Ocean tipping points - an overview

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Acknowledgments:
COMFORT project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 820989. The work reflects only the author's/authors' view; the European Commission and their executive agency are not responsible for any use that may be made of the information the work contains.

RCN project FORSTERKNINGSMIDLER No. 309382
RCN project INES No. 270061
RCN project KeyCLIM No. 295046

Sigma2 HPC project NN2980K
Sigma2 Storage project NS2980K

BCCR Earth system modelling support
BCCR Strategic project LOES

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Thank you for the invitation!

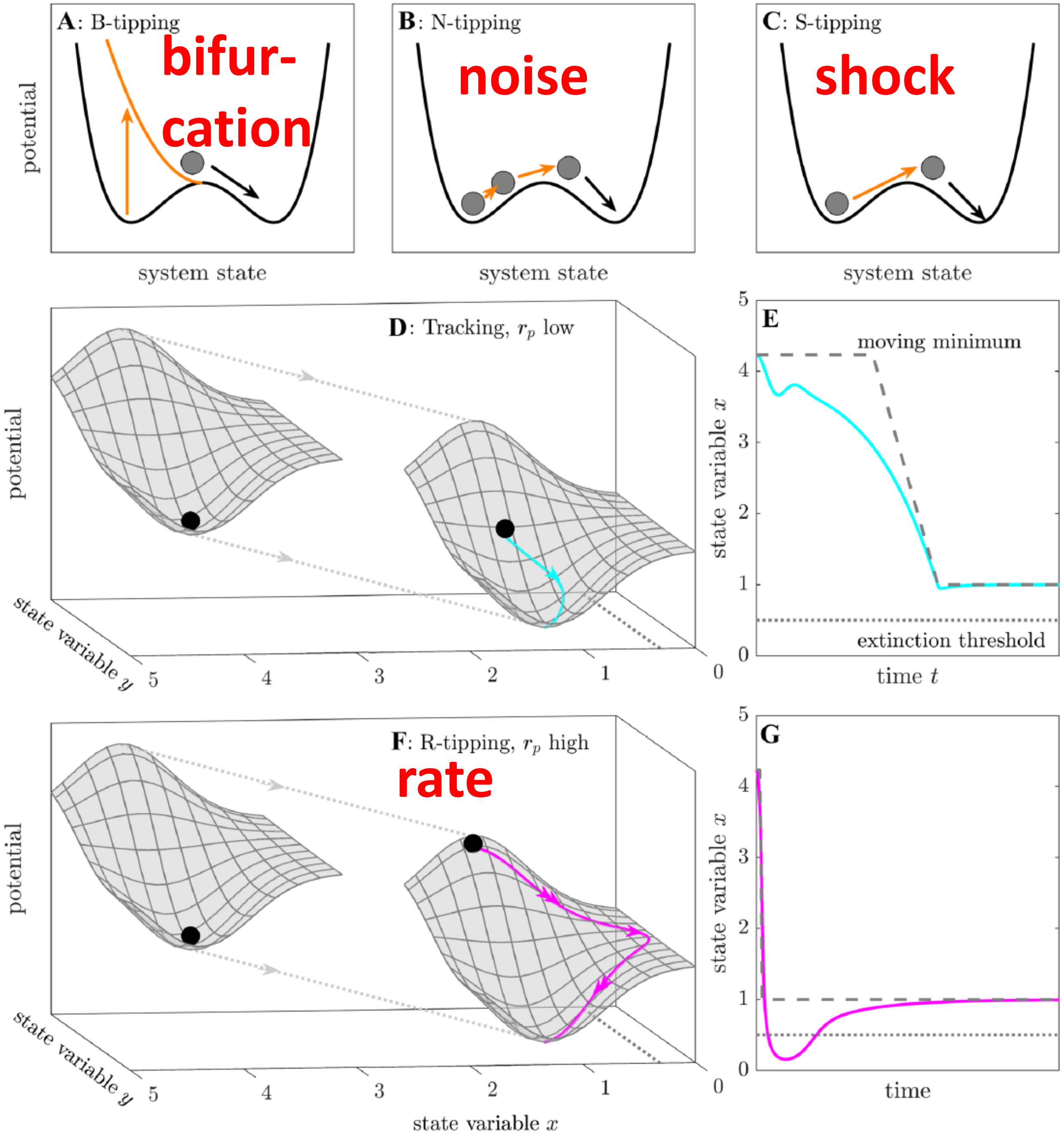
Tipping point: *(IPCC SROCC Glossary, 2019)*

A ***level of change in system properties***
beyond which a system reorganises, often in a non-linear manner,
and does not return to the initial state even if the drivers of the change are abated.
For the climate system, the term refers to a critical threshold at which global or regional climate changes from one stable state to another stable state.
Tipping points are also used when referring to impact:
the term can imply that an impact tipping point is (about to be) reached in a natural or human system.

Regime shift: *(Biggs et al., Ecology and Society, 2018, https://doi.org/10.5751/ES-10264-2303092018)*

Changes in ecosystems and social-ecological systems (SESs) are often experienced as relatively slow and incremental, but sometimes ***dramatically large, persistent, and often unexpected changes*** take place = regime shifts.

Tipping types



Vanselov et al., 2021
Theoretical Ecology
https://doi.org/10.1007/s12080-021-00522-w

cup = system properties
ball = state of system

R-tipping - rate induced

Claire Kiers, PhD, 2020,
https://doi.org/10.17615/2d03-0651
"… Here we get two distinct outcomes: the dishes come with the tablecloth or they get left behind.
The deciding factor between these outcomes is not how far the tablecloth moves, but how fast. …"

… easier to find cases for regime shifts than to quantify the thresholds …

The great ocean conveyor….

“Wally” Broecker

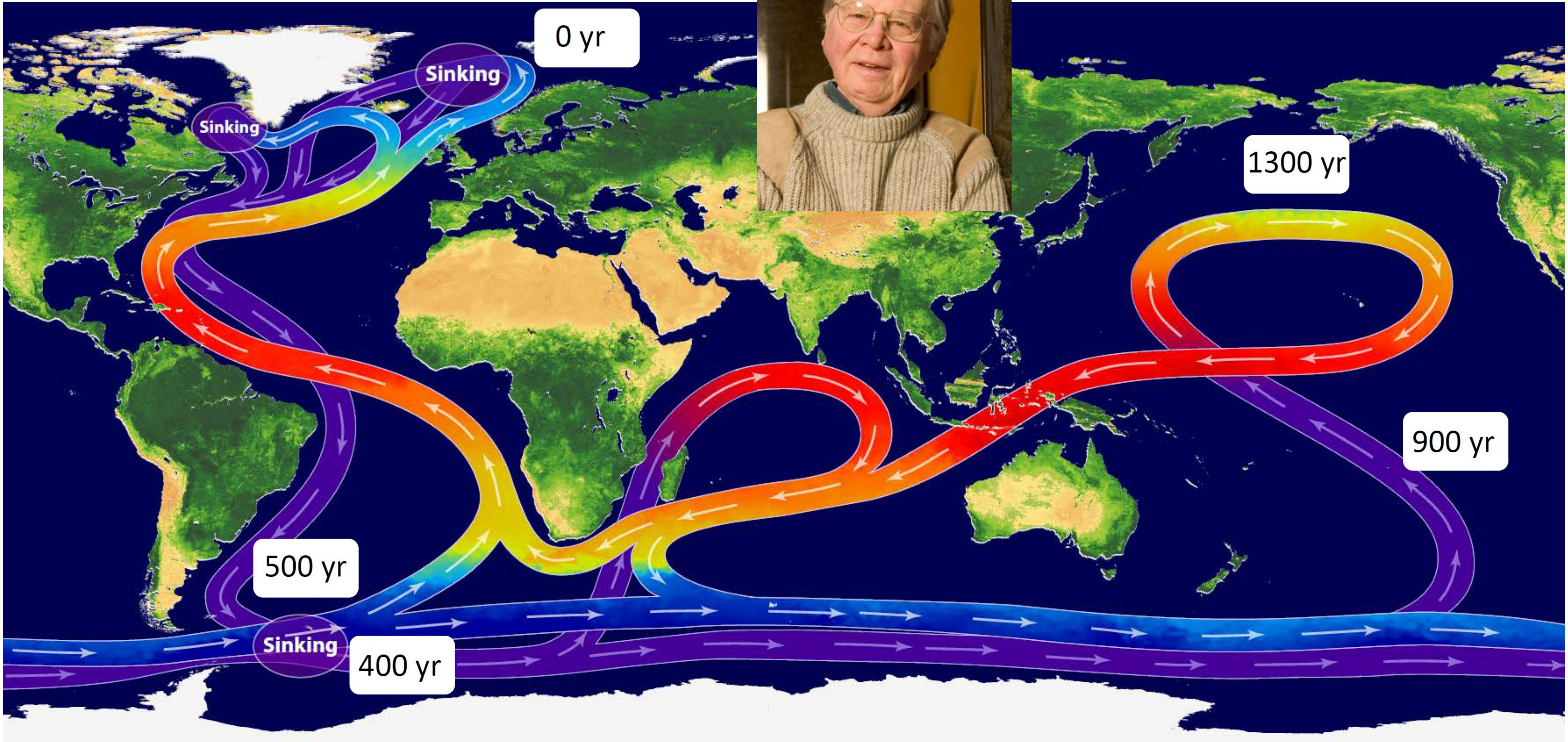
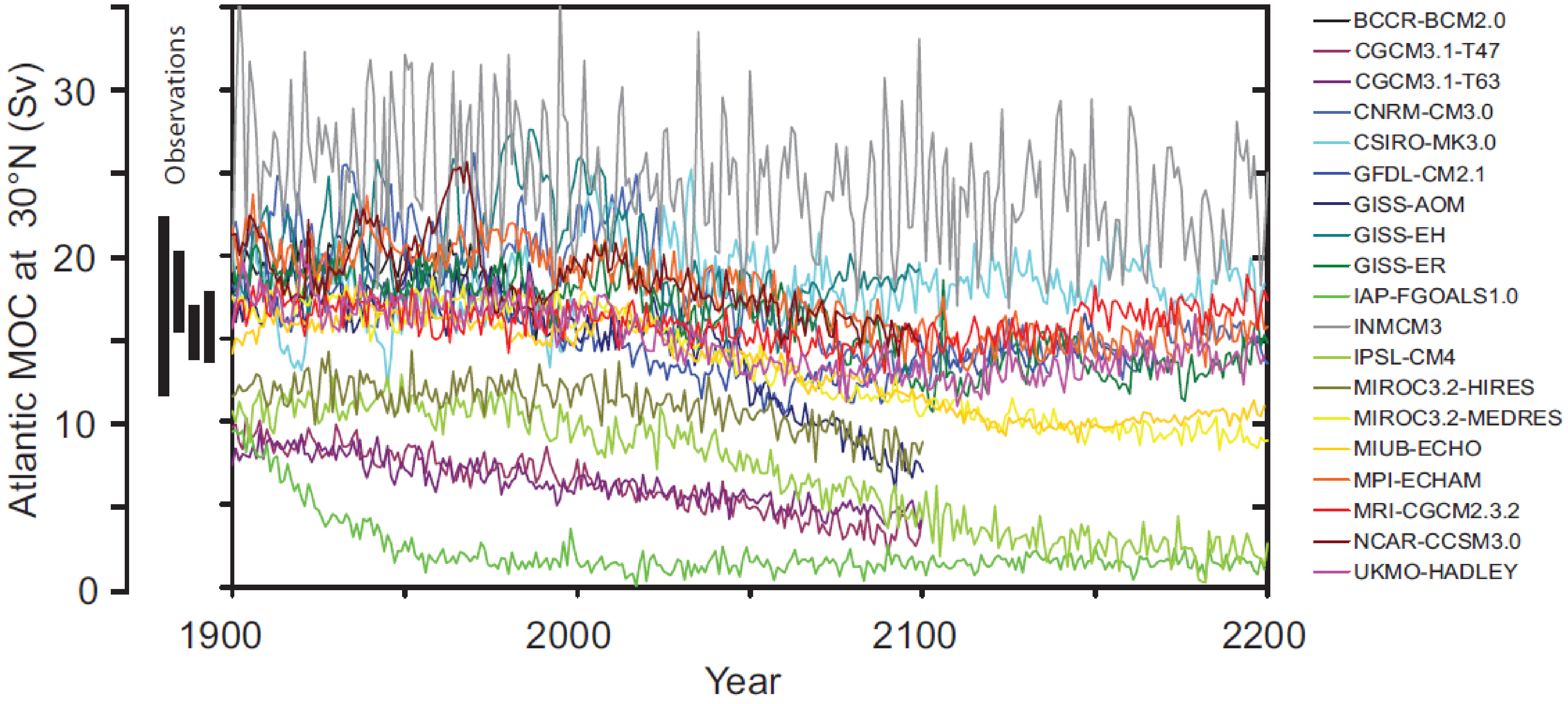


Image credit: **V. Byfield, National Oceanography Centre (NOC), licensed under CC BY 3.0.** The original figure was modified with mean age indications of water masses since their last contact with atmosphere. *(Published in this form in: Heinze et al., 2021, https://doi.org/10.1073/pnas.2008478118)*

The concern for an AMOC collapse:



SRES A1B

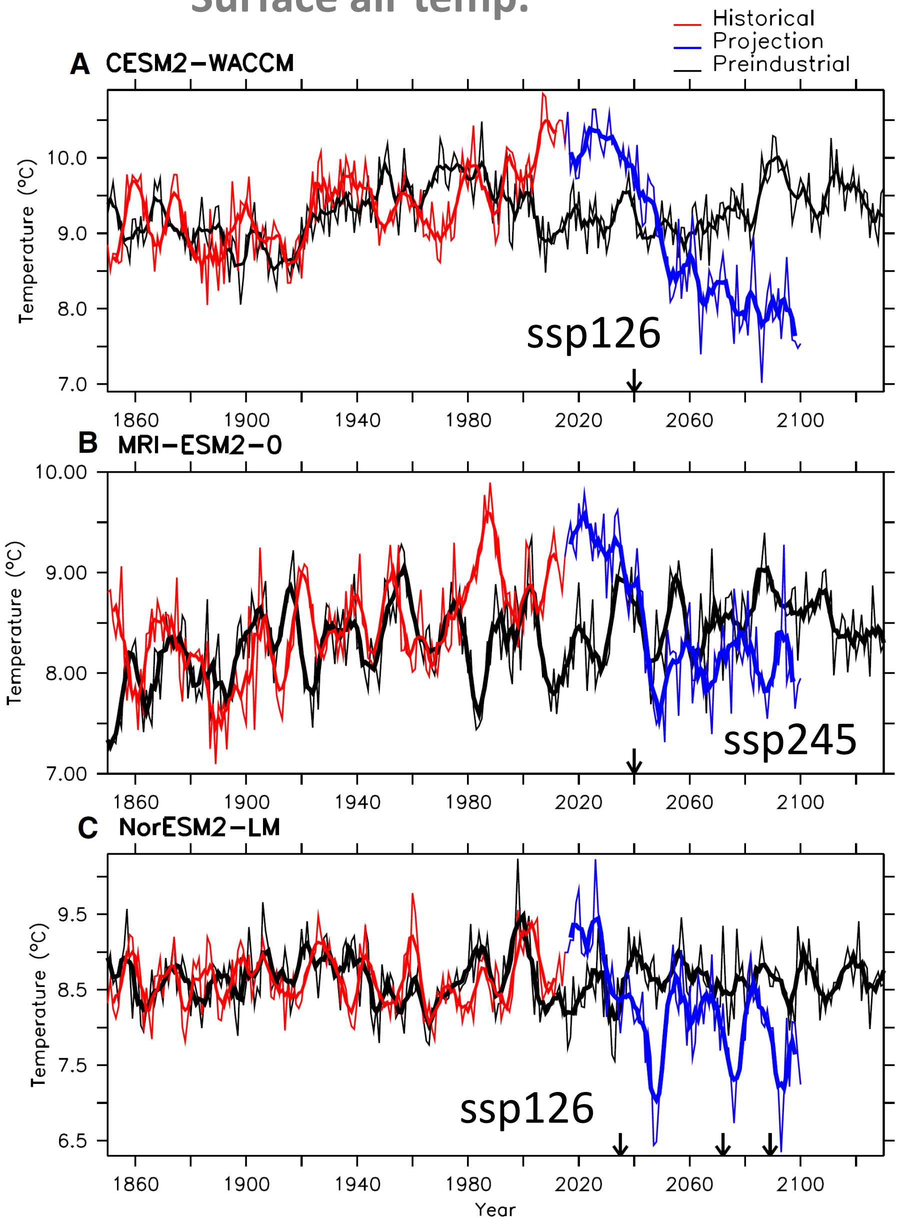
Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

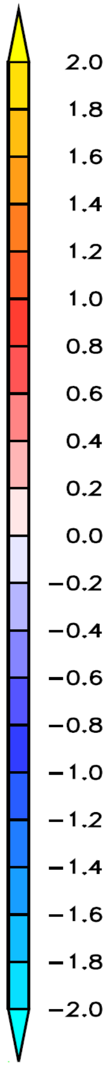
E.g. **Fabbri al.,** *Environ. Sci. Technol.*, 2021, SI, https://dx.doi.org/10.1021/acs.est.0c02928, SI1: Addition of freshwater in the North Atlantic (due to sea ice and Greenland ice sheet melting, river inputs and ocean precipitation) may reduce the density-driven sinking of North Atlantic waters until the Atlantic thermohaline circulation is significantly slowed down or even stopped

Abrupt cooling of the N.Atl. sub-polar gyre:

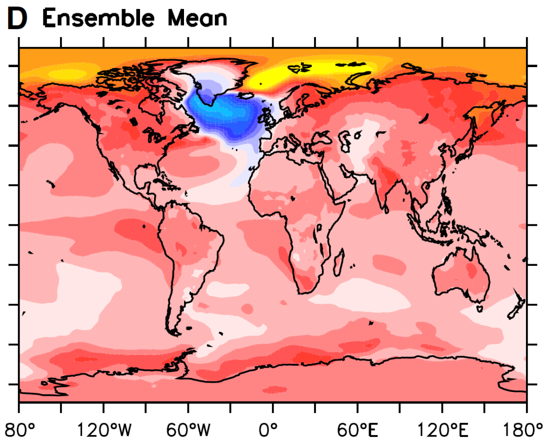
CMIP6

Surface air temp.

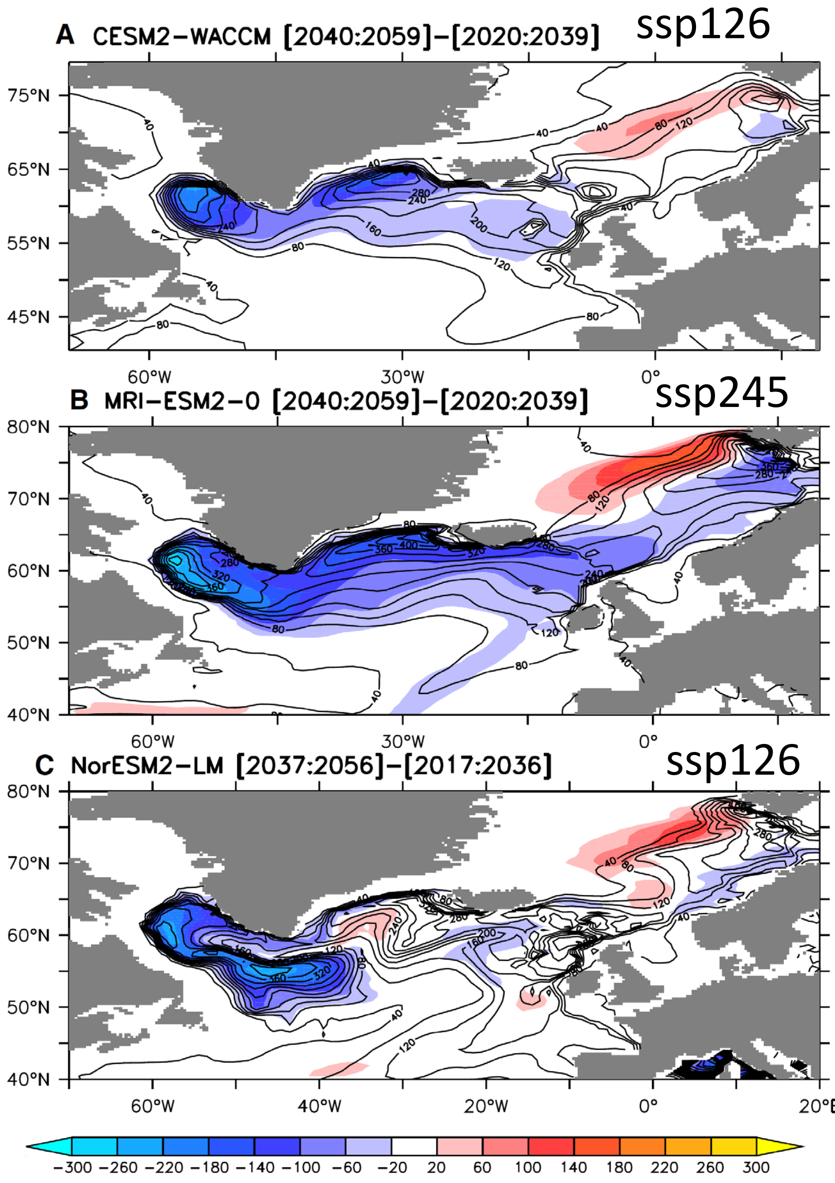




Δ surface air temp.



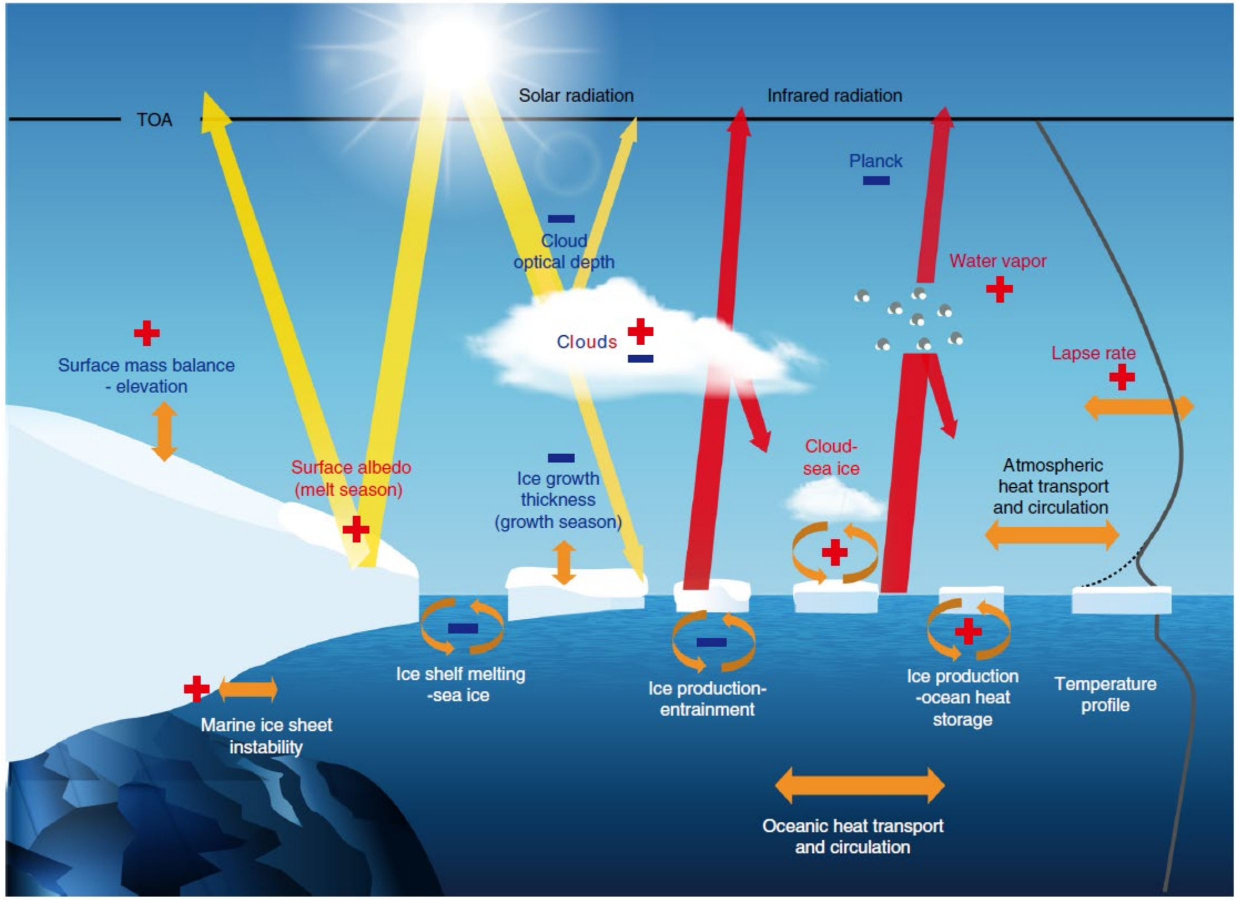
Δ ocean mixed layer depth



Swingedouw et al.,
Ann. N.Y. Acad. Sci.,
2021,
10.1111/nyas.14659

No occurrence for ssp585

Arctic and Antarctic sea ice changes:



Goosse et al, 2018, Nat. Comm., DOI: 10.1038/s41467-018-04173-0

See, e.g., **Fabbri et al.**, *Environ. Sci. Technol*., 2021, SI, https://dx.doi.org/10.1021/acs.est.0c02928

Arctic summer sea ice loss:

Ice-albedo feedback.

(Comment: but heat loss at open waters.)

Abrupt sea ice increase in Southern Ocean:

Warming reduces deep ocean convection (Indian sector).
Formation of a fresh surface layer and hence of sea ice.

See, e.g., **Bathiany et al.**, J. Clim., 2016, doi: 10.1175/JCLI-D-15-0466.1

Arctic winter sea ice loss:

"… Sea ice areal coverage remains high as long as sea ice still forms, and then drops to zero wherever the ocean warms sufficiently to no longer form ice during winter. …"

"How reversible is sea ice loss?"

See: J. K. Ridley, J. A. Lowe, and **H. T. Hewitt**, *The Cryosphere*, 6, 193–198, 2012 doi:10.5194/tc-6-193-2012

Offshore permafrost and gas hydrate stability:

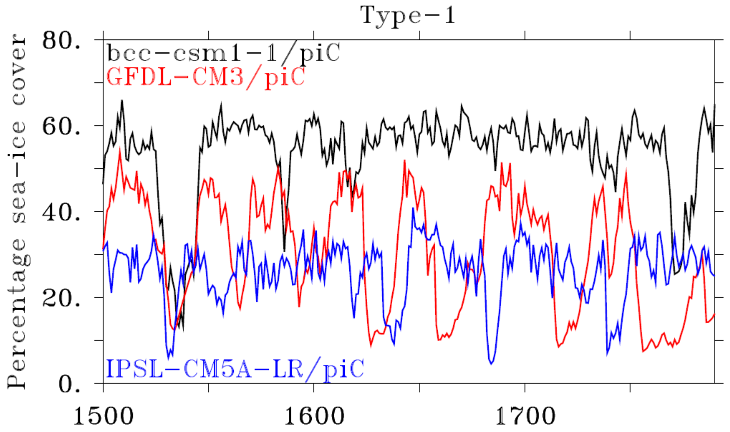
Depends on combination of T and p.

- *>800 Gt of CH_4 accumulated in the ESAS seabed? Potential for abrupt CH_4 release.*
- *Source: destabilizing hydrates or from free gas accumulations beneath permafrost.*

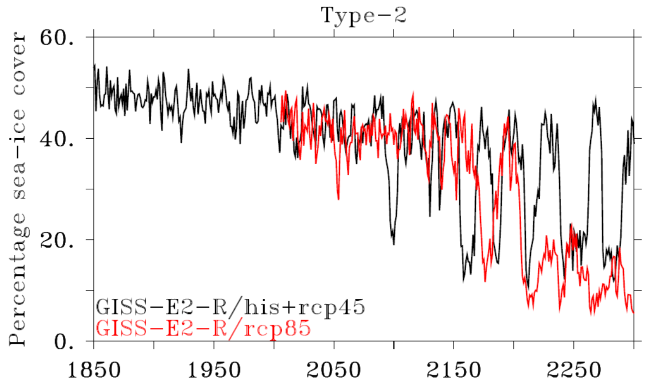
*See **Shakhova et al.**, Geosciences, 2019, 9, 251; doi:10.3390/geosciences9060251*

Arctic and Antarctic sea ice, abrupt changes from models:

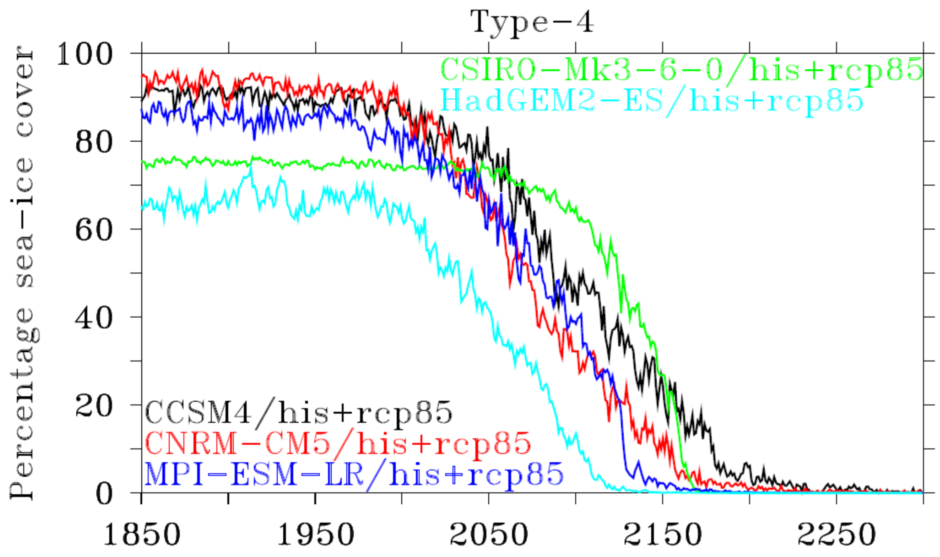
Type 1: Unforced Bimodal Switches in Sea Ice Cover. *(Southern Ocean).*



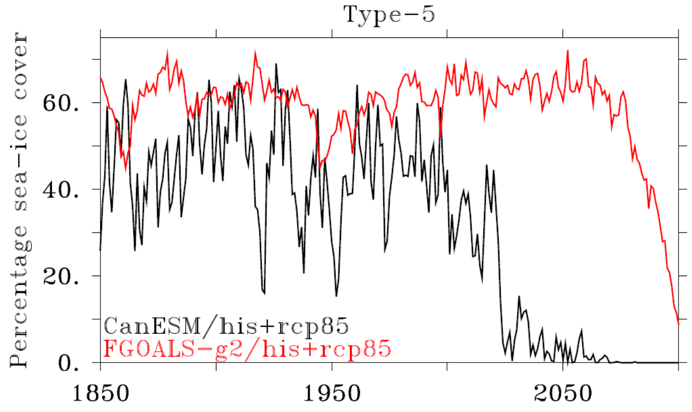
Type 2: Forced Bimodal Switches in Sea Ice Cover. *(Southern Ocean).*



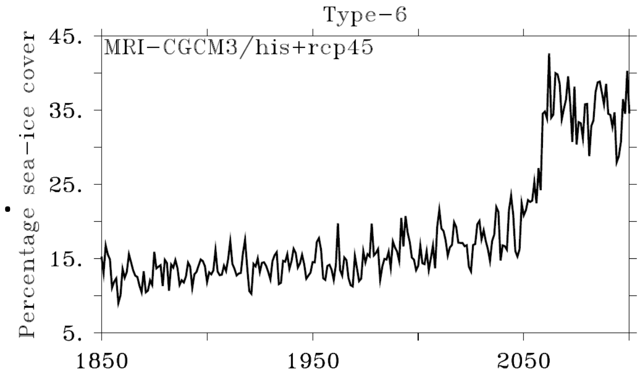
Type 4: Arctic Winter Sea Ice Collapse. *(Arctic Ocean).*



Type 5: Abrupt Regional Sea Ice Loss. *(Various regions).*



Type 6: Abrupt Sea Ice Increase. *(Southern Ocean).*

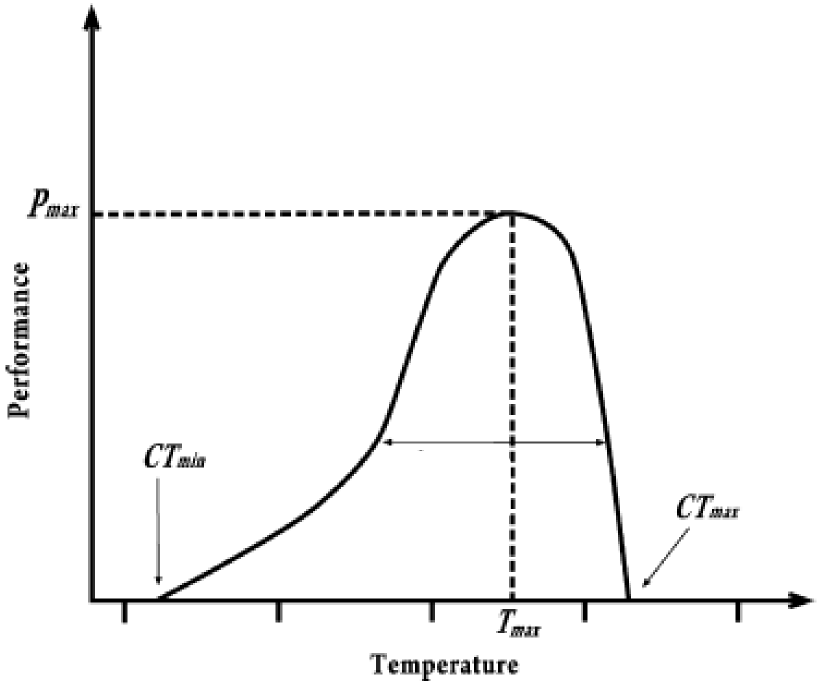


Drijfhout et al., PNAS, 2015, www.pnas.org/cgi/doi/10.1073/pnas.1511451112

Environmental thresholds:

Warming

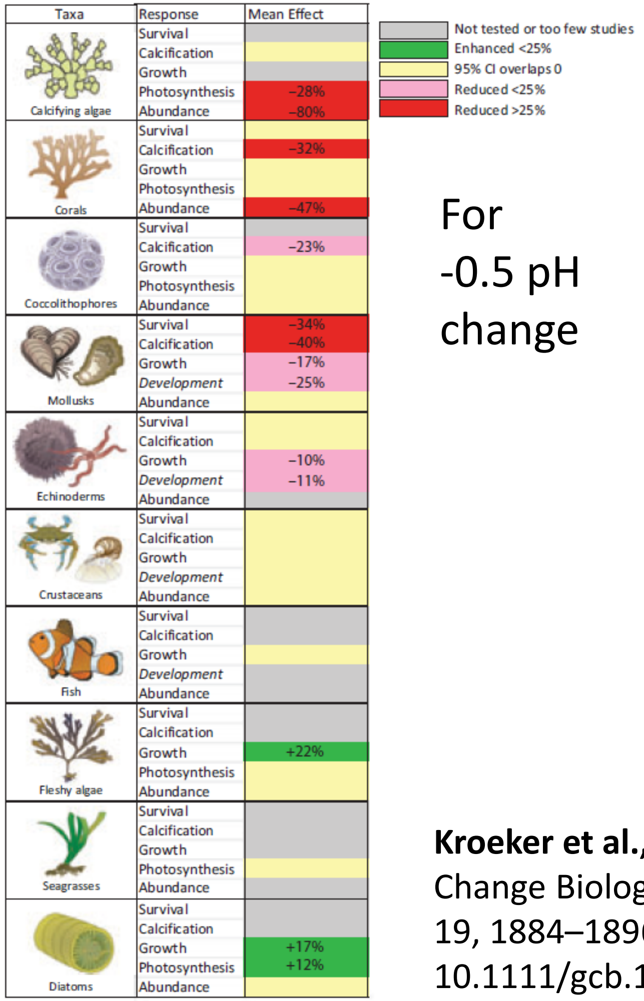
Asymmetric thermal performance curve of organisms



Monaco & Helmuth, Advances in Marine Biology, Vol. 60, 2011
DOI: 10.1016/B978-0-12-385529-9.00003-2 A

Ocean acidification

$CaCO_3$ saturation levels for different polymorphs



Taxa	Response	Mean Effect
Calcifying algae	Survival	
	Calcification	
	Growth	
	Photosynthesis	−28%
	Abundance	−80%
Corals	Survival	
	Calcification	−32%
	Growth	
	Photosynthesis	
	Abundance	−47%
Coccolithophores	Survival	
	Calcification	−23%
	Growth	
	Photosynthesis	
	Abundance	
Mollusks	Survival	−34%
	Calcification	−40%
	Growth	−17%
	Development	−25%
	Abundance	
Echinoderms	Survival	
	Calcification	
	Growth	−10%
	Development	−11%
	Abundance	
Crustaceans	Survival	
	Calcification	
	Growth	
	Development	
	Abundance	
Fish	Survival	
	Calcification	
	Growth	
	Development	
	Abundance	
Fleshy algae	Survival	
	Calcification	
	Growth	+22%
	Photosynthesis	
	Abundance	
Seagrasses	Survival	
	Calcification	
	Growth	
	Photosynthesis	
	Abundance	
Diatoms	Survival	
	Calcification	
	Growth	+17%
	Photosynthesis	+12%
	Abundance	

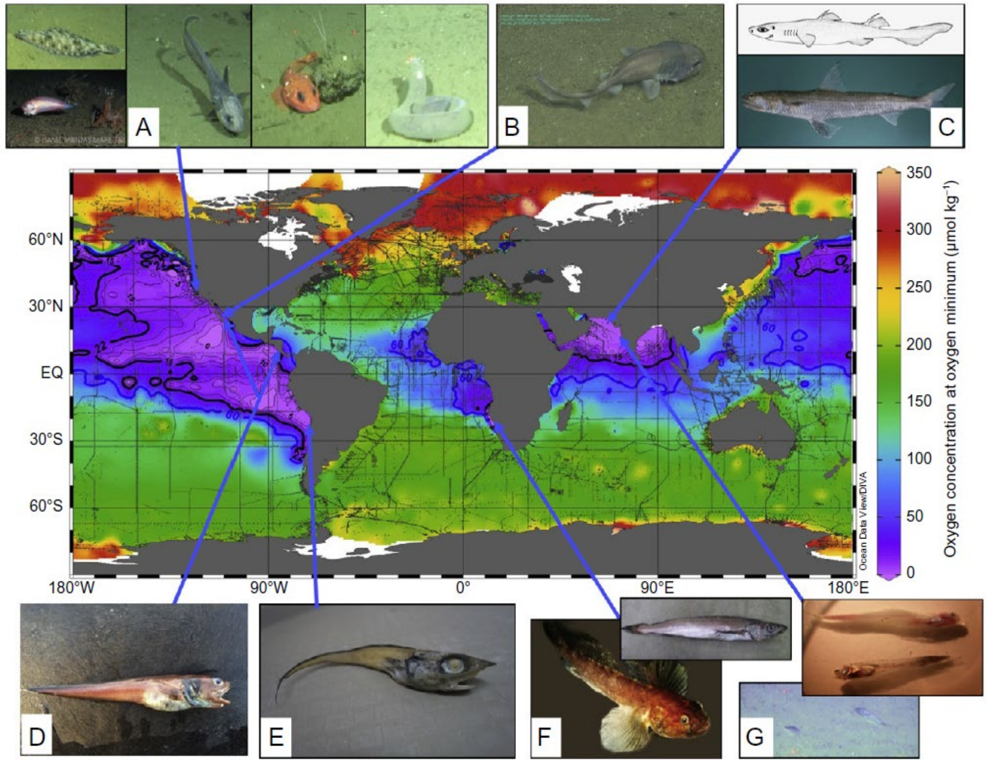
Not tested or too few studies
Enhanced <25%
95% CI overlaps 0
Reduced <25%
Reduced >25%

For -0.5 pH change

Kroeker et al., Global Change Biology (2013) 19, 1884–1896, doi: 10.1111/gcb.12179

De-oxygenation

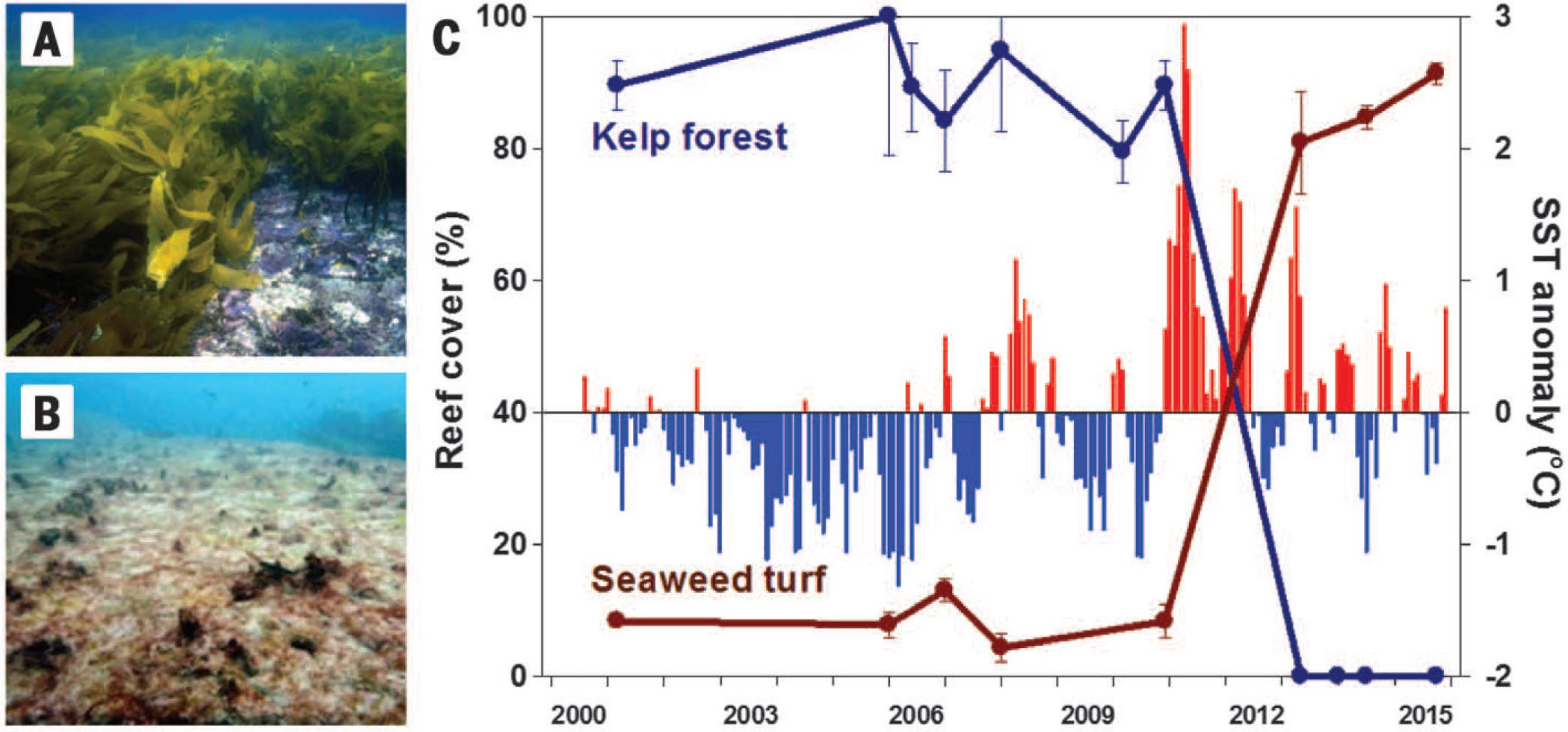
Lethal O_2 boundary for fishes ca. <60 µmol/L



Gallo & Levin, 2016, Advances in Marine Biology, Vol. 74, ch. 3, http://dx.doi.org/10.1016/bs.amb.2016.04.001

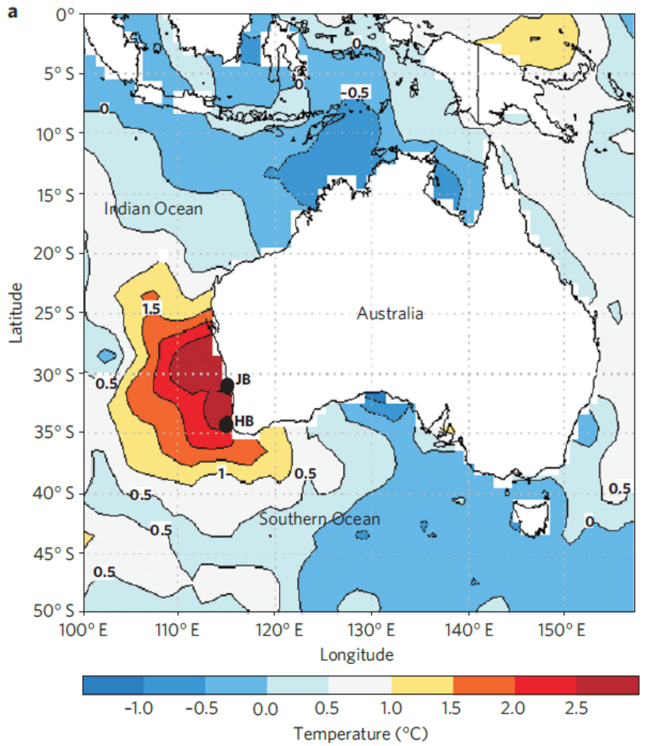
Ocean heat waves trigger change:

TROPICAL COASTAL ECOSYSTEM



Wernberg et al., Science, 2016, doi: 10.1126/science.aad8745

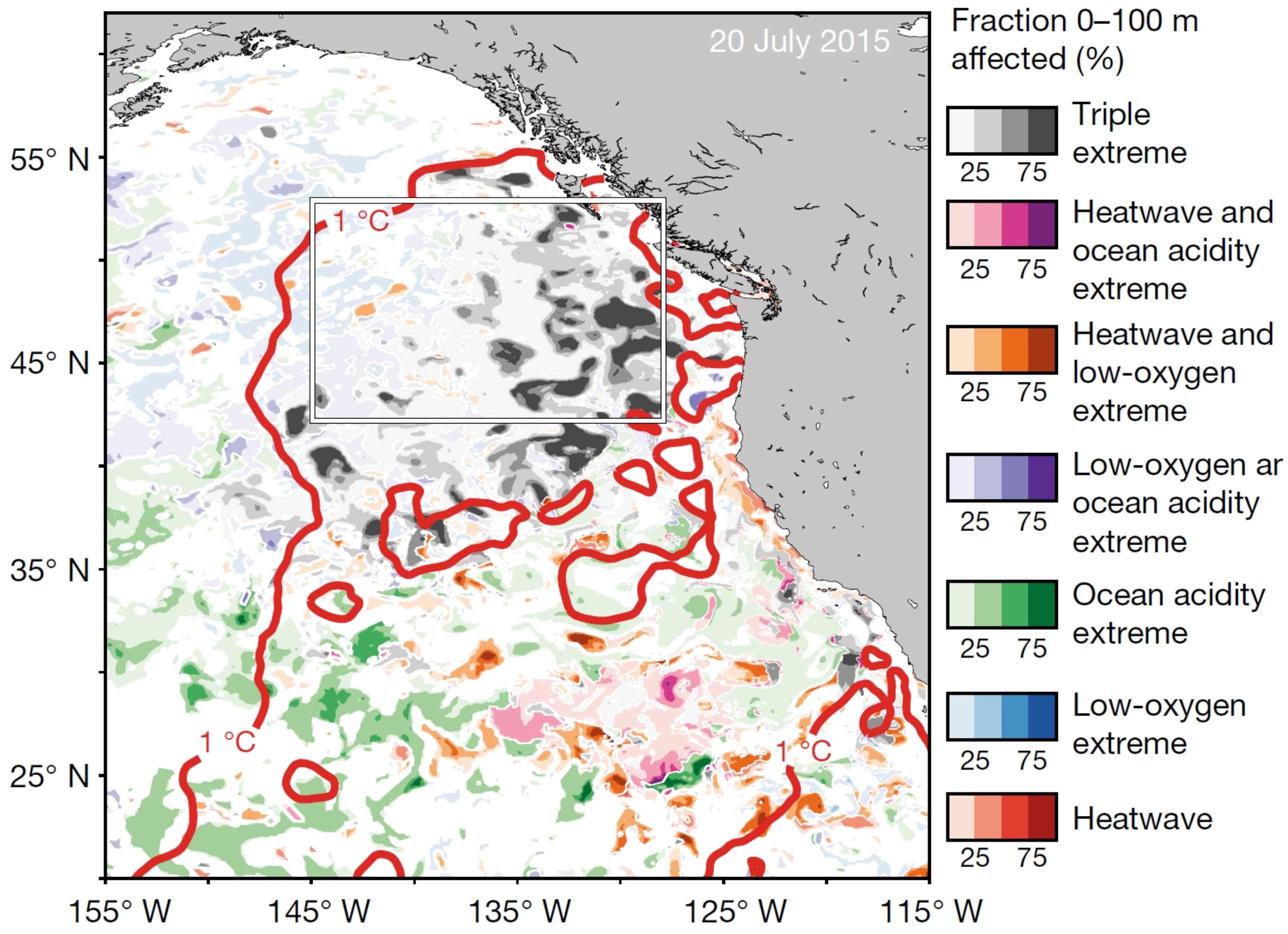
Wernberg et al., *Nature Clim. C.*, 2012, doi:10.1038/NCLIMATE1627



2011 heatwave

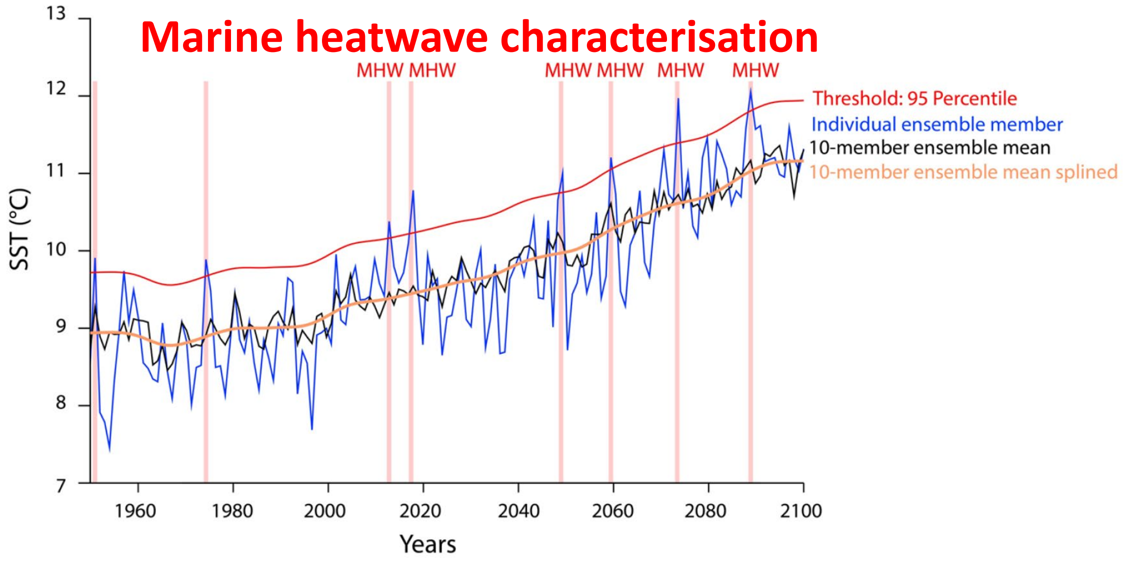
Marine extreme events:

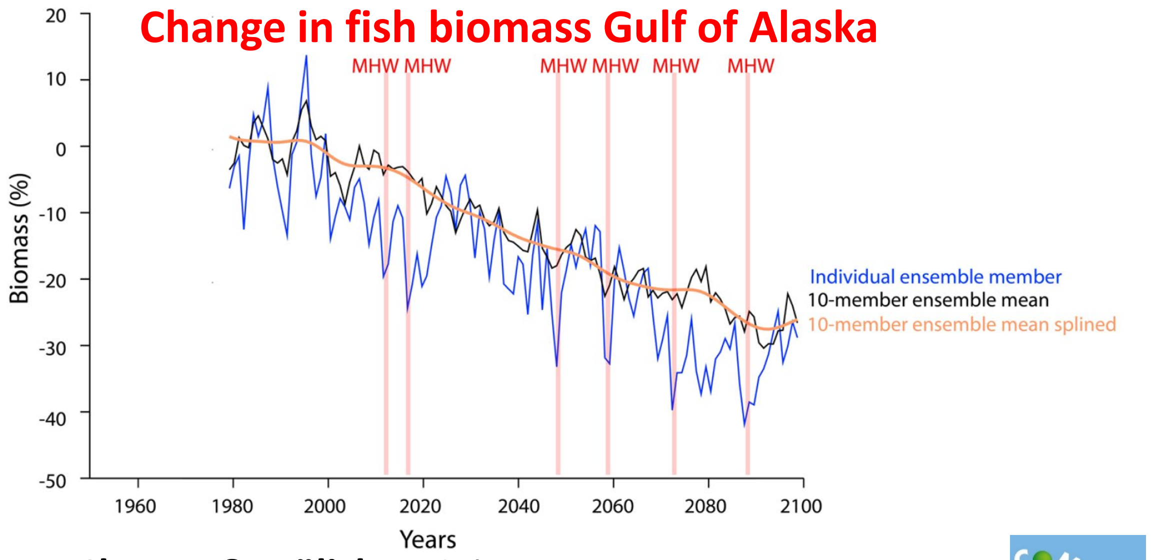
Compound extremes N.E. Pacific (model simulation)



Gruber et al., *Nature*, 2021, https://doi.org/10.1038/s41586-021-03981-7

Earth system model with a fish impact model

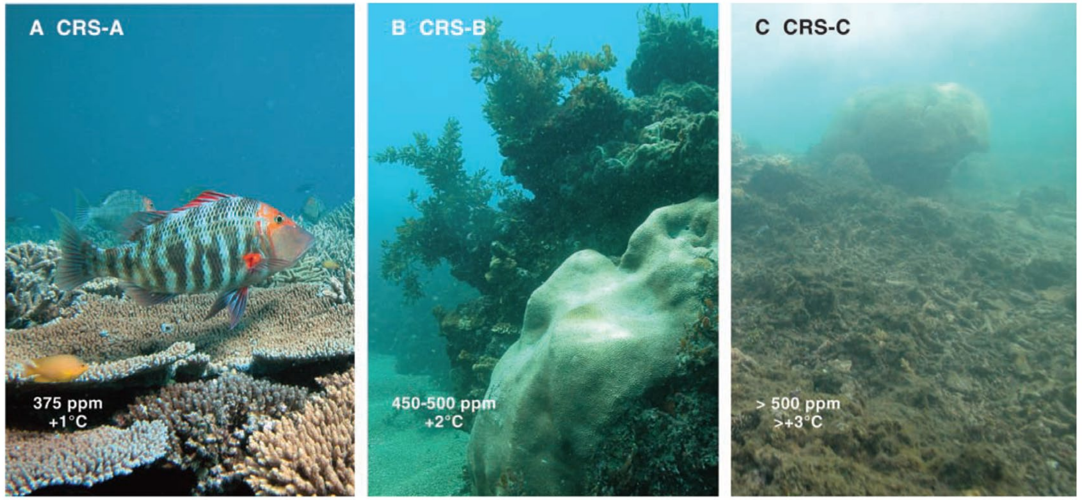




Cheung & Frölicher, *Sci. Reports*, 2020, https://doi.org/10.1038/s41598-020-63650-z

Loss of $CaCO_3$, living organisms - examples:

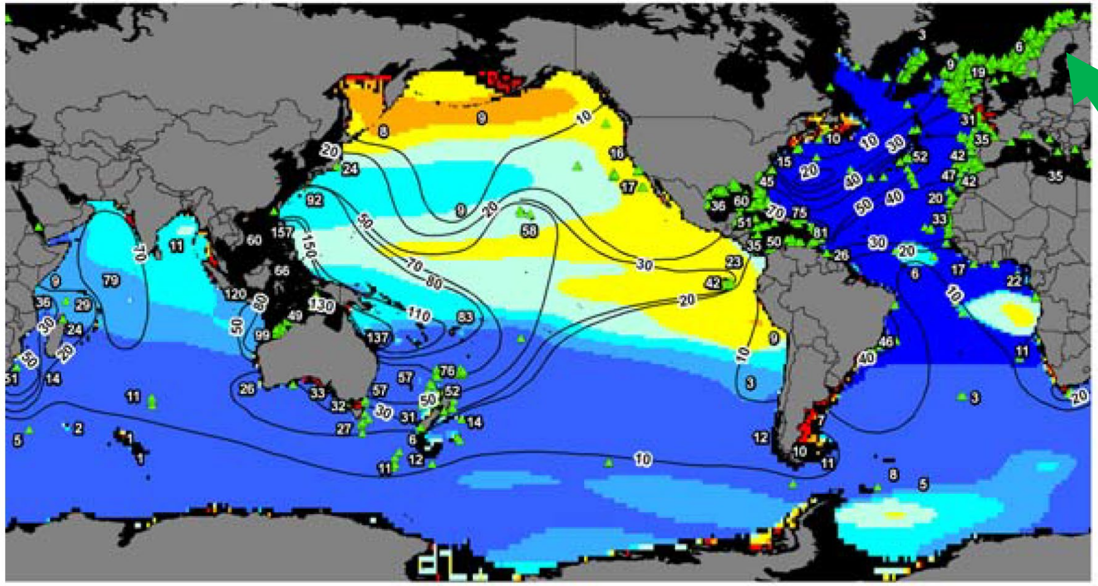
Warm water corals: ΔT, ΔpH



Hoegh-Guldberg et al., Science, 2007,
doi: 10.1126/science.1152509

A–Preind

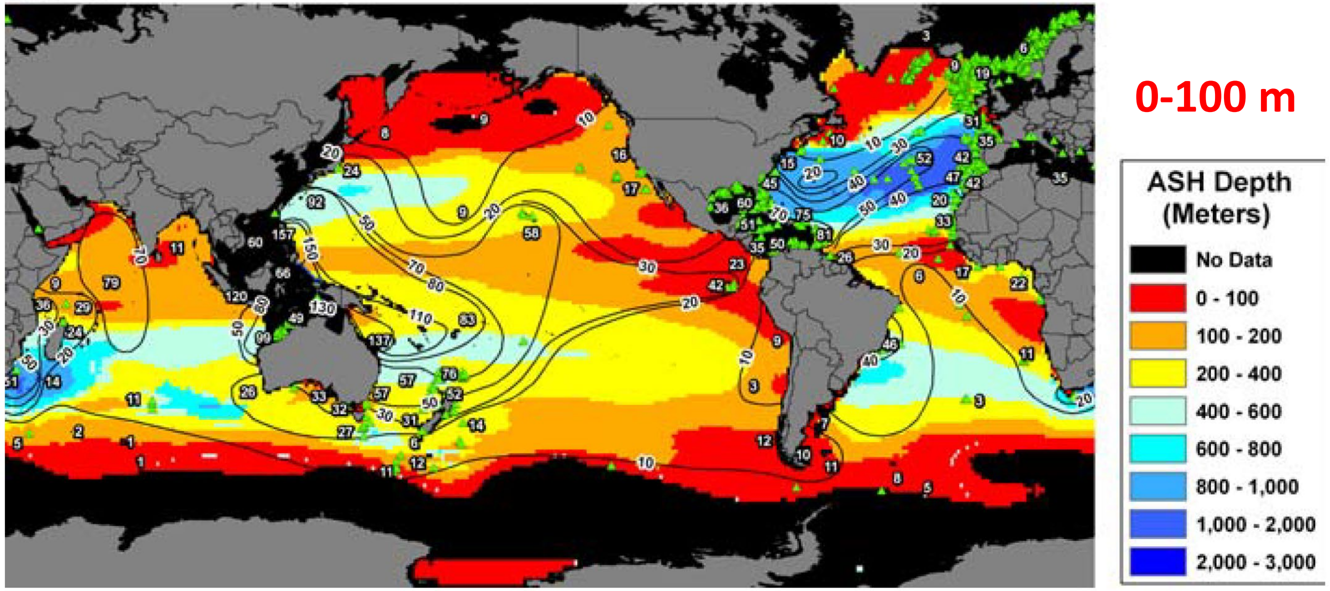
atm. pCO_2= 278 ppm



Also cold water corals

C–2099

atm. pCO_2= 788 ppm

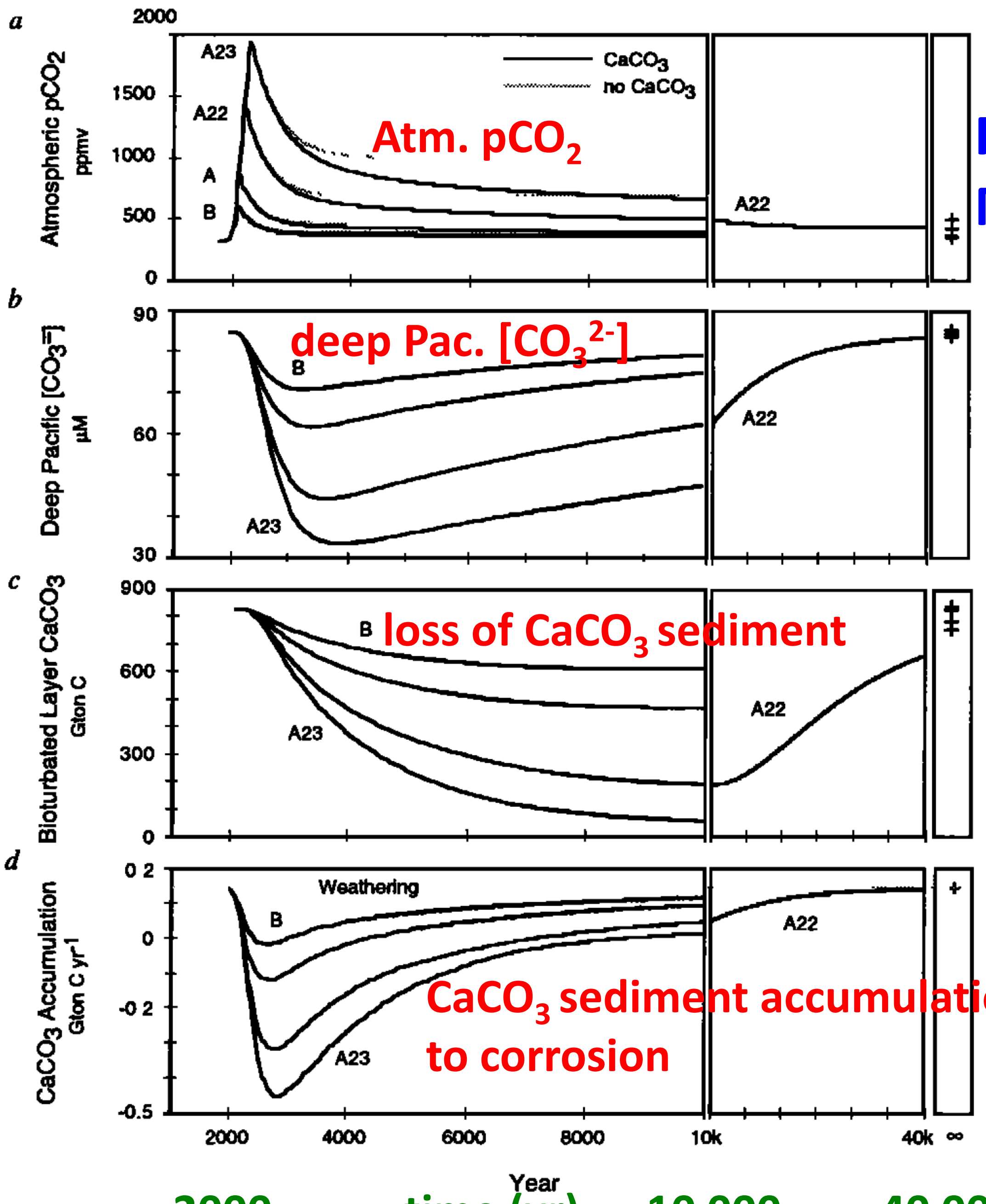


0-100 m

Showling of aragonite saturation horizon

Guinotte & Fabry, Ann N Y Acad Sci, 2008, doi: 10.1196/annals.1439.013

Loss of sedimentary $CaCO_3$:



2000 time (yr) 10 000 40 000

Future, MODEL

Quasi-irreversibility on human time scales, huge legacy effect also for atm. pCO_2

$CaCO_3$ surface sediment like "snow" on ocean mountains, this surface sediment is already doomed to vanish for long

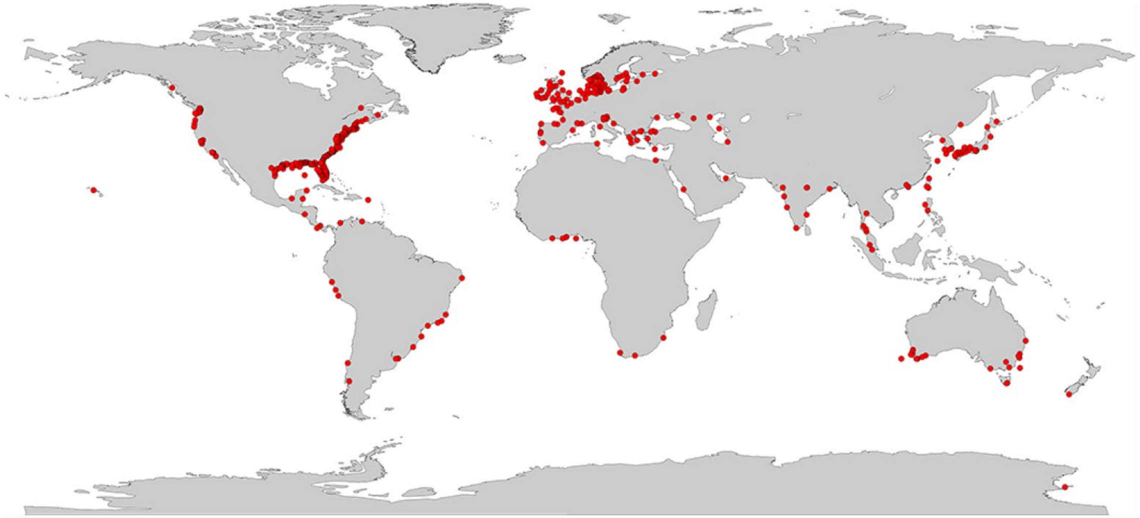
Archer, *Glob. Biogeochem. Cy.*, 1996, https://doi.org/10.1029/95GB03016

Present, OBSERVATION

Archer et al., *Geophys. Res. L.*, 1997, doi https://doi.org/10.1029/97GL00168

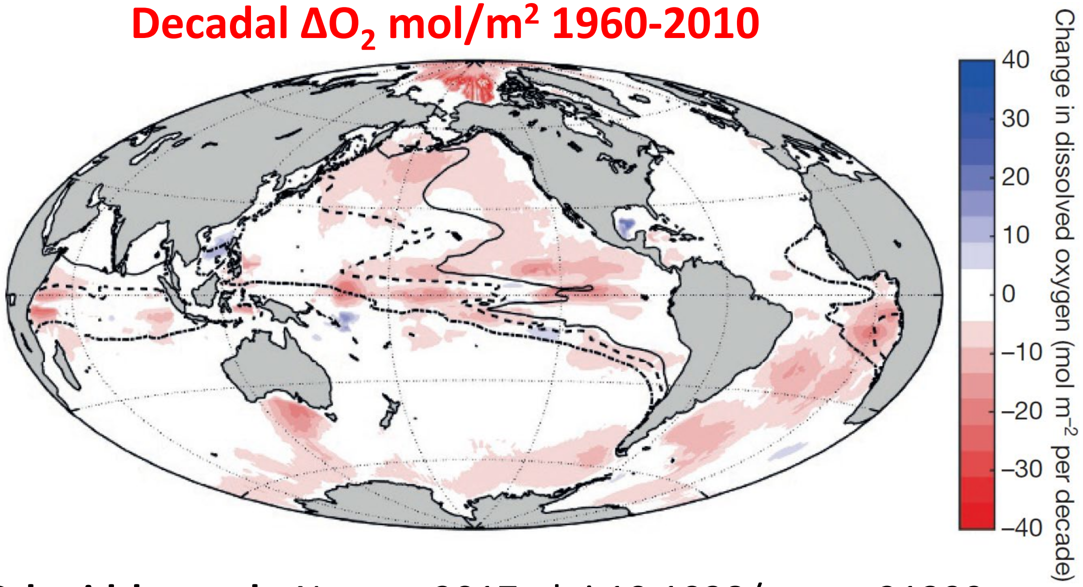
O_2 loss:

Coastal waters where $[O_2]$ ≤61 mmol kg^{-1} past 50 yrs

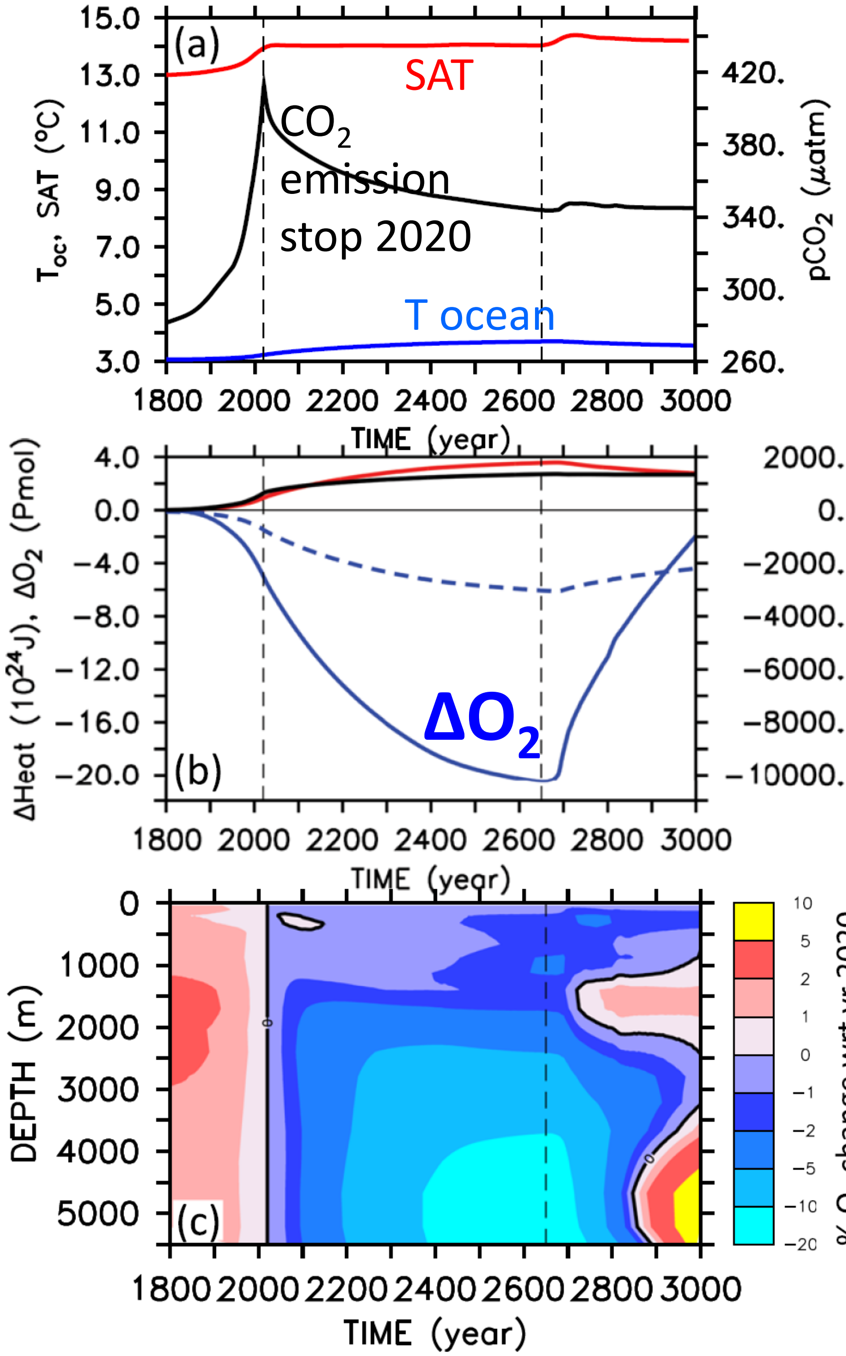


Breitburg et al., *Science*, 2018, doi: 10.1126/science.aam7240

Decadal ΔO_2 mol/m^2 1960-2010



Schmidtko et al., *Nature*, 2017, doi:10.1038/nature21399

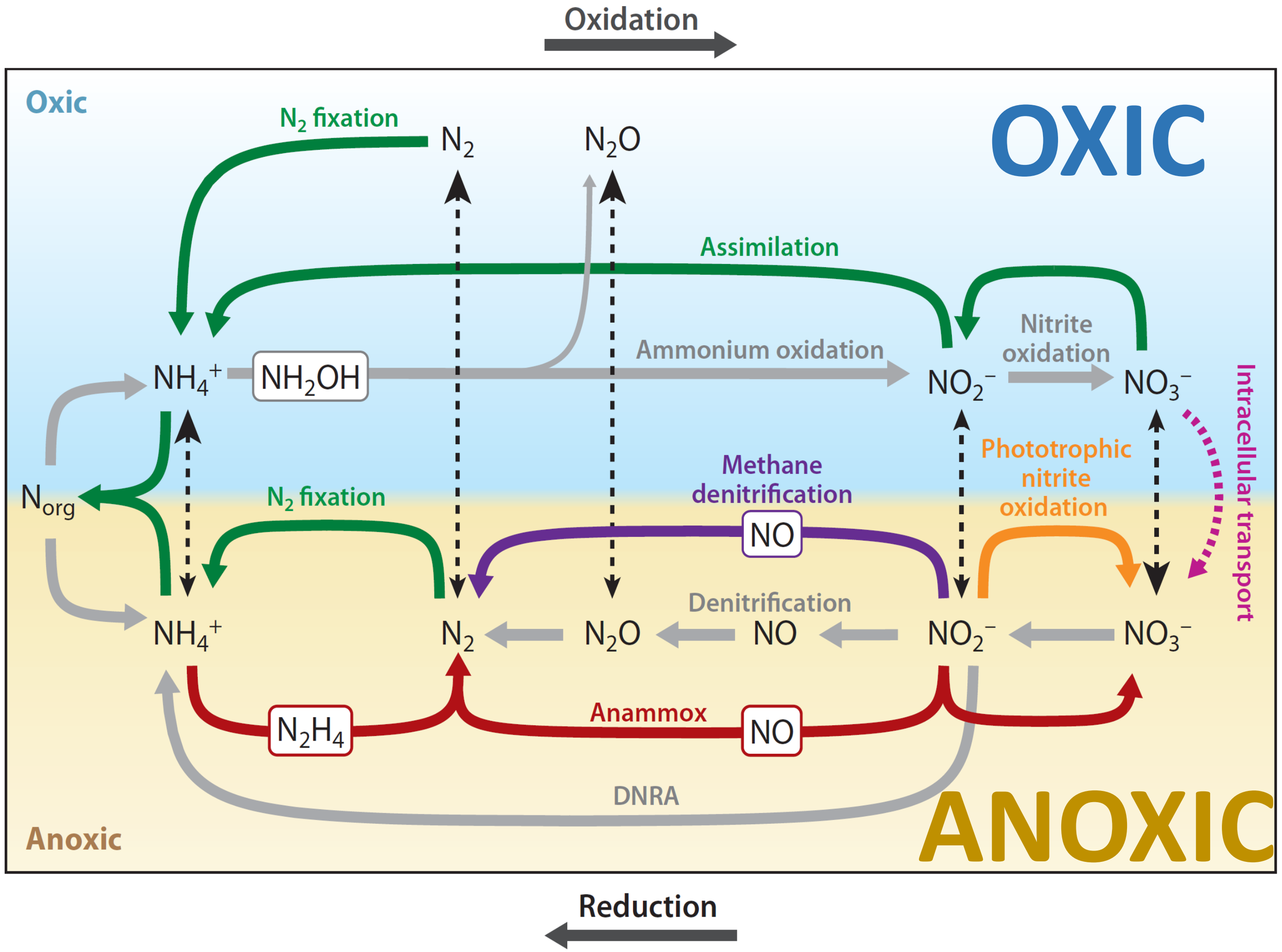


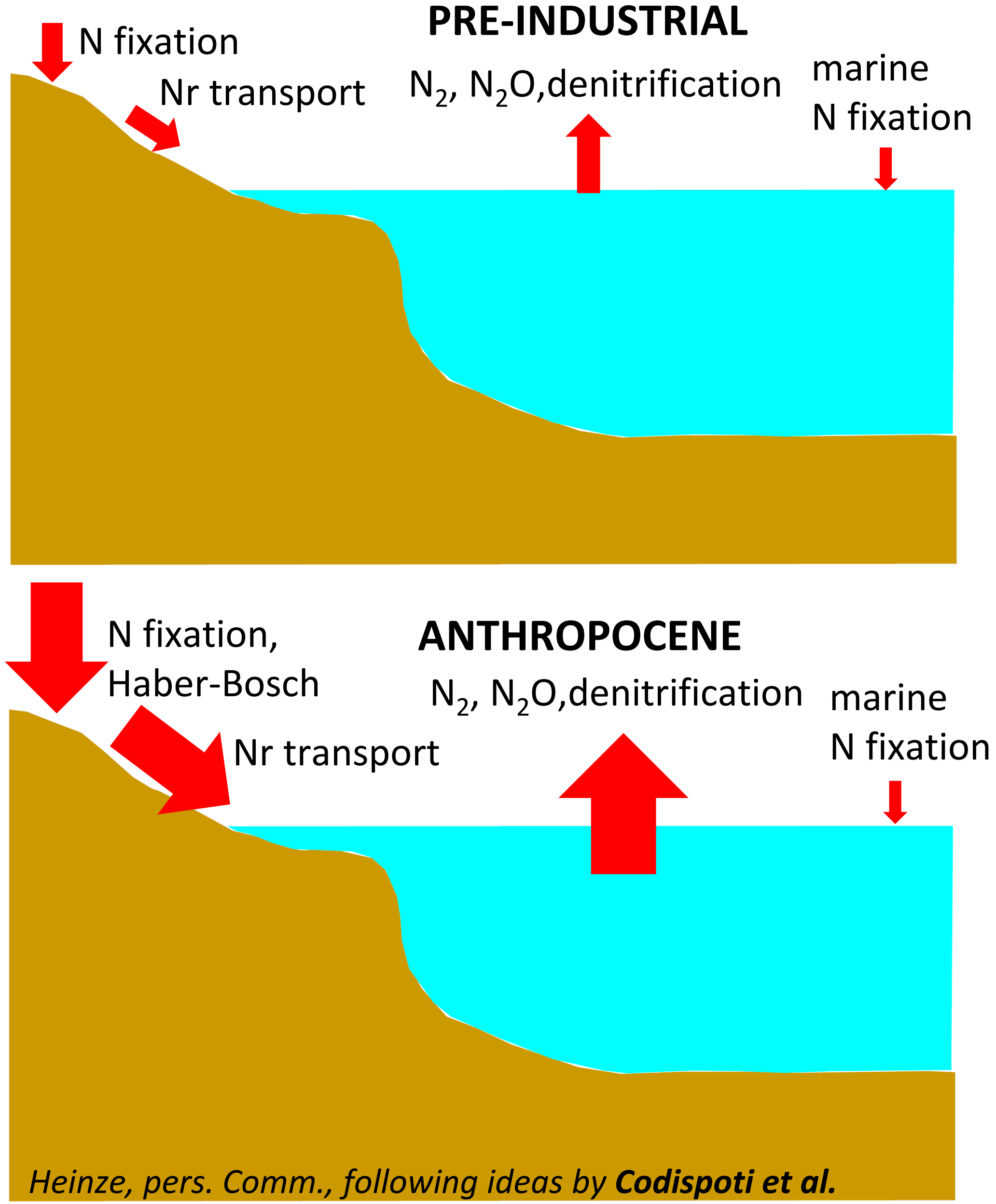
Quasi-irreversibility on human time scales

Oschlies et al., *Nature Comm.*, 2021, doi: https://doi.org/10.1038/s41467-021-22584-4

N_2O production under low O_2:

Switch between biogeochemical and ecological regimes!

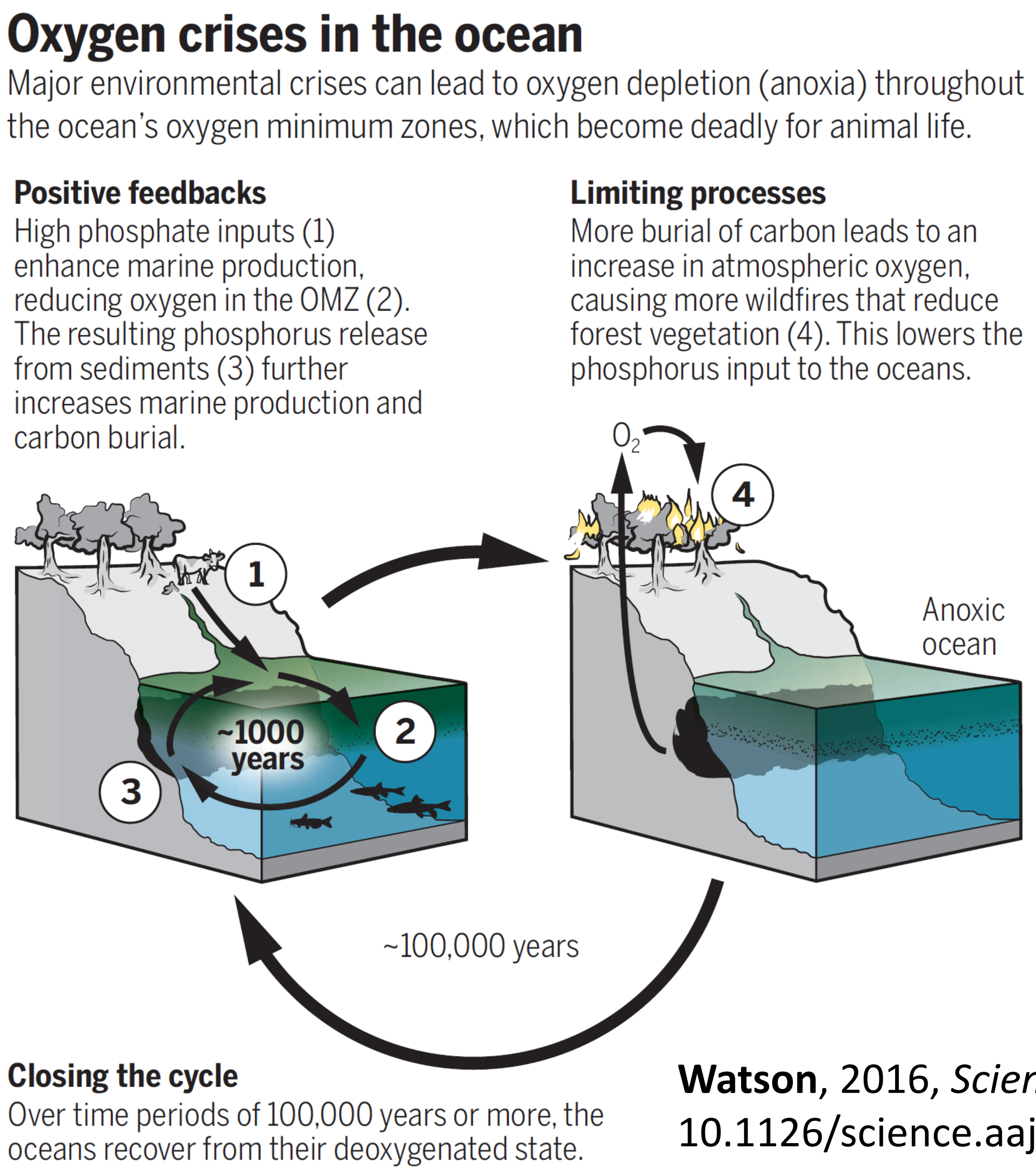


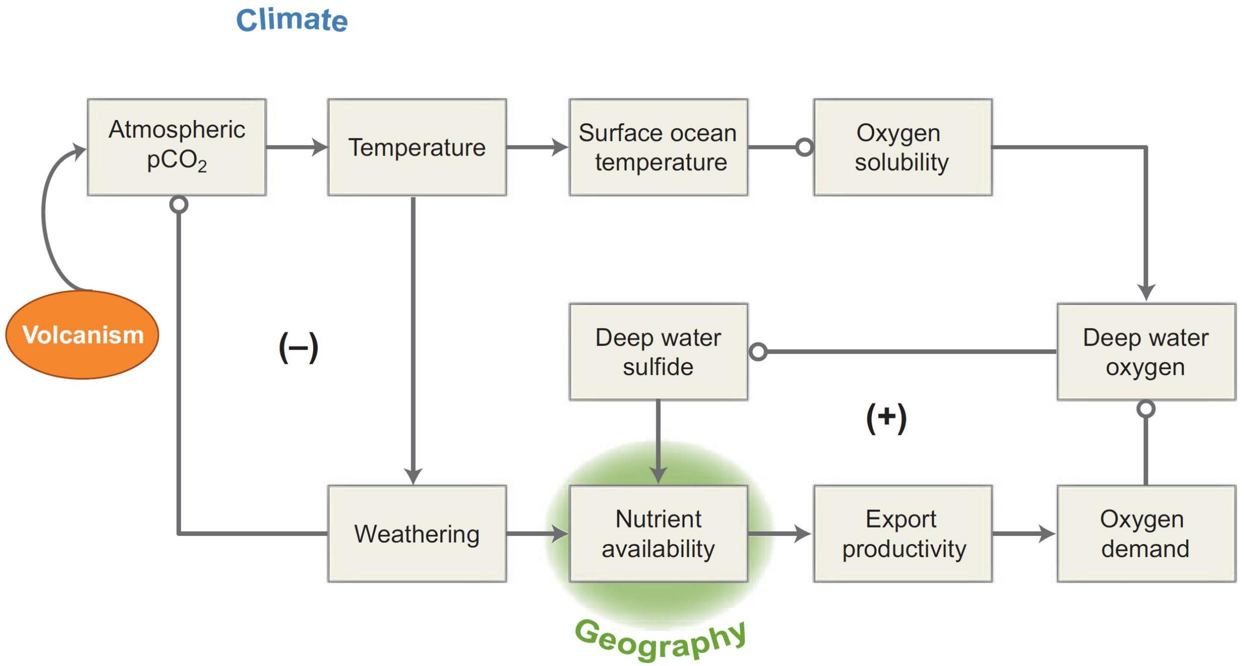


Thamdrup, 2012, *Annu. Rev. Ecol. Evol. Syst.*, doi: 10.1146/annurev-ecolsys-102710-145048

Heinze, pers. Comm., following ideas by ***Codispoti et al.*** *2001,DOI 10.3989/scimar.2001.65s285*

PO_4^{3-} & anoxia runaway following deoxygenation:

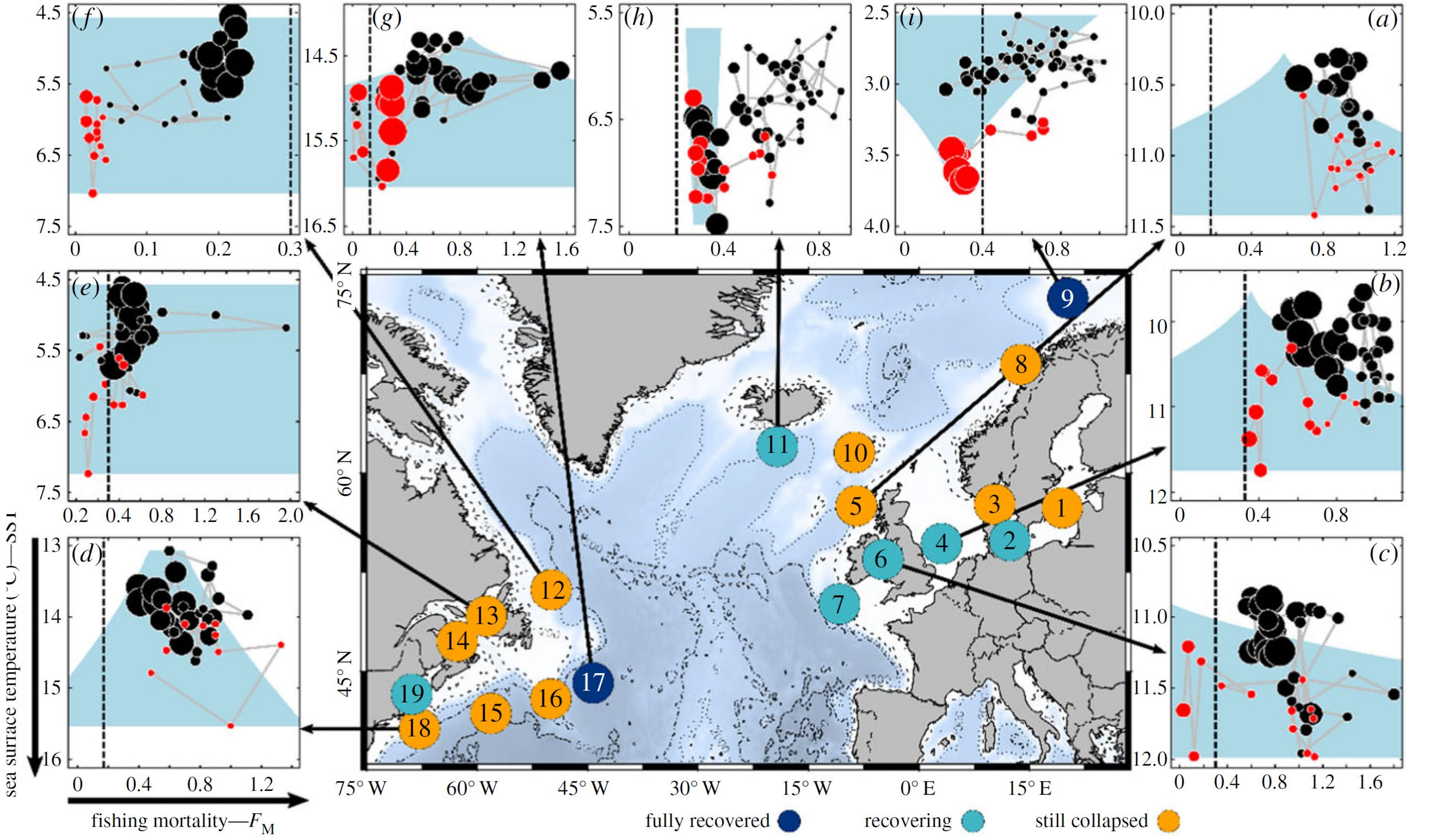




Watson, 2016, *Science*, doi: 10.1126/science.aaj2321

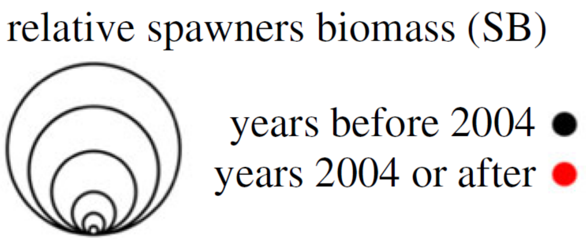
Meyer & Kump, 2008, *Annu. Rev. Earth Planet. Sci.*, doi:10.1146/annurev.earth.36.031207.124256

Fish impact, tipping through climate change and overfishing:



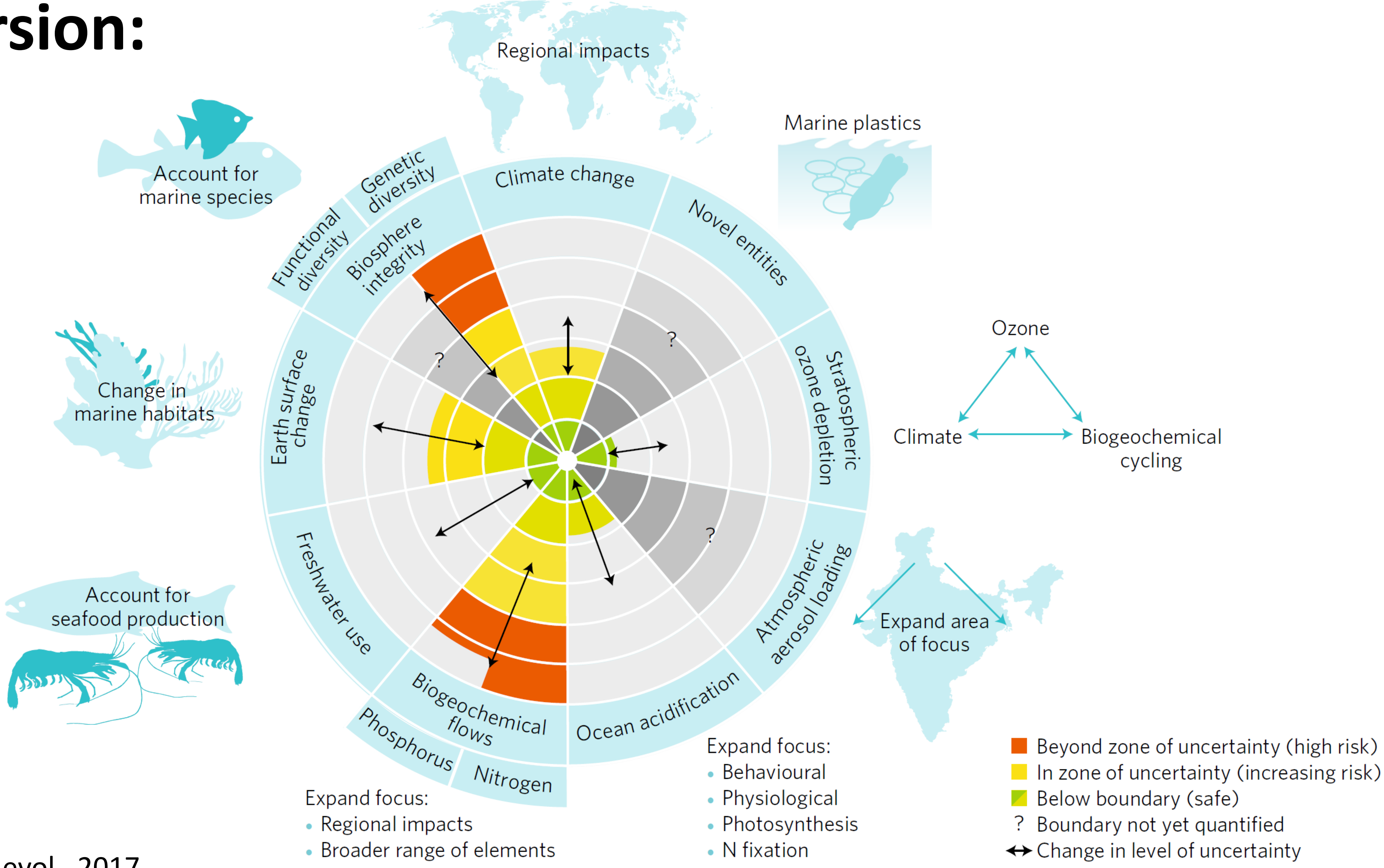
Statistical ("cusp") analysis of 19 Atlantic Cod stocks ca. 1960-2010

(cusp involving turning point as alternative to change point analysis)



Sguotti et al., Proc. R. Soc. B, 2019, http://dx.doi.org/10.1098/rspb.2018.2877

Planetary boundaries and safe operating space – marine version:

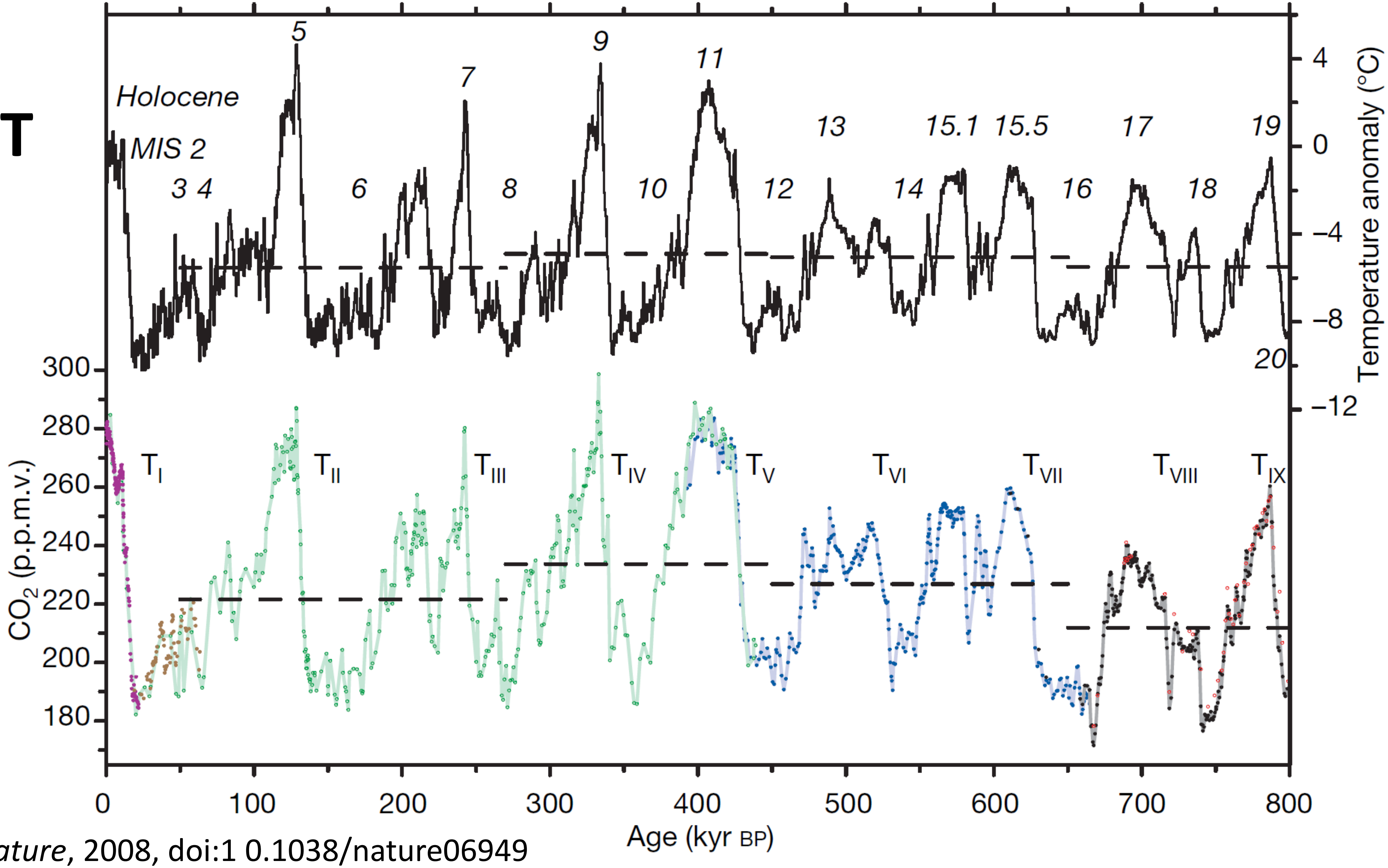


Nash et al., Nature ecol.&evol., 2017, https://doi.org/10.1038/s41559-017-0319-z

Glacial-Interglacial changes: …causes (?) … stable (?) states …

local ΔT

Global CO_2



Lüthi et al., *Nature*, 2008, doi:1 0.1038/nature06949

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 *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*)

IPCC SROCC Collins M., M. Sutherland, L. Bouwer, S.-M. Cheong, T. Frölicher, H. Jacot Des Combes, M. Koll Roxy, I. Losada, K. McInnes, B. Ratter, E. Rivera-Arriaga, R.D. Susanto, D. Swingedouw, and L. Tibig, 2019: Extremes, Abrupt Changes and Managing Risk. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

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Marine (Sectio			cts	idence)
Arctic s				
Ocean hypoxic events (Section 5.2)	Yes	for centuries to millennia at depth	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*)

Ocean deoxygenation and hypoxic events (Section 5.2)	Yes	Reversible at surface, but irreversible for centuries to millennia at depth
Ocean acidification (Section 5.2)	Yes	Reversible at surface, but irreversible for centuries to millennia at depth

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