Daily and seasonal ocean acidification extremes during the twenty-first century

Lester Kwiatkowski & James Orr

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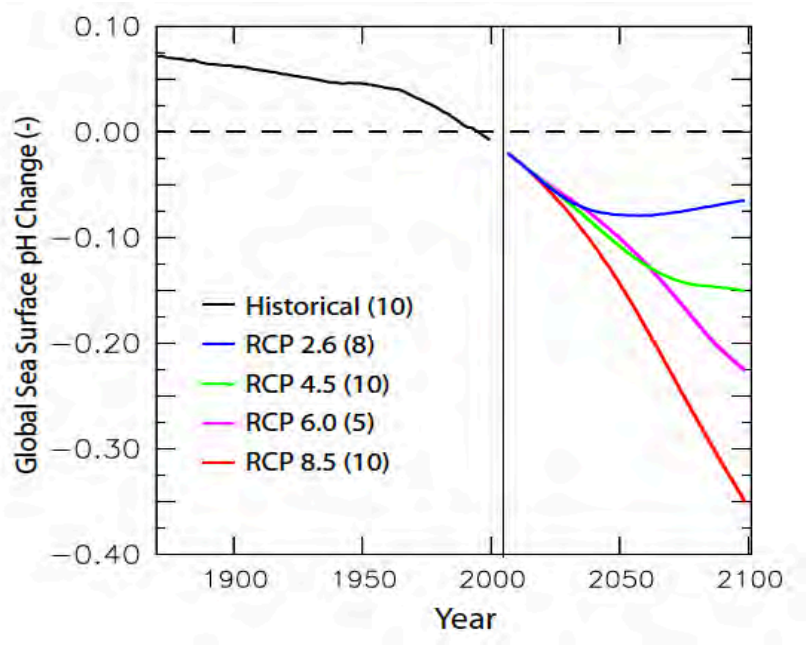
The context: what is the temporal variability of ocean acidification?



Bopp et al., *Biogeosciences* (2013)

Temporal mismatch

OA projections (annual-decadal)	**≠**	**Organism sensitivities (< hourly)**

- Seasonal OA variability can be similar magnitude to expected mean changes this century
- How this variability responds to climate change is crucial to projecting marine impacts

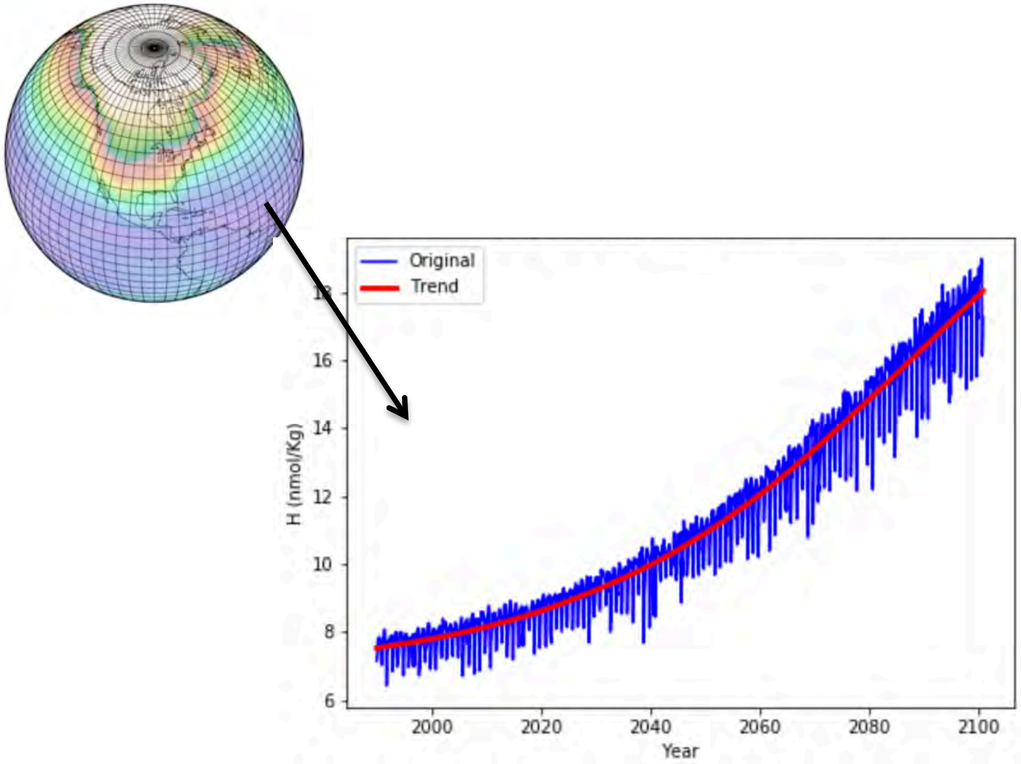
ESM projections of changing carbonate chemistry seasonality

Model name	Model abbreviation	Simulations				
		piControl	RCP8.5	1pctCO2	esmFixClim1	esmFdbk1
Community Earth System Model version 1 biogeochemistry	CESM1-BGC[1,2]	✔	✔	✖	✖	✖
Centre National de Recherches Météorologiques Earth System Model Coupled Model version 5	CNRM-ESM1[3]	✔	✔	✖	✖	✖
Geophysical Fluid Dynamics Laboratory Earth System Model version 2G	GFDL-ESM2G[4]	✔	✔	✖	✖	✖
Geophysical Fluid Dynamics Laboratory Earth System Model version 2M	GFDL-ESM2M[4]	✔	✔	✔	✔	✔
Hadley Centre Global Environment Model version 2- Earth System	HadGEM2-ES[5]	✔	✔	✖	✖	✖
Institut Pierre Simon Laplace Coupled Model version 5A-LR	IPSL-CM5A-LR[6]	✔	✔	✔	✔	✔
Institut Pierre Simon Laplace Coupled Model version 5A-MR	IPSL-CM5A-MR[6]	✔	✔	✖	✖	✖
Max-Planck-Institut für Meteorologie Earth System Model LR version	MPI-ESM-LR[7]	✔	✔	✔	✔	✔
Max-Planck-Institut für Meteorologie Earth System Model MR version	MPI-ESM-MR[7]	✔	✔	✖	✖	✖

- 9 CMIP5 ESMs with ocean biogeochemistry
- **Surface ocean** carbonate chemistry computed from **monthly** T, C_T, A_T, S, P, Si – *mocsy package*
- Output fields regridded to a 1° x 1° regular grid
- Focus on biologically important **$[H^+]$**, **pH**, **Ω_{arag}**

Kwiatkowski & Orr, *NCC* (2018)

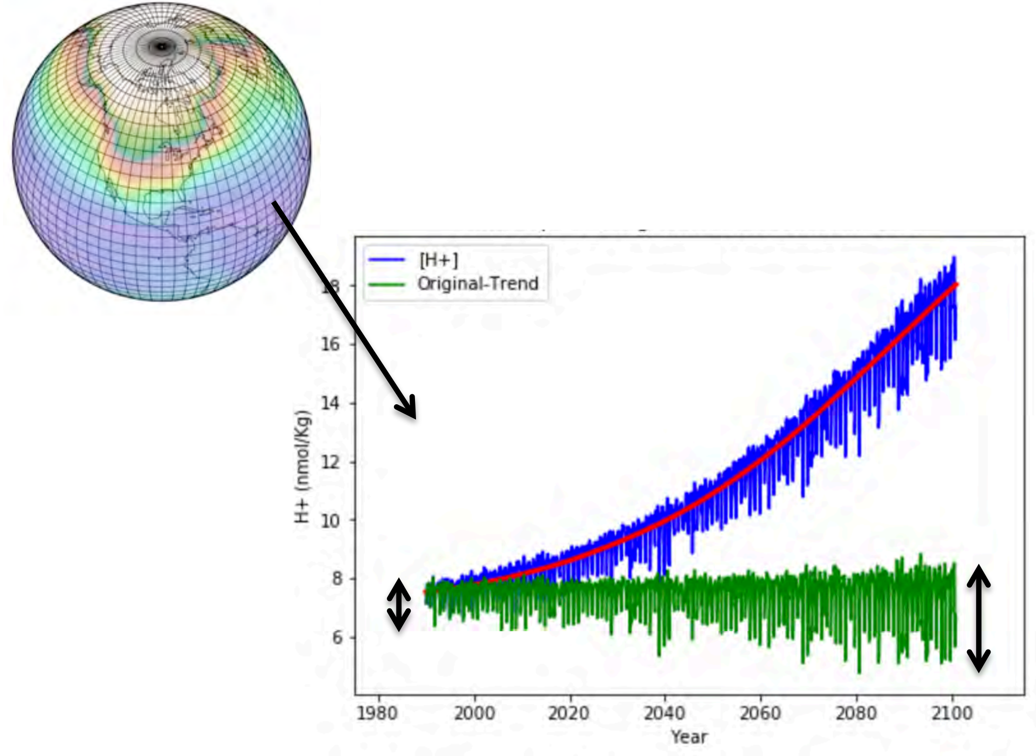
Methods: computing seasonal amplitude changes



- Projected seasonal amplitude evaluated for RCP8.5 (2006-2100) relative to historical (1990-1999)
- Seasonal amplitude anomalies determined by subtracting cubic spline fit from time series in each grid cell

Kwiatkowski & Orr, *NCC* (2018)

Methods: computing seasonal amplitude changes



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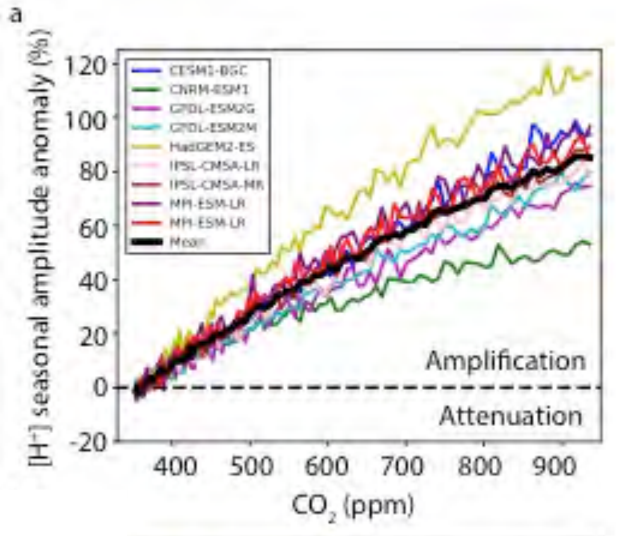
Kwiatkowski & Orr, *NCC* (2018)

Global seasonal amplitude anomalies in RCP8.5

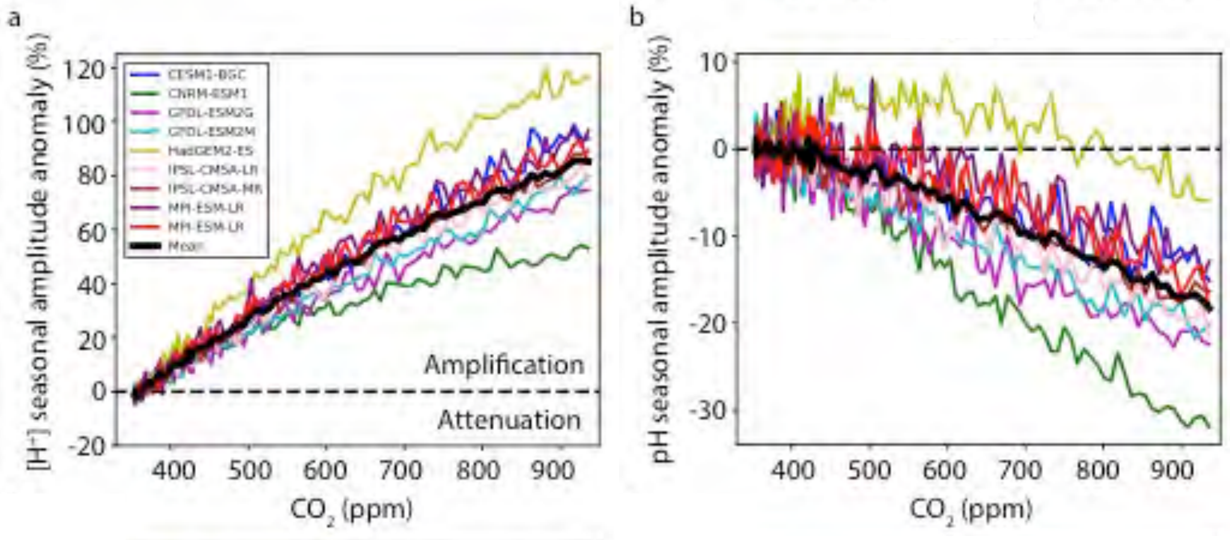


$[H^+]$ seasonality ↑ **81±16%**

↑ **Amplification**
↓ **Attenuation**

Kwiatkowski & Orr, *NCC* (2018)

Global seasonal amplitude anomalies in RCP8.5



$[H^+]$ seasonality ↑ **81±16%**

pH seasonality ↓ **16±7%**

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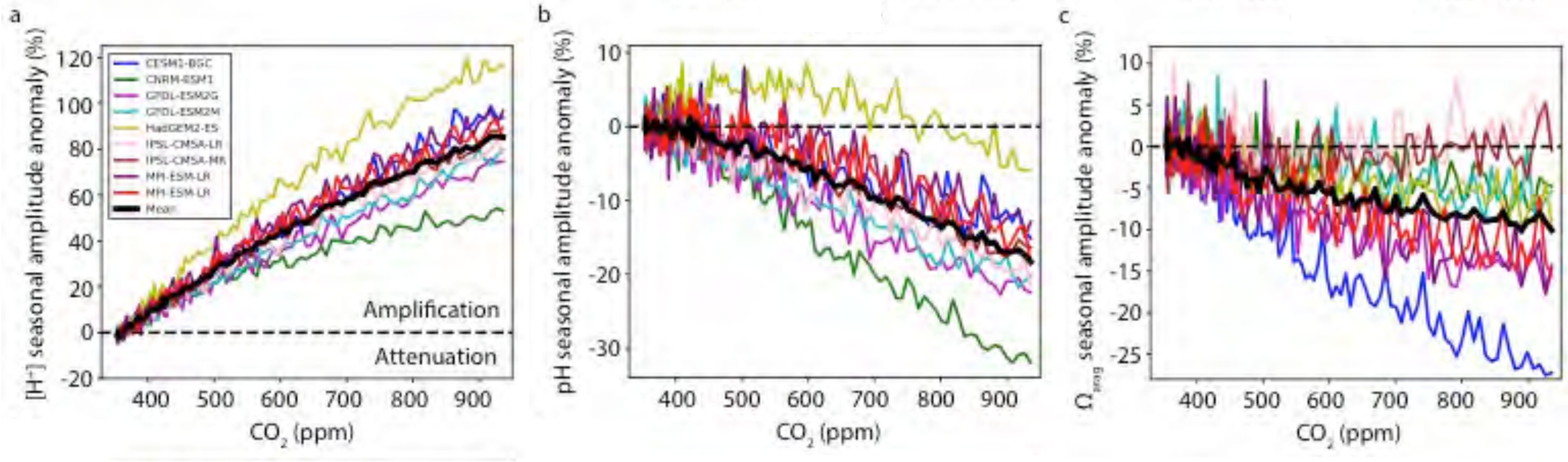
Kwiatkowski & Orr, *NCC* (2018)

Global seasonal amplitude anomalies in RCP8.5



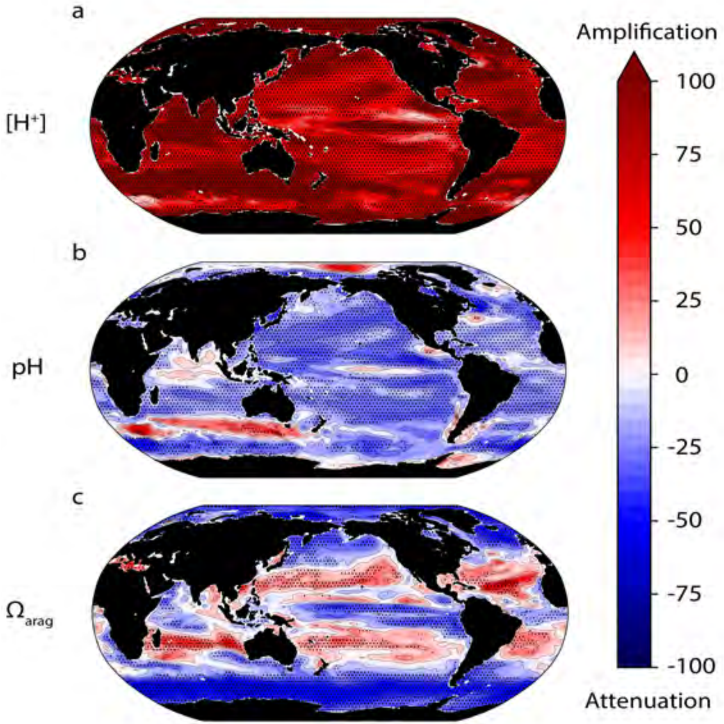
$[H^+]$ seasonality ↑ **81±16%**　　**pH** seasonality ↓ **16±7%**　　$\mathbf{\Omega_{arag}}$ seasonality ↓ **9±8%**

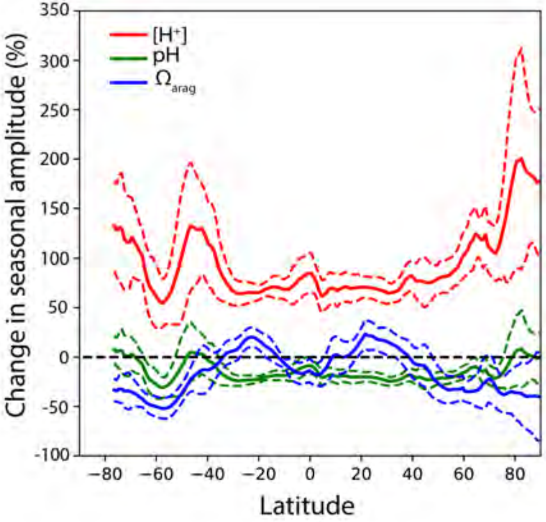
↑	**Amplification**
↓	**Attenuation**

Kwiatkowski & Orr, *NCC* (2018)

Spatially contrasting amplitude changes

21st century change in seasonality (%)



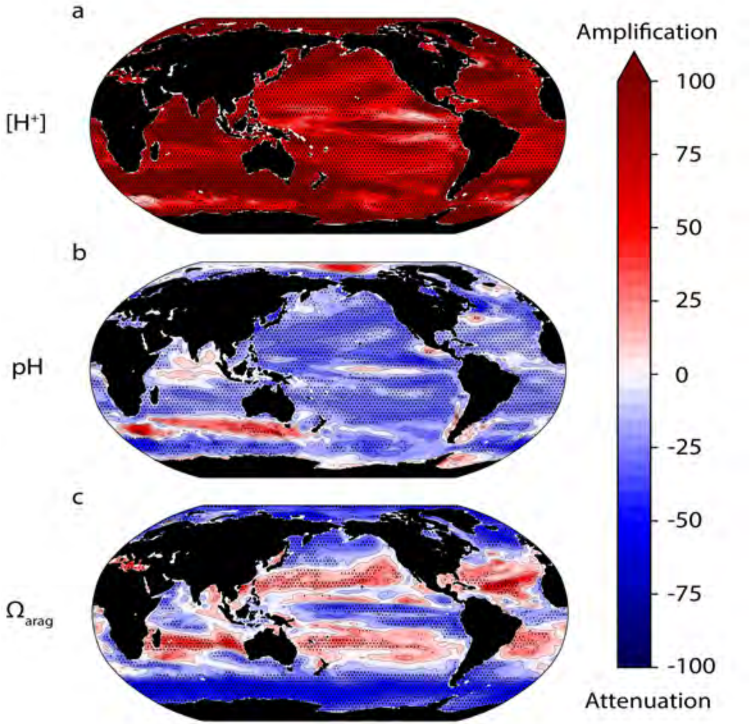


- $[H^+]$ ↑ greater in high lats (147% in the Arctic)
- pH ↓ typically greater in low and mid-lats
- Ω_{arag} ↓ >40% in the temperate-to-polar regions

- But there is ↑ of up to 30% in the subtropics

Seasonal $[H^+]$ amplification but pH attenuation?

21st century change in seasonality (%)



Counterintuitive, but a result of the log scale of pH

$$d\,pH = \frac{-1}{2.303}\frac{d[H^+]}{[H^+]}$$

$[H^+]$ = Annual mean $[H^+]$
d $[H^+]$ = Seasonality of $[H^+]$

$[H^+]$ increase (**117±3%**) > **d$[H^+]$** increase (**81±16%**)

Kwiatkowski & Orr, *NCC* (2018)

Determining the drivers of seasonality change

1. **Idealised simulations (<u>ultimate</u> geochemical and climate drivers):**

1pctCO2: CO_2 increases from 280 ppm by 1%/yr until 4xCO_2 (**total effect**)

esmFixClim1: CO_2 of *1pctCO2* but radiative module sees constant CO_2 of 280 ppm (**geochemical effect**)

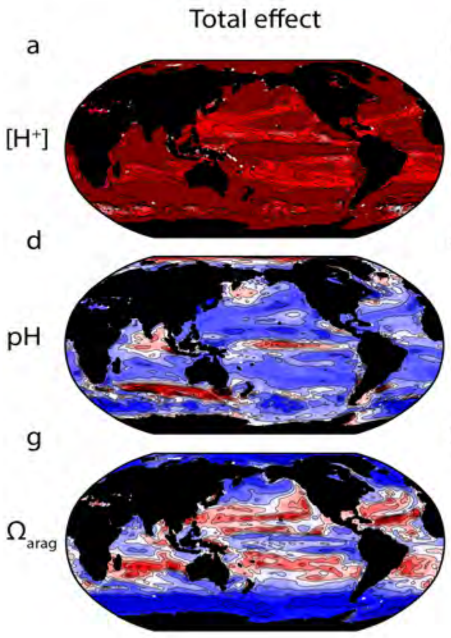
esmFdbk1: CO_2 constant at 280 ppm but radiative module sees CO_2 of *1pctCO2* (**radiative/climate effect**)

2. **First order Taylor series deconvolutions (<u>proximate</u> A_T/C_T/T/S drivers):**

$$\Delta y = \left(\frac{\partial y}{\partial C_T}\right)\Delta C_T + \left(\frac{\partial y}{\partial A_T}\right)\Delta A_T + \left(\frac{\partial y}{\partial T}\right)\Delta T + \left(\frac{\partial y}{\partial S}\right)\Delta S$$

Kwiatkowski & Orr, *NCC* (2018)

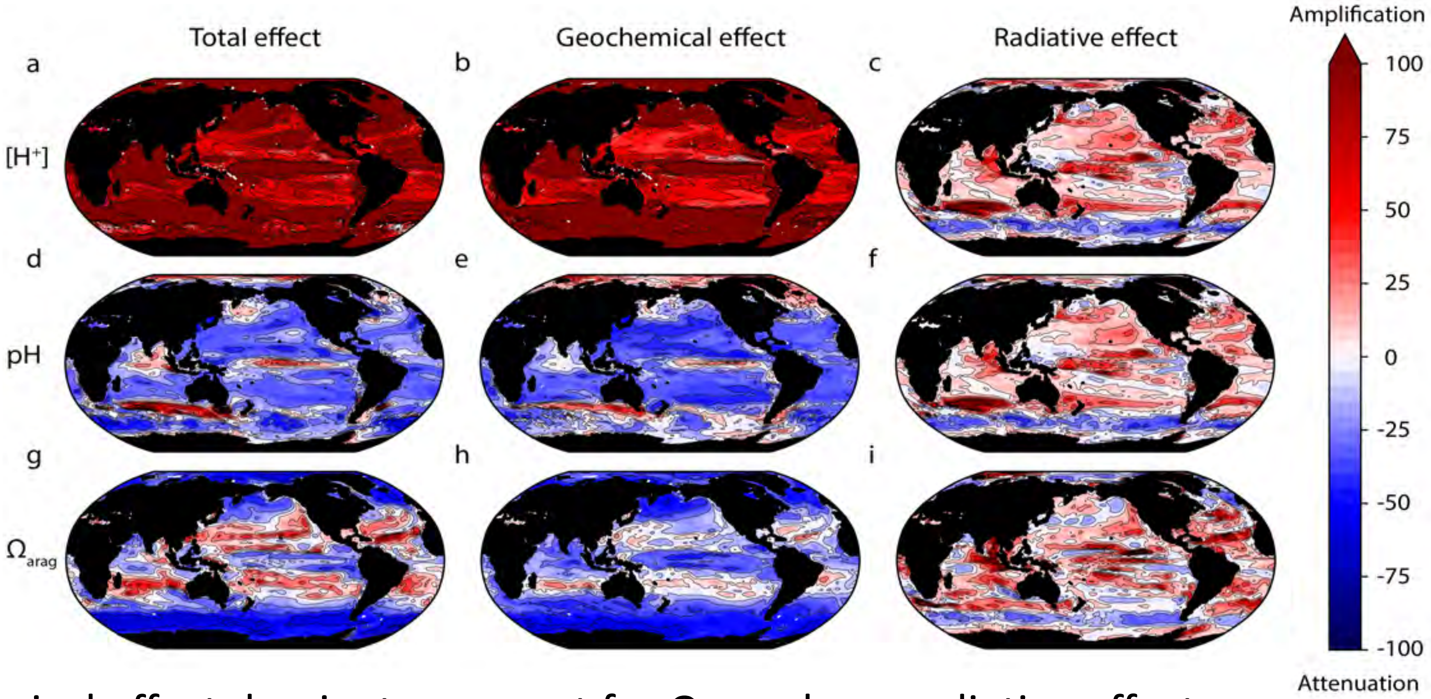
Idealised simulations: geochemical effect generally dominates



- **Changes in the *1pctCO2* very similar to of RCP8.5**
- **Indicates CO_2 is the dominant driver** of seasonality changes in RCP8.5 and not CH_4, O_3, aerosols etc
- Validates the use of *esmFixClim1* and *esmFdbk1* simulations to partition radiative and geochemical influences

Kwiatkowski & Orr, *NCC* (2018)

Idealised simulations: geochemical effect generally dominates



Geochemical effect dominates, except for Ω_{arag} where radiative effect dominates in the subtropics where buffer capacity is greatest

Kwiatkowski & Orr, *NCC* (2018)

Taylor series deconvolutions: proximate drivers of seasonality change

$$\Delta y = \left(\frac{\partial y}{\partial C_T}\right)\Delta C_T + \left(\frac{\partial y}{\partial A_T}\right)\Delta A_T + \left(\frac{\partial y}{\partial T}\right)\Delta T + \left(\frac{\partial y}{\partial S}\right)\Delta S$$

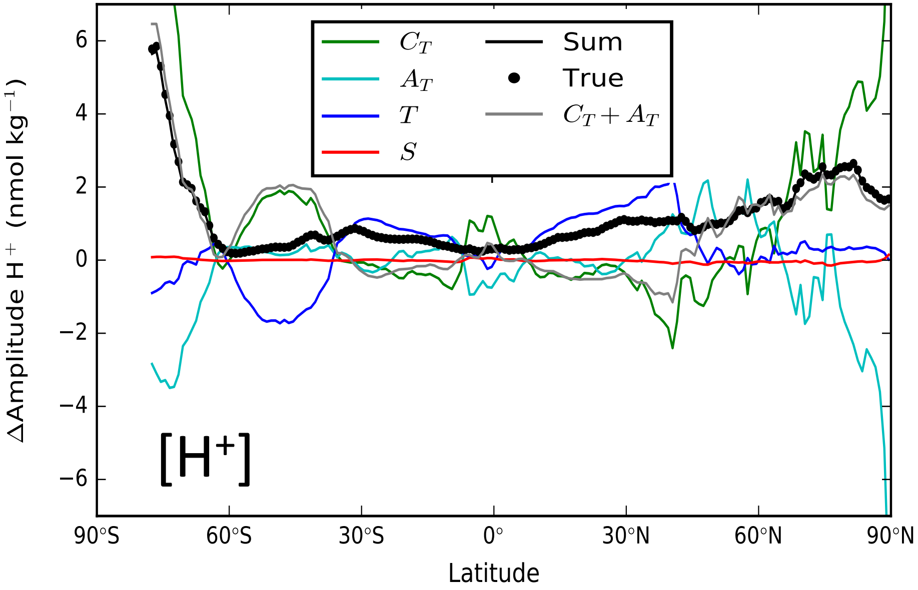
$[H^+]$ and Ω_{arag} (independently)

Partial differentials/ sensitivity terms estimated numerically

ΔT, ΔC_T, ΔA_T and ΔS represent the change in variables synchronous with Δy

- **GFDL-ESM2M** model (representative of multi-model mean)
- Reproduces changes in seasonal amplitude of $[H^+]$ and Ω_{arag} to within <<1 %

Deconvolutions: proximate drivers of [H^+] seasonality change



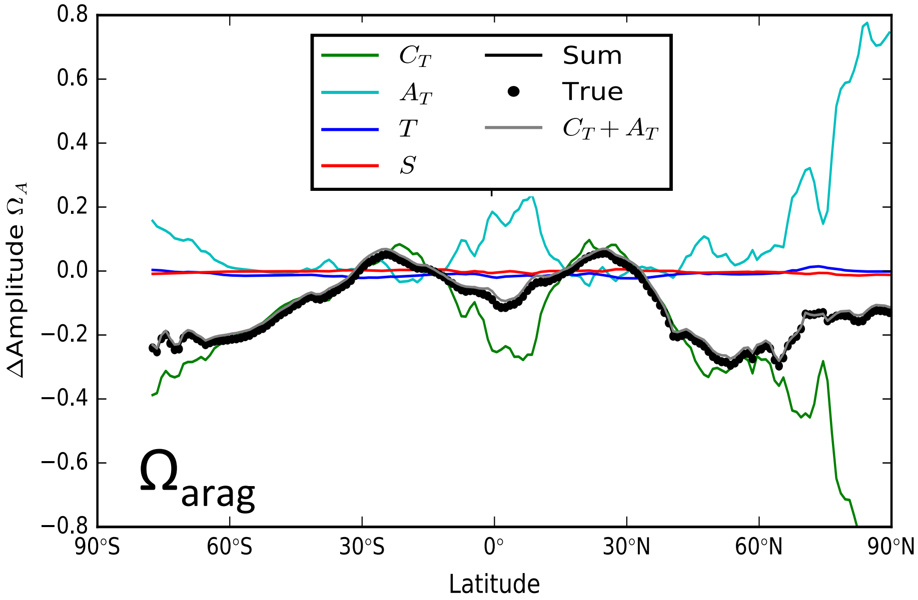
[H^+]

Amplification **(high lats)**- residual of opposing increases in $(\partial H^+/\partial C_T)\Delta C_T$ and $(\partial H^+/\partial A_T)\ \Delta A_T$ that dominates

Amplification **(low lats)**- A_T and C_T terms compensate and increases in $(\partial H^+/\partial T)\ \Delta T$ dominate

Kwiatkowski & Orr, *NCC* (2018)

Deconvolutions: proximate drivers of Ω_{arag} seasonality change



Ω_{arag}

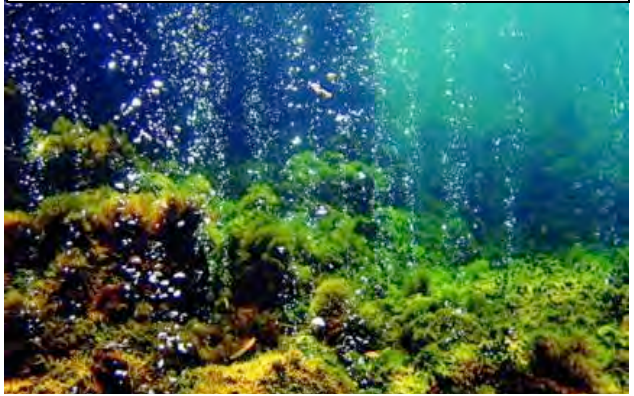
Attenuation-decline in C_T term $((\Omega_{arag}/C_T)\ \Delta C_T)$ outweighs increase in A_T term $((\Omega_{arag}/A_T)\ \Delta A_T)$.

Amplification- little change in A_T term, C_T term increases due to a larger change in ΔC_T

Kwiatkowski & Orr, *NCC* (2018)

Similar diurnal changes to chemistry variability?

CO_2 vents: analogues of the future ocean



Diurnal chemistry variability (Ischia, Mediterranean sea)

	pH	ΔpH	$[H^+]$ nmol/kg	$\Delta[H^+]$ nmol/kg	Ω_{arag}	$\Delta\Omega_{arag}$
Control	8.38	0.09	4.17	0.86	6.00	0.84
Vent	8.08	0.10	8.32	1.95	3.67	0.67
Diurnal Amp/Att		↑11%		↑122%		↓20%

Kerrison et al., 2011

- **CO_2 vent sites show similar changes in diurnal chemistry as CMIP5 seasonal projections**

Kwiatkowski & Orr, *NCC* (2018)

Conclusions

- CMIP5: **seasonal $[H^+]$ amplification**, **pH attenuation**, and **Ω_{arag} amplification and attenuation** - **geochemical** and **climatic** drivers

- **Amplified $[H^+]$ seasonality impacts ➔ exposure to acidosis**

  - **Low latitudes**, **earlier**/**later** exposure in **summer**/**winter**

  - **High latitudes**, **earlier**/**later** exposure when **photosynthesis low**/**high**

- **Generally attenuated Ω_{arag} seasonality impacts ➔ exposure to low Ω_{arag}**

  - **exacerbated**/**dampened** impacts in **summer highs** /**winter lows**

  - **opposite in the subtropics** (amplification projected)

- **Diurnal variability to be similarly affected as seasonal variability?**

Thanks, any questions?

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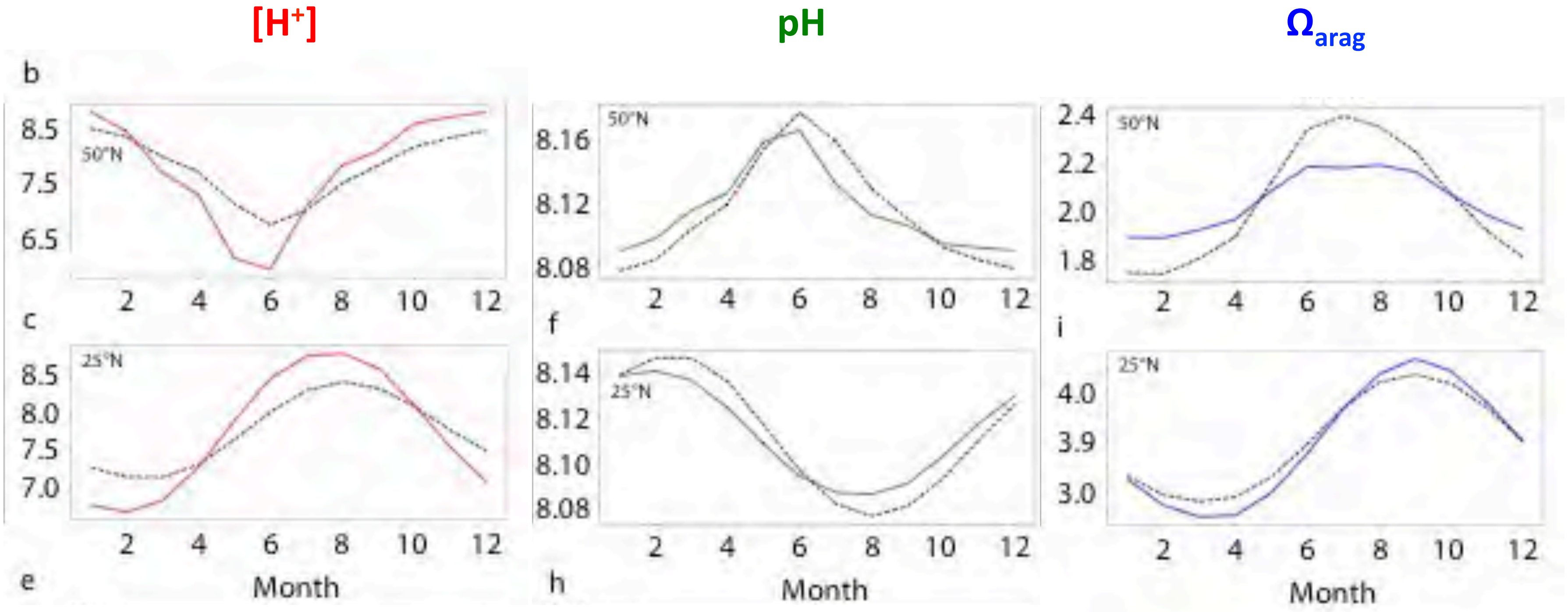
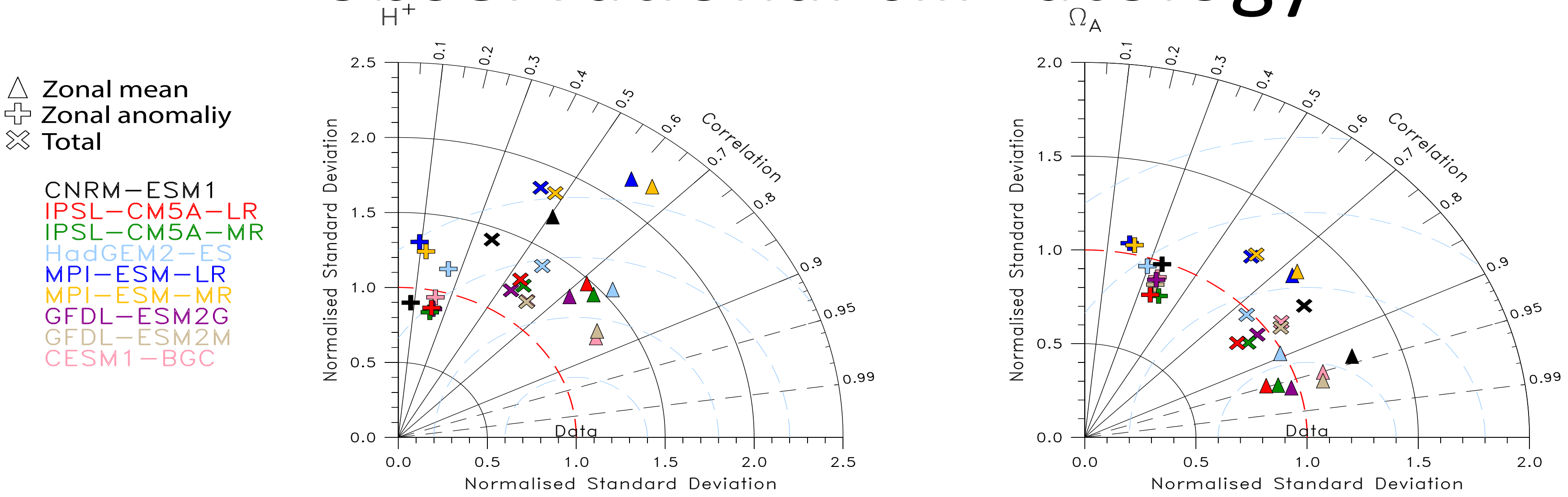
Additional slides

Zonal mean changes in seasonal cycles
1990s (black)
2090s (colours)



Model evaluation against an observational climatology



Taylor diagrams for seasonal variations in H^+ and Ω_{arag}. Colours designate individual models, shapes designate the space-time components. The total seasonal component (x), computed from monthly maps of temporal deviations (monthly means minus annual mean), is separated into 2 orthogonal components: zonal mean (triangles) and zonal anomaly (pluses). Observational reference = Takahashi et al. (2014).

Kwiatkowski & Orr, NCC (2018)

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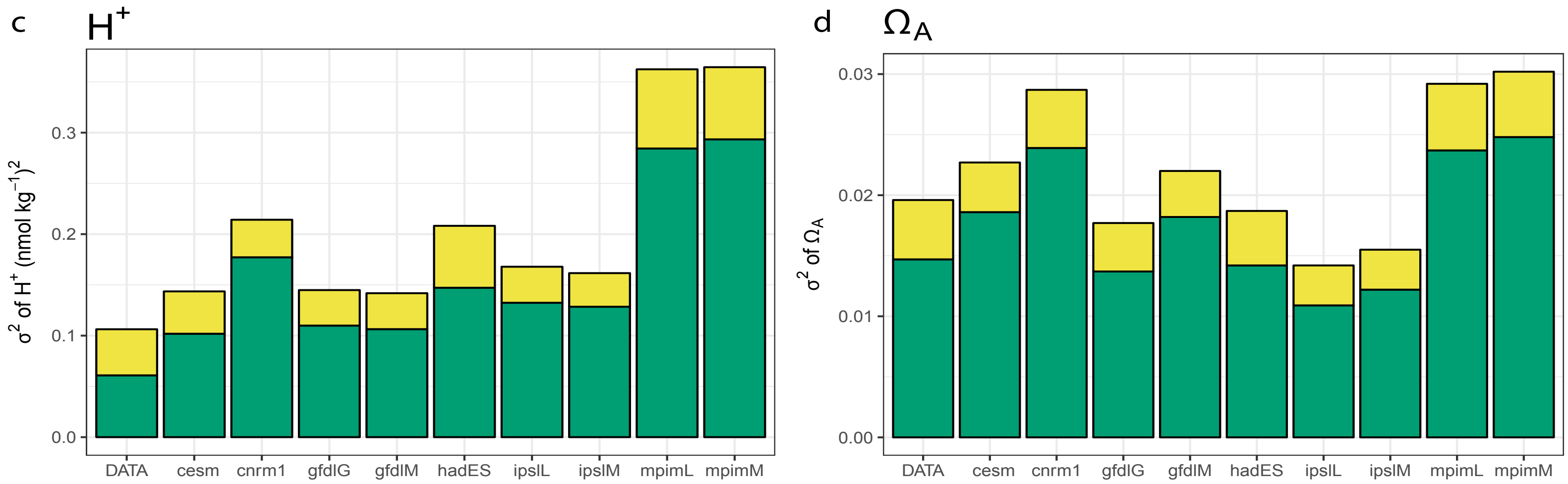
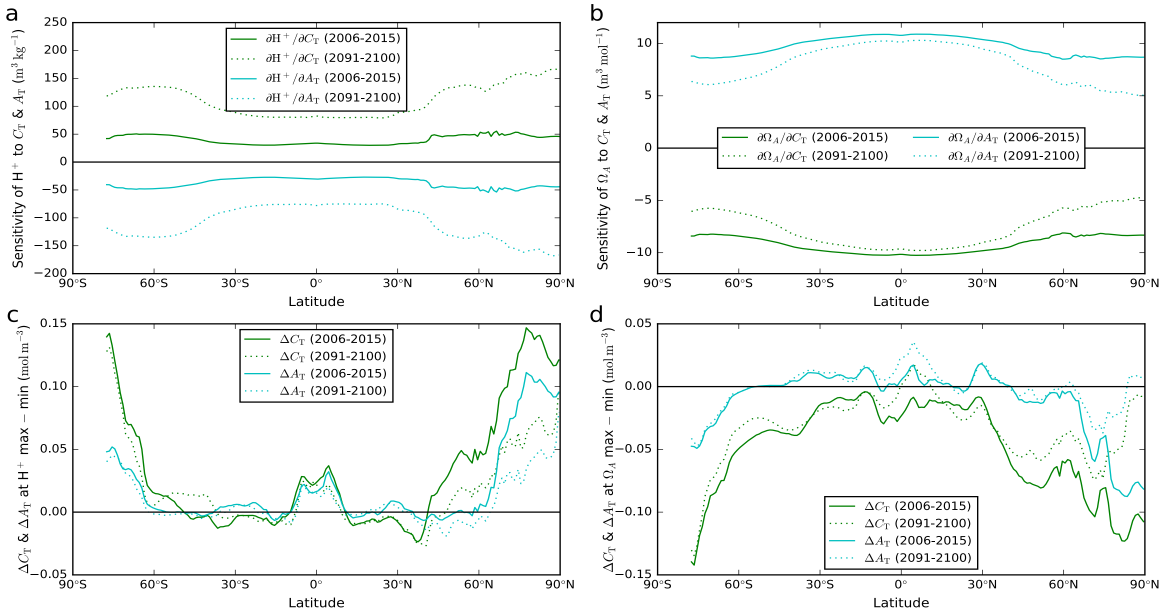


The total temporal variance of H^+ and Ω_{arag} seasonal cycles divided into zonal means (green) and zonal anomalies (yellow)

- Models overestimate the zonal-mean component of H^+ temporal variance
- Models encompass observed variance for Ω_{arag}

Kwiatkowski & Orr, NCC (2018)

Deconvolutions: proximate drivers of seasonality change



Separation of C_T and A_T terms into sensitivities and amplitude changes for $[H^+]$ and Ω_{arag} in the RCP8.5 simulation of the GFDL-ESM2M model.

The zonal mean sensitivities of a, $[H^+]$ and b, Ω_{arag} to C_T and A_T shown as means for 2006-2015 and 2091-2100 along with corresponding zonal mean ΔC_T and ΔA_T taken between monthly maximum and minimum for c, $[H^+]$ and d, Ω_{arag} .

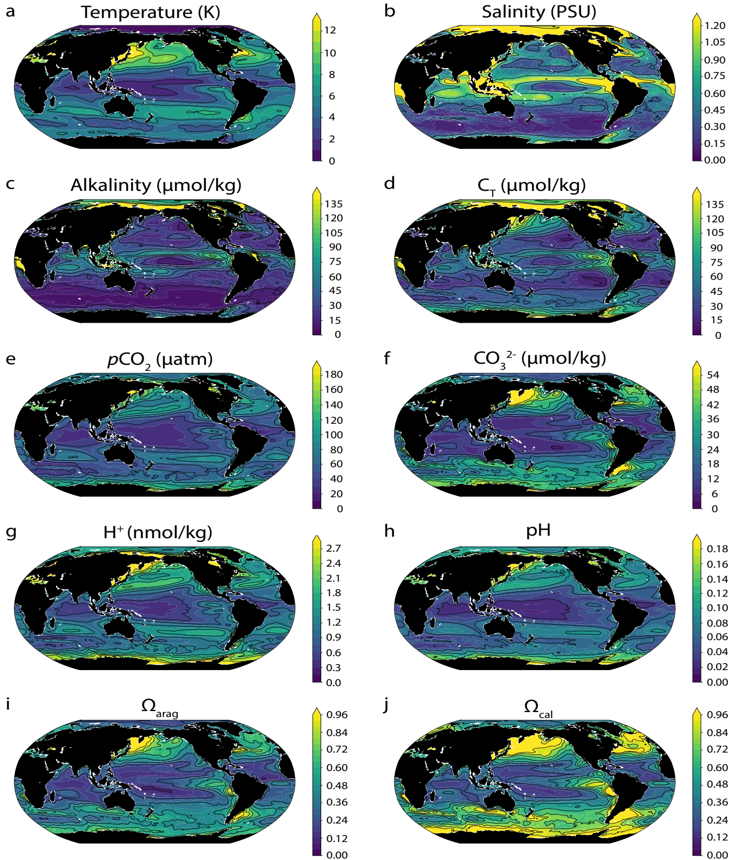
ESM projections of changing carbonate chemistry seasonality

- Calcifying species can experience depressed **calcification, growth and survival rates** at lower calcium carbonate saturation state (**Ω**) (e.g. Kroeker et al., 2010; Albright et al., 2016; Kwiatkowski et al., 2016a, 2016b).

- Teleost fish and marine invertebrates, ion exchange is reduced by extracellular acidosis or high external **[H^+]**, depressing **protein synthesis and metabolic rates** (e.g. Langenbuch et al., 2006; Pörtner, 2008).

- **Physiological and behavioural functioning** is also sensitive to $\boldsymbol{p}\mathbf{CO_2}$, with high external concentrations impairing olfactory discrimination (e.g. Munday et al., 2009) and predator-prey responses (e.g. Watson et al., 2014; Watson et al., 2017).

ESM projections of changing carbonate chemistry seasonality



Chemistry seasonal cycles result of different physical and biological processes.

pH seasonality largely driven by T in low lats and photosynthesis/respiration in high lats

Ω seasonality largely driven by the variability of alkalinity and DIC with less influence of T

Seasonal variability can be a similar order of magnitude to changes expected over the 21st century

Kwiatkowski & Orr, *NCC* (2018)