Ocean acidification and its impacts on marine organisms and ecosystems

James C. Orr

Laboratoire des sciences du climat & de l'environnement

cea cnrs Université de Versailles Saint-Quentin-en-Yvelines

Sciences de l'environnement Institut Pierre Simon Laplace

IAEA

Ocean Acidification International Coordination Centre

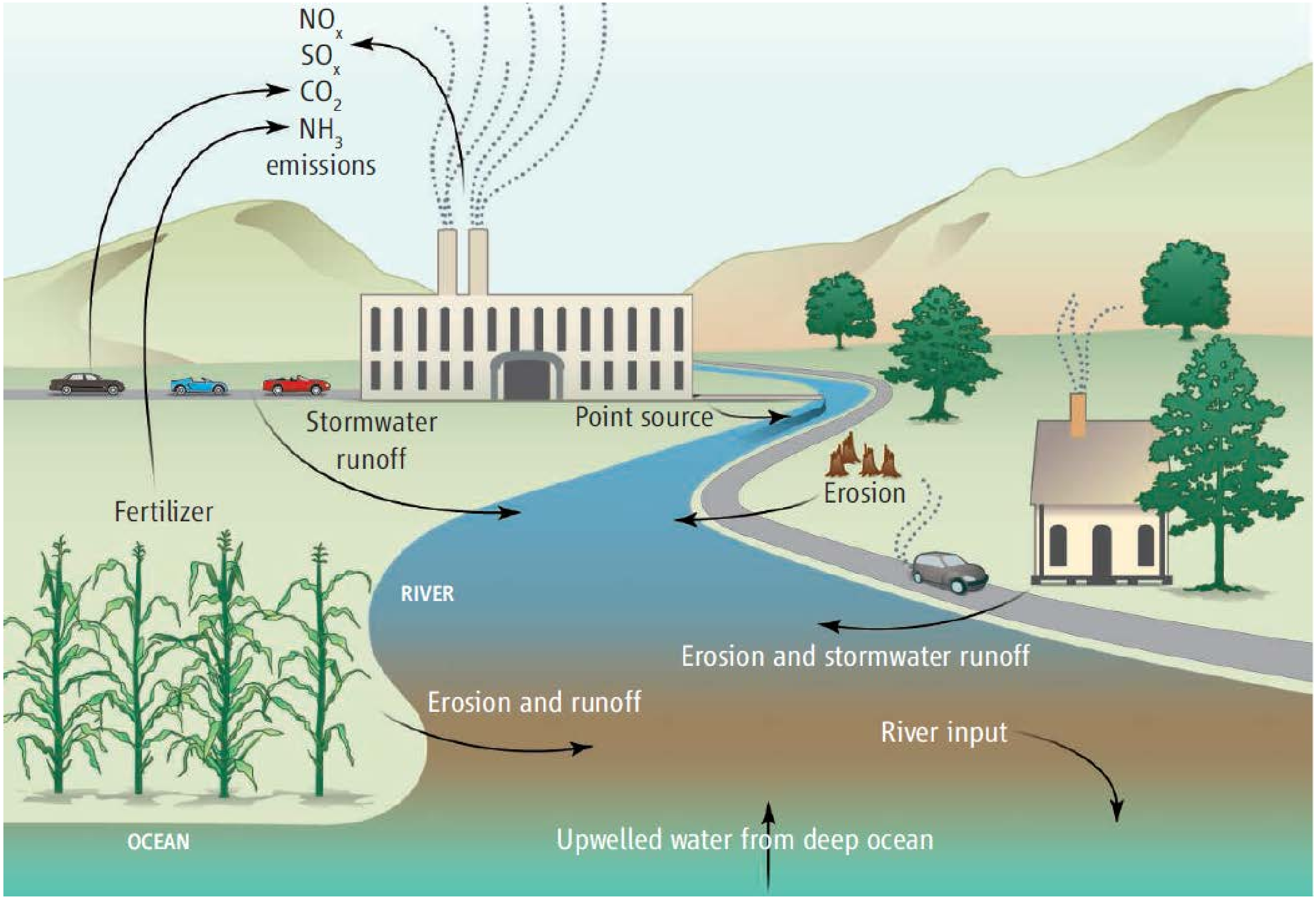
OA-ICC

SOLAS-IMBER Ocean Acidification Working Group

solas Surface Ocean Lower Atmosphere Study

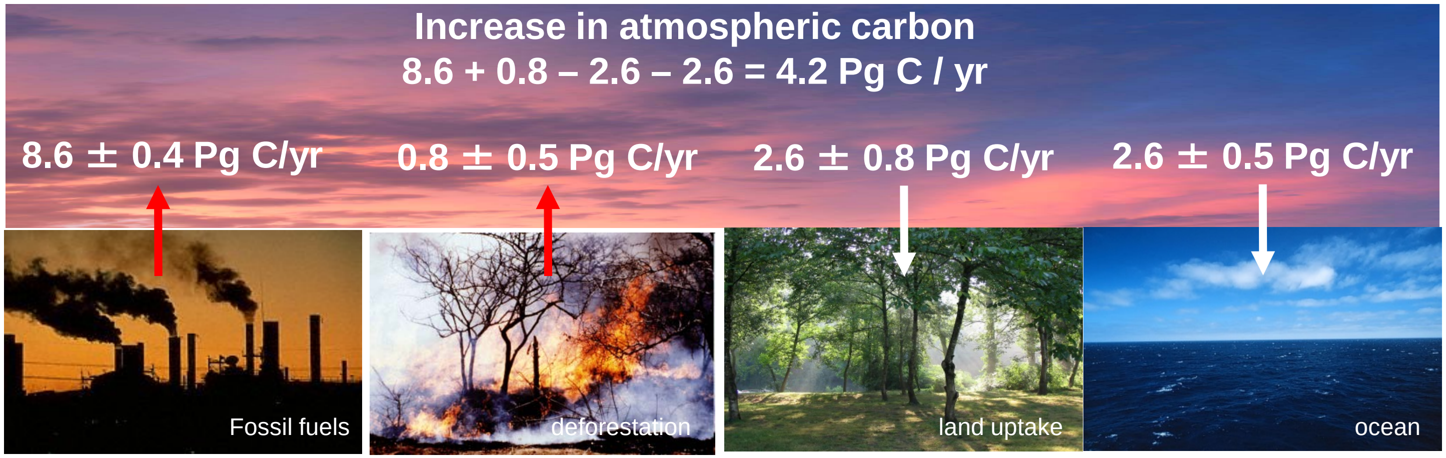
IMBER Integrated Marine Biogeochemistry and Ecosystem Research

Ocean acidification largely due to atmospheric CO_2 increase



Kelly et al (2011, Science)

Ocean absorbs 1/4 of man-made CO_2 emissions



2002-2013 Carbon budget *Global Carbon Project (2013)*

Half of emitted CO_2 remains in atmosphere (causing global warming)

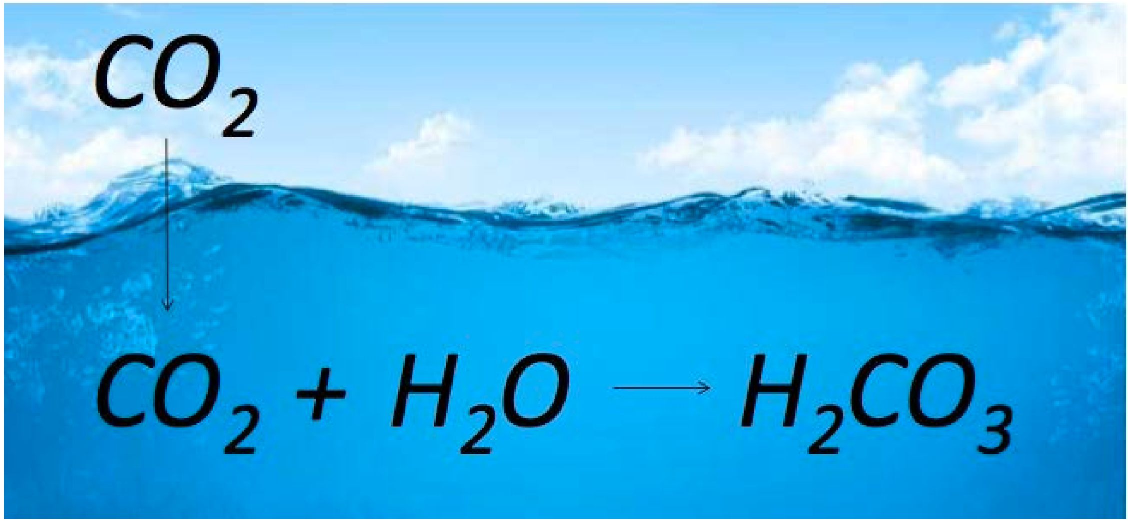
Half absorbed by ocean & land (trees, plants, and soils)

Ocean absorbs 24 million tons of CO_2 every day

GLOBAL CARBON PROJECT

·Le Quéré et al 2013; CDIAC Data; Global Carbon Project 2013

More atmospheric CO_2 means increased ocean acidity



Schematic: Sam Dupont, University of Gothenburg

CO_2 is an acid gas (it produces acid when combined with water)

Each of us adds 4 kg CO_2 per day to the ocean (increasing acidity, reducing pH)

Ocean acidity up by 26% since start of industrial age (most in last 40 years)

Acidity could increase by 170% by 2100

Ocean acidification follows atmospheric CO_2 increase

Ocean absorbs ¼ of anthropogenic CO_2 emissions

$$CO_2 + H_2O \rightarrow H^+ + HCO_3^-$$

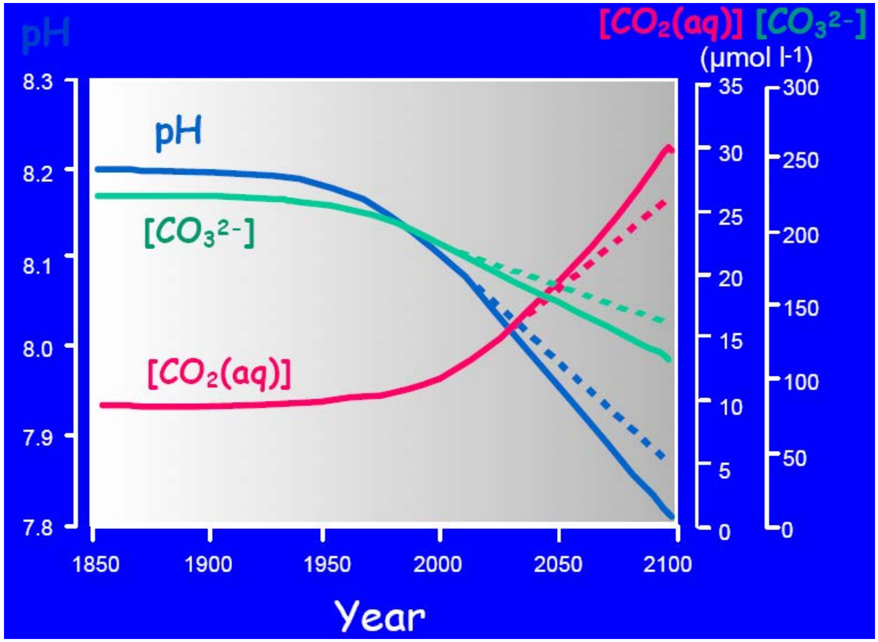
$$H^+ + CO_3^{2-} \rightarrow HCO_3^-$$

$$\underbrace{H_2O + CO_2}_{\text{acid}} + \underbrace{CO_3^{2-}}_{\text{base}} \rightarrow 2HCO_3^-$$

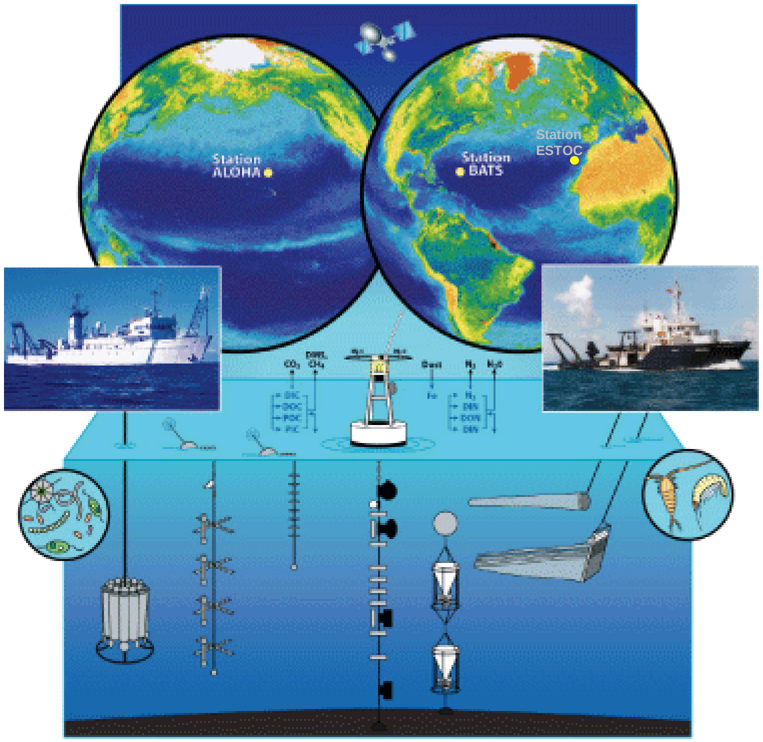
CO_2 is an acid gas

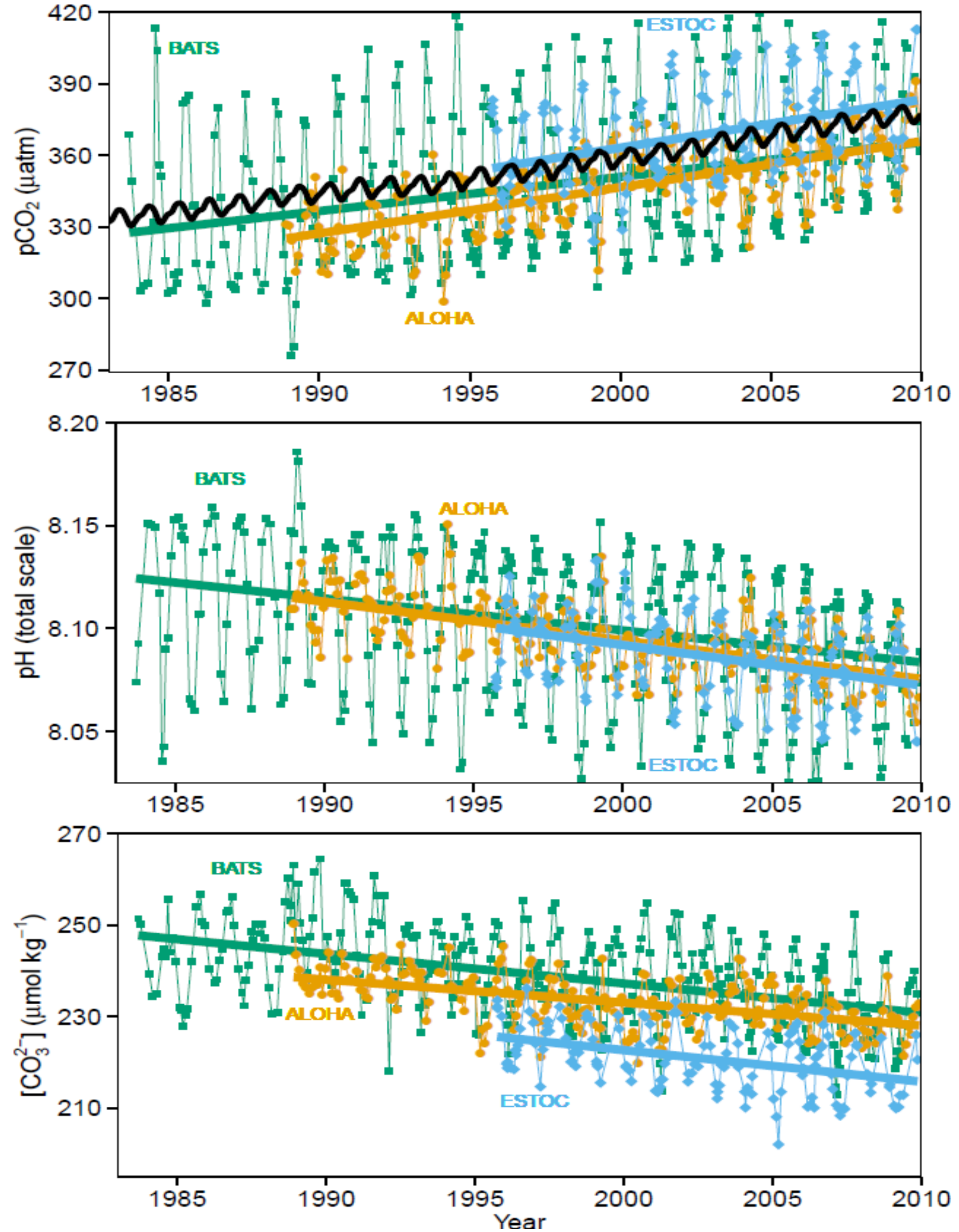
Ocean acidity +26% during industrial era, so far

$$\uparrow [H^+] = \sqrt{\frac{K'_1 K'_2 [CO_2]}{[CO_3^{2-}]}} \quad \begin{matrix}\uparrow \\ \downarrow\end{matrix}$$



Change in pH from ocean acidification already measurable

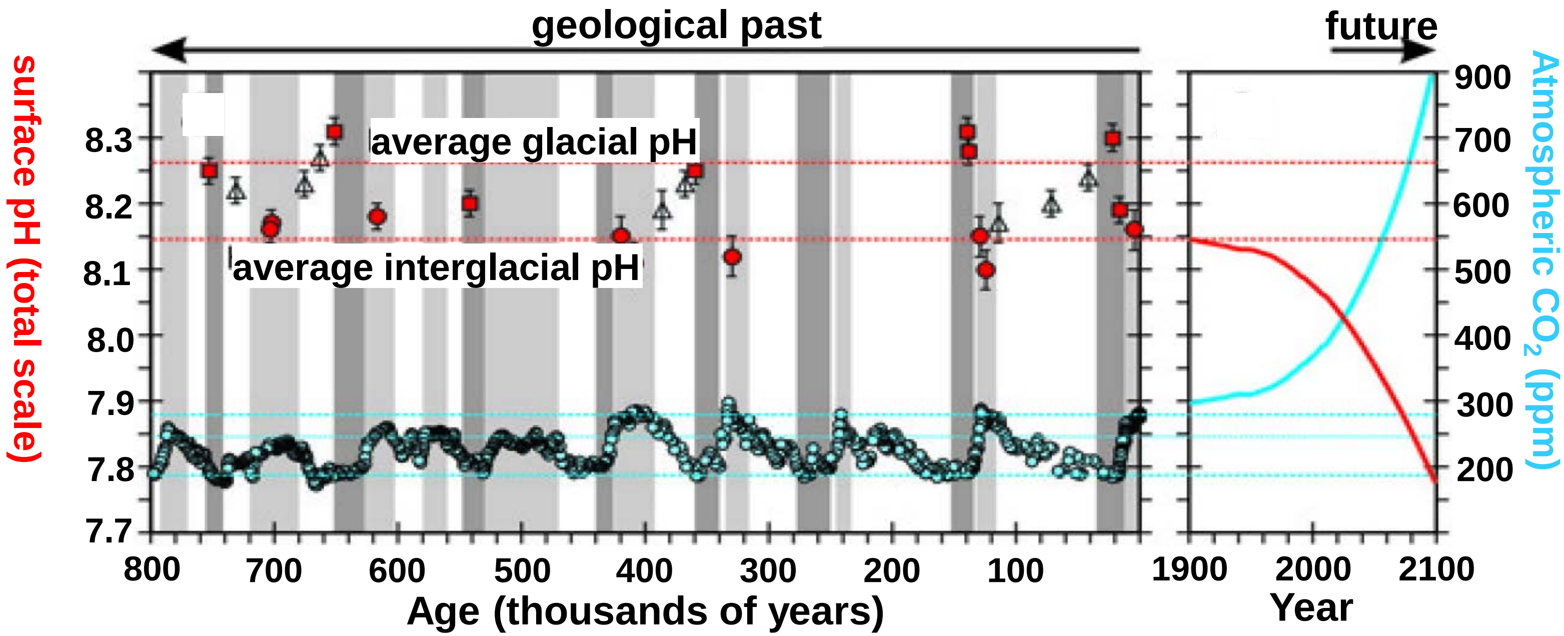




Data:
Bates (2007)
Dore et al. (2009)
Santana-Casiano et al. (2007)
Gonzàles-Dàvila et al. (2010)

IPCC AR5 WG1 Report, Chap. 3 (2013)

Today's rate of ocean acidfication may be unprecedented

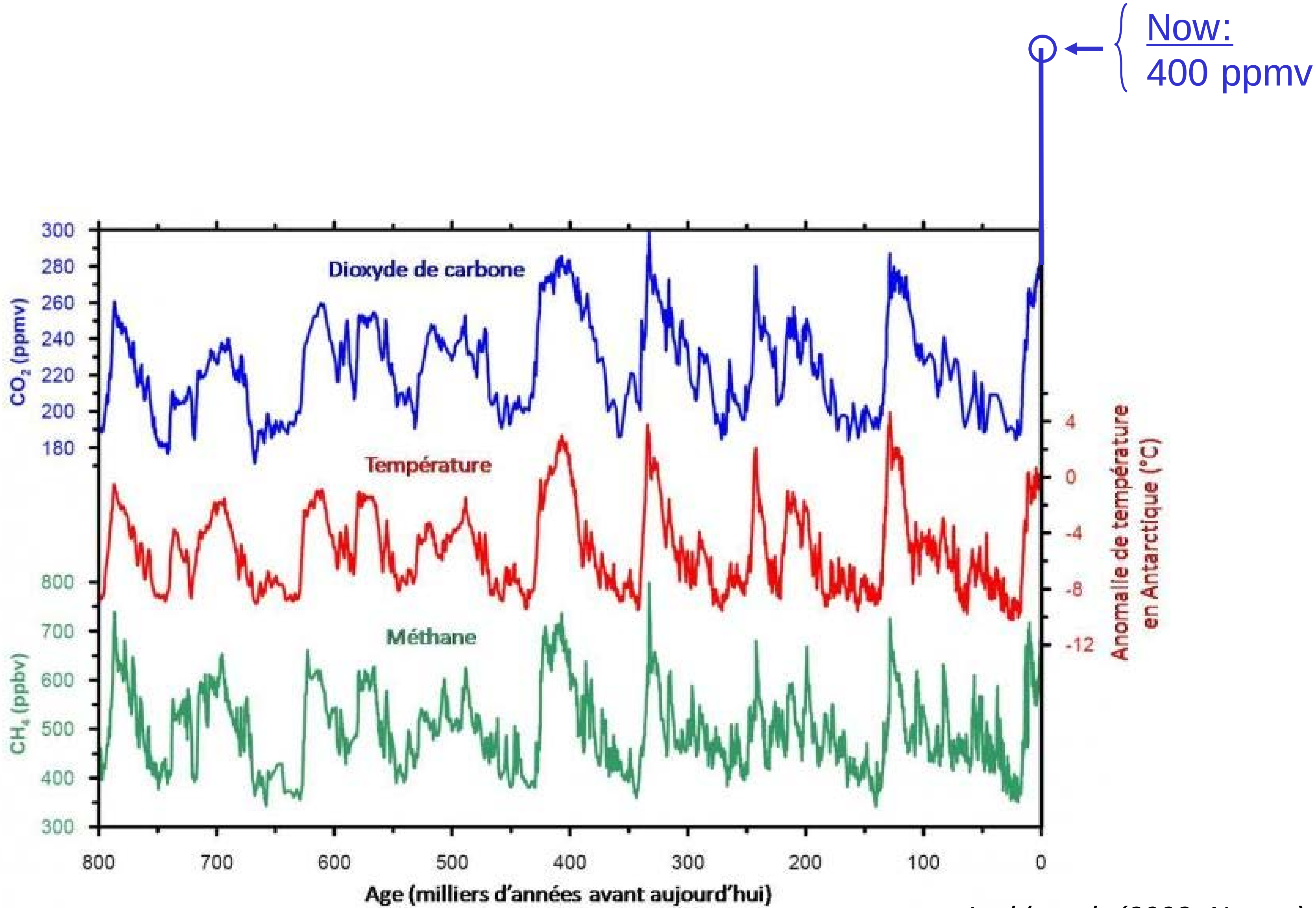


Barker and Ridgwell (2012)

Current change:

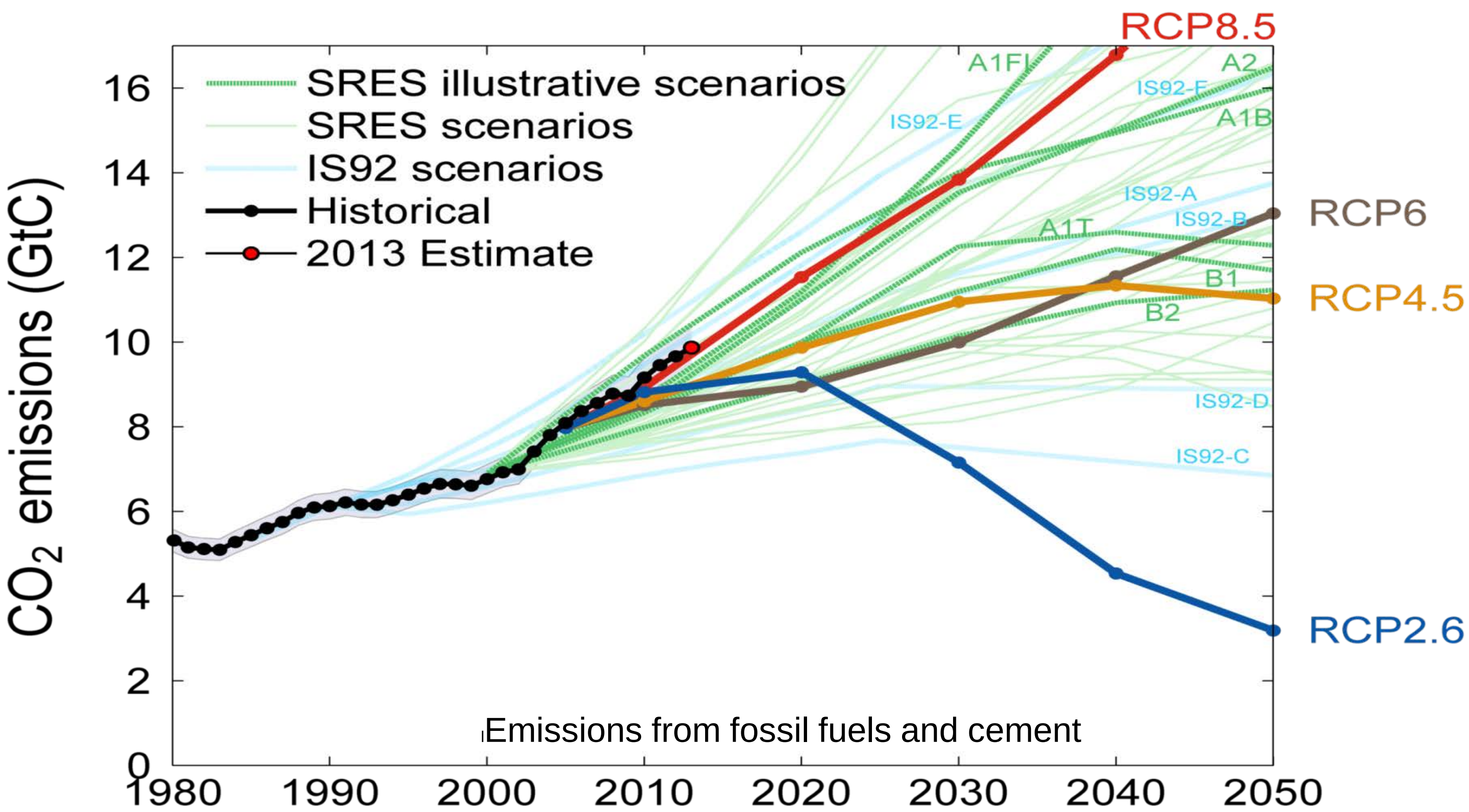
- overwhelms natural variations (last 800 000 years)
- may be 10 times faster than natural event (55 million years ago)
- rate may be unprecedented (over last 300 million of years)
- 26% increase in acidity (H^+) during industrial era
- 100% increase (or more) projected by 2100

Today's ocean acidfication appears as instantaneous spike



Luthi et al. (2008, Nature)

Current emissions tracking high emission scenarios

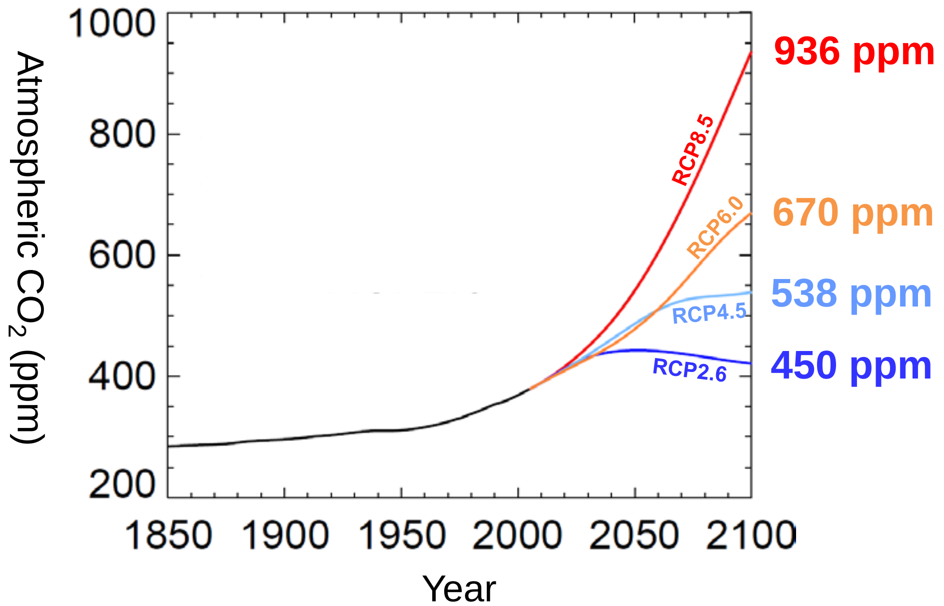


IPCC: 4 generations of emission scenarios

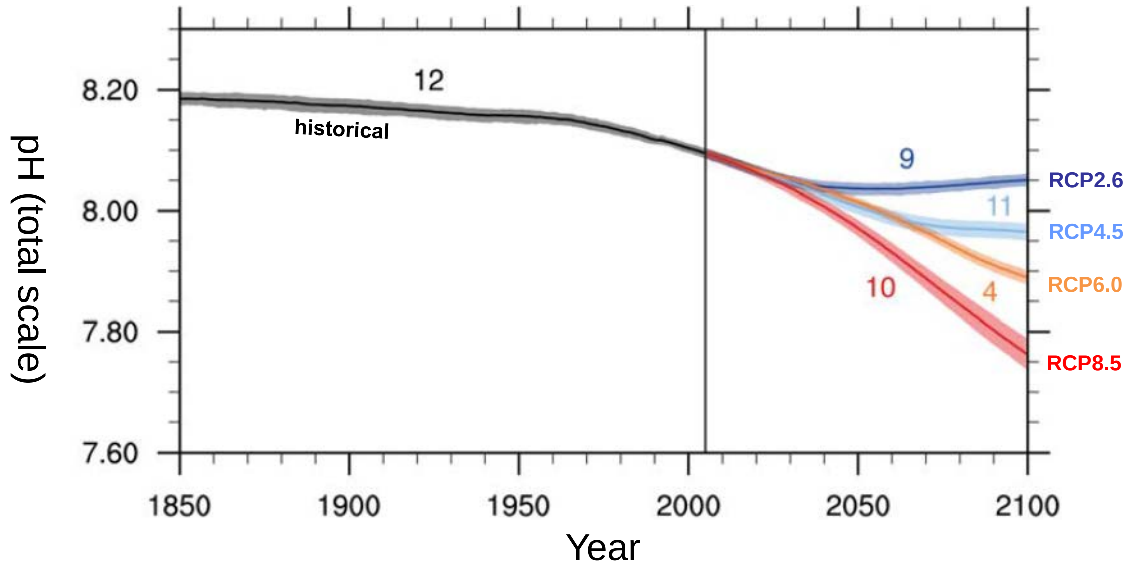
Peters et al. 2012a; CDIAC Data

Projected future surface pH ranges widely between scenarios

Future atmospheric CO_2 (latest IPCC scenarios)



Intensity of ocean acidification (change in pH) varies by a factor of 3

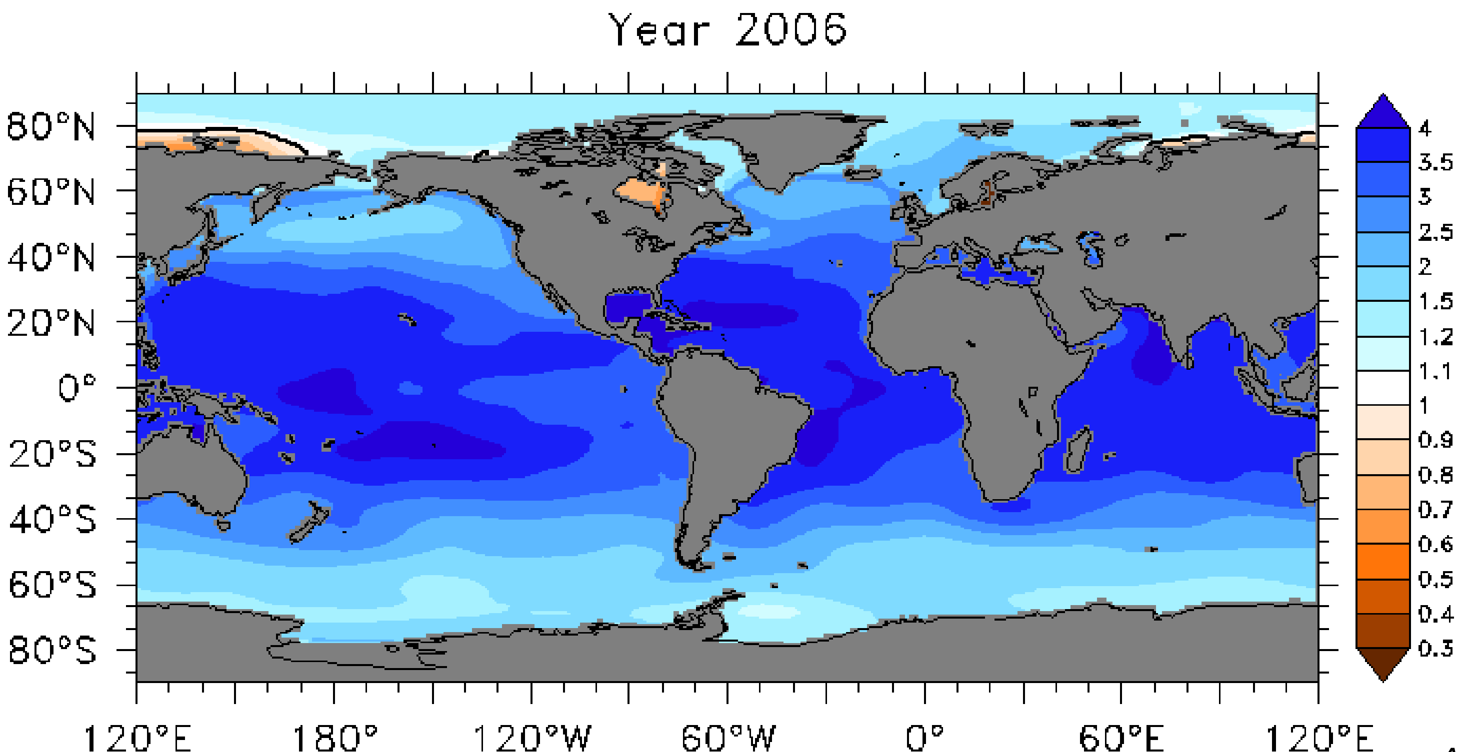


IPCC AR5 WG1, Technical Summary (2013)

see also Bopp et al. (2013)

Polar oceans corrosive to shell material within decades

Models project that cold waters soon become corrosive to aragonite, a ($CaCO_3$) mineral in some marine shells & skeletons



Corrosivity of waters to aragonite (when < 1, aragonite dissolves)

Animation
Copyright: James C. Orr

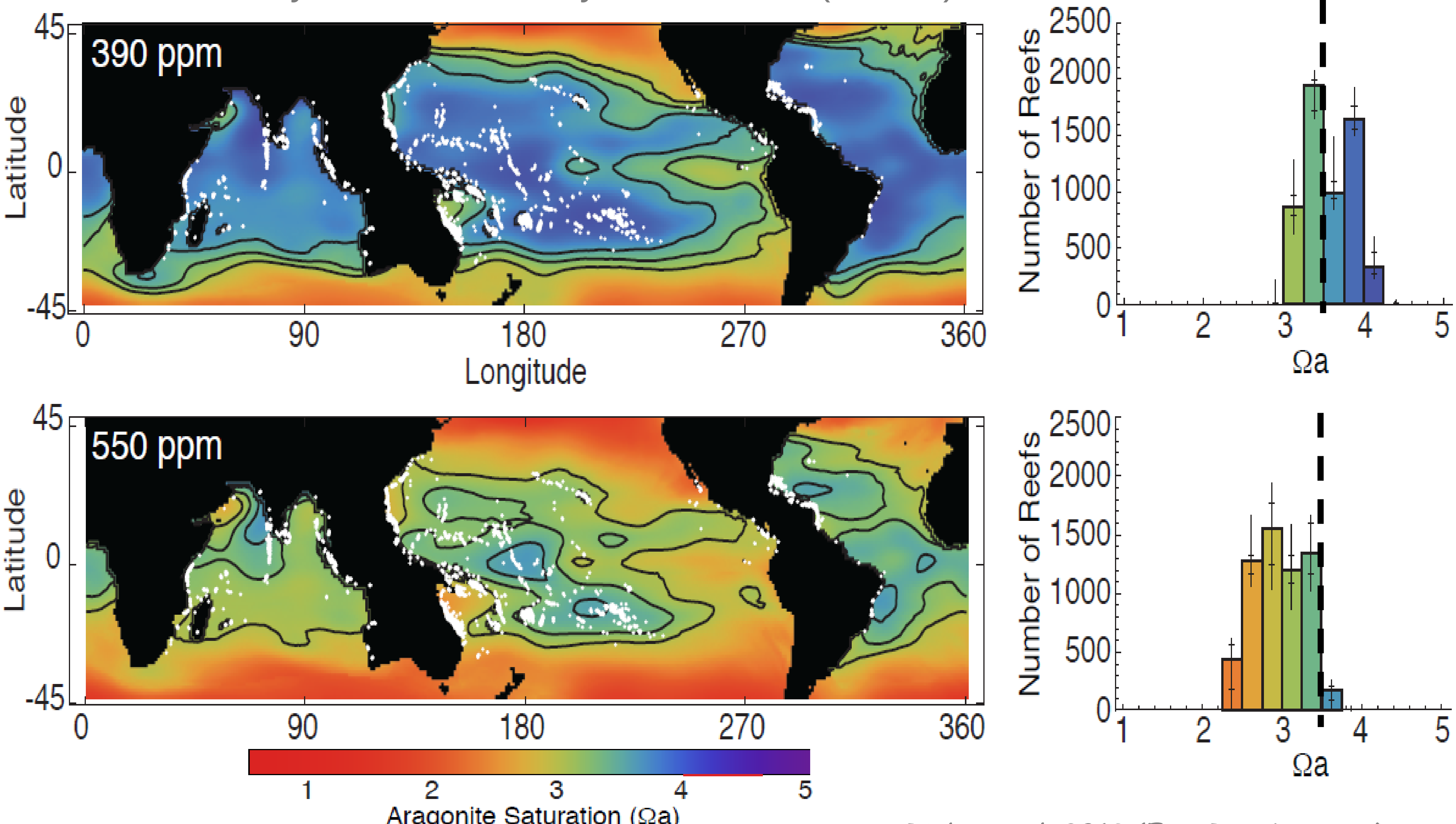
Latest model projections (IPCC AR5 WG1, 2013)

Confirms original warnings: Orr et al. (2005), Caldeira & Wickett (2005), Steinacher et al. (2009)

see also Bopp et al. (2013)

Most tropical corals exposed to potentially unsustainable chemical conditions by mid-century (e.g., $\Omega_{arag} < 3.0$)

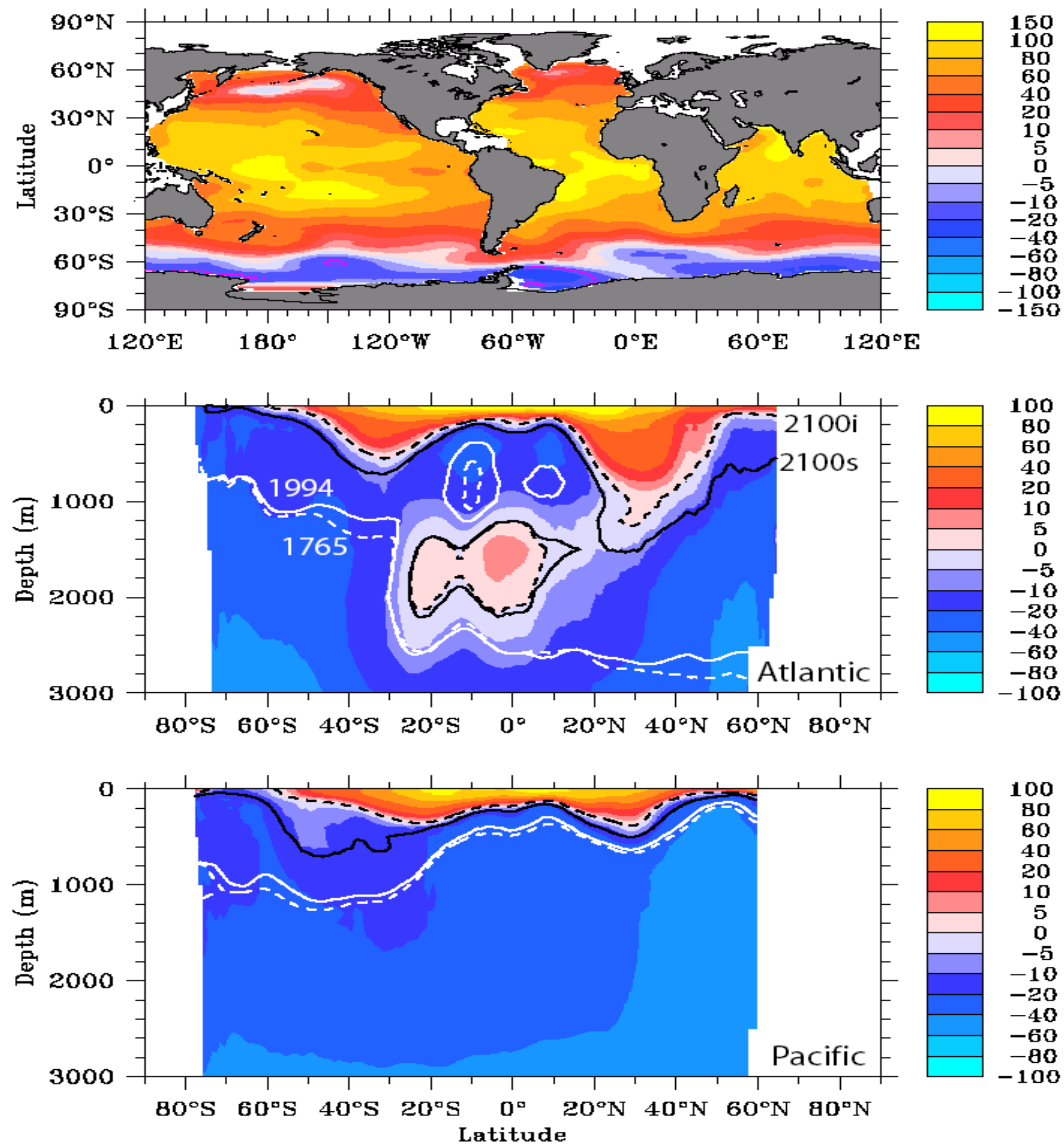
Analysis of 13 Earth System Models (CMIP5)



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

By 2100... Large changes in subsurface saturation state ($\Delta[CO_3^{2-}]_A$) [in μmol kg-1]

- Surface undersaturation ($\Delta[CO_3^{2-}]_A < 0$)
  - Southern Ocean
  - Subarctic Pacific
- Shoaling of the aragonite saturation horizon (i.e., $\Delta[CO_3^{2-}]_A = 0$)
  - Southern Ocean
    (by ~1000 m)
  - North Atlantic
    (by ~3000 m)



Orr et al. 2005 (Nature)

Most cold-water corals (made of aragonite) will be exposed to these corrosive conditions before 2100

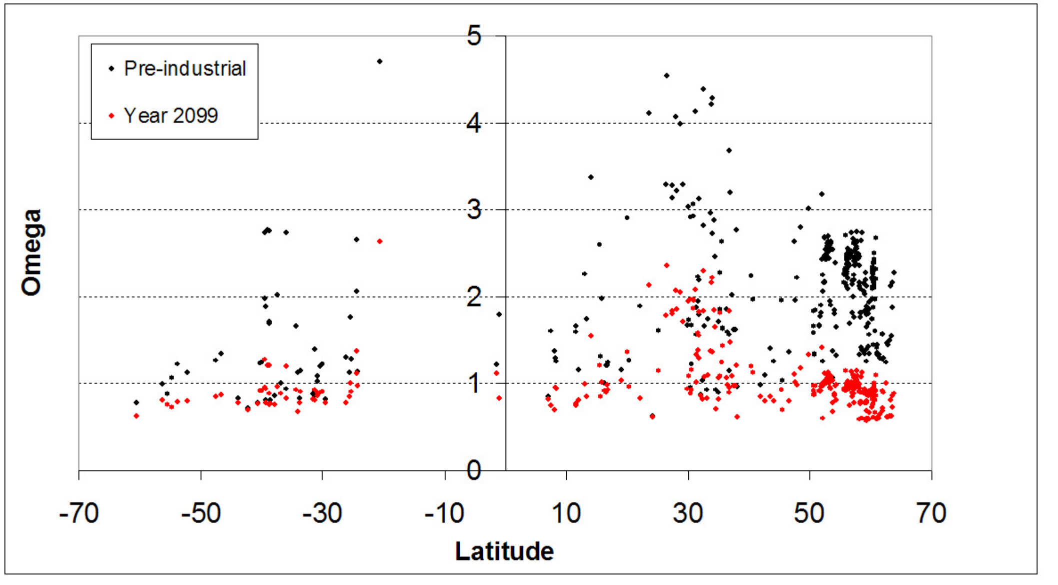
Deep, cold-water corals:

2005 : 95% avec $\Omega_A > 1$

2100 : 35% avec $\Omega_A > 1$

Lophelia pertusa

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)

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

Day 1

Day 2

Day 16

Image: Victoria Fabry, California State University San Marcos

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)

Manipulative studies used to evaluate biological responses

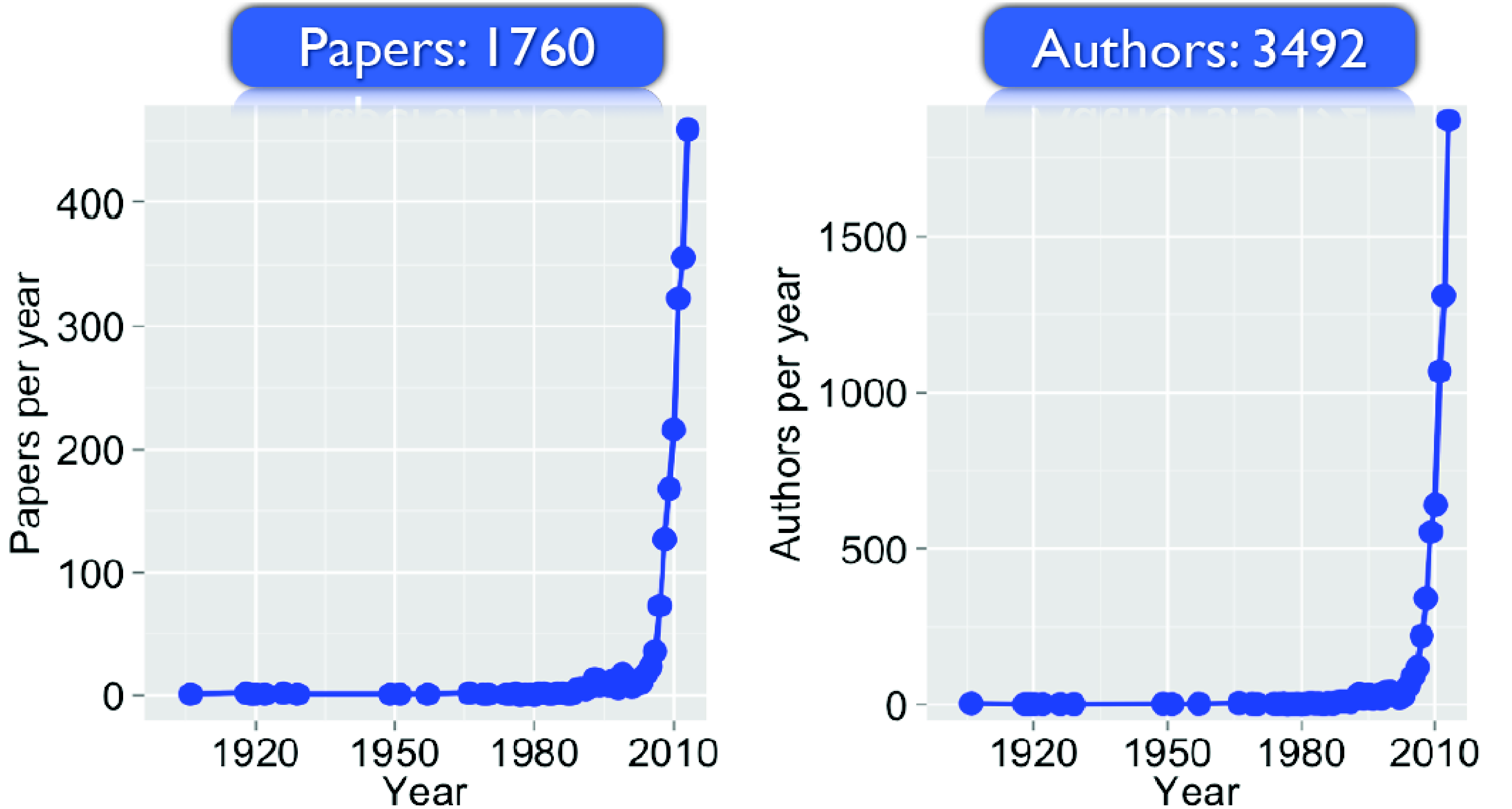
- Lab perturbation experiments

- Field observations near CO_2 vents
(natural, long-term perturbations)

- Mesocosm experiments (in the water; on the sediments)

- Free Ocean CO_2 Enrichment (FOCE) experiments

Acidification research in its infancy; growing exponentially

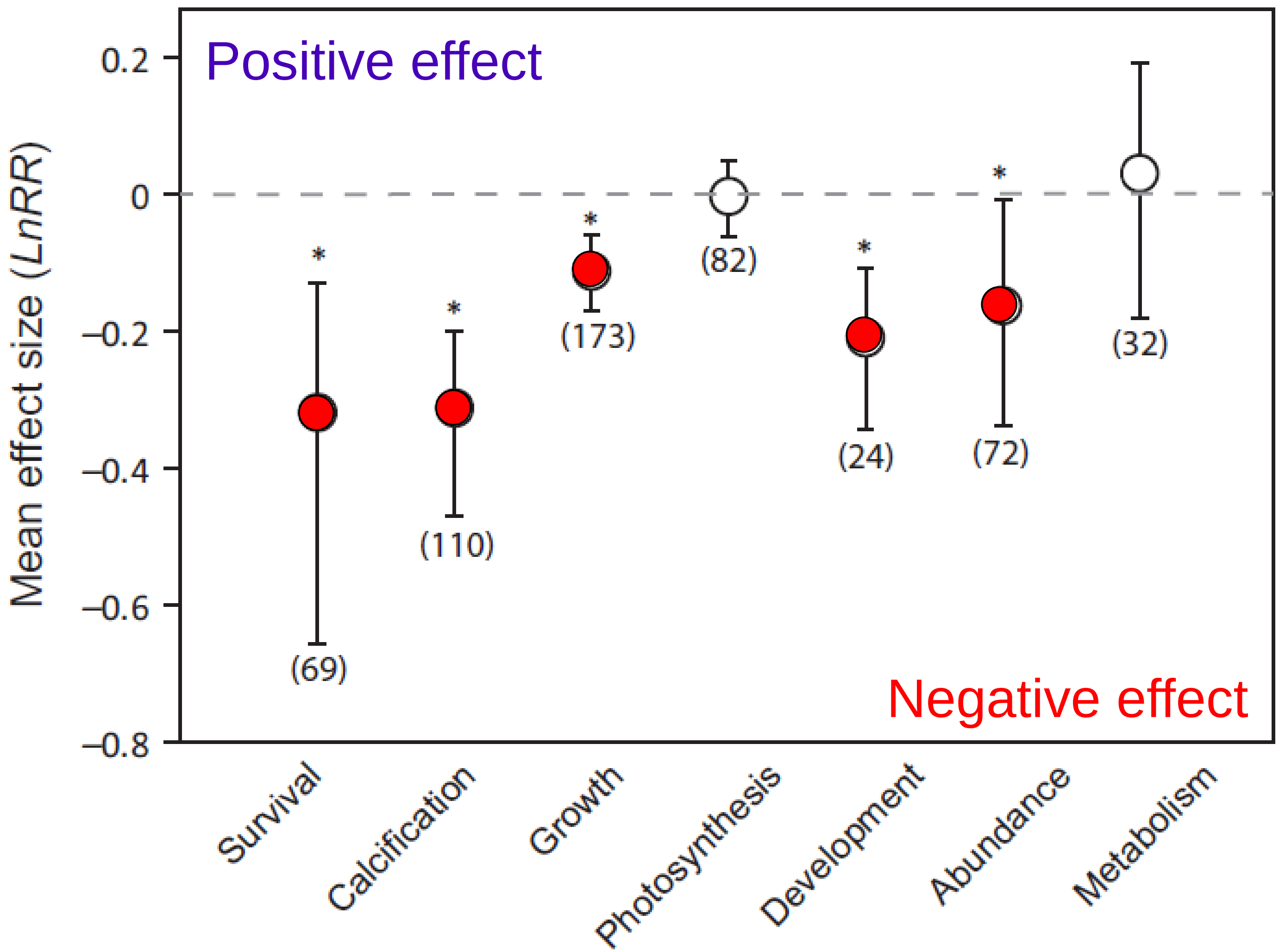


	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
papers	18	24	36	73	127	168	216	323	356	459
authors	58	92	120	221	341	554	640	1068	1312	1868

Update of Gattuso & Hansson (2011); Gattuso et al. (2011)

OA: #1 research front in Ecol. & Environ. Sci. (Thompson-Reuters Web of Knowledge)

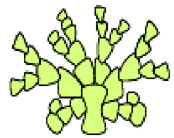
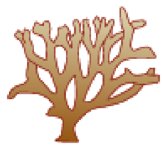
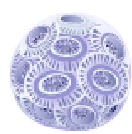
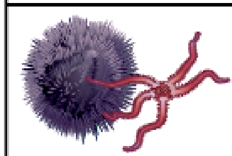
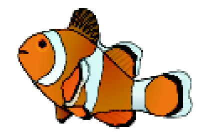
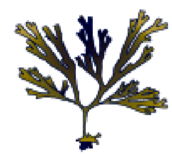
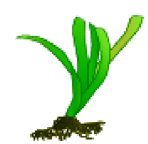
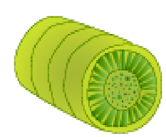
Acidification adversely affects diverse groups



Kroeker et al. (2013, Global Change Biol.)

But large diversity of effects on different groups

Legend
Enhanced <25%
No effect
Reduced <25%
Reduced >25%
Not tested

Taxa	Response	Mean Effect
 Calcifying algae	Survival	
	Calcification	
	Growth	
	Photosynthesis	-28%
	Abundance	-80%
 Corals	Survival	
	Calcification	-32%
	Growth	-23%
	Photosynthesis	
	Abundance	-47%
 Coccolithophores	Survival	
	Calcification	-9%
	Growth	
	Photosynthesis	
	Abundance	
 Molluscs	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	
 Fleshy algae	Survival	
	Calcification	
	Growth	+22%
	Photosynthesis	
	Abundance	
 Seagrasses	Survival	
	Calcification	
	Growth	
	Photosynthesis	
	Abundance	
 Diatoms	Survival	
	Calcification	
	Growth	+12%
	Photosynthesis	
	Abundance	

Kroeker et al. (2013, Global Change Biol.)

Acidification likely to change marine ecosystems

Organisms react differently

Corals and shell builders decline

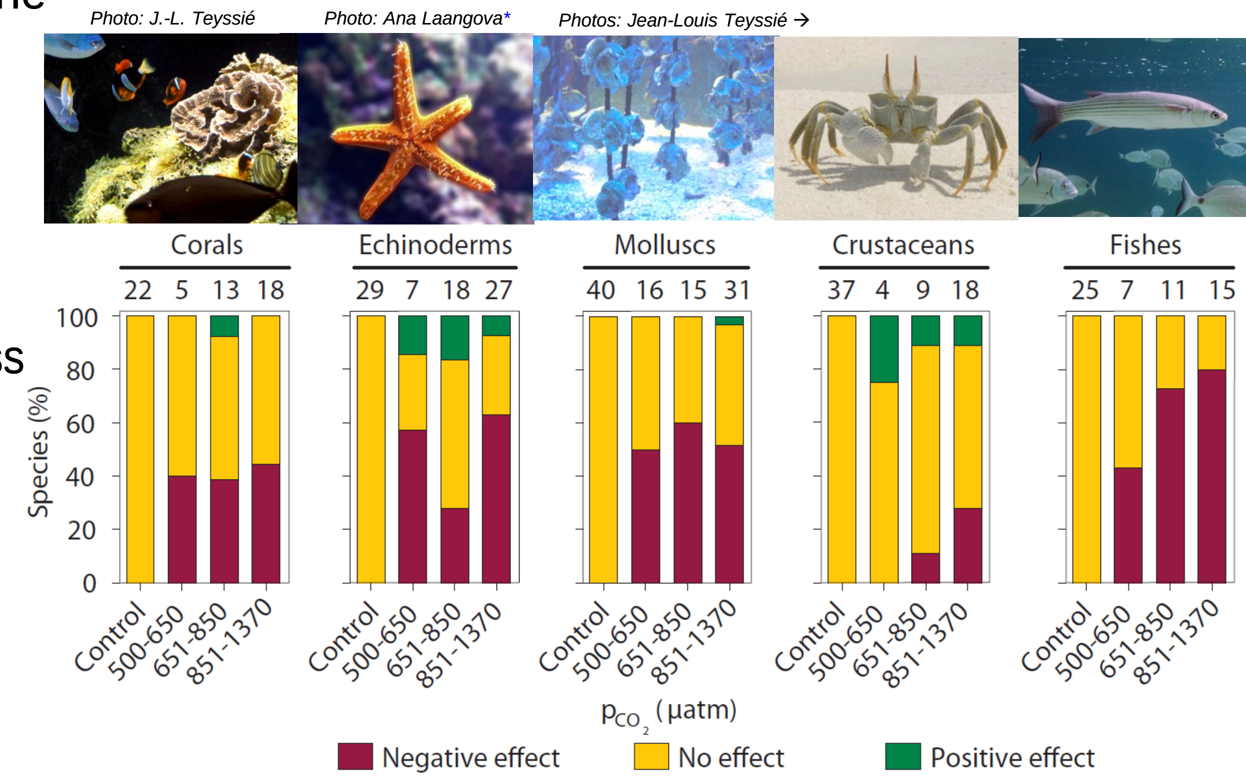
Seagrasses may increase

Fish become disoriented

Predators affected by prey loss

Potential fish catch decline

Synthesis of existing experimental studies



Wittmann & Pörtner (2013, Nature Clim. Change)

Ocean areas naturally rich in CO_2 confirm expected future trends

- Less biodiversity
- Fewer calcifiers
- More fragile shells
- More invasive species
- More seagrasses, degraded corals

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)

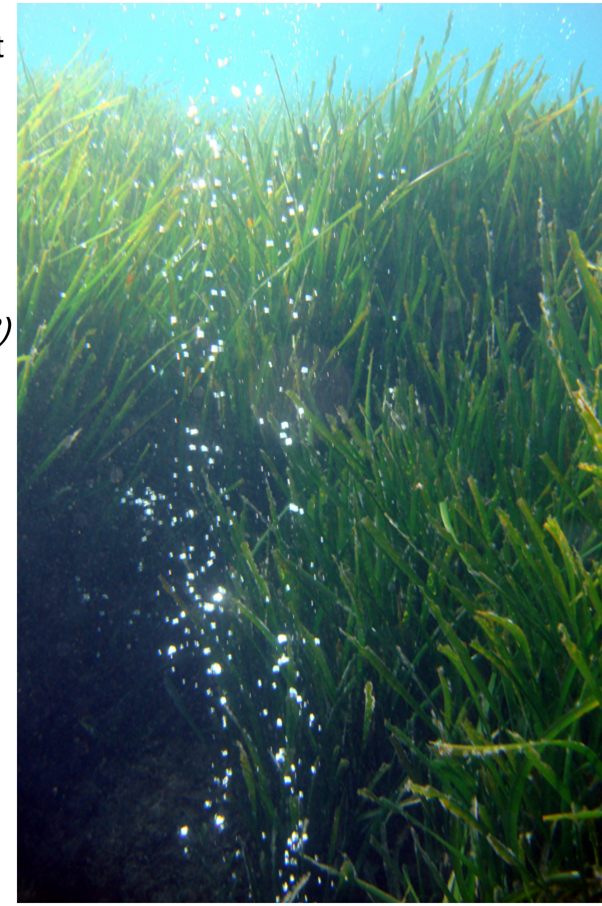


Photo: Jason Hall-Spencer, University of Plymouth

Photo: Steve Ringman, Seattle Times

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

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

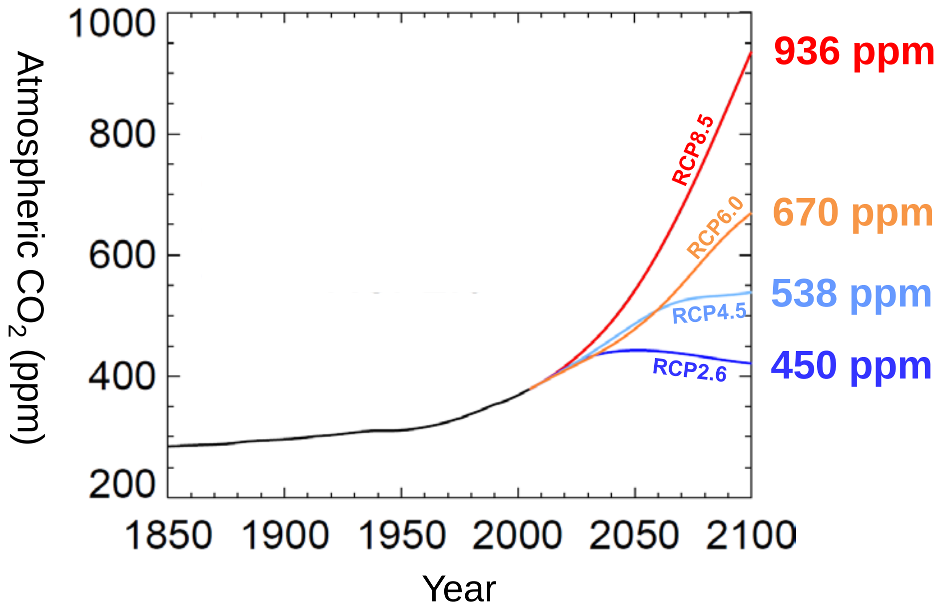
- Ocean acidification not happening in isolation

Photo: Rodolfo Quevenco, IAEA

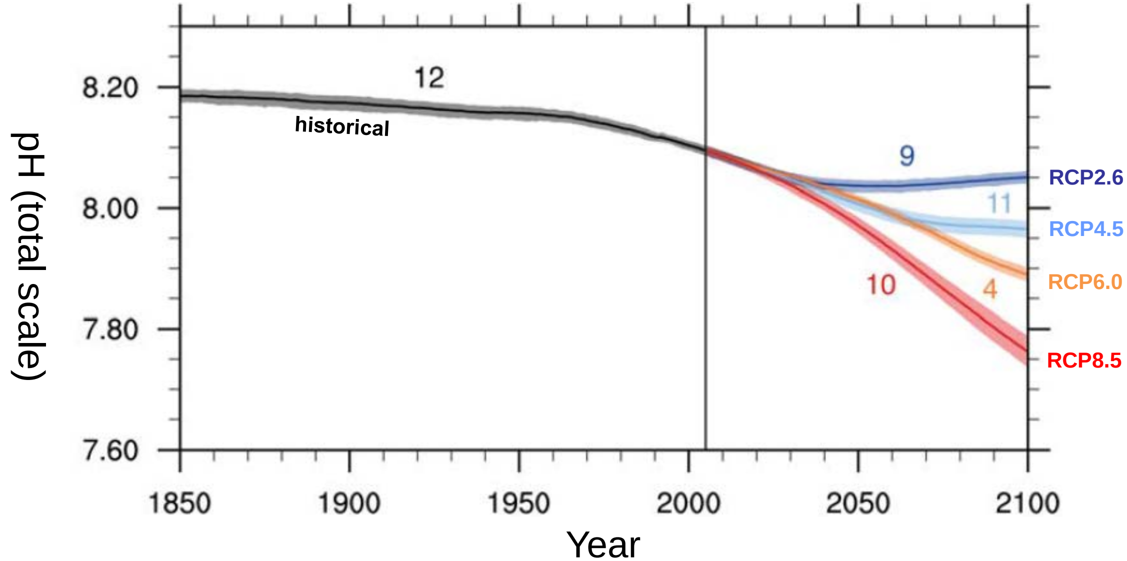
Photo: Jean-Louis Teyssié, IAEA

The intensity of ocean acidification depends on us

Future atmospheric CO_2 (latest IPCC scenarios)



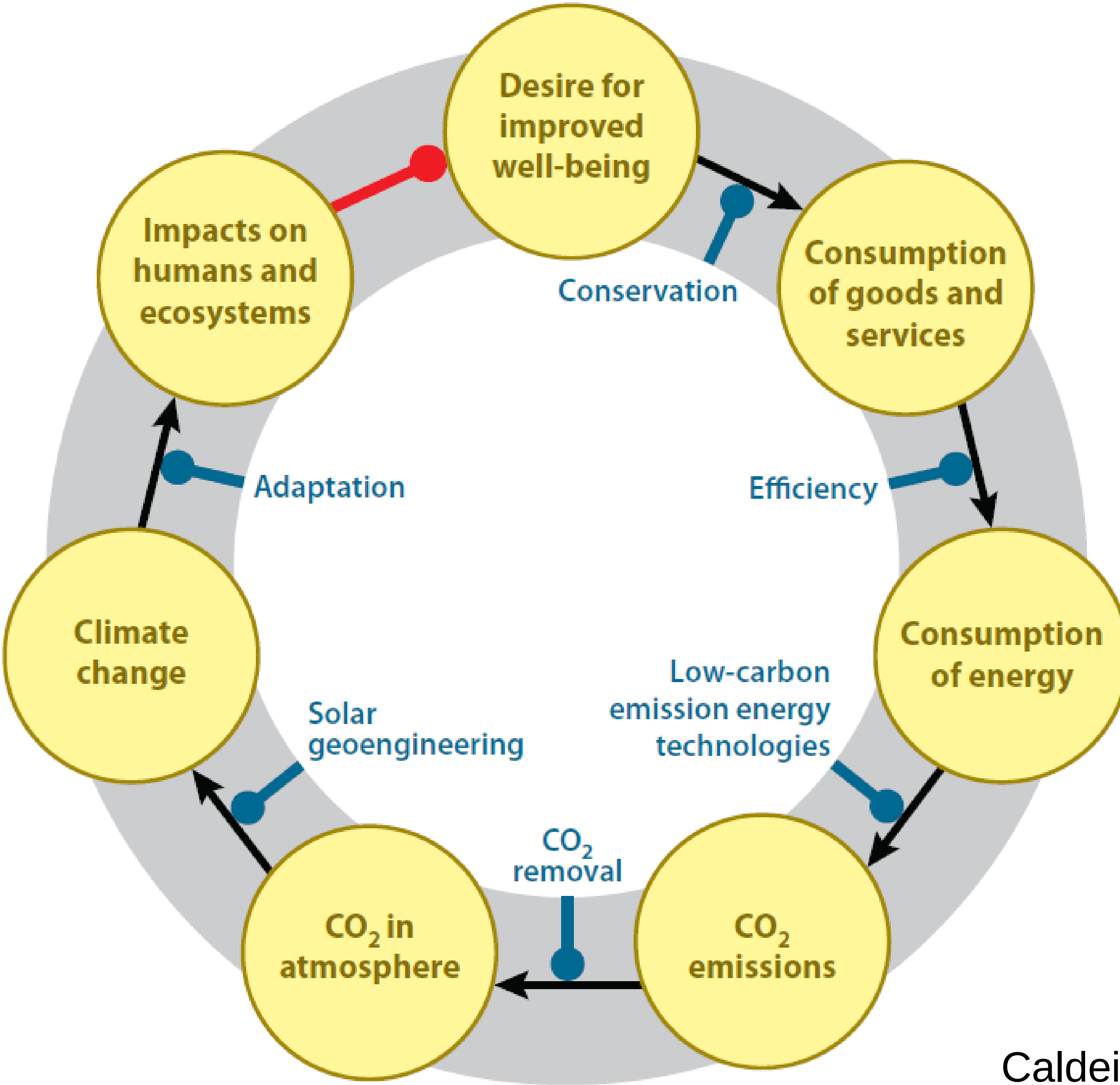
Intensity of ocean acidification (change in pH) varies by a factor of 3



IPCC AR5 WG1, Technical Summary (2013)

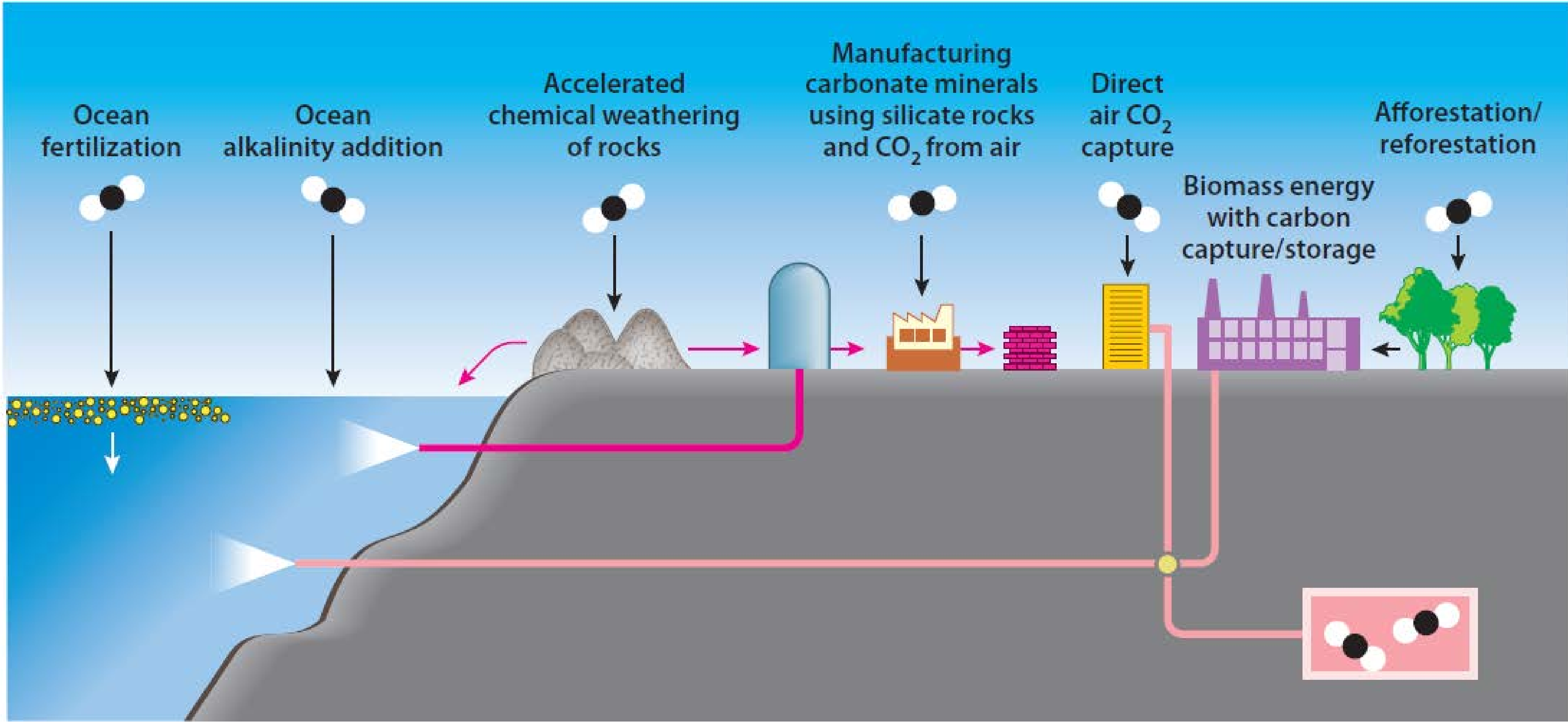
see also Bopp et al. (2013)

Diverse measures required to limit CO_2 buildup



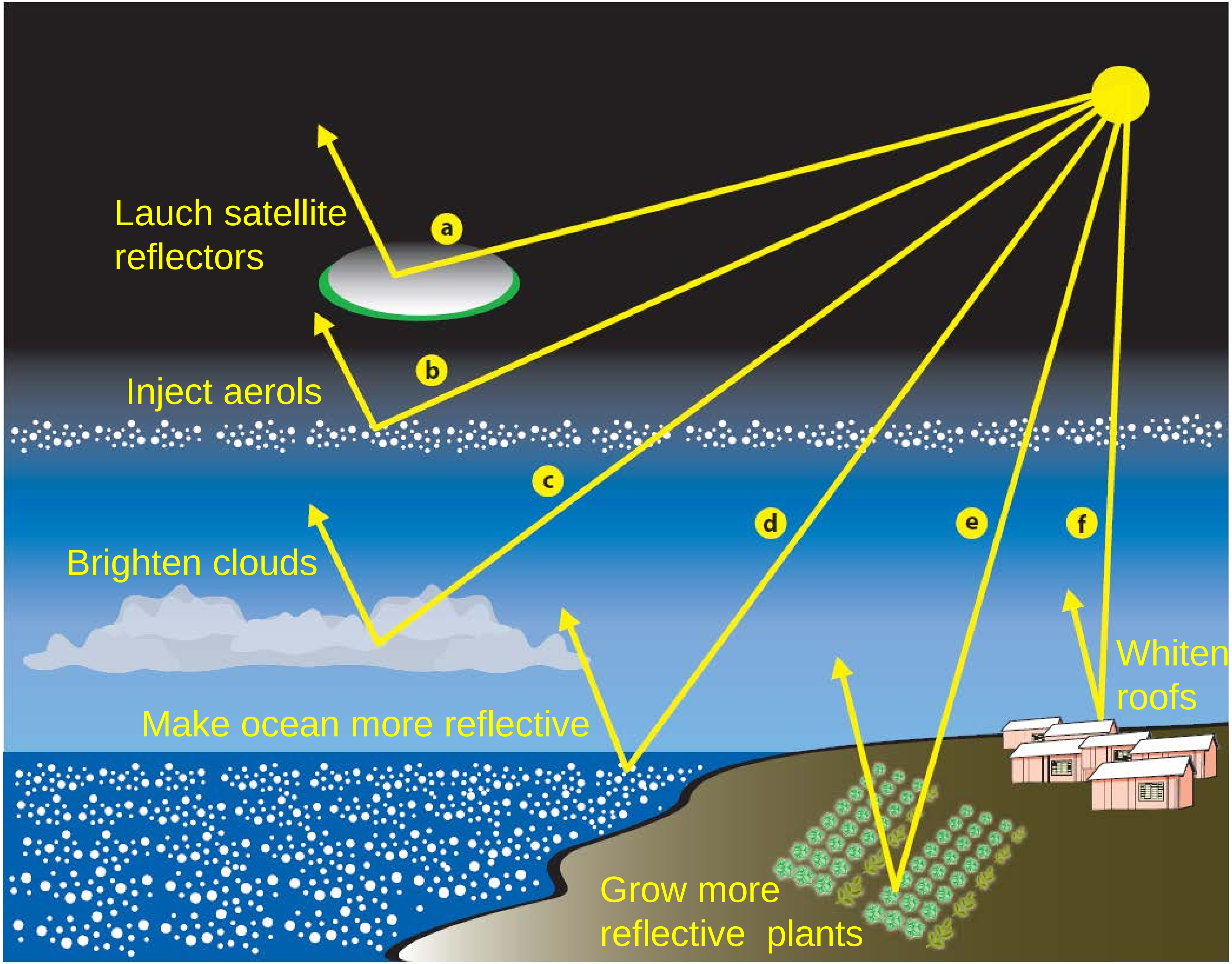
Caldeira et al. (2013)

Many proposals for CO_2 removal (CDR)



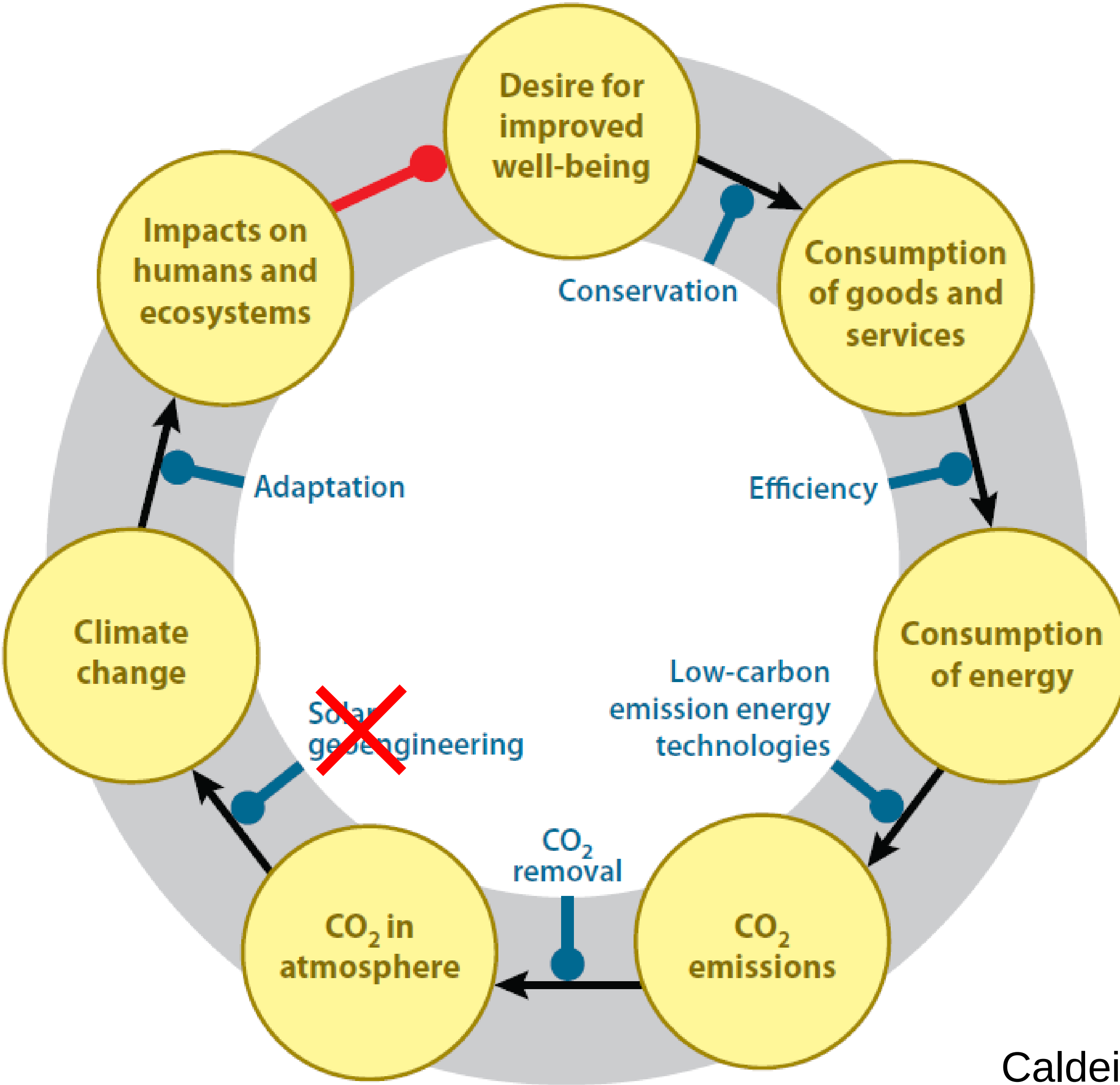
Caldeira et al. (2013)

Solar radiation management – no fix for acidification



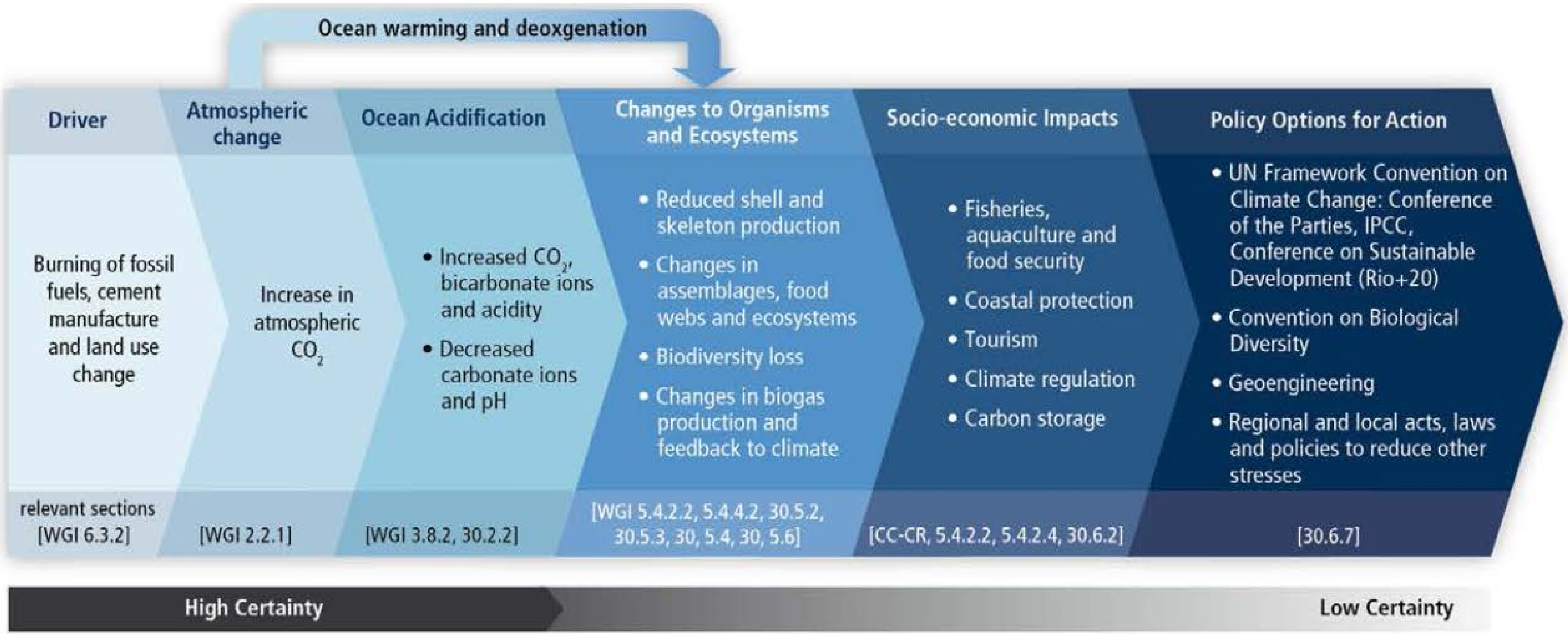
Caldeira et al. (2013)

SRM would worsen ocean acidification



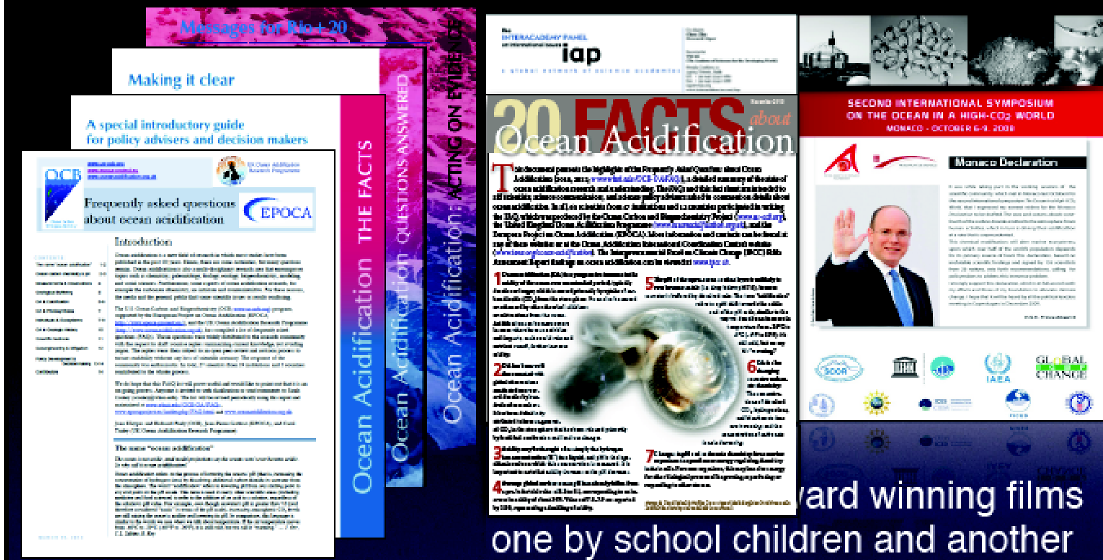
Caldeira et al. (2013)

Uncertainty grows as we try to assess how acidification affects us and how to manage it



Gattuso et al., Box CC-OA. Ocean Acidification, IPCC WGII, Final Draft, Chapter 6, 31 March 2014.

Dissemination and outreach

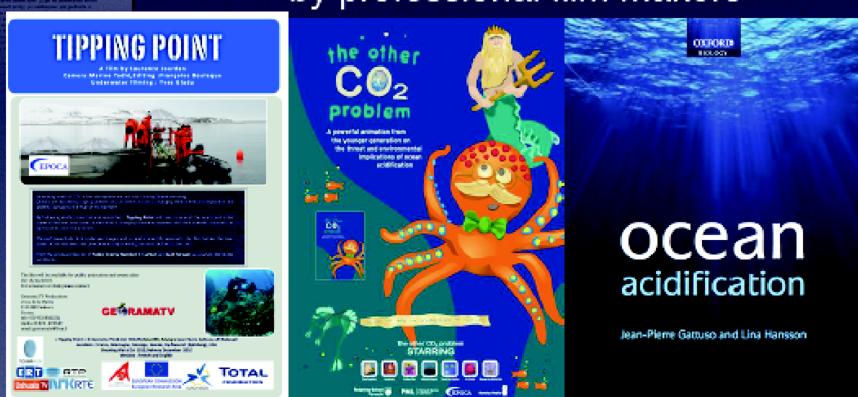


Documents for policy makers – some written by EPOCA's Reference User Group of stakeholders

World leading website and blog on ocean acidification

ard winning films one by school children and another by professional film makers

Dialogue with policy makers and media at climate change negotiations in Copenhagen, Cancun, Capetown and Warsaw



After C. Turley

Useful resources

OA-ICC web page:

http://www.iaea.org/ocean-acidification

Acidification news stream (blog):

http://news-oceanacidification-icc.org

General information:

http://ocean-acidification.net