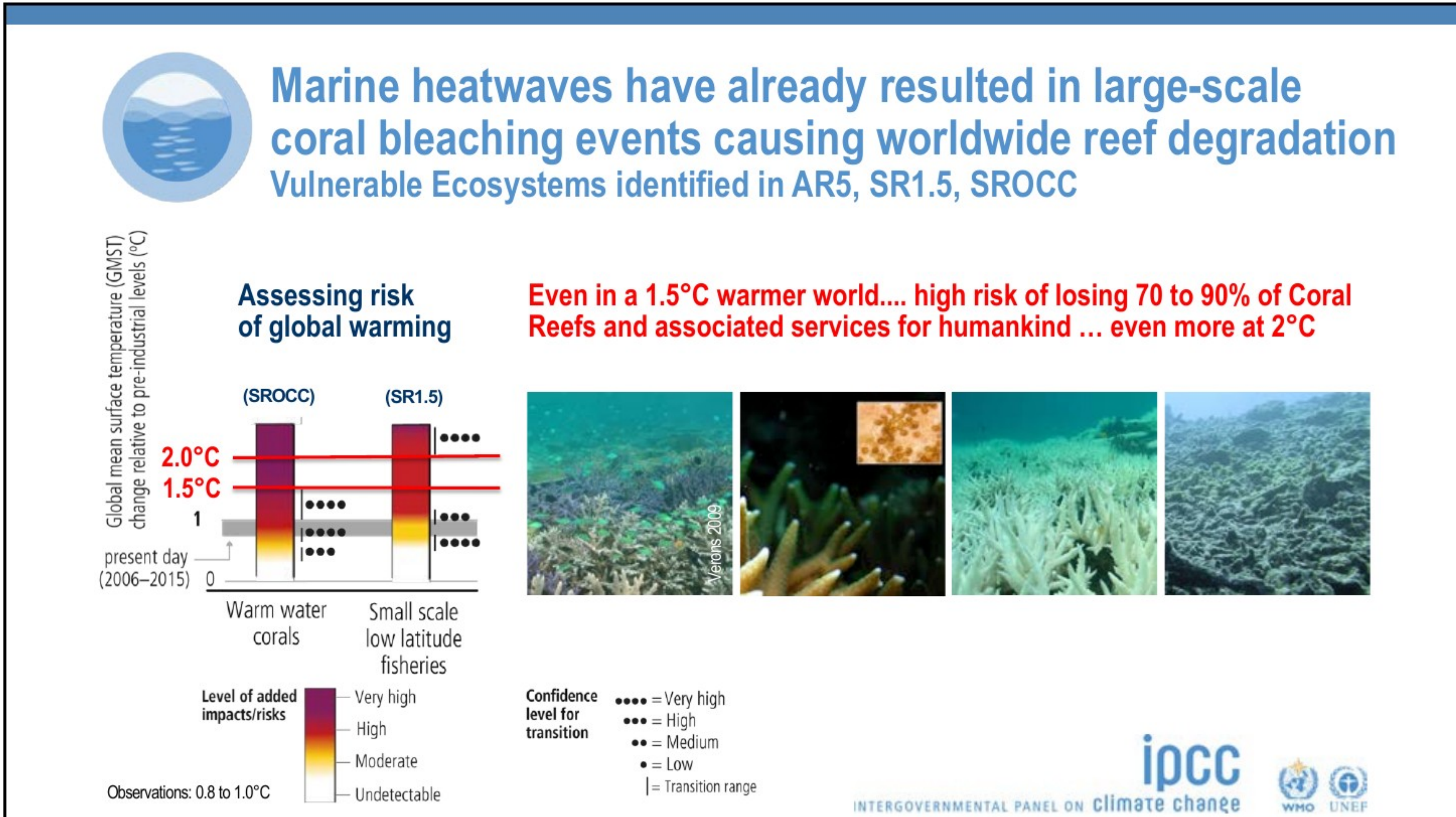
Image: Victoria Fabry, California State University San Marcos

Most tropical corals projected to be exposed to unsustainable chemical conditions by mid-century (e.g., Ω_{arag} < 3.0)



Ricke et al. 2013 (Env. Res. Lett.)

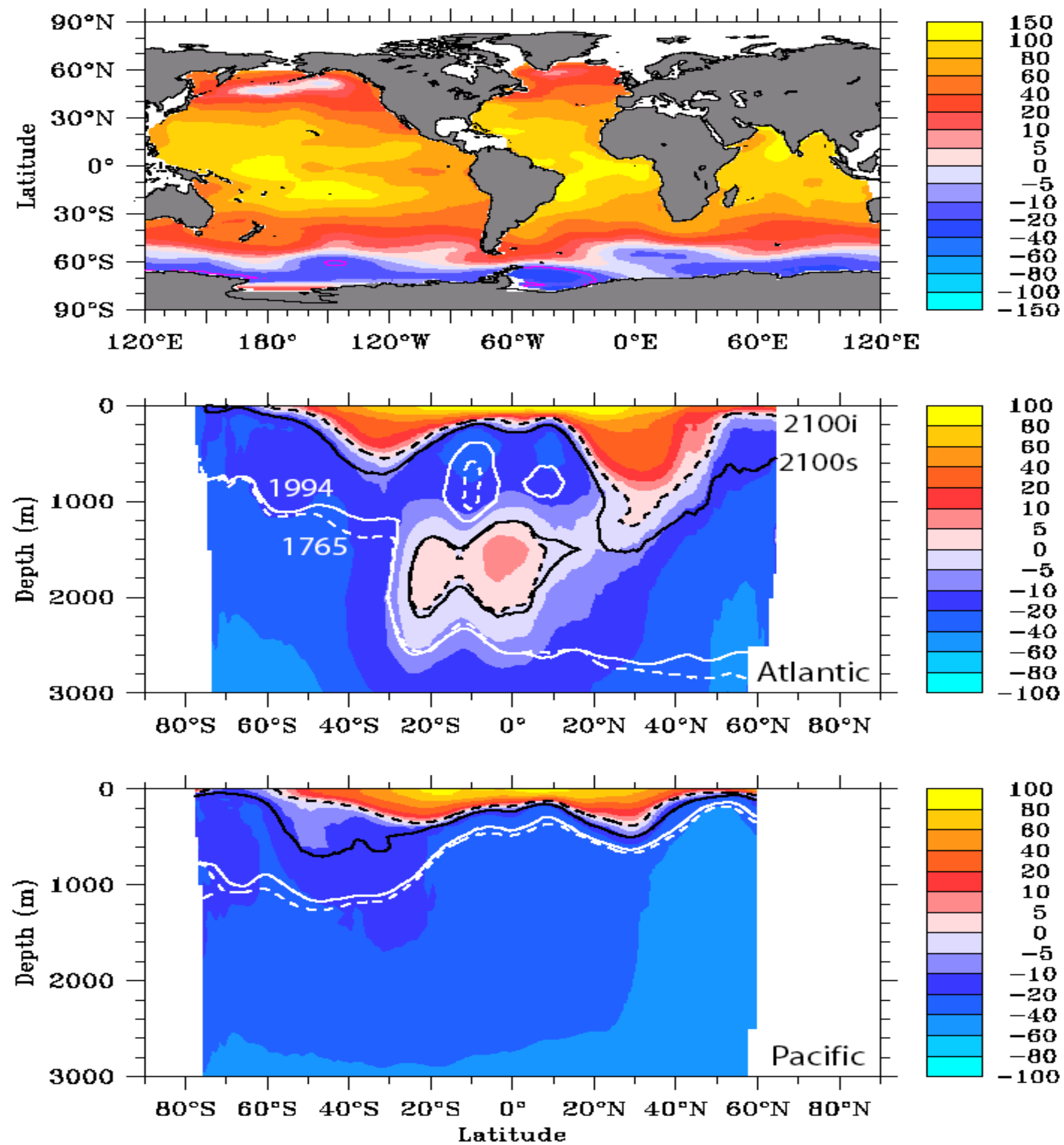
Analysis of 13 Earth System Models (CMIP5)



IPCC SROCC report

By 2100 there are large changes in subsurface corrosivity to $CaCO_3$

- Surface undersaturation
  - Southern Ocean
  - Subarctic Pacific
- Shoaling of aragonite saturation horizon
  - S. Ocean by 1000 m
  - N. Atlantic by 3000 m



Orr et al. 2005 (Nature)

Most cold-water corals will be exposed to corrosive conditions during this century

<u>Deep, cold-water corals:</u>

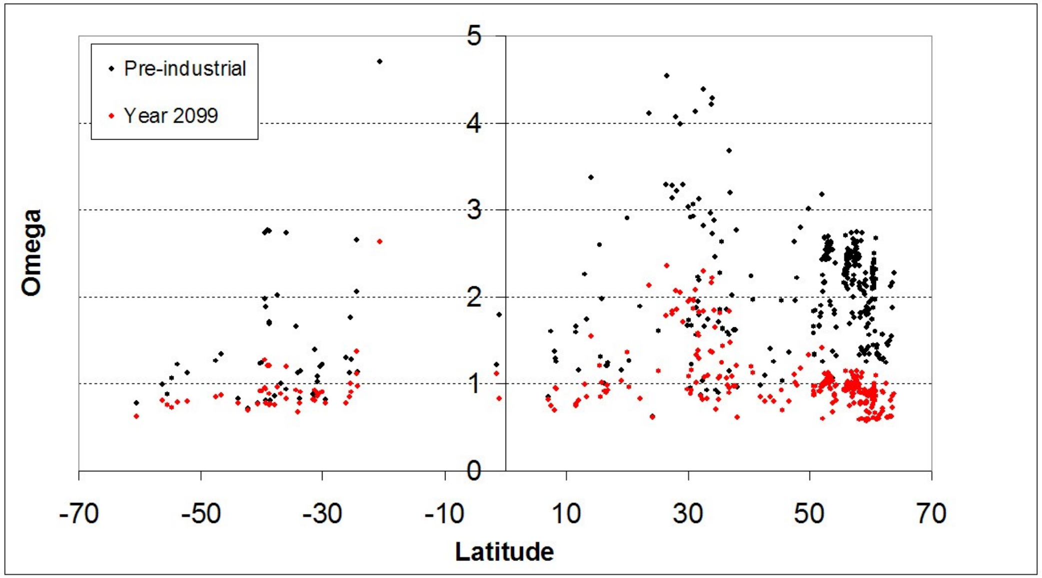
2005 : 95% avec $\Omega_A > 1$

2100 : 35% avec $\Omega_A > 1$

Lophelia pertusa

The JAGO-Team

L. pertusa **with expanded tentacles ready to capture zooplankton**



Guinotte et al. (2006)
Davies et al. (2008)
Fautin et al. (2009)
Tittensor et al. (2010)

Regions that are naturally rich in CO_2 confirm expected trends

- less biodiversity
- fewer shells & corals
- more fragile shells
- invasive species
- more seaweed, coral degradation

CO_2 bubbles rise from seafloor at Ischia, Bay of Naples, a natural lab to study acidification

Hall-Spencer et al. (2008)

Rodolfo-Metalpa et al. (2008)

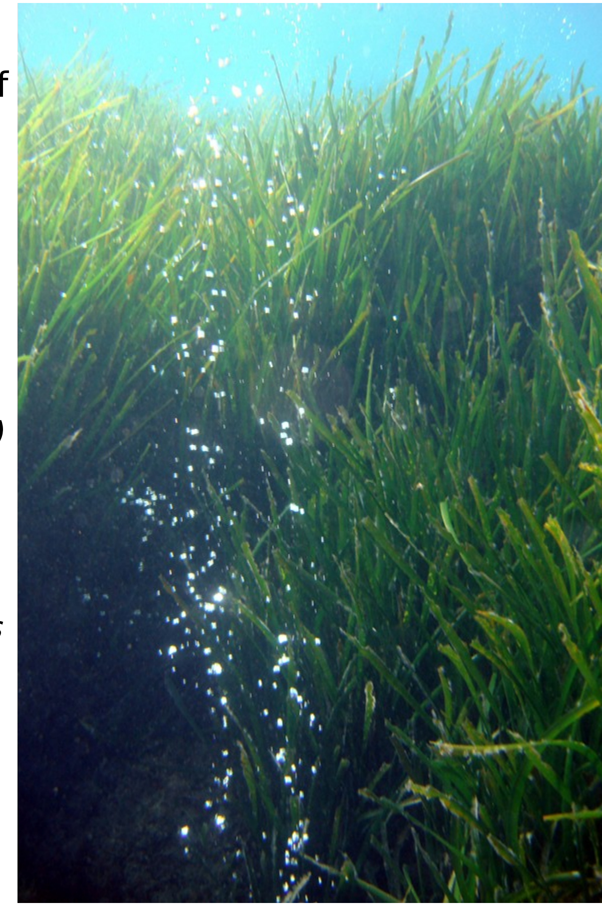


Photo: Jason Hall-Spencer, Plymouth University

Photo: Steve Ringman, Seattle Times

Another natural CO_2 vent site in Papua, New Guinea, used to study effects of acidification on corals

Acidification likely to change marine ecosystems

Organisms react differently

Corals and shell builders decline

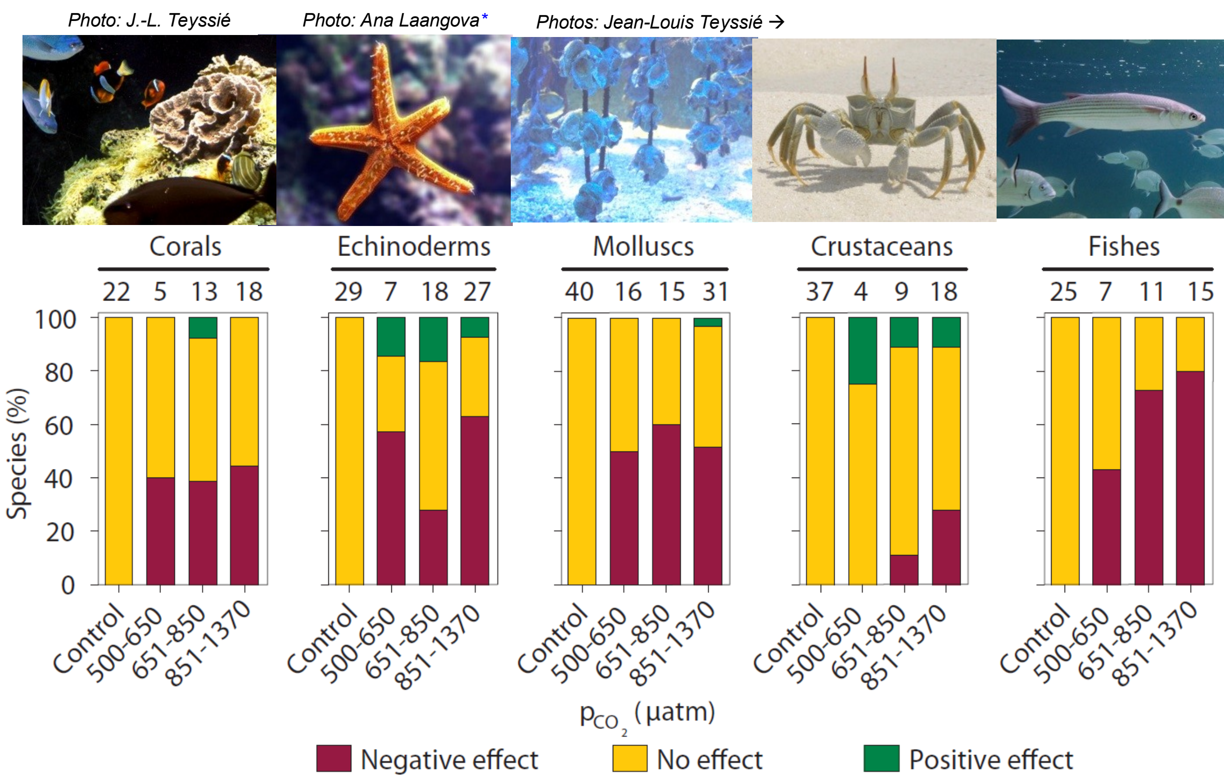
Seagrasses may increase

Fish become disoriented

Predators affected by prey loss

Potential fish catch decline

Synthesis of existing experimental studies



Wittmann & Pörtner (2013, Nature Clim. Change)

Ocean acidification will also affect humans

- Fish is primary source of animal protein for 1 billion people, mostly in developing countries (FAO)

- Coral reefs provide
  - home for millions of species
  - storm protection for coastlines
  - income from tourism
  - biodiversity legacy for future

- Ocean acidification already affecting oyster industry (U.S. west coast)

- Ocean acidification may well affect aquaculture, fisheries, and human livelihoods

Photo: Rodolfo Quevenco, IAEA

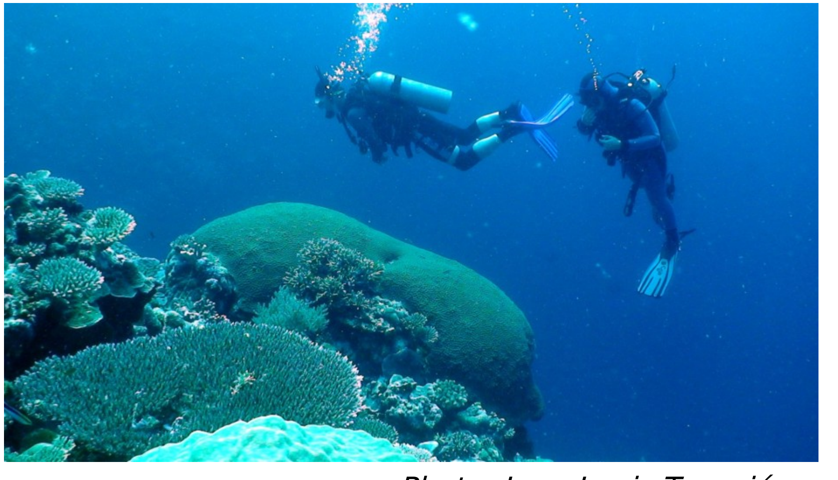
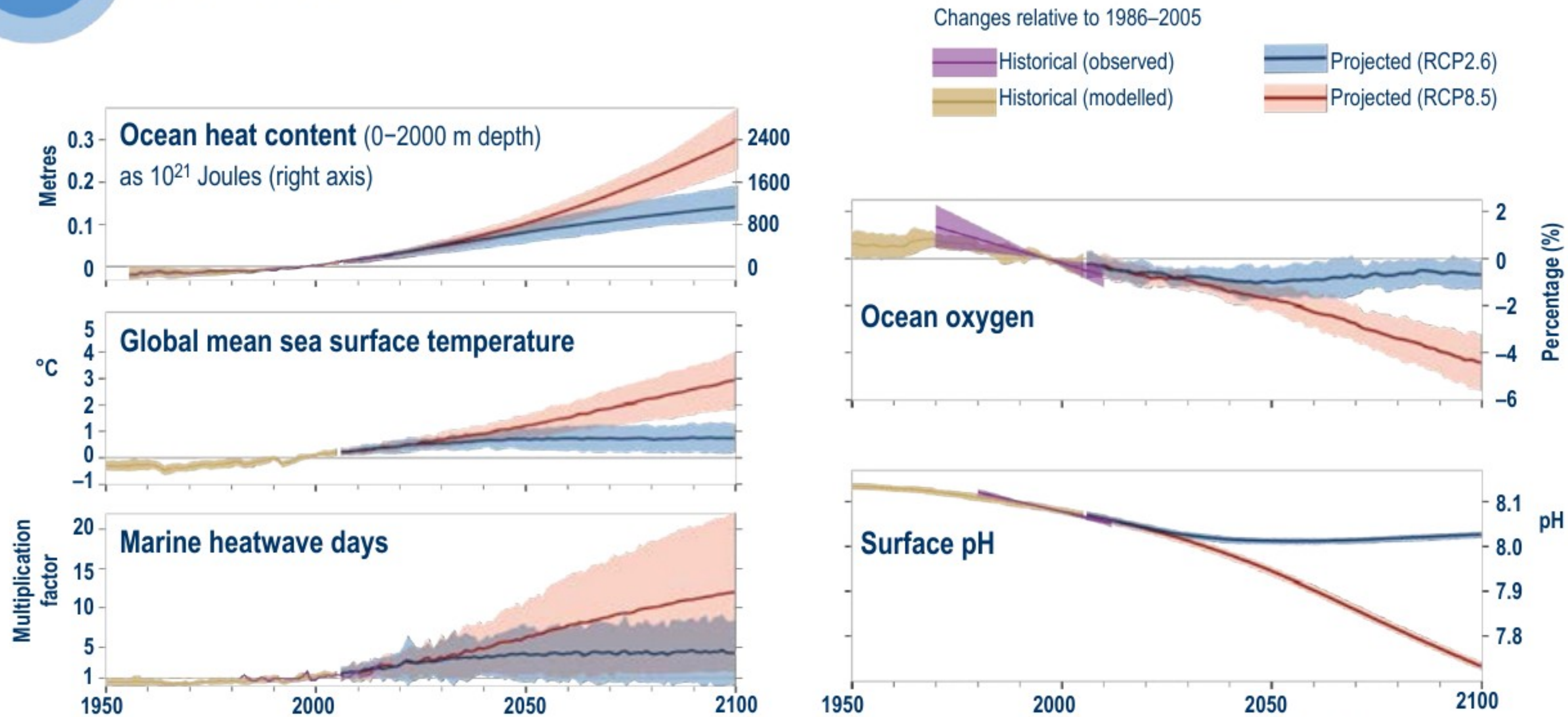


Photo: Jean-Louis Teyssié, IAEA

The ocean is projected to transition to unprecedented conditions



INTERGOVERNMENTAL PANEL ON climate change

IPCC SROCC report

Summary

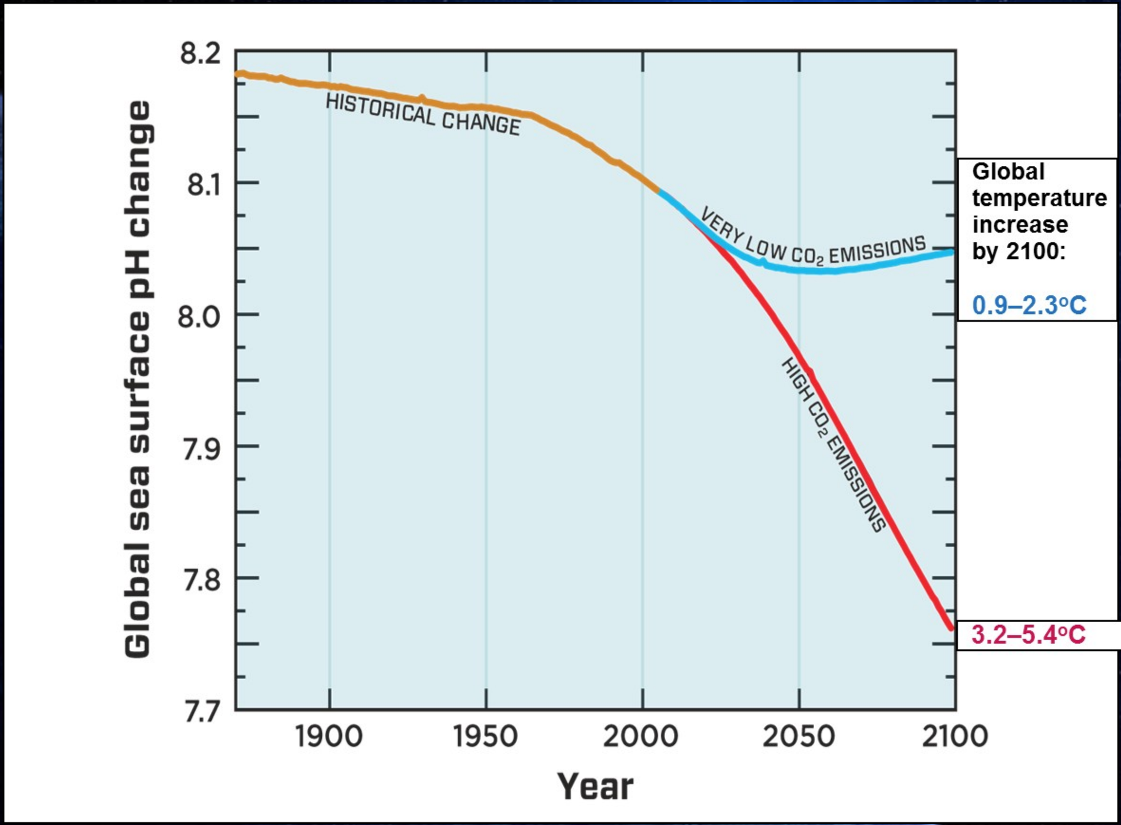
Ocean Acidification

Already detectable

Fast

Caused by CO_2 emissions

Negative impacts on ecosystems



Bopp et al. 2013

IGBP, IOC, SCOR (2013) Ocean Acidification Summary for Policy makers

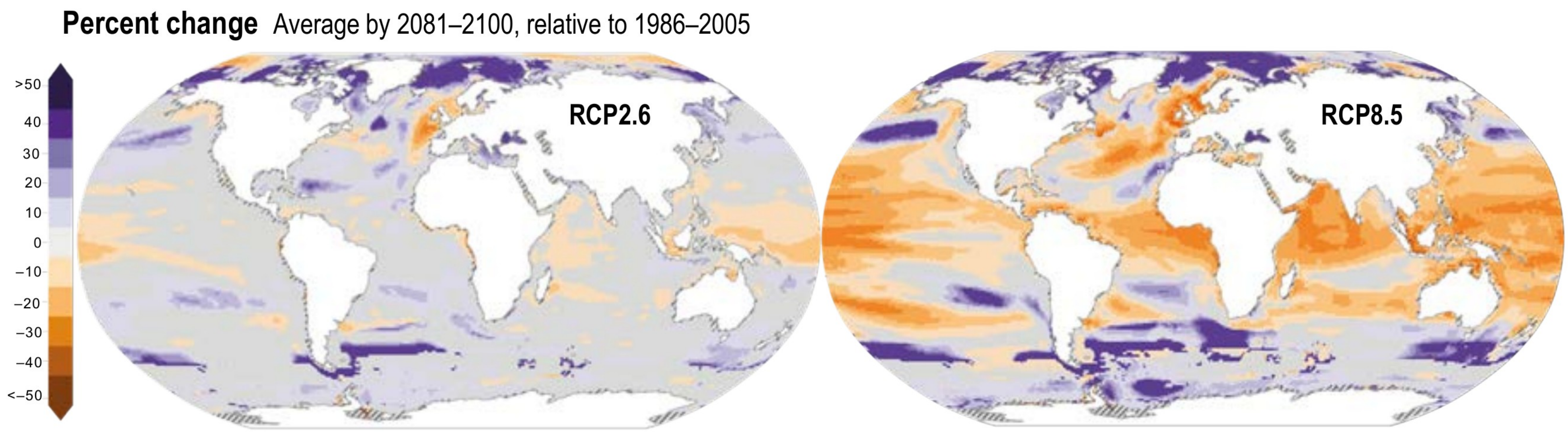
Future projections of egg survival for polar and Atlantic cod across the Arctic

James Orr (LSCE)
Fanny Dubanton (LSCE, Ecole Polytechnique)

Photo: Peter Leopold (NPL)

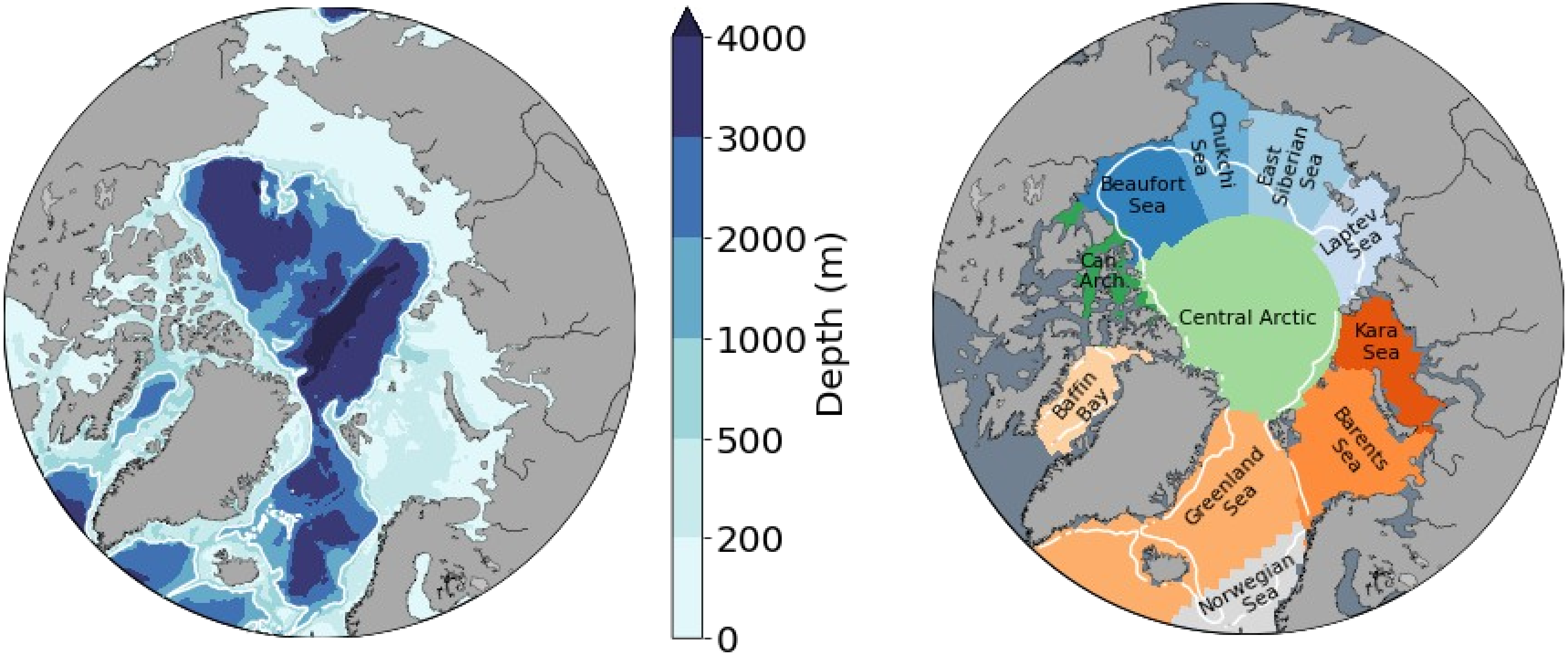
Global warming leads to poleward migration of fish biomass

Change in marine biomass of fish & invetebrates (1986-2005 to 2081-2100)



IPCC SROCC report

Arctic Ocean is mostly shallow continental shelves and includes many regional seas



Two basic questions

Can **Polar cod** survive climate change?

Will climate change allow **Atlantic cod** to invade the Arctic?

Polar cod *(Boreogadus saida)* is omnipresent in the Arctic Ocean

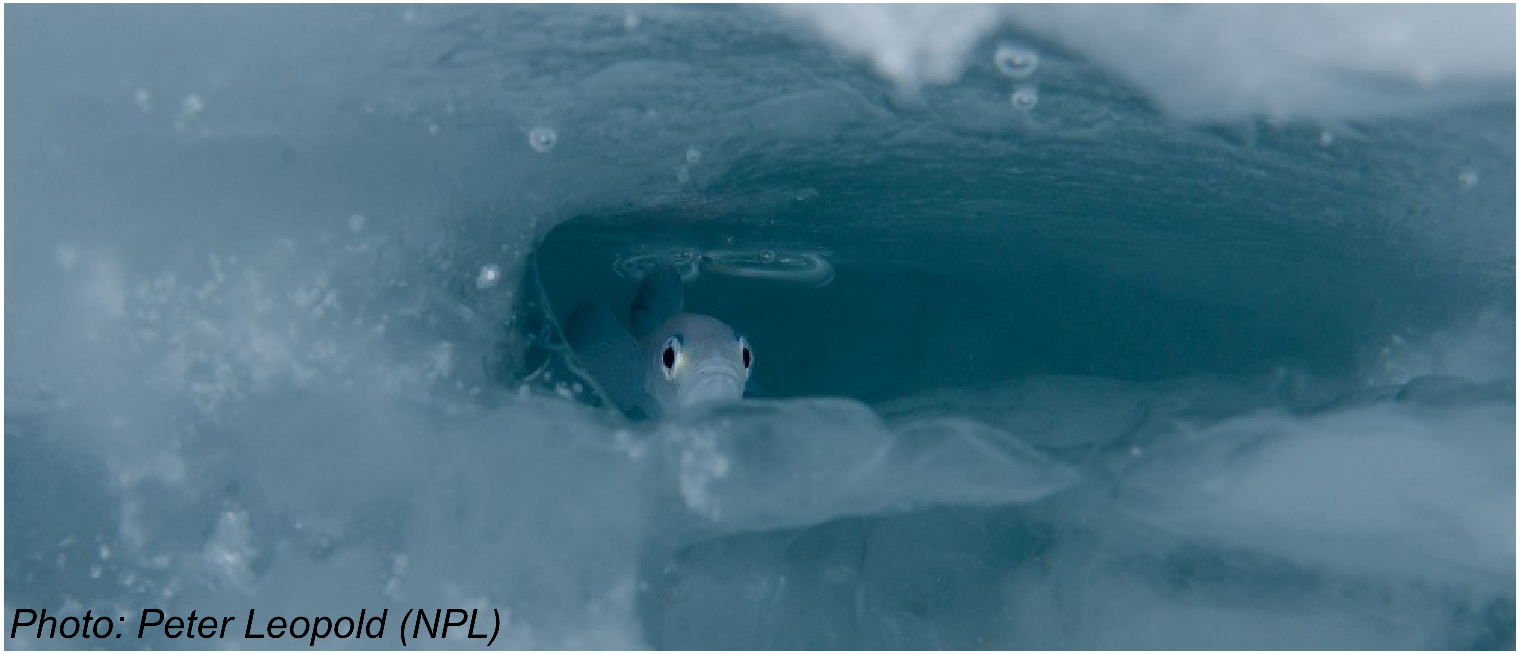
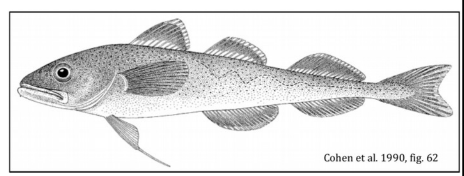
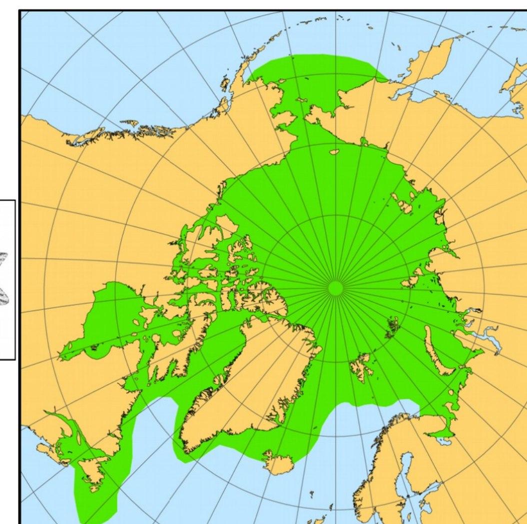


Photo: Peter Leopold (NPL)

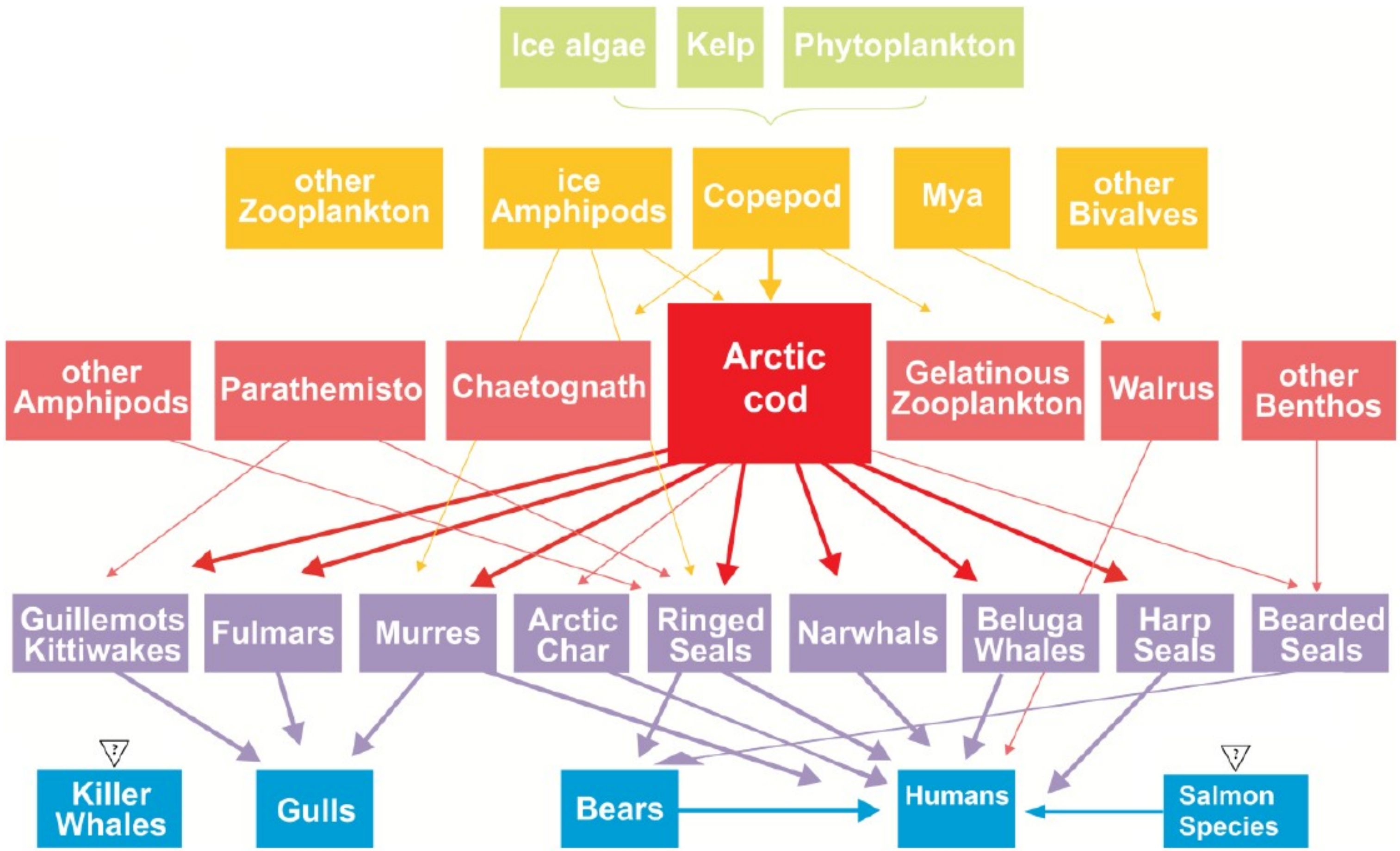
Polar cod is sympagic.
It relies on sea ice for spawning, habitat, food, etc



Cohen et al. 1990, fig. 62



Polar cod *(Boreogadus saida)* is a central element of the Arctic Ocean ecosystem



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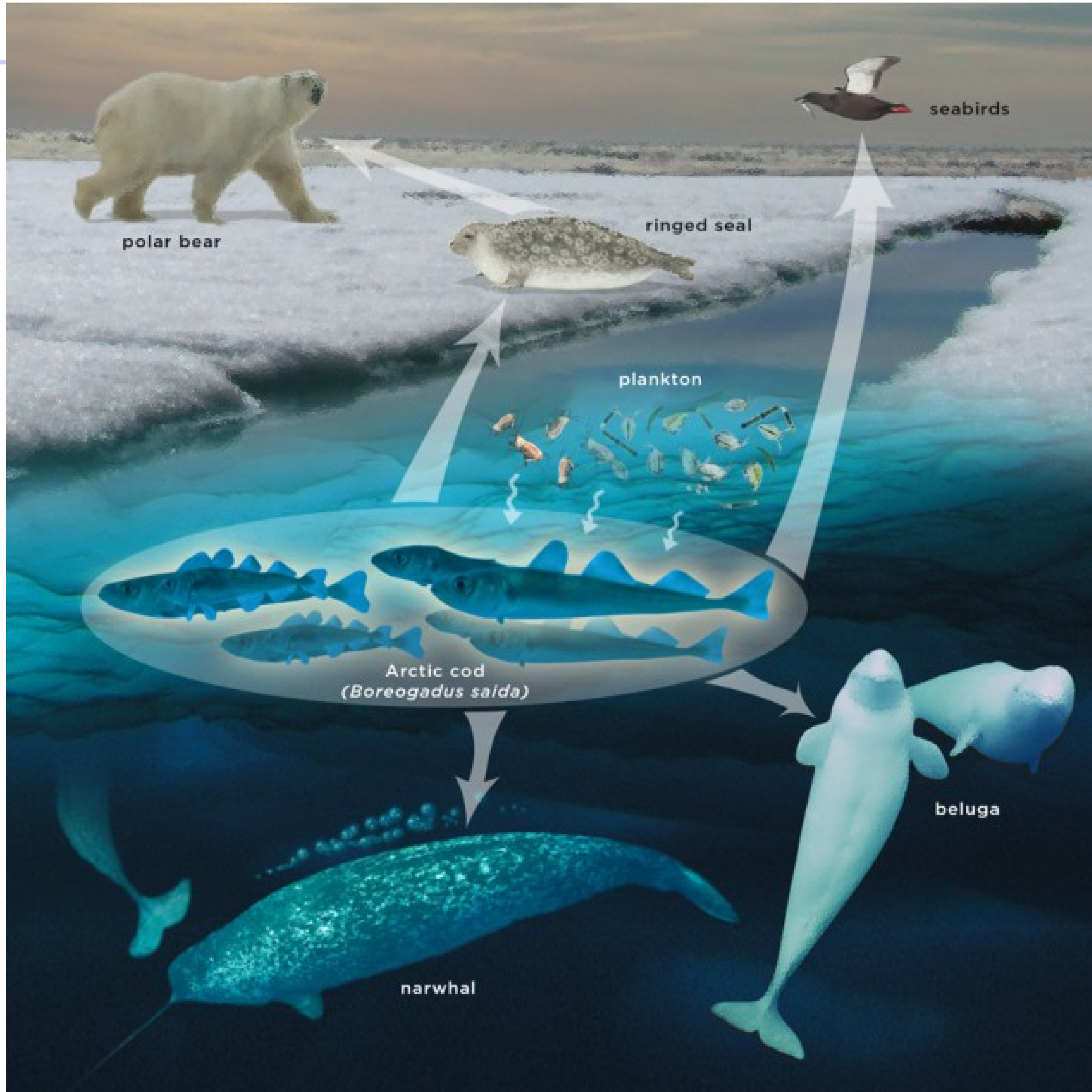
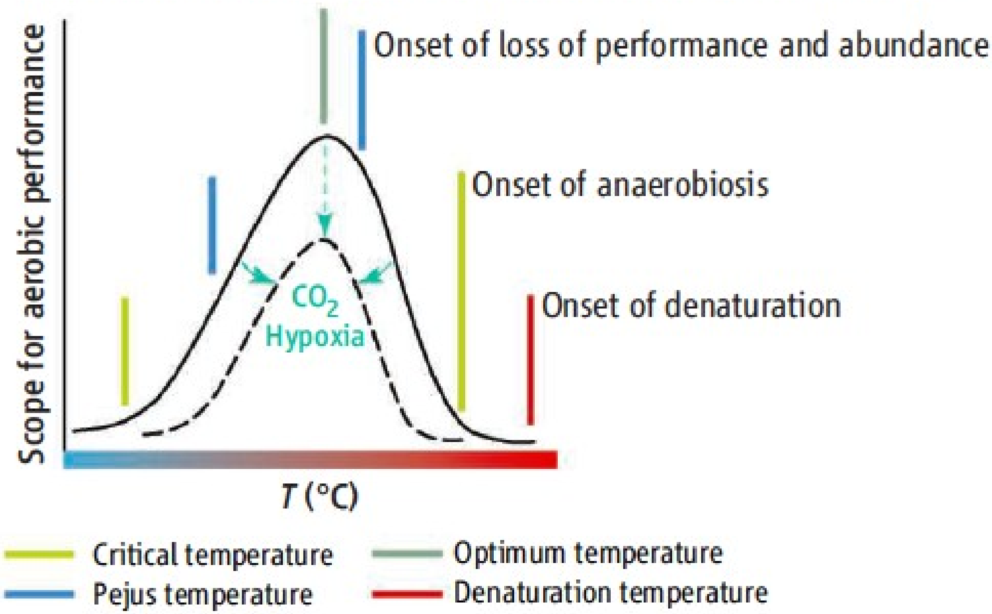
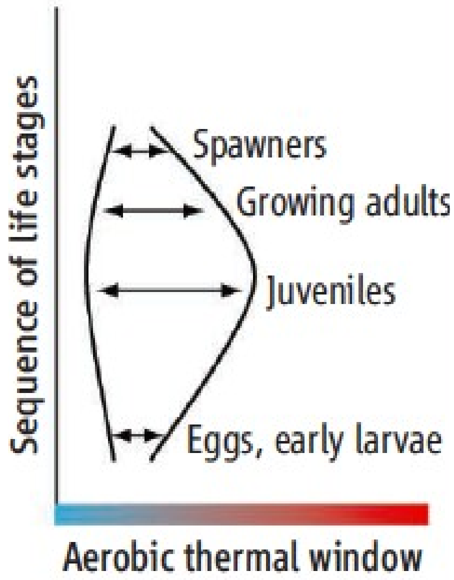


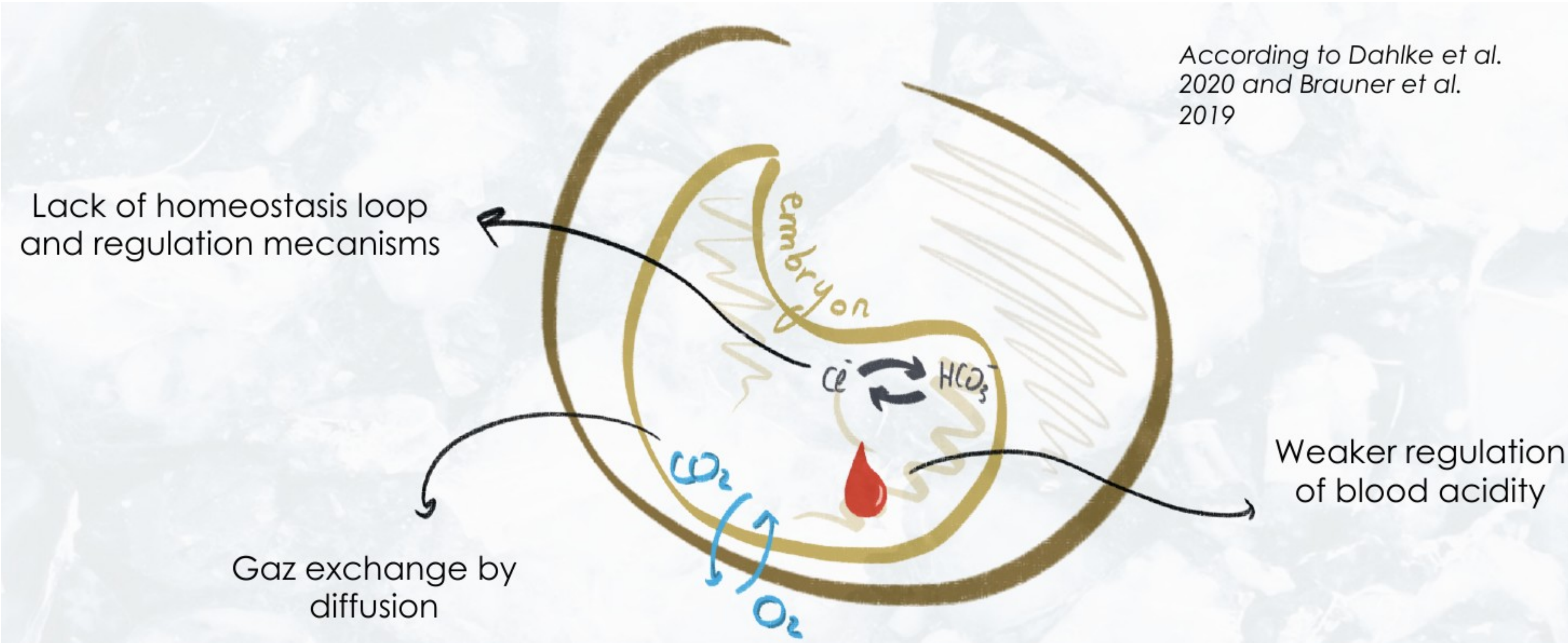
Fish have limited thermal tolerance, especially eggs & spawners



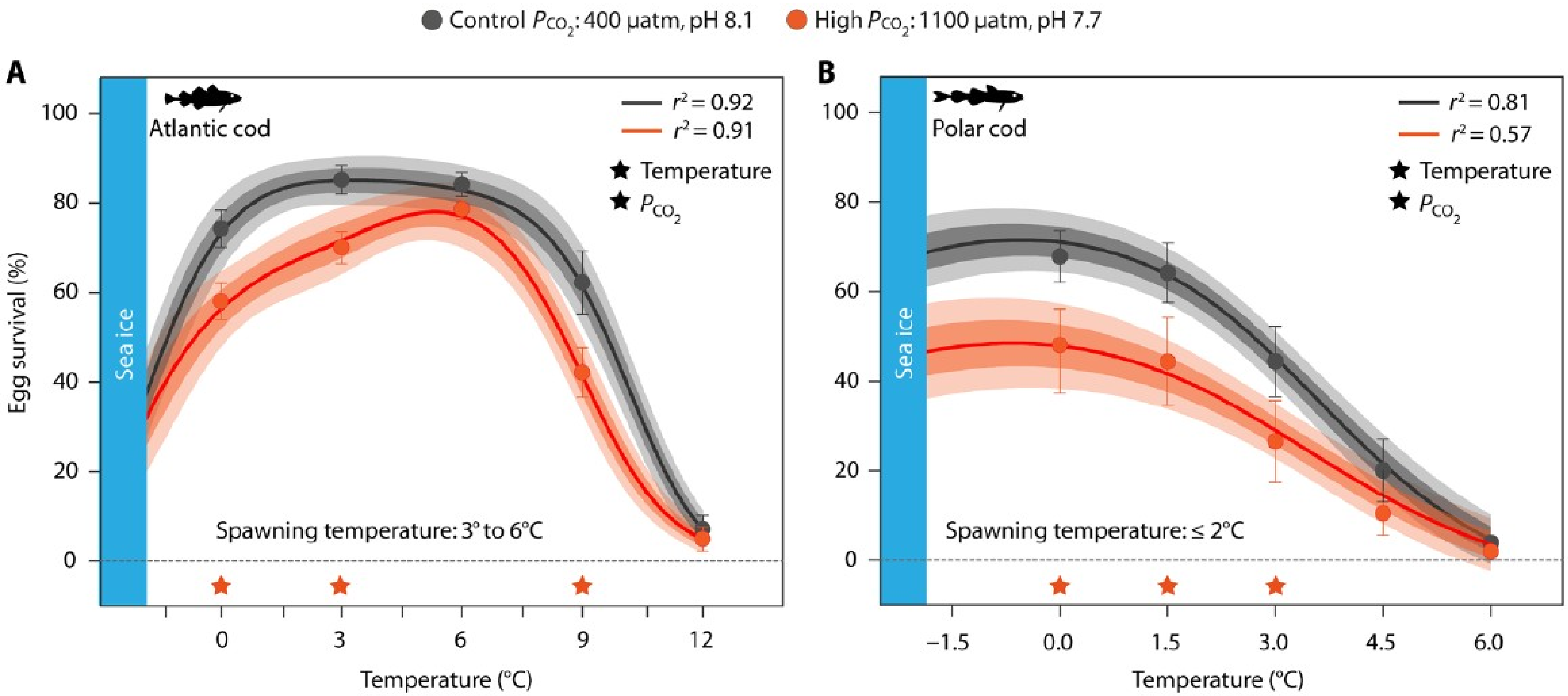


Pörtner and Farrell (2008)

Warming & acidification affect embryos (eggs) more than adults

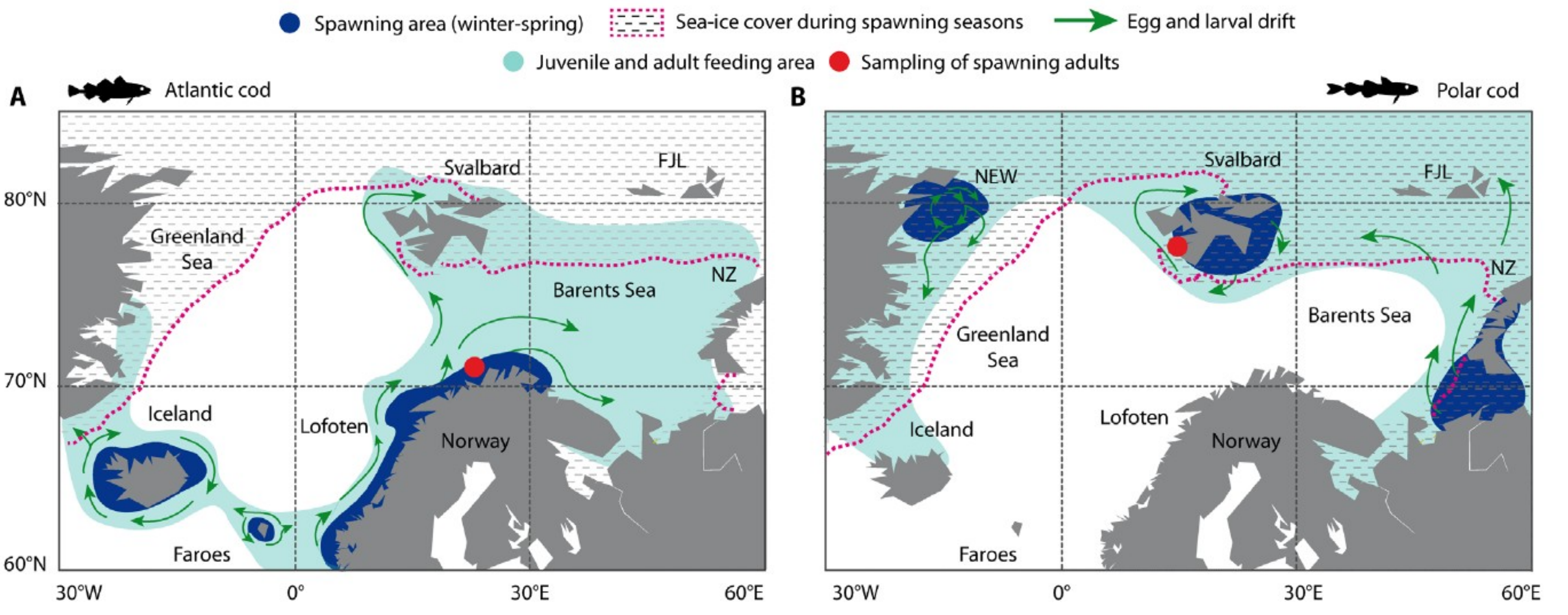


Egg survival was measured experimentally as a function of temperature and pCO_2



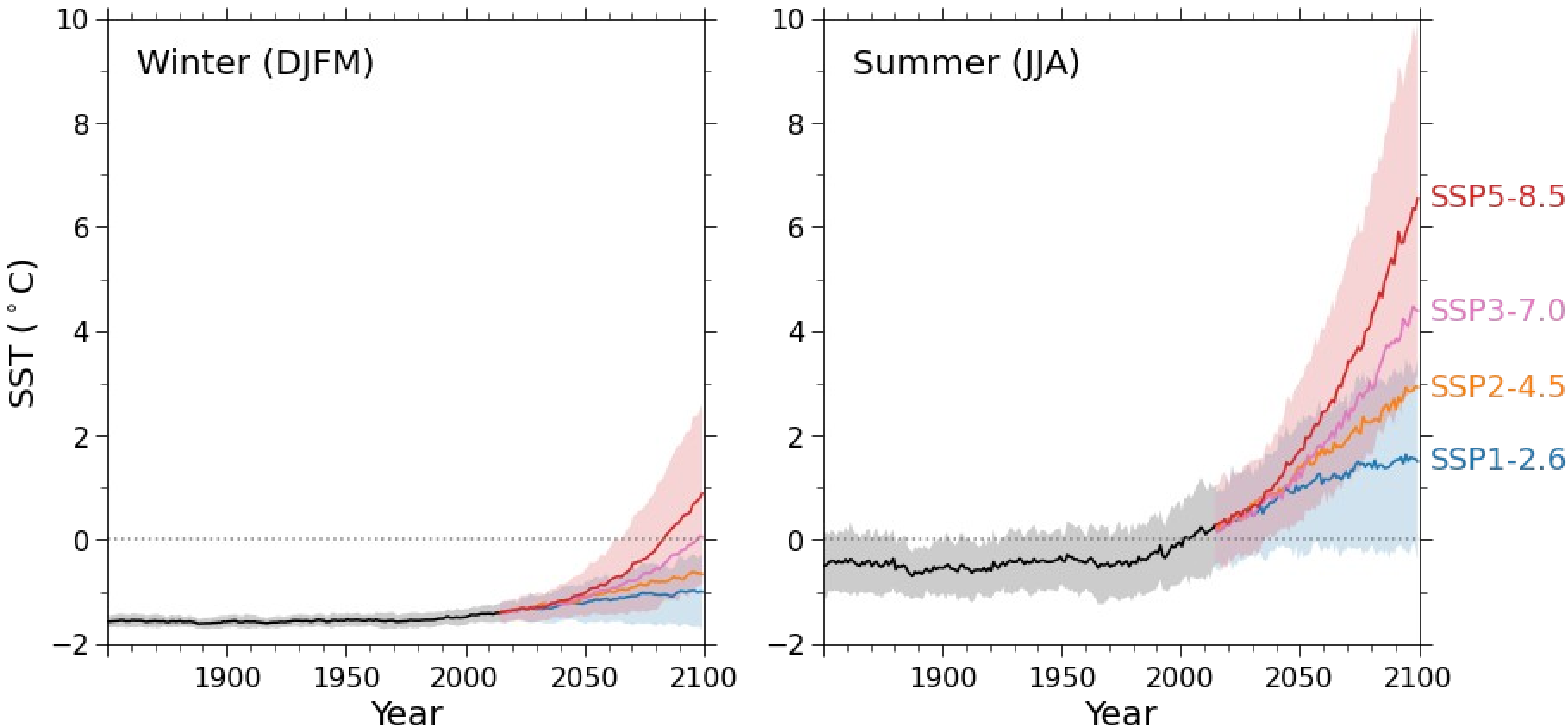
Dahlke et al. (2018, Sci. Adv.)

Current spawning areas have exhibit high habitat suitability (PES > 90%)



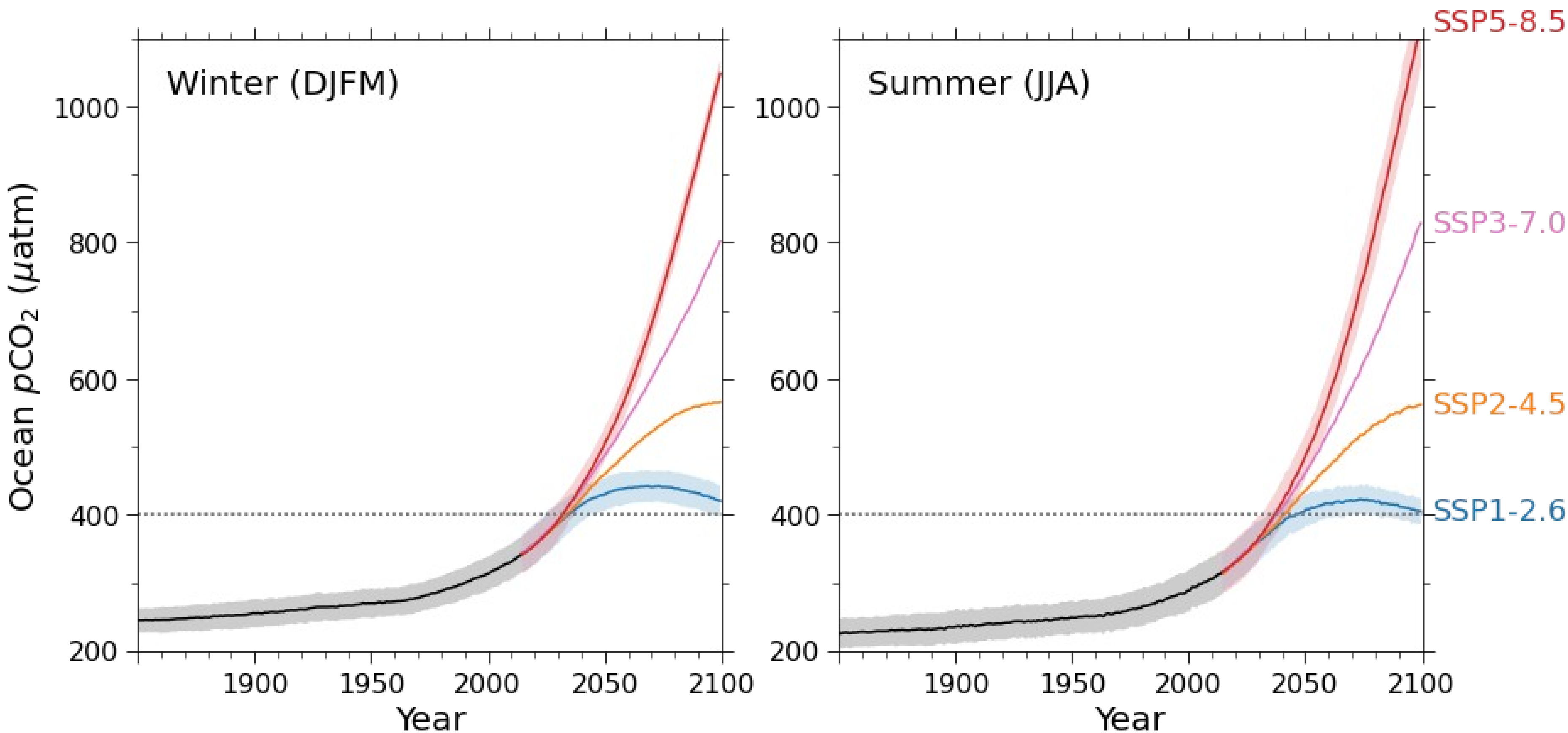
Dahlke et al. (2018, Sci. Adv.)

Arctic surface sea-surface temperature increases less in winter than summer (opposite of air surface temperature)



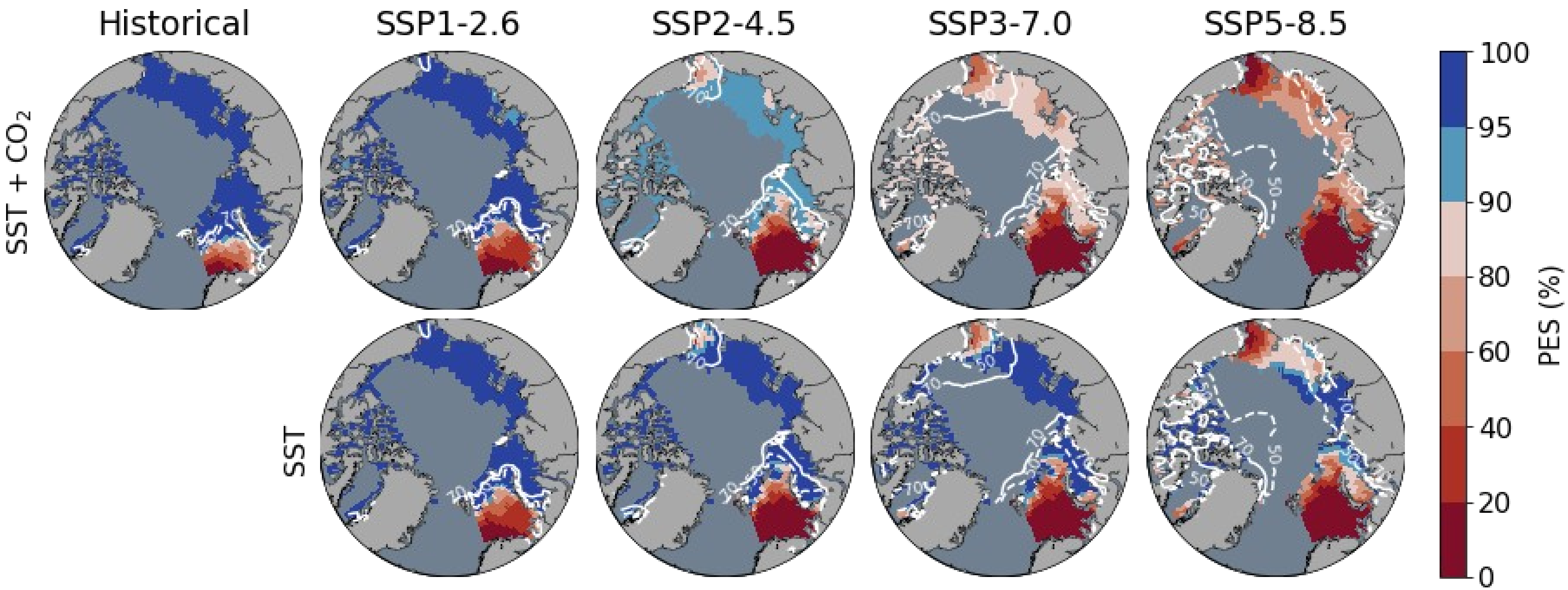
18 CMIP6 models: mean ± 1σ

Ocean pCO_2 has increased greatly, nearly uniformly, closely following the atmospheric CO_2 increase

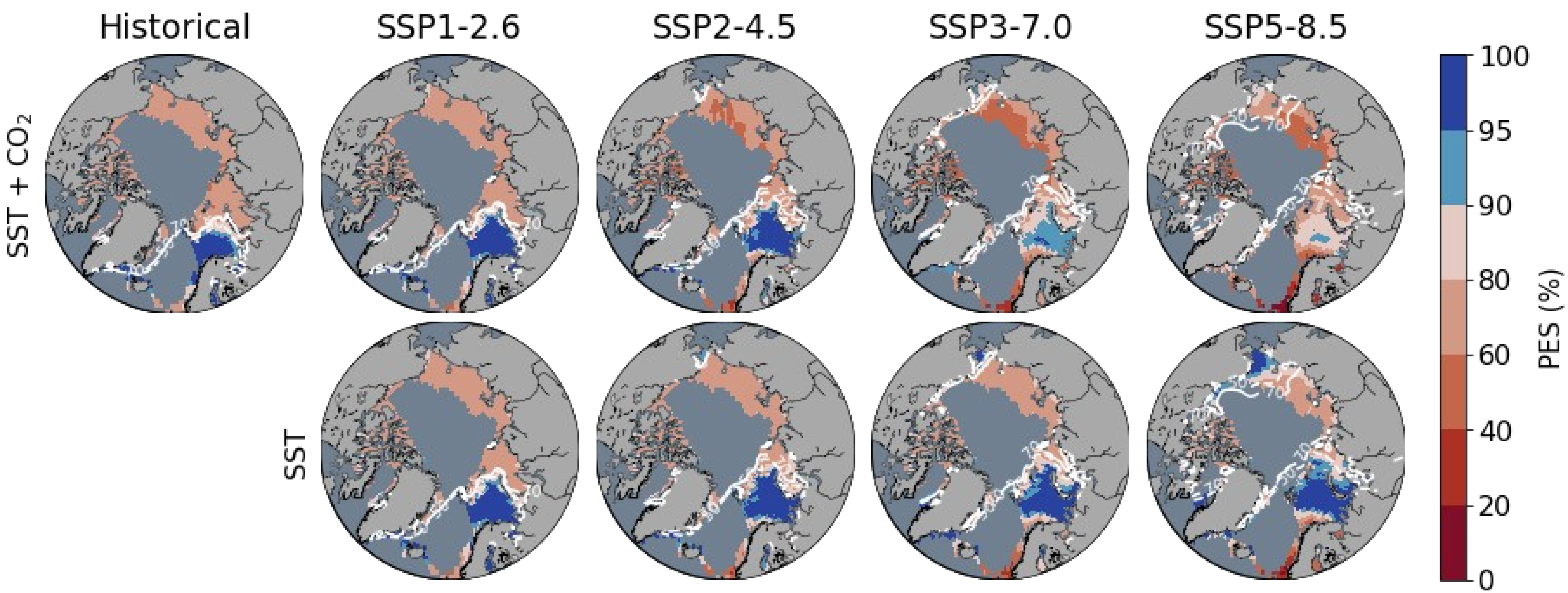


18 CMIP6 models: mean ± 1σ

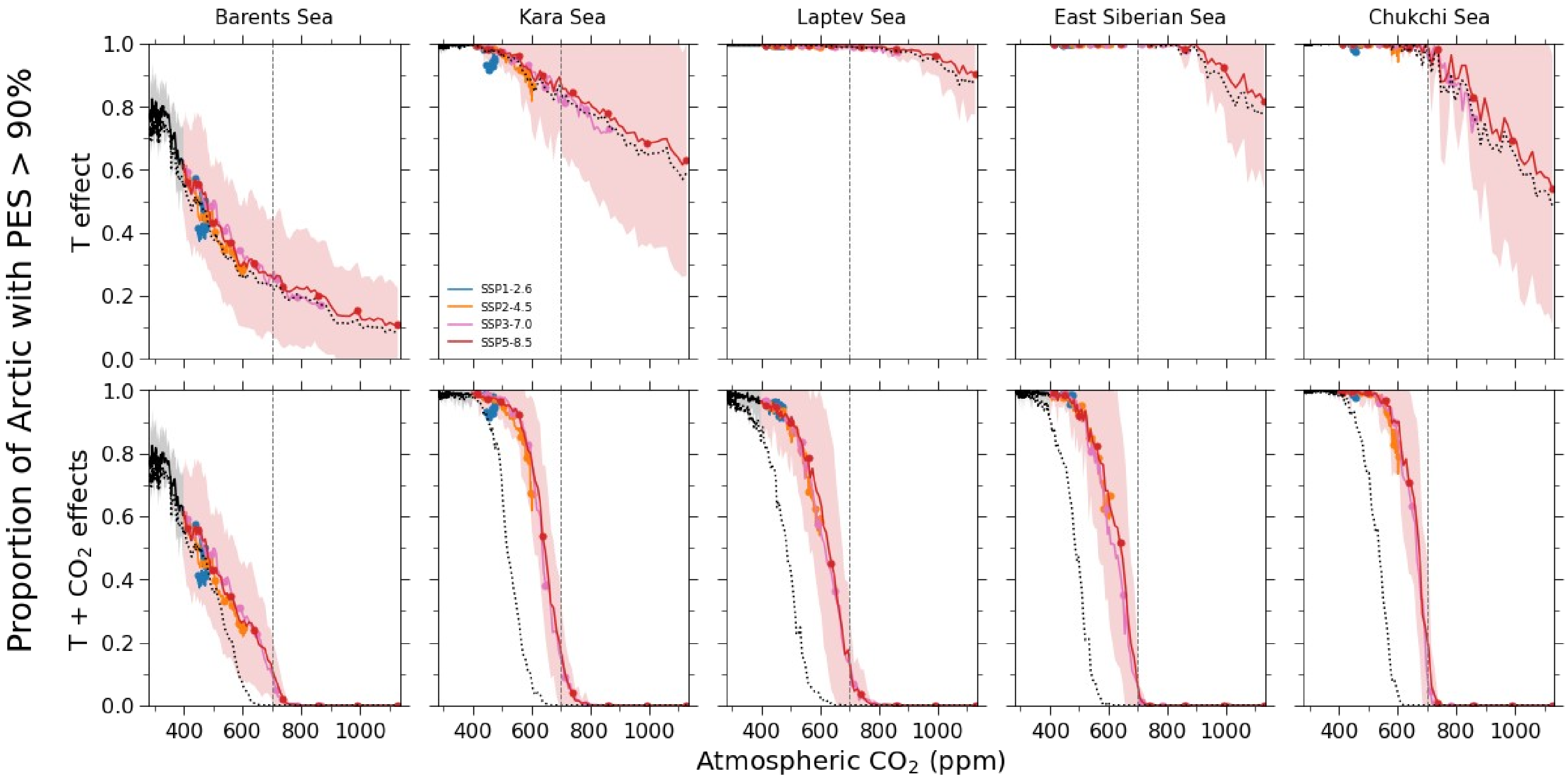
For Polar cod eggs, all suitable habitat disappears by 2100 except in the low-end, and perhaps mid-range, scenarios



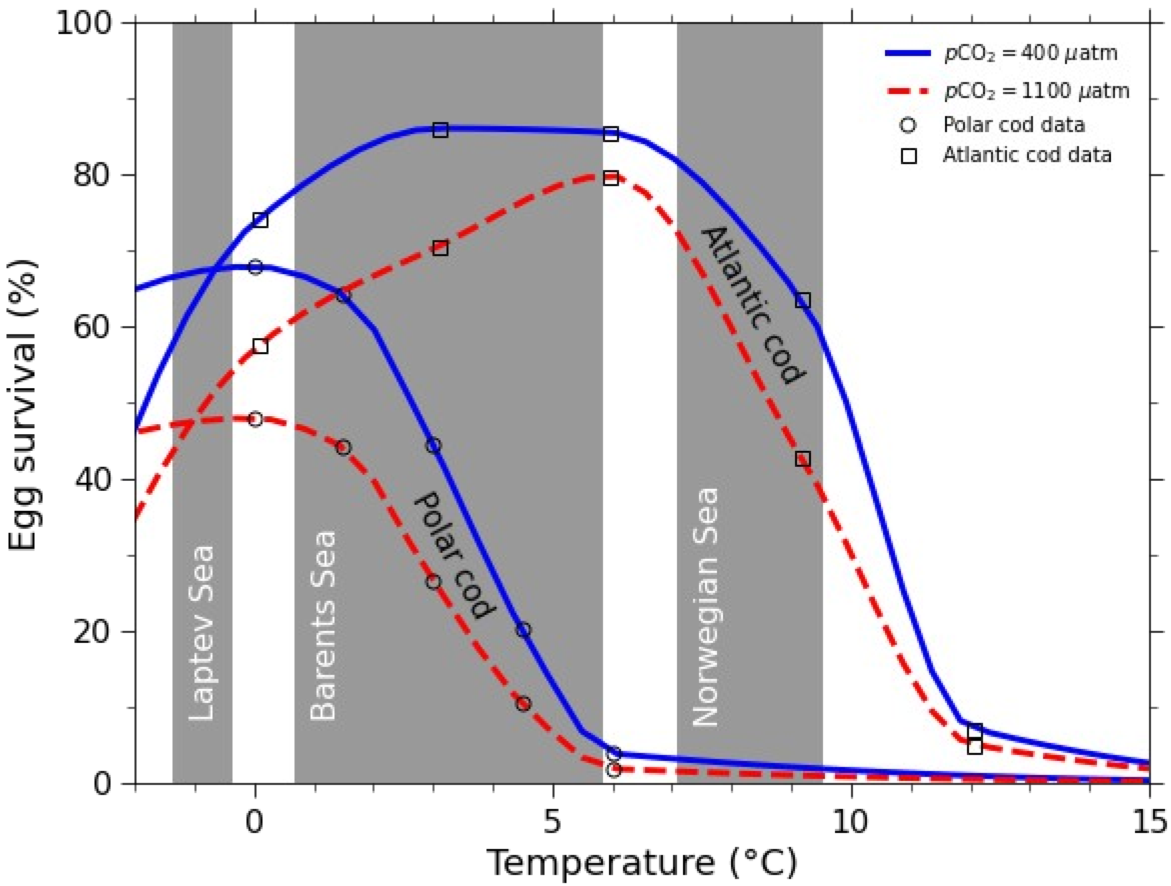
For Atlantic cod, traditional spawning grounds disappear, but might move to the Barents Sea in lower scenarios



Fraction of area with suitable habitat (PES > 90%) remains if we consider only warming but disappears with added acidification



The thermal windows for the two cod species do not coincide

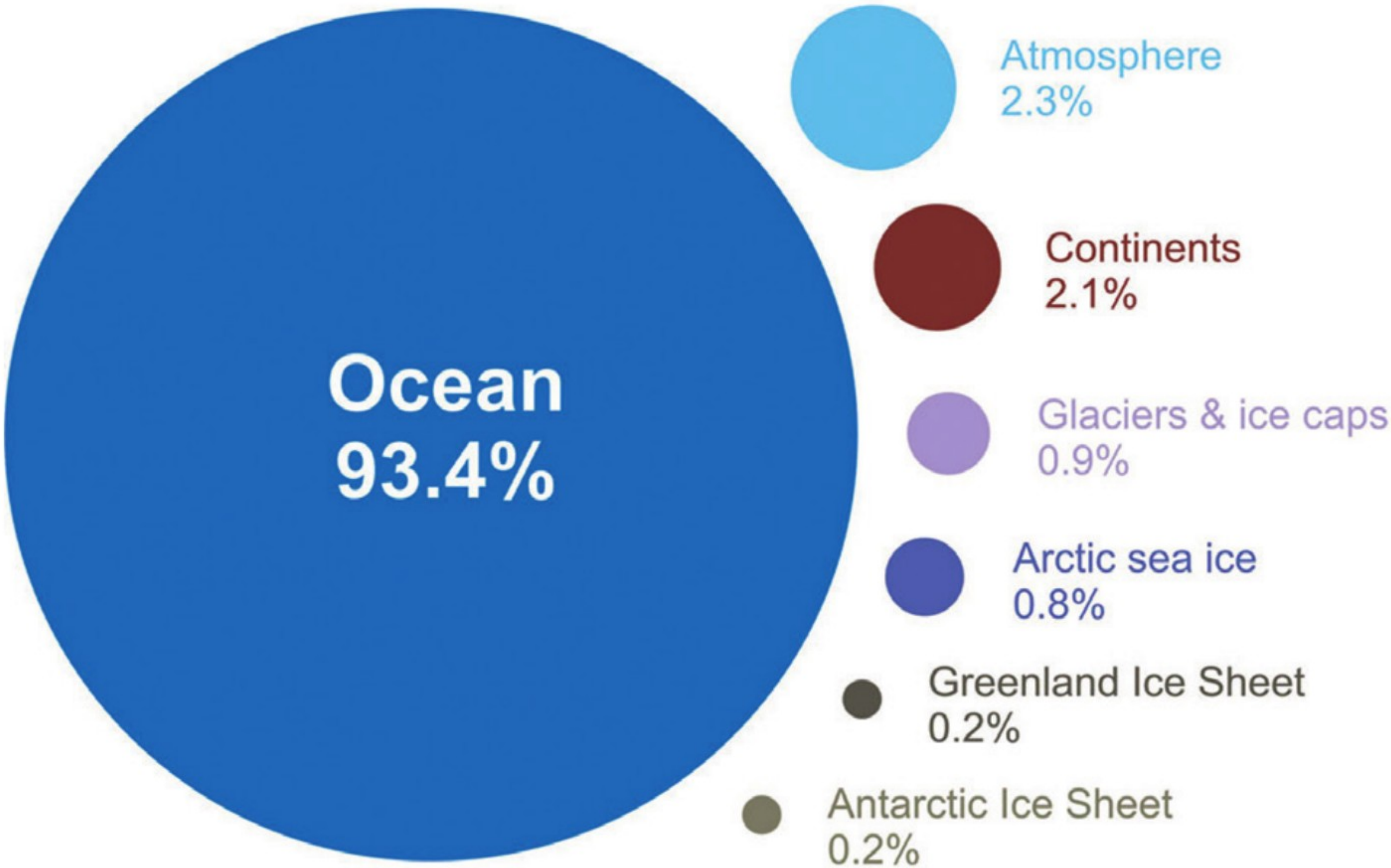


Conclusion

All polar cod spawning habitat lost when atm CO_2 > 700 ppm

Atlantic cod spawning forced to move & lost under high scenario

Most of the heat from anthropogenic global warming is absorbed by the ocean



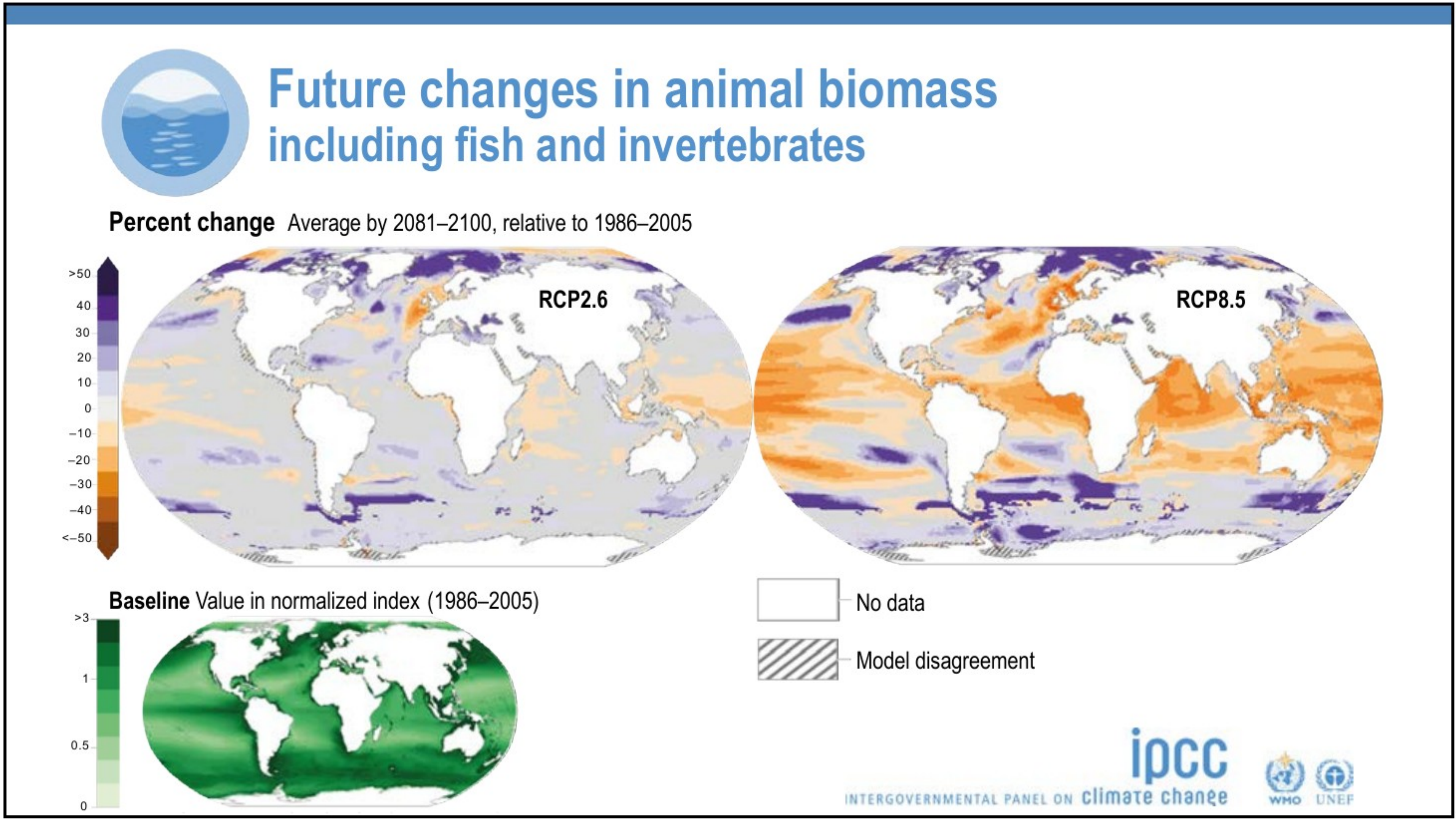
Gattuso *et al.* 2015

Manipulative studies used to evaluate biological resp

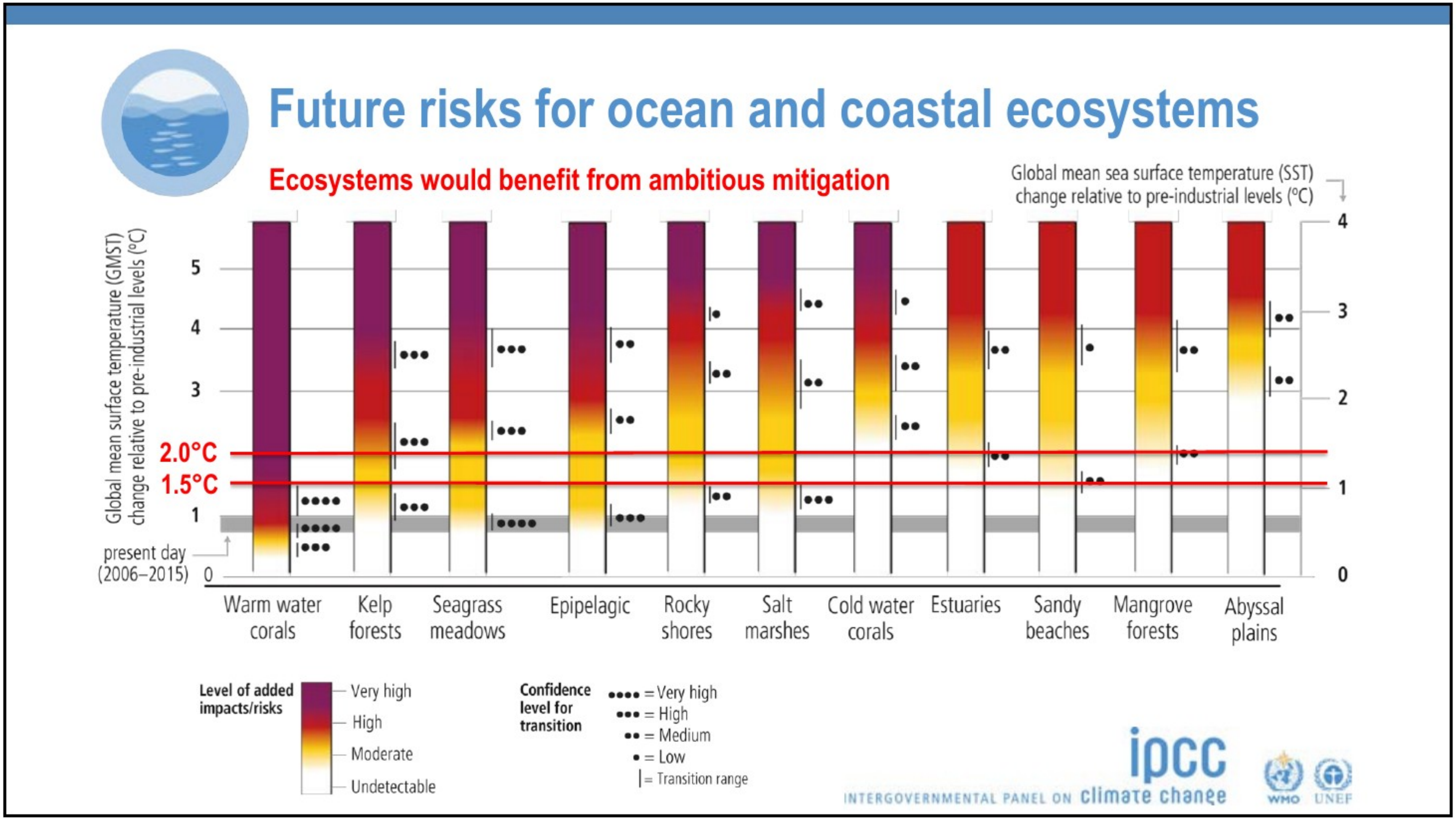
- Lab perturbation experiments
- Field observations near CO_2 vents (natural, long term)
- Mesocosm experiments (in the water; on the sediments)
- Free Ocean CO_2 Enrichment (FOCE) experiments

Conclusions

- General *Amplification* in seasonal cycles of surface pCO_2 & $[H^+]$
  vs. *Attenuation* in seasonal cycles of surface pH and Ω_A
- In the Arctic, today's seasonal minima in pCO_2 & $[H^+]$ become tomorrow's seasonal maxima
- That phase change worsens summer acidity by ~30% compared to an amplification with no phase change
- How these big increases in summer SST, pCO_2, and $[H^+]$ will affect the Arctic Ocean BGC & ecosystems has been ignored

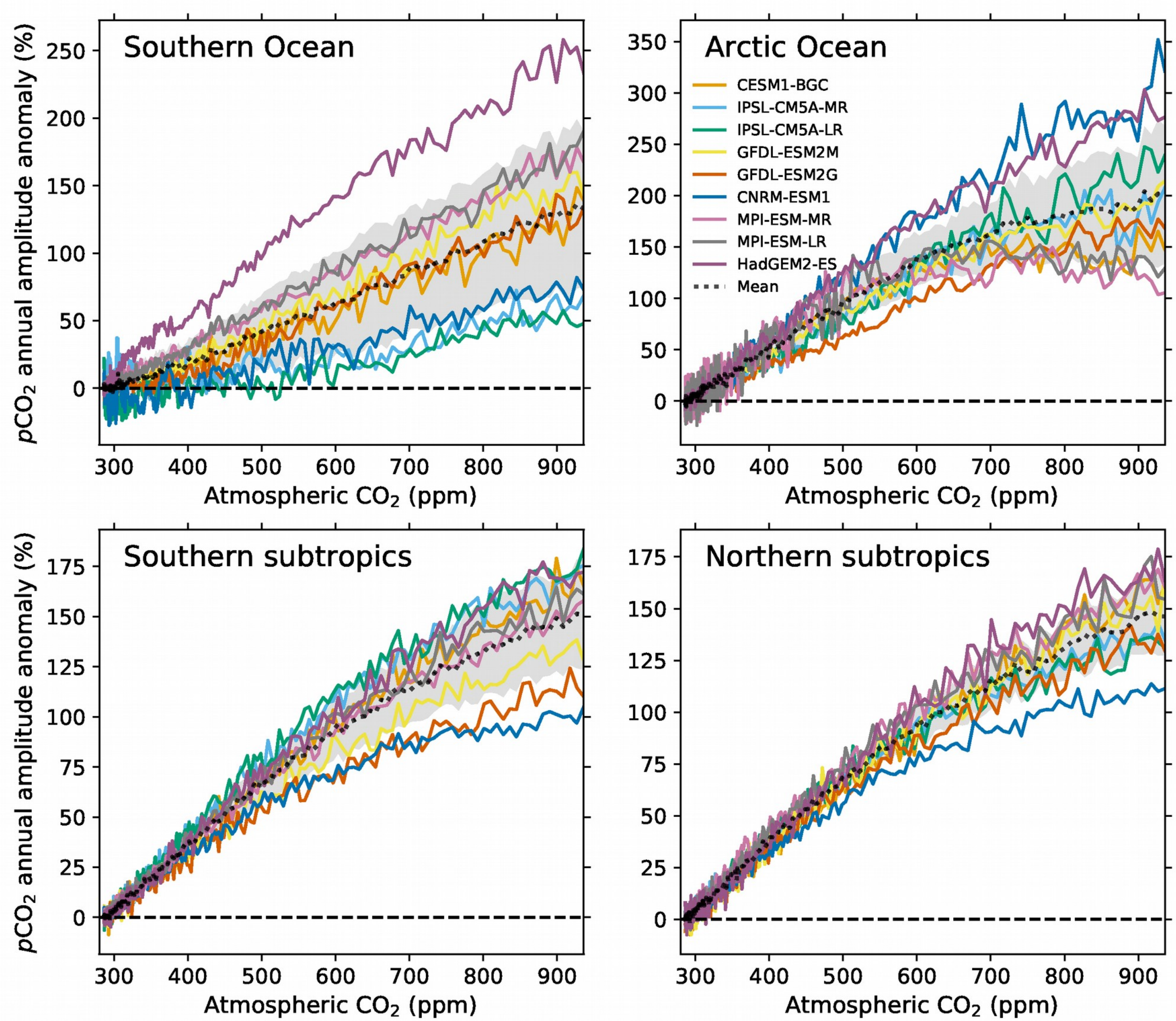


IPCC SROCC report



IPCC SROCC report

Seasonal amplitude of surface ocean acidity & pCO_2 increases, particularly in polar oceans

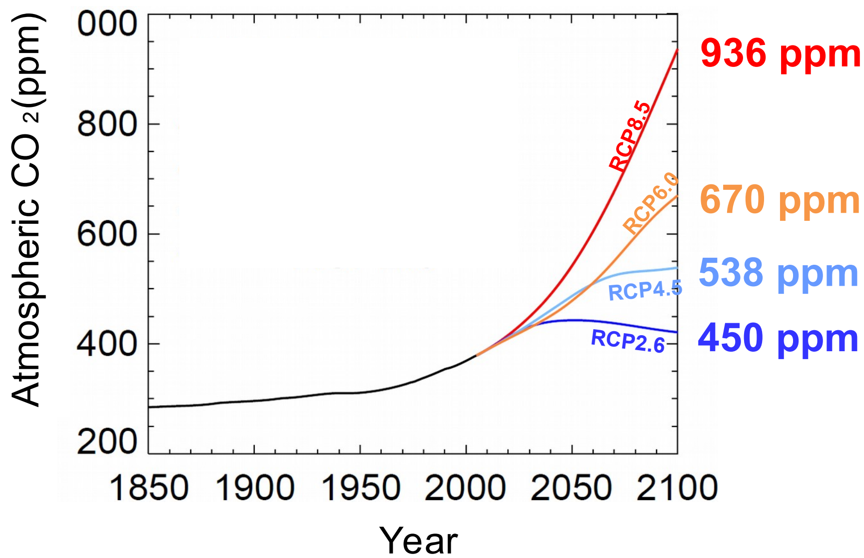


9 CMIP5 models under RCP8.5

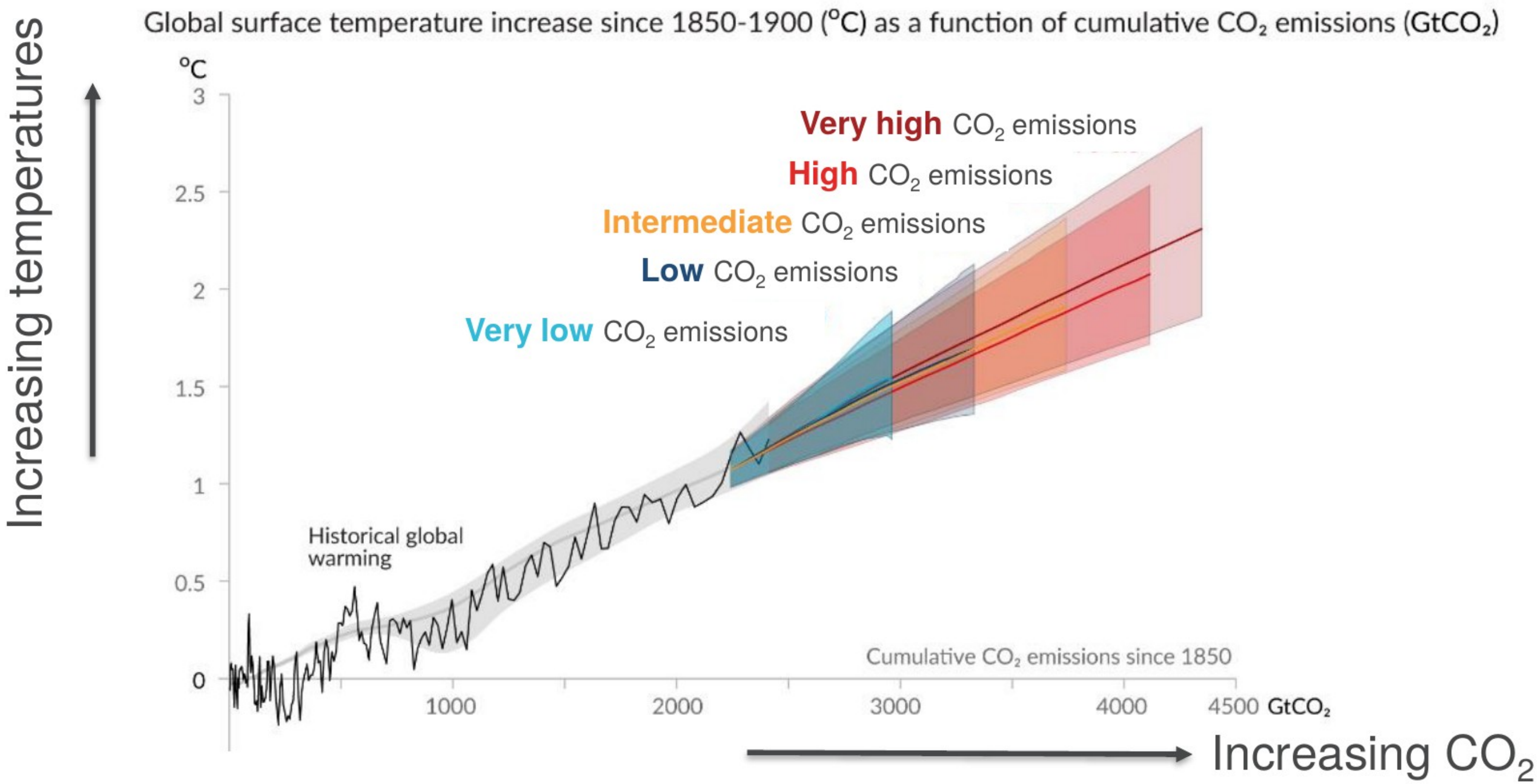
Kwiatkowski & Orr (2018, Nat. Clim Change)

Different scenarios result in large future differences in atm CO_2

Atmospheric CO_2
(IPCC scenarios)



Every tonne of CO_2 emissions adds to global warming



IPCC AR6 WG1 report