Responses to Ocean Acidification on Varying Temporal and Spatial Scales

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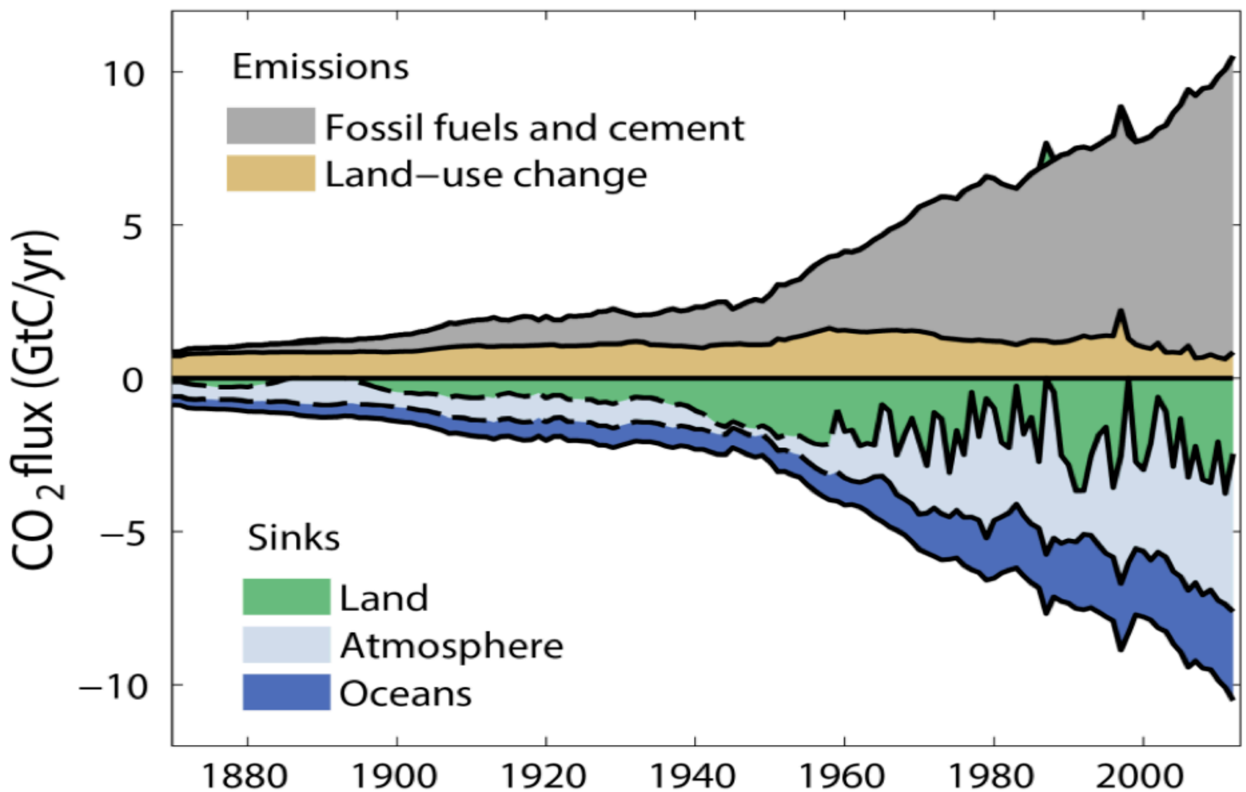
Global Carbon Balance

Emissions to the atmosphere are balanced by the sinks

Average sinks since 1870: 41% atmosphere, 31% land, 28% ocean

Average sinks since 1959: 45% atmosphere, 28% land, 27% ocean



Sources 2003-2012

8.6 ± 0.4 PgC

0.8 ± 0.5 PgC

Sinks 2003-2012

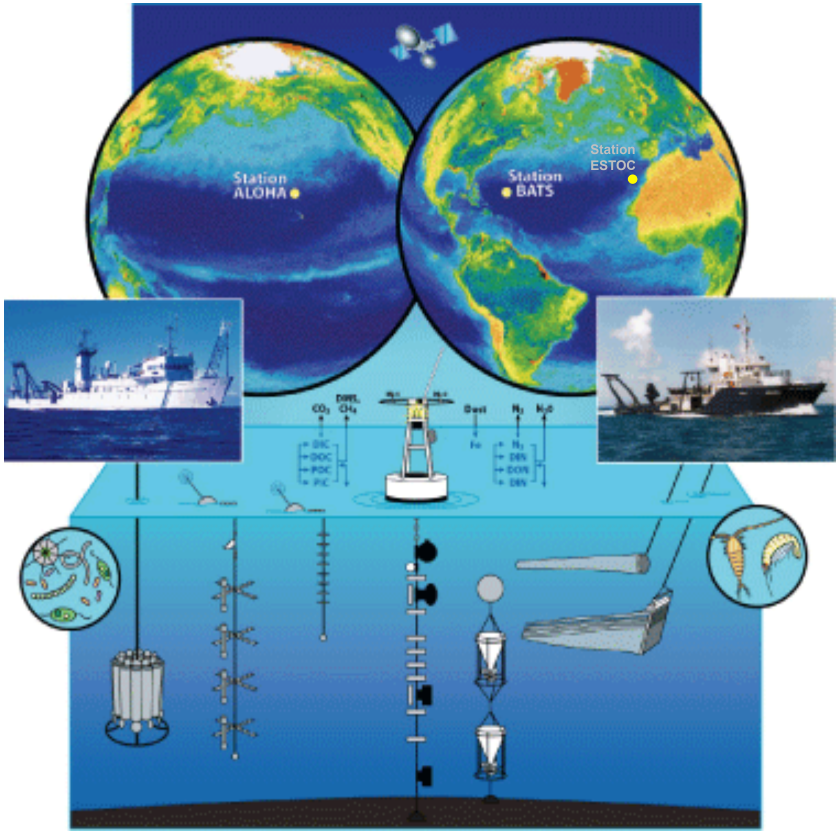
2.6 ± 0.8 PgC

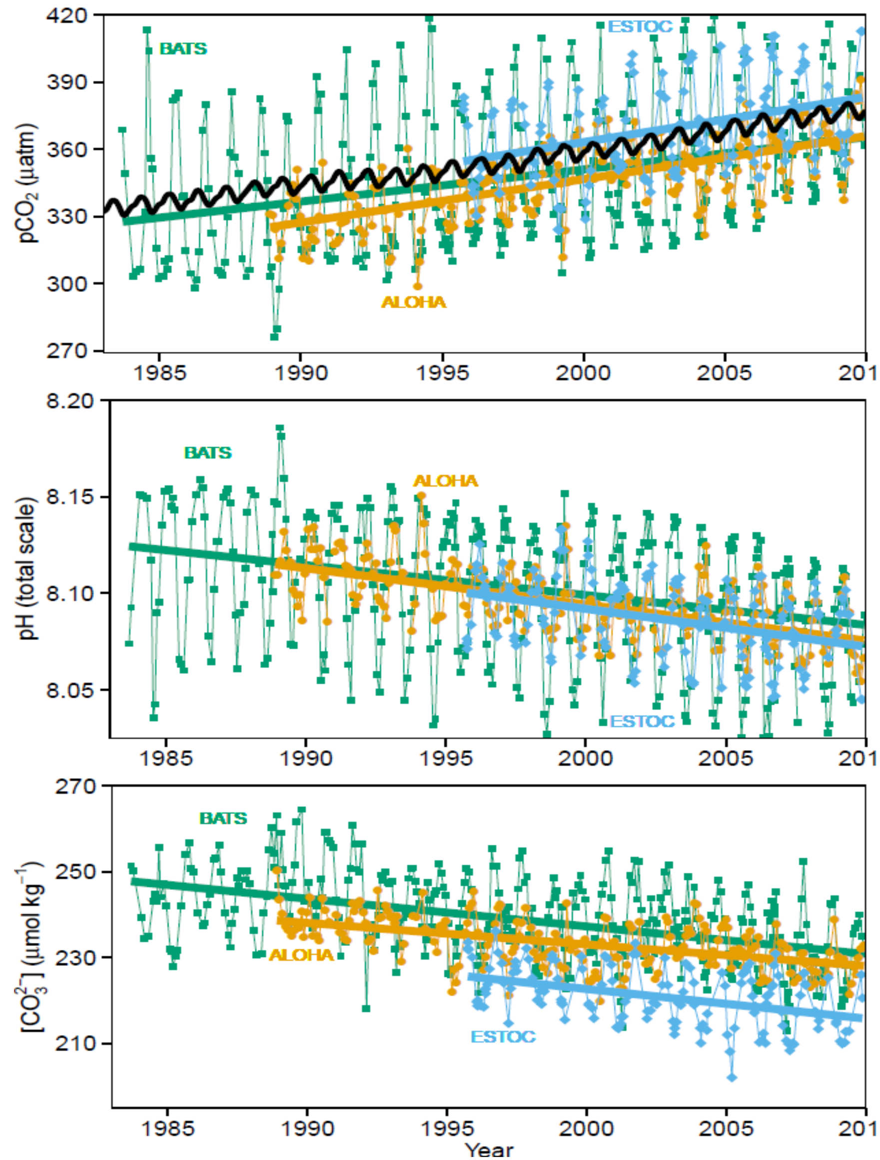
4.3 ± 0.1 PgC

2.6 ± 0.5 PgC

Source: CDIAC Data; Houghton & Hackler (in review); NOAA/ESRL Data; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2013; Global Carbon Project 2013

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)

In-situ pH change = -0.0019 ± 0.0002 yr^{-1}

Saturation State

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

calcium — carbonate — calcium carbonate

Saturation State

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

$\Omega>1$ $CaCO_3$ precipitates

$\Omega=1$ equilibrium

$\Omega<1$ $CaCO_3$ dissolves

Common carbonate minerals:

aragonite (more soluble) and calcite (less soluble)

Long-term Impacts of Acidification (after Joos et al., 2011)

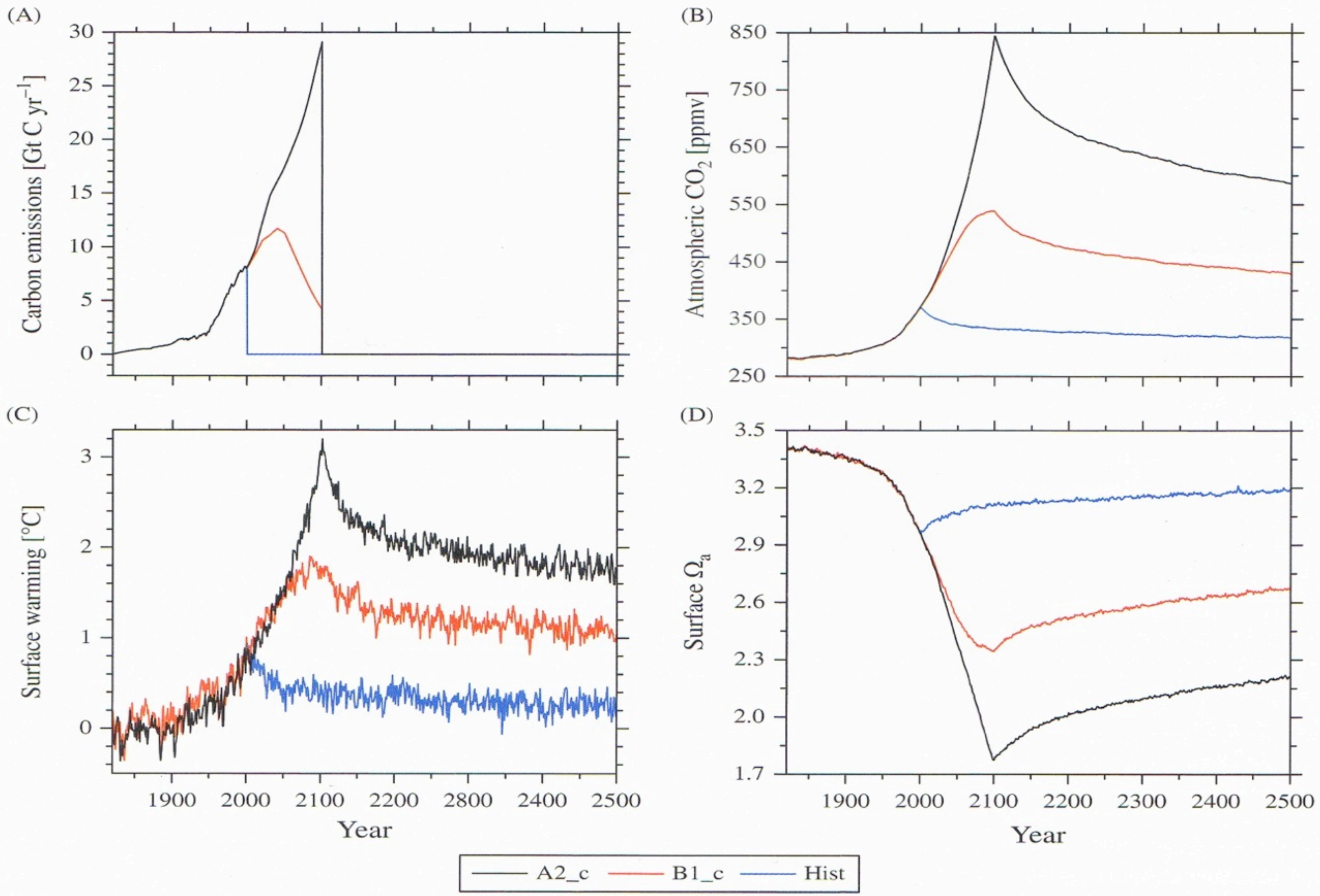
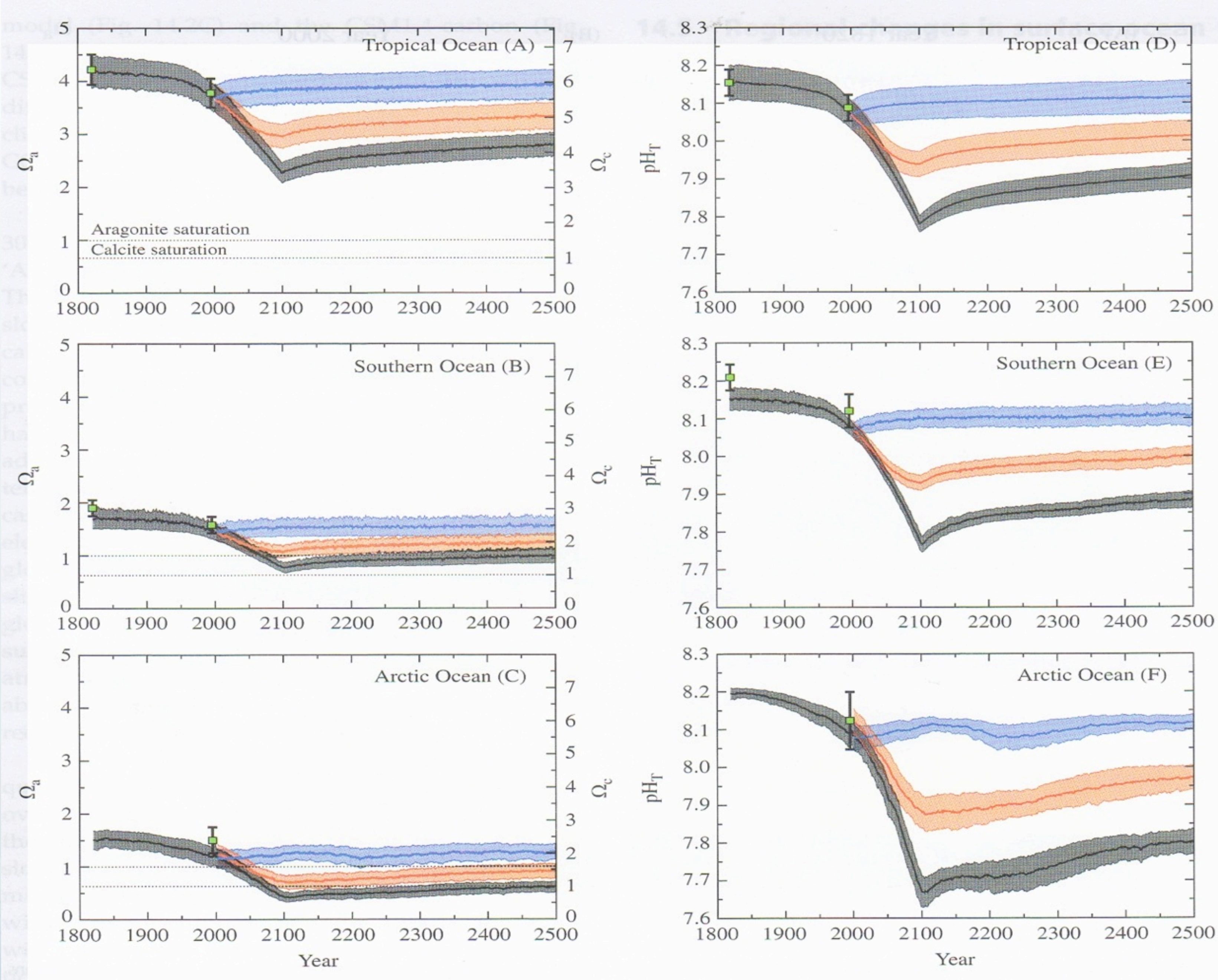


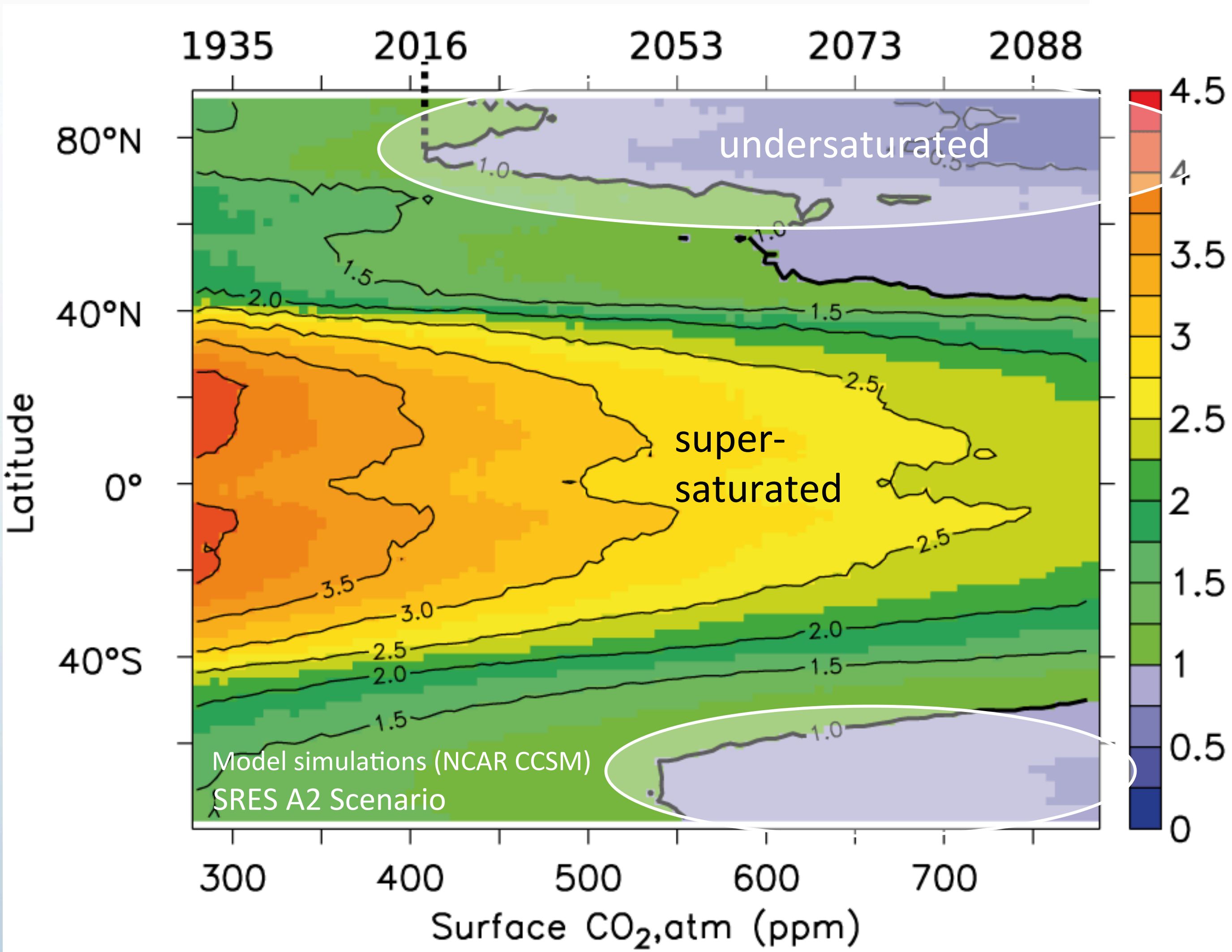
Figure 14.4 Long-term impact of 21st century carbon emissions. (A) Carbon emissions, (B) atmospheric CO_2, (C) global-mean surface air-temperature change, and (D) global average saturation state of surface waters with respect to aragonite (Ω_a) for three illustrative emissions commitment scenarios evaluated with the NCAR CSM1.4-carbon model (Frölicher and Joos 2010). In the high 'A2_c' case and the low 'B1_c' case, 21st century emissions follow the SRES A2 and SRES B1 business-as-usual scenario, respectively. Emissions are set to zero in both cases after 2100. In the 'Hist' case, emissions are stopped in the year 2000.

Long-term Impacts of Acidification (after Joos et al., 2011)



Projections

Evolution of ocean acidification during this century



Zonal mean surface ocean saturation state Ω_{arag} at annual minimum

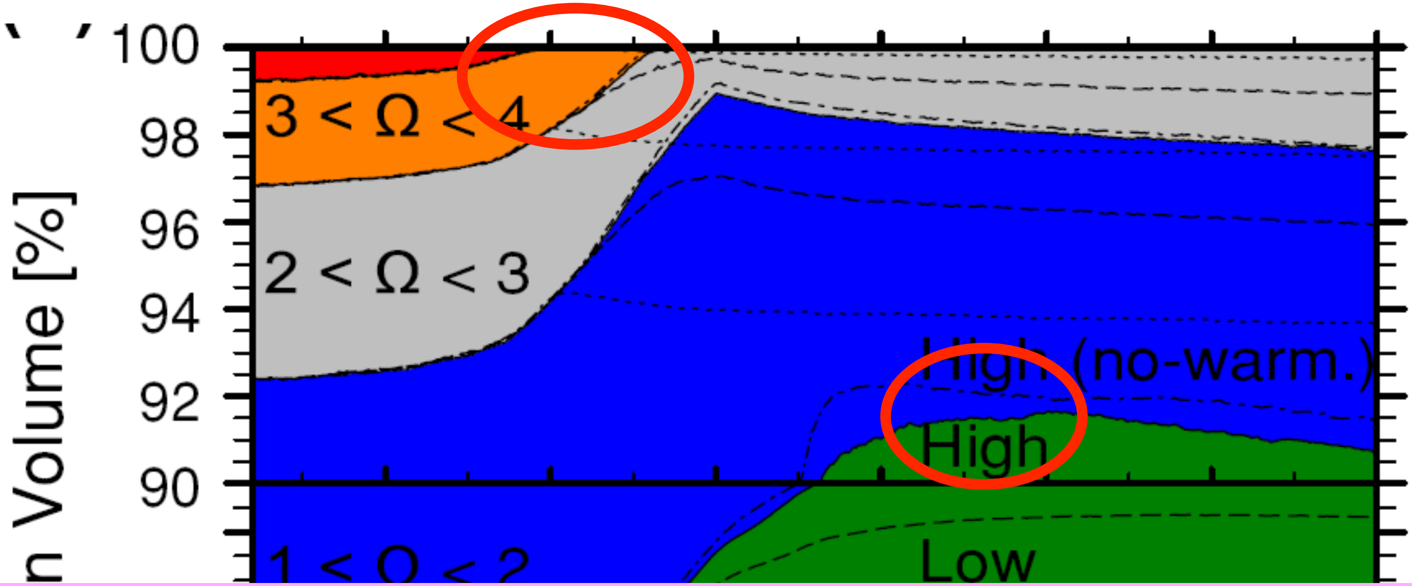
$$\Omega_{arag} = \frac{[CO_3^{2-}]}{[CO_3^{2-}]^{sat}}$$

High latitudes become undersaturated substantially earlier than the low latitudes

Steinacher et al. (2009)

Changes in saturation state by classes for a high 21st century carbon emission commitment scenario

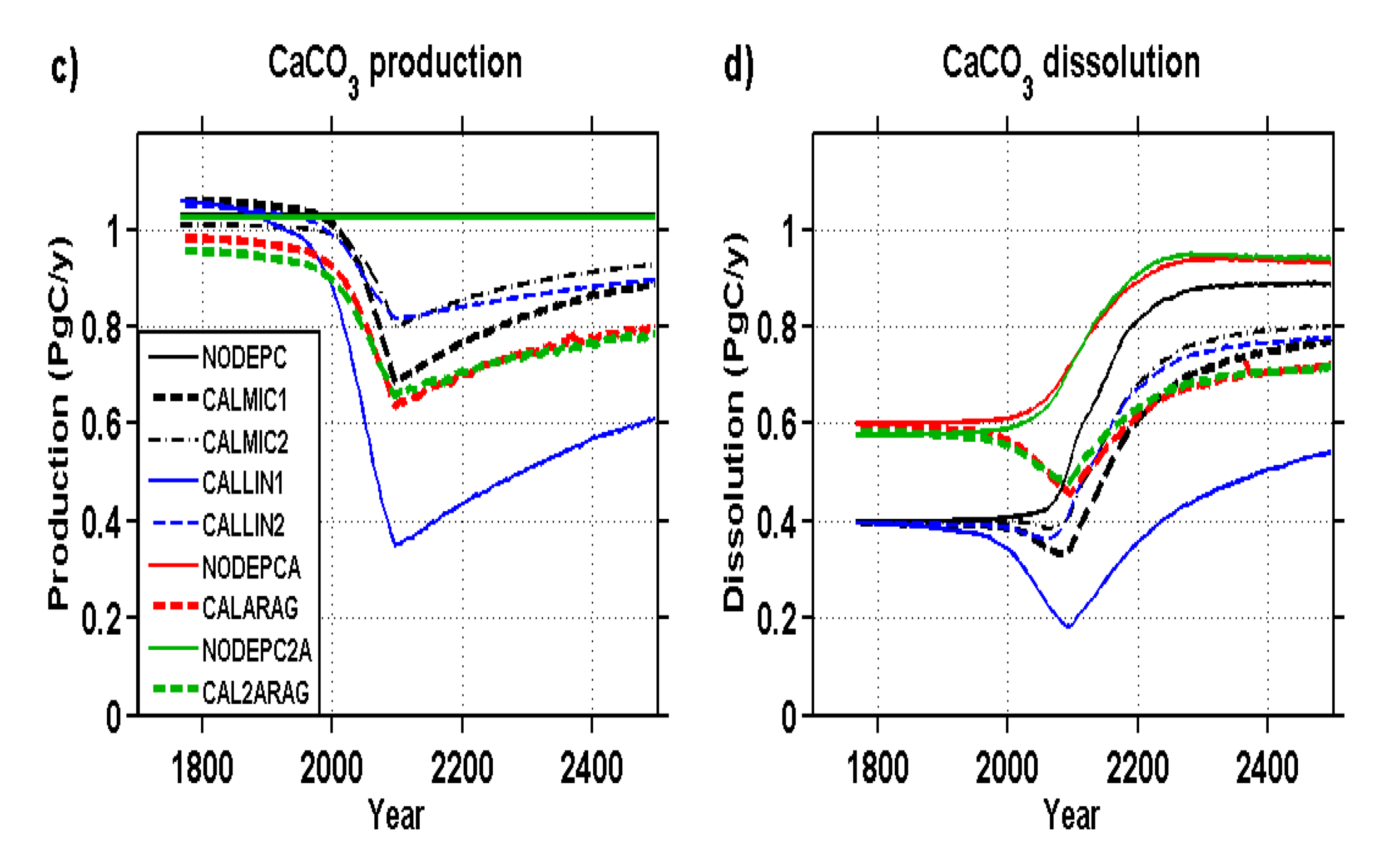
UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH



The volume of oversaturated water decreases from preindustrial 48% to 8% by 2300 for high 21st century emissions

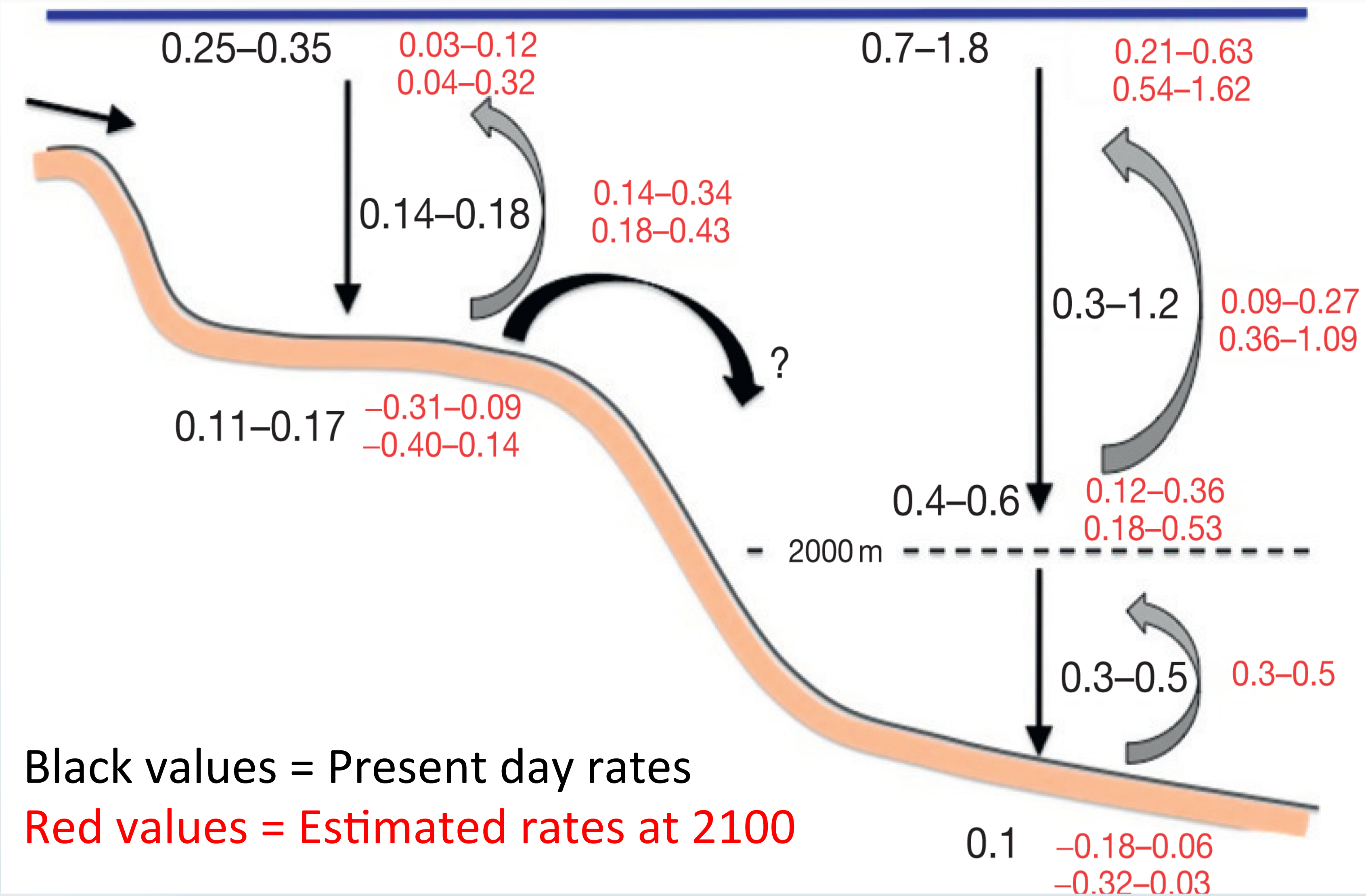
(Frölicher and Joos, CD, 2010)

Impact of Acidification on $CACO_3$ Production and Dissolution



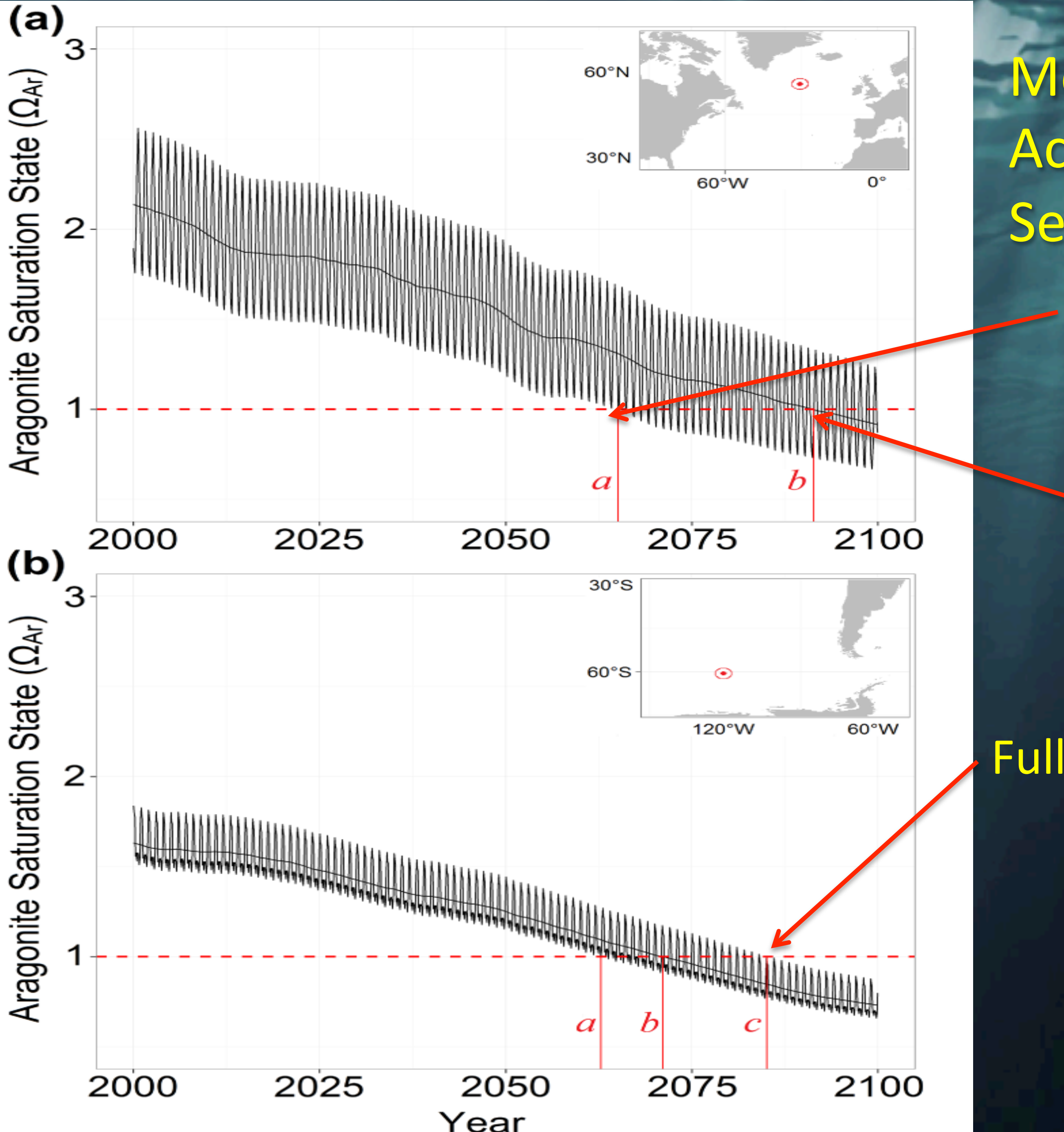
Simulations from the Bern3D Model with Calcite only and Calcite + Aragonite Production (from Gangsto, Joos and Gelen Biogeosciences, 2011)

Impact of Acidification on the Global $CACO_3$ Budget

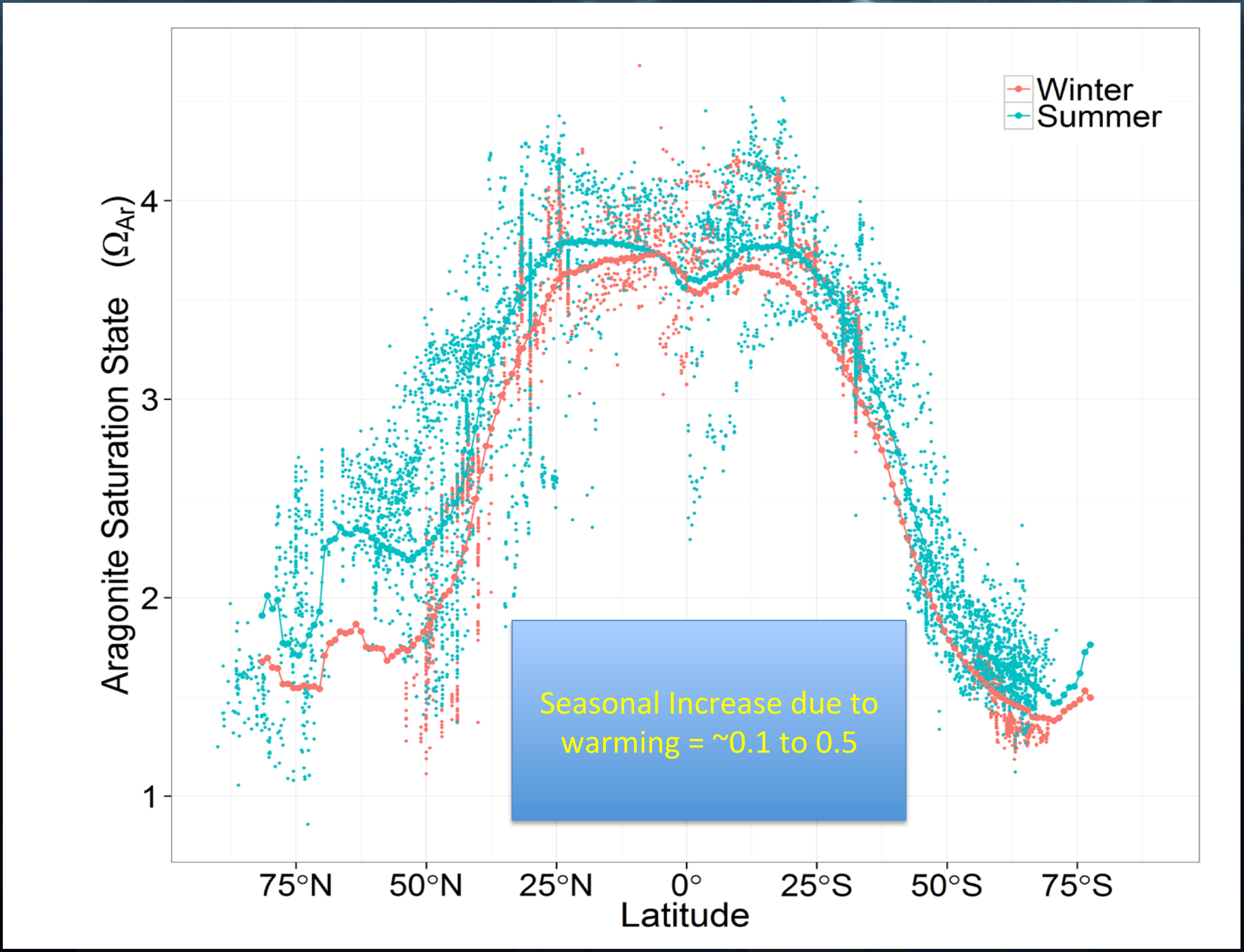


Andersson, A., Chapter 8.19 in Treatise on Geochemistry, 2014.

Modeled Ocean Acidification Time Series

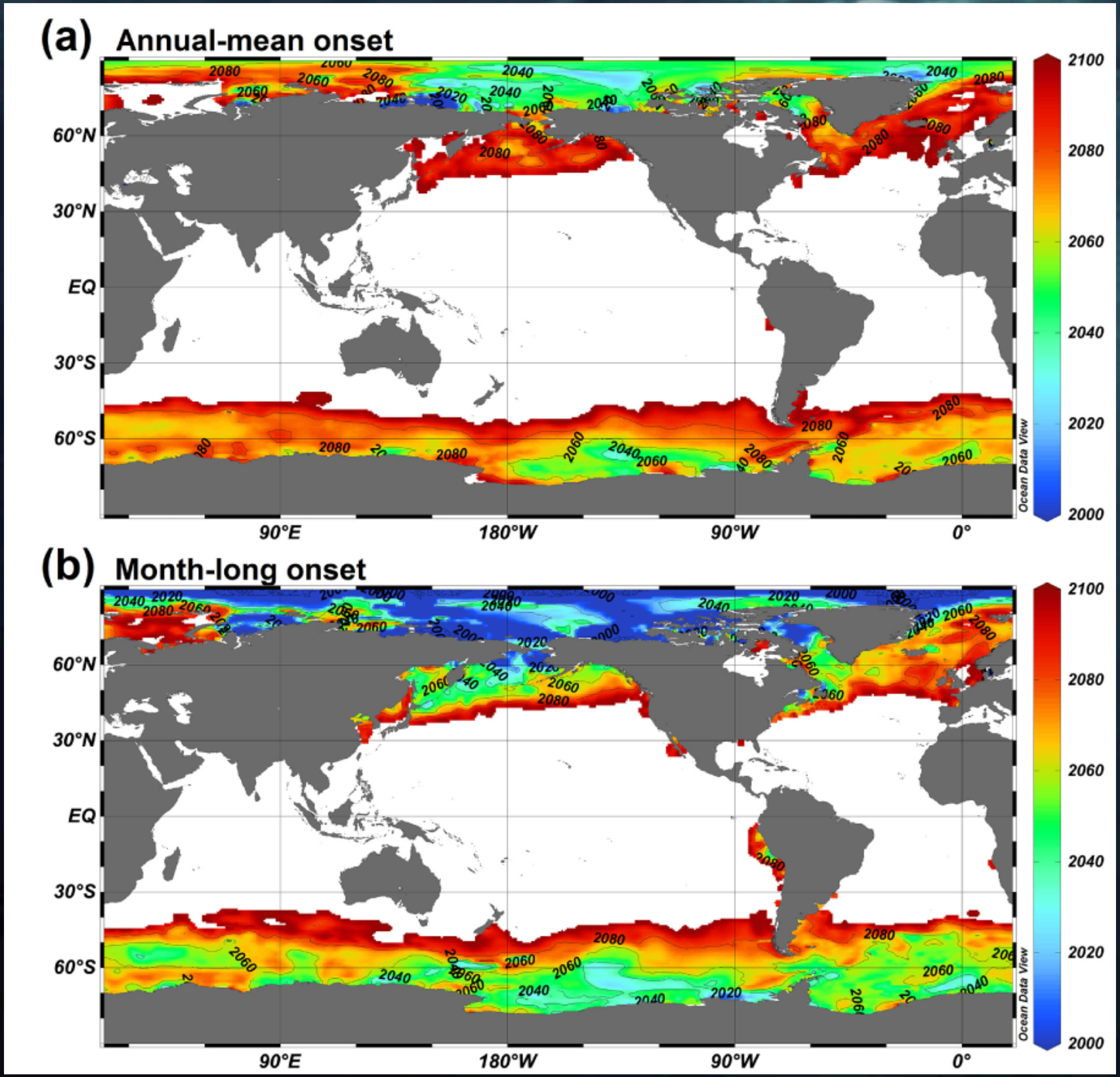


Sasse et al 2015



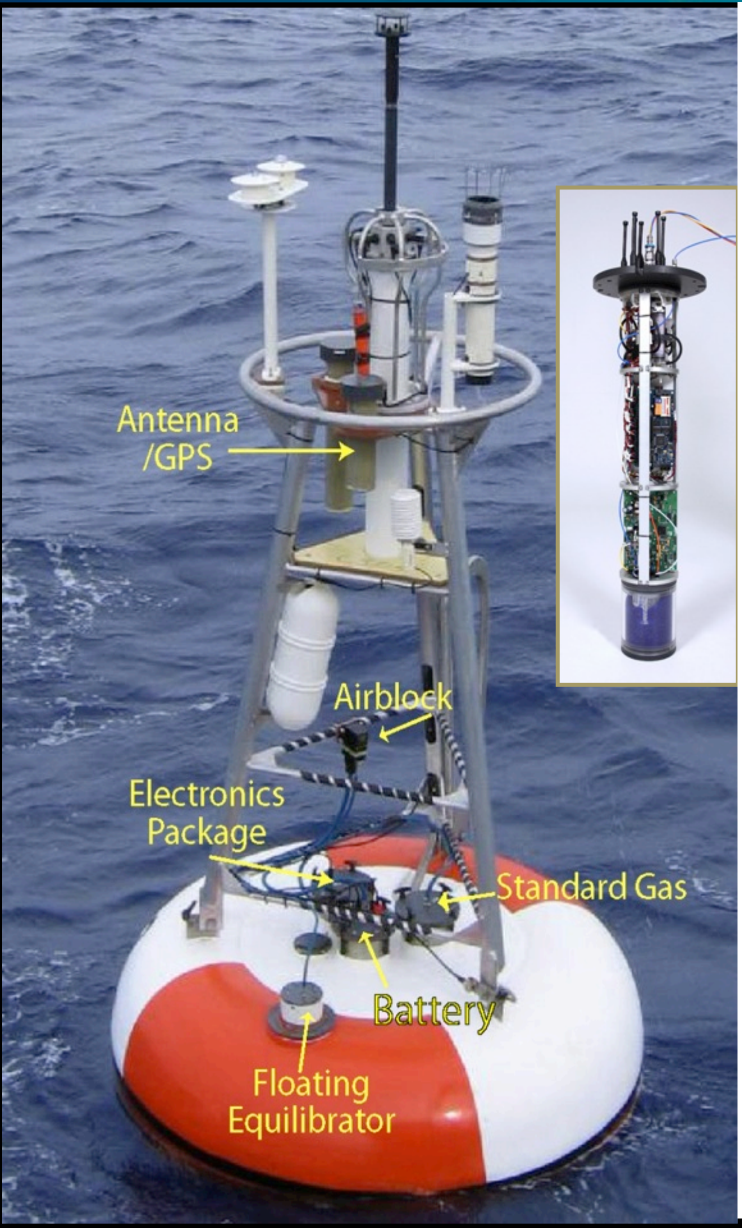
Sasse et al., 2015

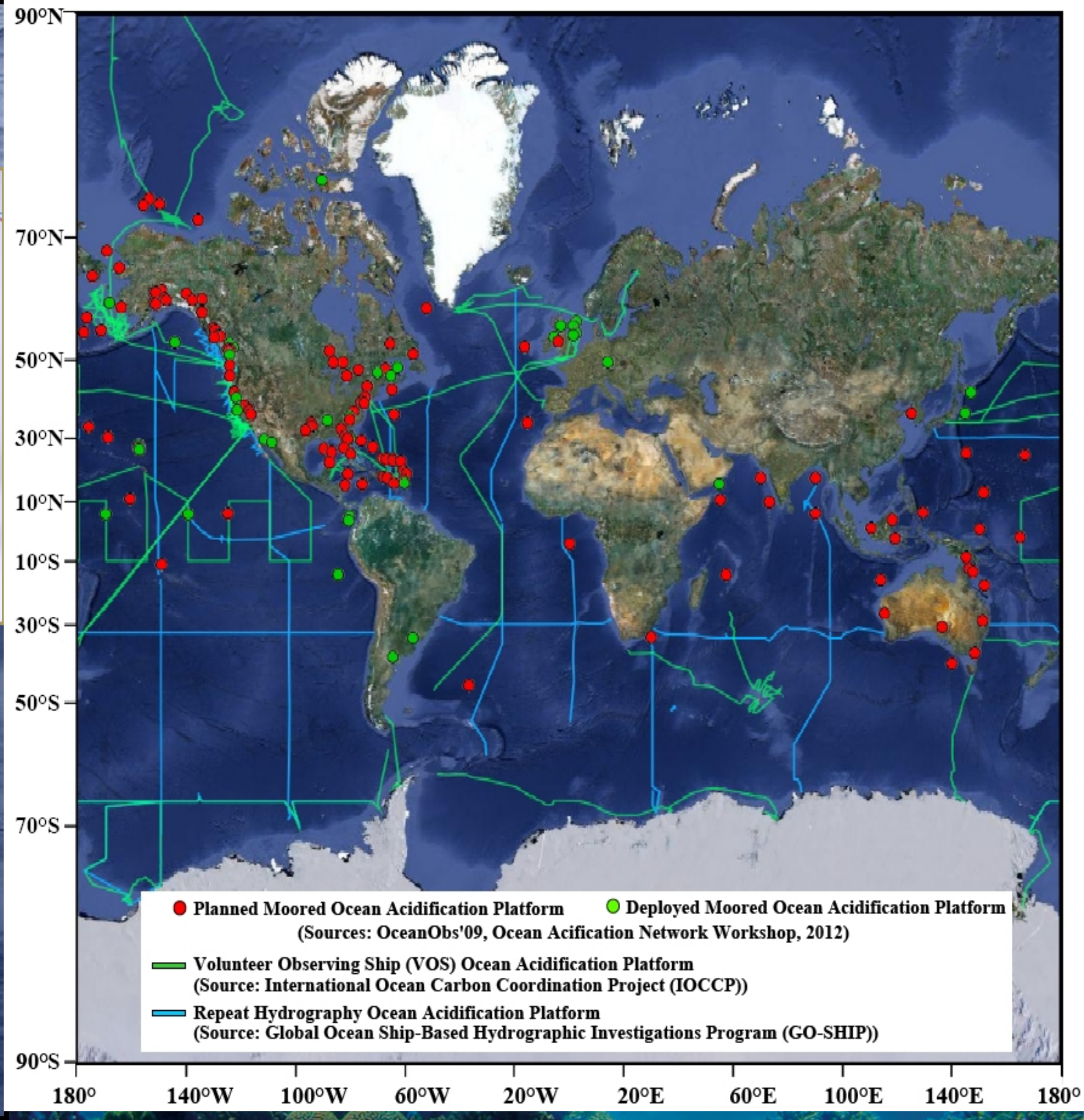
Model Estimate of the Time of First Occurrence of Aragonite Undersaturation



Sasse et al., 2015

Global Ocean Acidification Observing Network (GOA-ON) = Monitoring Physics, Chemistry and Biology of Global Ocean



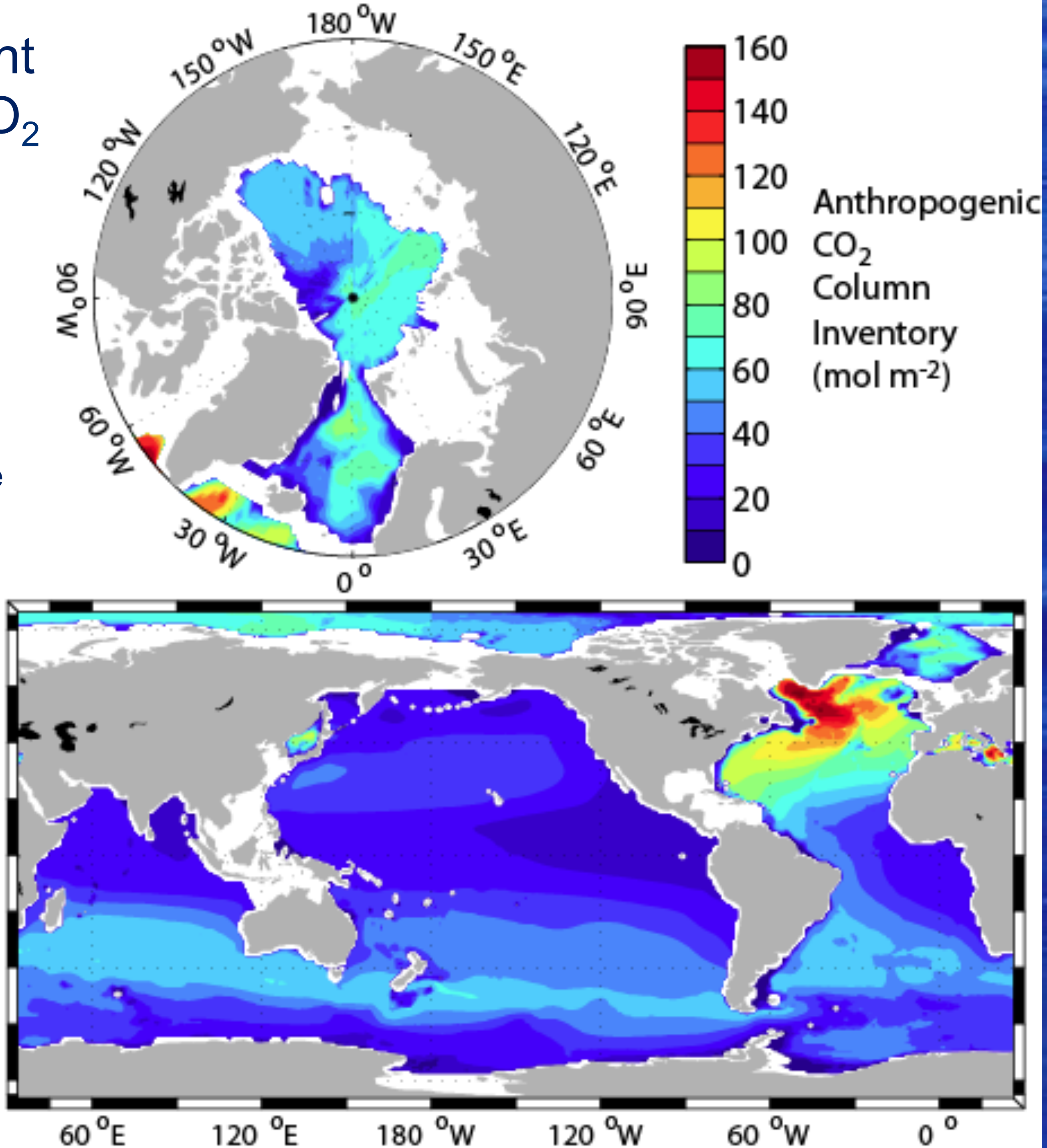


Estimate of current Anthropogenic CO_2 Distributions

Total 2010 Inventory: 150 ± 25 Pg C

~ 6% (8.2 Pg C) stored in Marginal Seas (including the Arctic)

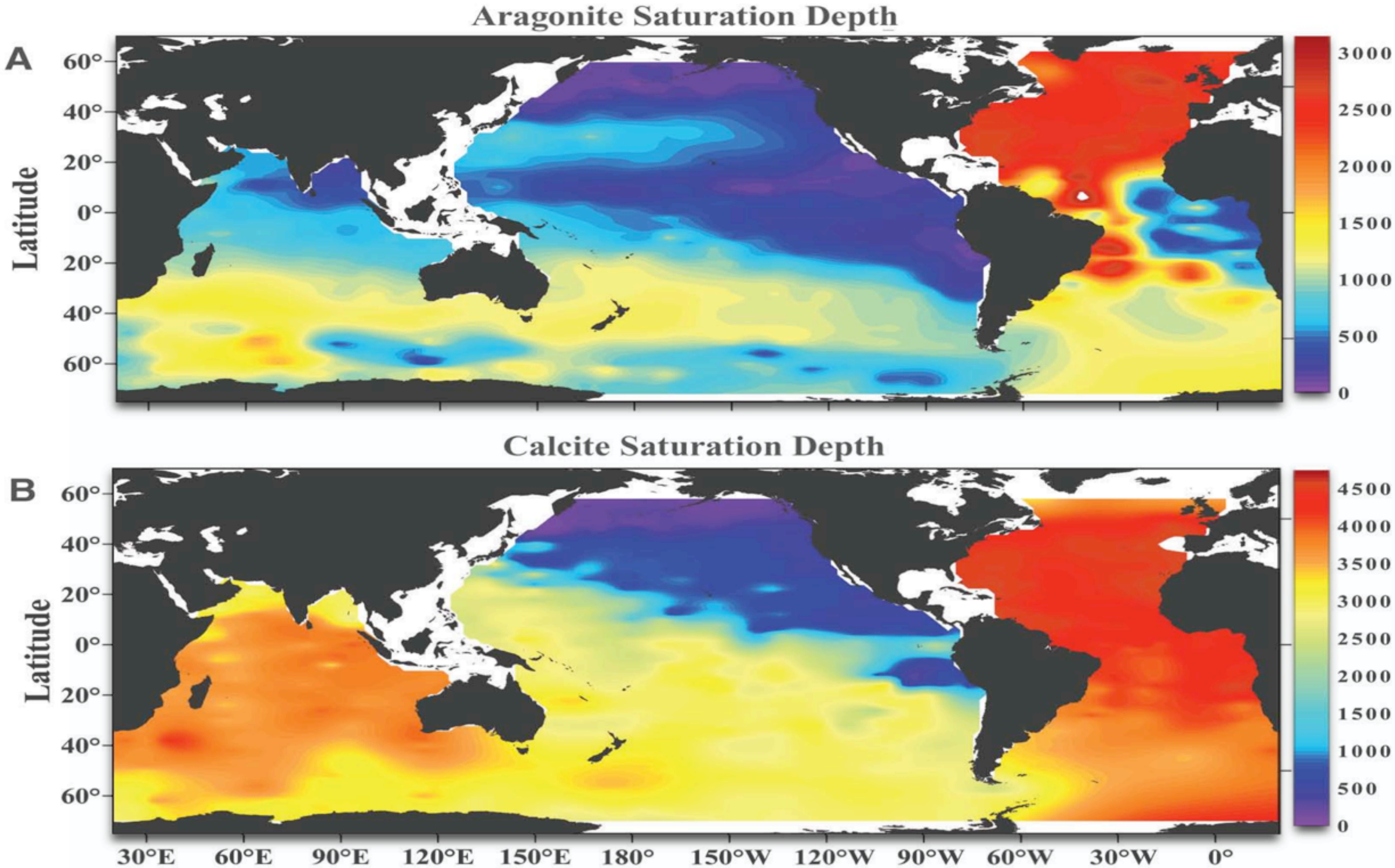
Khatiwala et al 2013



From: the global Ocean excluding the marginal seas (Khatiwala et al., 2009), 140 ± 25 Pg C thru 2008; Arctic Ocean (Tanhua et al., 2009) 2.6 – 3.4 Pg C; the Nordic Seas (Olsen et al., 2010) 1.0 – 1.5 Pg C; the Mediterranean Sea (Schneider et al., 2010) 1.5 – 2.4 Pg C; the East Sea (Sea of Japan) (Park et al., 2006) 0.40 ± 0.06 Pg C.

-after Lee et al., 2011

Observed aragonite & calcite saturation depths

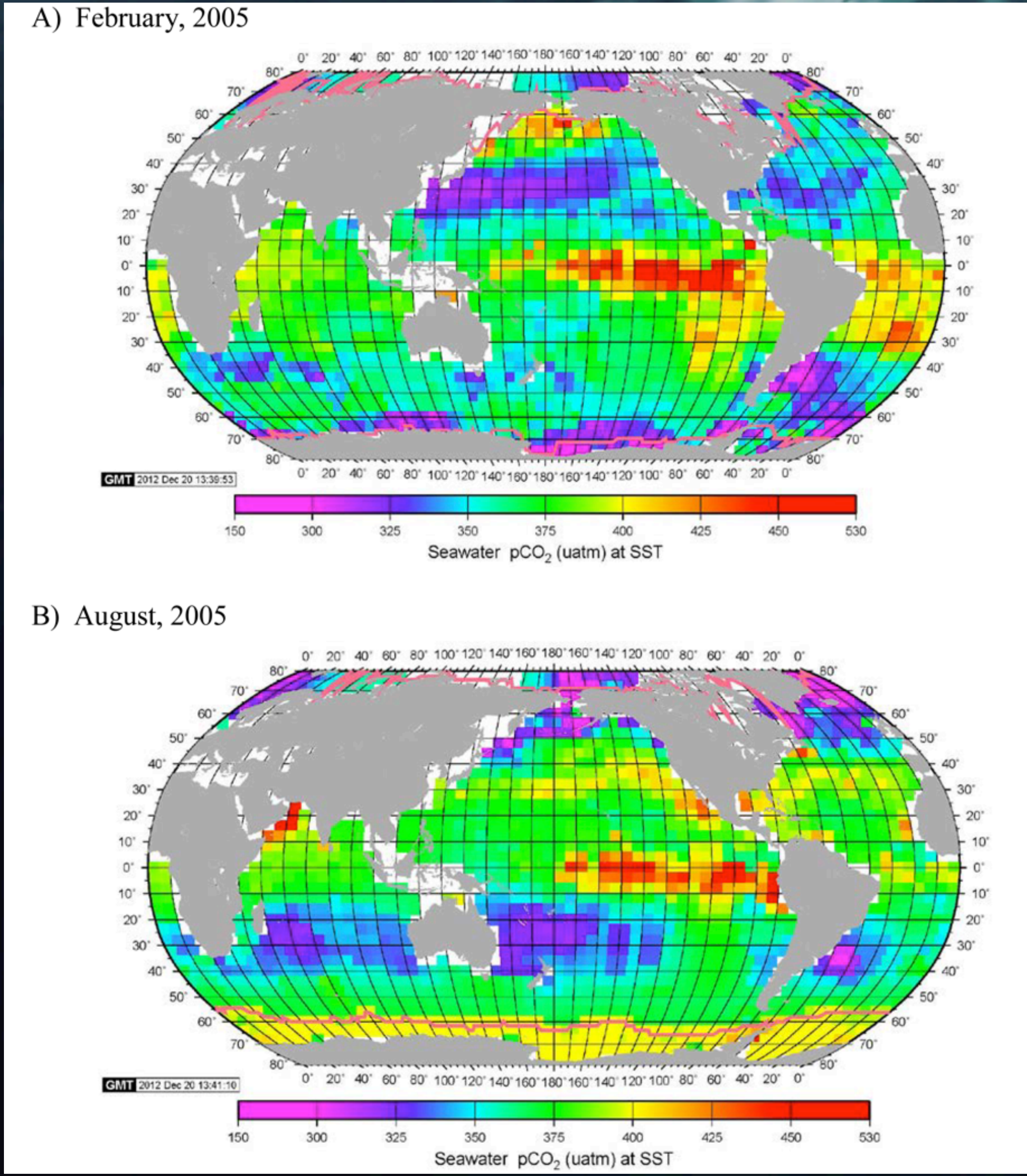


Ocean CO_2 Chemistry

Feely *et al.* (2004)

The **aragonite saturation state** migrates towards the surface at the rate of 1-2 m yr^{-1}, depending on location.

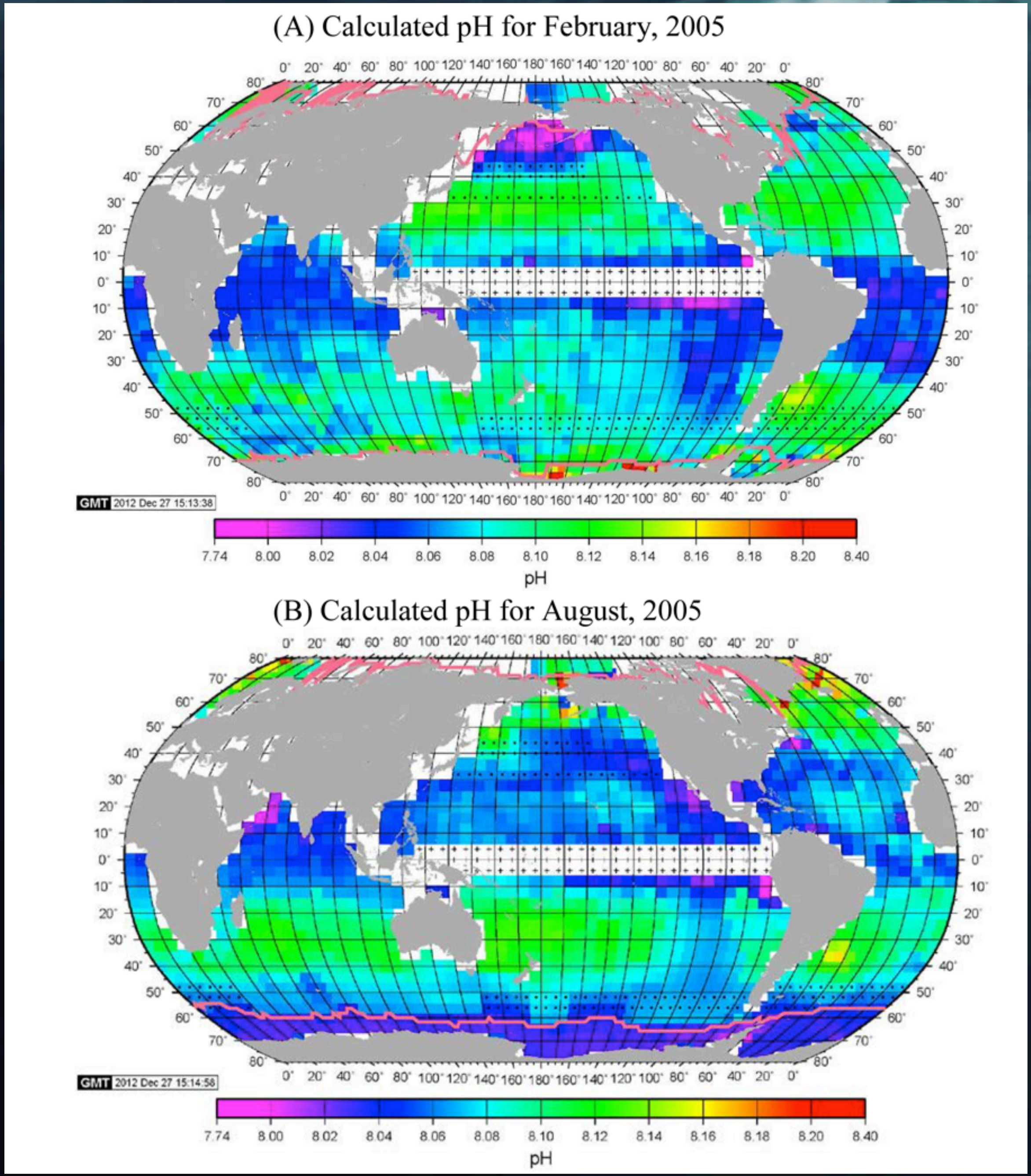
Takahashi et al 2014 pCO_2 Climatology for 2005



Based on more than 6 million surface pCO_2 measurements.

Takahashi et al Mar. Chem., 2014

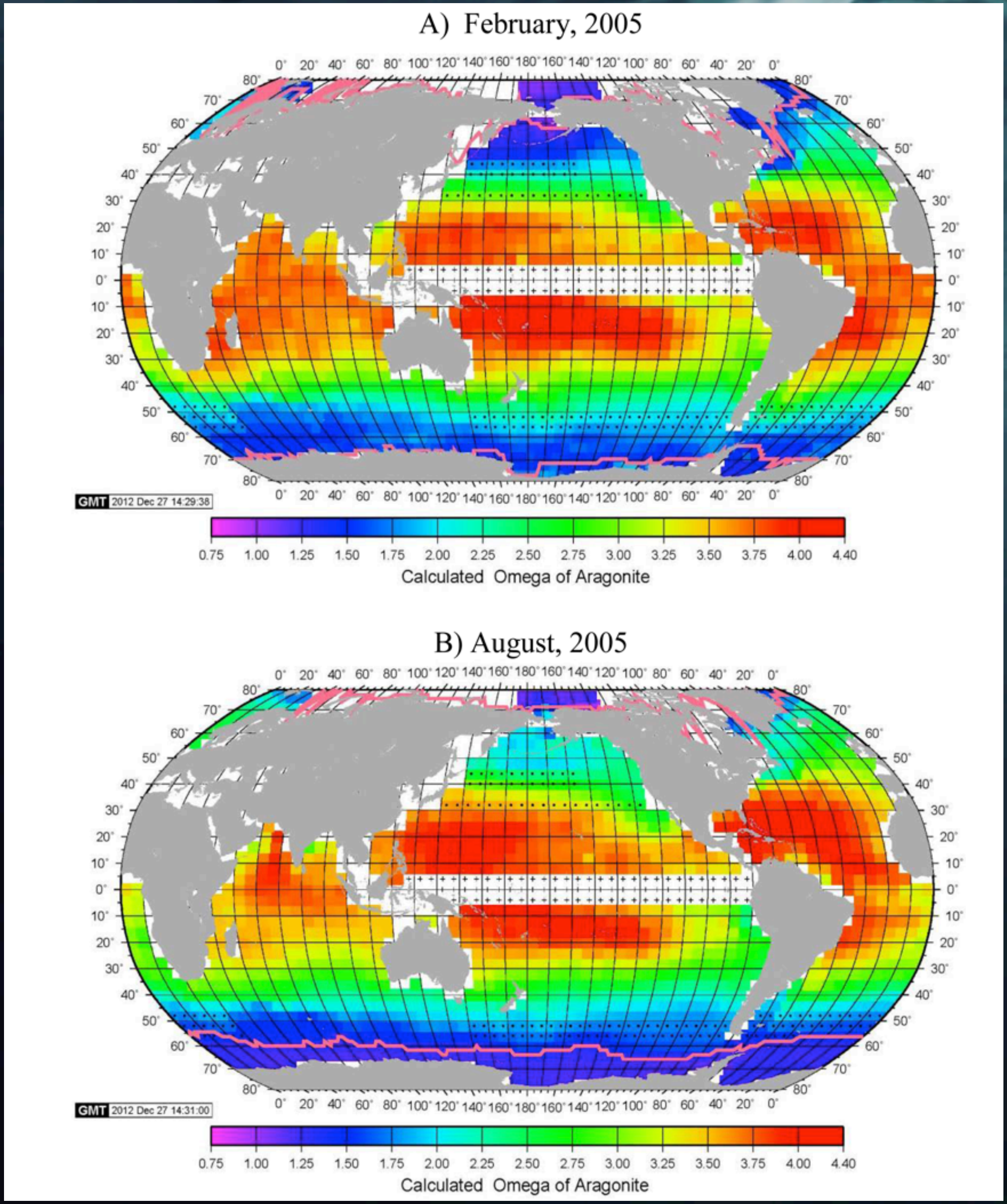
Takahashi et al 2014 pH Climatology for 2005



Based on more than 6 million surface pCO_2 measurements and 16,000 DIC, TALK pairs.

Takahashi et al Mar. Chem., 2014

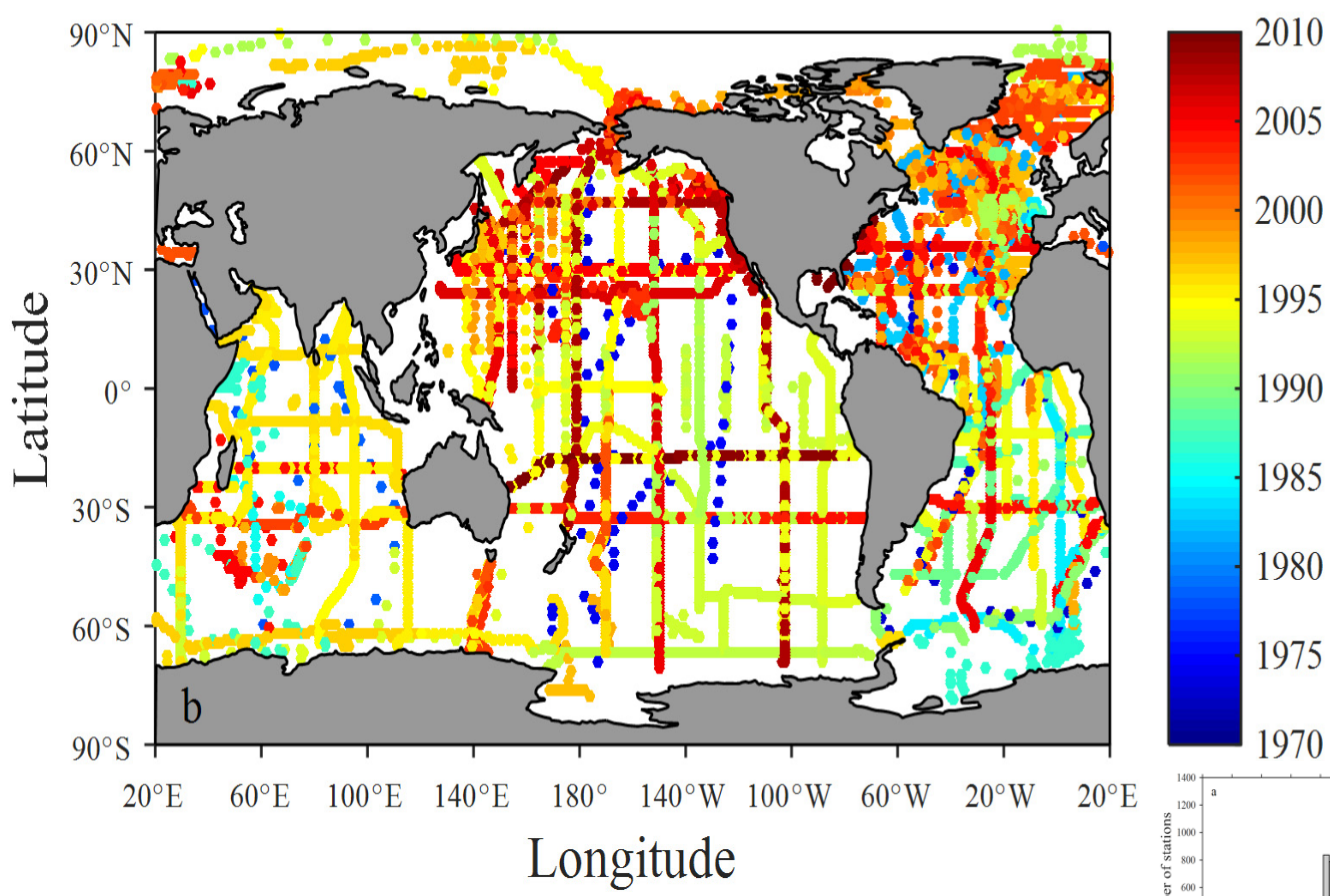
Takahashi et al Aragonite Saturation Climatology for 2005

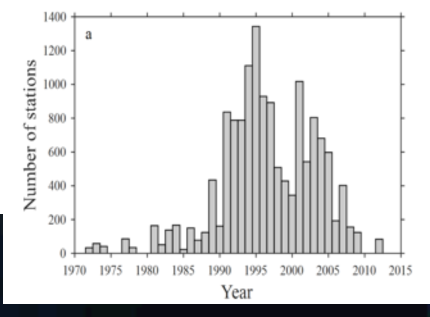


Based on more than 6 million surface pCO_2 measurements and 16,000 DIC, TALK pairs.

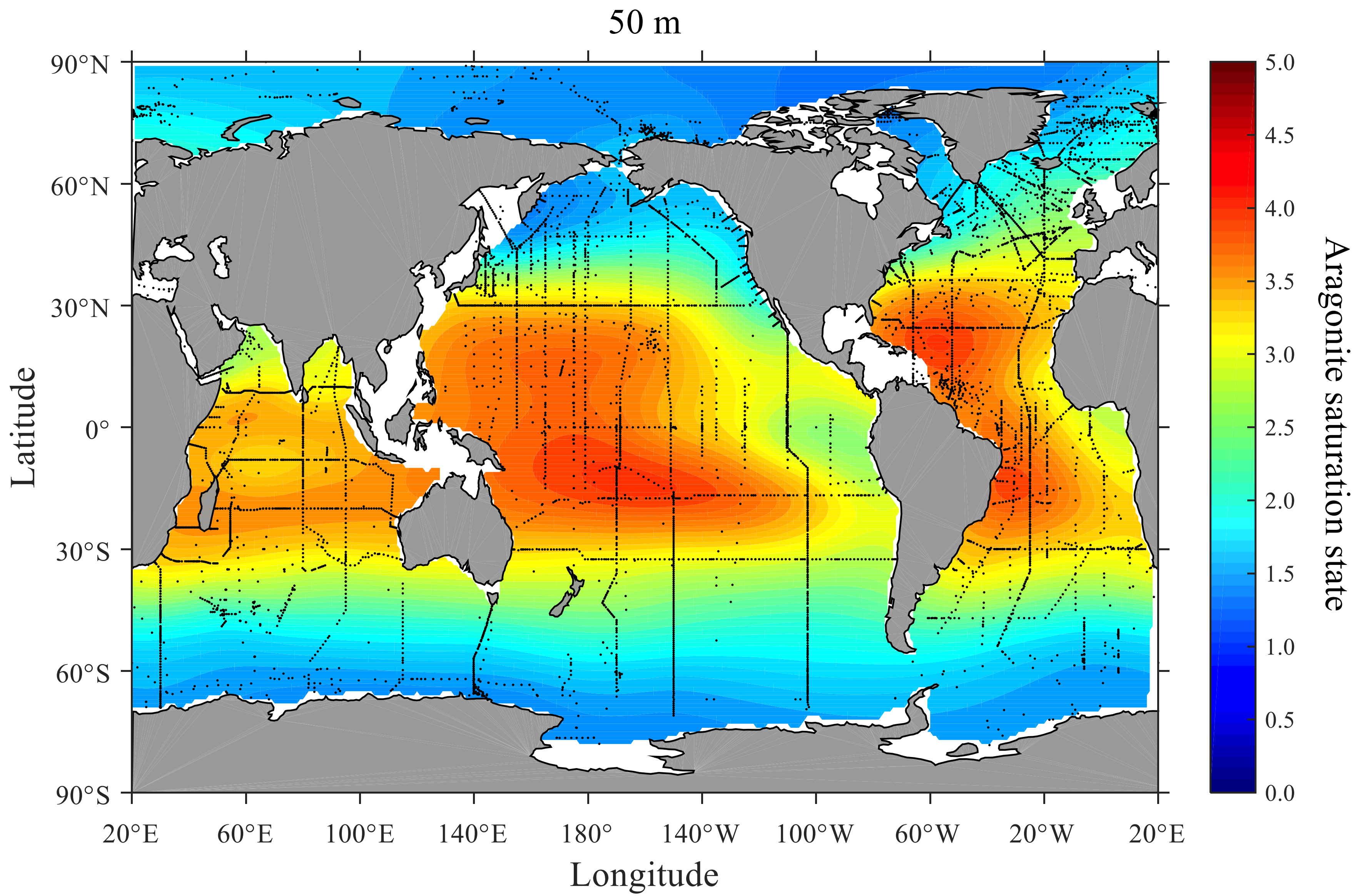
Takahashi et al Mar. Chem., 2014

GLODAP 1 + Carina + Pacifica thru 2012





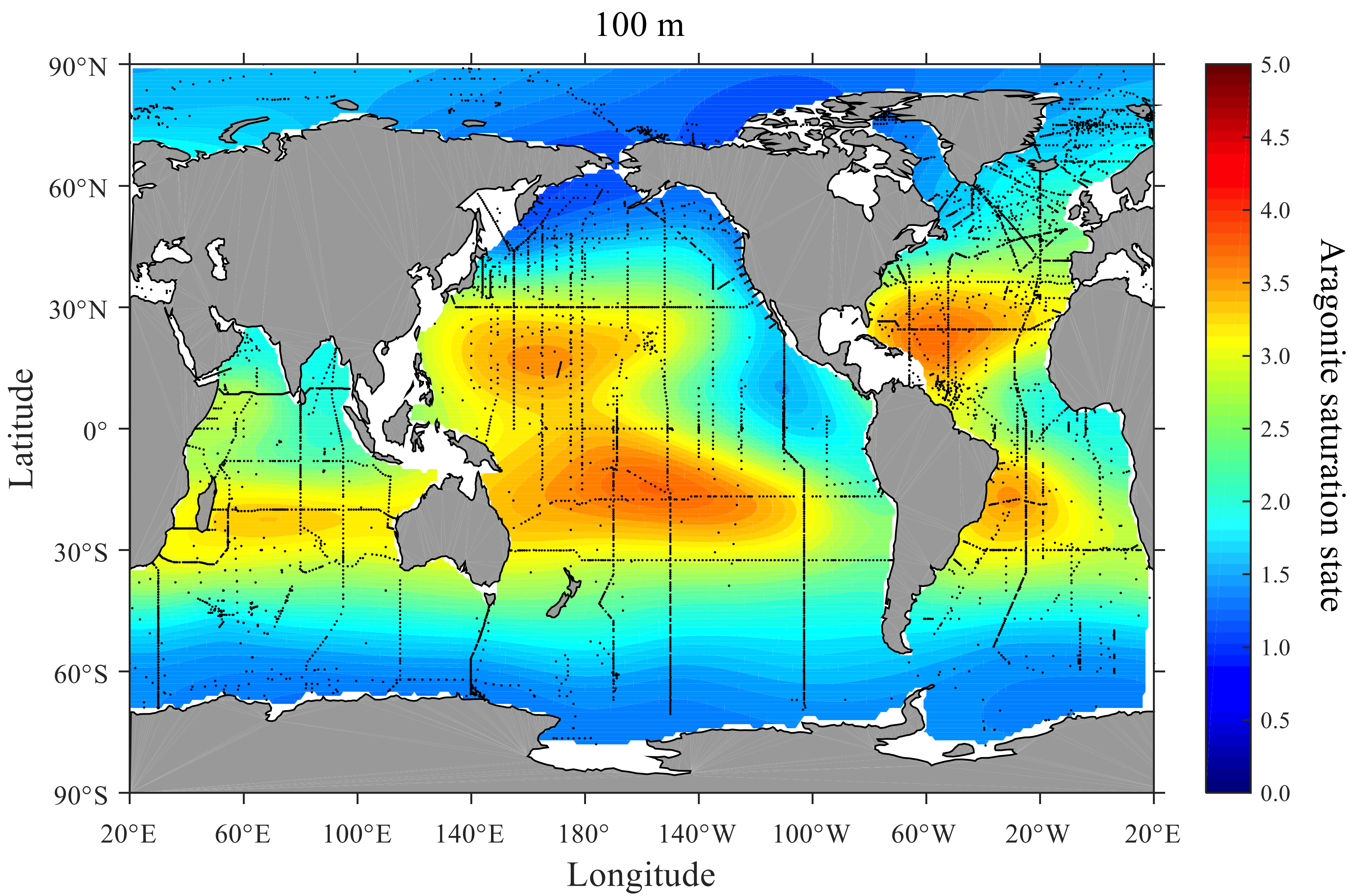
Aragonite Saturation State at 50 m



Reference Year: 2000

Li-Qing Jiang et al., submitted)

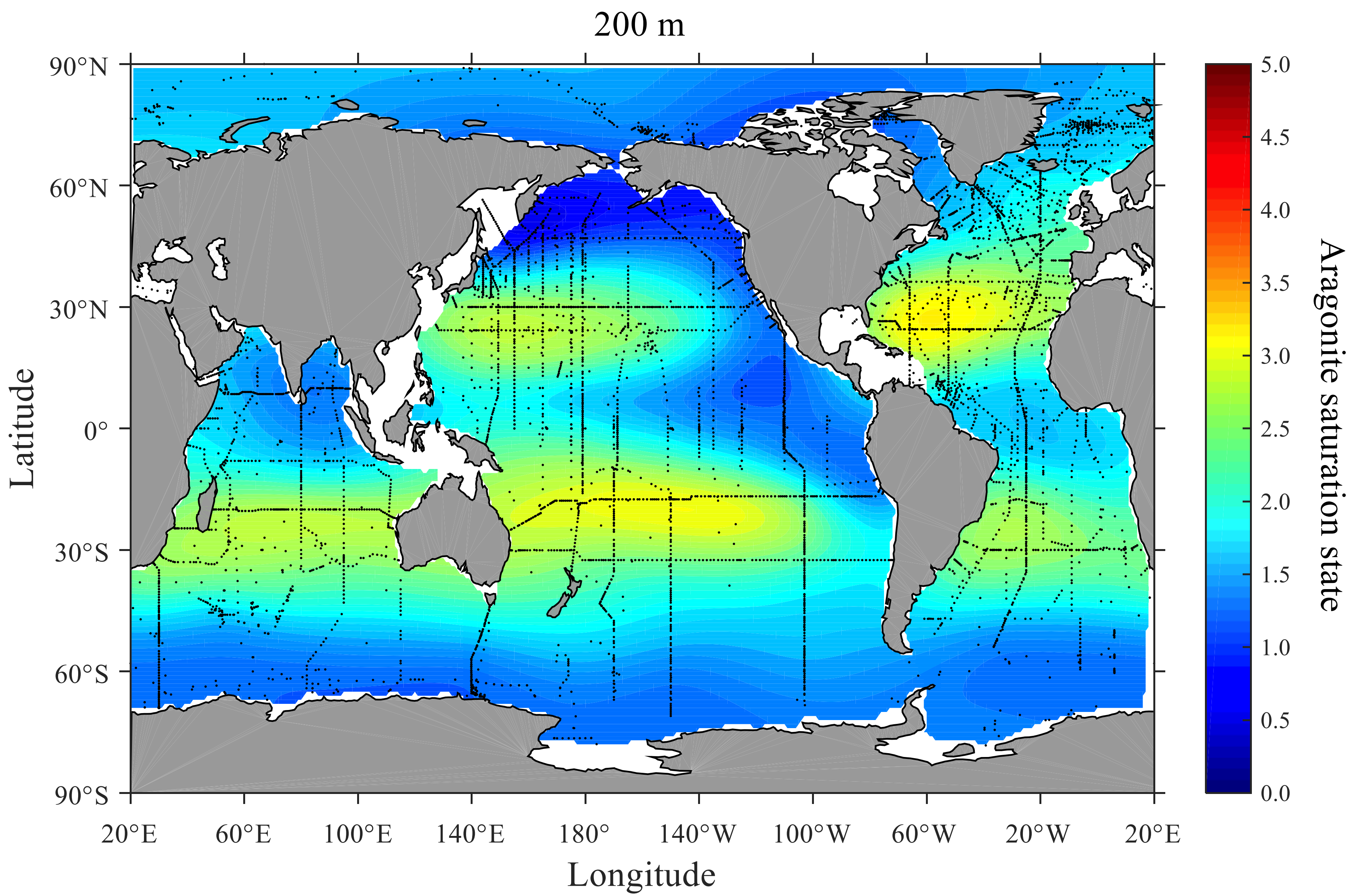
Aragonite Saturation State at 100 m



Reference Year: 2000

Li-Qing Jiang et al., submitted)

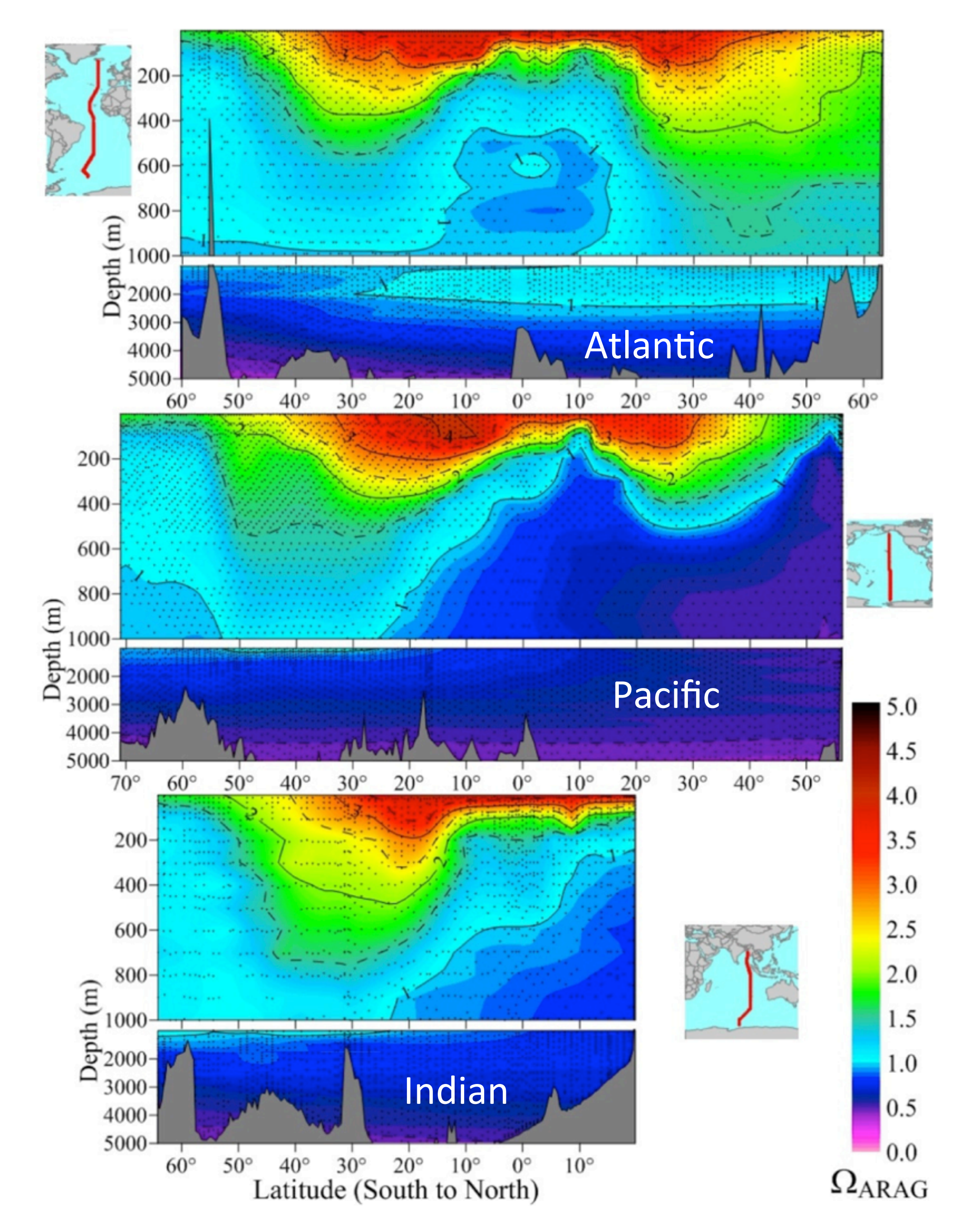
Aragonite Saturation State at 200 m



Reference Year: 2000

Li-Qing Jiang et al., submitted)

North-South Vertical Profiles of Aragonite Saturation State in the Atlantic, Pacific and Indian Oceans



Li-Qing Jiang et al., (submitted)

Results: Anthropogenic carbon

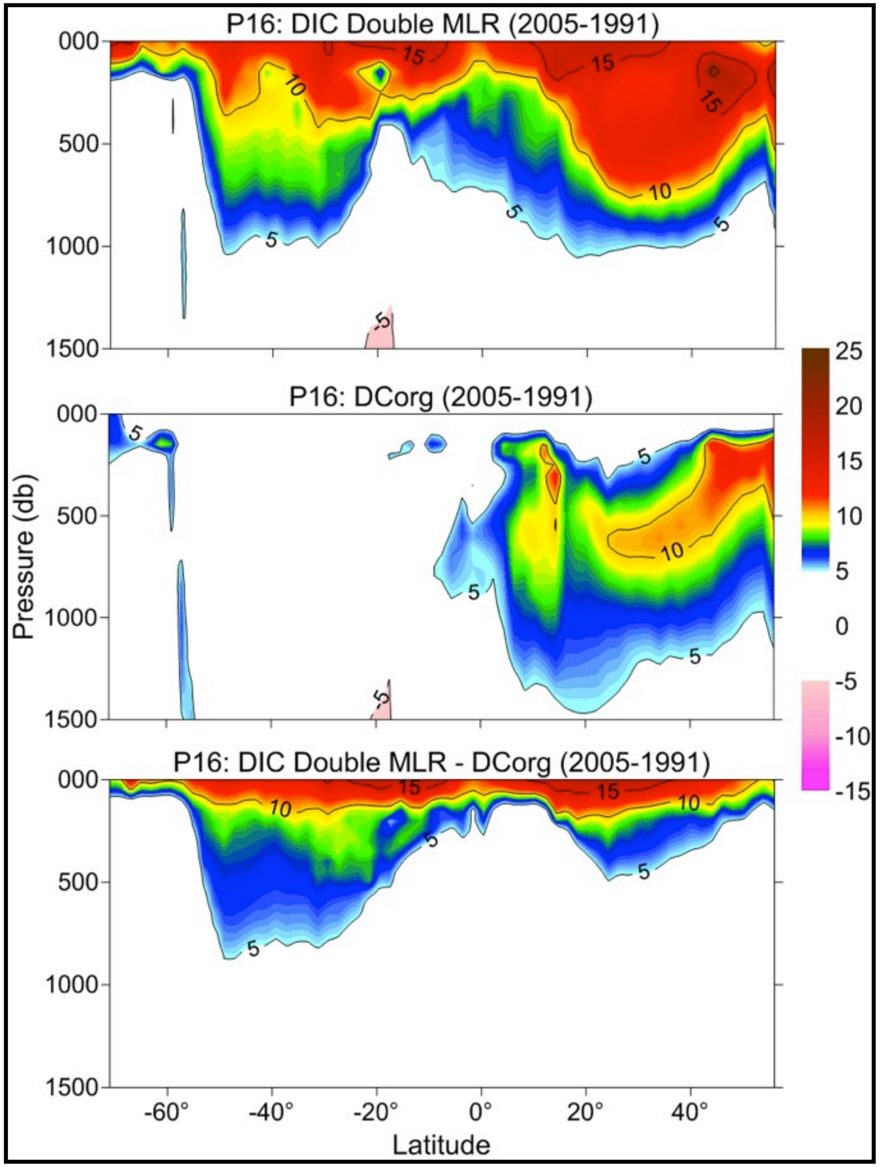
- **P16 (152°W) eMLR Section**

eMLR function without AOU shows a very large DIC change in the North Pacific)

The AOU eMLR function isolates the change in apparent remineralization rate

Subtracting the AOU eMLR from the DIC eMLR gives the atmospheric CO2 uptake

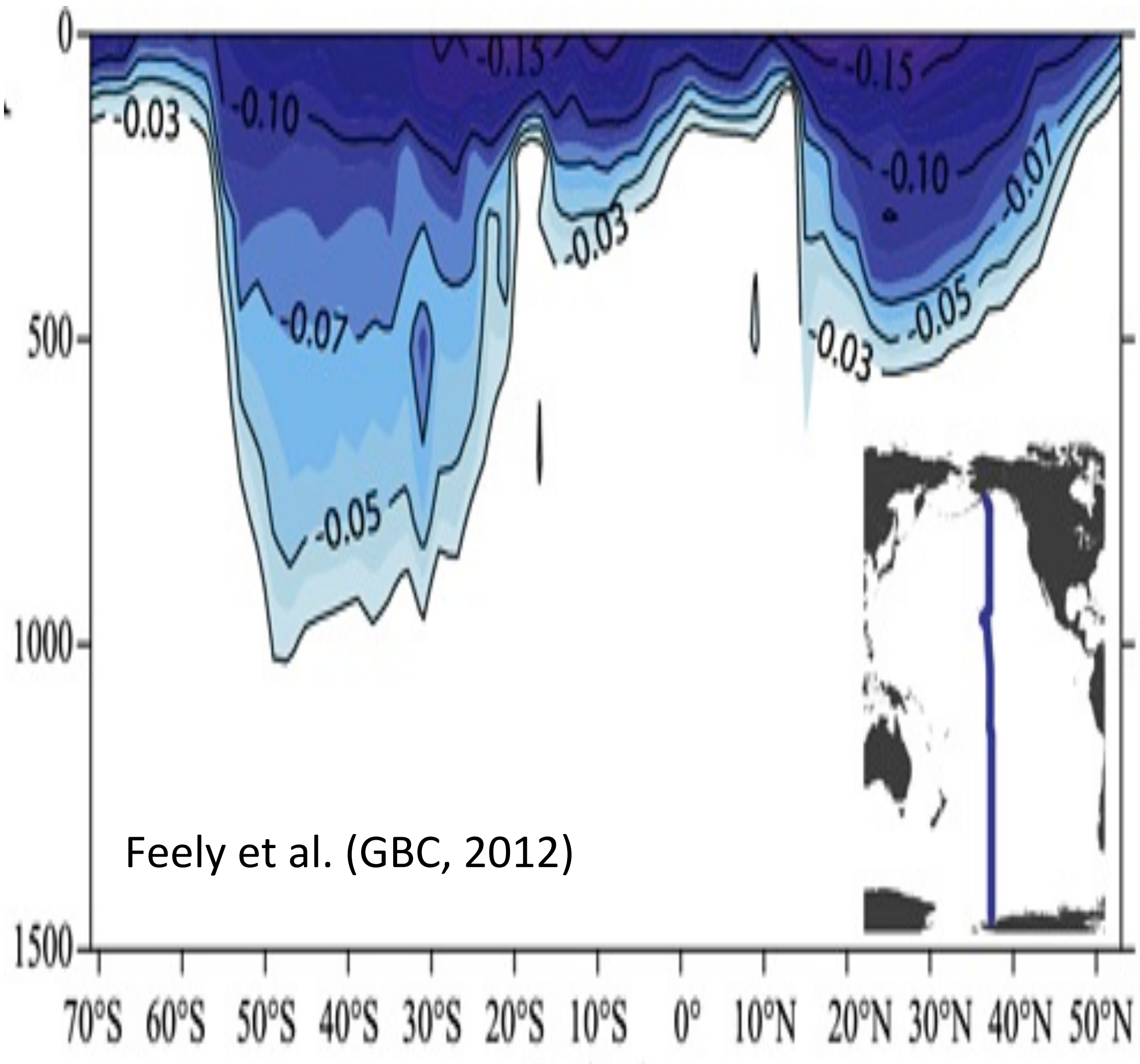
* AOU converted to C units using Redfield Ratio



Sabine et al., 2008

Aragonite Saturation State Change (2005/06-1991)

P16 (152°W) eMLR section of aragonite saturation state changes



As more CO_2 enters the ocean, it dissociates to form carbonic acid, the water's acidity increases and aragonite saturation state decreases.

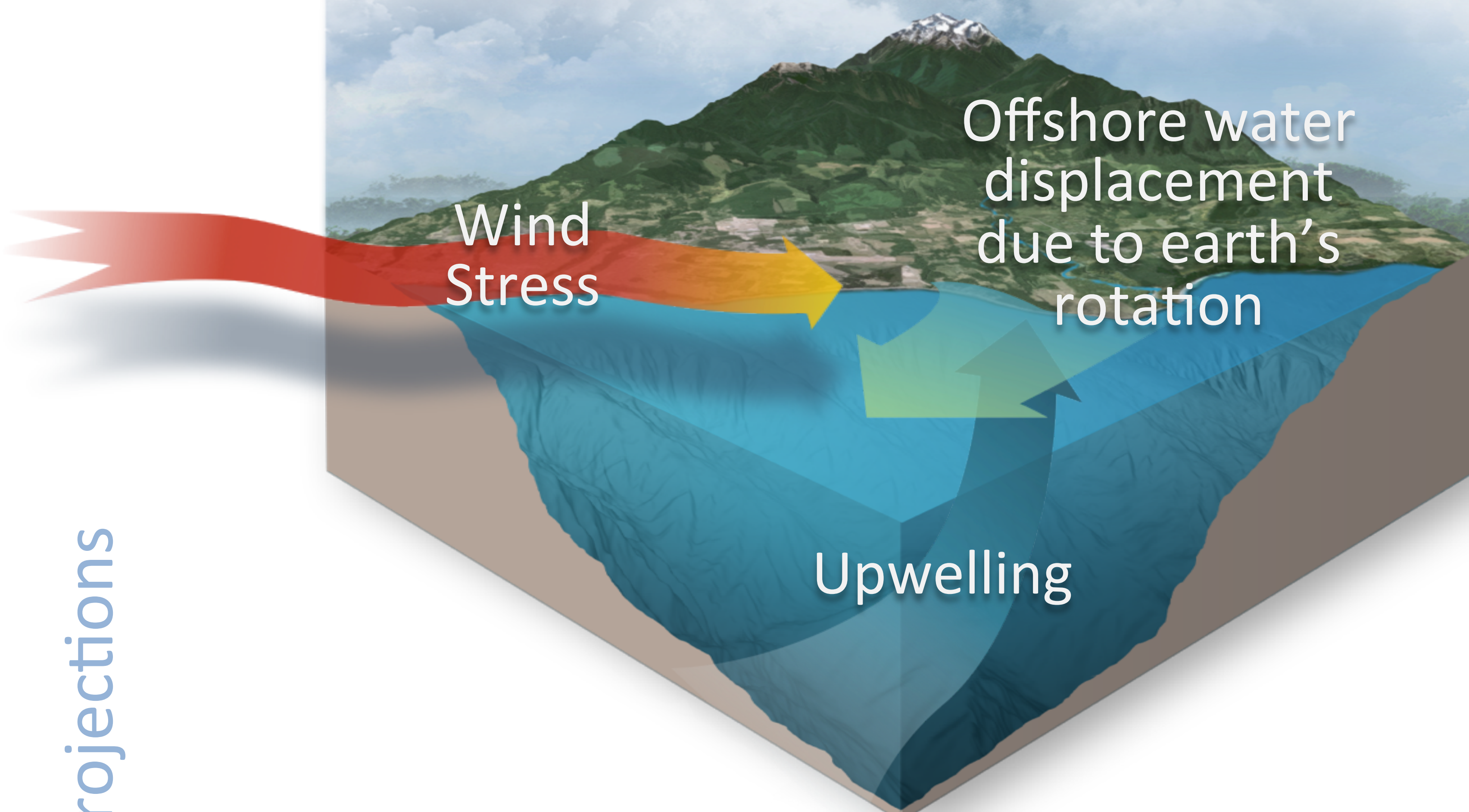
Feely et al., GBC 2012

pH and $\Omega_{aragonite}$ State Changes

Region	pH Change (pH units yr^{-1})	$\Omega_{Aragonite}$ Shoaling (m yr^{-1})	$\Omega_{Aragonite}$ Change (% yr^{-1})	Study	Study Period
Pacific Southern Ocean (S4P)	−0.0022 ± 0.0004	1.8 (Ω=1.3)	−0.47 ± 0.10	this study	1992−2011
Pacific Southern Ocean (P16S)	−0.0024 ± 0.0009	2.0 (Ω=1.3)	−0.50 ± 0.20	this study	1995−2011
Polar Zone Southern Ocean	−0.0020 ± 0.0003			Midorikawa et al, 2012	1963−2003
Drake (PZ)	−0.0015 ± 0.0008		−0.46 ± 0.4	Takahashi et al., 2014	2002−2012
Drake (SAZ)	−0.0023 ± 0.0007		−0.69 ± 0.4	Takahashi et al., 2014	2002−2012
S.W. Pacific (Munida)	−0.0013 ± 0.0003		−0.43 ± 0.13	Bates et al., 2014	1998−2012
S. Pacific		1.9 ± 0.8 (Ω=1.0)	−0.35 ± 0.05	Feely et al., 2012	1991−2005
S. Pacific	−0.0016			Waters et al., 2011	1994−2008
N.W. Pacific	−0.0015 ± 0.005			Midorikawa et al., 2010	1983−2007
N.W. Pacific	−0.002		−0.34	Ishii et al., 2011	1994−2008
N. Pacific	−0.0017			Byrne et al., 2010	1991−2006
N. Pacific		1 ± 0.6 (Ω=1.0)	−0.34 ± 0.04	Feely et al., 2012	1994−2004
N. Pacific (ALOHA)	−0.0018 ± 0.0001		−0.28	Dore et al., 2009	1988−2007
N. Pacific (HOT)	−0.0016 ± 0.0001		−0.28 ± 0.04	Bates et al., 2014	1988−2012
N. Pacific (HOT)	−0.0018 ± 0.0001		−0.27 ± 0.03	Takahashi et al., 2014	1988−2009
Iceland Sea	−0.0023 ± 0.0003	4 (Ω=1.0)	−0.48 ± 0.07	Olafsson et al., 2009	1985−2008
Irminger Sea	−0.0026 ± 0.0006		−0.40 ± 0.20	Bates et al., 2014	1983−2012
N. Atlantic (BATS)	−0.0017 ± 0.0001		−0.26 ± 0.02	Bates et al., 2014	1983−2012
N. Atlantic (BATS)	−0.0018 ± 0.0002		−0.34 ± 0.03	Takahashi et al., 2014	1983−2010
N. Atlantic (ESTOC)	−0.0018 ± 0.0002		−0.34 ± 0.07	Bates et al., 2014	1995−2012
N. Atlantic (ESTOC)	−0.0017 ± 0.0001		−0.36	González-Dávila et al., 2010	1995−2004
N. Atlantic (ESTOC)	−0.0020 ± 0.0004		−0.29 ± 0.06	Takahashi et al., 2014	1996−2010
Carribbean (CARIACO)	−0.0025 ± 0.0004		−0.18 ± 0.08	Bates et al., 2014	1995−2012
E. Equatorial Indian	−0.0016 ± 0.0001		−0.25 ± 0.01	Xue et al., 2014	1962-2012

Williams et al, Mar Chem, in press

Natural processes that could accelerate ocean acidification in coastal waters

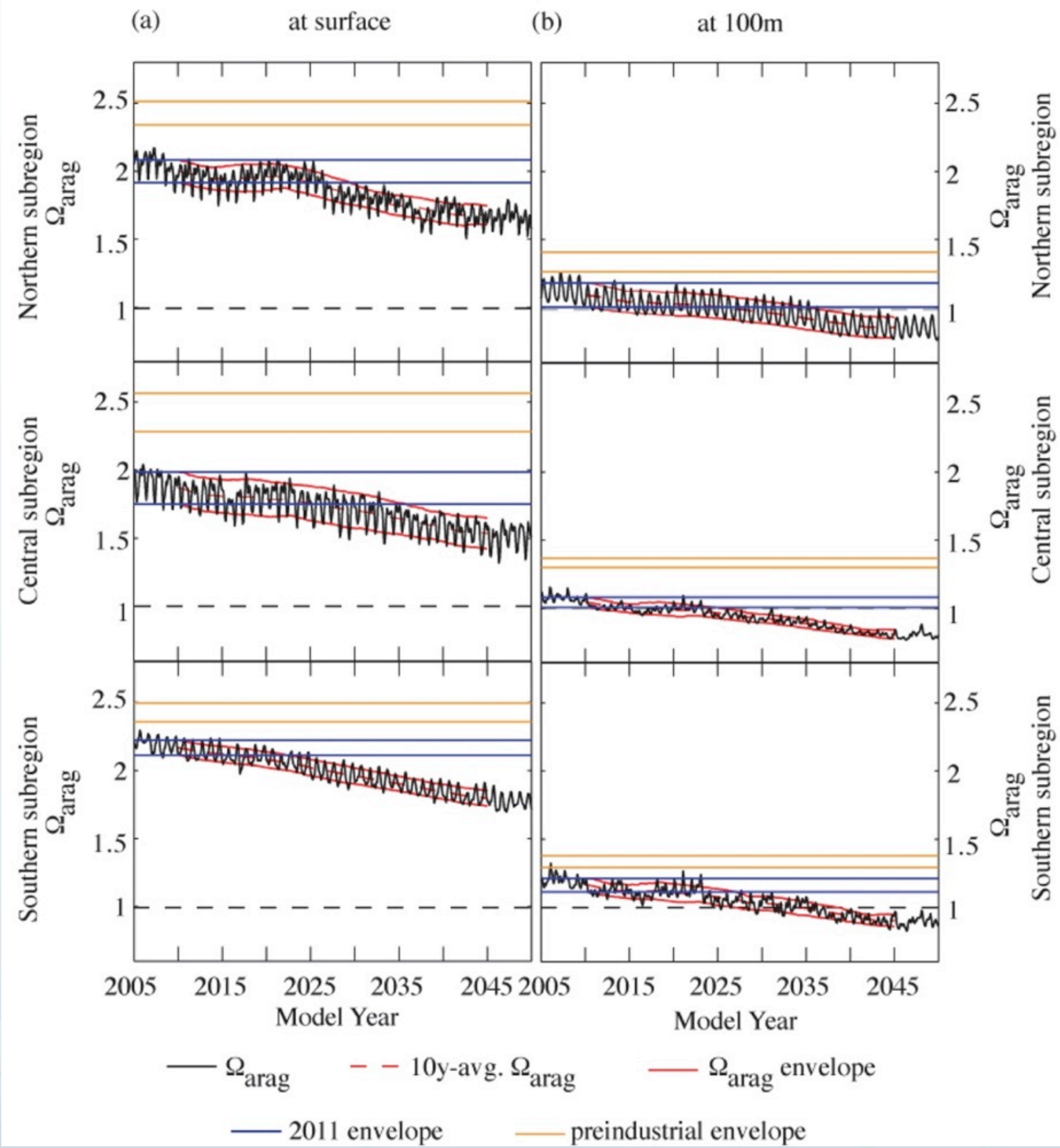


Projections

brings high CO_2, low pH, low Ω, low O_2 water to surface

Coastal Upwelling

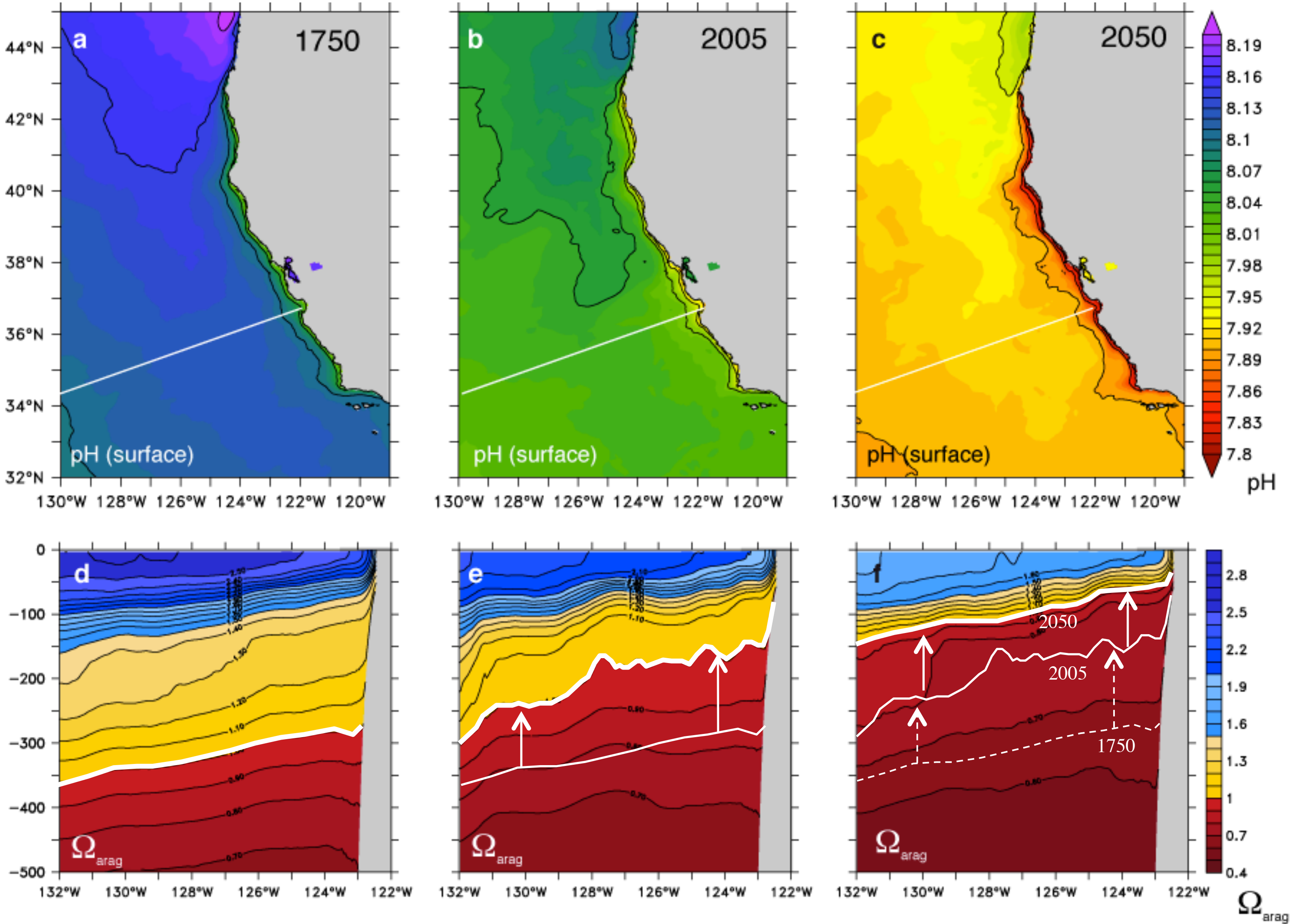
Long-term Impacts of Acidification In the California Current Ecosystem



- 0.5 Decrease in Ω_{arag} Since the pre-industrial era
- From the pre-industrial to the present Ω_{arag} has decreased below the envelope of natural variability in all regions.
- Over the next 20-30 years Ω_{arag} will decrease below the present envelope of variability.

Hauri et al 2013

Evolution since 1750 and projection until 2050



Strong shoaling of the saturation horizon from 1750 to 2050

Gruber et al. (2012)

Conclusions

- pH decreases in surface oceans range from 0.0013 to 0.0026 yr^{-1}.

- Surface Ω_{ar} decreases in surface oceans from 0.18 to 0.47% yr^{-1}.

- Seasonally, surface Ω_{ar} above 40° latitudes was about 0.1 to 0.5 higher during warmer months than during colder months in the open-ocean waters of both hemispheres.

- Decadal changes of Ω_{ar} in the Atlantic and Pacific Oceans showed that Ω_{ar} in waters shallower than 100 m depth decreased by 0.10±0.09 (–0.40±0.37% yr^{-1}) on average between the decade spanning 1989-1998 to the decade spanning 1998-2010.

- Strong shoaling of the aragonite saturation horizon will occur in the upwelling, arctic and antarctic regions over the next few decades.