Sea ice feedbacks cause more greenhouse cooling than greenhouse warming at high northern latitudes on multi-century timescales

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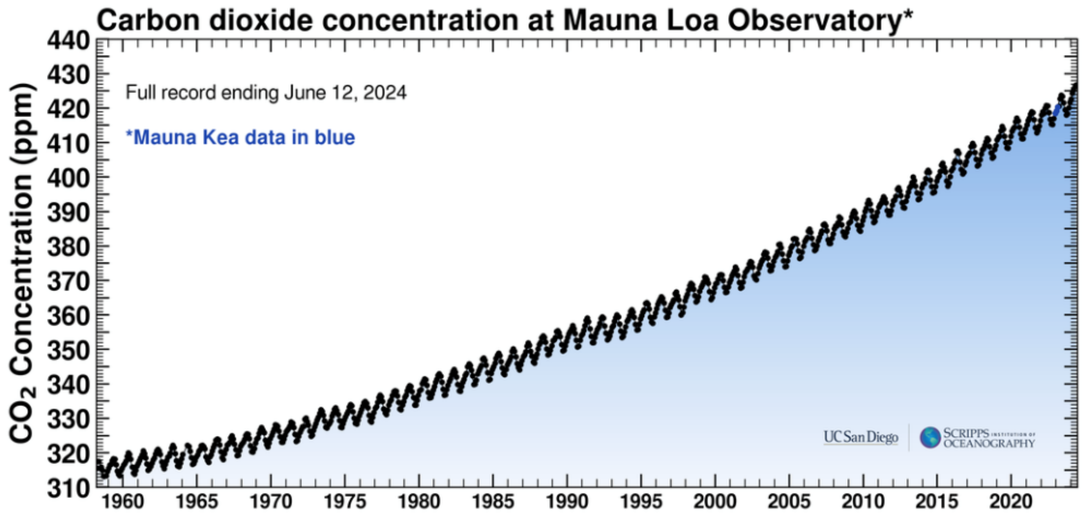
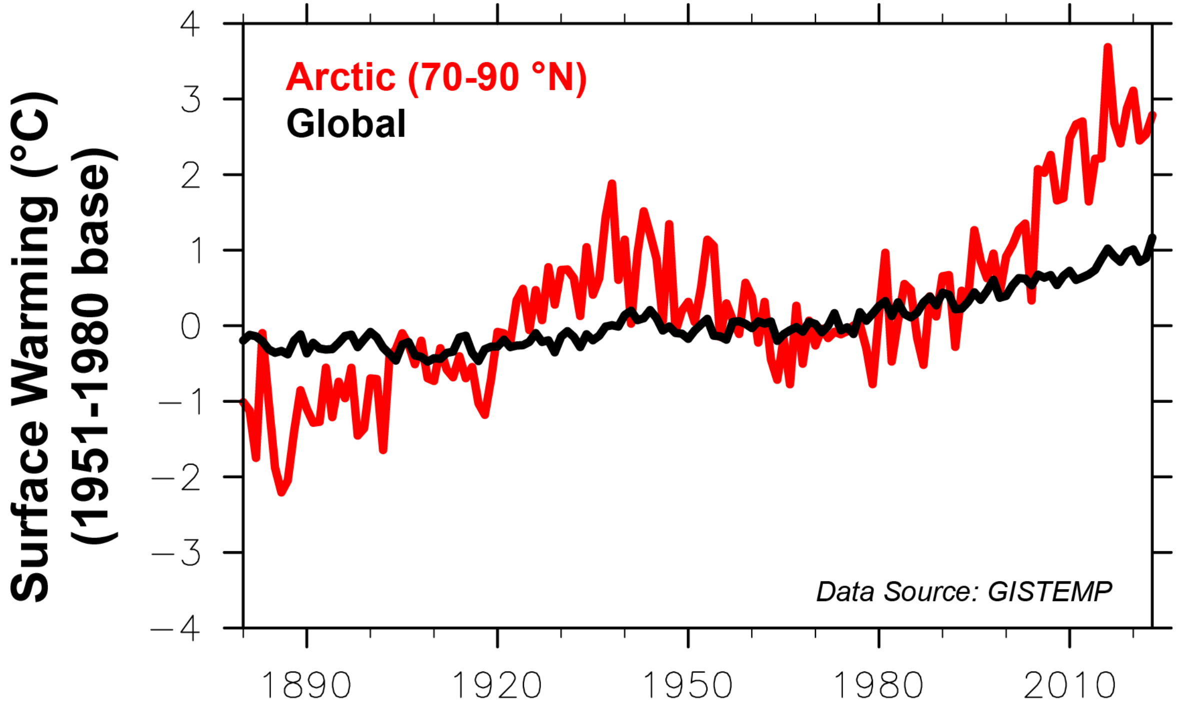
Image: My foot in melting Arctic sea ice

Observed greenhouse gas increases and surface warming almost everywhere, especially in the Arctic

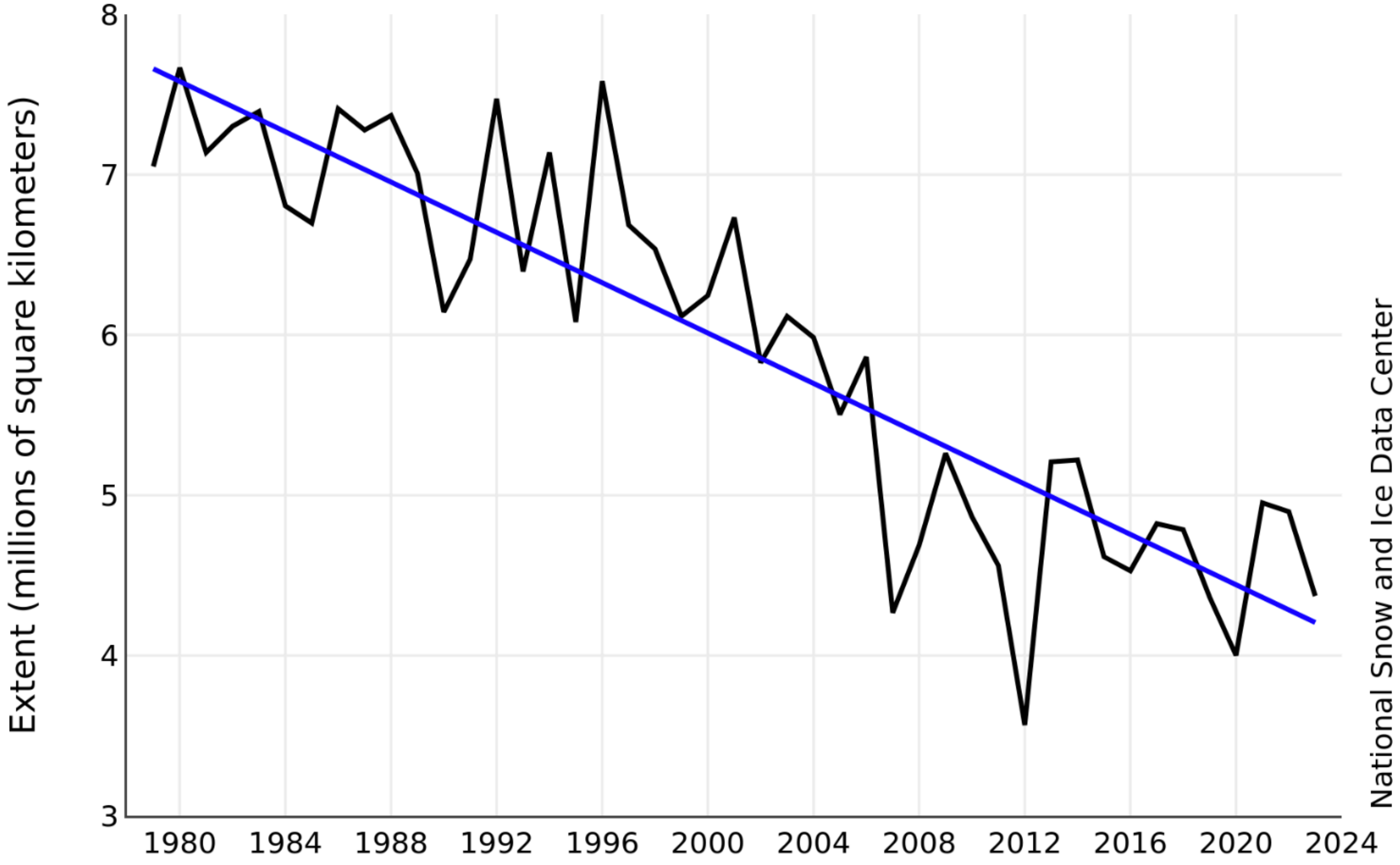
*Latest CO_2 reading: 427.44 ppm



Data Source: [*https://keelingcurve.ucsd.edu/*](https://keelingcurve.ucsd.edu/)



Are you expecting a new September Arctic sea ice record minimum soon? I am.



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Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world

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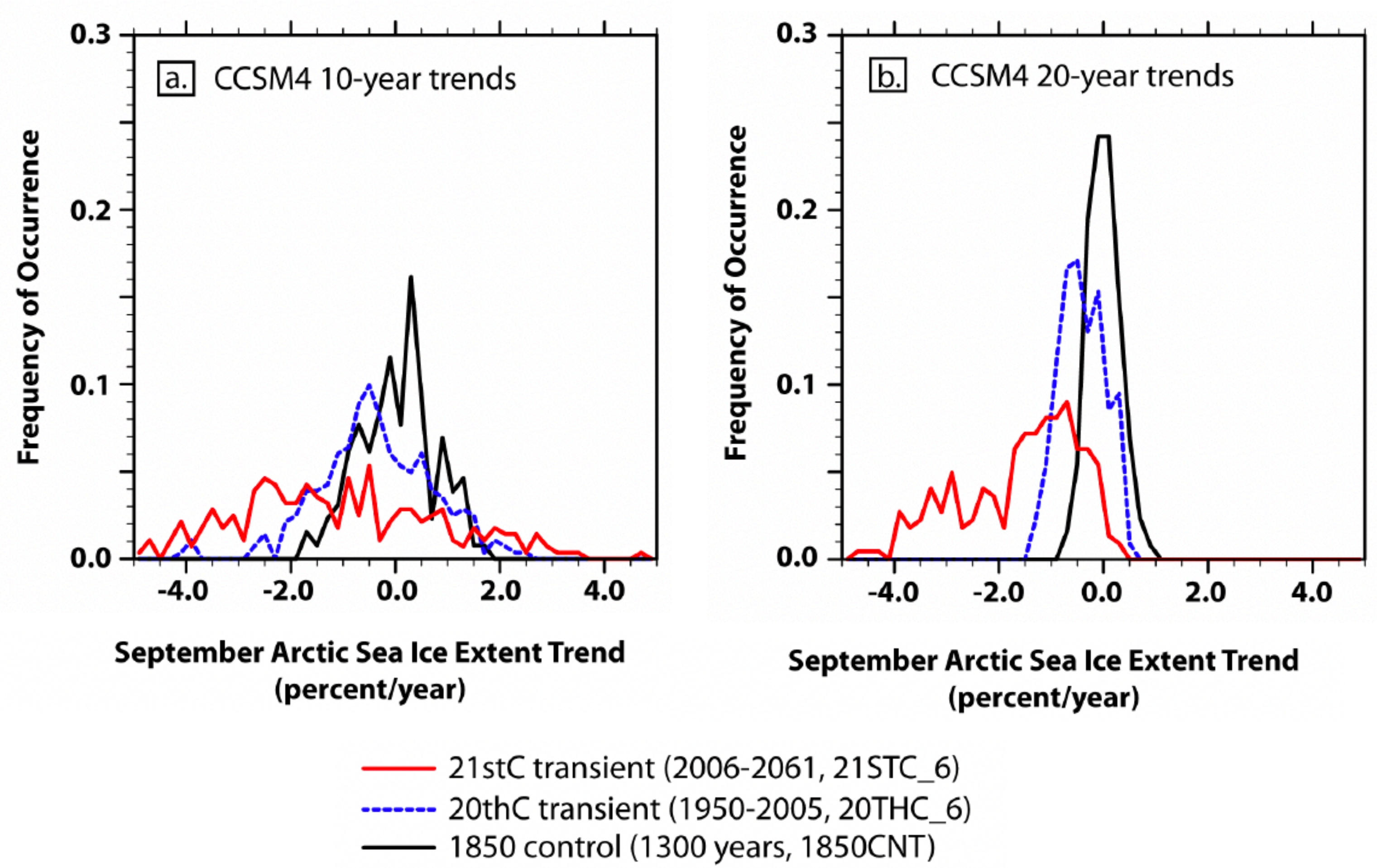
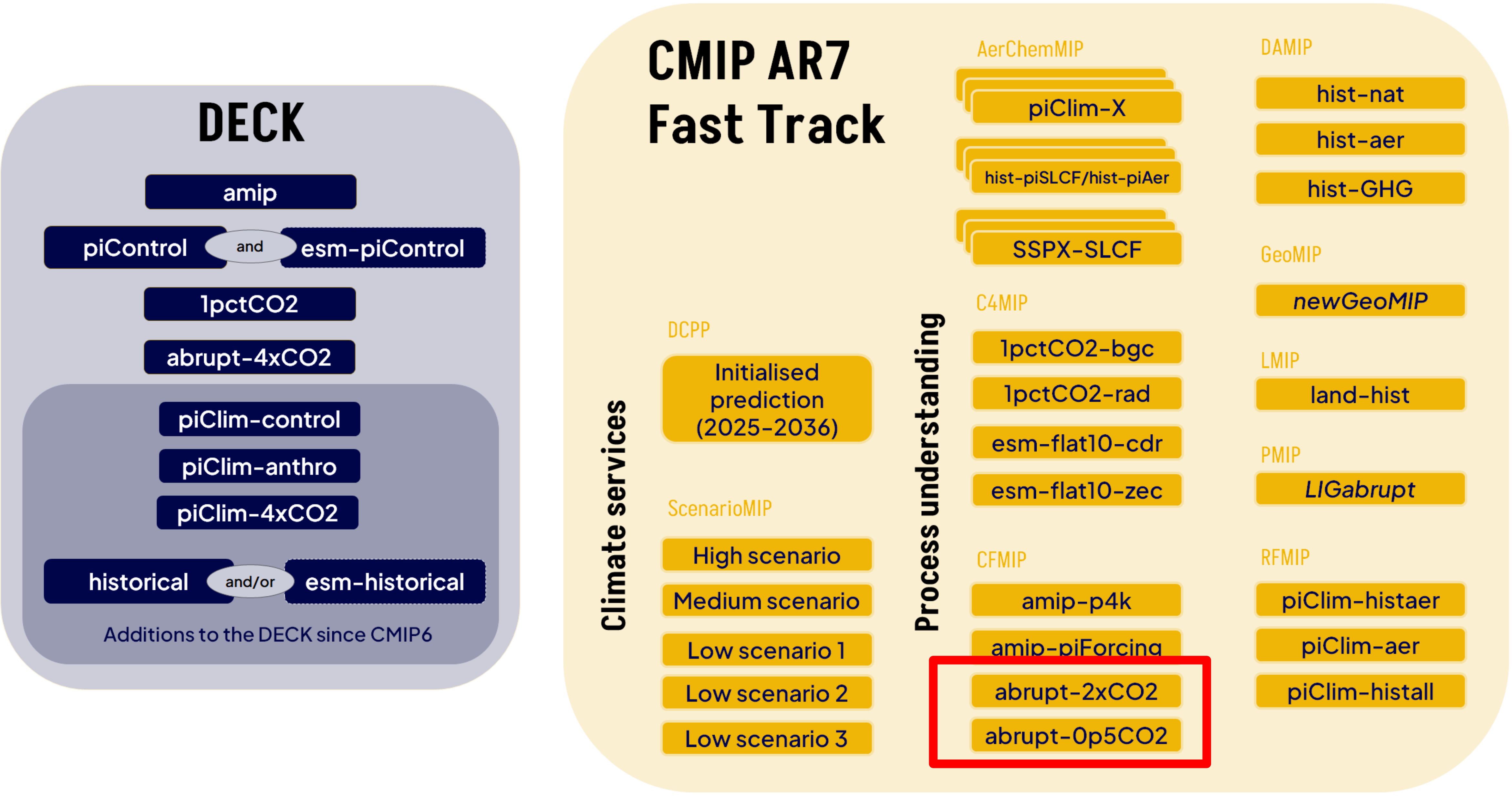



DECK
amip
piControl
and
esm-piControl
1pctCO2
abrupt-4xCO2
piClim-control
piClim-anthro
piClim-4xCO2
historical
and/or
esm-historical
Additions to the DECK since CMIP6
CMIP AR7
Fast Track
Climate services
DCPP
Initialised prediction (2025-2036)
ScenarioMIP
High scenario
Medium scenario
Low scenario 1
Low scenario 2
Low scenario 3
Process understanding
AerChemMIP
piClim-X
hist-piSLCF/hist-piAer
SSPX-SLCF
C4MIP
1pctCO2-bgc
1pctCO2-rad
esm-flat10-cdr
esm-flat10-zec
CFMIP
amip-p4k
amip-piForcing
abrupt-2xCO2
abrupt-0p5CO2
DAMIP
hist-nat
hist-aer
hist-GHG
GeoMIP
newGeoMIP
LMIP
land-hist
PMIP
LIGabrupt
RFMIP
piClim-histaer
piClim-aer
piClim-histall

Challenge: Many experiments only run 150 years (per CMIP protocols).

Solution: Extend existing experiments to provide context on climate sensitivity constraints. (e.g., https://www.longrunmip.org/).

	Description	Reference	tau global	tau 45-90 °N	tau 70-90 °N
CNT	Fully coupled 1850 control	Kay et al. 2015	n/a	n/a	n/a
$2xCO_2$	Abrupt $2xCO_2$ fully coupled	Frey and Kay 2017 (years 1-150); this work (years 151-1000)	219 yrs.	200 yrs.	200 yrs.
$0.5xCO_2$	Abrupt $0.5xCO_2$ fully coupled	Chalmers et al. (years 1-150); this work (years 151-1000)	567 yrs.	437 yrs.	284 yrs.

Table 1. Model runs used in this study. All runs use the Community Earth System Model version 1 Large Ensemble version (CESM1-LE, Kay et al. 2015) at the standard one-degree horizontal resolution. Last four columns on the right provide equilibration timescale (years) for the surface temperature response. The equilibration timescale (tau) found by fitting surface temperature (TS) data over all 1000 years of the simulation to an exponential: TS(year)=aEXP(tau*year).

Long runs more important for cooling than for warming!

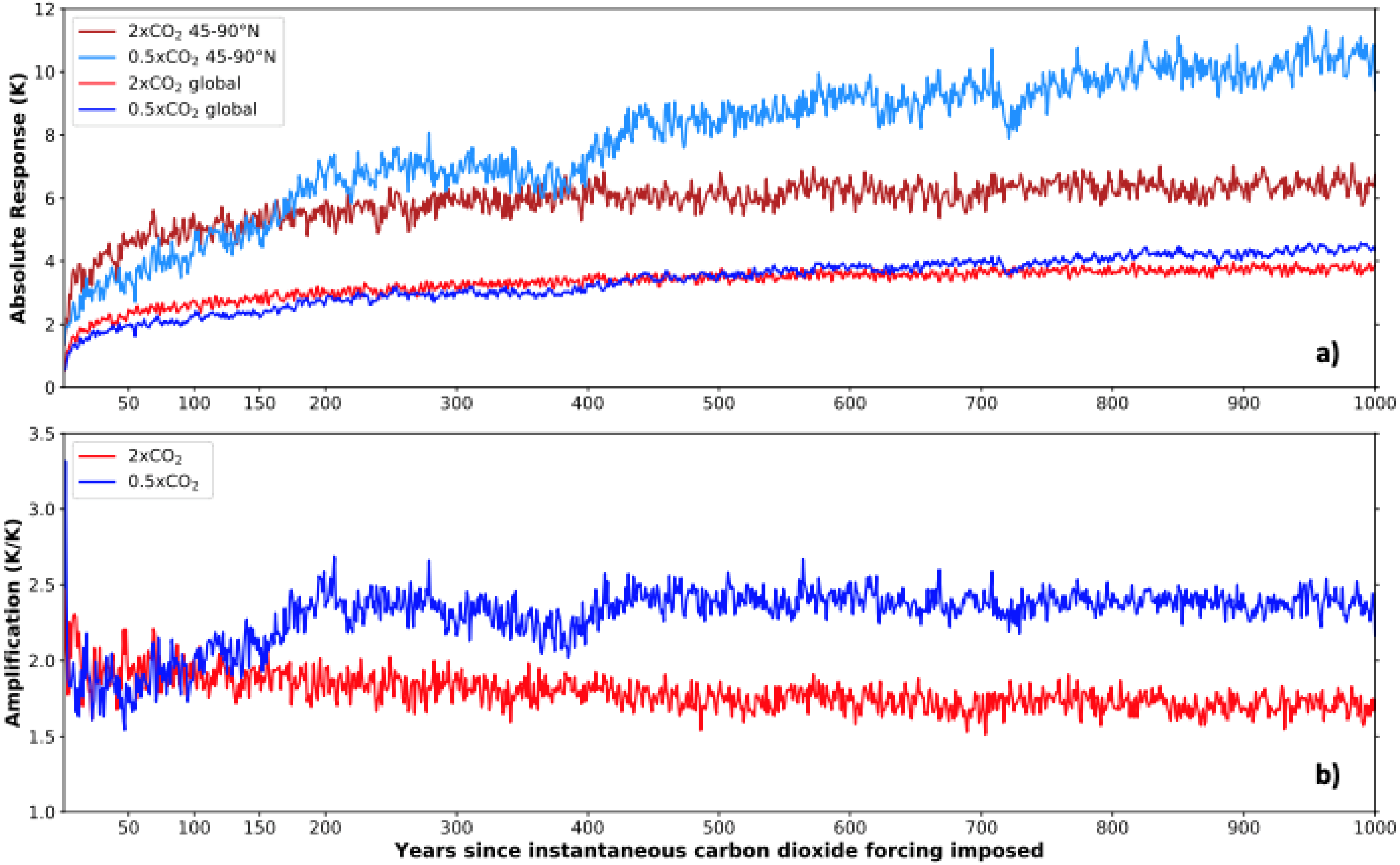
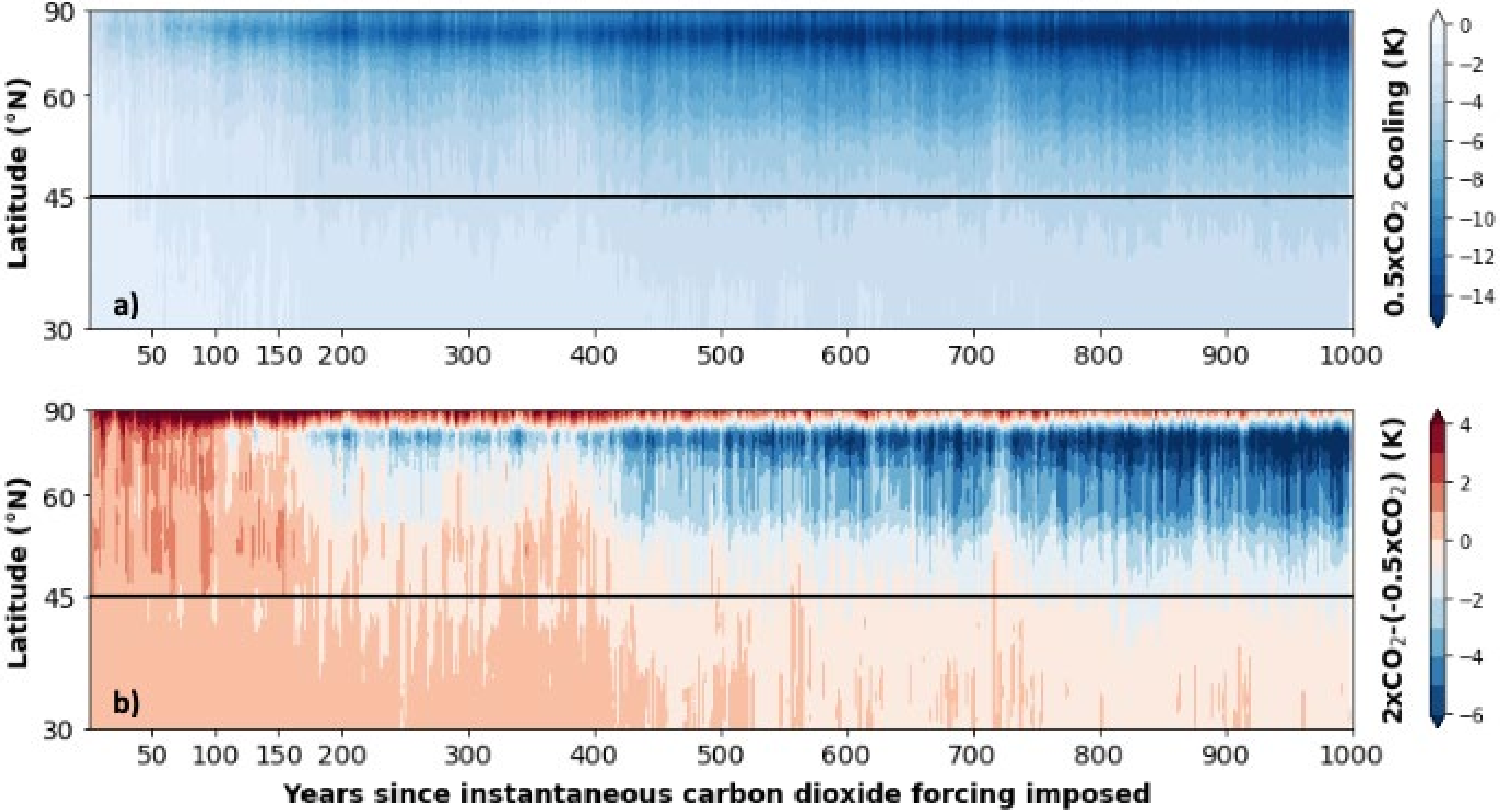


Figure 1. Time series of annual mean surface temperature responses to $2xCO_2$ and $0.5xCO_2$ instantaneous carbon dioxide forcing: a) Global and high northern latitudes (45-90 °N) absolute response; b) Amplification, i.e., high northern latitude values divided by global values. All responses are relative to the 1850 control run (CNT years 400-1399, see Table 1).



a)
b)
Latitude (°N)
90
60
45
30
50
100
150
200
300
400
500
600
700
800
900
1000
0.5xCO2 Cooling (K)
0
−2
−4
−6
−8
−10
−12
−14
2xCO2-(-0.5xCO2) (K)
4
2
0
−2
−4
−6
Years since instantaneous carbon dioxide forcing imposed

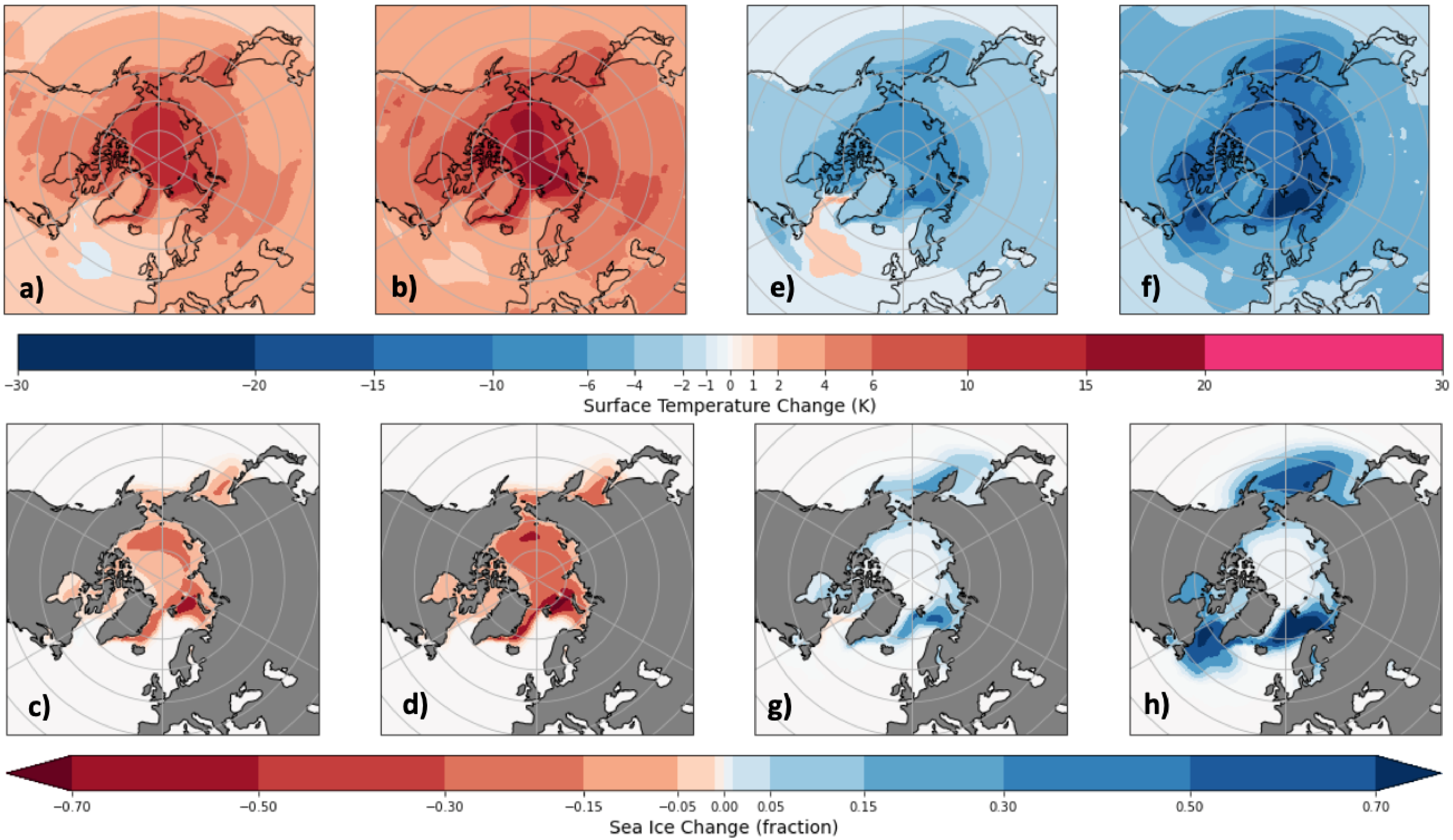


Figure 3. Polar maps of annual high northern latitude response: a) 2xCO_2 surface temperature early (years 1-150), b) 2xCO_2 surface temperature late (years 850-100), c) 0.5xCO_2 surface temperature early, d) 0.5xCO_2 surface temperature late, e-h) as in a-d) but for sea ice. All responses are relative to the 1850 control (years 400-1399 CNT, Table 1).

Why more cooling than warming?

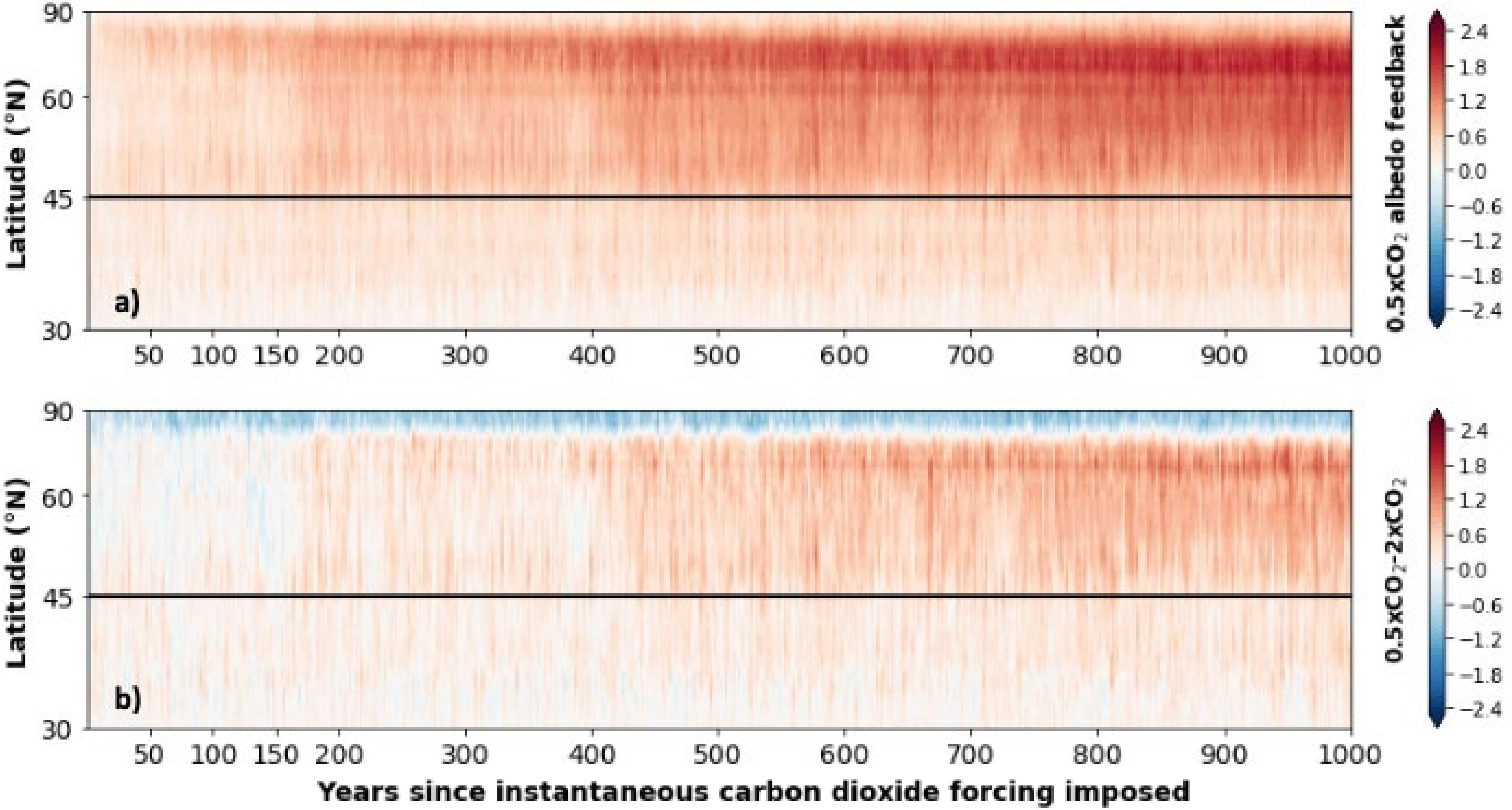
It's not the CO_2 radiative forcing.

$2xCO_2$ forcing >> 0.5x CO_2 forcing

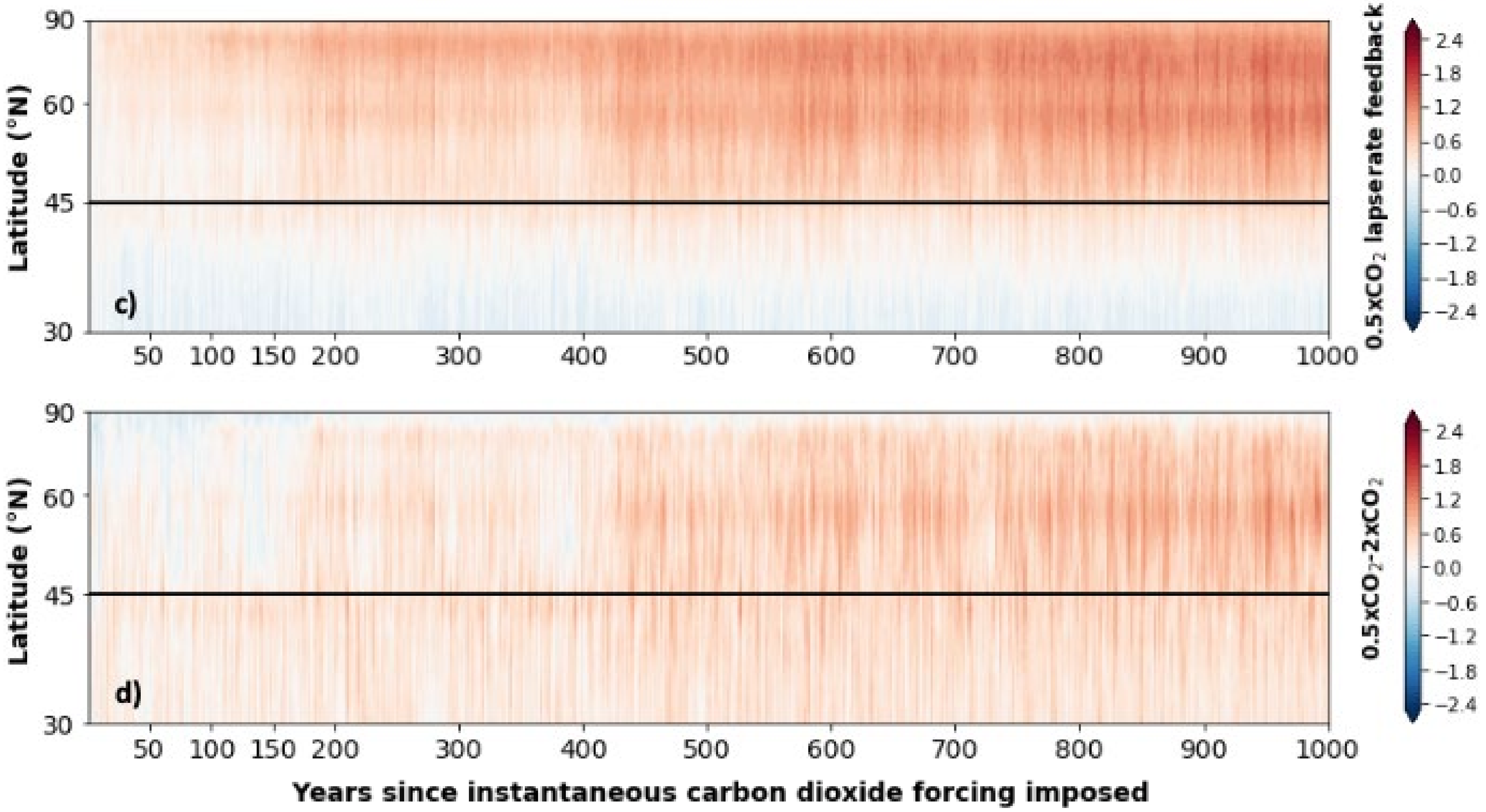
Description	CNT_2×CO_2	CNT_0.5×CO_2
Global mean surface temperature response (K)	2.75 ± 0.03	−2.28 ± 0.03
ERF_fSST (W m^{-2})	3.82 ± 0.05	−3.44 ± 0.06
ERF_reg (W m^{-2})	3.84 ± 0.69	−3.26 ± 0.58

From Chalmers et al. 2022 – Table 2

It’s the sea-ice associated feedbacks: surface albedo and lapse rate



It’s the sea-ice associated feedbacks: surface albedo and lapse rate



Summary

- **After 150 years – CESM1 shows more 2xCO_2 warming than 0.5xCO_2 cooling due to stronger 2xCO_2 radiative forcing and more positive 2xCO_2 feedbacks.**
- **After 1000 years – CESM1 shows more 0.5xCO_2 cooling than 2xCO_2 warming due to feedbacks associated with sea ice expansion (positive lapse rate and surface albedo feedbacks).**
- **How do we use 0.5xCO_2 experiments (with LGM) to constrain climate sensitivity?**

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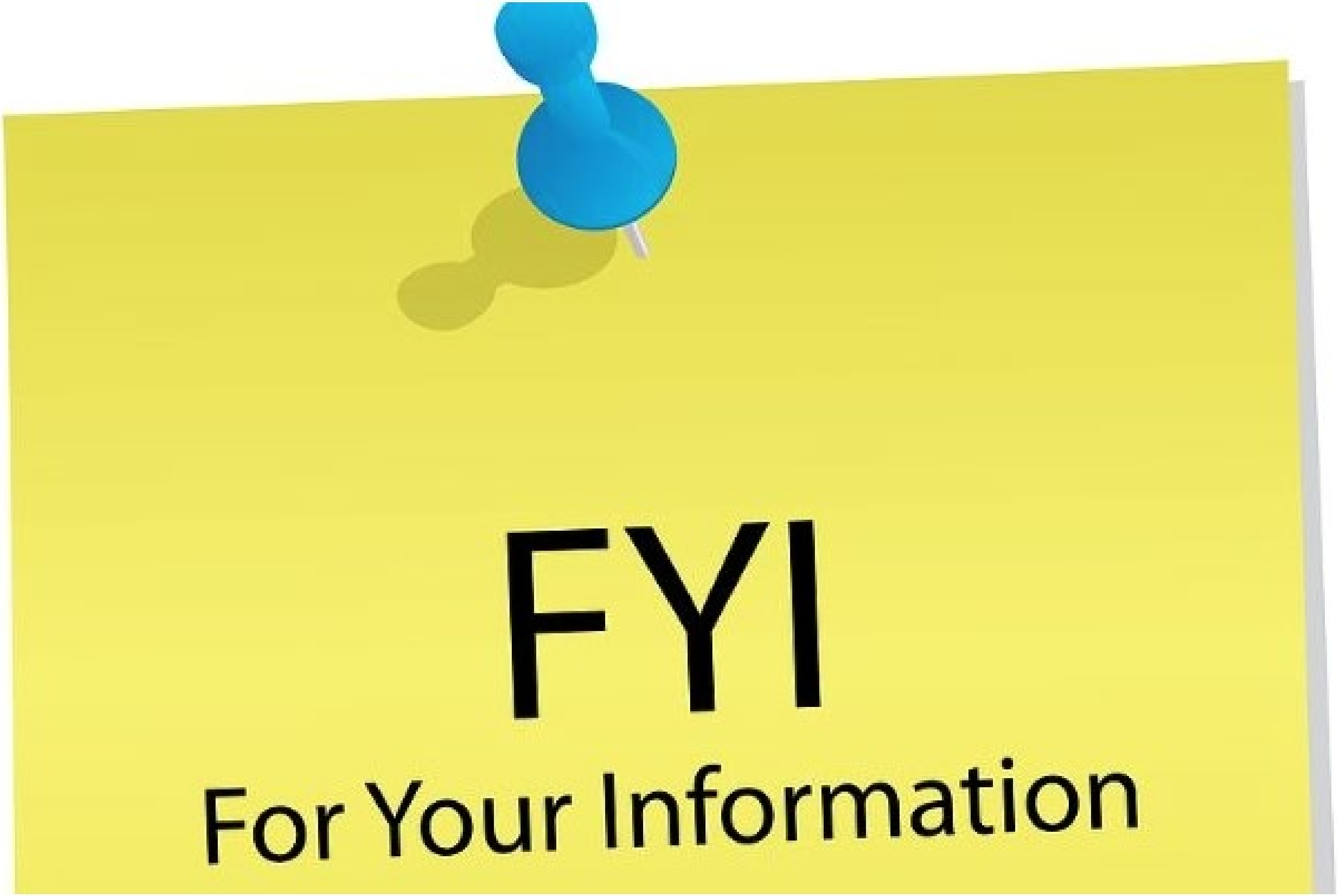
U.S. National Science Foundation


FYI
For Your Information

Climate models have long shown greater-than-global Arctic surface warming due to unique positive feedbacks (surface albedo, lapse rate)

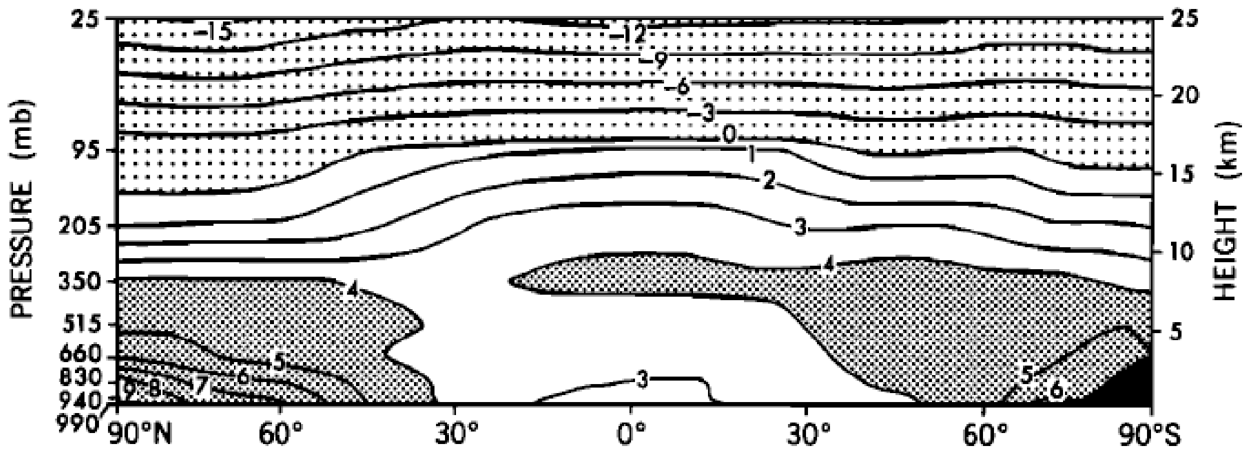


Fig. 14. Latitude height distribution of the zonal mean difference in annual mean temperature (degrees Kelvin) of the model atmosphere between the 4 × CO_2 and 1 × CO_2 experiment.

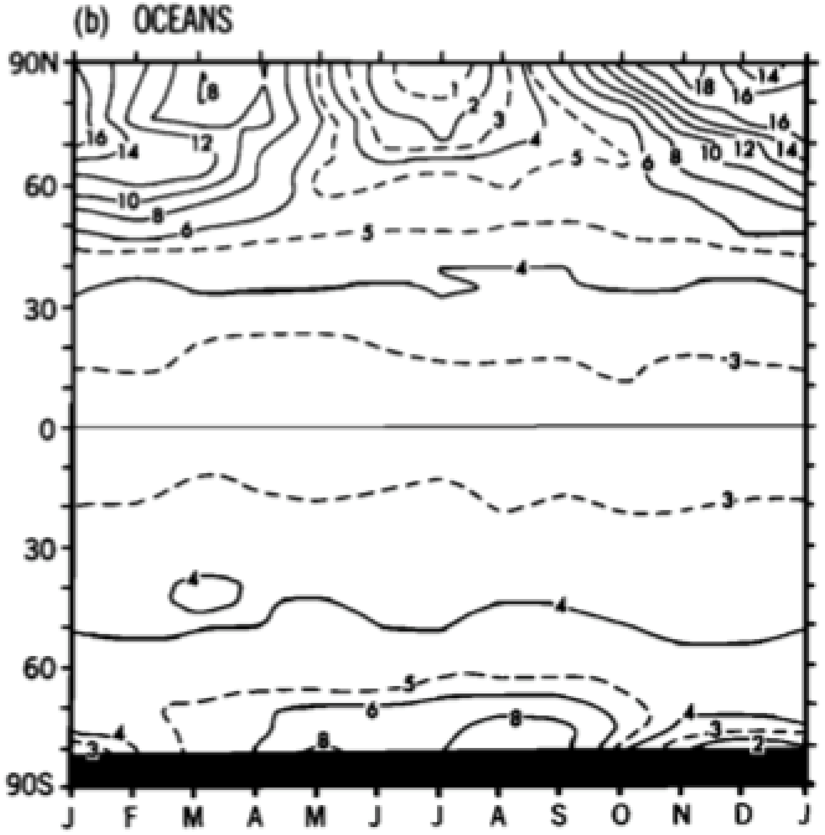
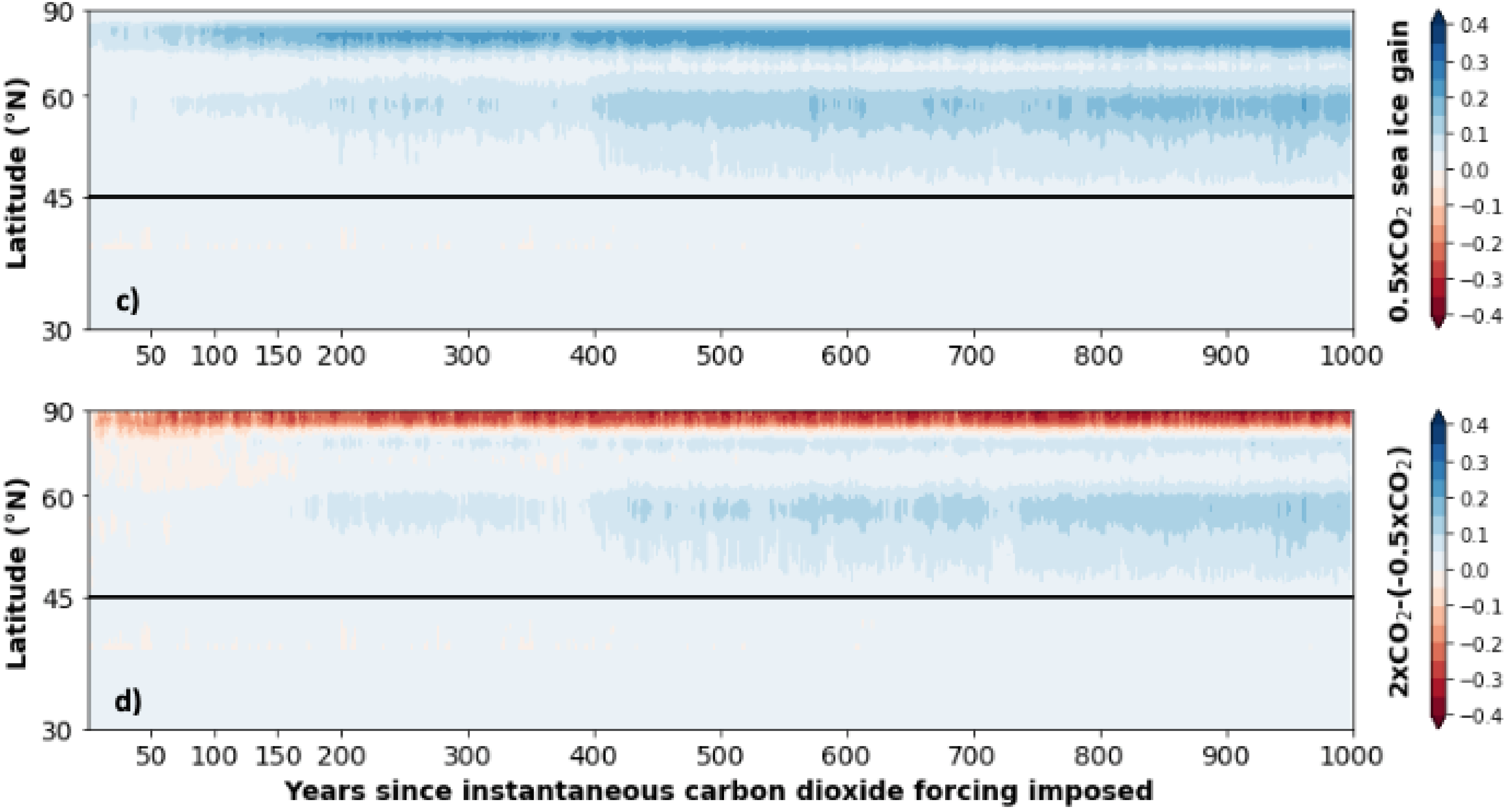


Fig. 16. Latitude-time distribution of zonal mean difference in surface air temperature (degrees Kelvin) between the 4 × CO_2 and 1 × CO_2 experiment. (*a*) Oceans and continents, (*b*) oceans, and (*c*) continents. The difference is computed at the lowest finite difference level located at about 70 m above the earth's surface.

Figures from Manabe and Stouffer 1980
Similar results in many more recent studies.



90
60
45
30
Latitude (°N)
c)
50 100 150 200 300 400 500 600 700 800 900 1000
0.5xCO$_2$ sea ice gain
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
90
60
45
30
Latitude (°N)
d)
50 100 150 200 300 400 500 600 700 800 900 1000
Years since instantaneous carbon dioxide forcing imposed
2xCO$_2$-(-0.5xCO$_2$)
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4

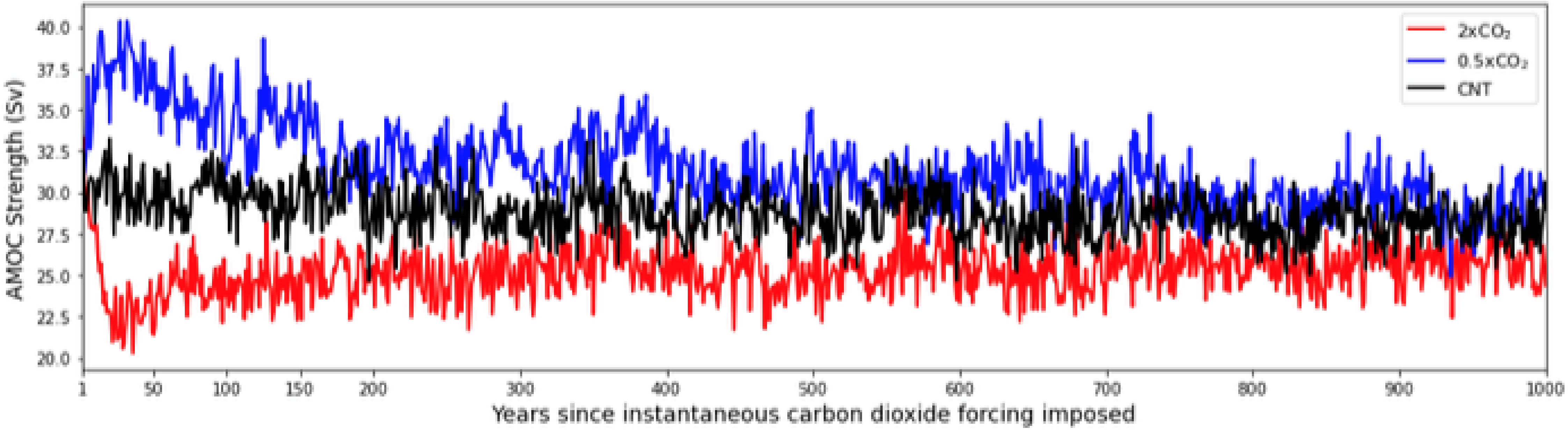


Figure 4. Timeseries of Annual Mean Max Atlantic Meridional Overturning Circulation (AMOC) strength. AMOC strength defined as the maximum meridional overturning in Sverdrups (Sv) in the North Atlantic (30 to 55 degrees N and 800-2,000 meters depth). CNT plotted for years 400-1399.

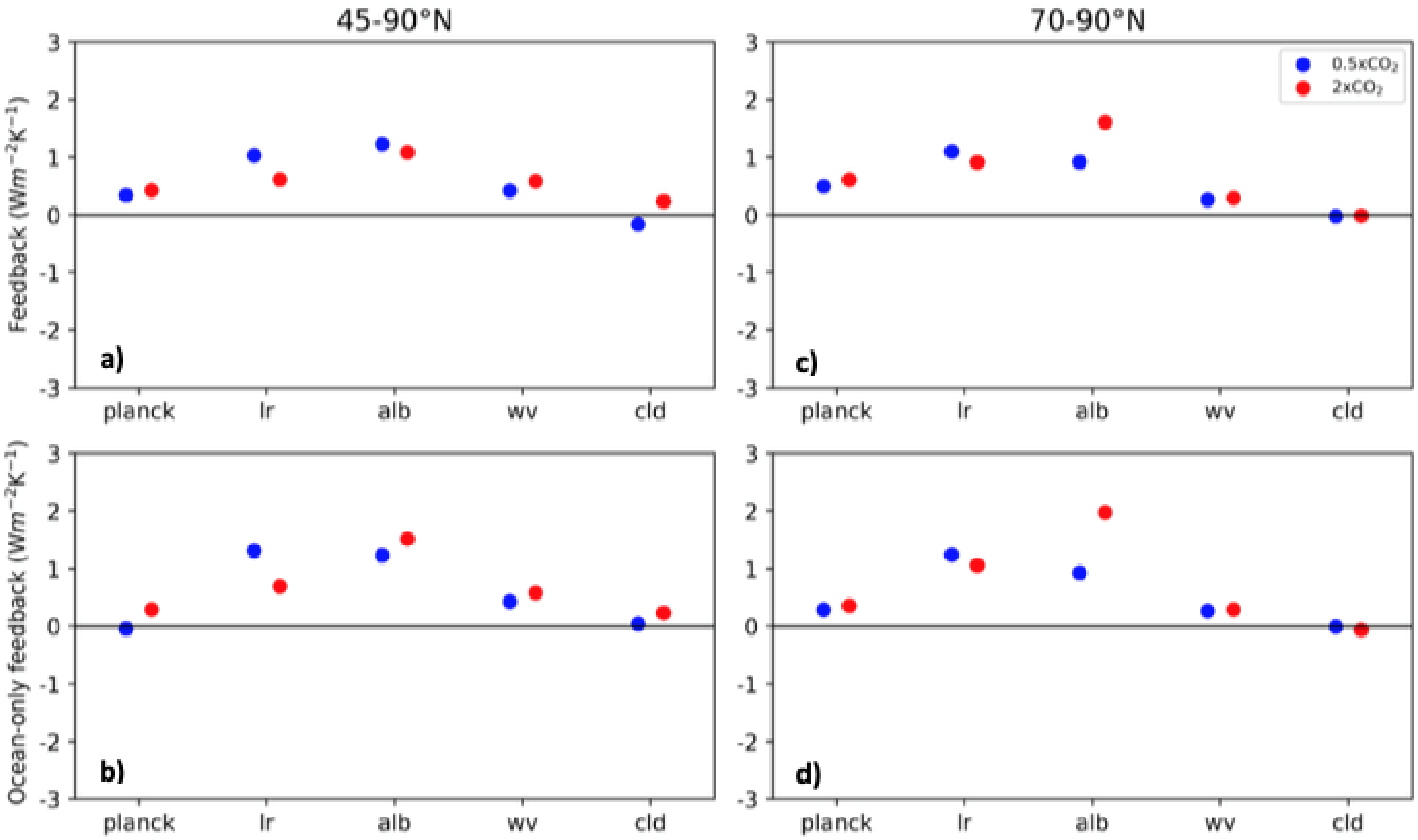
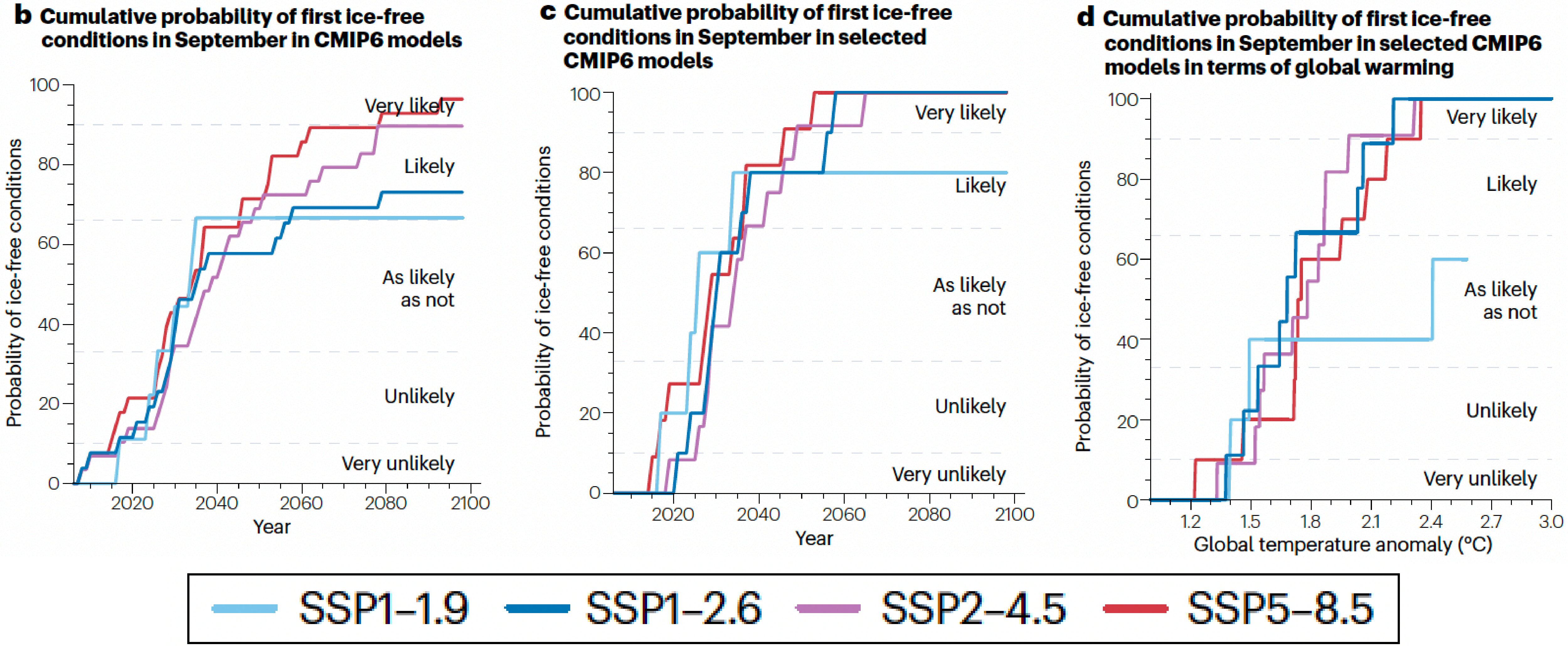


Figure 5. High Northern Hemisphere Radiative Feedback Parameters: a) 45-90 °N, b) 70-90 °N, c-d) as in a-b) but for ocean only. Feedback parameters calculated for years 850-999 with CNT years 400-549 as a reference climate for the Planck ("planck"), lapse rate ("lr"), surface albedo ("alb"), water vapor ("wv") and cloud ("cld") feedbacks.



"Although definition differences and model selection influence the specifics of ice-free predictions, ***they all indicate that ice-free conditions tend to occur at least once by 2050 under all assessed scenarios****, and become a frequent occurrence thereafter under all scenarios except SSP1-1.9."*

Figure 3 from Jahn, Holland, and Kay (2024)

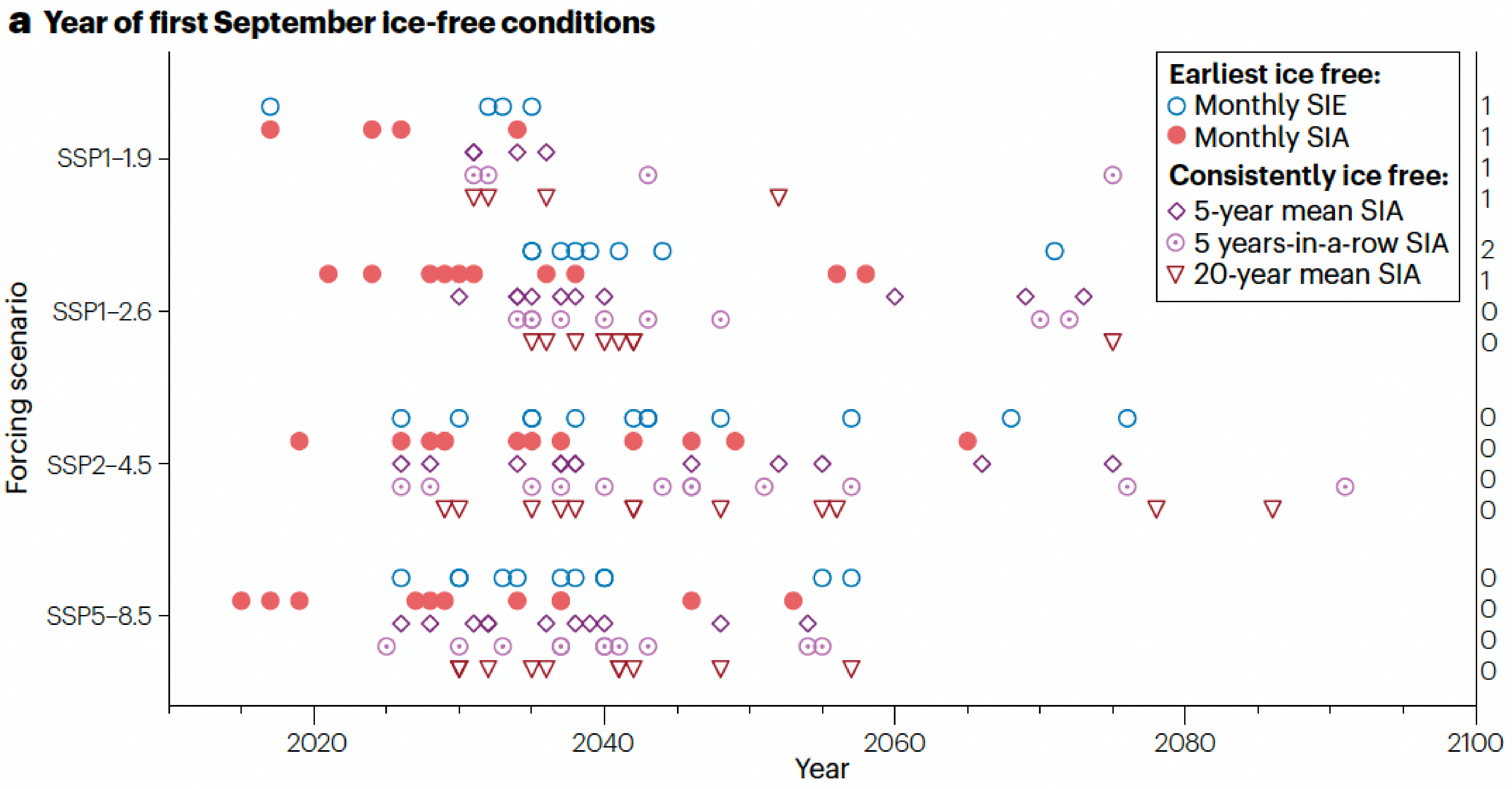


Figure 3 from Jahn, Holland, and Kay (2024)