Predicting Coral Calcification Response to Ocean Acidification

From Microscale Mechanisms to Macroscale Responses

Weifu Guo, Nathan Mollica, Anne Cohen and others
Woods Hole Oceanographic Institution

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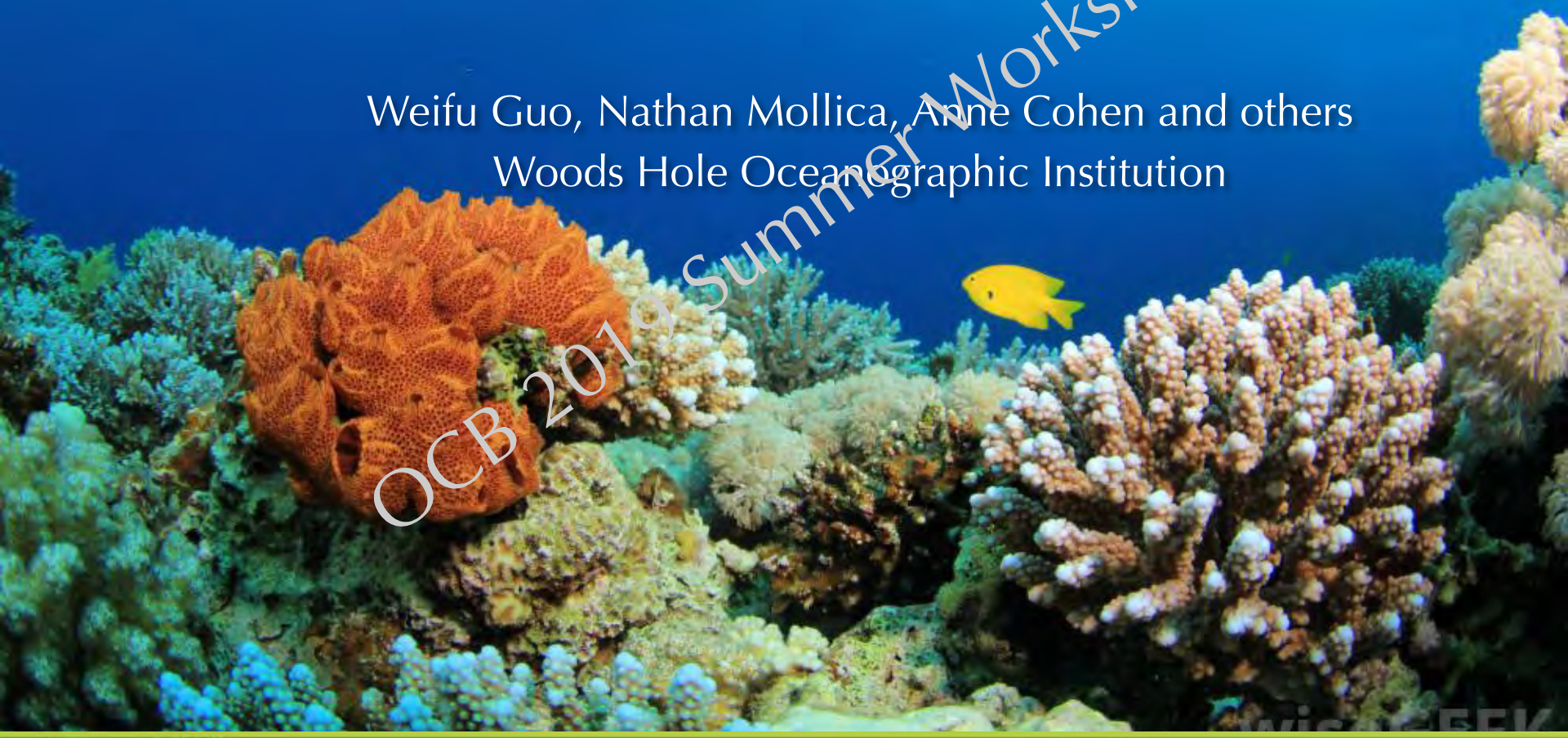

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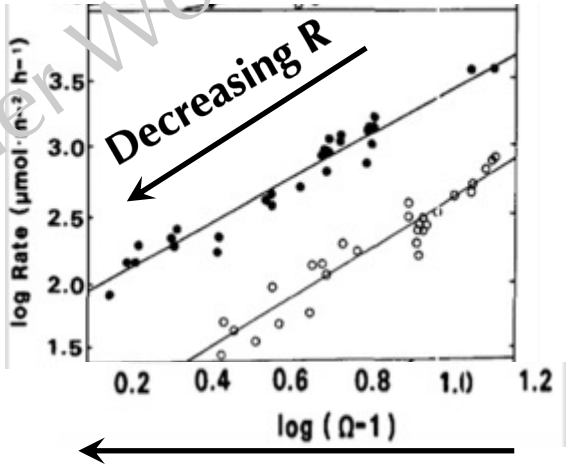
Ocean Acidification and Its Impact on Coral Calcification

Ocean acidification is expected to reduce coral calcification

Corals require $[CO_3^{2-}]$ to build their aragonite ($CaCO_3$) skeleton



Decreasing pH, $[CO_3^{2-}]$, Ω

$$R_{precipitation} = k \times (\Omega - 1)^n$$

$$pH_{sw} \downarrow \dashrightarrow [CO_3^{2-}] \downarrow \dashrightarrow \Omega \downarrow \dashrightarrow R_{precipitation} \downarrow$$

Projection: ~48% in R_{precip} by 2100, due to 0.14-0.43 unit pH drop

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Ocean Acidification and Its Impact on Coral Calcification

Laboratory Manipulation Experiments

Calcification responses vary among different species and differ from abiotic expt.

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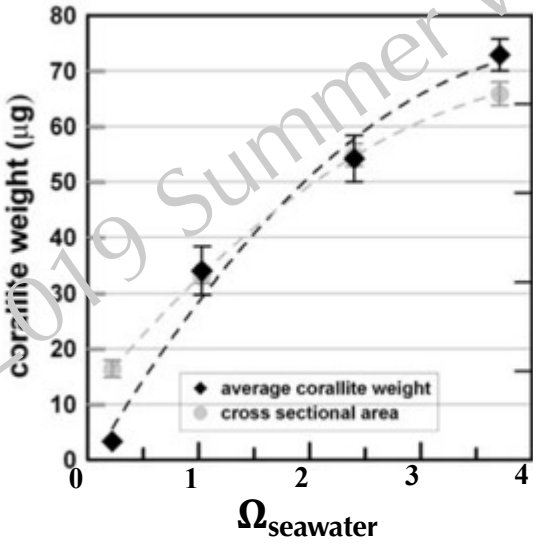
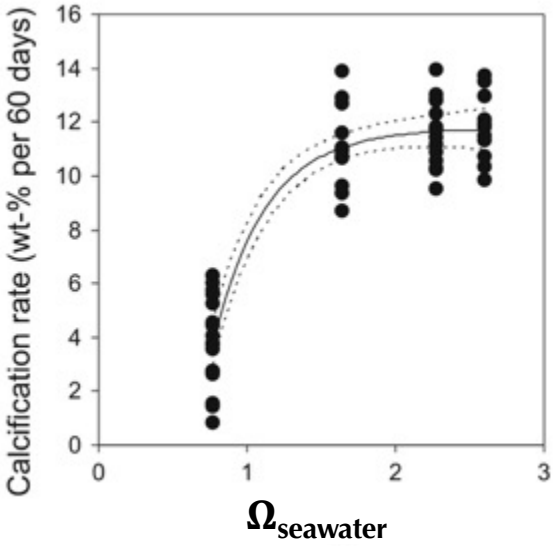
Favia fragum



Oculina arbuscula



Corals reared under controlled conditions

(a). Addition of acid (e.g. HCl)

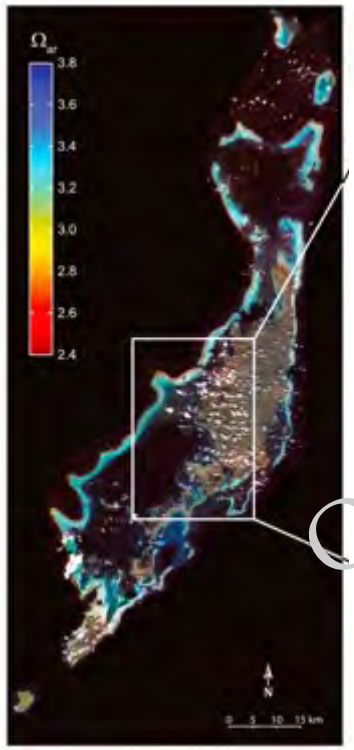
(b). Equilibration with Air/CO_2(high pCO_2)

e.g. Cohen et al. 2009, Ries et al. 2010, Ries 2011 and many others

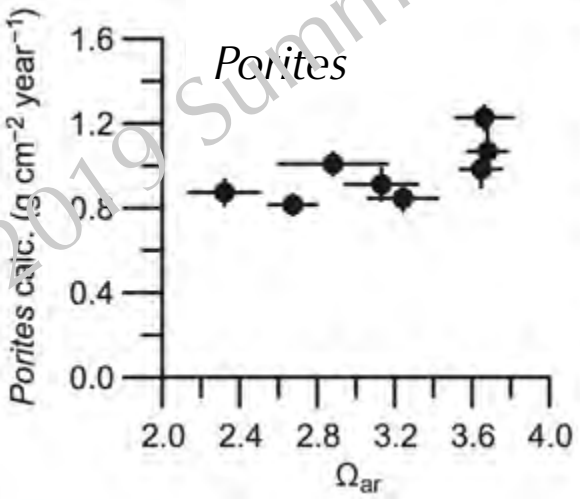
Ocean Acidification and Its Impact on Coral Calcification

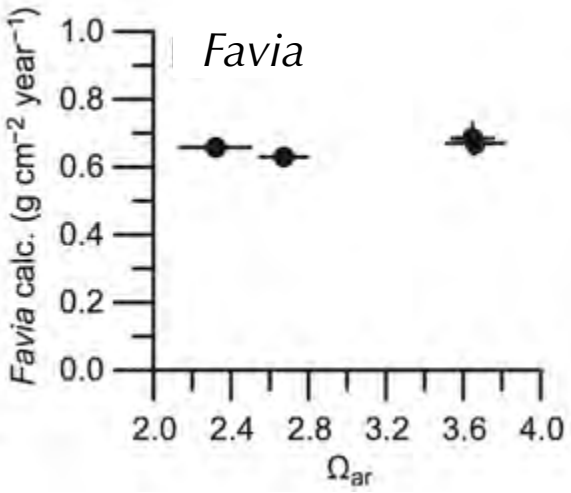
Measurements at naturally low-pH reefs

Corals living in low pH (Ω_{sw}) reef do not show significant decline in calcification



Palau reefs
(western tropical Pacific)





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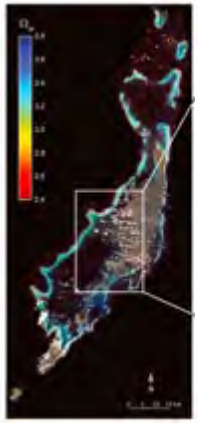
Shamberger et al. 2014, Barkley et al. 2015

OA Impact: Inconsistent Results

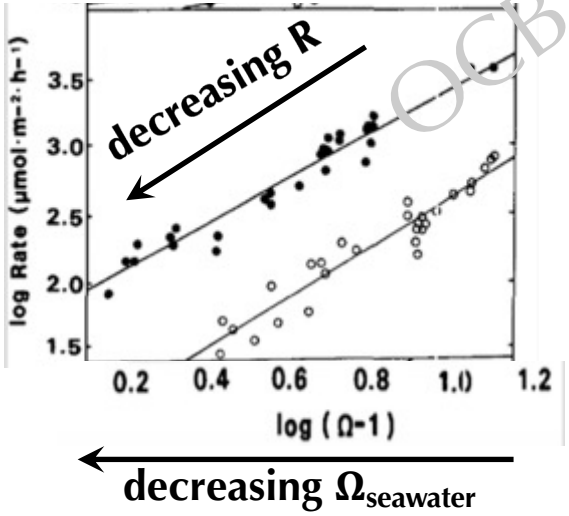
Inconsistent results hinder predictions of coral response to OA

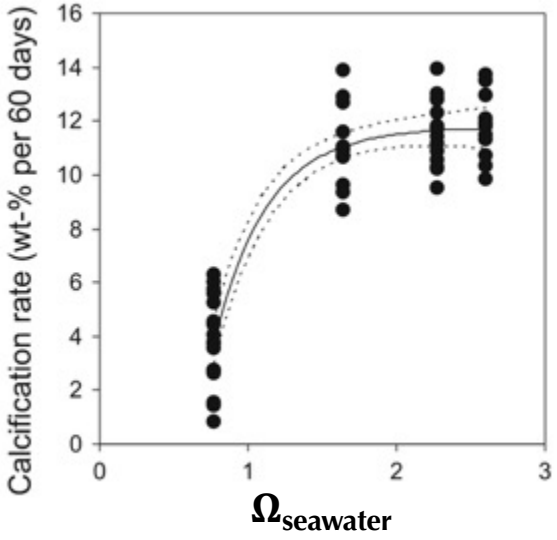
Abiotic Expt.

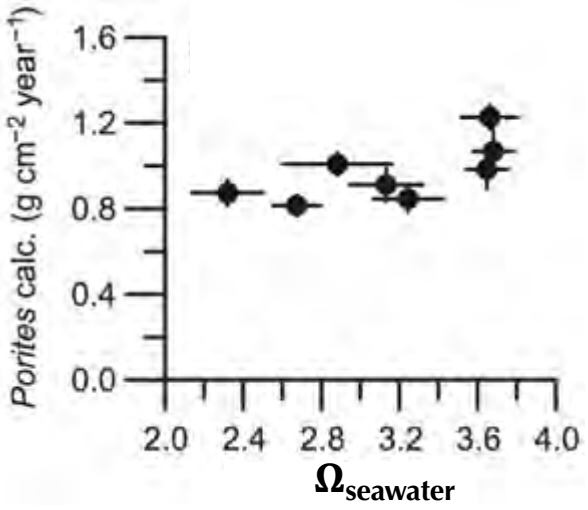
Culture Expt.



Reef Meas.







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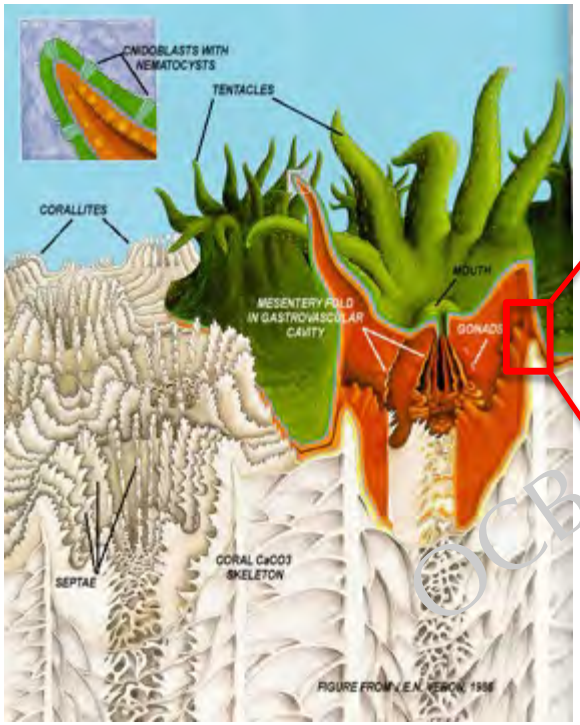
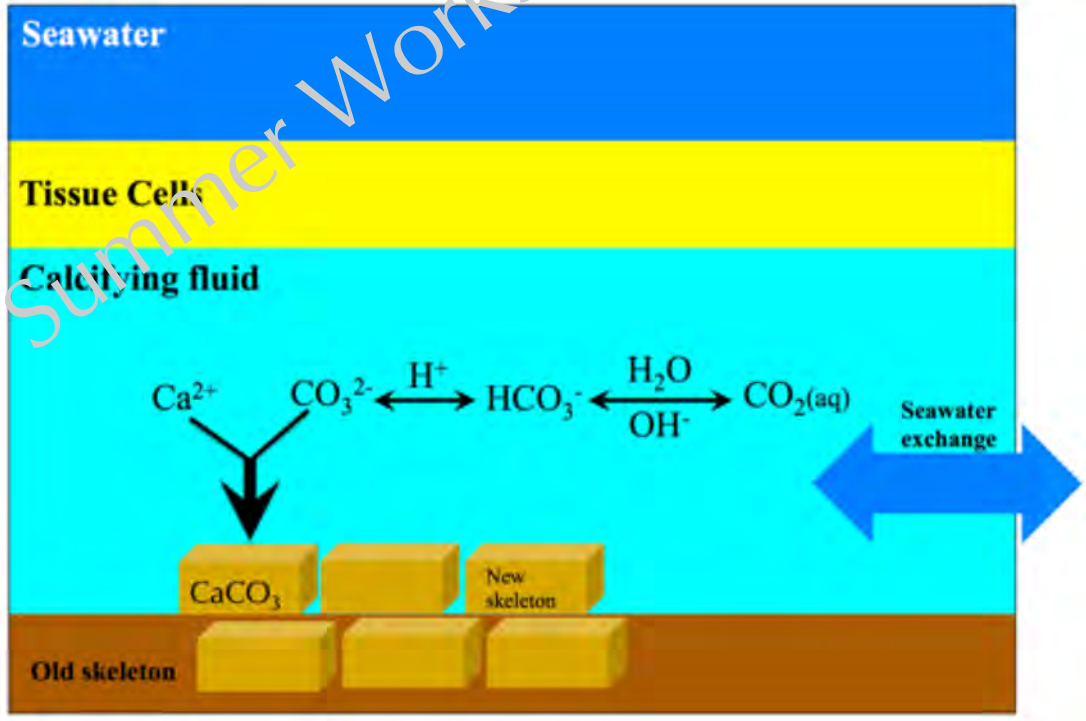
Mechanism of Coral Calcification

Coral calcification does not occur directly from seawater, but within an extracellular calcifying fluid or medium





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Corals regulate the chemistry of their calcifying fluid, leading to an internal calcification environment significant different from ambient seawater.

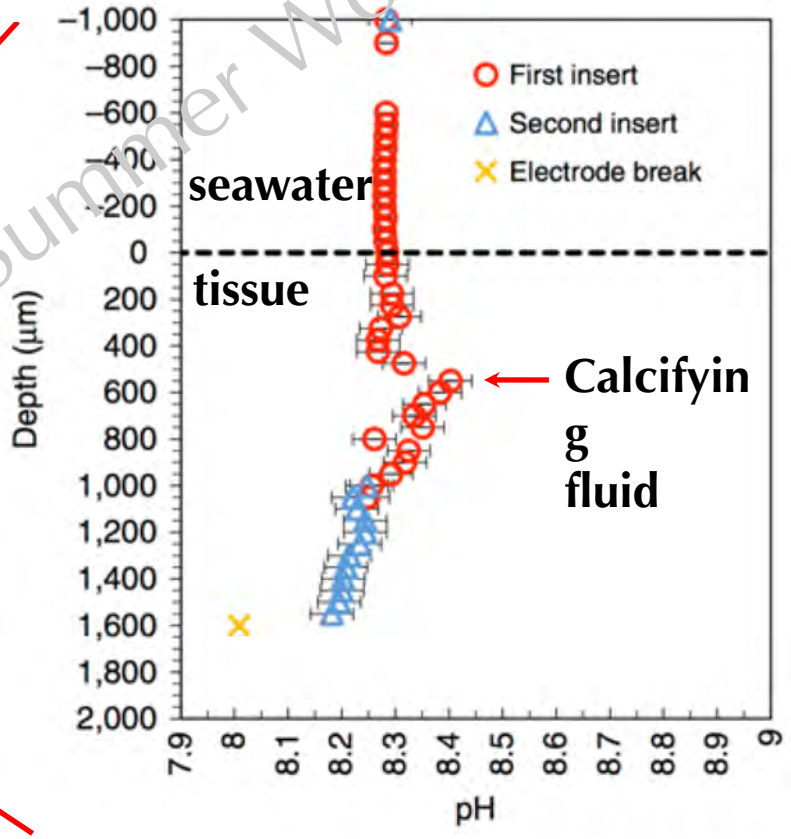
Modified after Veron 1986, *Cohen and McConnaughey 2003, Adkins et al. 2003*

Chemistry of coral calcifying fluid

Corals up-regulate pH of their calcifying fluid to promote calcification

- pH microelectrode
- pH sensitive dyes
- Geochemical proxies (boron isotope, B/Ca)

Microelectrode tip



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Cai et al. 2016

Chemistry of coral calcifying fluid

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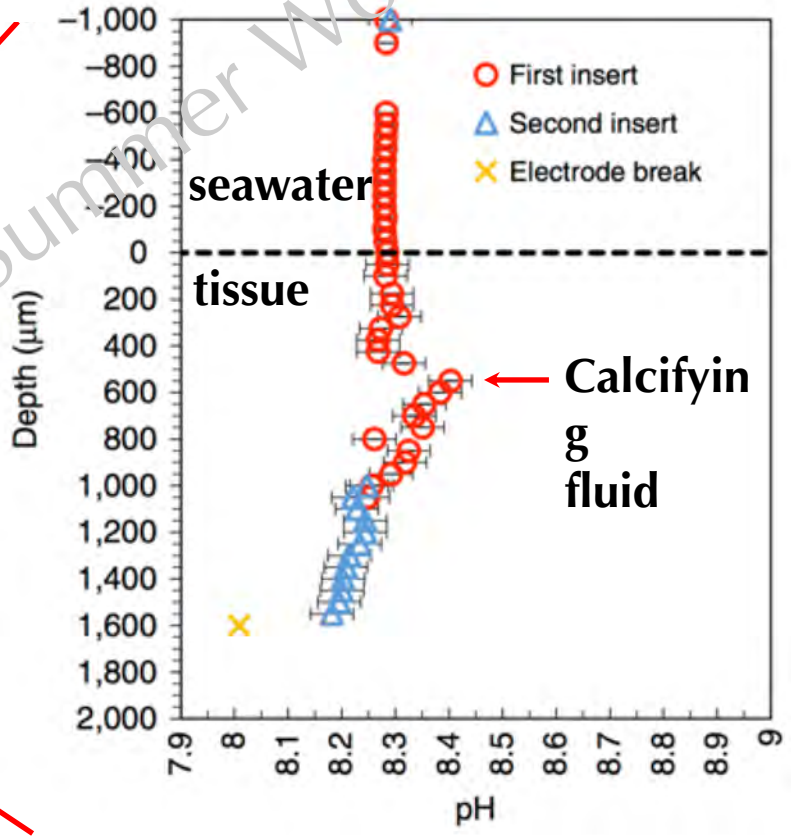

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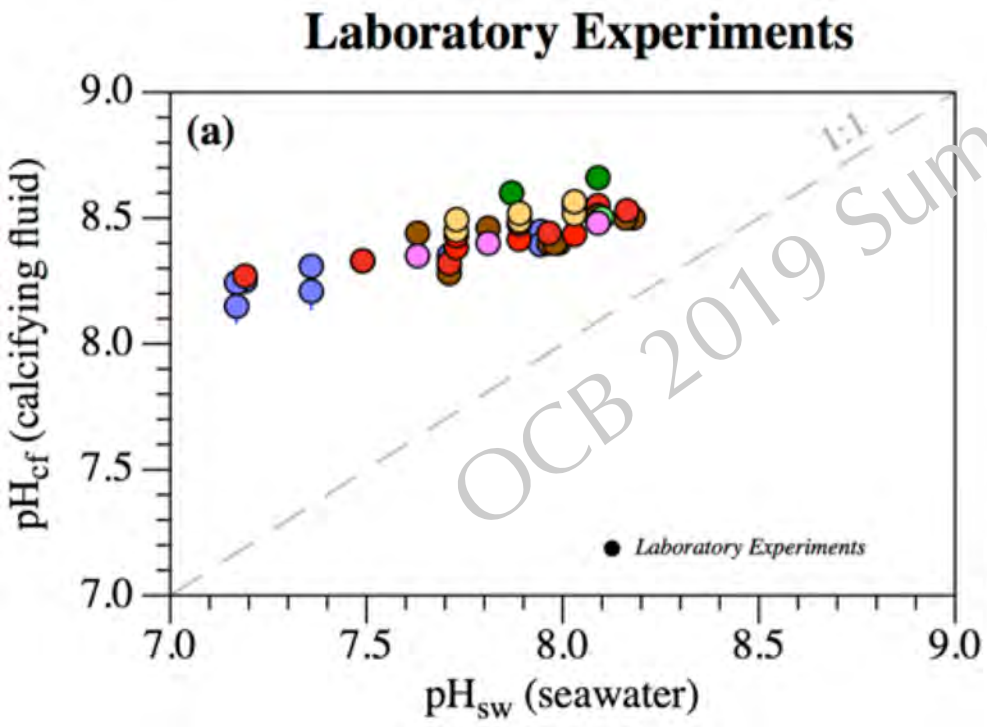
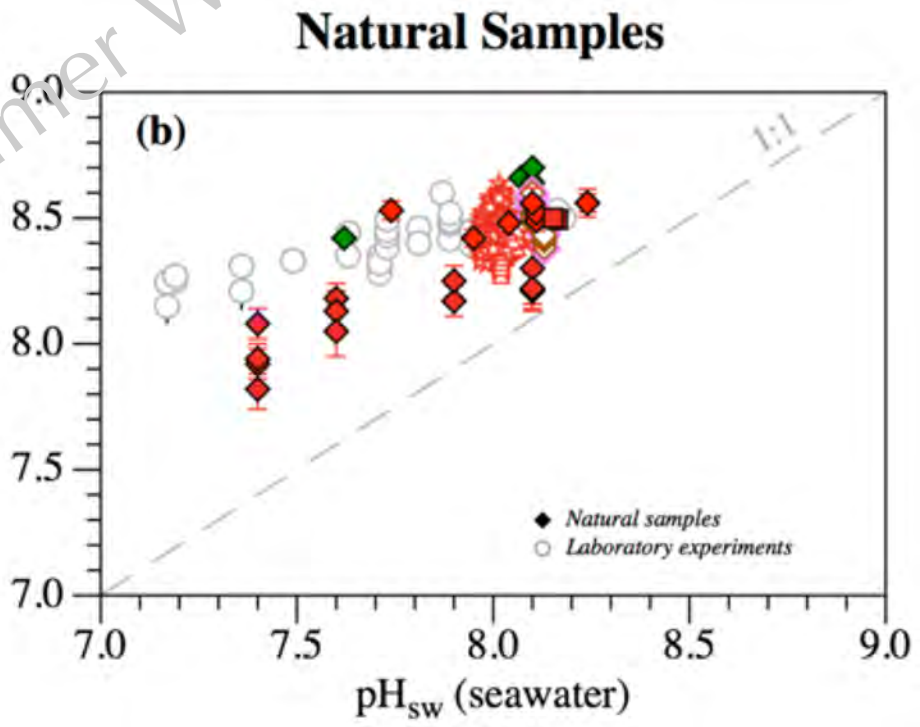
If corals can actively regulate their calcifying fluid chemistry, does OA still matter ?

Cai et al. 2016

Chemistry of coral calcifying fluid

Corals calcifying fluid pH correlate with seawater pH in lab expt., but show more variability in natural samples.





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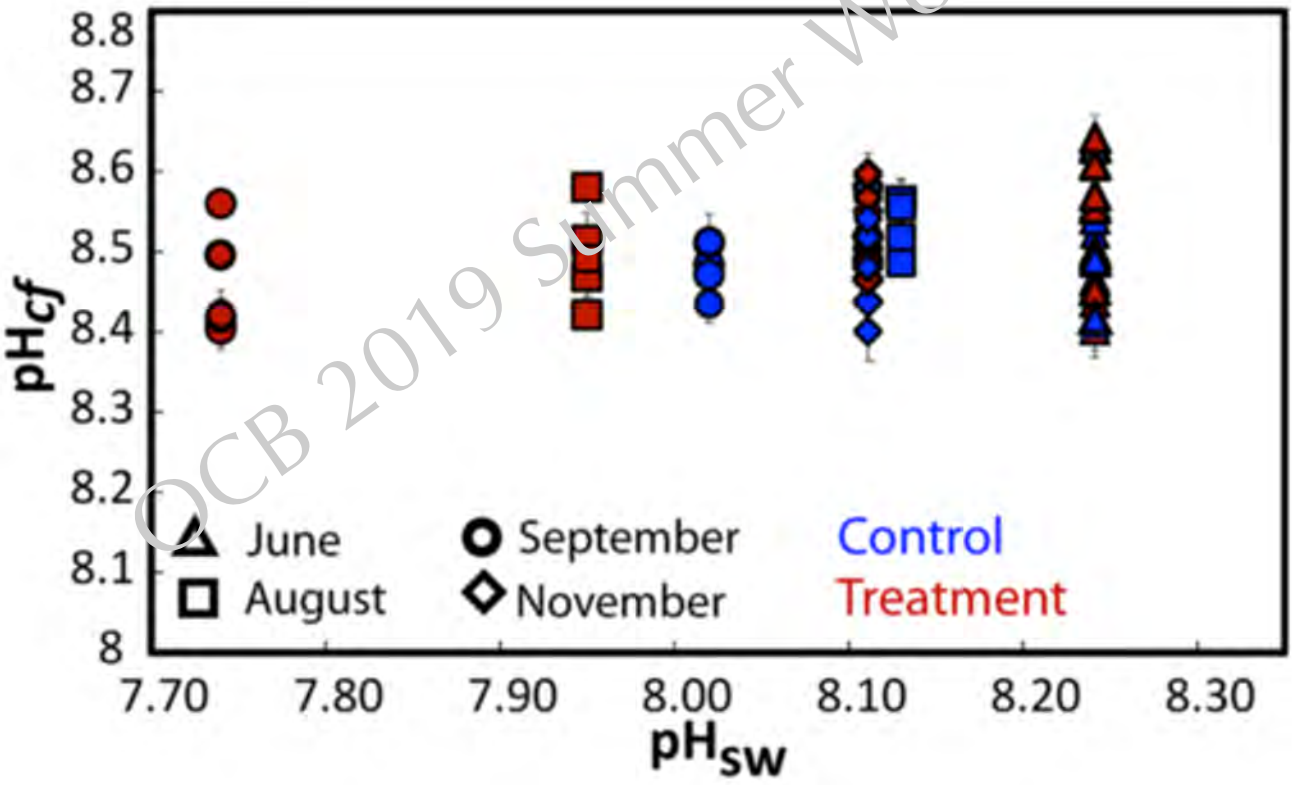
Compilations from Guo. 2019

Chemistry of coral calcifying fluid

***Porites* corals in field manipulation experiments, despite large pH_{sw} changes, show relatively constant pH_{cf}.**



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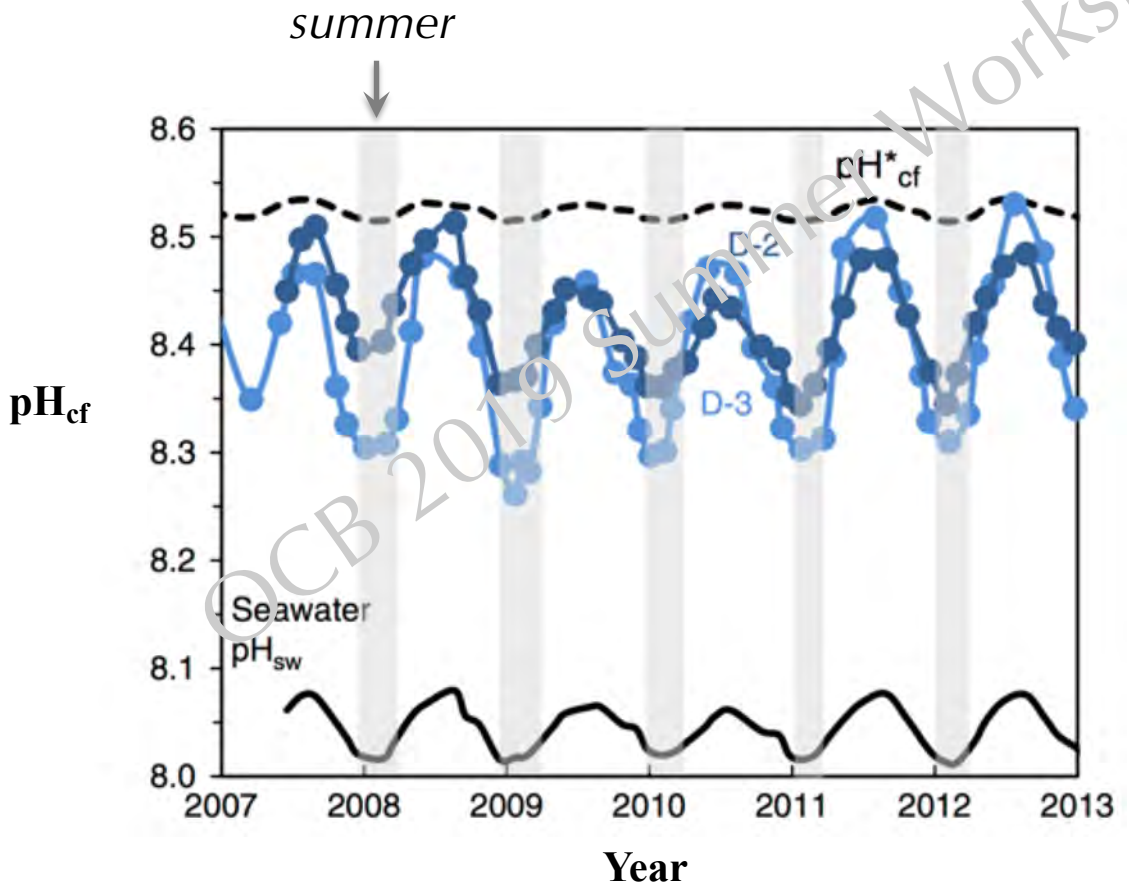
Georgiou et al. 2015, PNAS

Chemistry of coral calcifying fluid

***Porites* corals (Great Barrier Reef), despite small pH_{sw} changes, show large variations in pH_{cf} that negatively correlate with temperature.**



pH^*_{cf}: pHcf expected from the lab expt. correlations

McCulloch et al. 2017, Nat. Comm.

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Chemistry of coral calcifying fluid

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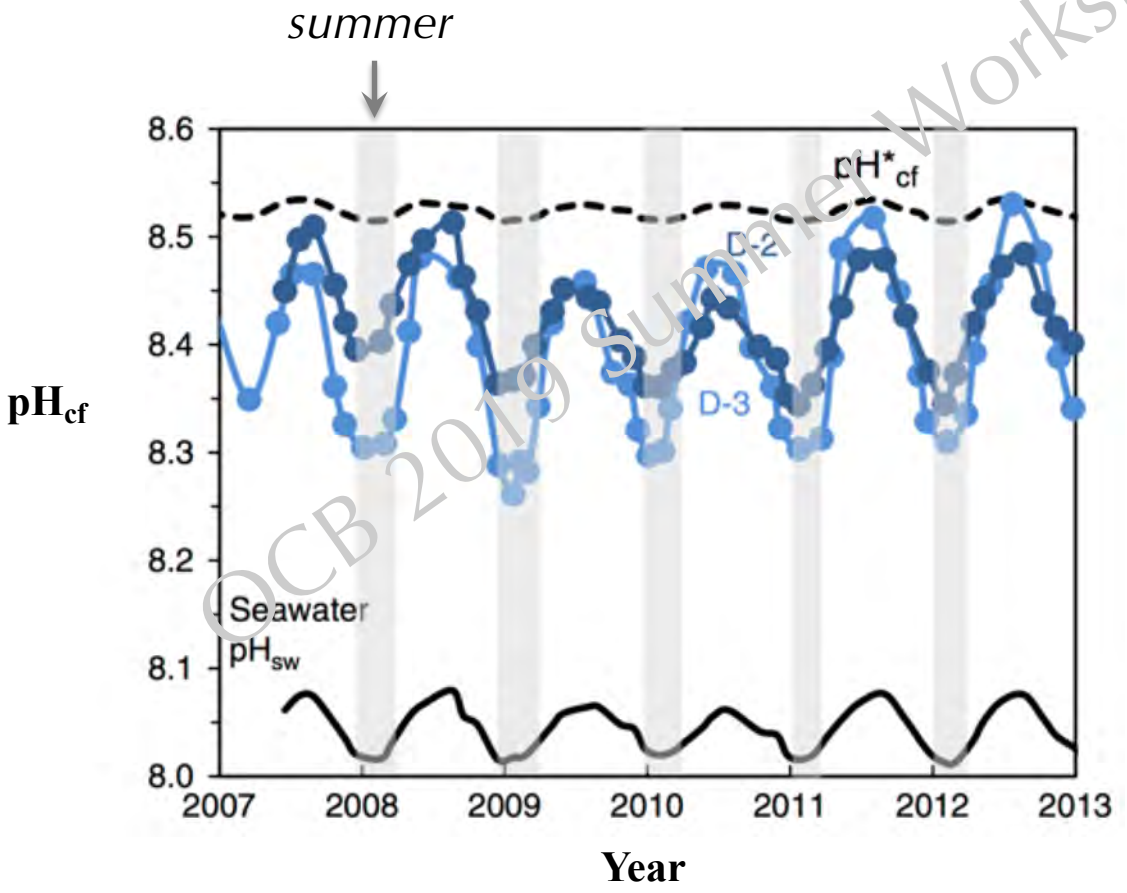

pH^*_{cf}: pHcf expected from the lab expt. correlations

Such decoupling between pH_{cf} and pH_{sw} has raised questions about adaptation, acclimation and/or the role of non-pH factors in modulating OA impact.

McCulloch et al. 2017, Nat. Comm.

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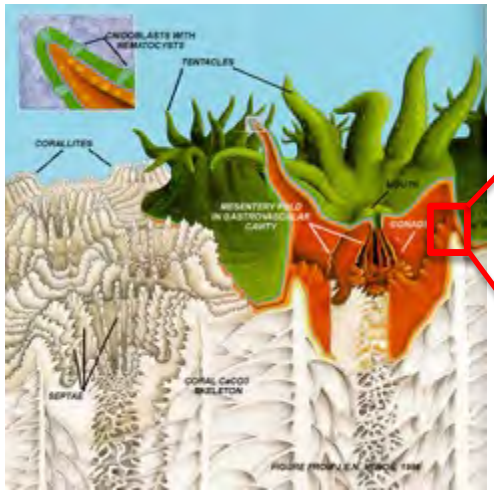
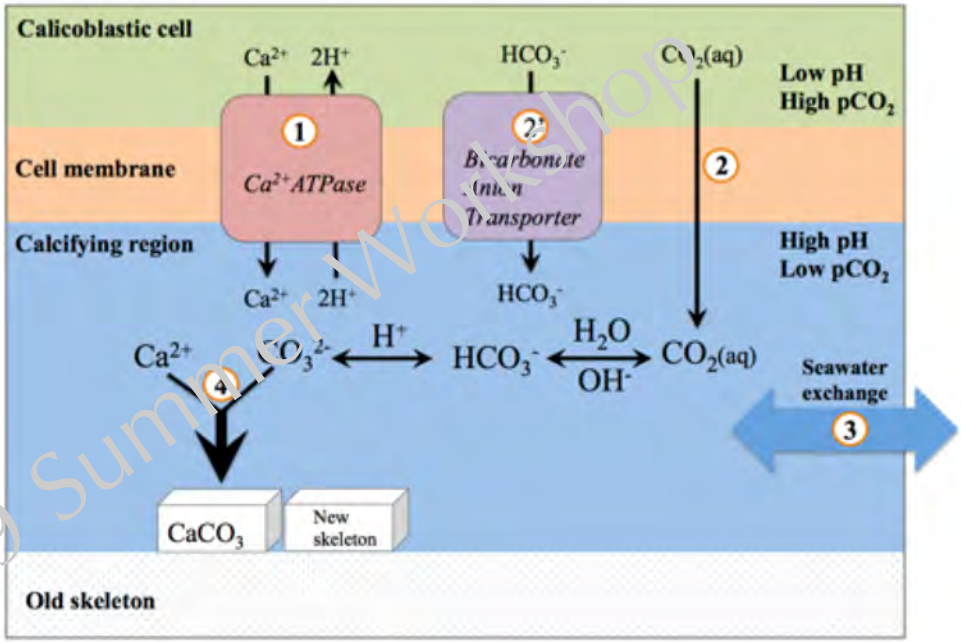
Corals' regulation of calcifying fluid pH





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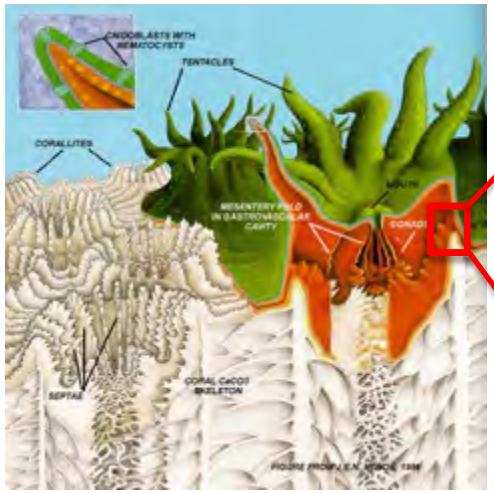
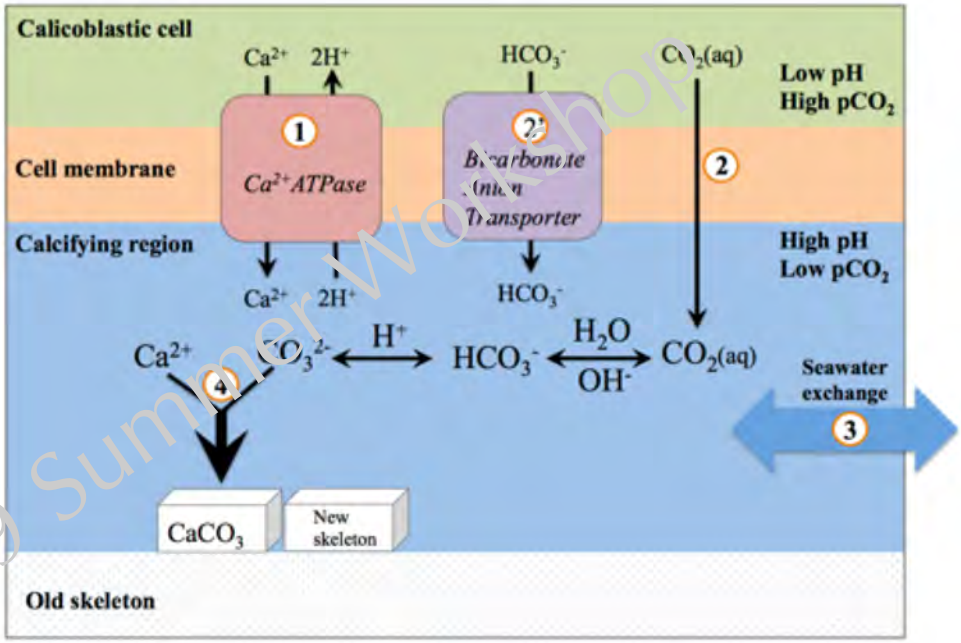
Key processes:

(1) Active pumping of Ca^{2+} and H^{+} across cell membrane via enzymes (e.g. CaATPase)
(2) Passive diffusion of CO_2 across cell membrane and/or active transport of HCO_3^-
(3) Leakage of seawater via various openings and junctions inside cell membrane
(4) Carbonate precipitation

Modified after Cohen and McConnaughey 2003, Adkins et al. 2003

A Physicochemical Model of Coral Calcifying Fluid pH Regulation





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Model Simulation

Inputs

Seawater

T, salinity, [Ca^{2+}]
Alkalinity, pH, etc

→

Parameters

(1) CaATPase pumping rate (P)
(2) Carbon flux across membrane (C)
(3) Seawater exchange rate (E)

(4) $R = k \times (\Omega_{cf}-1)^n$

Steady state

→

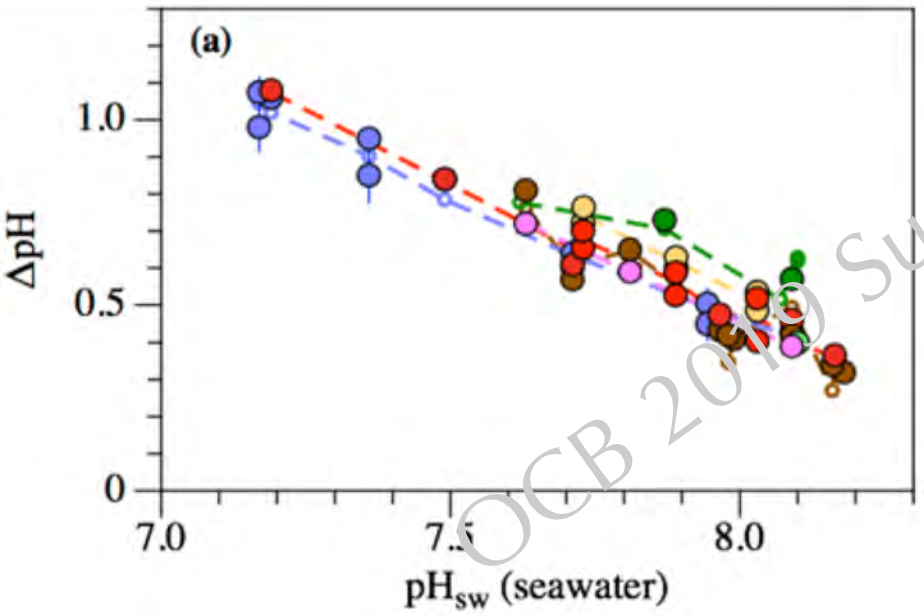
Outputs

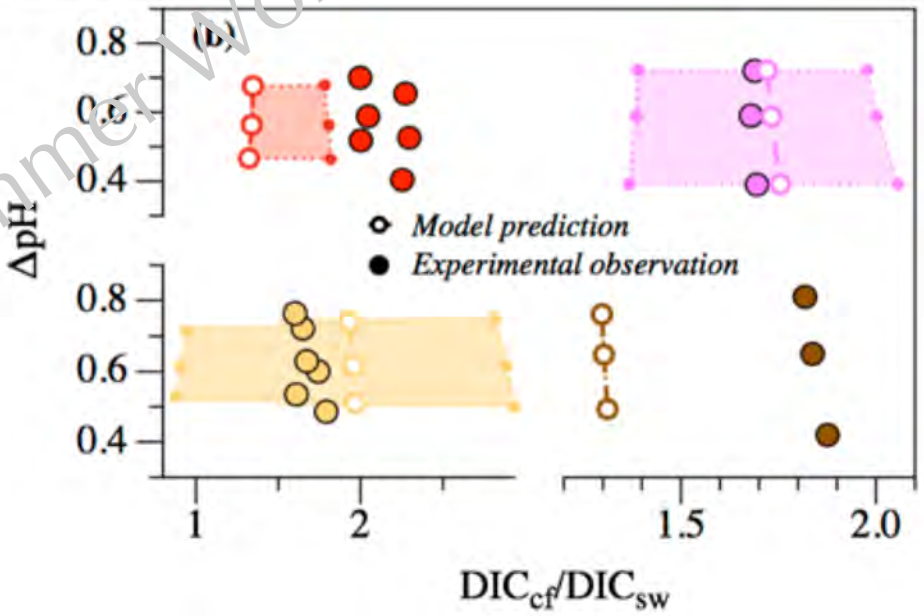
pH_{cf}
DIC_{cf}
TA_{cf}

Guo. 2019, Sci. Rep.

A Physicochemical Model of Coral Calcifying Fluid pH Regulation

Model parameters are optimized based on known constraints about pH_{cf}





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$\Delta pH = pH_{cf} - pH_{sw}$, pH elevation in calcifying fluid

The physicochemical model can explain the pH_{cf} variations in lab expt., and is consistent with independent constraints on DIC_{cf}

Guo. 2019, Sci. Rep.

A Physicochemical Model of Coral Calcifying Fluid pH Regulation

This model enables to partition the relative role of each factor in controlling pH_{cf}

- **Seawater buffering capacity and temperature exert the first-order control on the extent of pH elevation.**
- **Physiological regulation (P, C, E) contributes to some variability but remain relatively constant as seawater conditions change**

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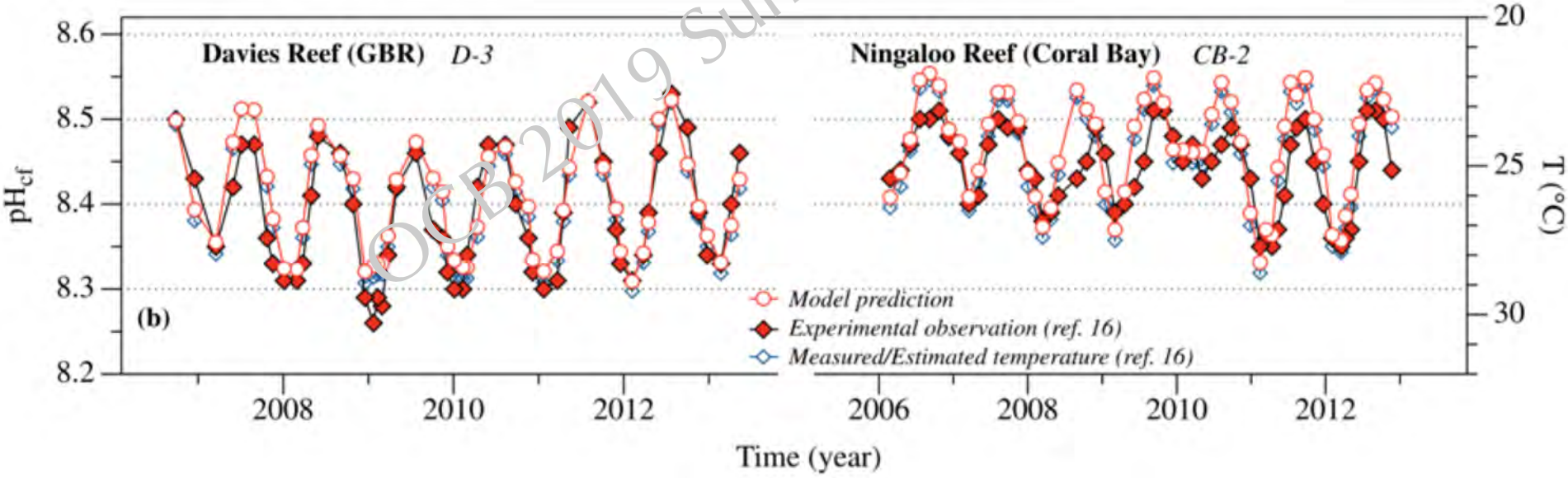

Model reproduces the variations of calcifying fluid pH in natural coral colonies

Guo. 2019, Sci. Rep.

Takeaway Messages (I)

- **Coral calcifying fluid, not seawater, places the direct control on coral calcification rate**

- **Despite physiological regulation, seawater buffering capacity and temperature exert the first-order control on the extent of pH elevation in the calcifying fluid.**

<u>Coral calcifying fluid (and thus coral calcification) should feel the OA.</u>

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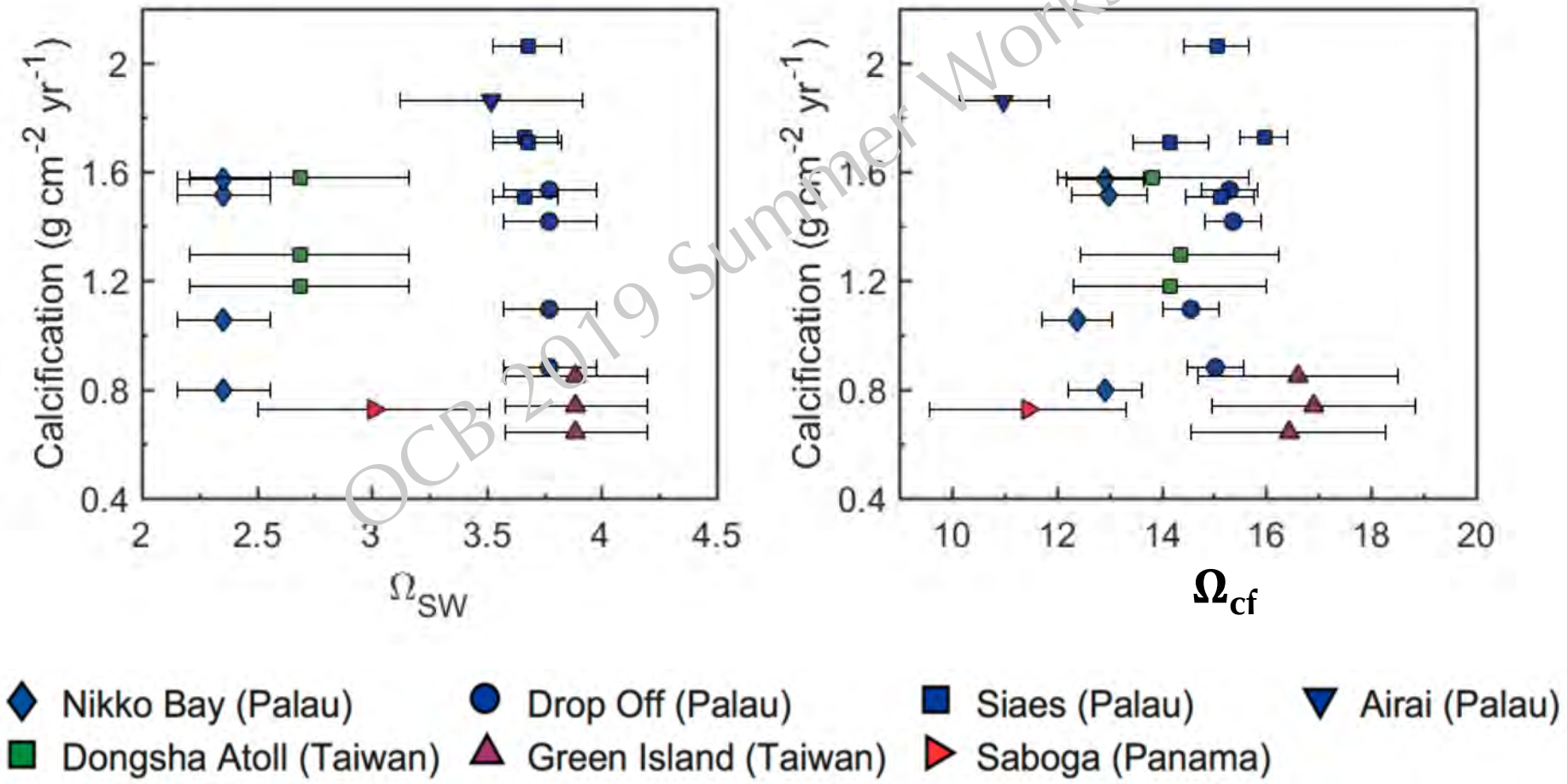
Coral Calcification Responds to Ω_{cf} ?

Coral (Porites) calcification does NOT respond to Ω_{cf} either



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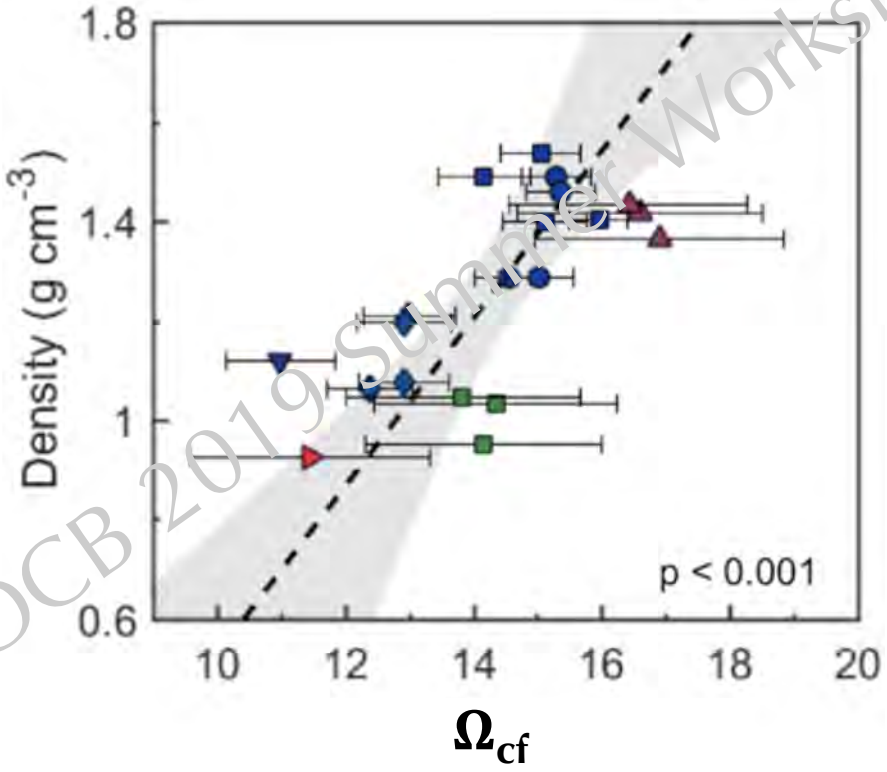
Mollica, Guo et al. 2018, PNAS

Coral Calcification Responds to Ω_{cf} ?

Coral skeletal density is sensitive to Ω_{cf}



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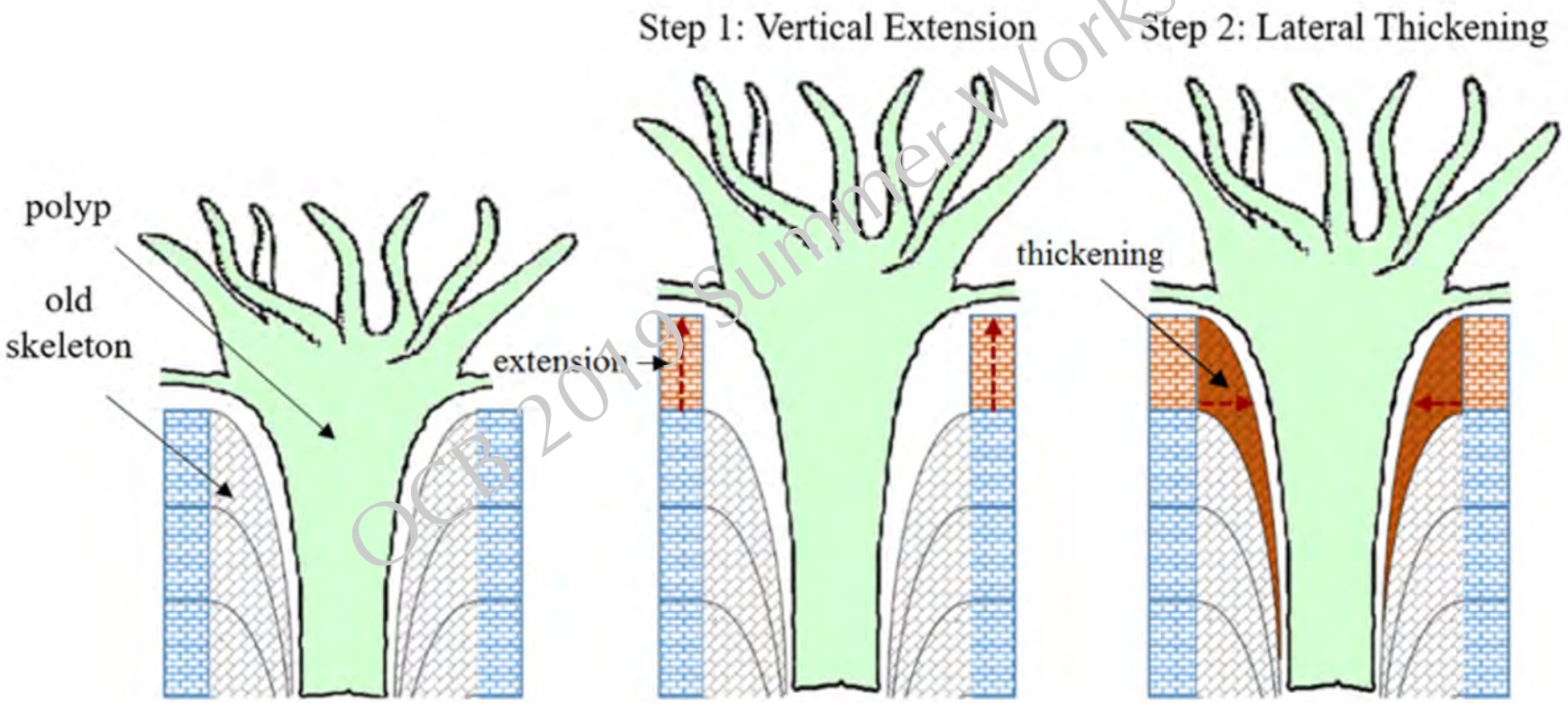
Nikko Bay (Palau)
Drop Off (Palau)
Siaes (Palau)
Airai (Palau)
Dongsha Atoll (Taiwan)
Green Island (Taiwan)
Saboga (Panama)

Mollica, Guo et al. 2018

A Two-Step Coral Skeletal Growth Model



biology-controlled not sensitive to OA

chemistry-controlled sensitive to OA

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Mollica, Guo et al. 2018, Barnes and Lough 1993, Taylor et al. 1993

A Two-Step Coral Skeletal Growth Model

A numerical model of coral (Porites) skeletal growth

Controls on coral skeletal density:

(1) rate of extension: higher extension → lower density
affecting the time spent within the tissue layer and subject to thickening

(2) temperature
affecting the kinetics of carbonate precipitation, and pH_{cf}

(3) seawater carbonate chemistry (e.g., pH): higher pH → higher density
affecting calcifying fluid chemistry (Ω_{cf})

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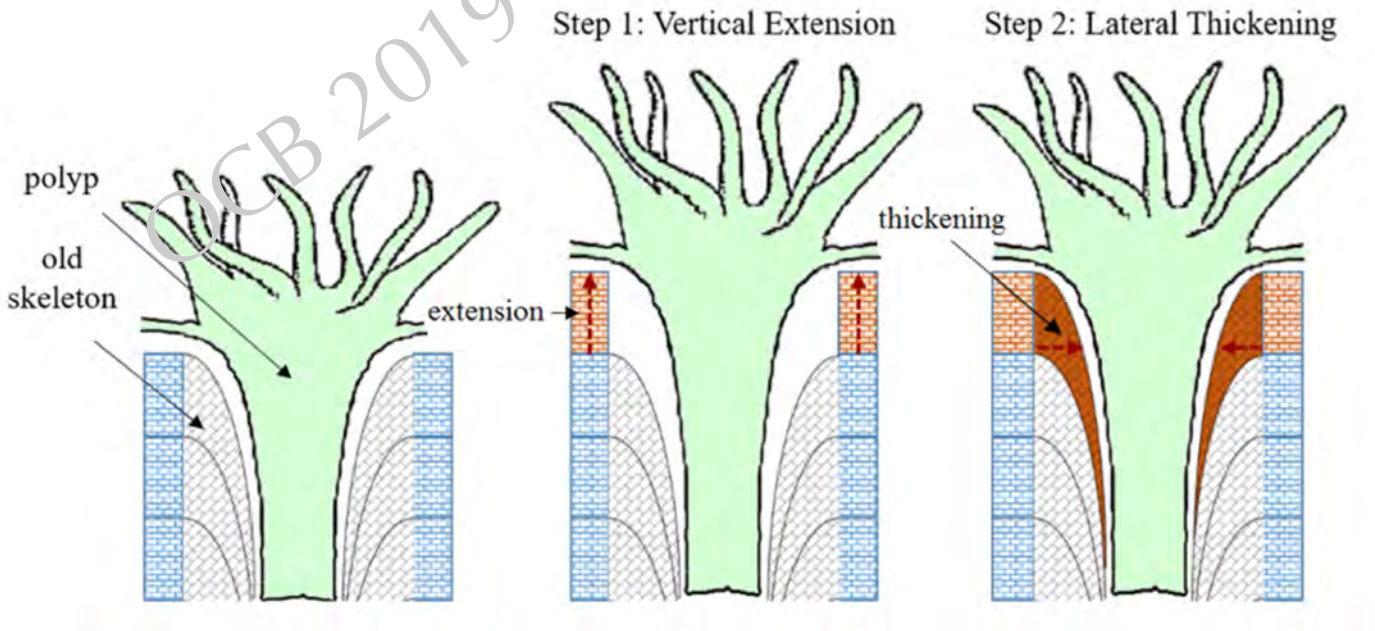
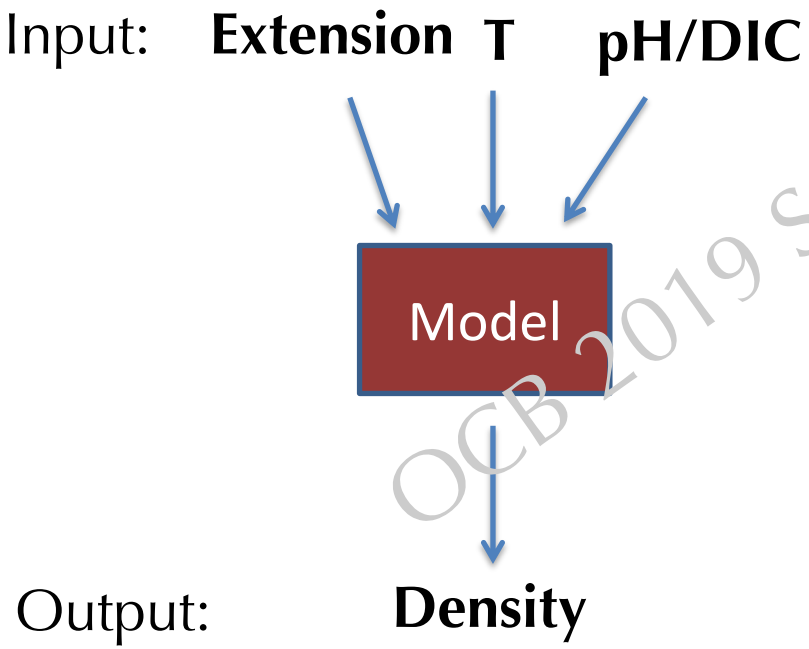
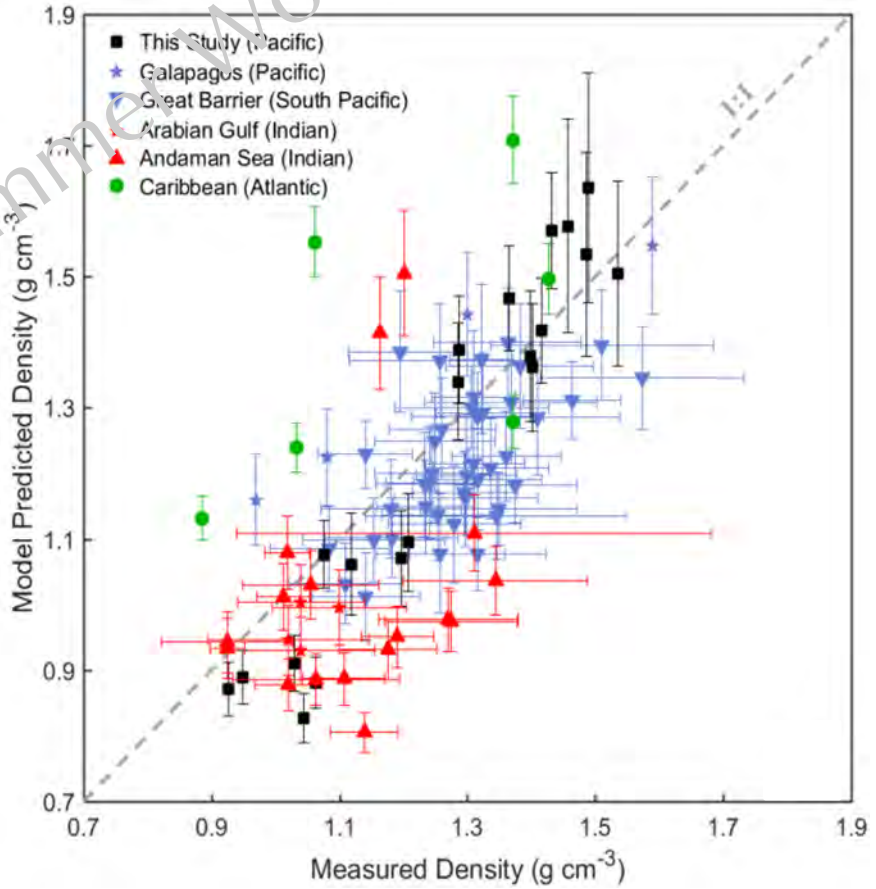


Mollica, Guo et al. 2018

A Two-Step Coral Skeletal Growth Model

Skeletal growth model quantitatively reproduces measured densities





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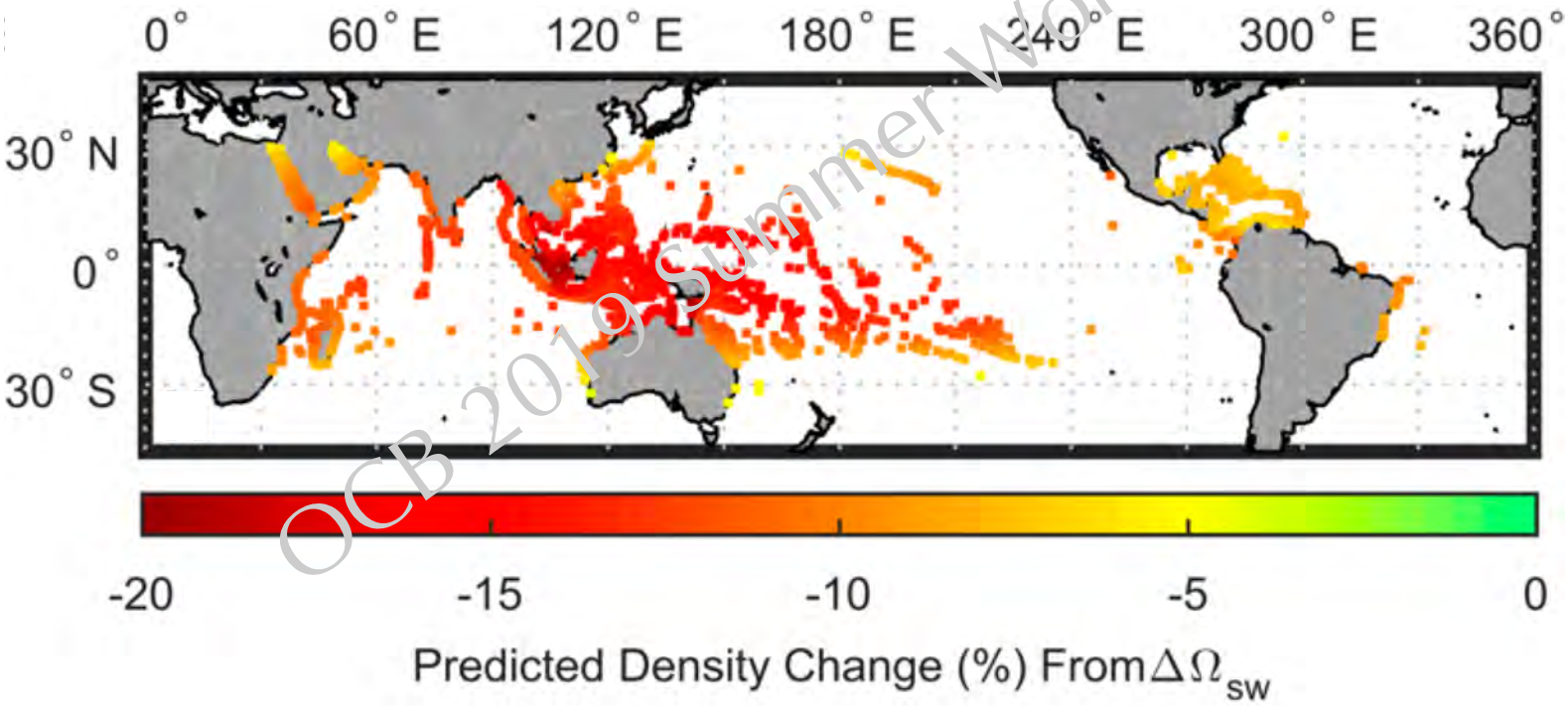
Mollica, Guo et al. 2018

Projection of OA Impact by 2100

Skeletal growth model enables quantitative prediction of OA impact

Seawater input : Global Climate Model (CESM-BGC, RCP 8.5 projection)



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Our model predicts that OA alone will drive up to 20% decline in *Porites* coral skeletal density by 2100

Mollica, Guo et al. 2018

Takeaway Messages (II)

- ***Porites*** **coral calcification is a two-step process, consisting of vertical extension and lateral densification**

- **Only densification is directly sensitive to changes in seawater chemistry and thus to OA.**

- **Ocean acidification alone will drive up to 20% decline in the skeletal density of reef-building *Porites* corals by 2100** (*Mollica et al. 2018, PNAS*)

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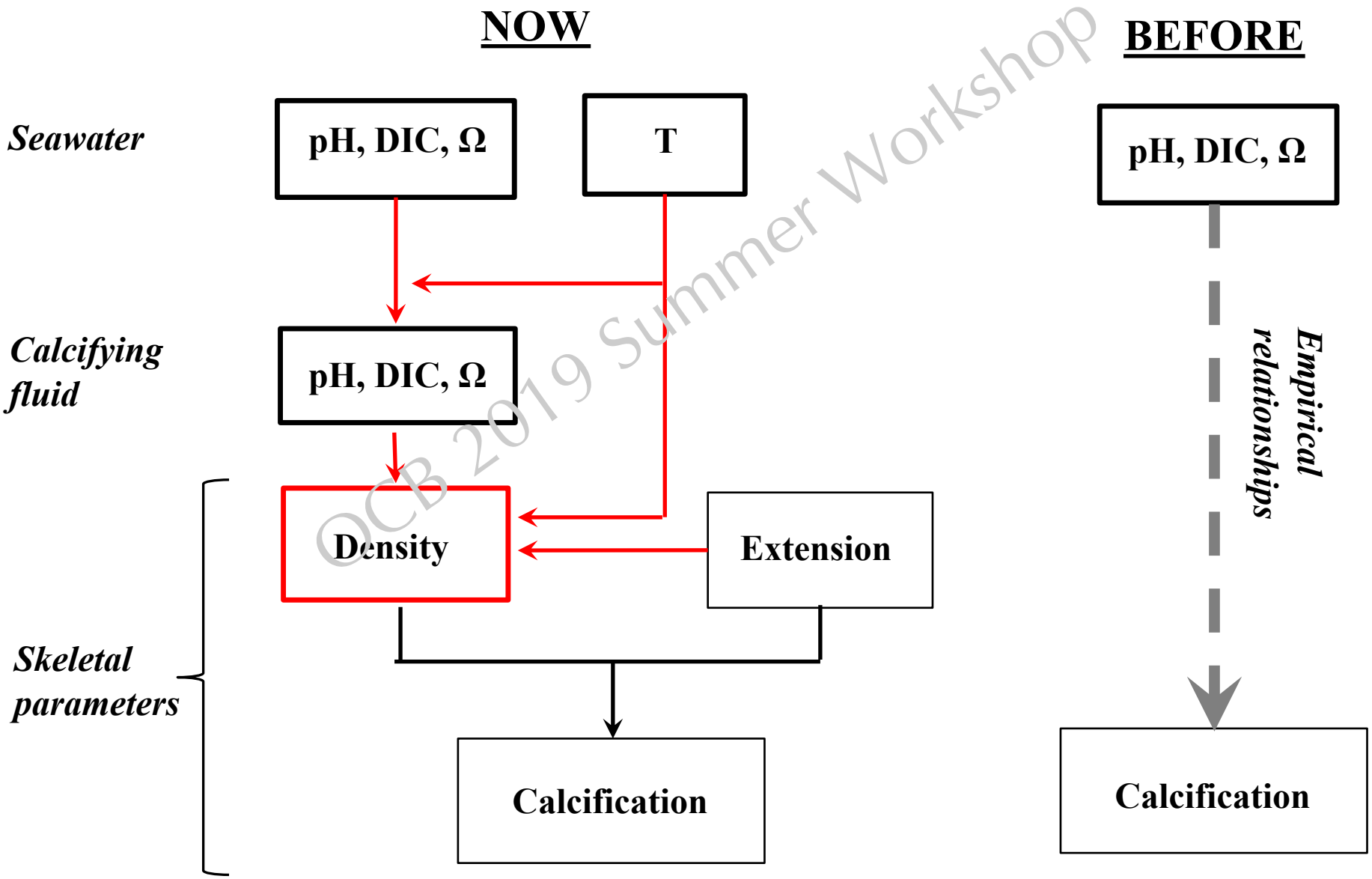
Predicting Coral Calcification Response to OA



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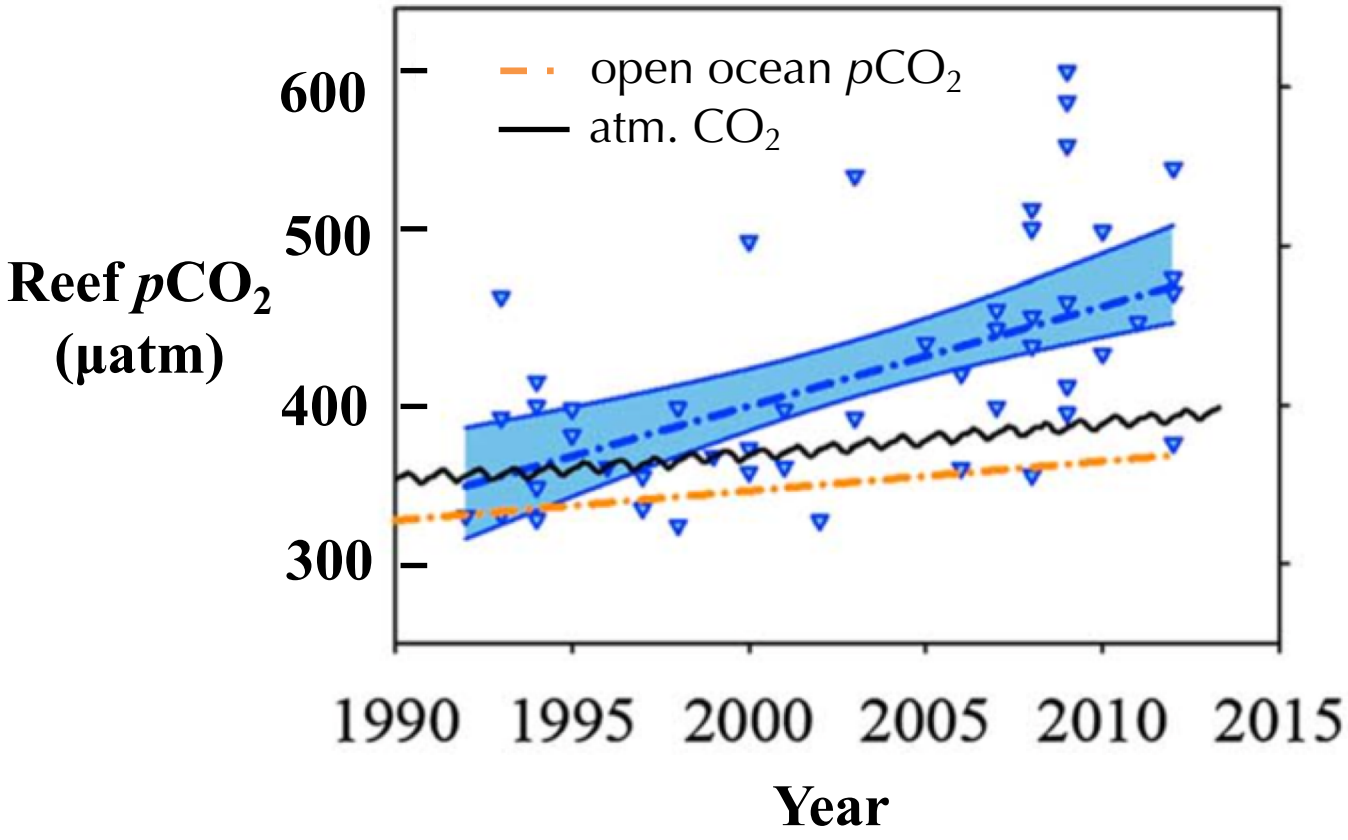
Predicting Coral Calcification Response to OA

- **Reef water carbonate chemistry is more dynamic than open ocean.**
- **Current understanding of controls on reef water carbonate chemistry is limited.**



Cyronak et al. 2014, GRL

Summary

- Ocean acidification affects coral calcification via its influence on coral calcifying fluid chemistry

- Coral (*Porites*) skeletal density is directly sensitive to ocean acidification, and is projected to decline by up to 20% by 2100 due to OA alone

- Are we there yet? Predicting coral calcification responses to OA
  - Not quite …
  - Better understanding and predictions of reef OA trends

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