



Ocean acidification update

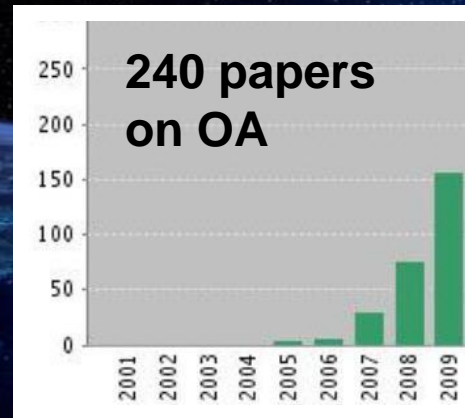
"After much research effort, we now know a lot more than when we started – although it is mostly knowing how little we now know"

Phil Williamson

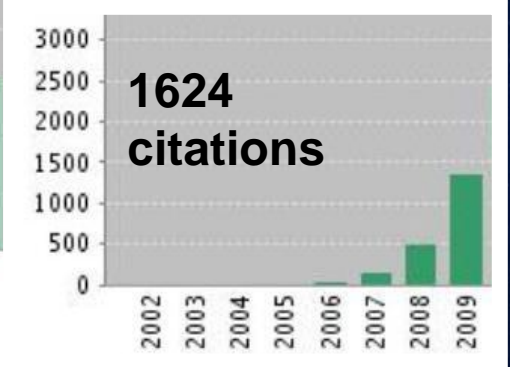
Science Coordinator (NERC/UEA)

UK Ocean Acidification research programme

Scientific interest in ocean acidification began to 'take off' around 5 years ago

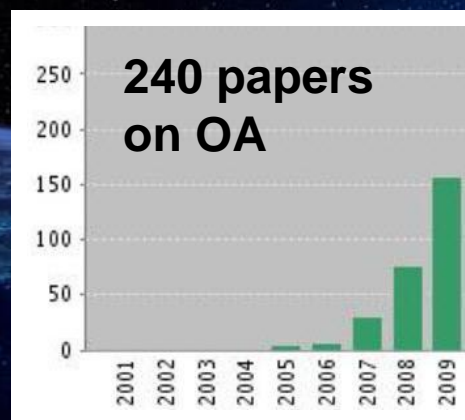


up to end of **2009**

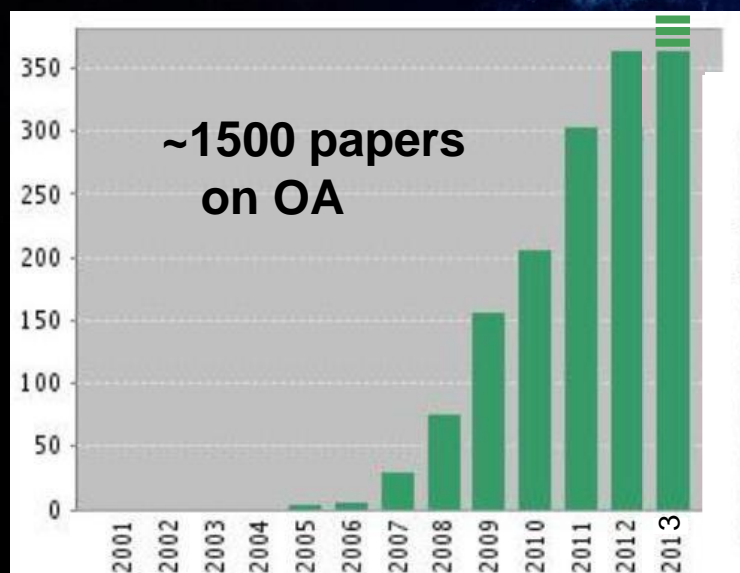
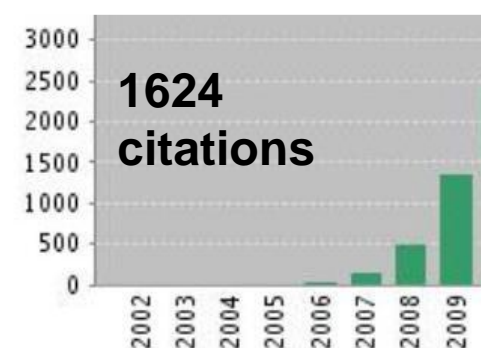


Scientific interest in ocean acidification began to 'take off' around 5 years ago

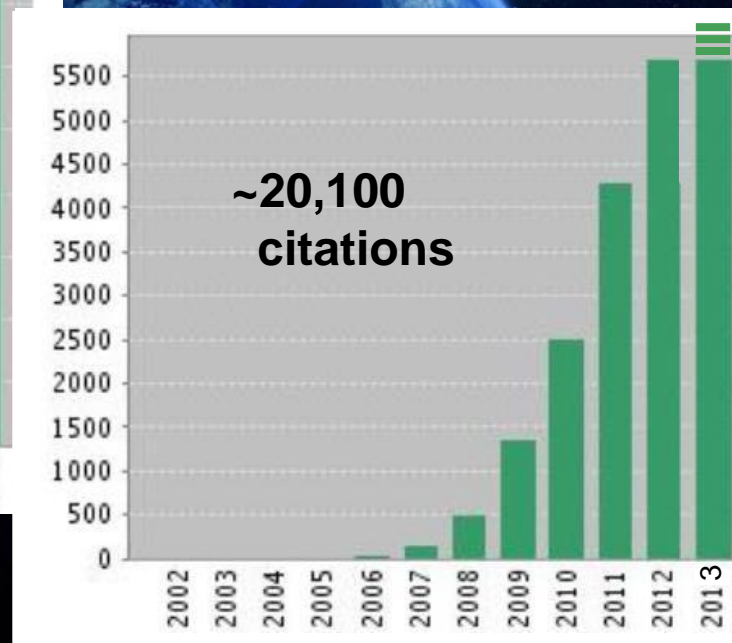
since then there has been a six-fold increase in OA publications



up to end of 2009



up to end of 2013

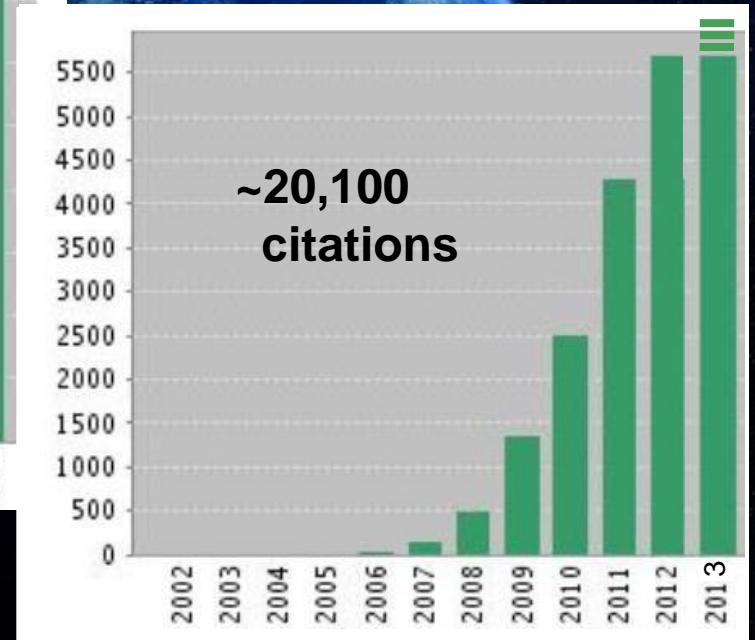
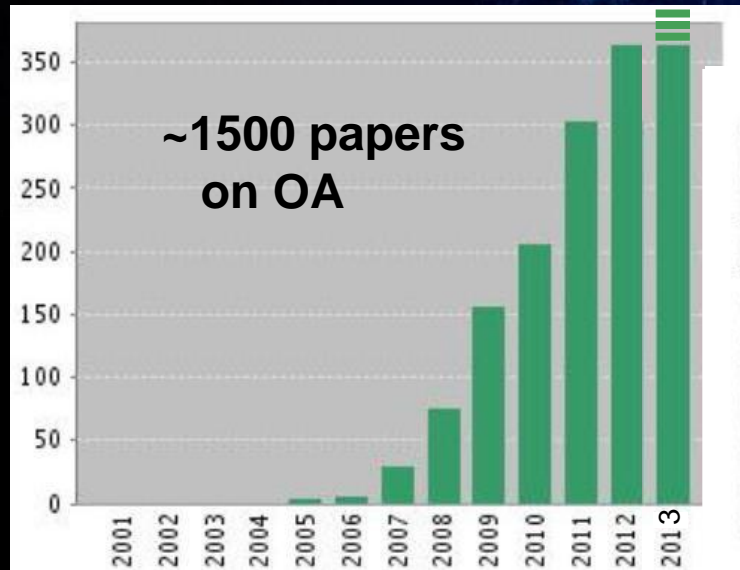
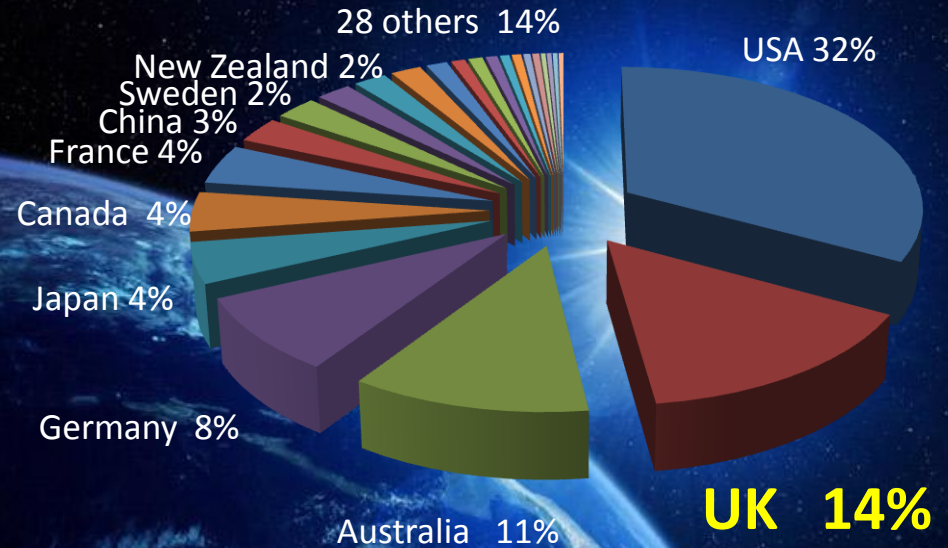


ISI World of Science data (provisional for 2013)

Scientific interest in ocean acidification began to 'take off' around 5 years ago

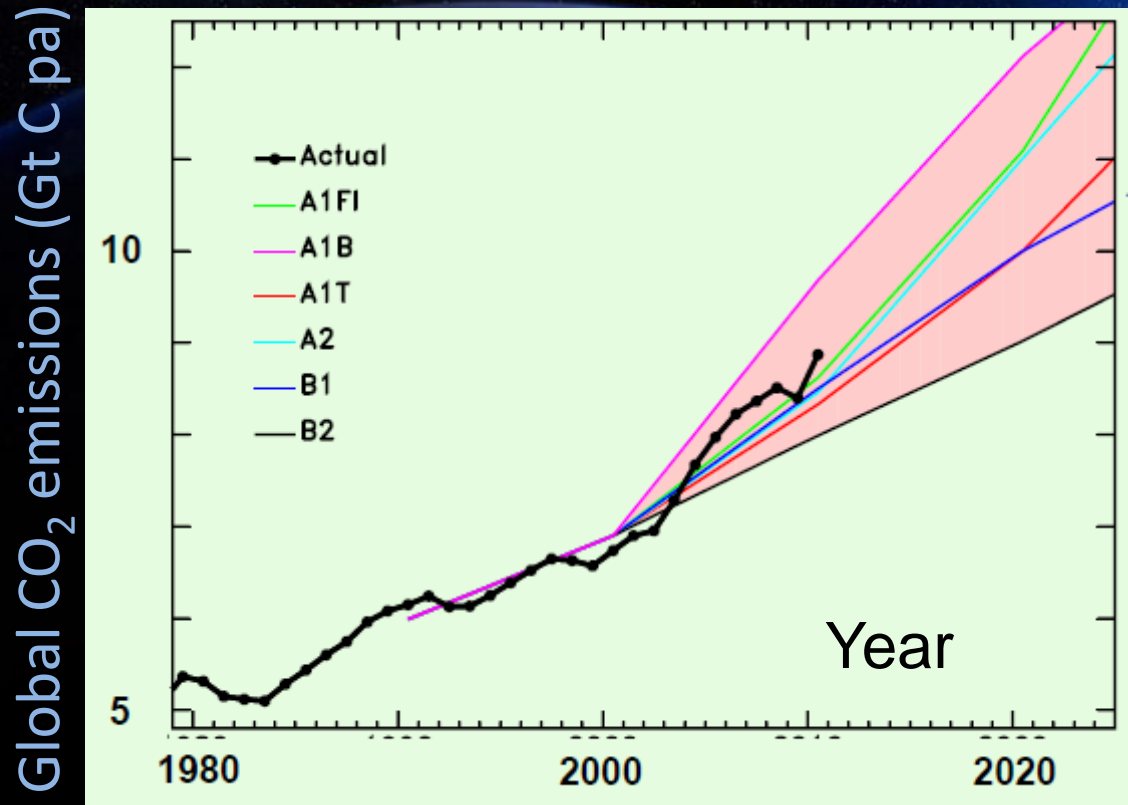
since then there has been a six-fold increase in OA publications with a major UK contribution

First authorship of OA publications 2005-11



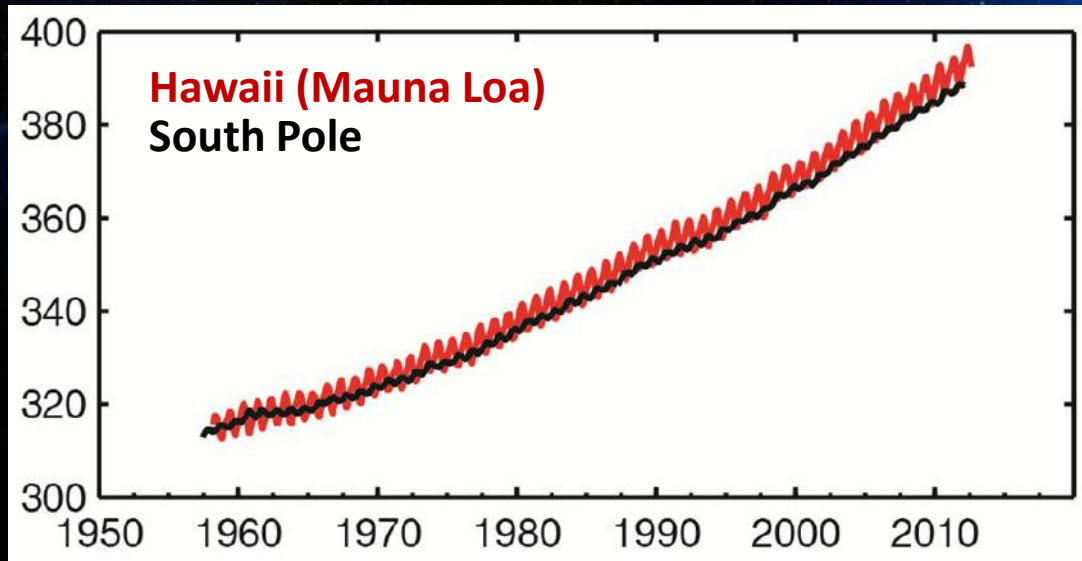
ISI World of Science data (provisional for 2013)

The driver for ocean acidification: increasing CO₂ emissions due to human activities



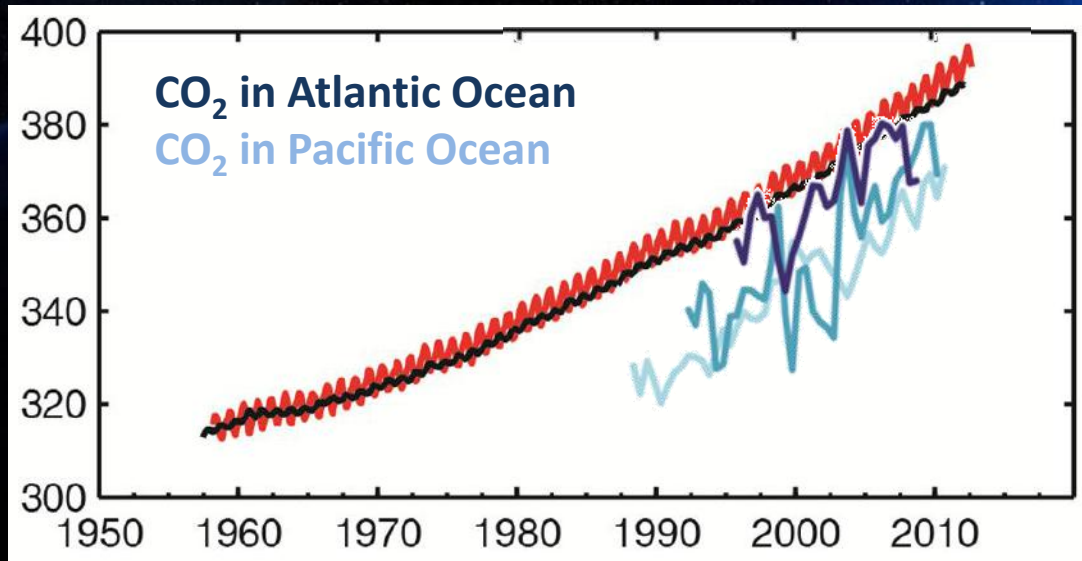
hence increased CO₂ in the atmosphere...

CO₂ in atmosphere (ppm)



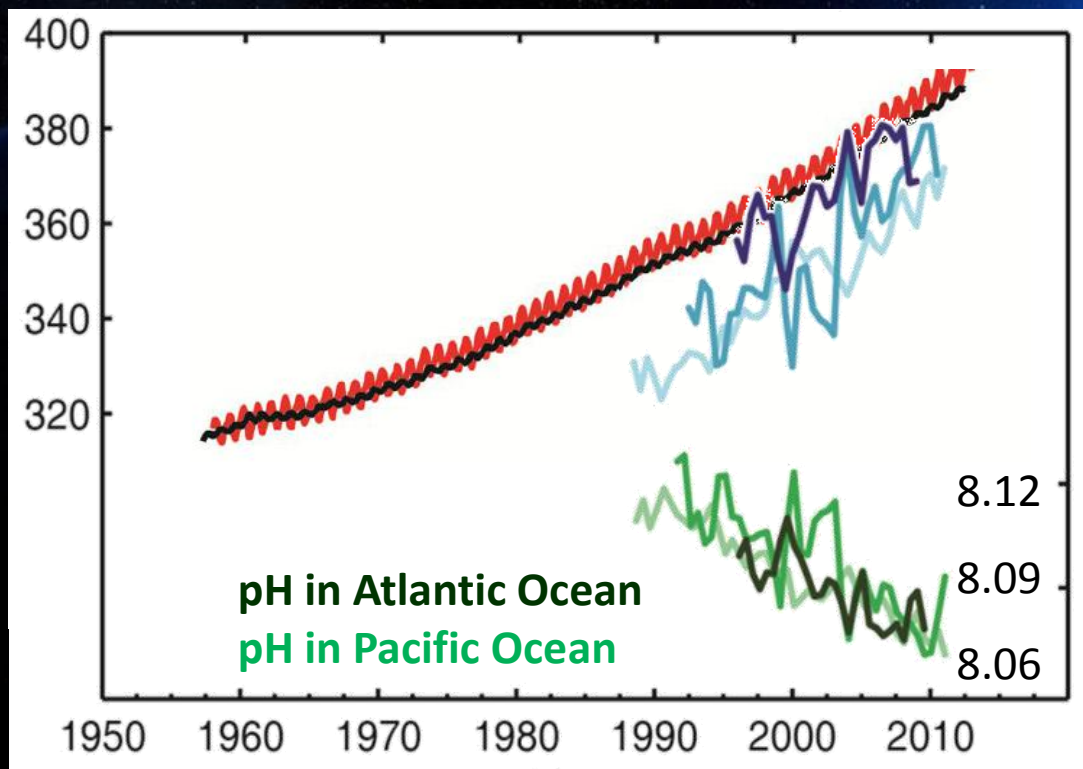
... and increased CO₂ in the upper ocean

CO₂ in upper ocean (μatm)
CO₂ in atmosphere (ppm)



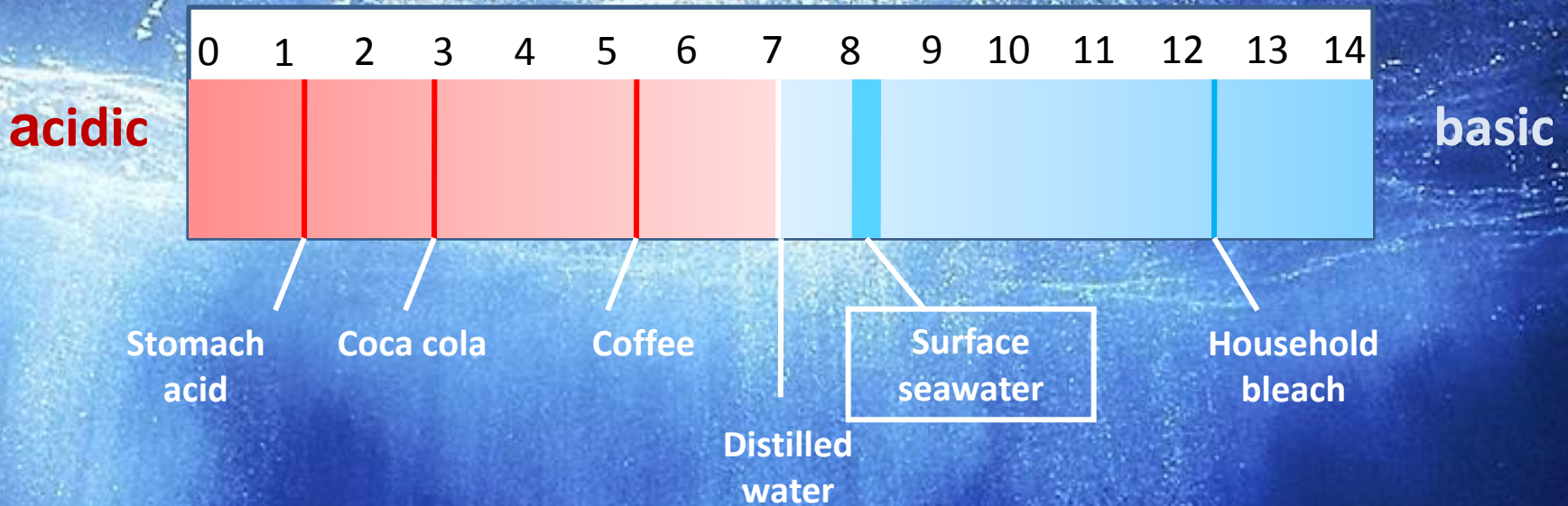
... and decreased upper ocean pH (*increased H^+*)

CO_2 in upper ocean (μatm)
 CO_2 in atmosphere (ppm)



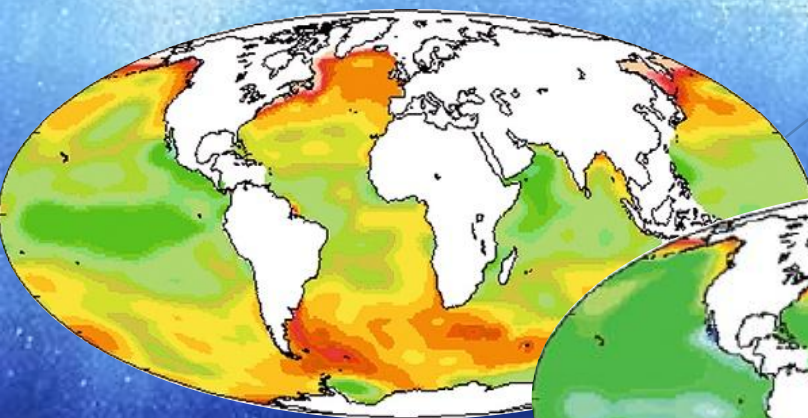
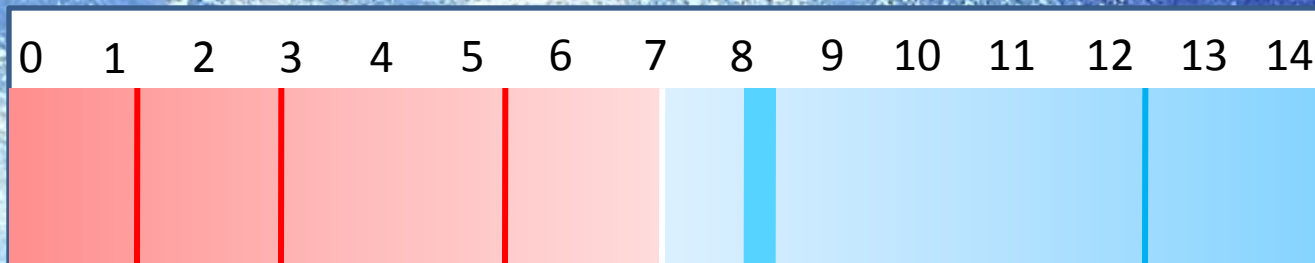
pH

pH scale: logarithmic

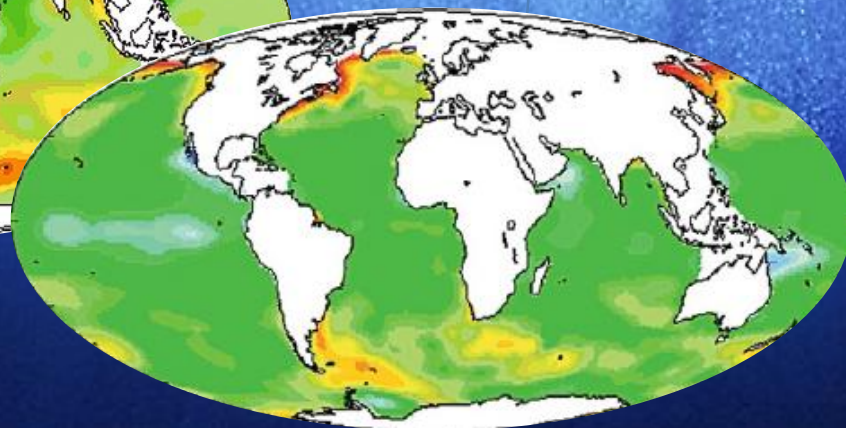


0.3 decrease in pH = doubling of H^+ concentration
(decrease is considered to be "acidification",
wherever on the scale it occurs)

pH scale: logarithmic



Pre-industrial

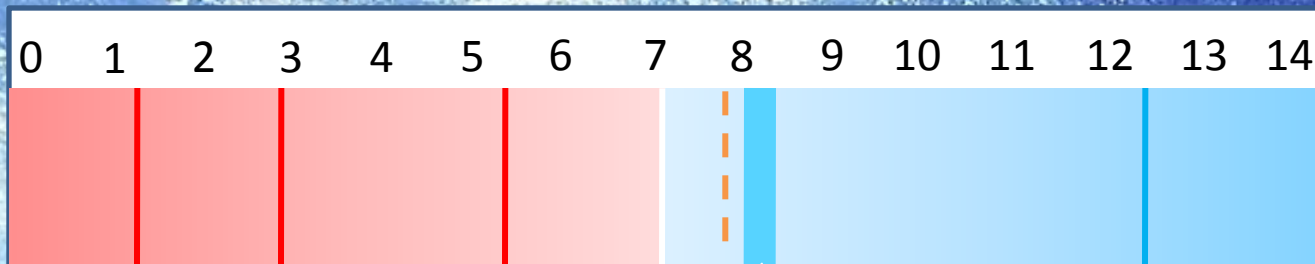


Present day

pH scale for maps



pH scale: logarithmic



Surface
seawater

Pre-industrial

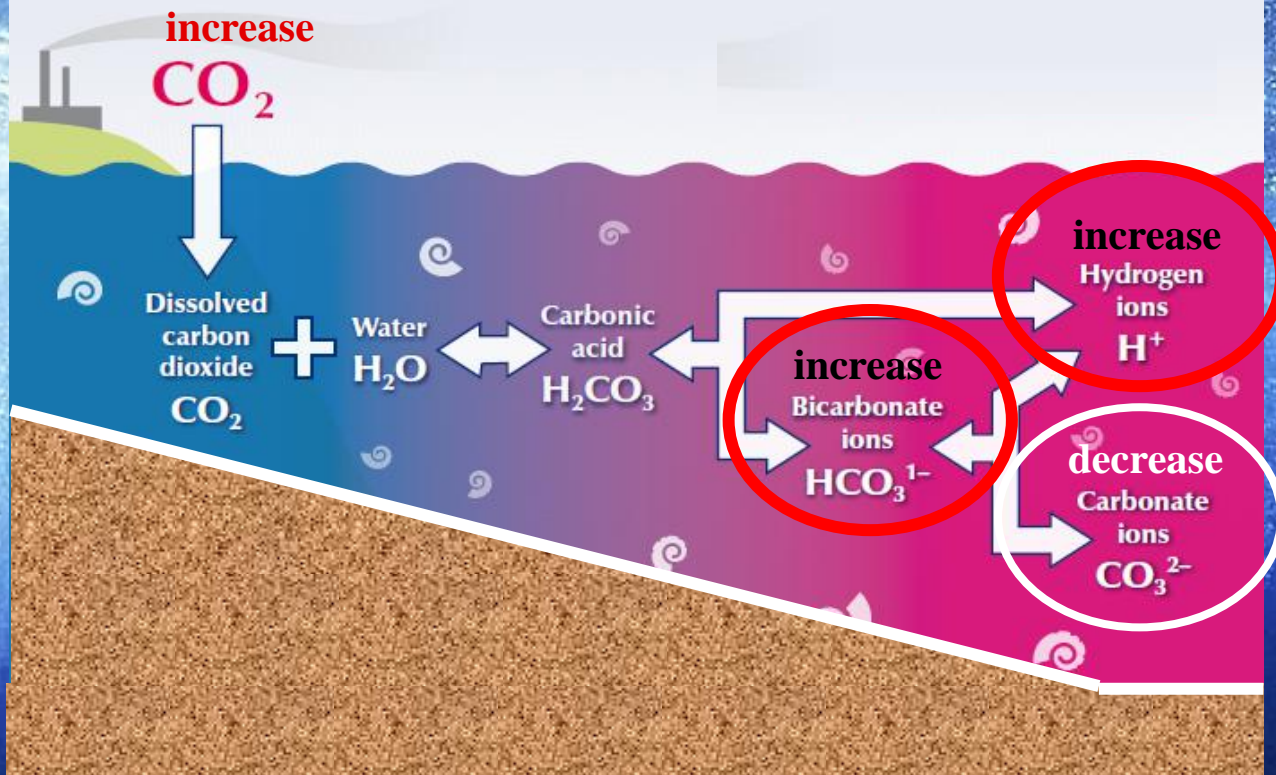
Present day

Projected for 2100
under 'business as usual'

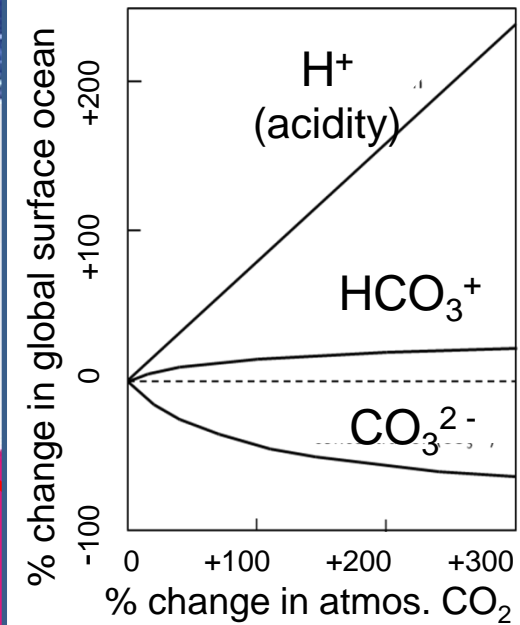
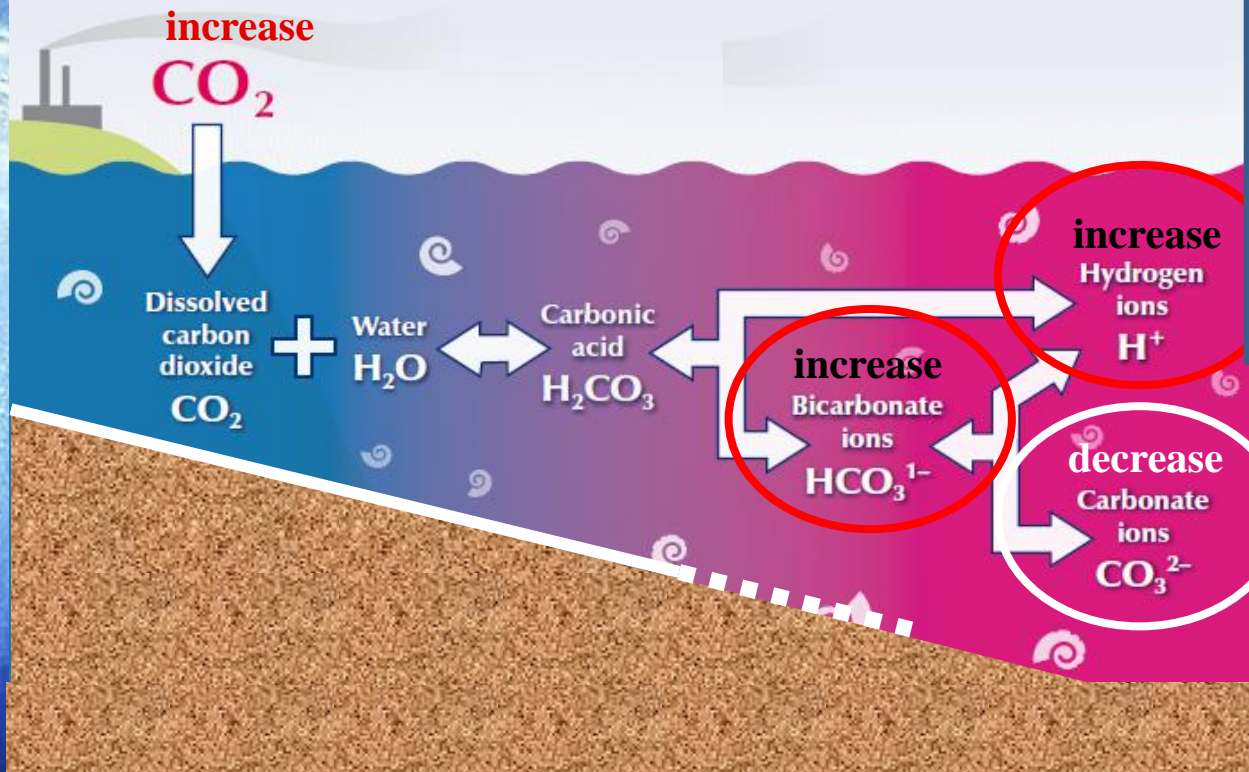
pH scale for maps



Increased H^+ is not the only change involved in ocean acidification

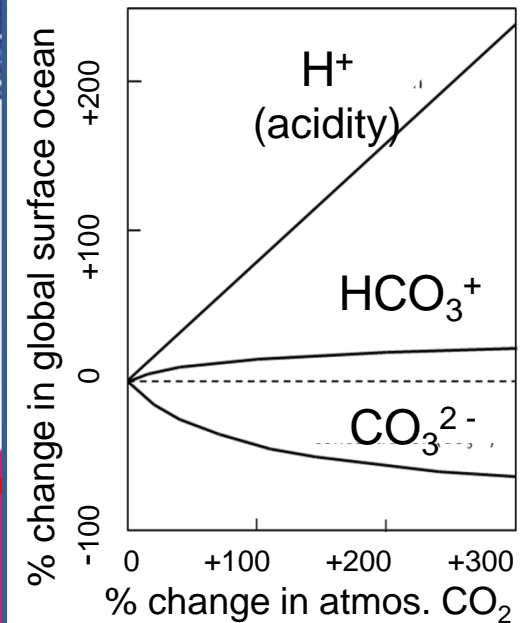
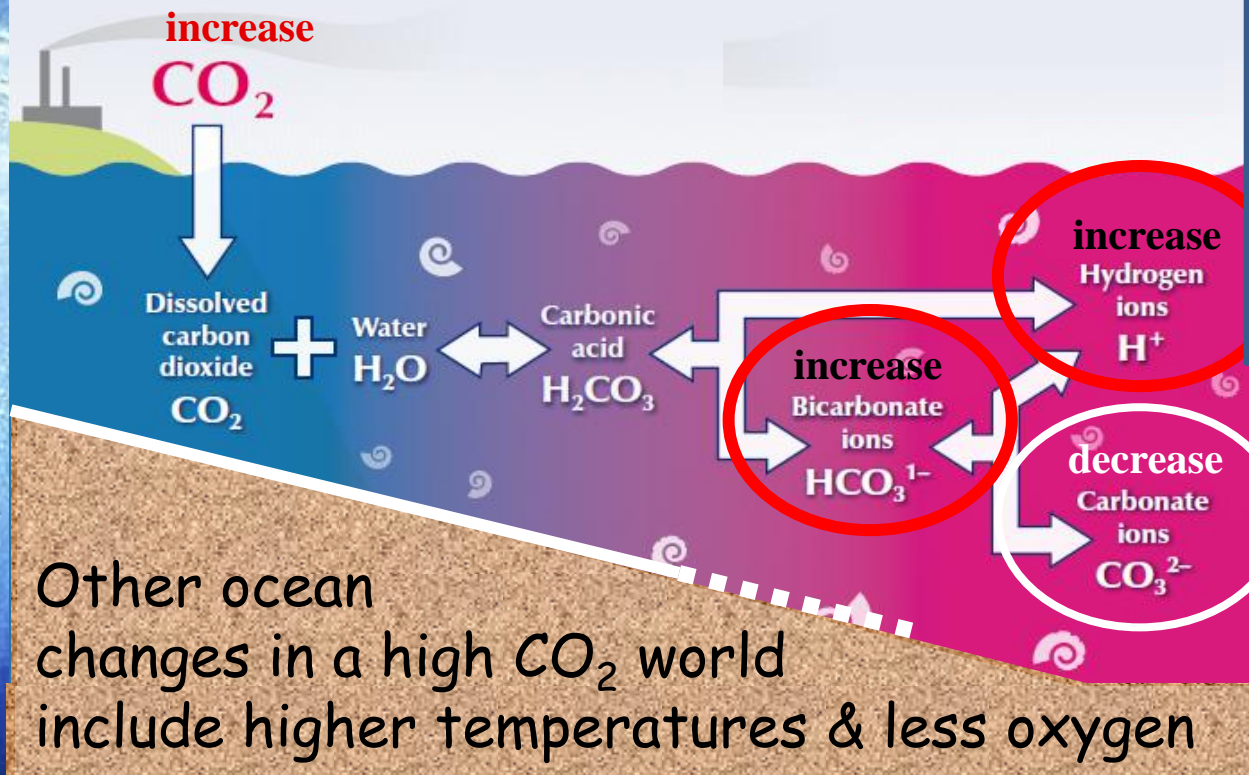


Increased H^+ is not the only change involved in ocean acidification



Affects calcium carbonate saturation state (Ω): when $\Omega < 1.0$, unprotected $CaCO_3$ dissolves

Increased H^+ is not the only change involved in ocean acidification



Affects calcium carbonate saturation state (Ω): when $\Omega < 1.0$, unprotected $CaCO_3$ dissolves

Organisms (and ecosystem processes) may respond to any one - or all - of these interacting variables

Overview of ocean acidification impacts #1

*Direct effects of
CO₂ and pH*

Indirect effects on:

Ecosystems

Ecosystem services

Animals, plants & microbes

Impacts on
organisms
(positive &
negative)

Impacts on
chemistry

Community
processes

Biogeo-
chemical
processes

Food web &
biodiversity
changes

Coastal
protection

Climate
processes

People (costs & values)

CO₂
increase

```
graph LR; CO2[CO2 increase] --> Org[Impacts on organisms]; CO2 --> Chem[Impacts on chemistry]; Org --> Comm[Community processes]; Org --> Biogeo[Biogeochemical processes]; Chem --> Biogeo; Comm <--> Biogeo; Comm --> Food[Food web & biodiversity changes]; Comm --> Coastal[Coastal protection]; Comm --> Climate[Climate processes]; Biogeo --> Coastal; Biogeo --> Climate; Food --- People[People costs & values]; Coastal --- People; Climate --- People;
```

The diagram illustrates the pathway of ocean acidification impacts. It begins with a red circle labeled 'CO₂ increase' at the bottom left. Two arrows lead from this circle to two yellow boxes: 'Impacts on organisms (positive & negative)' and 'Impacts on chemistry'. A vertical dashed line separates the 'Direct effects' from the 'Indirect effects'. Arrows from both yellow boxes point to the 'Indirect effects' section. 'Impacts on organisms' points to a green box 'Community processes' and an orange box 'Biogeochemical processes'. 'Impacts on chemistry' points to the 'Biogeochemical processes' box. There is a double-headed arrow between 'Community processes' and 'Biogeochemical processes'. From 'Community processes', three arrows point to 'Food web & biodiversity changes', 'Coastal protection', and 'Climate processes'. From 'Biogeochemical processes', two arrows point to 'Coastal protection' and 'Climate processes'. On the far right, a vertical label 'People (costs & values)' is positioned next to the three boxes representing ecosystem services: 'Food web & biodiversity changes', 'Coastal protection', and 'Climate processes'.

Overview of ocean acidification impacts #2

Direct effects of CO_2 and pH

Animals, plants & microbes

Impacts on organisms

Reproduction, behaviour and survival

Photosynthesis

Respiration, energetics and growth

Calcification

C:N and C:P ratios

N_2 fixation and nitrification

Sulphur metabolism (affecting DMSP & DMS)

Impacts on chemistry

Reduced Ω , shoaling of saturation horizon

CO_2 increase

Indirect effects on:

Ecosystems

Ecosystem services

Community

Changes in assemblage or abundance of:

- primary producers
- secondary producers
- decomposers
- habitat-structuring organisms

Decrease in food quality

Biogeochemical processes

Reduced biogenic CaCO_3 production

Changes in dissolved NO_x and NH_3

Change in dissolved DMS

Increased CaCO_3 dissolution

Food web and biodiversity changes

Decrease in abundance of commercially-exploited fish and shellfish

Reduced resilience to other environmental pressures

Biodiversity loss due to reductions in reef habitat

Coastal protection

Increased erosion due to reductions in reef habitat

Climate processes

Reduced strength of biological carbon pump

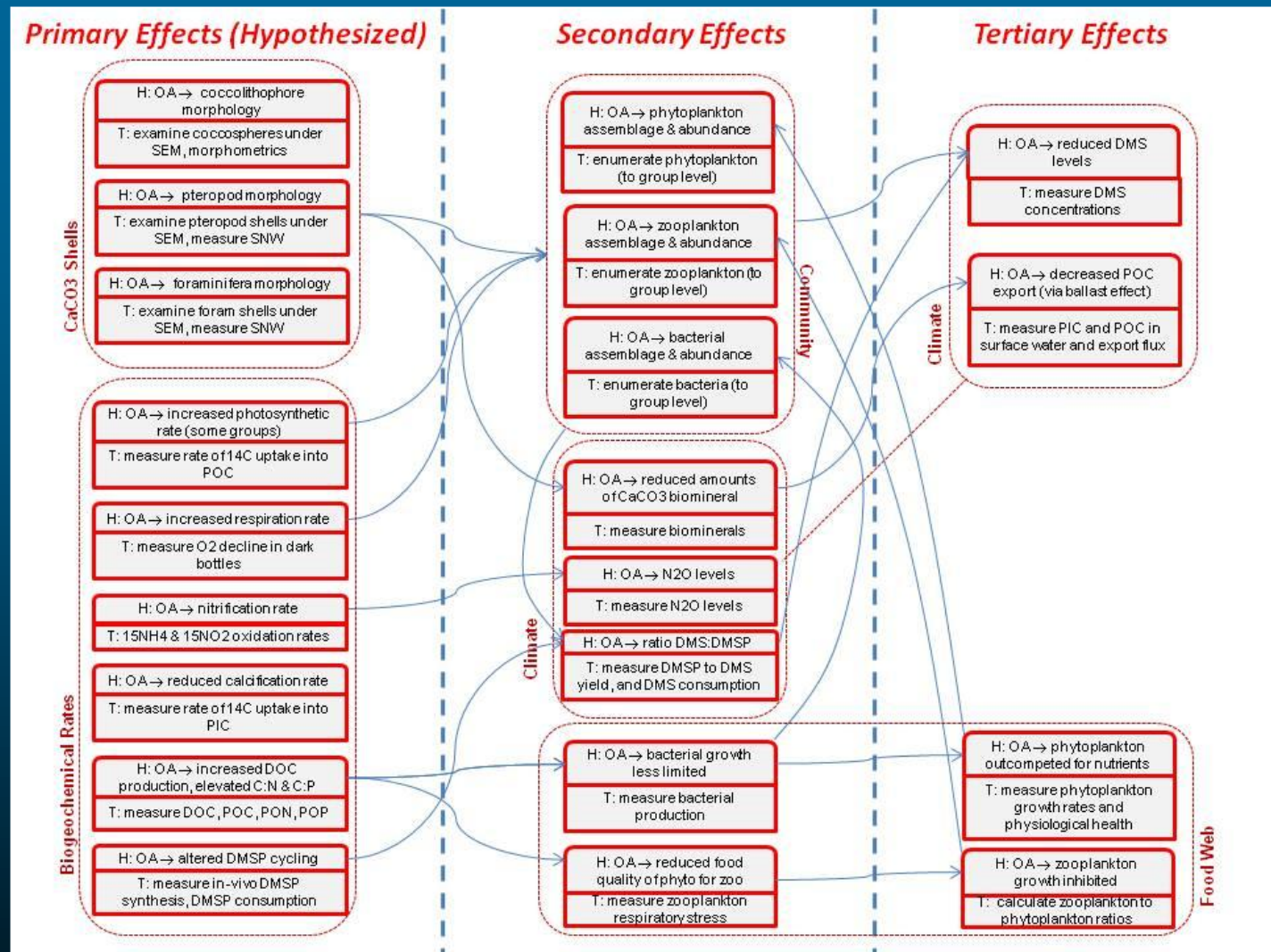
Change in N_2O and DMS release affecting climate forcing

People (costs & values)

DMS, dimethylsulphide; DMSP, dimethylsulphonioacetate; Ω , CaCO_3 saturation state.

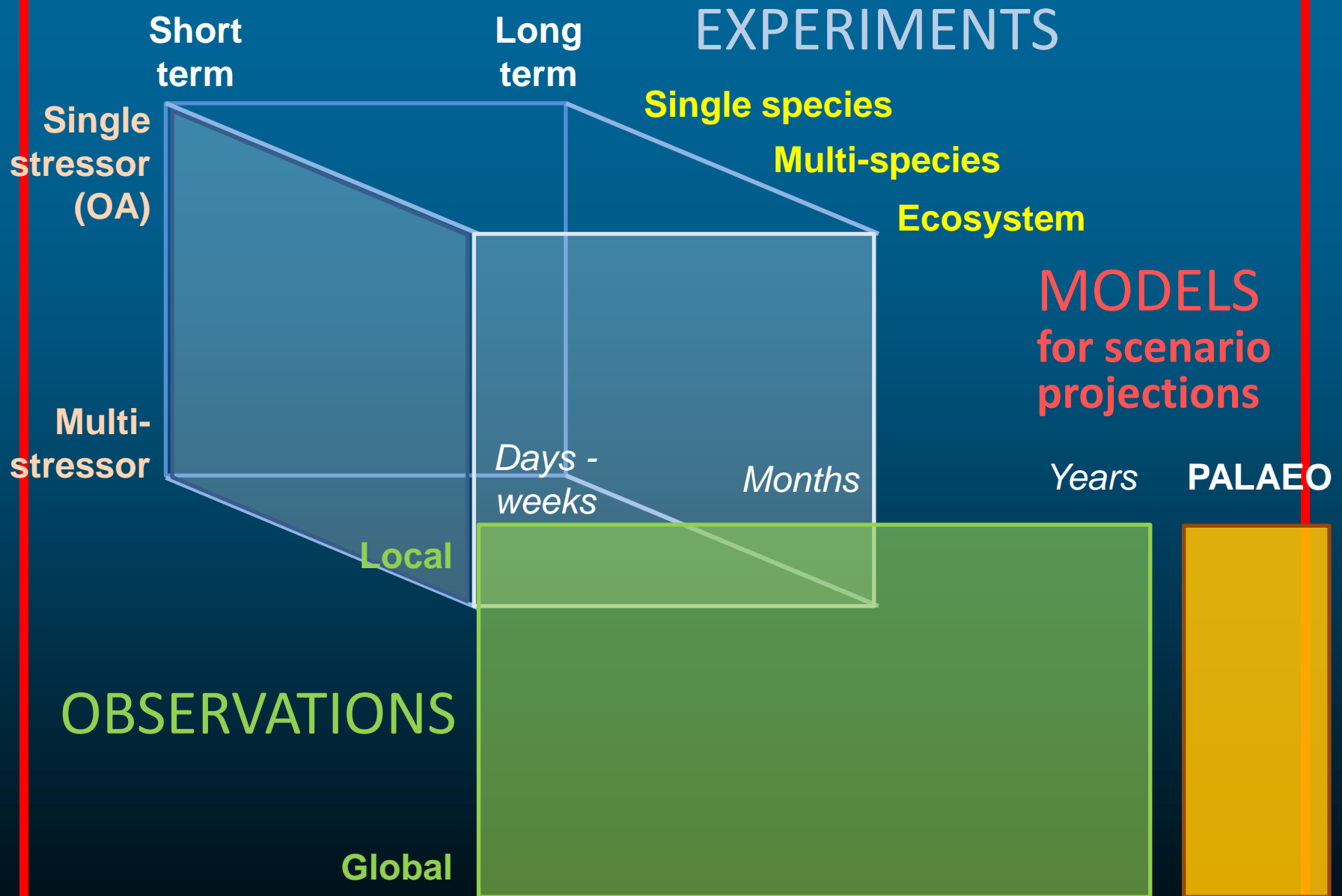
Williamson & Turley (2011), after Tyrrell

Overview of ocean acidification impacts #3



(original version of this diagram)

Evolving framework for OA research



Evolving framework for OA research

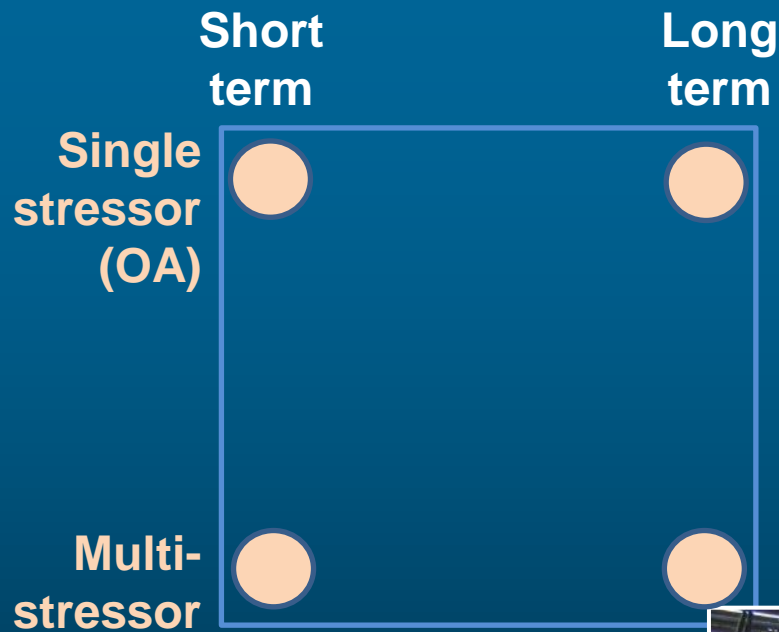


EXPERIMENTS

Single species



Evolving framework for OA research



EXPERIMENTS

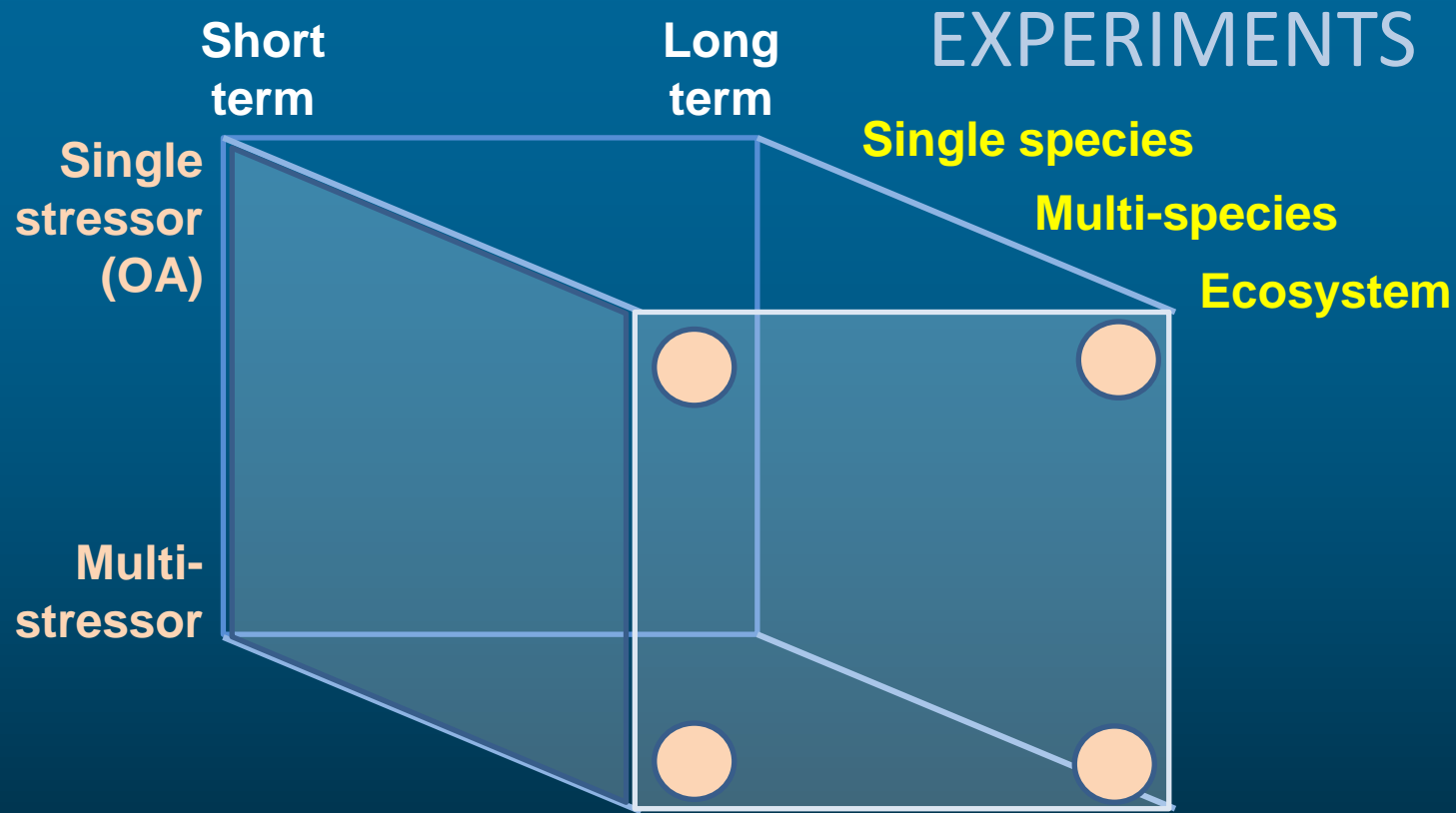
Single species



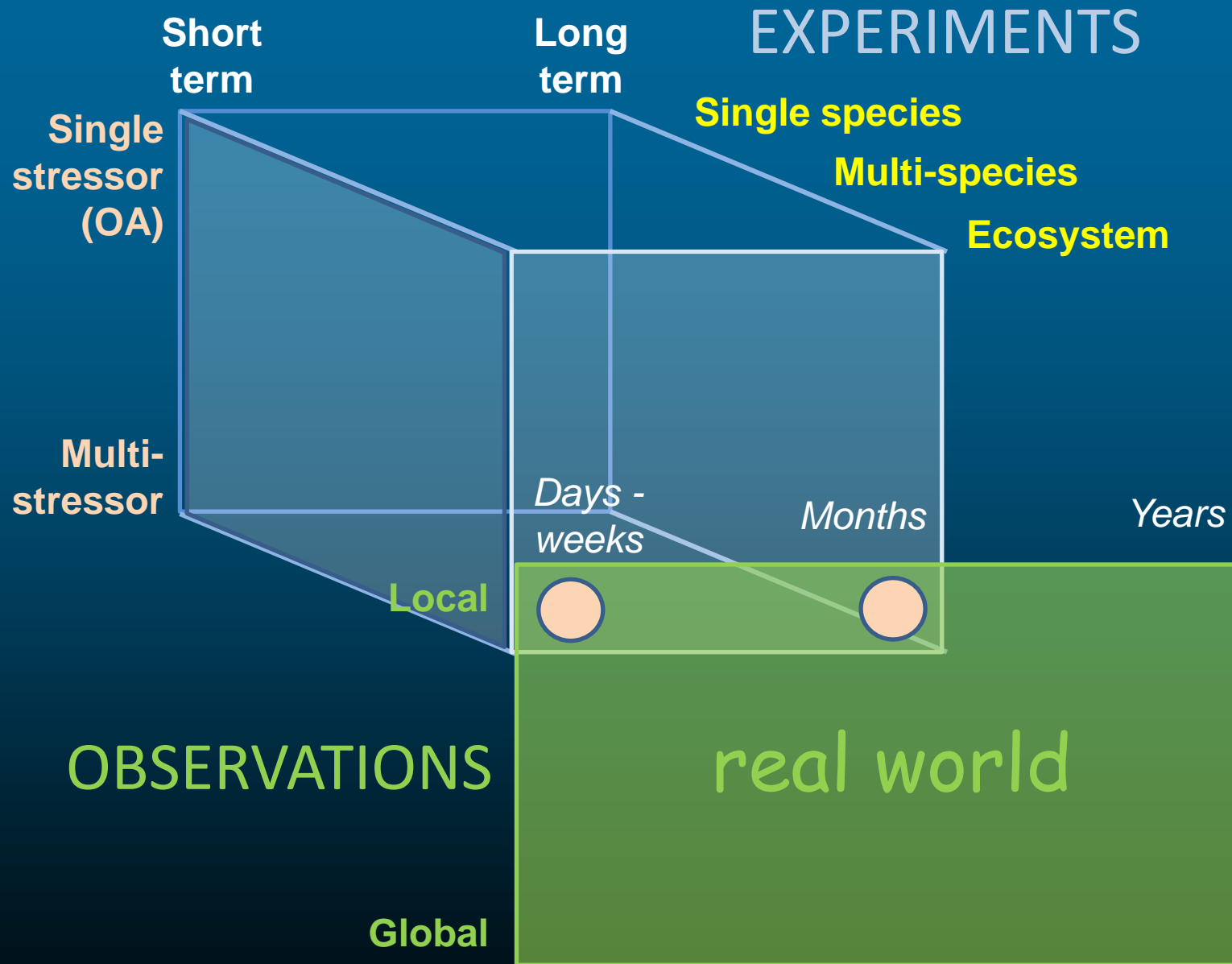
Other relevant variables include temperature, oxygen & food/nutrients



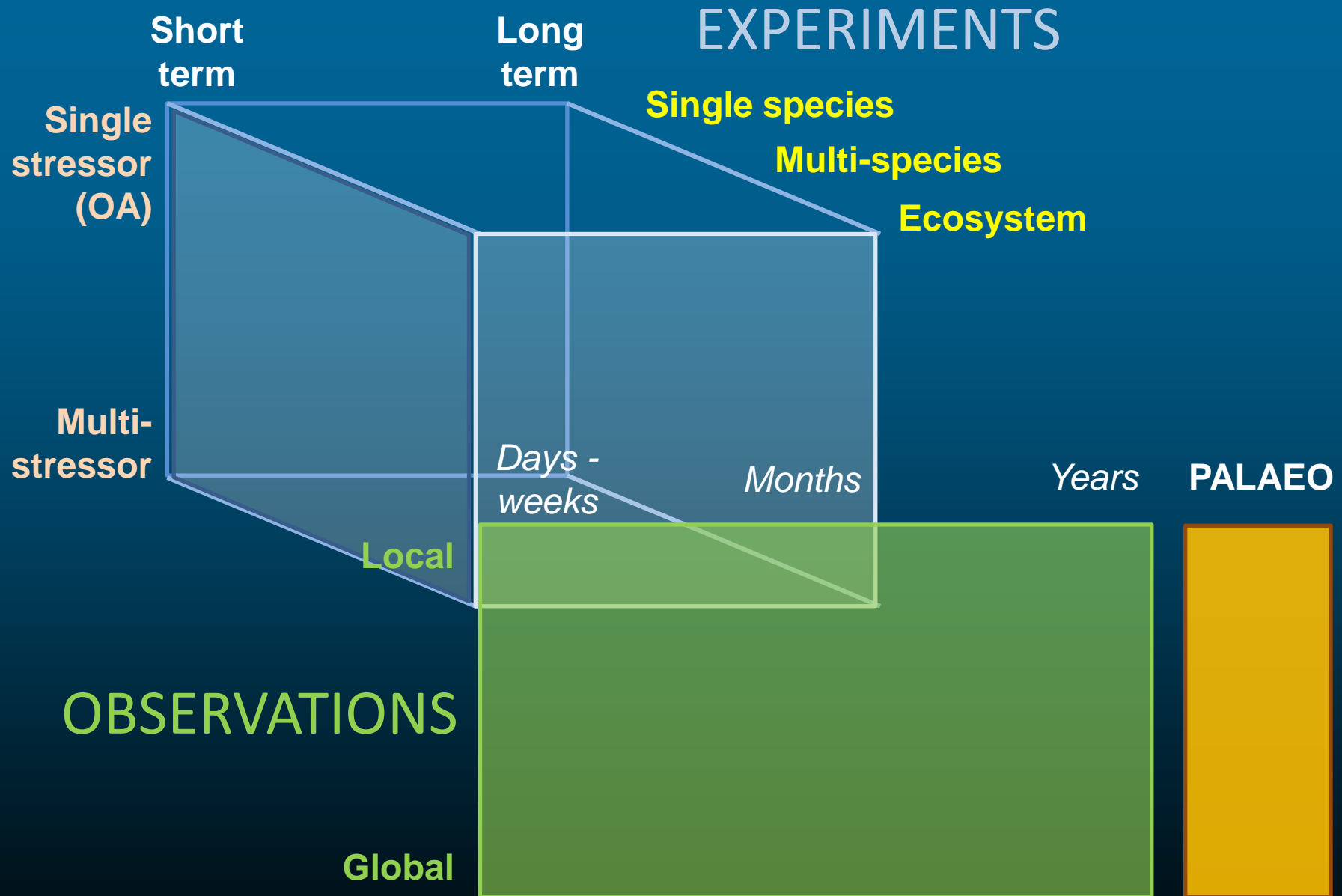
Evolving framework for OA research



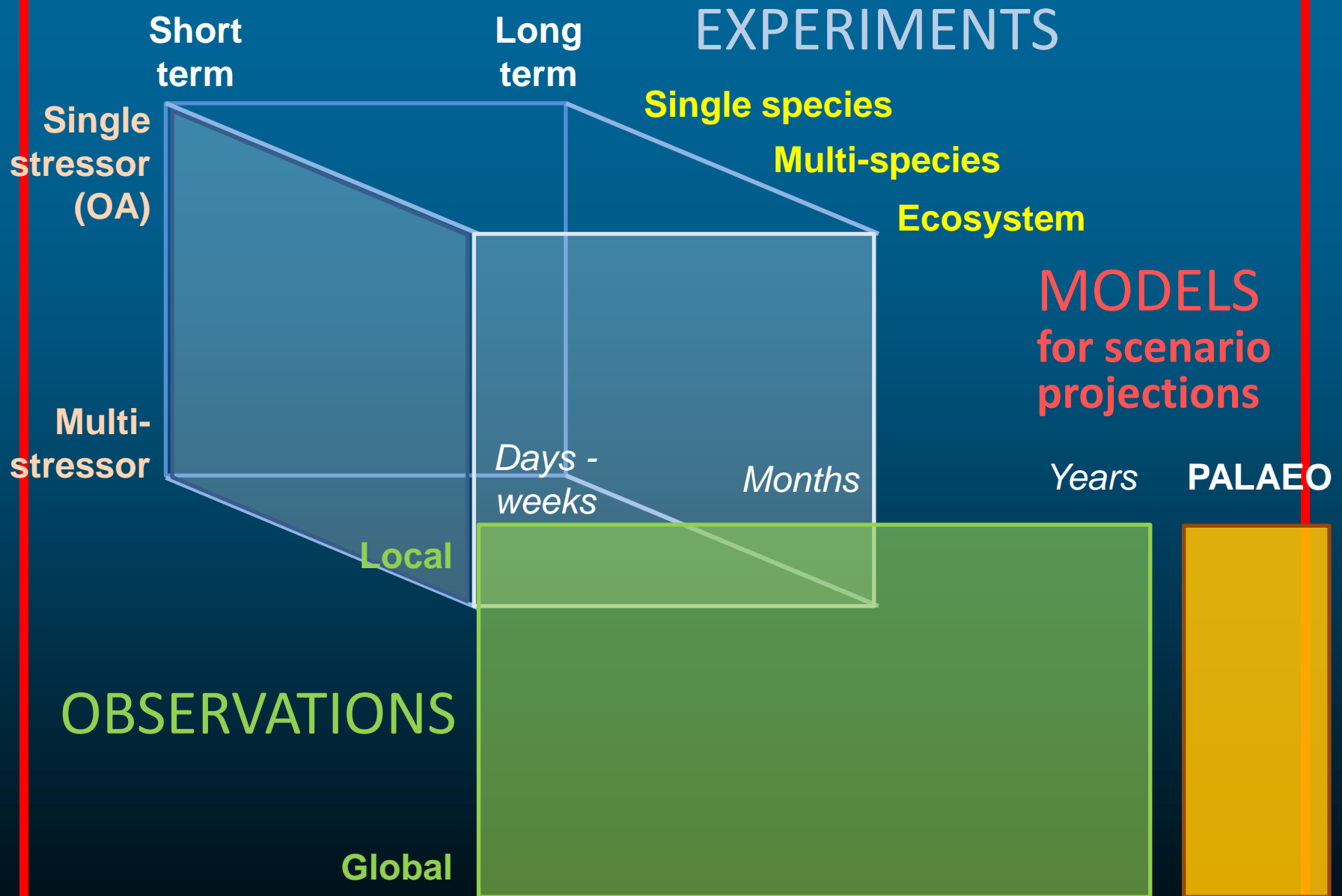
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Evolving framework for OA research

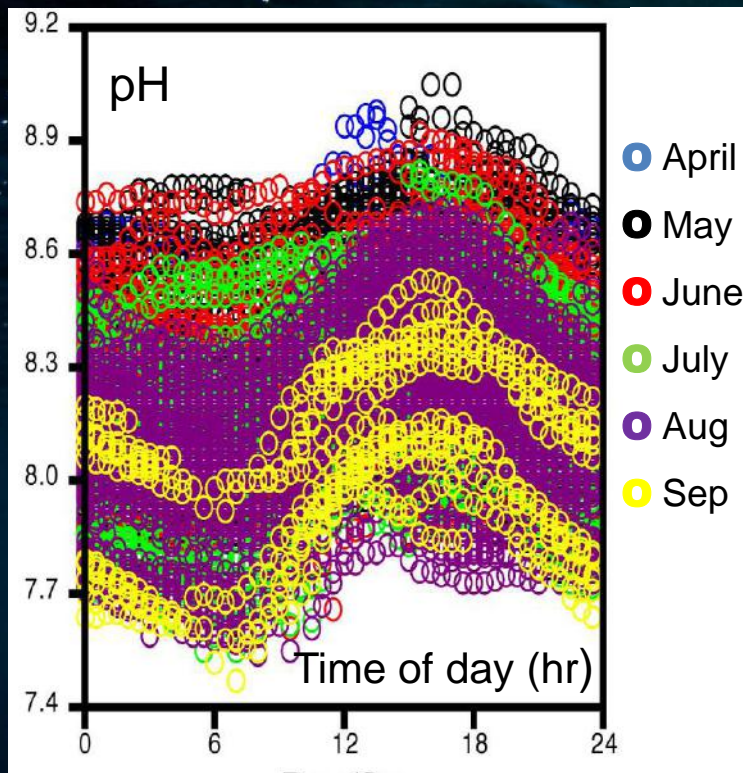


Evolving framework for OA research



Physico-chemical variability

In coastal waters and shelf seas, pH (and other carbon chemistry parameters) can vary greatly on daily and seasonal basis



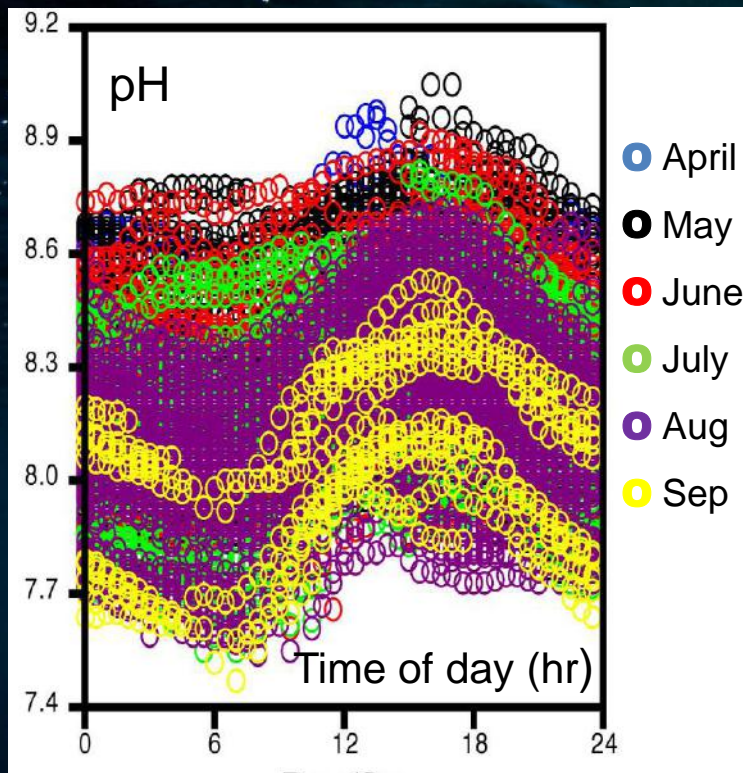
Diurnal and seasonal pH variability at Tatoosh Island WA, 2000-2007.

Wootton et al (2008)

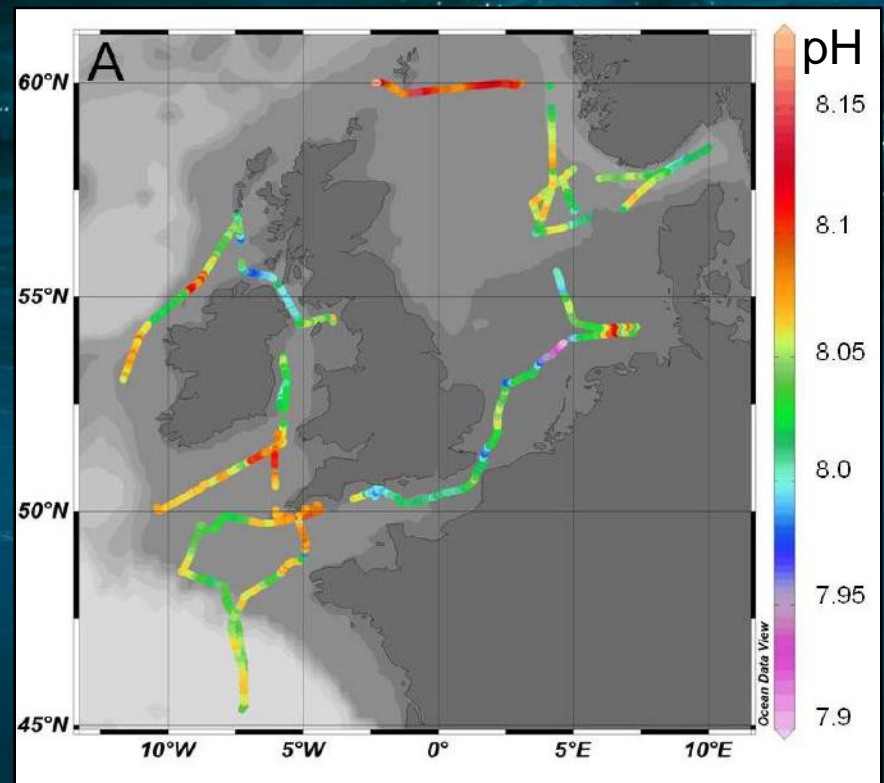


Physico-chemical variability

In coastal waters and shelf seas, pH (and other carbon chemistry parameters) can vary greatly on daily and seasonal basis – also spatially



Diurnal and seasonal pH variability at Tatoosh Island WA, 2000-2007.
Wootton et al (2008)

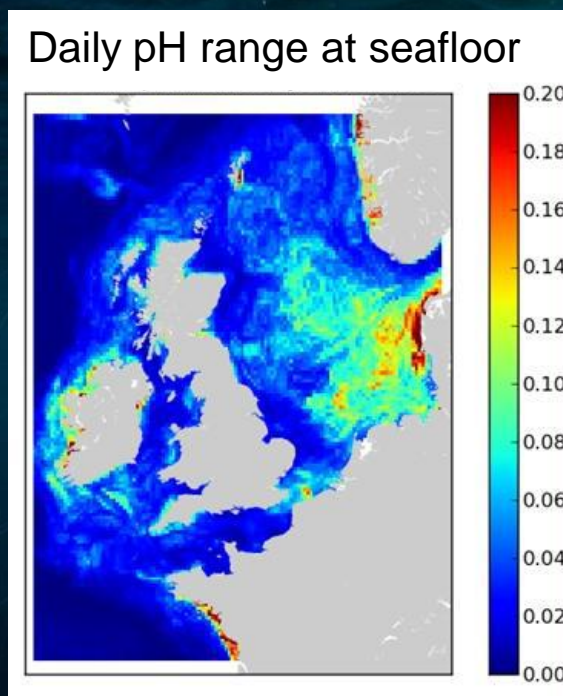


UKOA research cruise data 2011:
underway near-surface pH (*Rerolle et al*)

Physico-chemical variability

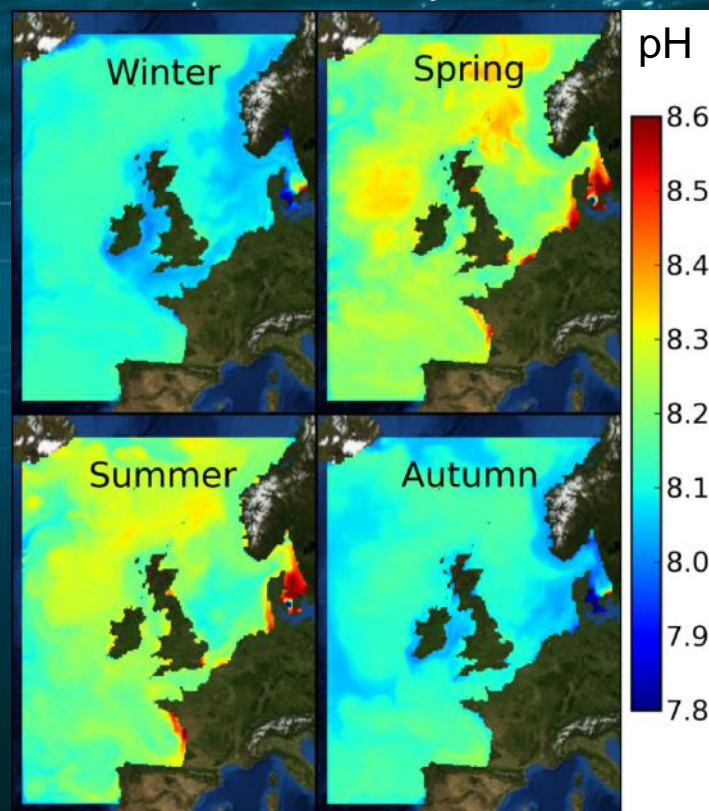
In coastal waters and shelf seas, pH (and other carbon chemistry parameters) can vary greatly on daily and seasonal basis – also spatially

This variability can now be simulated in high resolution models



Blackford et al; Artioli et al (2012)

Present day : sea surface



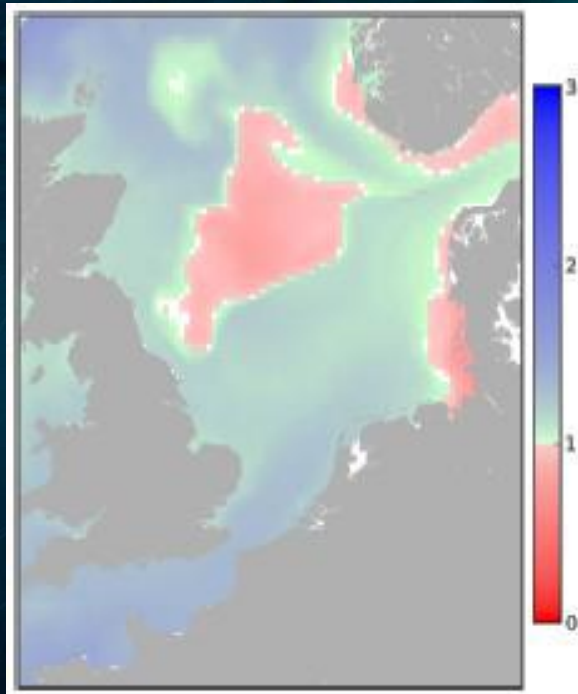
Physico-chemical variability

In coastal waters and shelf seas, pH (and other carbon chemistry parameters) can vary greatly on daily and seasonal basis – also spatially

This variability can now be simulated in high resolution models, that can be used in climate change scenarios

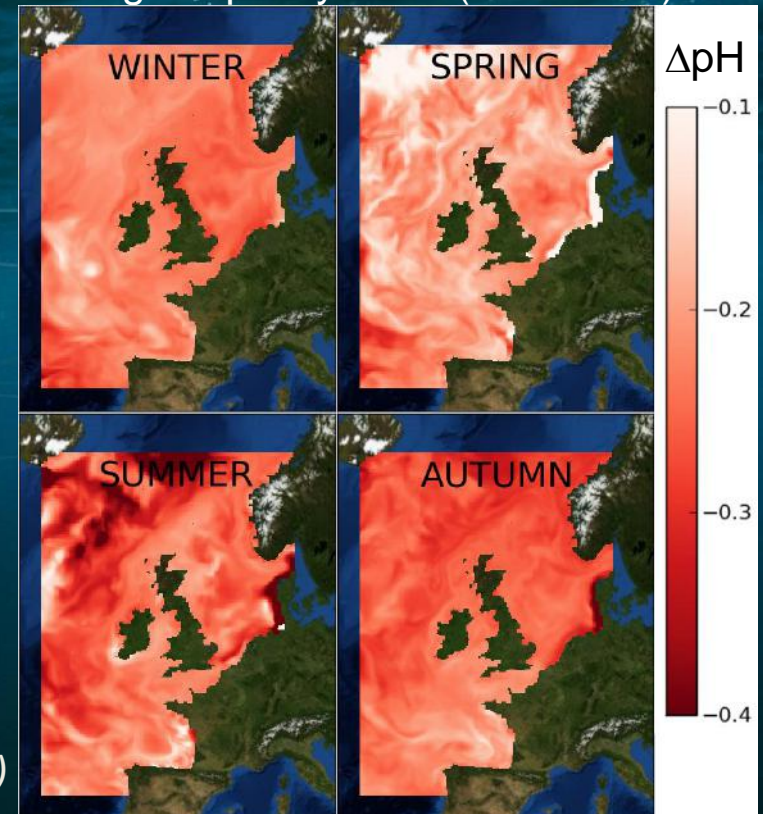
Aragonite saturation at sea floor by 2100 (IPCC A1B scenario)

Artioli et al (2013)



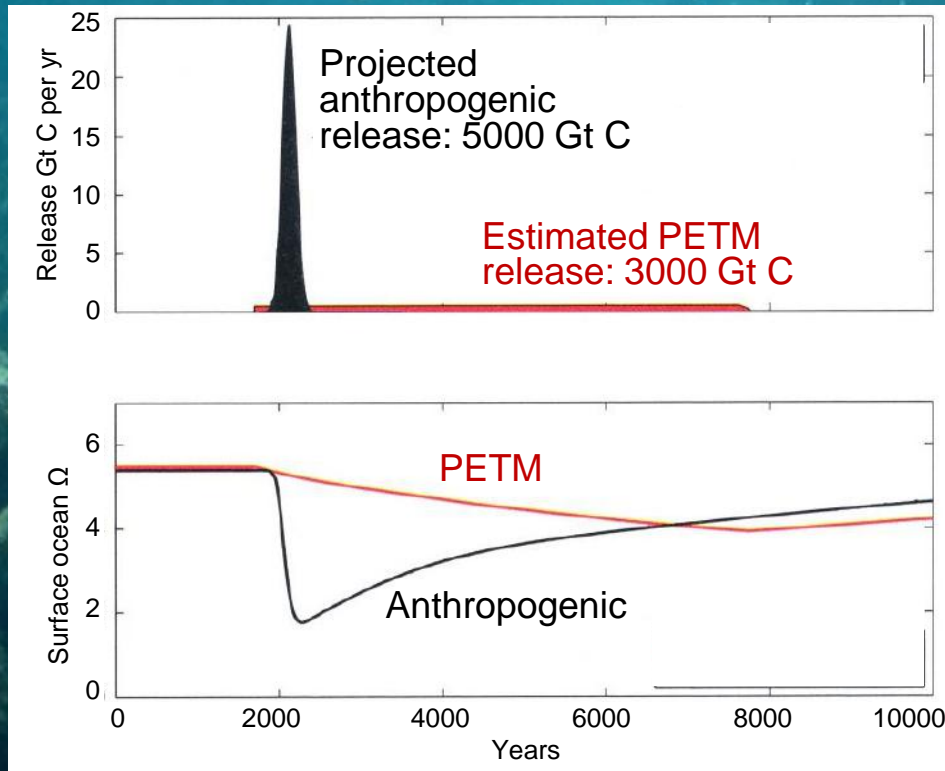
Artioli et al (2012)

Change in pH by 2100 (IPCC A1B)



Palaeo- studies: global OA has happened before

E.g. at Palaeocene-Eocene Thermal Maximum (PETM)

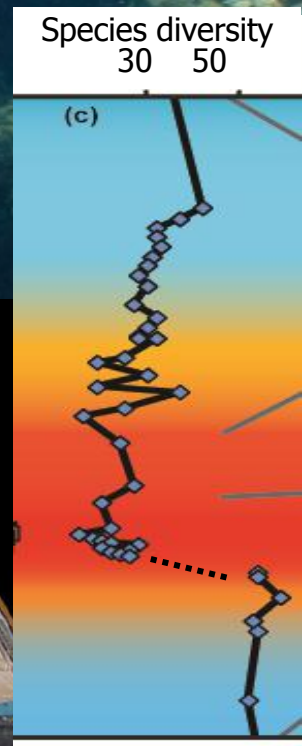


At PETM onset, ~35% of benthic foraminifera became extinct

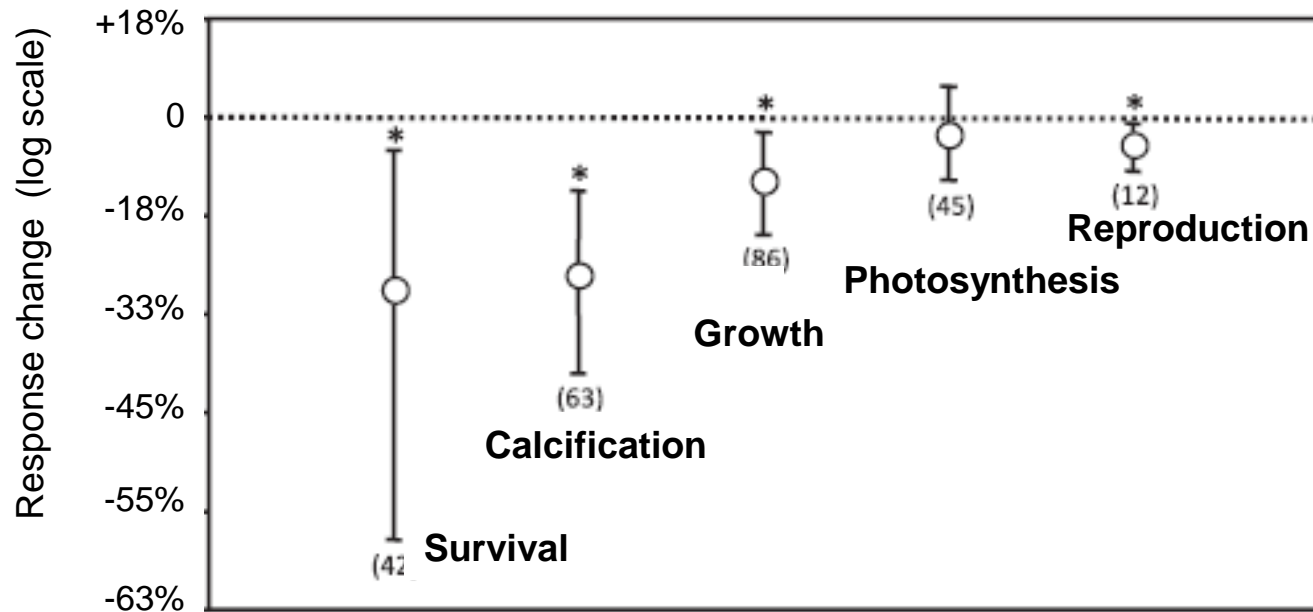
*Note: i) rate of OA change was then 10 times slower than now;
ii) recovery time was ~10,000 yr*

Zeebe & Ridgwell, 2011

Foster et al 2013



Metadata analysis based on single-species studies

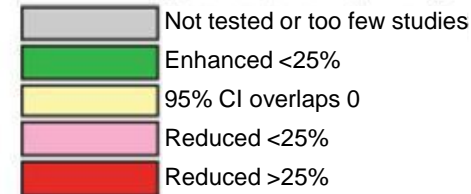







Effect of 0.4 pH decrease; all taxa combined






Kroeker et al. 2010

Metadata analysis based on single-species studies

Kroeker et al. 2013

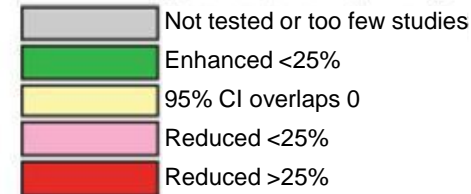







Taxa	Response	Mean Effect
 Calcifying algae	Survival	Not tested or too few studies
	Calcification	95% CI overlaps 0
	Growth	Not tested or too few studies
	Photosynthesis	-28%
	Abundance	-80%
 Corals	Survival	95% CI overlaps 0
	Calcification	-32%
	Growth	95% CI overlaps 0
	Photosynthesis	95% CI overlaps 0
	Abundance	-47%
 Coccolithophores	Survival	Not tested or too few studies
	Calcification	-23%
	Growth	95% CI overlaps 0
	Photosynthesis	95% CI overlaps 0
	Abundance	95% CI overlaps 0
 Molluscs	Survival	-34%
	Calcification	-40%
	Growth	-17%
	<i>Development</i>	-25%
	Abundance	95% CI overlaps 0
 Echinoderms	Survival	95% CI overlaps 0
	Calcification	95% CI overlaps 0
	Growth	-10%
	<i>Development</i>	-11%
	Abundance	Not tested or too few studies






 Crustaceans	Survival	95% CI overlaps 0
	Calcification	95% CI overlaps 0
	Growth	95% CI overlaps 0
	<i>Development</i>	95% CI overlaps 0
	Abundance	95% CI overlaps 0
 Fish	Survival	Not tested or too few studies
	Calcification	Not tested or too few studies
	Growth	95% CI overlaps 0
	<i>Development</i>	Not tested or too few studies
	Abundance	Not tested or too few studies
 Fleshy algae	Survival	Not tested or too few studies
	Calcification	Not tested or too few studies
	Growth	+22%
	Photosynthesis	95% CI overlaps 0
	Abundance	95% CI overlaps 0
 Seagrasses	Survival	Not tested or too few studies
	Calcification	Not tested or too few studies
	Growth	Not tested or too few studies
	Photosynthesis	95% CI overlaps 0
	Abundance	Not tested or too few studies
 Diatoms	Survival	Not tested or too few studies
	Calcification	Not tested or too few studies
	Growth	+17%
	Photosynthesis	+12%
	Abundance	95% CI overlaps 0

Metadata analysis based on single-species studies

Kroeker et al. 2013



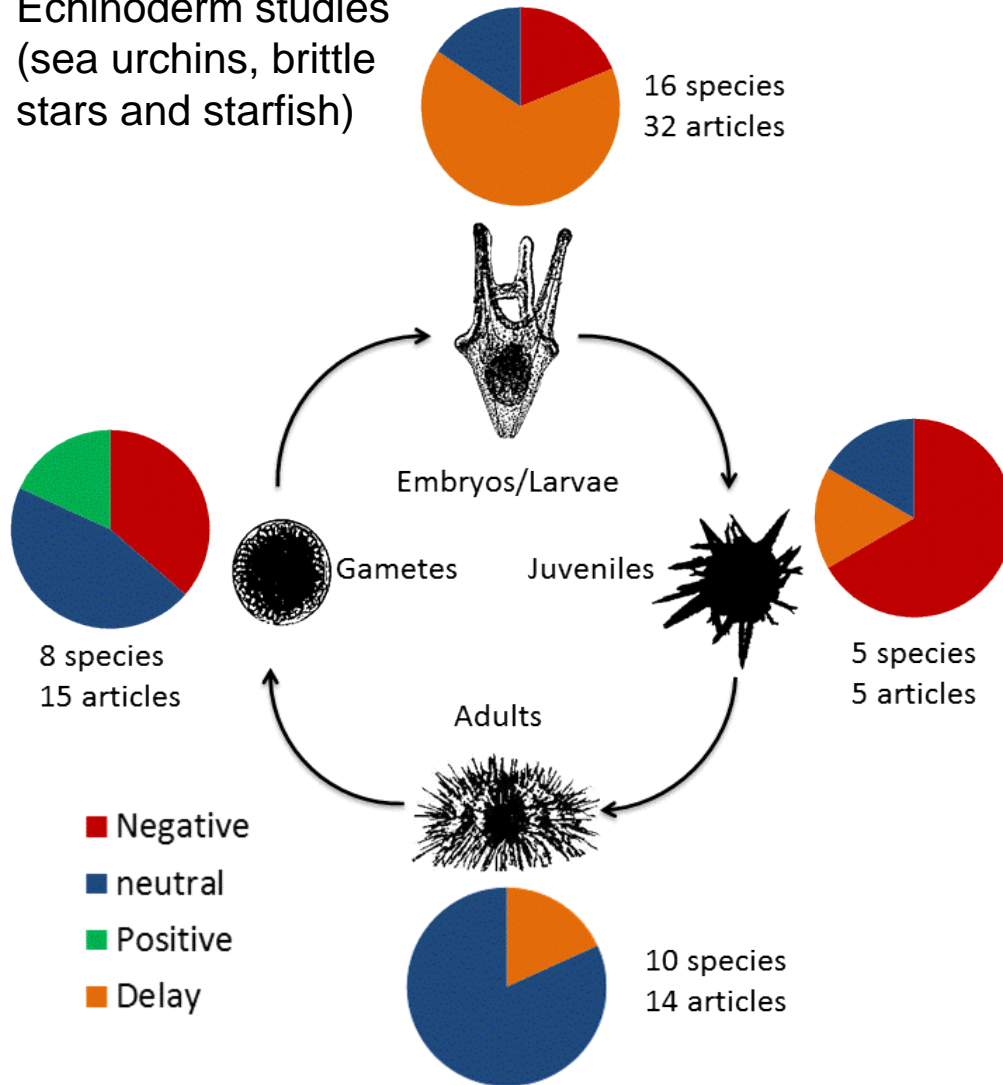
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Such analyses need to be carefully interpreted!

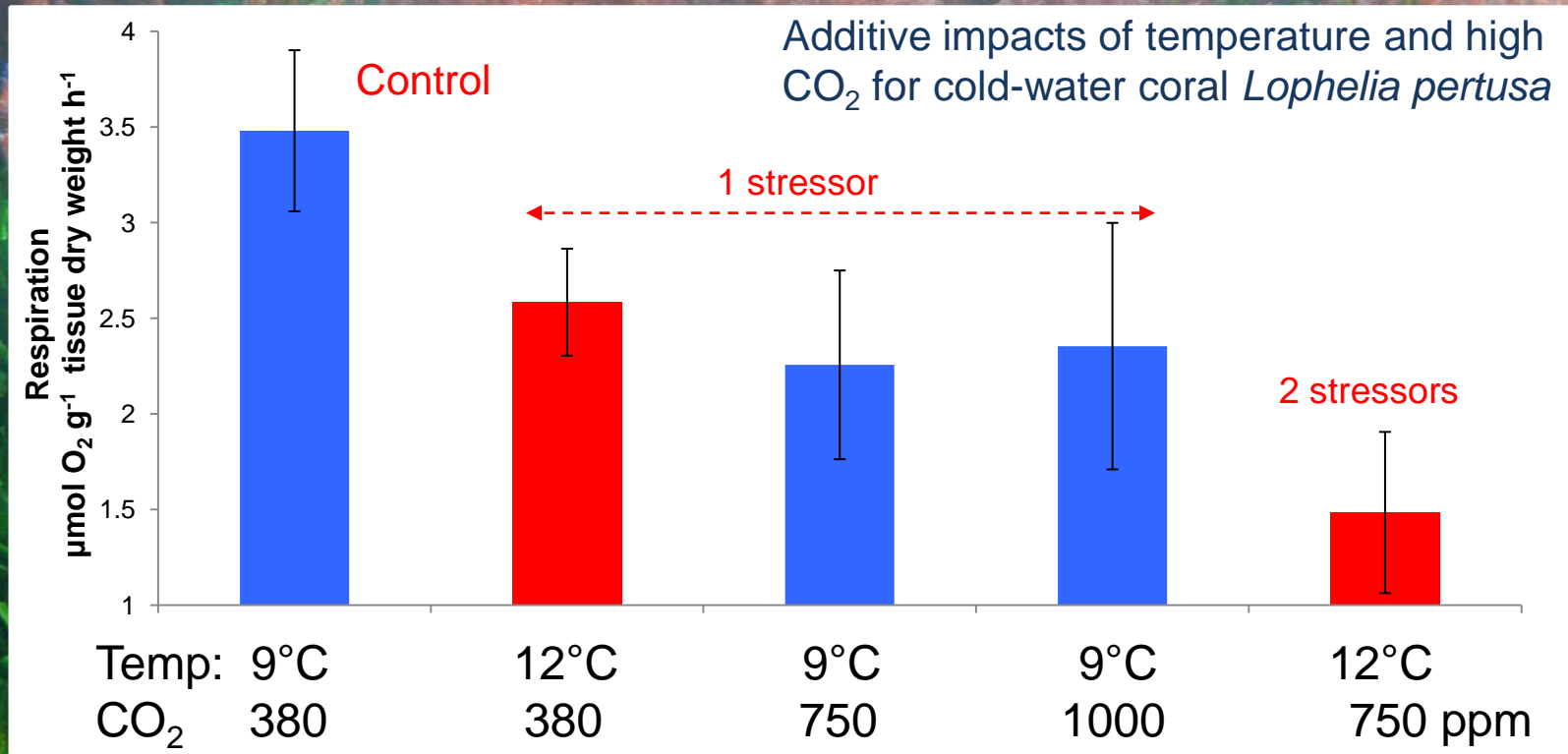
Intra-taxon variability in response to OA

Echinoderm studies
(sea urchins, brittle
stars and starfish)



**Early life stages –
embryos, larvae and
juveniles – are much
more sensitive to OA
than adults**

Multi-stressor studies show that interactions can be additive/synergistic or antagonistic

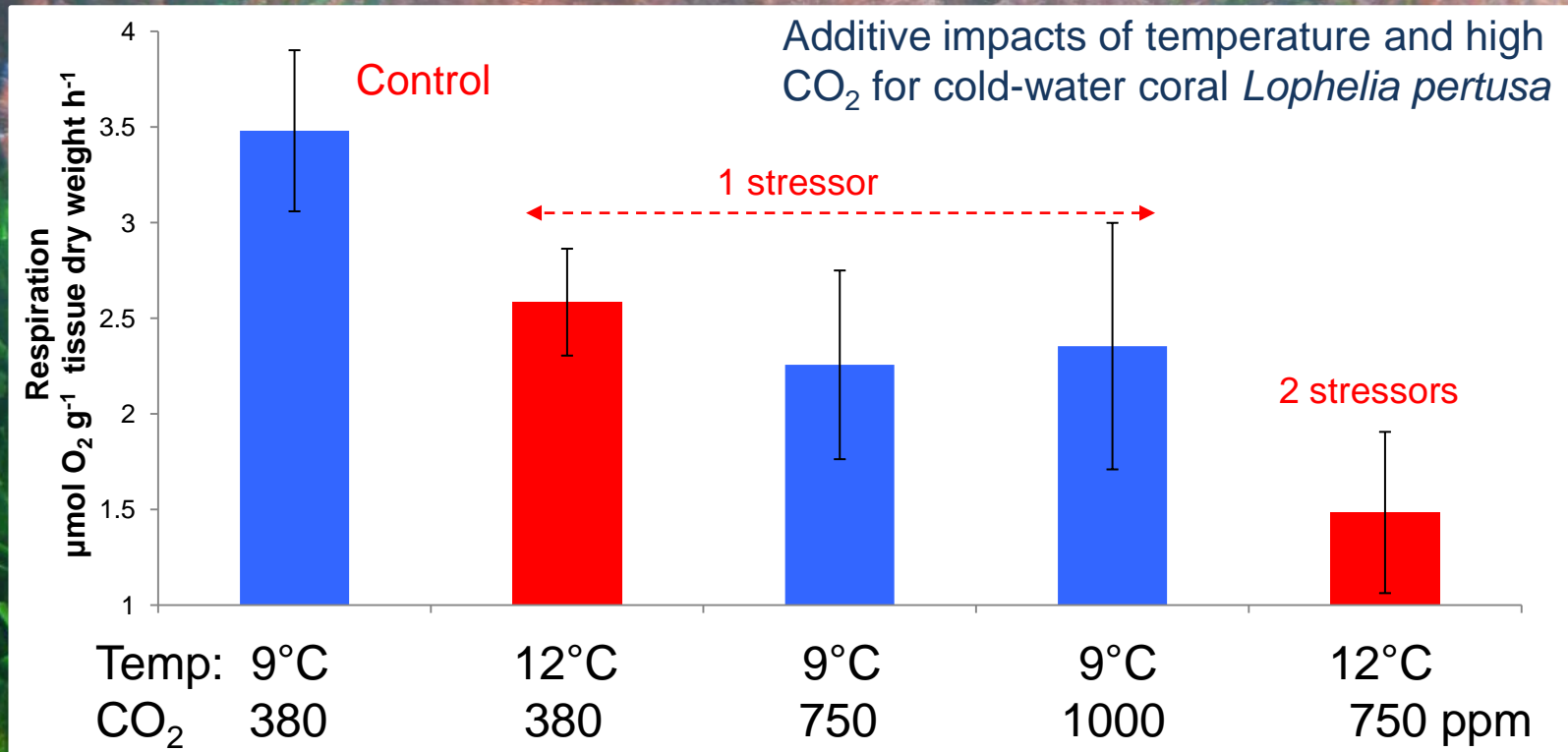


Preliminary data: Hennige & Murray

Photo: Jason Hall-Spencer

Multi-stressor studies show that interactions can be additive/synergistic or antagonistic

*But multi-factor experiments are complex
(and food quality/quantity may be critical)*

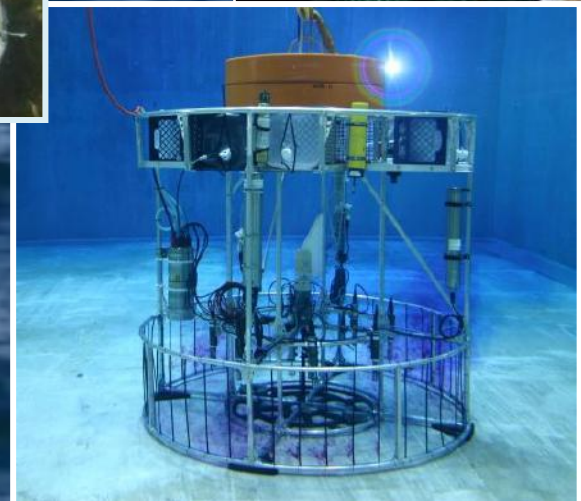


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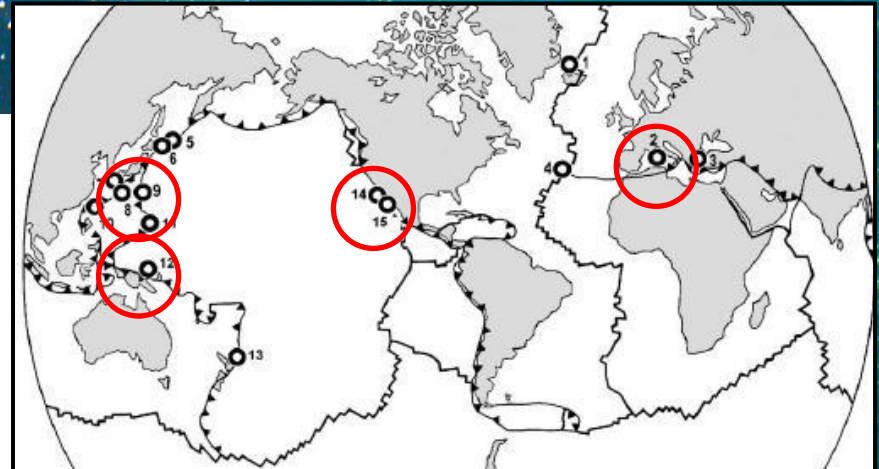
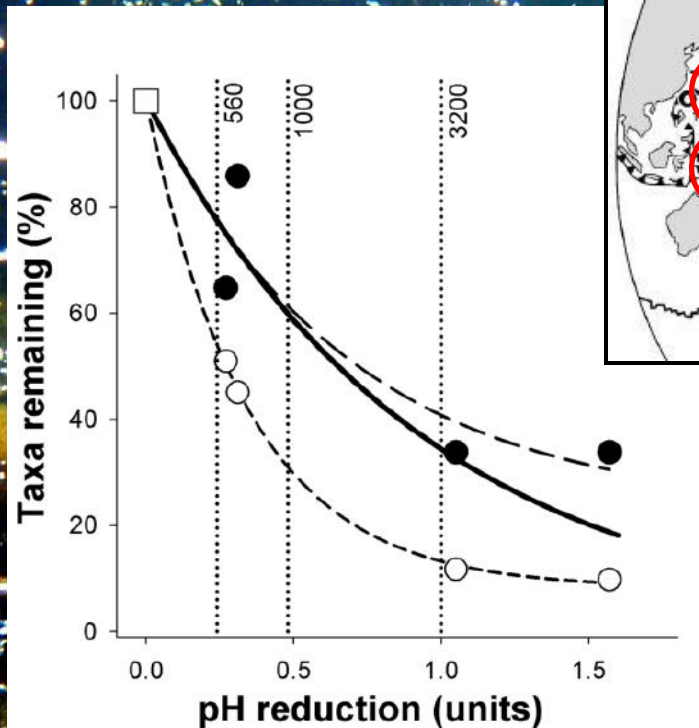
Photo: Jason Hall-Spencer

Multi-species and ecosystem-scale experiments

Mesocosms and Free Ocean CO₂ Enrichment (FOCE) studies: *ecologically more realistic, but high cost for multi-factor replicates*



Natural experiments at ecosystem-scale

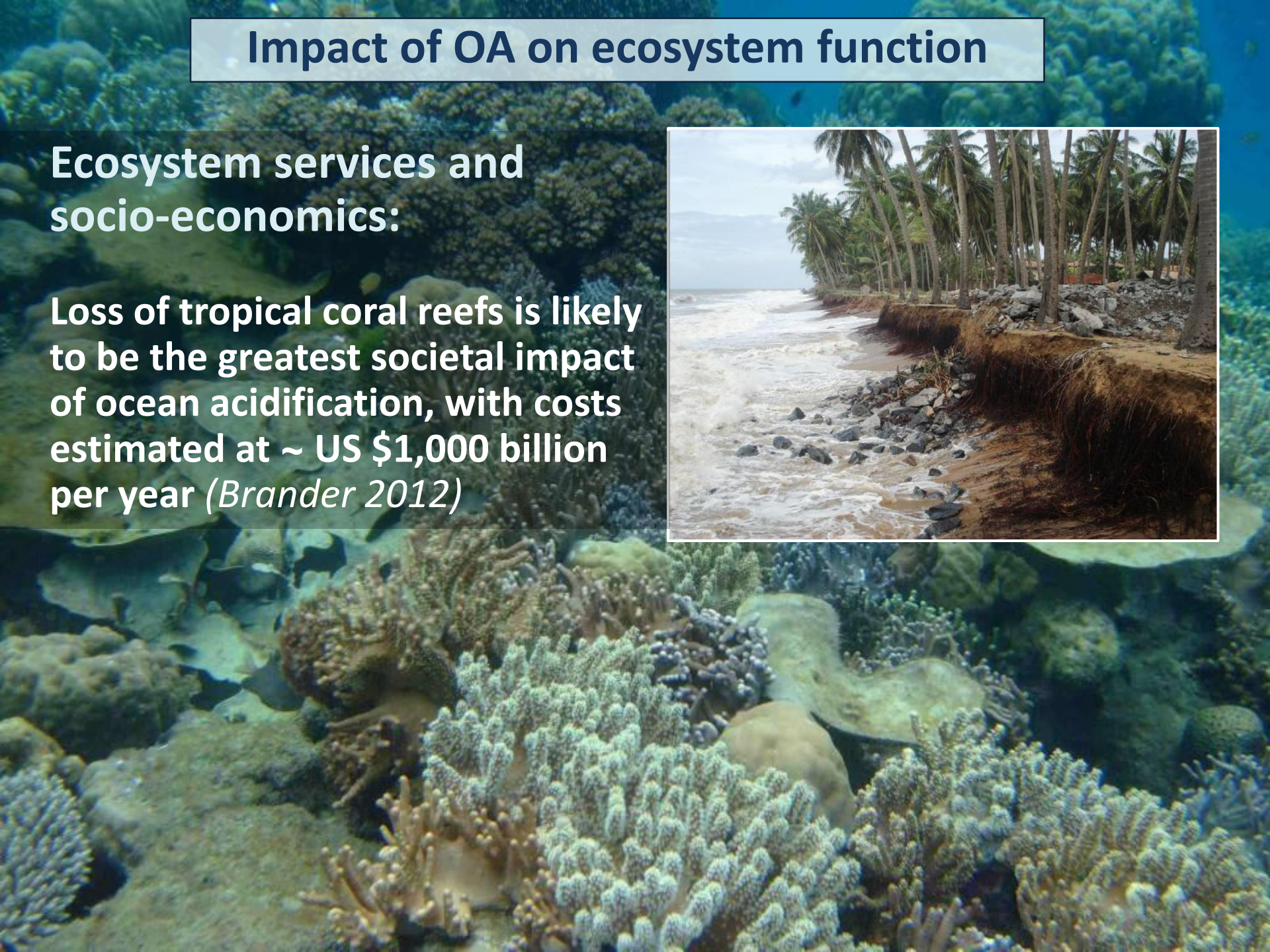


High CO₂ vents (in the Mediterranean, USA, Japan, and Papua New Guinea) show dramatic biodiversity loss and community shifts, favouring seagrasses and non-calcified algae

Impact of OA on ecosystem function

Ecosystem services and socio-economics:

Loss of tropical coral reefs is likely to be the greatest societal impact of ocean acidification, with costs estimated at ~ US \$1,000 billion per year (*Brander 2012*)

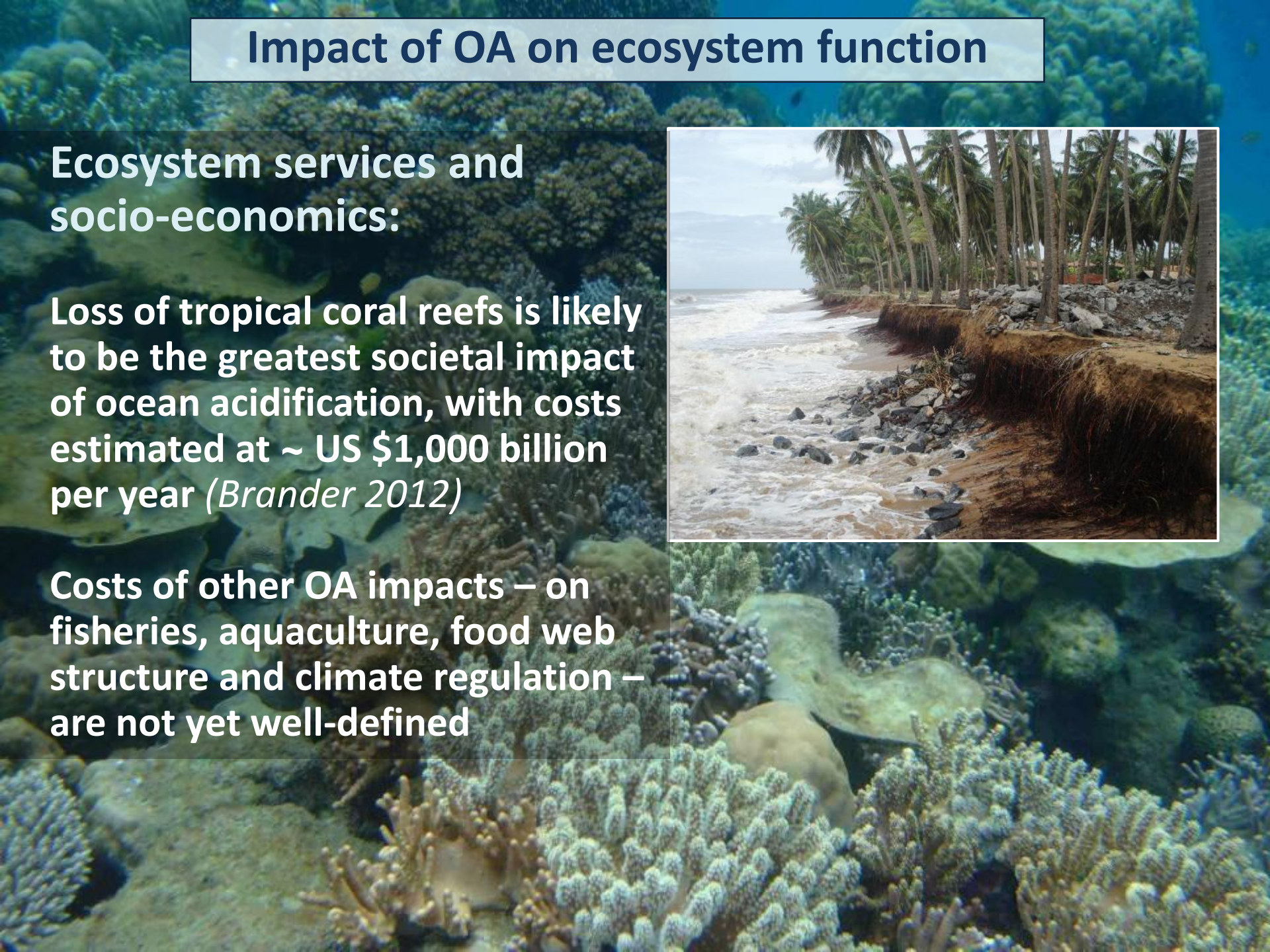


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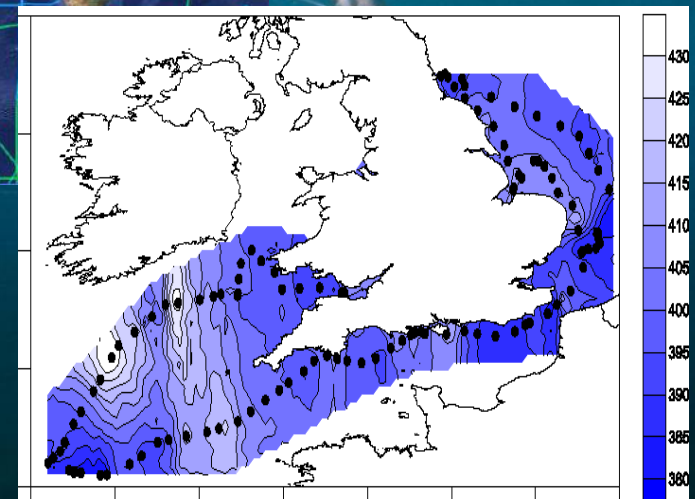
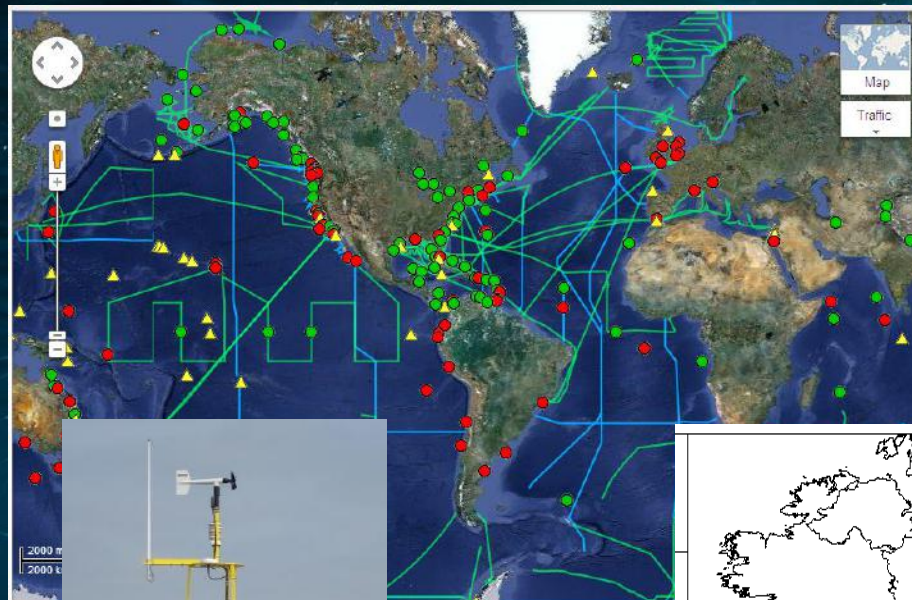
Costs of other OA impacts – on fisheries, aquaculture, food web structure and climate regulation – are not yet well-defined



Observational requirements

Urgent need to develop global observing network for OA and ecosystem response, linked to existing observing systems

UK work by Cefas,
Marine Scotland,
NOC, PML and
university research
groups





Main recent achievements

- Importance of multiple stressors
- Improved techniques
- Awareness of biological variability
- Awareness of chemical variability
- Importance of scope for adaptation
- Insights from palaeo- studies
- Development of ecosystem-level studies

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with acknowledgements to UKOA researchers, funders & others