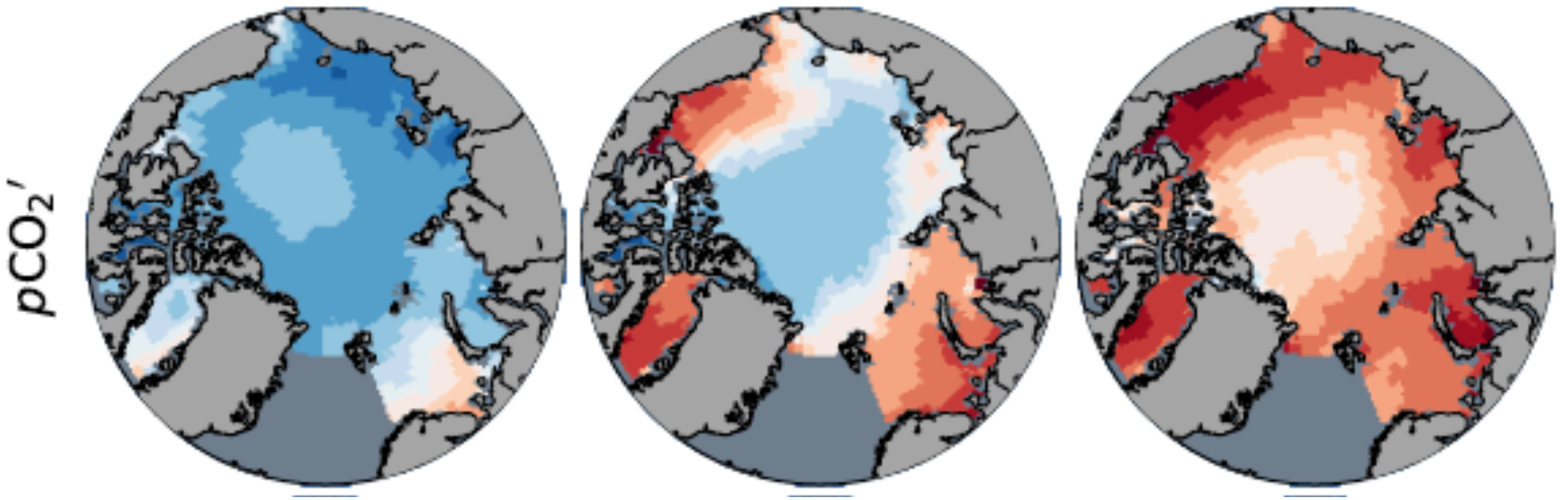
# Ocean biogeochemical tipping points in ESMs: a regime shift in Arctic ocean chemistry ?




**Lester Kwiatkowski & James Orr**

Institut Henri Poincaré
04/10/2023

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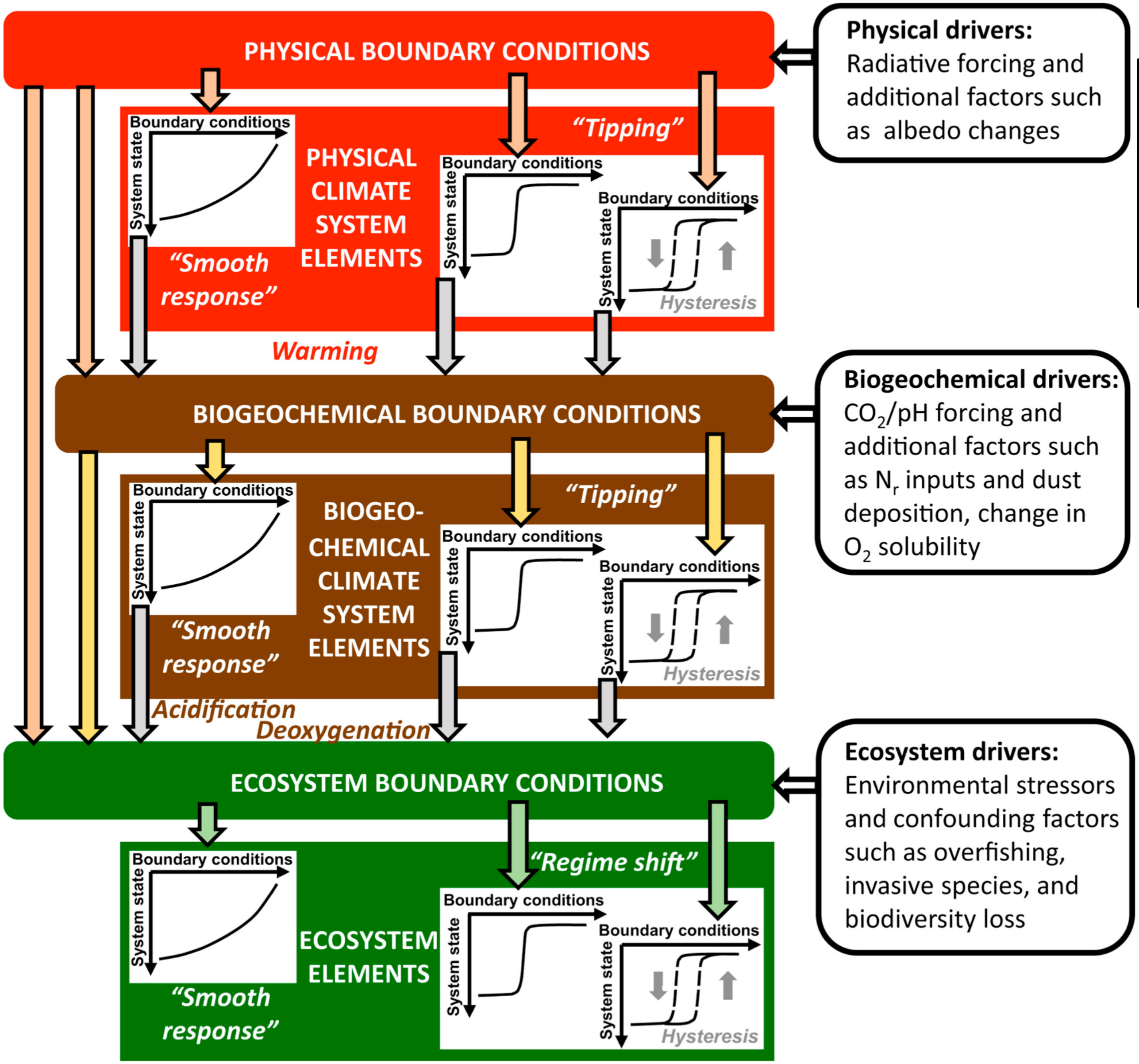


**Cascading tipping behaviour through physical, biogeochemical and ecosystem boundary conditions**

**Focus today**

**Generally unresolved in ESMs (ecosystem models required)**

**Heinze et al, *PNAS* (2021)**

# IPCC SROCC identified MHWs, deoxygenation and acidification as potential abrupt ocean changes with variable reversibility

| Change in system component | Potentially abrupt | Irreversibility if forcing reversed (time scales indicated) | Impacts on natural and human systems; global *vs.* regional *vs.* local | Projected likelihood and/or confidence level in 21st century under scenarios considered |
|---|---|---|---|---|
| **Ocean** | | | | |
| Atlantic Meridional Overturning Circulation (AMOC) collapse (Section 6.7) | Yes | Unknown | Widespread; increased winter storms in Europe, reduced Sahelian rainfall and agricultural capacity, variations in tropical storms, increased sea levels on Atlantic coasts | *Very unlikely*, but physically plausible |
| Subpolar gyre (SPG) cooling (Section 6.7) | Yes | Irreversible within decades | Similar to AMOC impacts but considerably smaller | *Medium confidence* |
| Marine heatwave (MHW) increase (Section 6.4) | Yes | Reversible within decades to centuries | Coral bleaching, loss of biodiversity and ecosystem services, harmful algal blooms, species redistribution | *Very likely* (*very high confidence*) for physical change<br>*High confidence* for impacts |
| Arctic sea ice retreat (Section 3.3) | Yes | Reversible within decades to centuries | Coastal erosion in Arctic (may take longer to reverse), impact on mid-latitude storms (*low confidence*); rise in Arctic surface temperatures (*high confidence*) | *High confidence* |
| Ocean deoxygenation and hypoxic events (Section 5.2) | Yes | Reversible at surface, but irreversible for centuries to millennia at depth | Major changes in ocean productivity, biodiversity and biogeochemical cycles | *Medium confidence* |
| Ocean acidification (Section 5.2) | Yes | Reversible at surface, but irreversible for centuries to millennia at depth | Changes in growth, development, calcification, survival and abundance of species, for example, from algae to fish | *Virtually certain* (*very high confidence*) |

**Tipping point:** ***"A level of change in system properties beyond which a system reorganizes, often in a non-linear manner, and does not return to the initial state even if the drivers of the change are abated."***
(IPCC, SROCC, 2019)

**Collins et al, IPCC, *SROCC* (2019)**

# IPCC SROCC identified MHWs, deoxygenation and acidification as potential abrupt ocean changes with variable reversibility

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Reversibility timescales

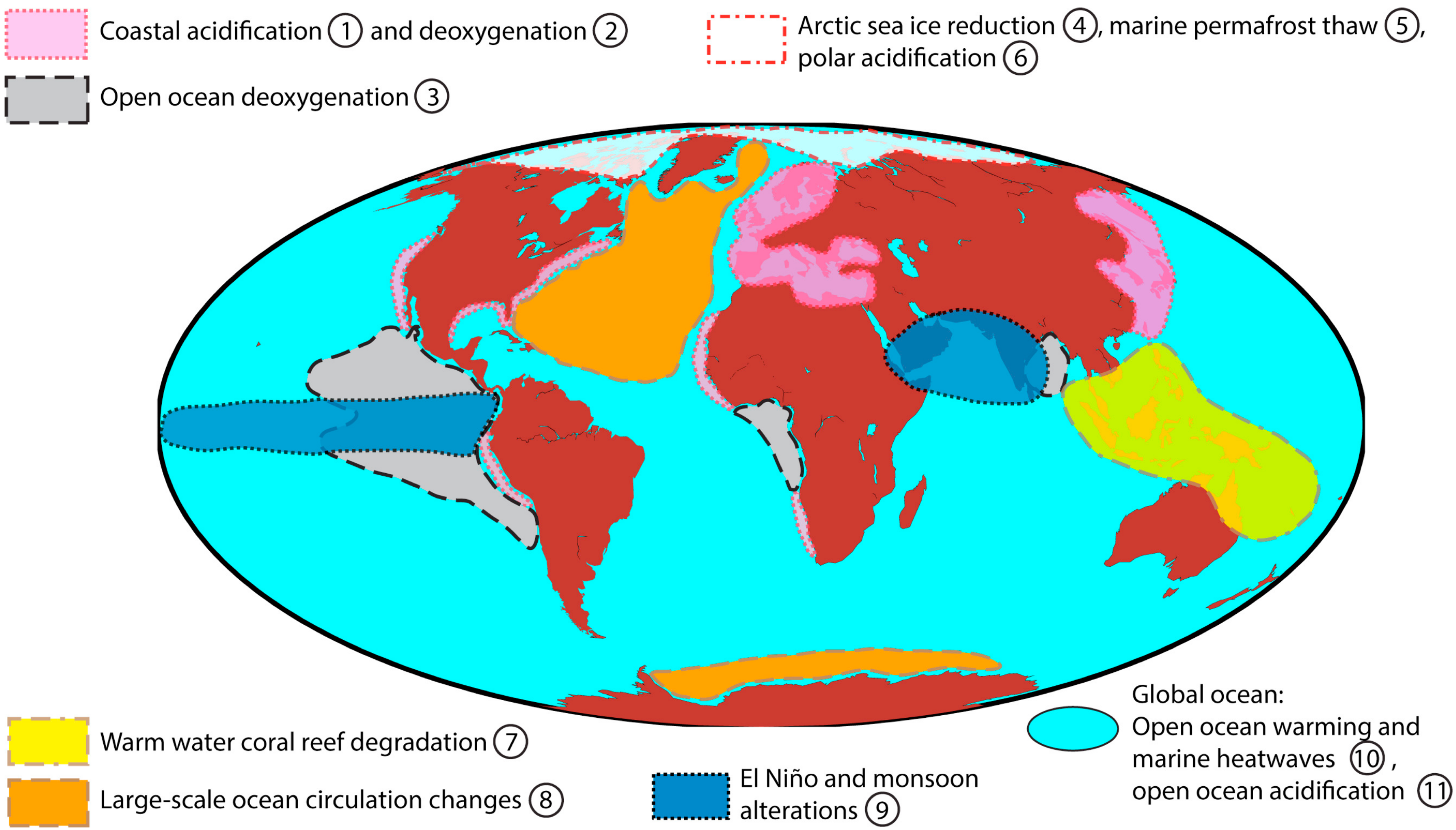
Marine heat waves -decades/centuries

Deoxygenation – reversible at surface, $10^2$-$10^3$ yrs at depth

Acidification – reversible at surface, $10^2$-$10^3$ yrs at depth

**Collins et al, IPPC, *SROCC* (2019)**

# Potential ocean tipping elements related to warming, deoxygenation and acidification




**Heinze et al, *PNAS* (2021)**

# Key biogeochemical abrupt change/tipping point papers to emerge from the COMFORT project

**Our common future ocean in the Earth system – quantifying coupled cycles of carbon, oxygen, and nutrients for determining and achieving safe operating spaces with respect to tipping points: COMFORT (Horizon 2020)**

SCIENCE ADVANCES | RESEARCH ARTICLE

ECOLOGY

**Abrupt shifts in 21st-century plankton communities**

B. B. Cael[1]*, Stephanie Dutkiewicz[2], Stephanie Henson[1]

Research Article | Open Access

**Biogeochemical Timescales of Climate Change Onset and Recovery in the North Atlantic Interior Under Rapid Atmospheric $CO_2$ Forcing**

Leonardo Bertini, Jerry Tjiputra

Perspective

**Biogeochemical extremes and compound events in the ocean**

https://doi.org/10.1038/s41586-021-03981-7

Nicolas Gruber[1], Philip W. Boyd[2], Thomas L. Frölicher[3,4] & Meike Vogt[1]

Article

**Arctic Ocean annual high in $p_{CO_2}$ could shift from winter to summer**

https://doi.org/10.1038/s41586-022-05205-y

James C. Orr[1], Lester Kwiatkowski[2] & Hans-Otto Pörtner[3]

LETTER • OPEN ACCESS

**Hysteresis of the Earth system under positive and negative $CO_2$ emissions**

Aurich Jeltsch-Thömmes[2], Thomas F Stocker and Fortunat Joos

Published 3 December 2020 • © 2020 The Author(s). Published by IOP Publishing Ltd
Environmental Research Letters, Volume 15, Number 12

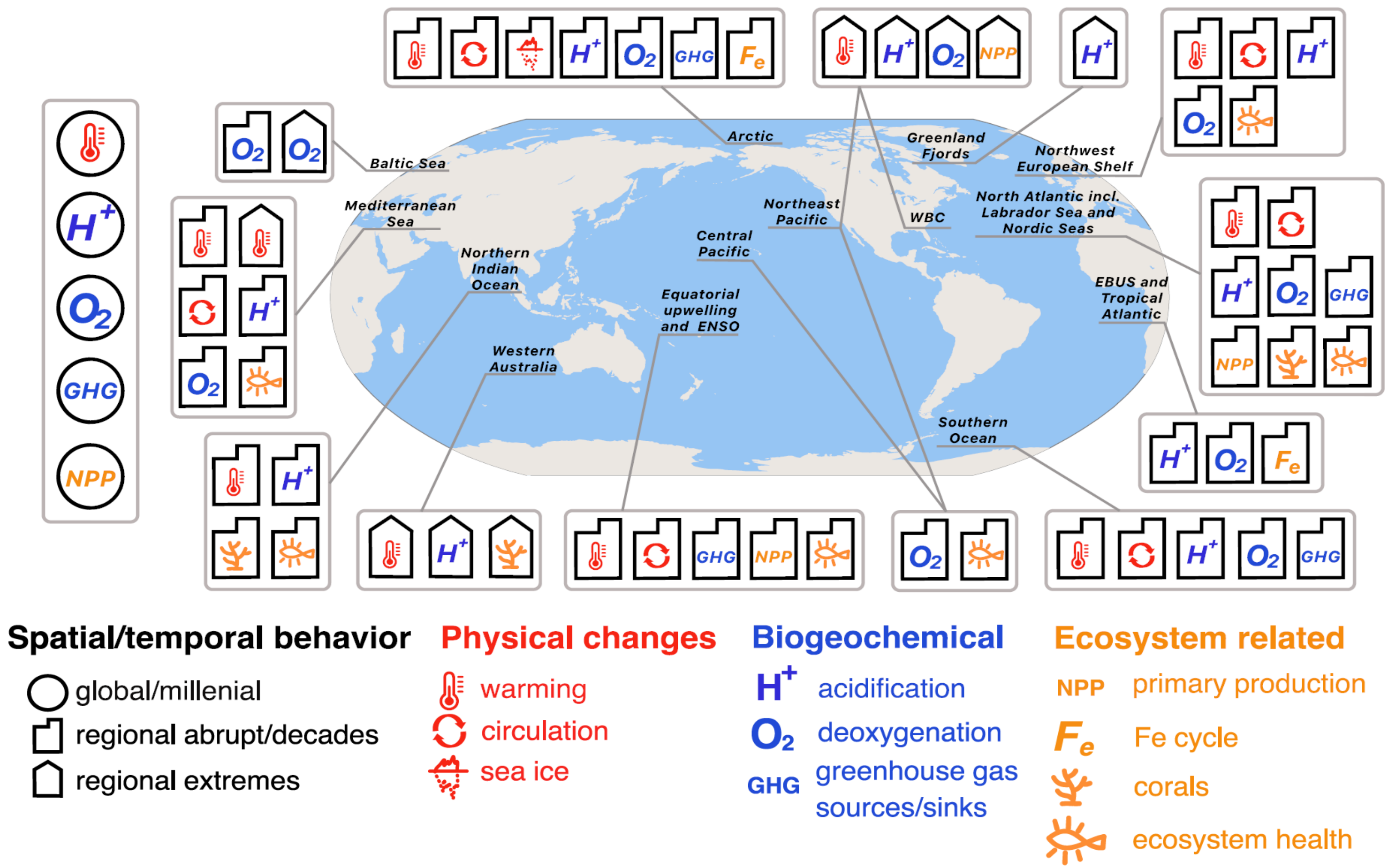
Extensive OBGC publications

But - **reversibility rarely addressed** and if so typically in EMICs not ESMs (indicative of ESM simulations performed in CMIP5/6?)

- **early warning indicators receive limited attention**

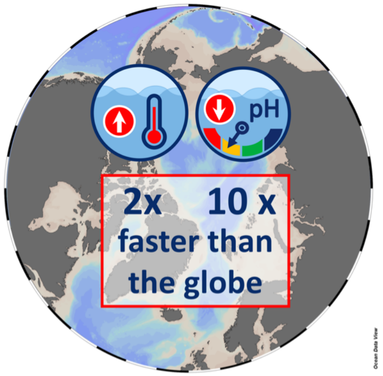
# Key biogeochemical abrupt change/tipping point papers to emerge from the COMFORT project

## Synthesis/review of ocean biogeochemical abrupt change/tipping points



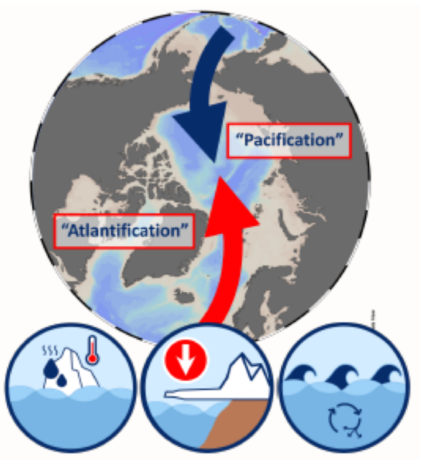

Heinze et al, *Biogeosciences* (in review)

# COMFORT reiterated the sensitivity of the Arctic Ocean to abrupt change and potential tipping points




**Warming 2x faster and acidifying 10x faster than the global mean**

**Arctic Ocean currents are changing due to increased freshwater inputs and are invaded by the waters from the Atlantic and Pacific Oceans**





**Extreme events expected to become more frequent and intense, due to summer sea-ice & Greenland ice sheet loss, wildfires, and permafrost thaw**

**COMFORT policy brief (2023)**

# Ocean acidification and why we might care about it

Seawater that is absorbing carbon dioxide from atmosphere

Free hydrogen ions

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \Leftrightarrow 2H^+ + CO_3^{2-}$$

Carbon dioxide in atmosphere

Carbonic acid

Bicarbonate ions

Carbonate ions

**Pteropod dissolving in $\Omega_{arag} < 1$ seawater**

$pCO_2$ ↑

$HCO_3^-$ ↑

$H^+$ ↑

$CO_3^{2-}$ ↓

pH ↓

$\Omega_{arag}$ ↓

$\Omega_{calc}$ ↓

# Temporal variability: Seasonal phasing of $pCO_2$ in the Arctic Ocean

**Ocean $pCO_2$ is increasing**

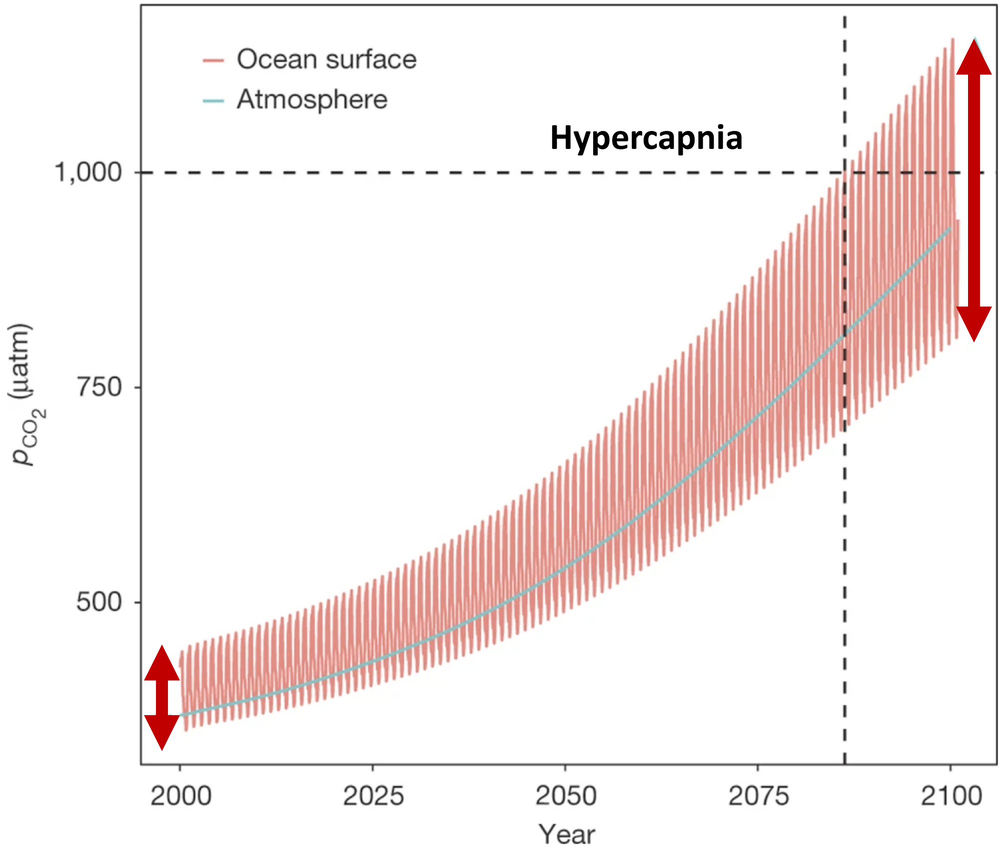
- **focus here is on seasonal cycle**

**Changing seasonal cycles can…**

**- Influence when critical organism thresholds are crossed e.g.**

- **hypercapnia ($pCO_2$)**
- **Acidosis ($H^+$)**
- **$\Omega_{arag}$ undersaturation**

**- Impact air-sea gas exchange**



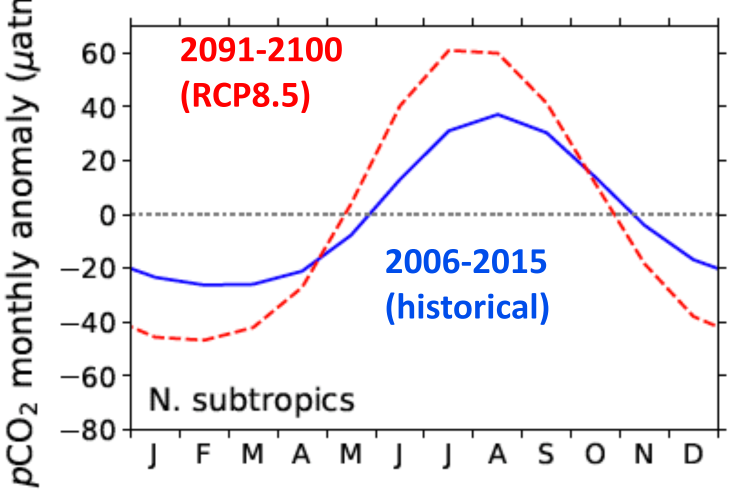

**McNeil & Sasse, *Nature* (2016)**

# Amplification of $p$CO$_2$ seasonal cycle in the surface ocean

**The $p$CO$_2$ seasonal cycle is projected to amplify in the surface ocean**

**...but seasonal phasing (max/mins) near identical**

**CMIP5 multi-model mean**




typically thermally driven seasonal cycles of $p$CO$_2$ in oligotrophic regions

**Amplification supported by observations (e.g. Landschutser et al., NCC, 2018)**

**Kwiatkowski & Orr, *NCC* (2018)**
**Orr, Kwiatkowski & Pörtner, *Nature* (2022)**

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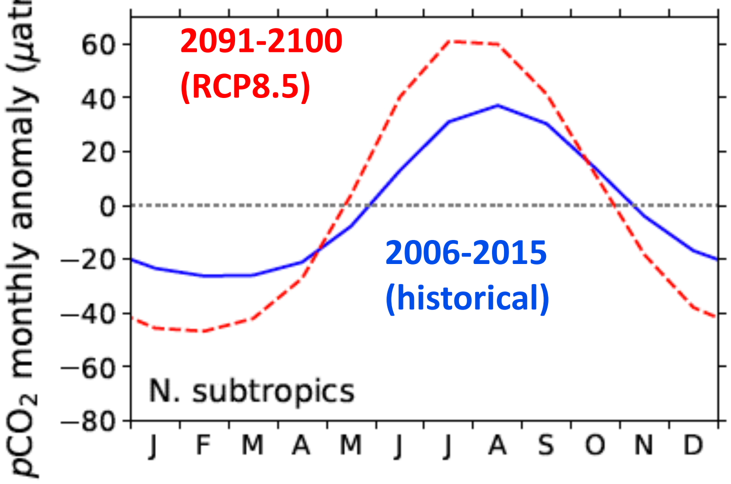



**Amplification driven by ocean carbon uptake (not climate change)**

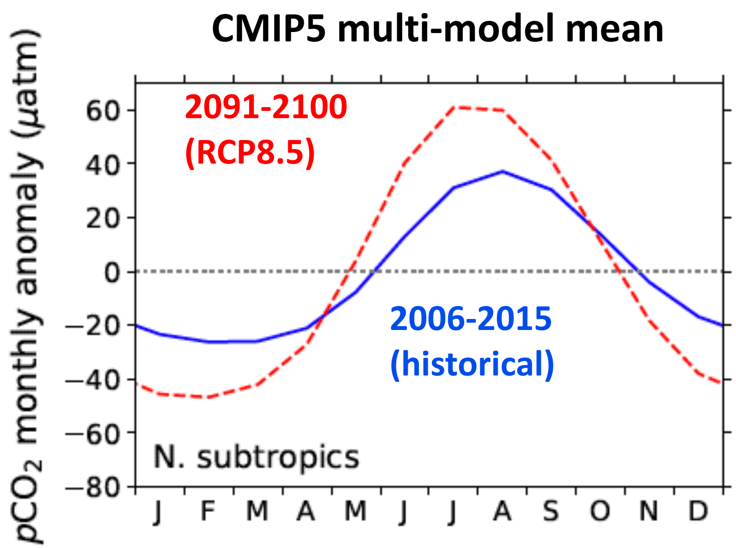
**i.e. Geochemical not Radiative**

**-seen in "$CO_2$-only" simulations where model radiative module see constant $CO_2$ (e.g. esmfixclim1)**

**Kwiatkowski & Orr, *NCC* (2018)**
**Orr, Kwiatkowski & Pörtner, *Nature* (2022)**

# Amplification of $pCO_2$ seasonal cycle in the global surface ocean

**The $pCO_2$ seasonal cycle is projected to amplify in the surface ocean**




**...but seasonal phasing (max/mins) near identical**

**Amplification driven by ocean carbon uptake (not climate change)**

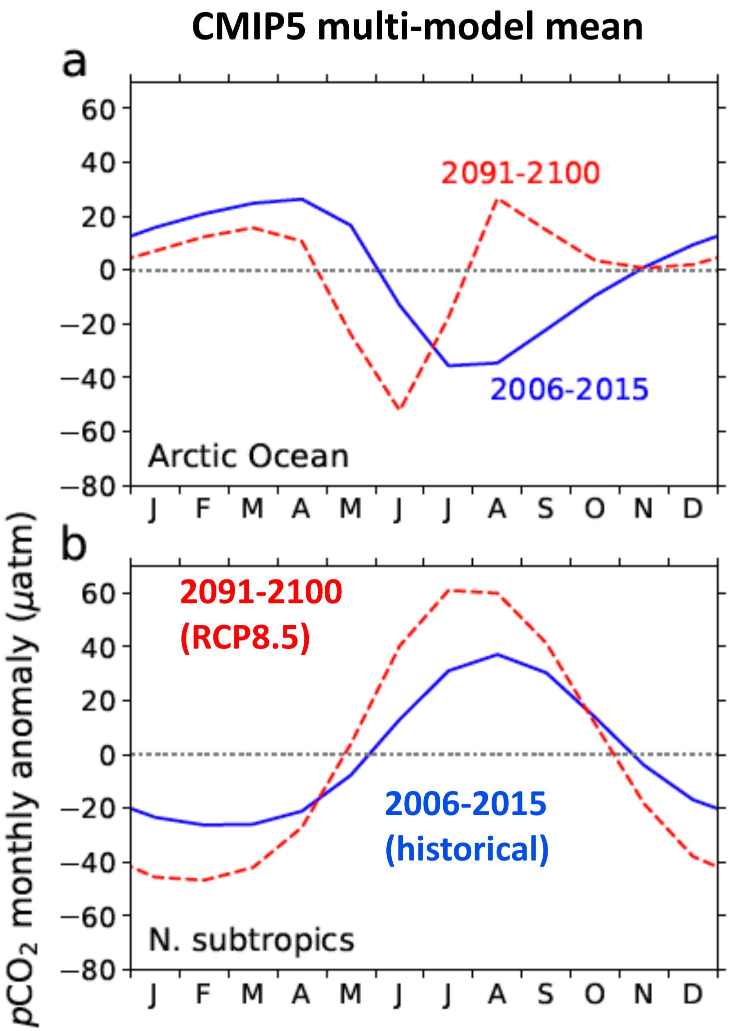
**i.e. Geochemical not Radiative**

$$p'_{CO_2} \approx \frac{\partial p_{CO_2}}{\partial T}T' + \frac{\partial p_{CO_2}}{\partial S}S' + \frac{\partial p_{CO_2}}{\partial A_T}A'_T + \frac{\partial p_{CO_2}}{\partial C_T}C'_T$$

**Ocean carbon uptake increases the sensitivity of $pCO_2$ to it's driving variables**

**Kwiatkowski & Orr, *NCC* (2018)**
**Orr, Kwiatkowski & Pörtner, *Nature* (2022)**

# But $pCO_2$ seasonal cycle "breakdown" in the Arctic Ocean




**In the Arctic Ocean,**

**$pCO_2$ seasonal cycle is near-inverted**

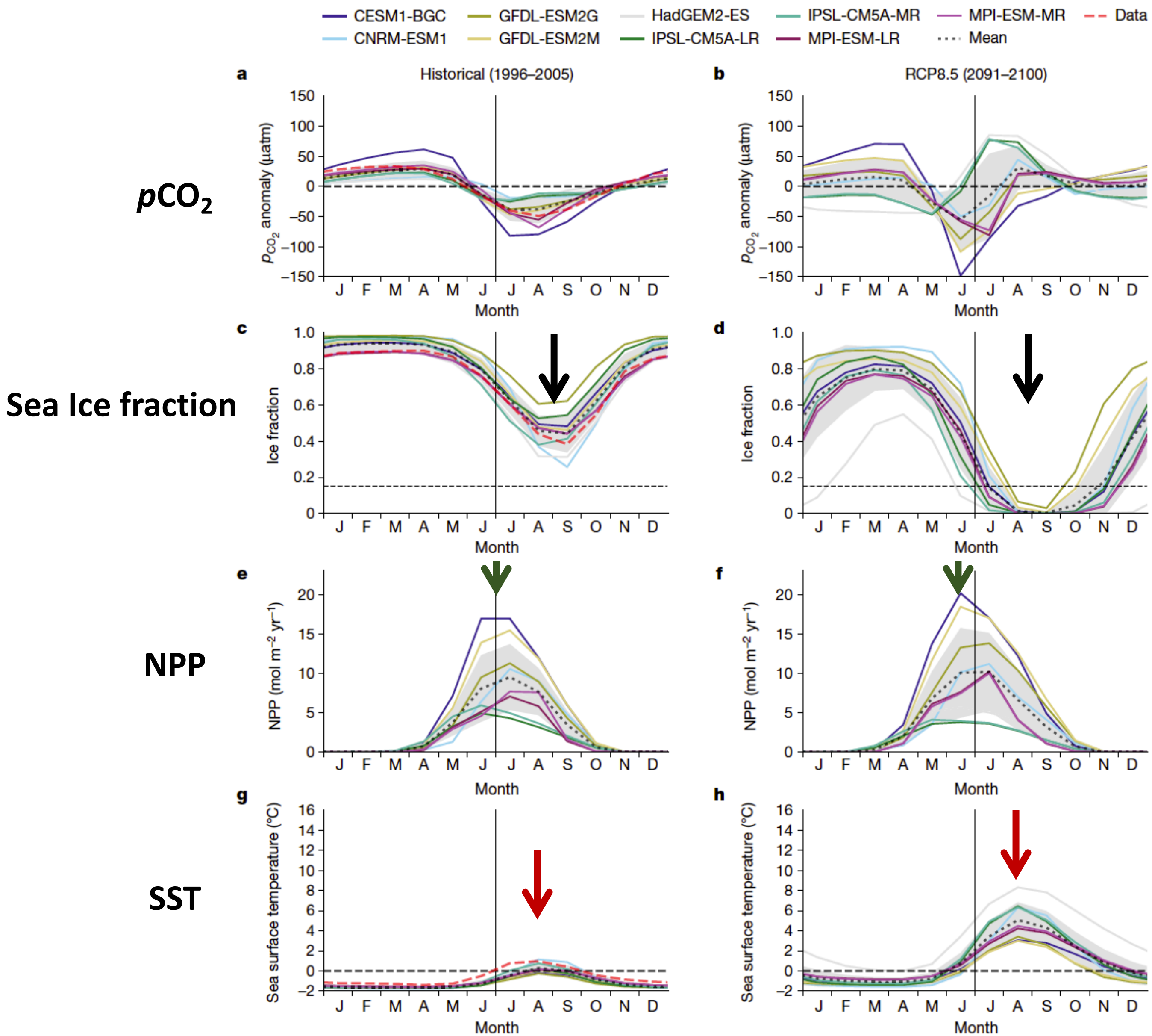
**Summer min becomes a summer max**

**$pCO_2$ summers are becoming winters**

**Potential impact on sensitive species as this is the Arctic growth period**

**Orr, Kwiatkowski & Pörtner, *Nature* (2022)**

# Similar seasonal phasing of Arctic sea ice, NPP and SST (unlike $pCO_2$) but very different amplitudes




Orr, Kwiatkowski & Pörtner, *Nature* (2022)

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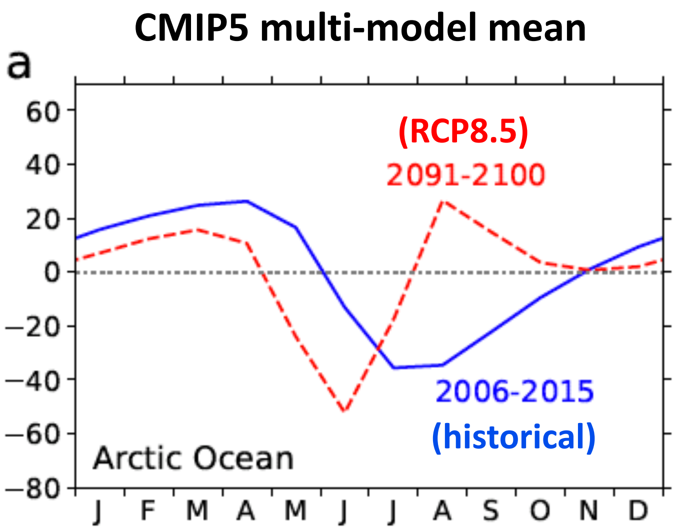
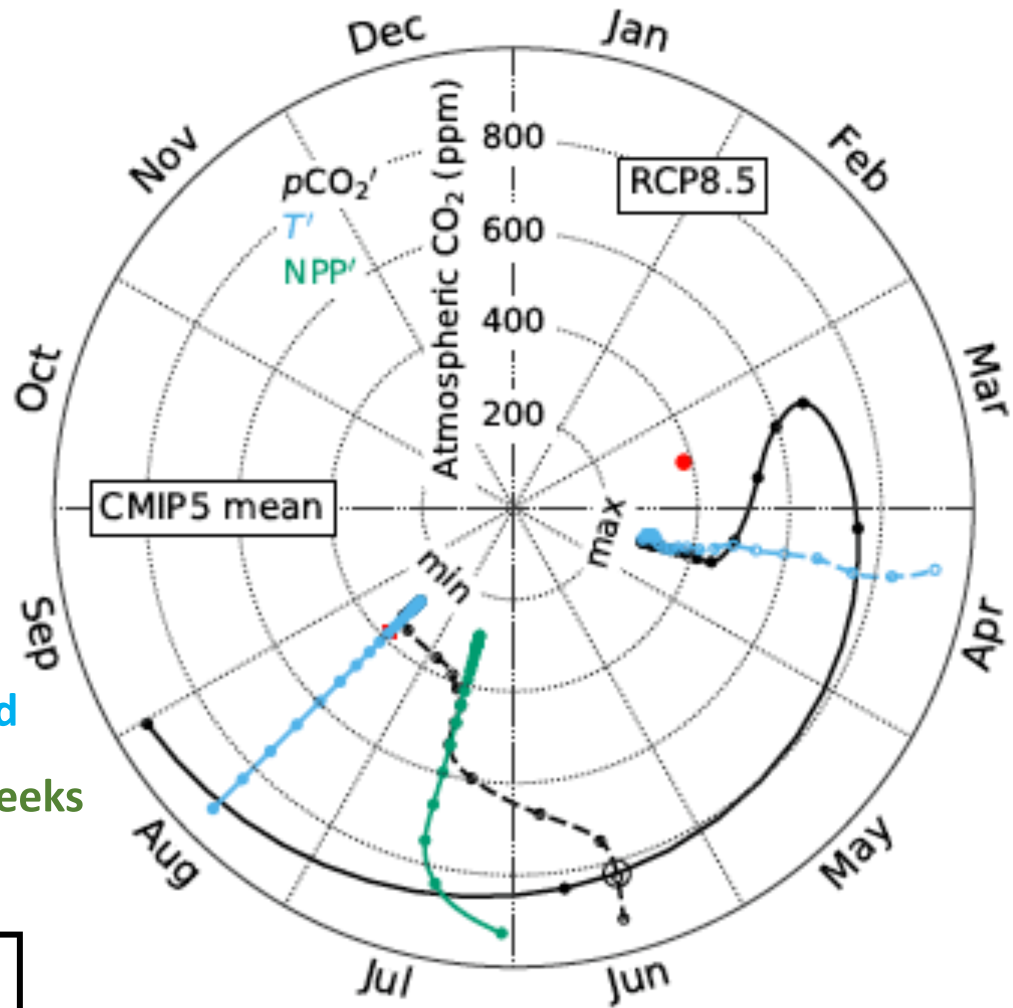



**<u>Under RCP8.5</u>**

**SST min and max months unchanged**

**Phytoplankton NPP max occurs 2-weeks**

**(earlier spring bloom phenology)**

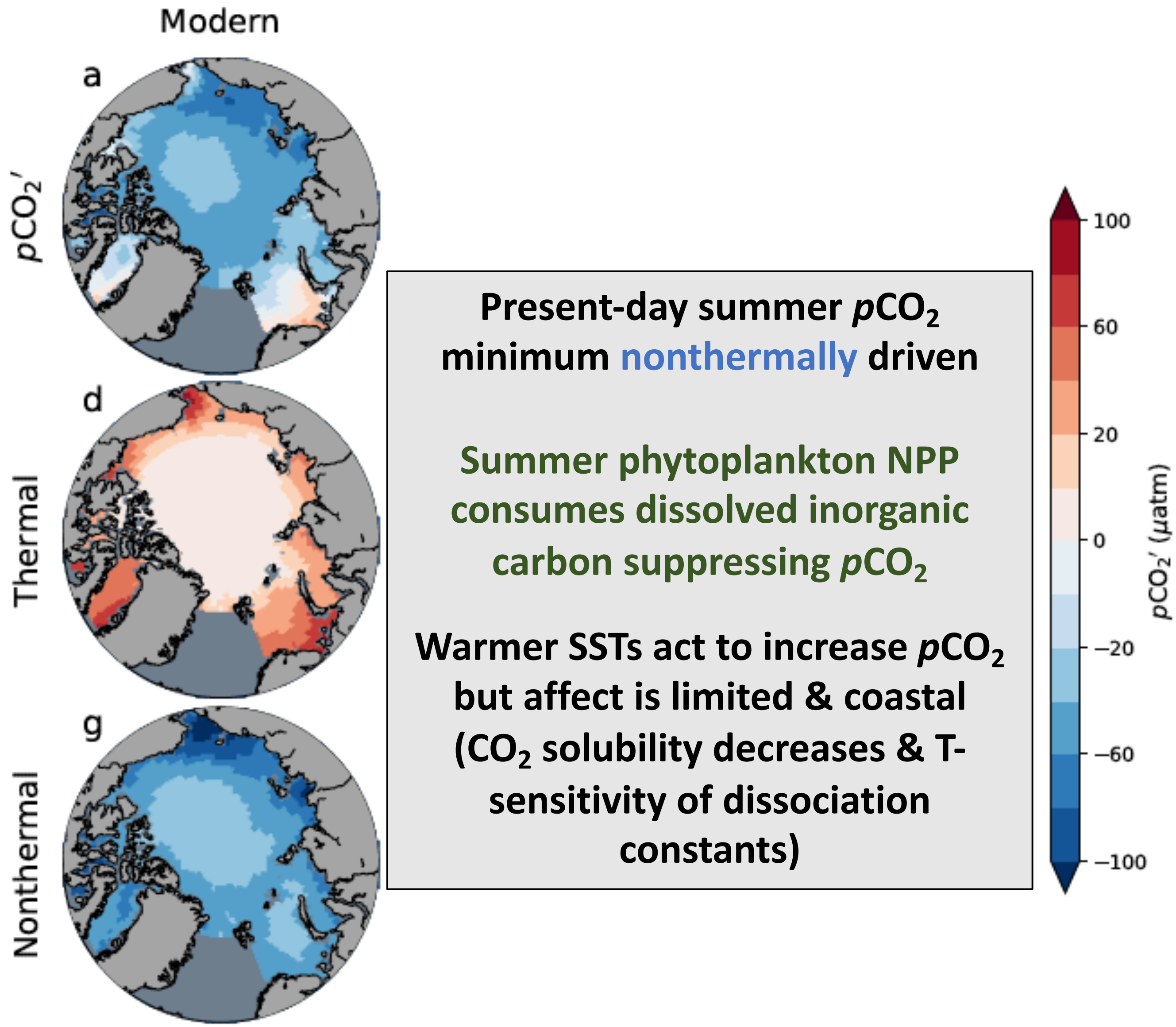
**However…**

**$pCO_2$ max occurs 4-months earlier**

**$pCO_2$ min occurs 2-months later**

**Orr, Kwiatkowski & Pörtner, *Nature* (2022)**

# Current summer seasonal $pCO_2$ minimum biologically driven




CMIP5 mean

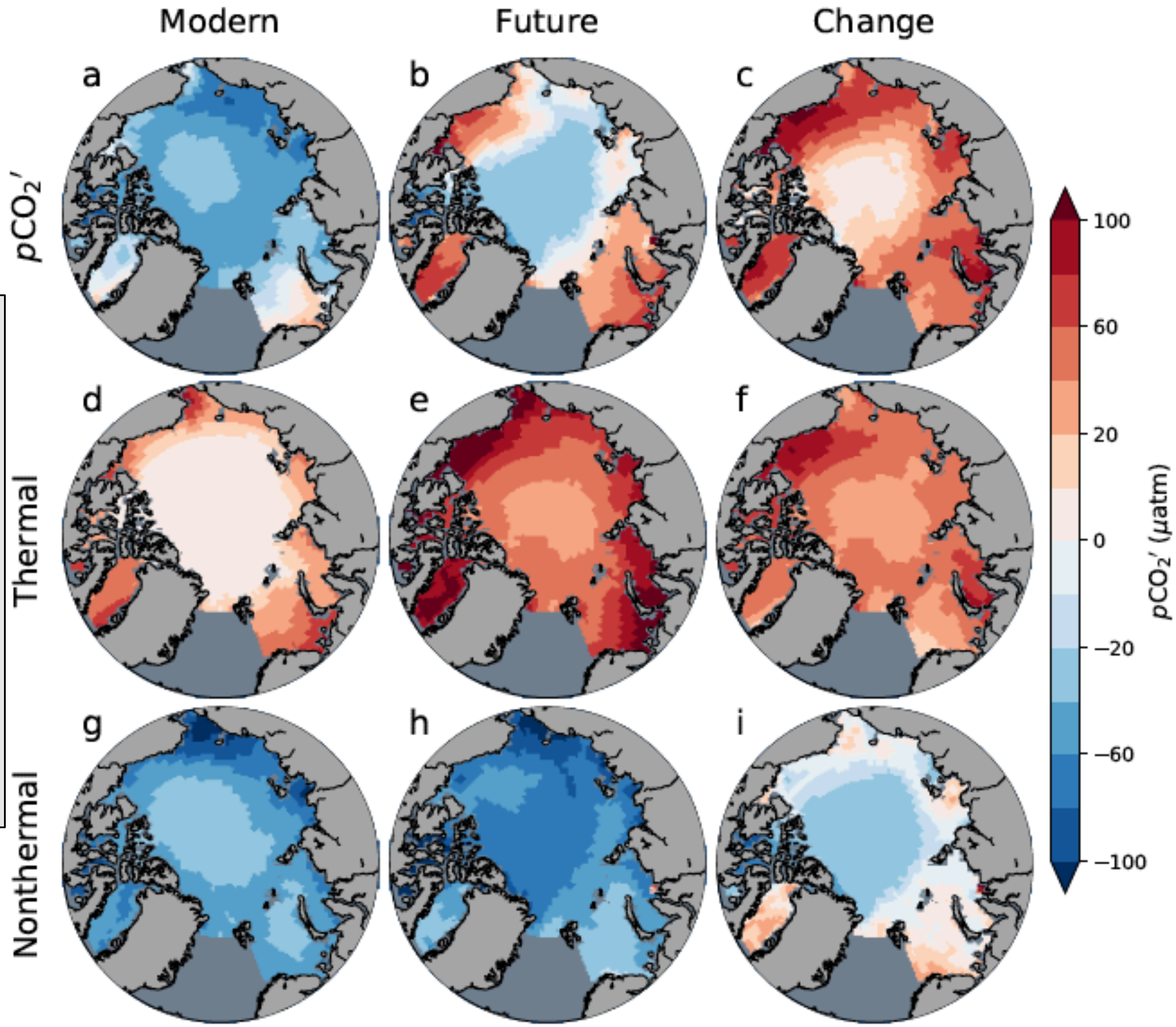
**Present-day summer $pCO_2$ minimum nonthermally driven**

**Summer phytoplankton NPP consumes dissolved inorganic carbon suppressing $pCO_2$**

**Warmer SSTs act to increase $pCO_2$ but affect is limited & coastal ($CO_2$ solubility decreases & T-sensitivity of dissociation constants)**

**Orr, Kwiatkowski & Pörtner, *Nature* (2022)**

# But future summer seasonal $pCO_2$ max is thermally driven




CMIP5 mean

But in future (2091-2100) under high emissions,

**Growth in thermal component overwhelms nonthermal**

- particularly in coastal ocean

Orr, Kwiatkowski & Pörtner, *Nature* (2022)

# But future summer seasonal $pCO_2$ max is thermally driven

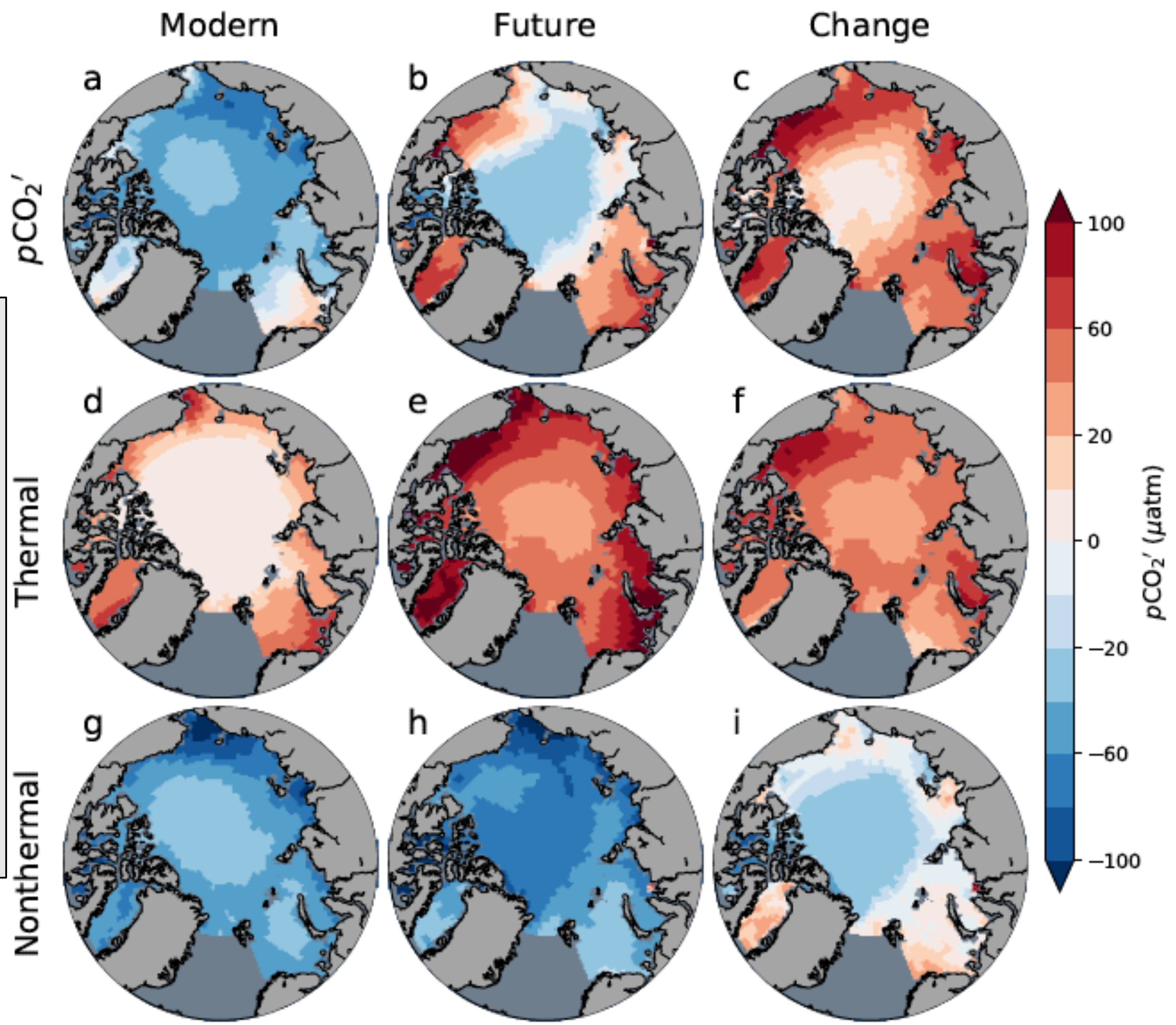
$$\left(\frac{\partial pCO_2}{\partial T}\right)\Delta T$$

↑

**Growth in thermal component is driven by seasonal SST anomalies (not thermal sensitivity)**

**i.e. climate change not ocean carbon uptake**

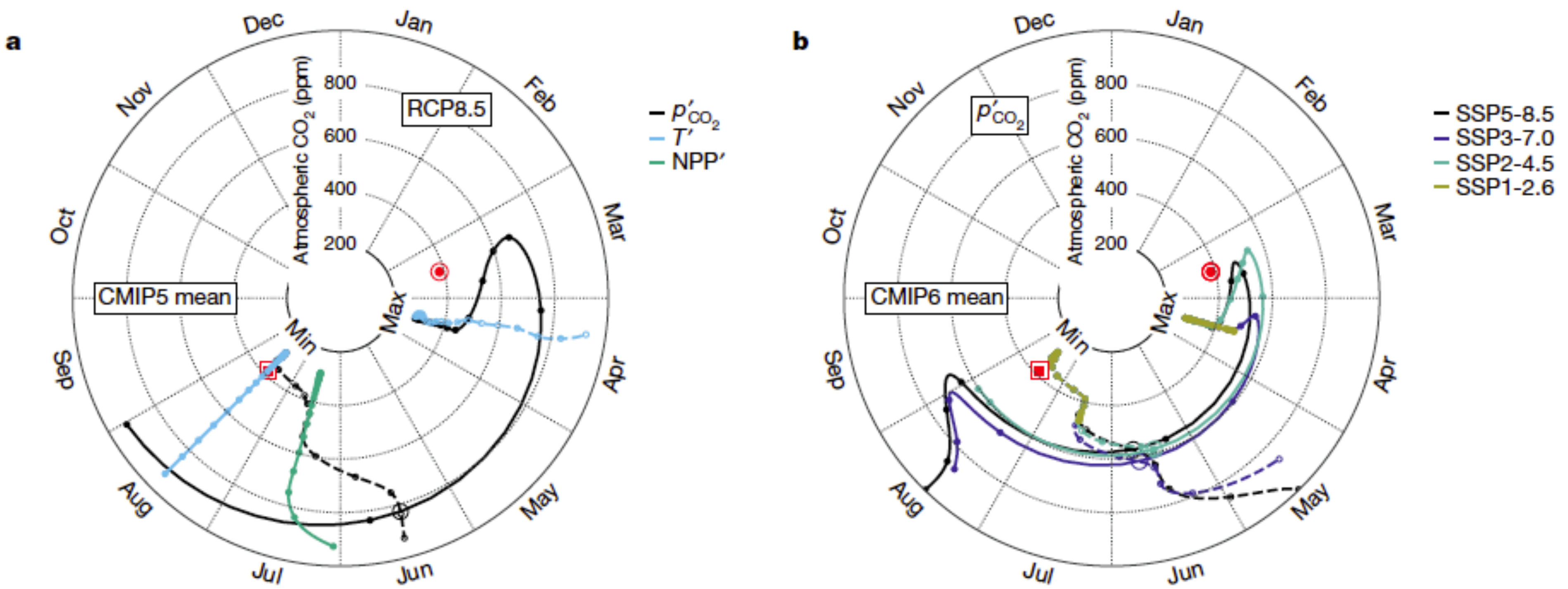
**(unlike global amplification)**




**CMIP5 mean**

**Orr, Kwiatkowski & Pörtner, *Nature* (2022)**

# Similar $pCO_2$ phase shift in CMIP6 (at lower atmospheric $CO_2$)




**Phase shift occurs at 500-600ppm in CMIP6 (compared to 700-800ppm in CMIP5)**

**Models have - Higher ECS**
**- Greater warming**
**- Greater Arctic ice loss**

**Orr, Kwiatkowski & Pörtner, *Nature* (2022)**

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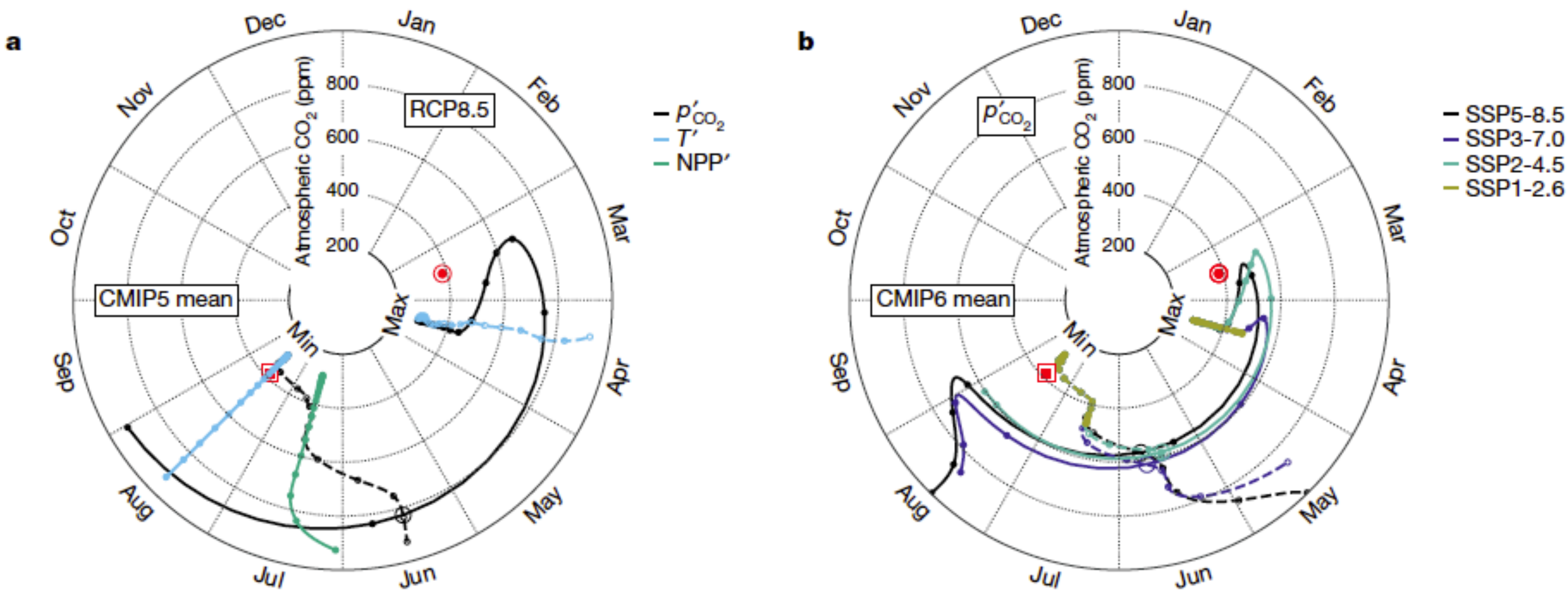



**Phase shift occurs at 500-600ppm in CMIP6 (compared to 700-800ppm in CMIP5)**

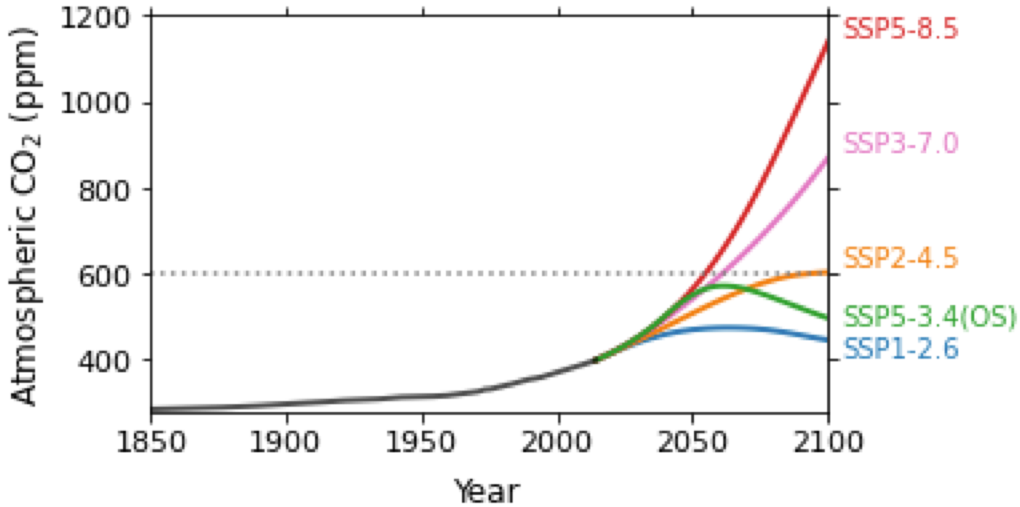
**Models have**
- **Higher ECS**
- **Greater warming**
- **Greater Arctic ice loss**

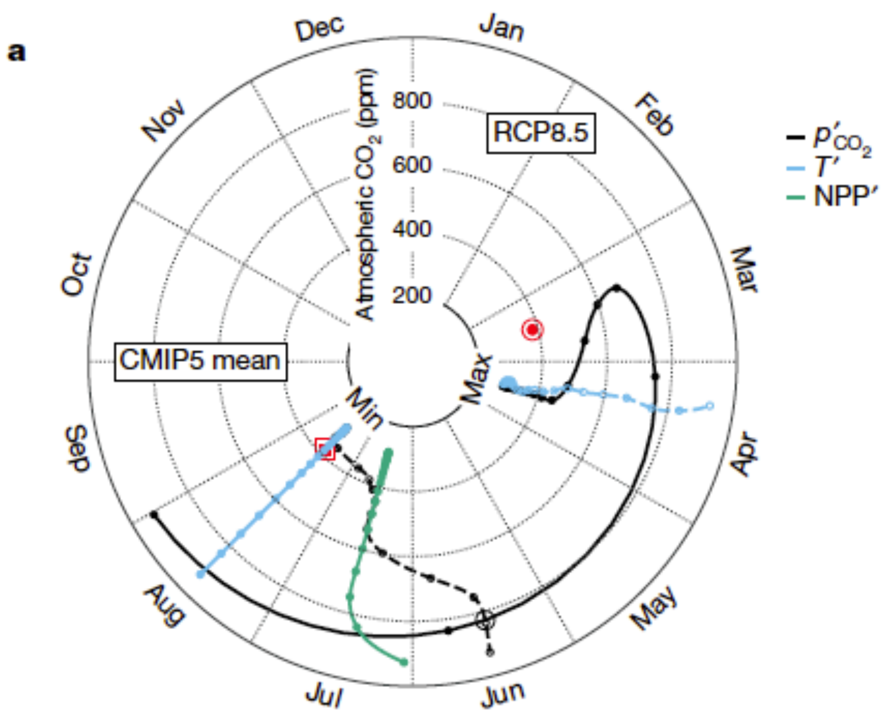
→ **An opportunity to explore reversibility in overshoot scenarios (SSP5-3.4)**

**Orr, Kwiatkowski & Pörtner, *Nature* (2022)**

# Is the change in $p$CO$_2$ seasonality a tipping point/reversible?

**If atmospheric $CO_2$ concentration is reduced does the seasonal cycle return to "normal" and how fast?**




SSP5-3.4(OS) – peak $CO_2$ 570 ppm 2061 then decreases to 500 ppm 2100

**Kwiatkowski & Orr, (*in prep*)**

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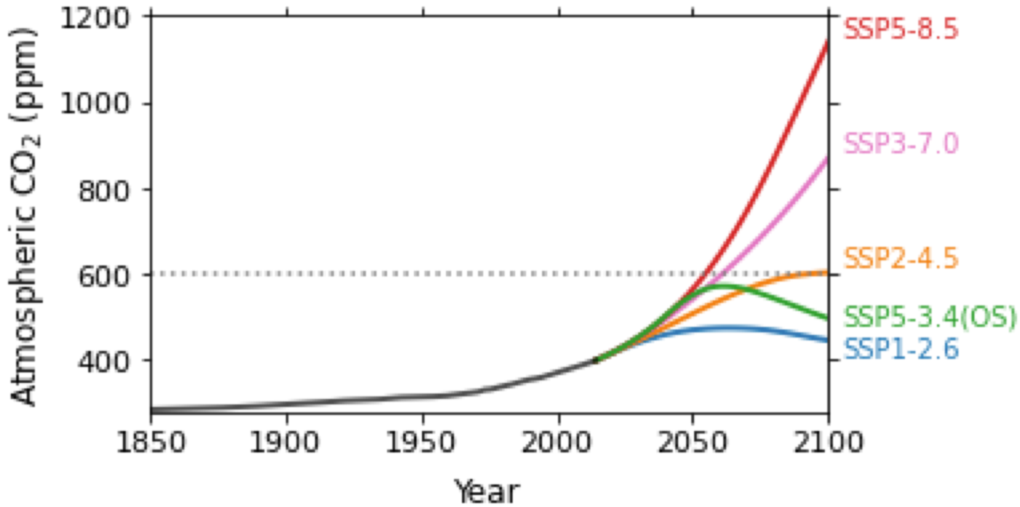


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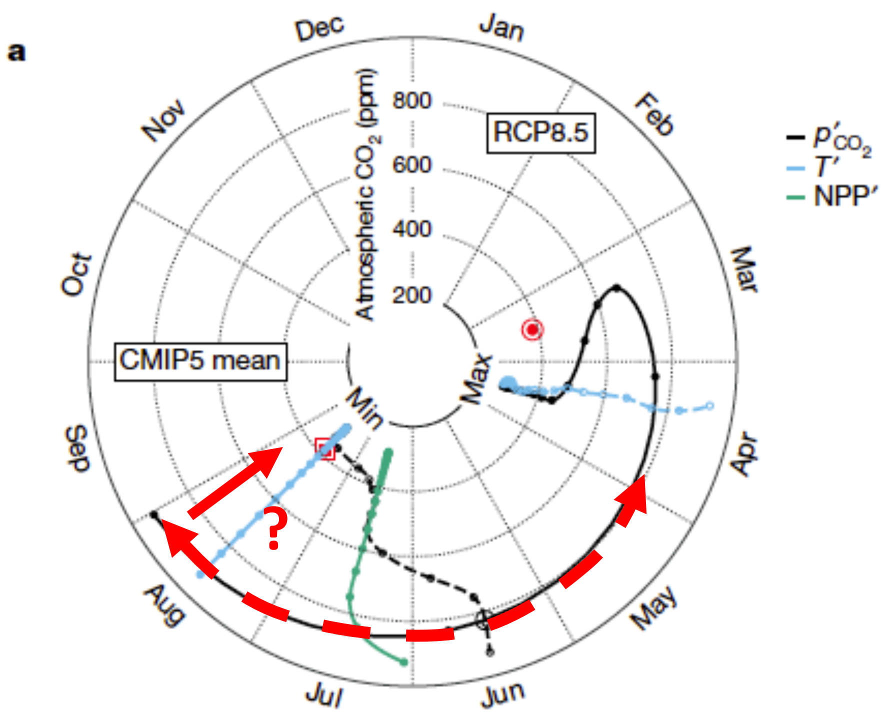
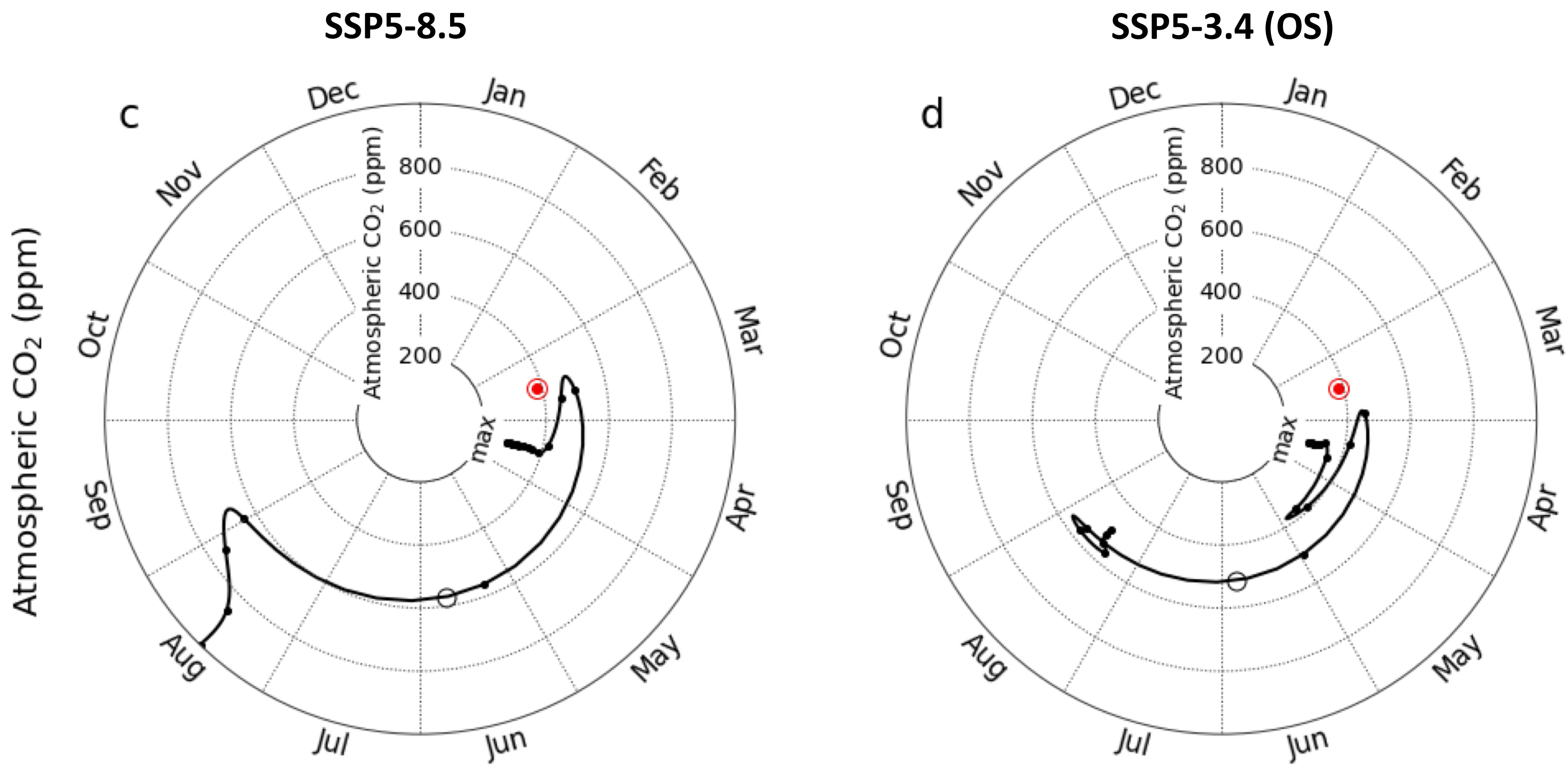



Kwiatkowski & Orr, (*in prep*)

# Limited indication of reversibility in the multi-model mean

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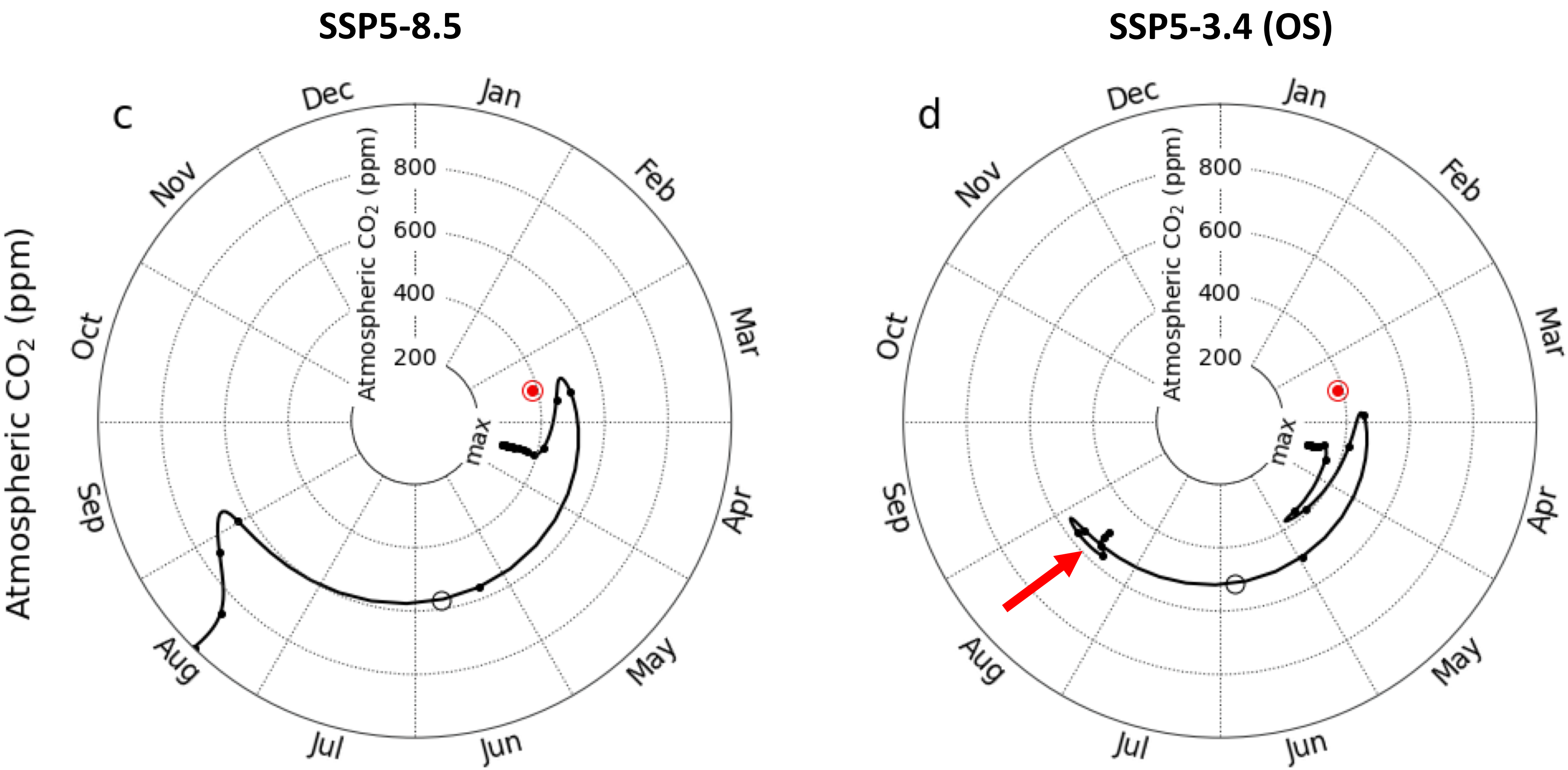
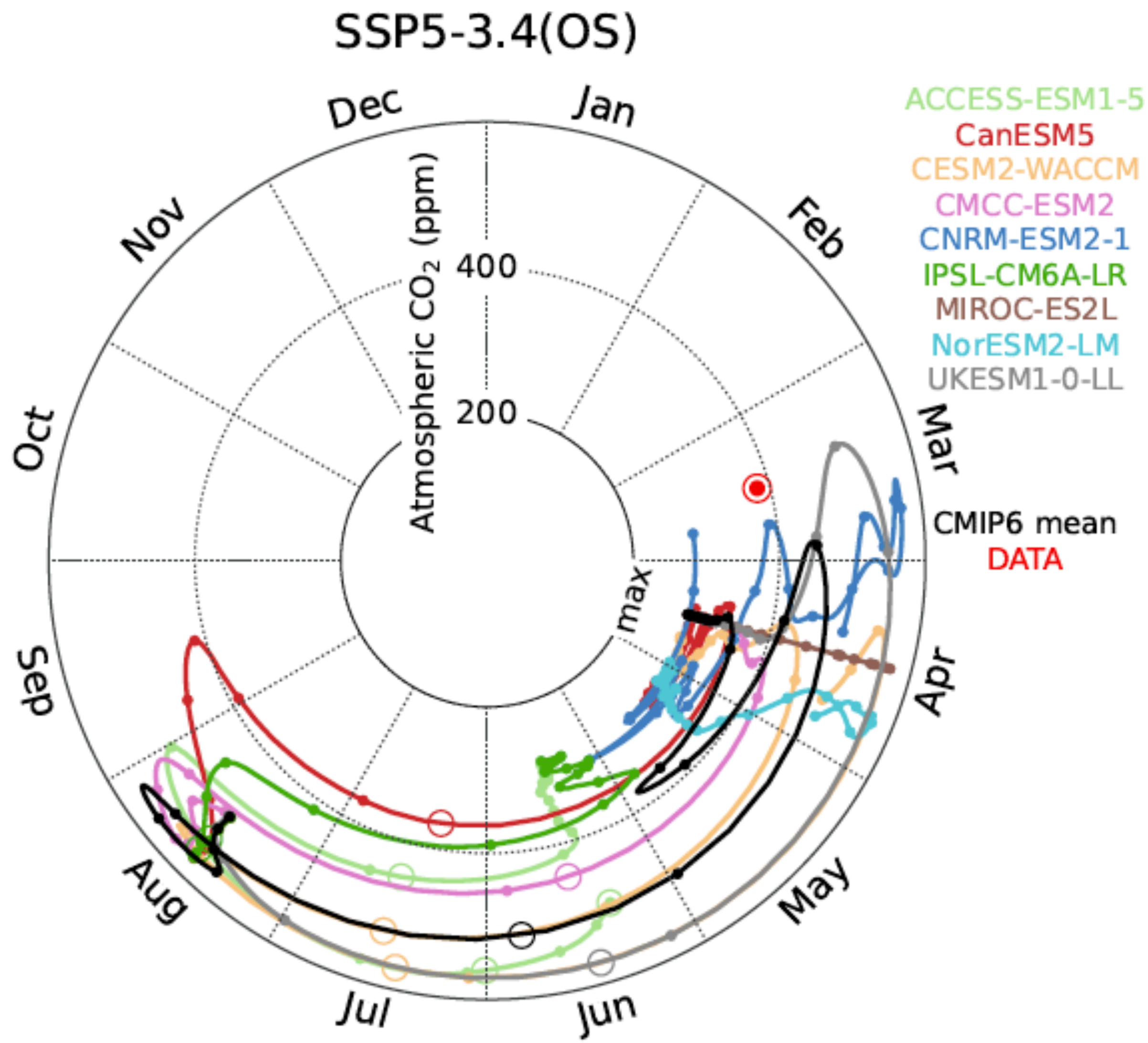



**$p$CO$_2$ max stays in August from 570 to 500 ppm**
**(was in May previously at 500 ppm)**
**Negative hysteresis? Irreversibility?**

**Kwiatkowski & Orr, (*in prep*)**

# Limited indication of reversibility in the multi-model mean: but lots of model uncertainty

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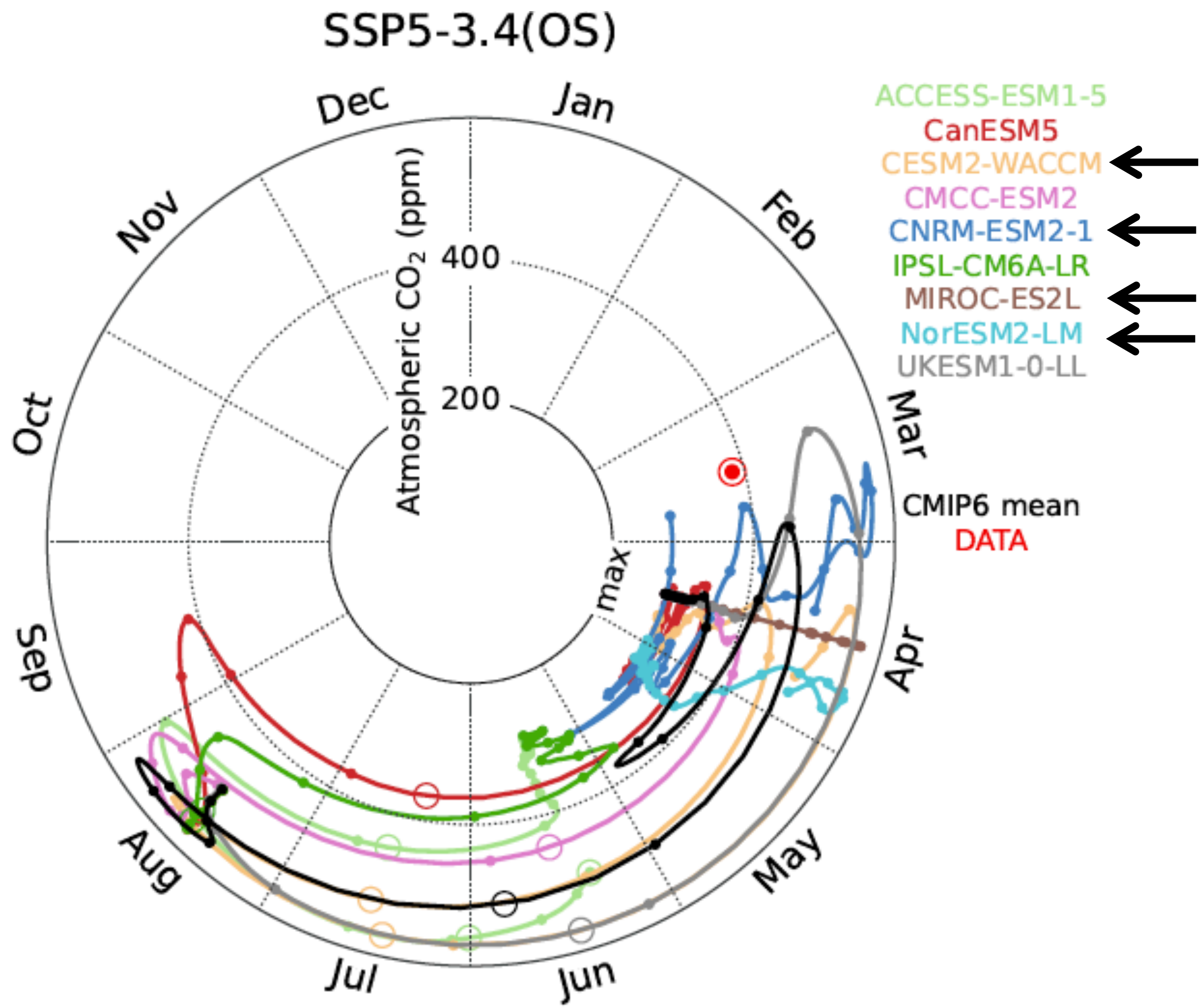
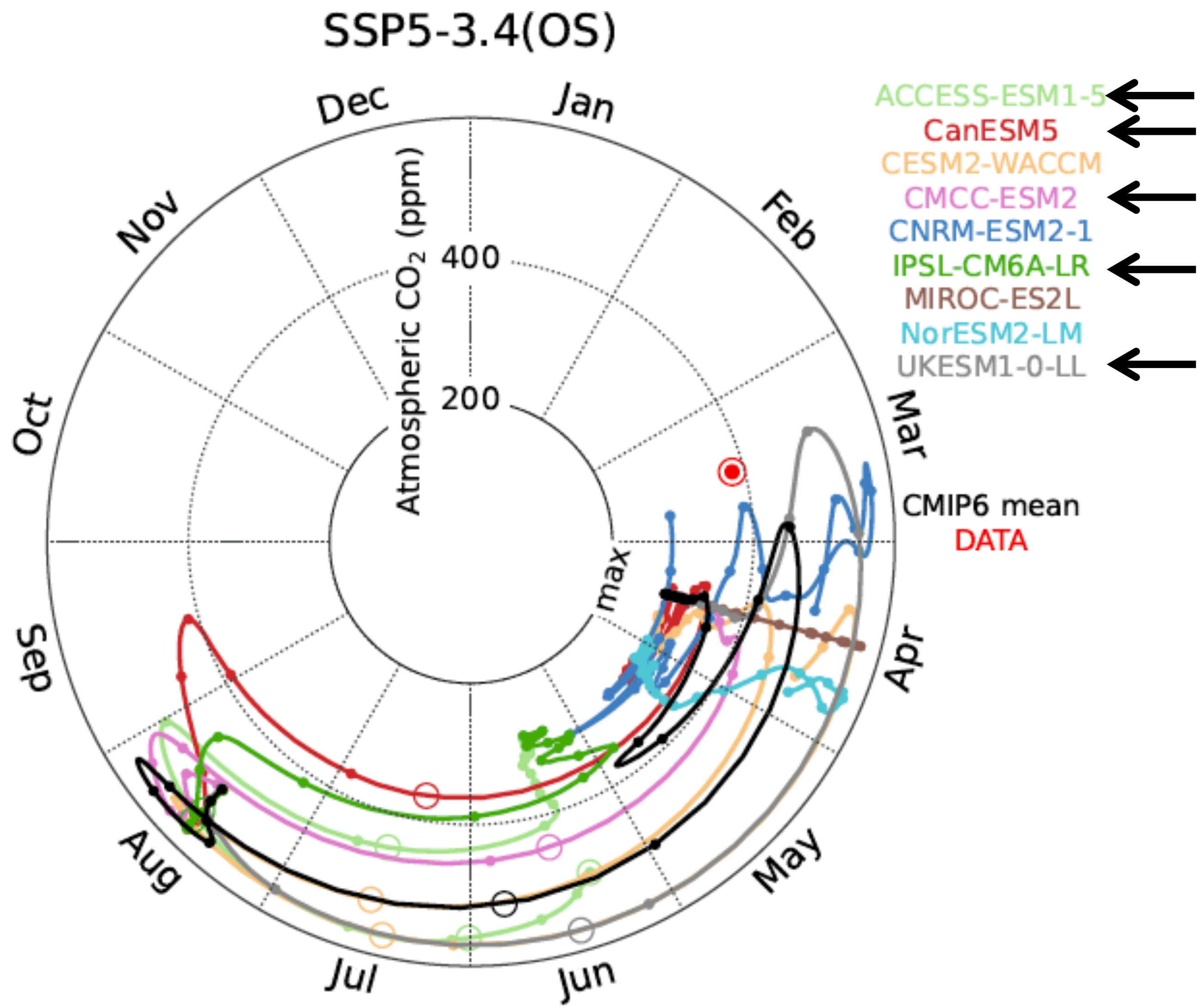



**4/9 models show no/limited phase shift in SSP5-3.4 (OS)**

**Kwiatkowski & Orr, (*in prep*)**

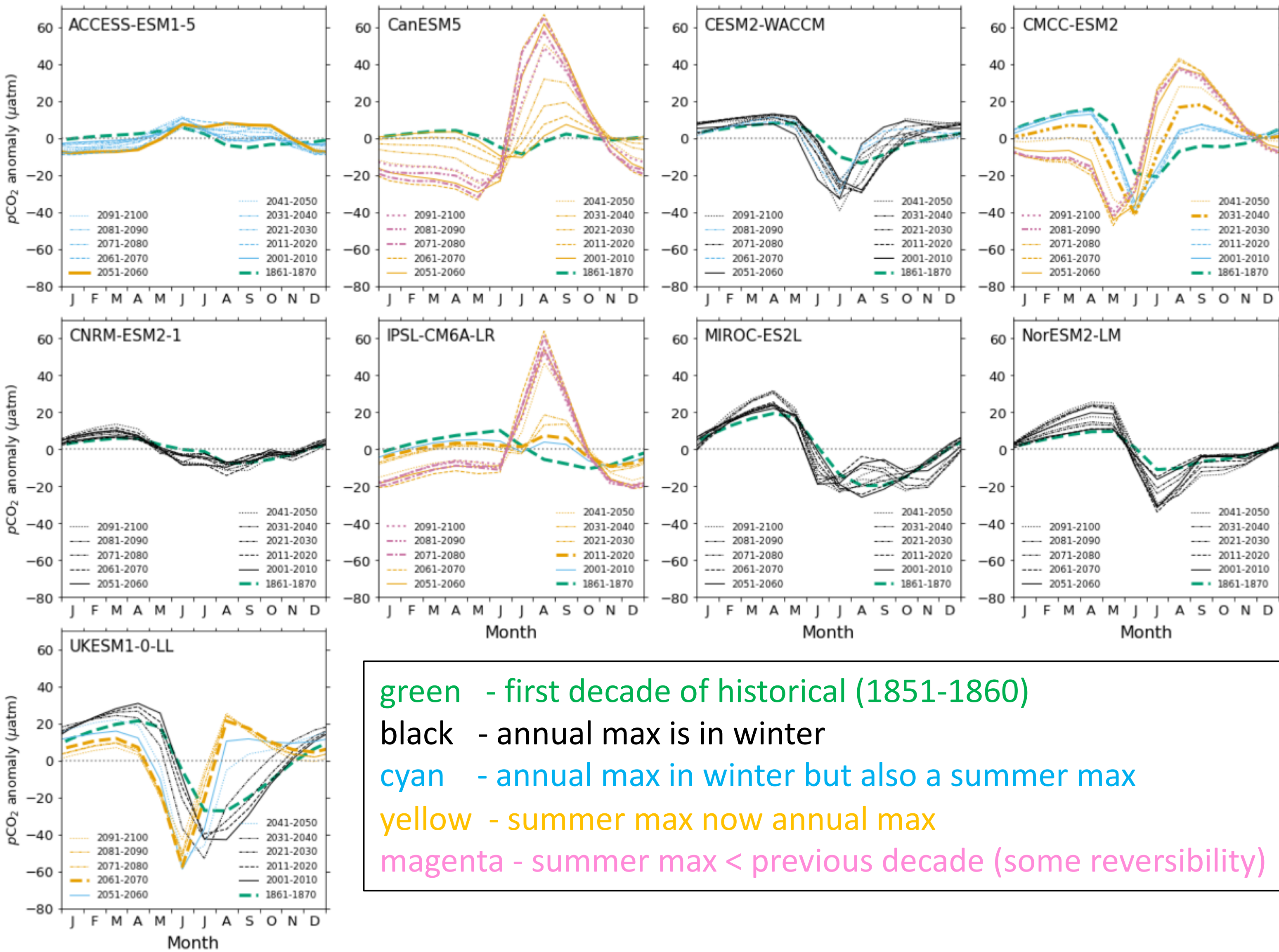
# Limited indication of reversibility in the multi-model mean: but lots of model uncertainty




**5/9 models show major phase shift (with variable reversibility)**

**Kwiatkowski & Orr, (*in prep*)**

# Variable $pCO_2$ phase shift reversibility across CMIP6 models




green - first decade of historical (1851-1860)

black - annual max is in winter

cyan - annual max in winter but also a summer max

yellow - summer max now annual max

magenta - summer max < previous decade (some reversibility)

**Kwiatkowski & Orr, (*in prep*)**

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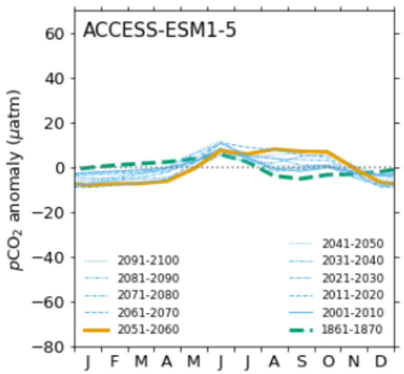
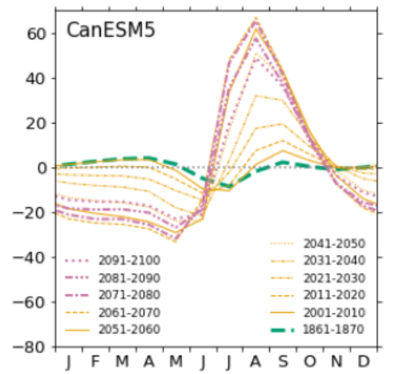
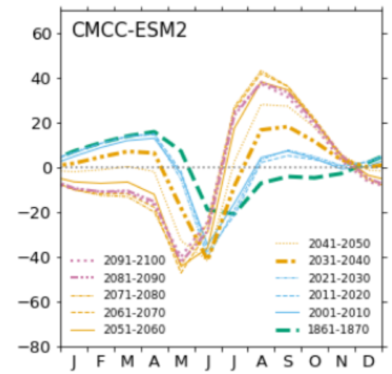
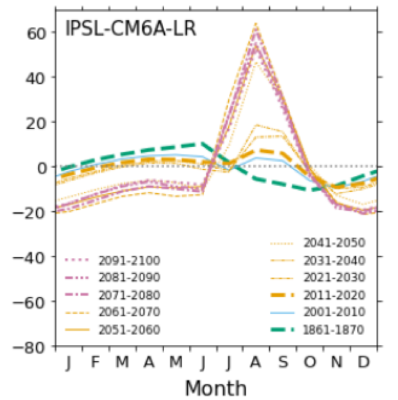
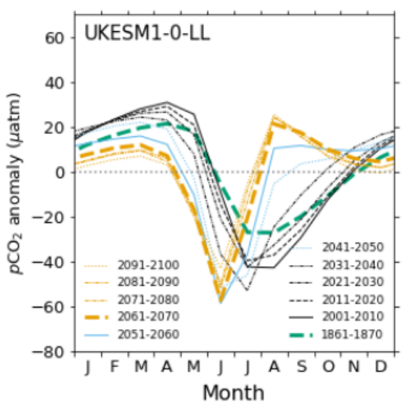



**5 models where the summer max becomes annual max**

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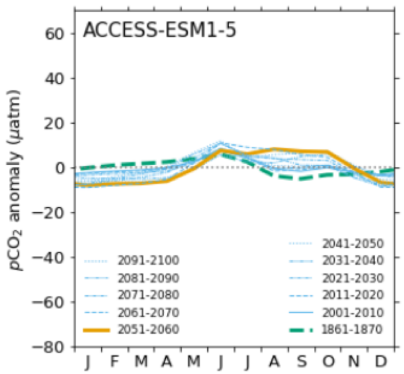
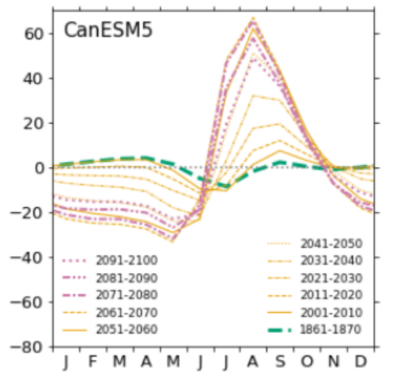
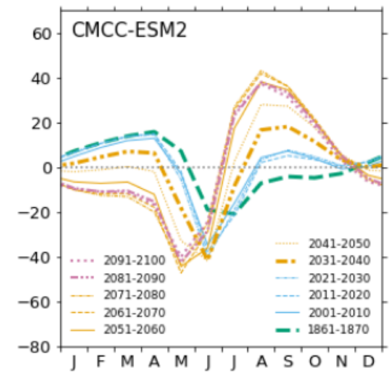
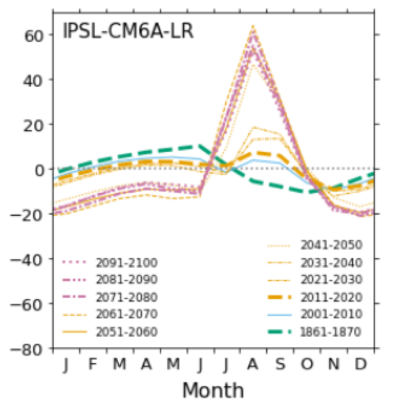
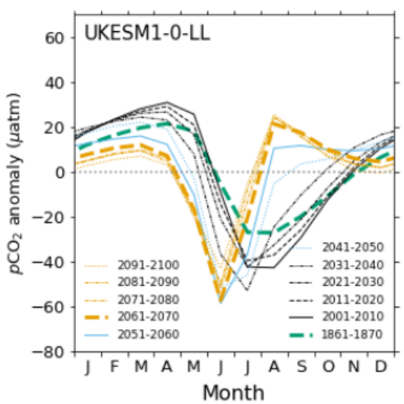


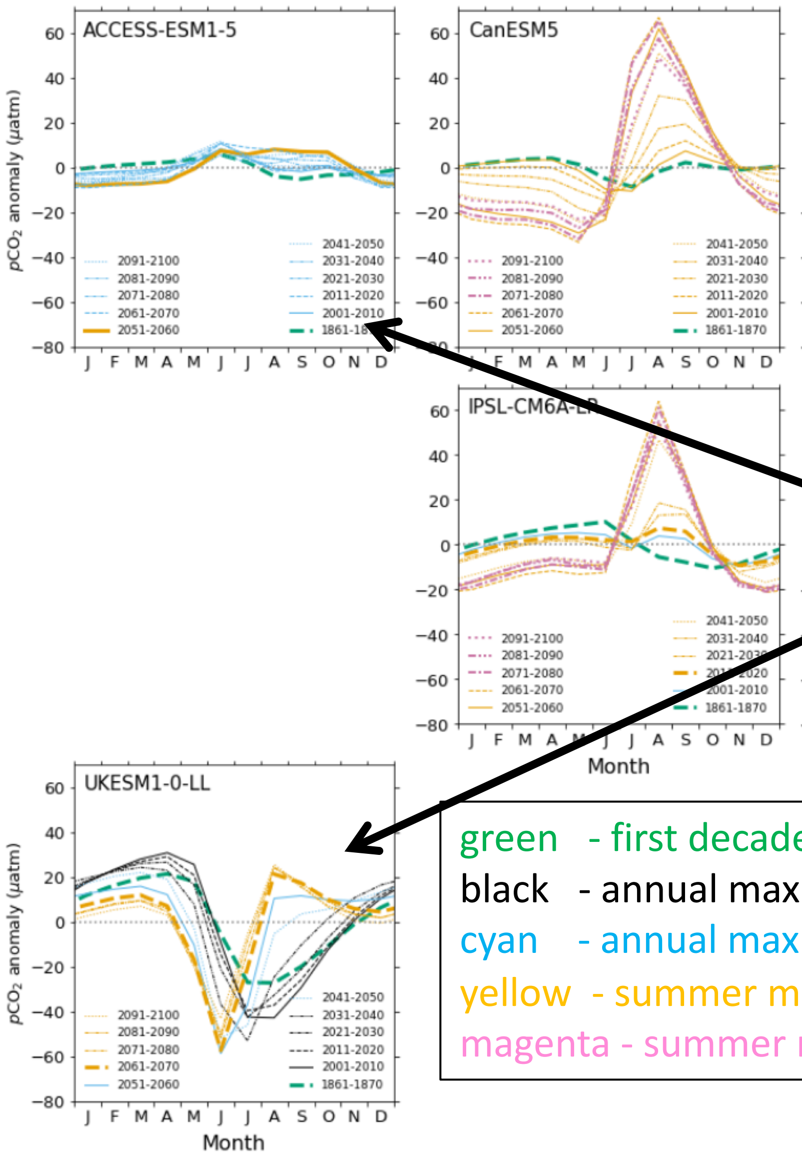

**3/5 show declines in summer $pCO_2$ max as atmospheric $CO_2$ declines (reversibility with negative hysteresis?)**

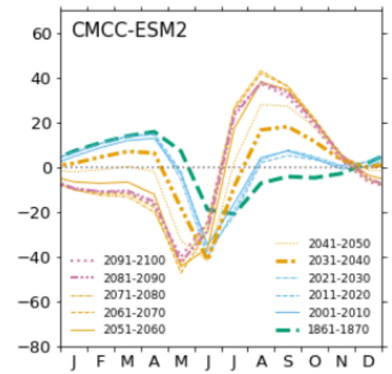



green - first decade of historical (1851-1860)
black - annual max is in winter
cyan - annual max in winter but also a summer max
yellow - summer max now annual max
magenta - summer max < previous decade (some reversibility)

**Kwiatkowski & Orr, (*in prep*)**

# Variable $pCO_2$ phase shift reversibility across CMIP6 models



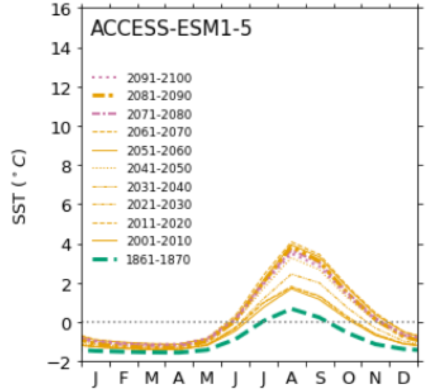



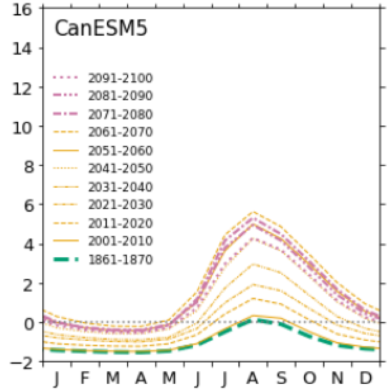

**2/5 show consistent summer $pCO_2$ max as atmospheric $CO_2$ declines (irreversibility)**

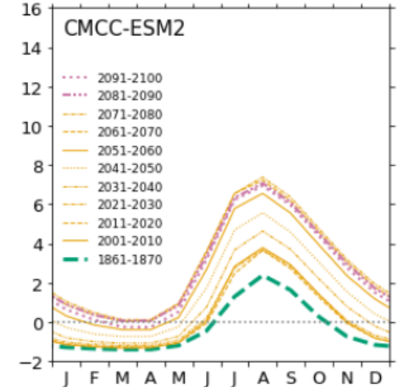
green - first decade of historical (1851-1860)
black - annual max is in winter
cyan - annual max in winter but also a summer max
yellow - summer max now annual max
magenta - summer max < previous decade (some reversibility)

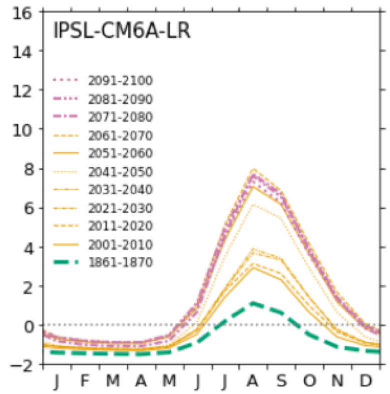
**Kwiatkowski & Orr, (*in prep*)**

# Extent of SST amplitude declines (with declining $CO_2$) appear to explain the reversibility

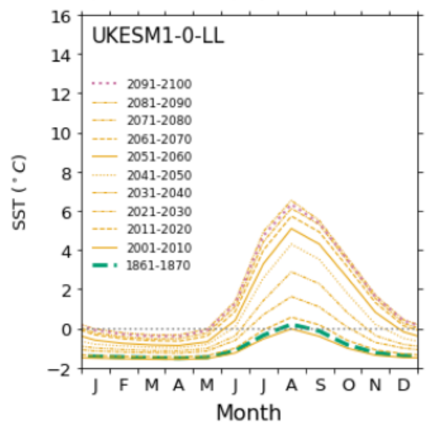


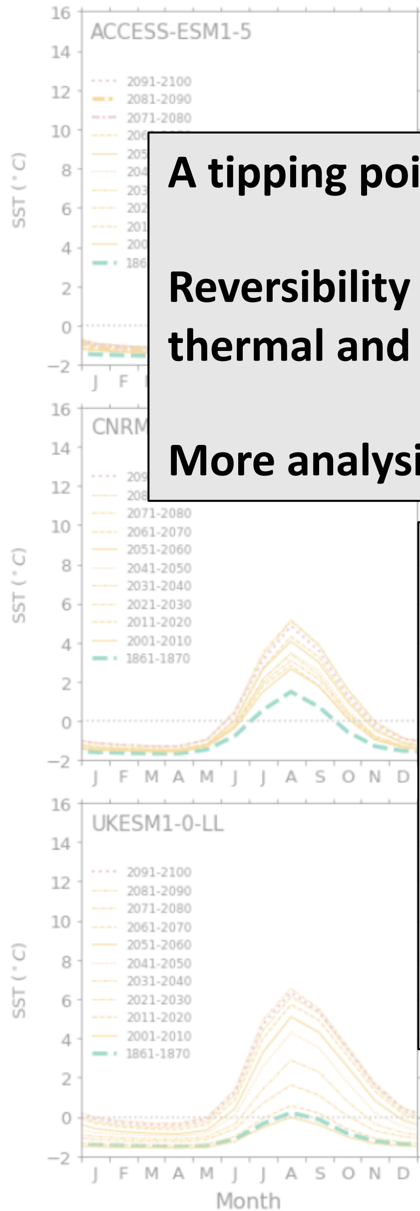

**The models with greatest SST amplitude reductions are those with greatest *p*$CO_2$ reversibility**




green - first decade of historical (1851-1860)
yellow - summer SST max > previous decade
magenta - summer SST max < previous decade (some reversibility)

**Kwiatkowski & Orr, (*in prep*)**

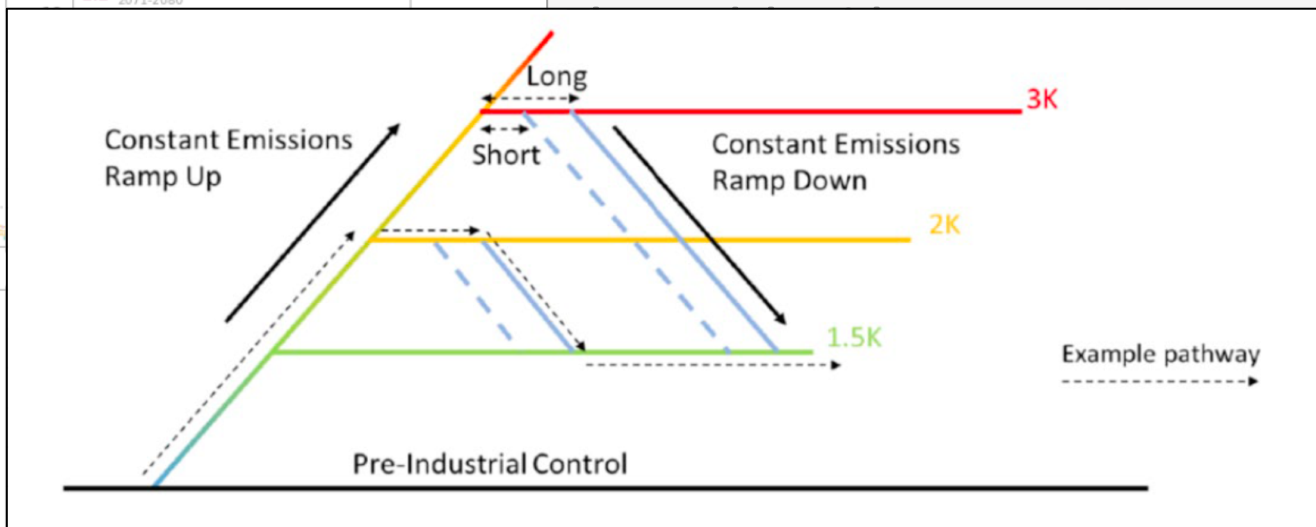
# Extent of SST amplitude declines (with declining $CO_2$) appear to explain the reversibility




**A tipping point cascade, initiated by Arctic sea ice loss?**

**Reversibility determined by sea ice recovery and the balance between thermal and nonthermal (planktonic) drivers of the *p*$CO_2$ seasonal cycle?**

**More analysis required, <u>more overshoot scenarios would be very helpful</u>**



# Conclusions and future perspectives

**Many abrupt changes in ESM ocean biogeochemistry projections**
**…but few, established tipping elements/points & limited assessment of reversibility and early warning indicators in ESMs**

**Arctic Ocean *p*$CO_2$ seasonal cycle reorganization caused by a shift in opposing thermal/biological drivers under climate change**

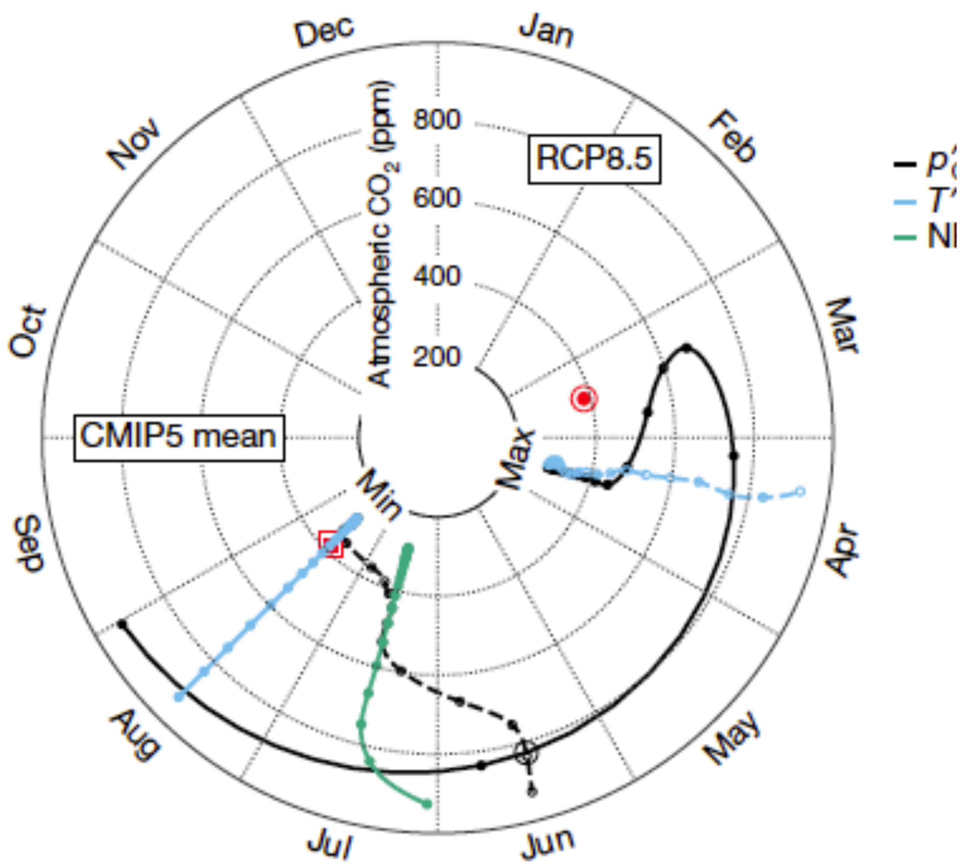
**May represent part of a sea ice driven tipping point cascade**

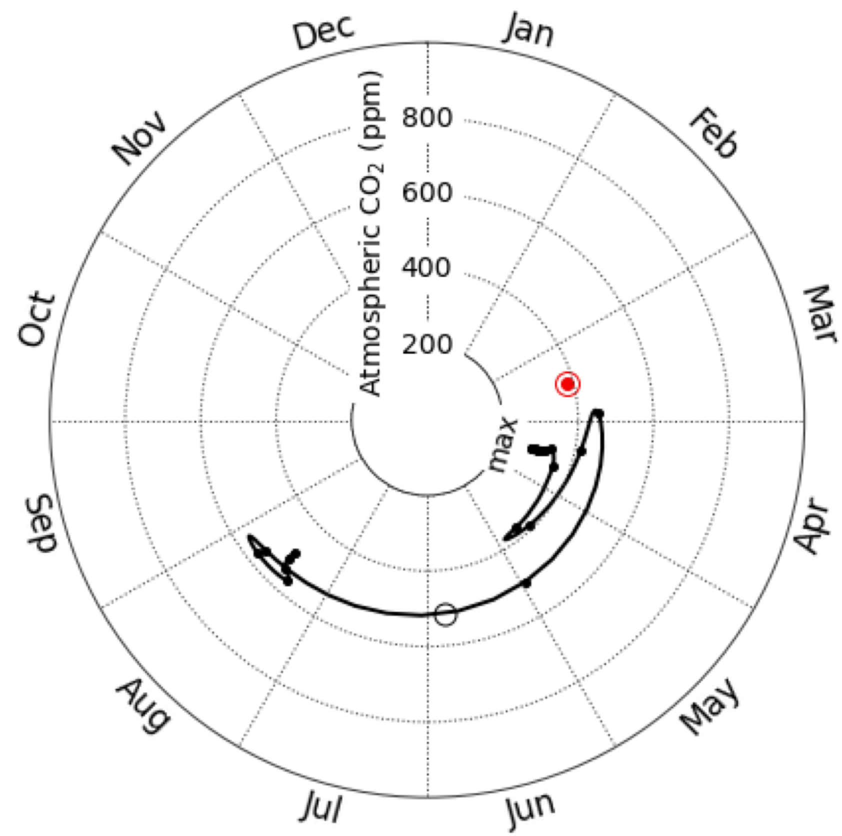
**Reversibility & hysteresis very model dependent in SSP5-3.4 overshoot scenario**

**Further OBGC tipping point assessments would benefit from harmonized protocols that cover a range in peak radiative forcing and negative emissions**

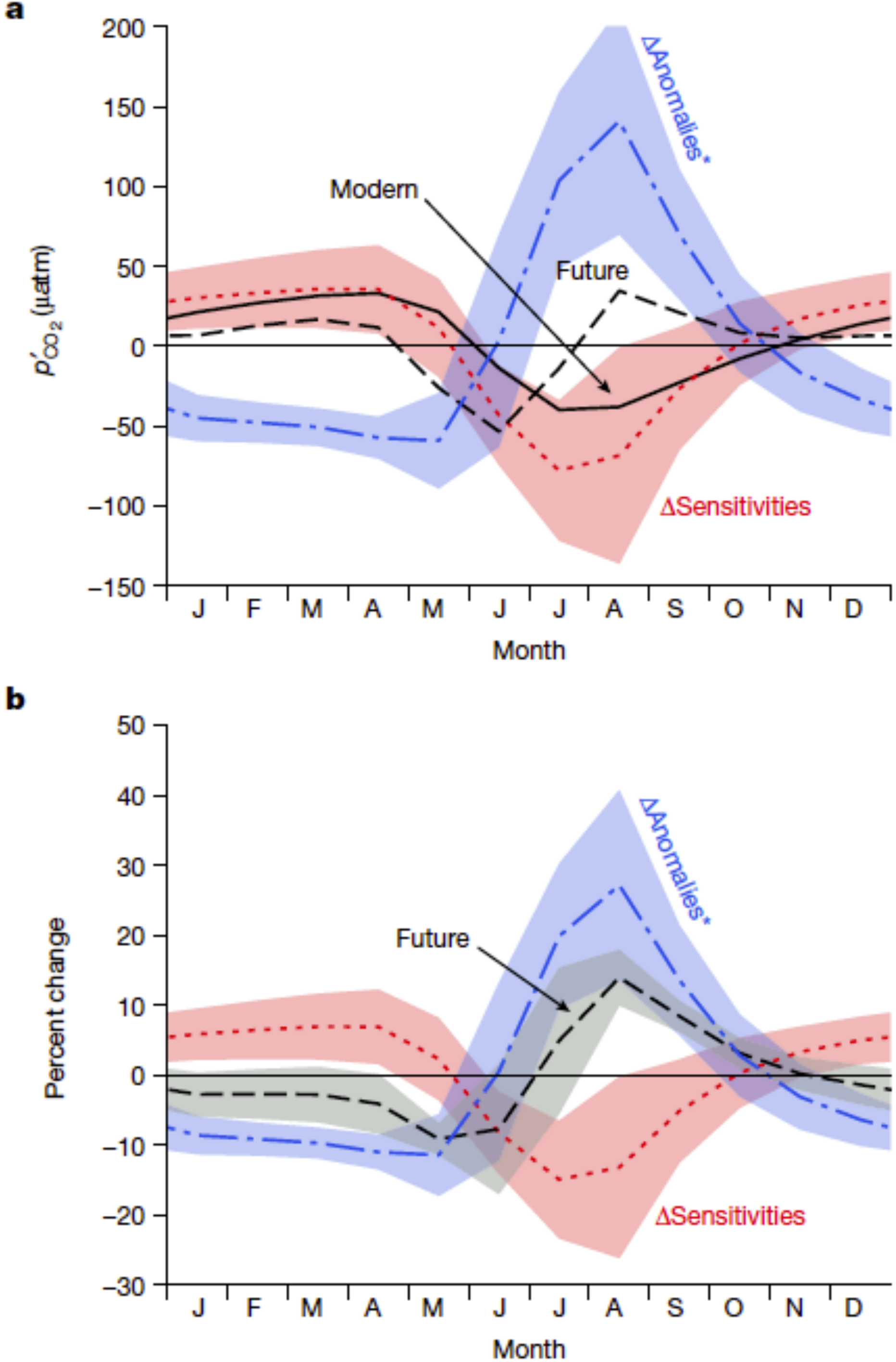
**New projects with tipping point focus: TIPESM, OptimESM, TIPMIP**

# Any questions?



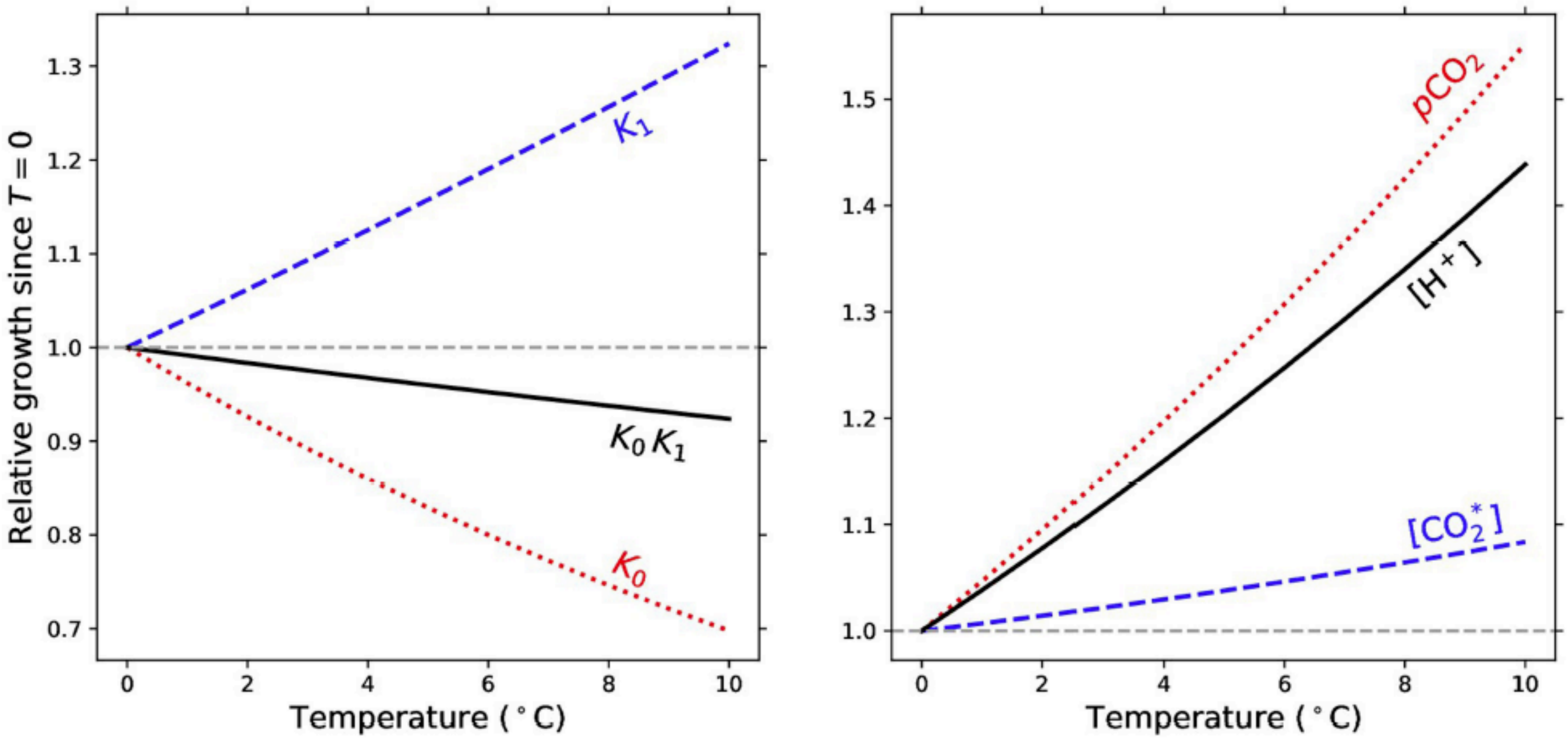
# Additional slides

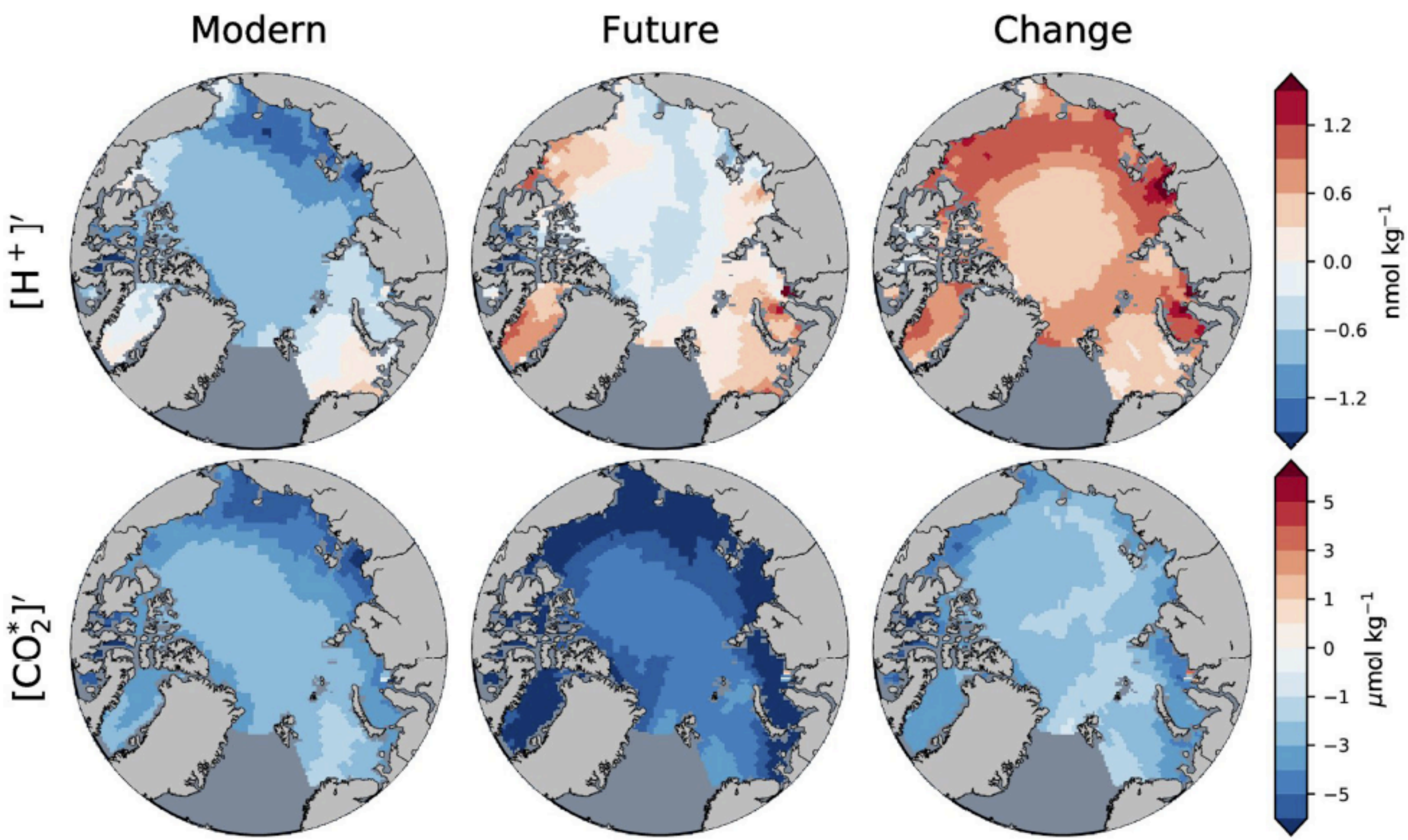

a
b
$p'_{CO_2}$ (μatm)
Percent change
Modern
Future
ΔAnomalies*
ΔSensitivities
J F M A M J J A S O N D
Month

# The temperature sensitivity of $pCO_2$, $[CO_2^*]$ and $[H^+]$

$$[CO_2^*] = K_0 C_f p_{CO_2}$$

$$p_{CO_2} = \frac{[H^+][HCO_3^-]}{C_f K_0 K_1}$$

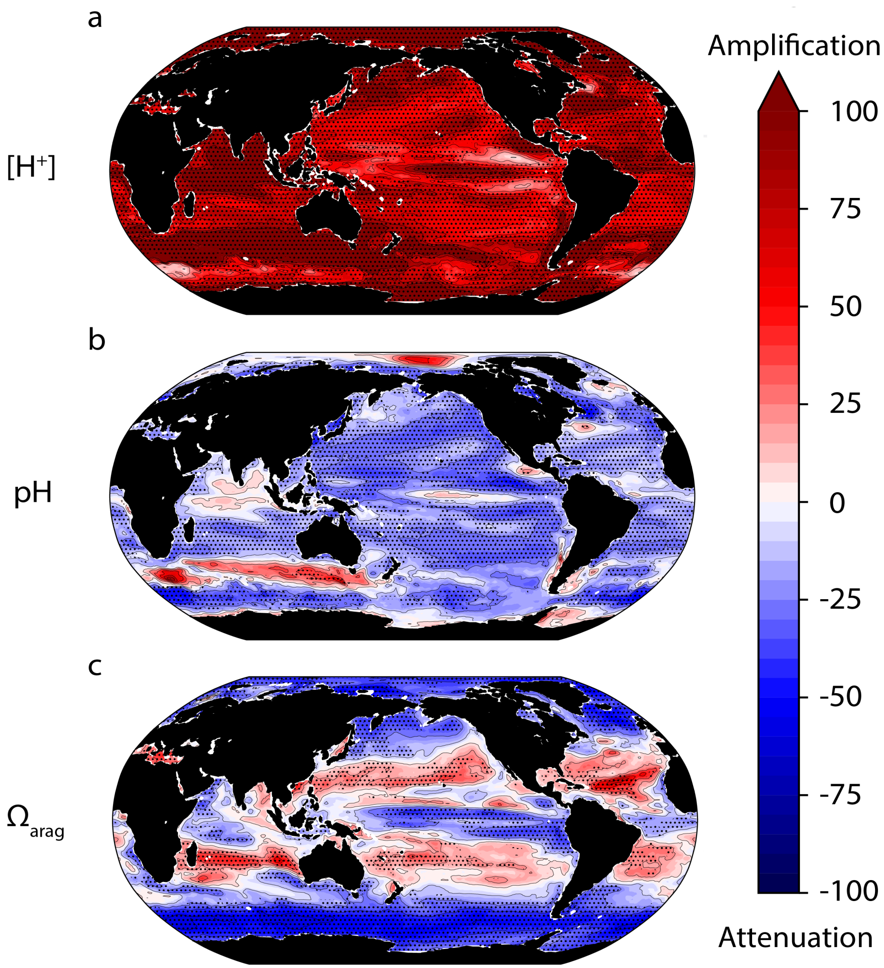




Modern
Future
Change
$[H^+]'$
$[CO_2^*]'$
nmol kg$^{-1}$
1.2
0.6
0.0
−0.6
−1.2
μmol kg$^{-1}$
5
3
1
0
−1
−3
−5

# Temporal variability: Changing seasonal amplitudes of the $CO_2$ system

***21st century change in peak-to-peak seasonality (%)***



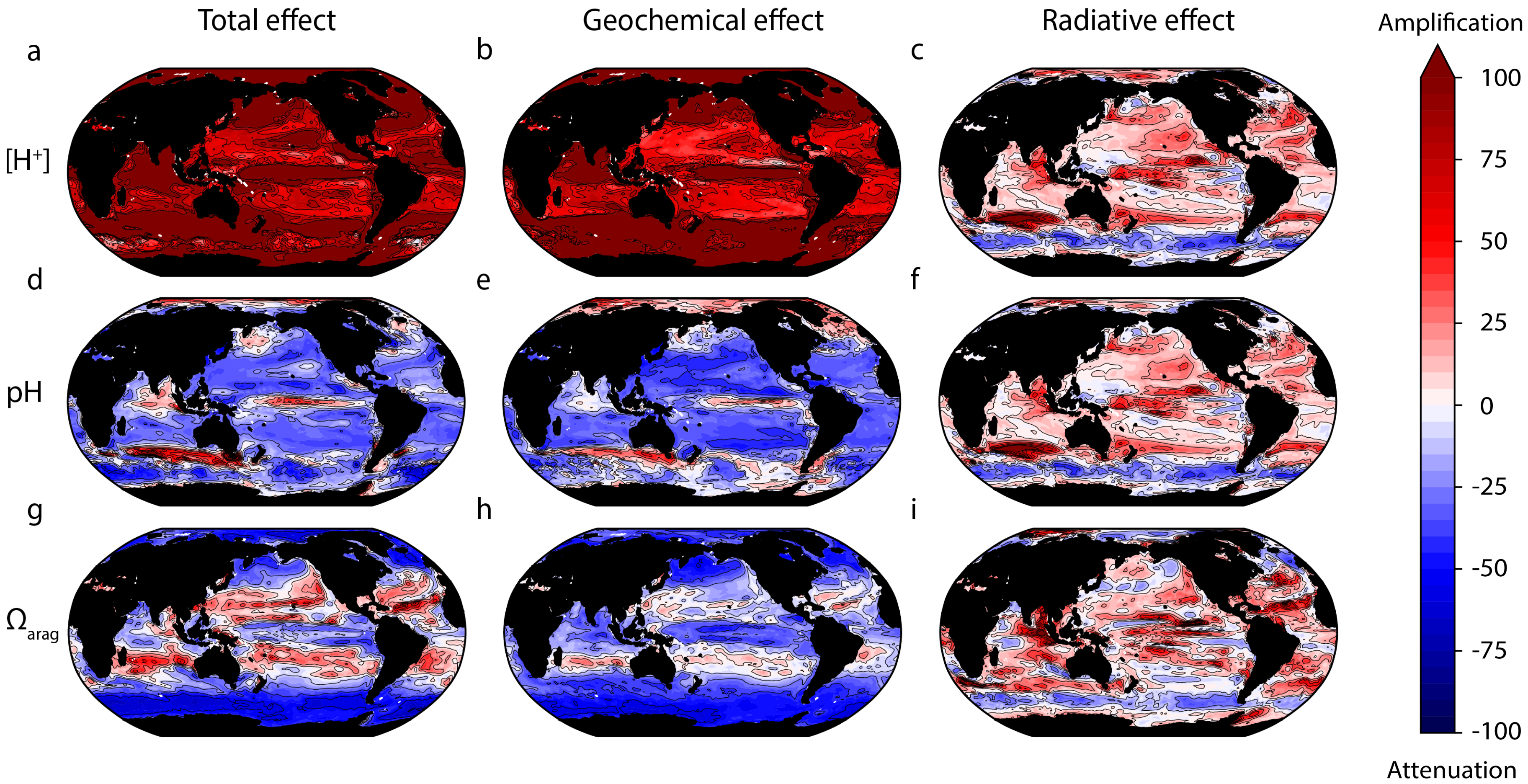

- **Large amplification (+88%) of the $[H^+]$ seasonal cycle**
- **Mild attenuation (-16%) of the pH seasonal cycle**
- **Regional amplification/attenuation of the $\Omega_{arag}$ seasonal cycle**

**- Supported by recent observations, Landschützer et al. (2018)**

**Kwiatkowski & Orr, *Nature Climate Change* (2018)**
**Kwiatkowski et al., *Biogeosciences* (2020)**

# Temporal variability: Changing seasonal amplitudes of the $CO_2$ system

**Seasonality change driven by the geochemical effect, except for $\Omega_{arag}$ where the radiative/climate effect dominates in the subtropics**




**Kwiatkowski & Orr, *Nature Climate Change* (2018)**

Tipping point: *“A level of change in system properties beyond which a system reorganizes, often in a non-linear manner, and does not return to the initial state even if the drivers of the change are abated.”*
(IPCC, SROCC, 2019)