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Hemispheric asymmetry of the Hadley-cell change in CO_2 removal scenario

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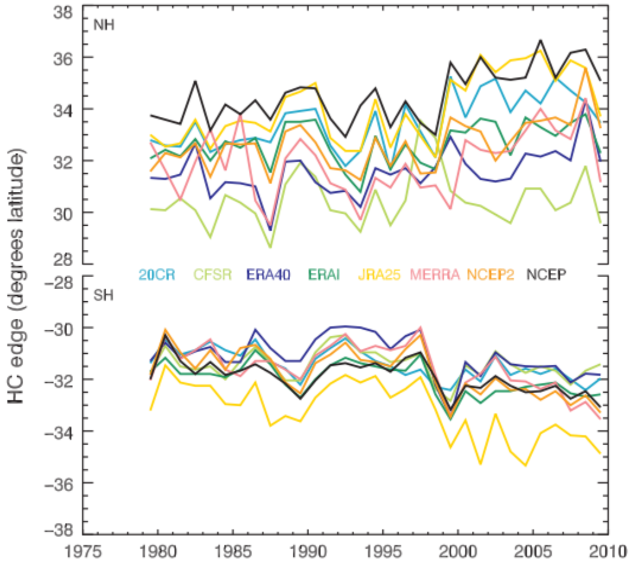
Introduction

The Hadley-cell (HC) edge

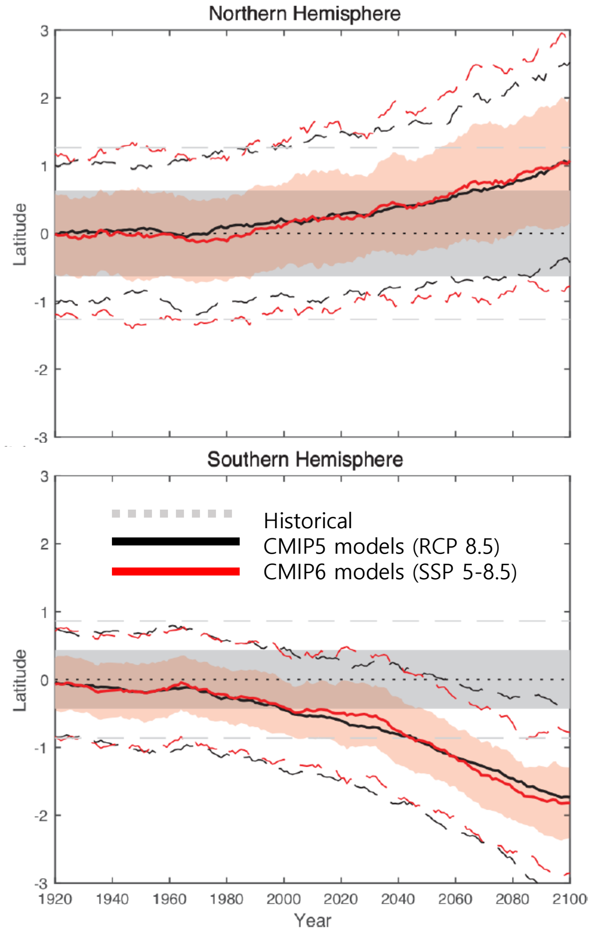
- The Hadley circulation (HC) shifts poleward in response to the increasing CO_2 in observations and climate models.

[Reanalysis]



Lu et al. (2014)

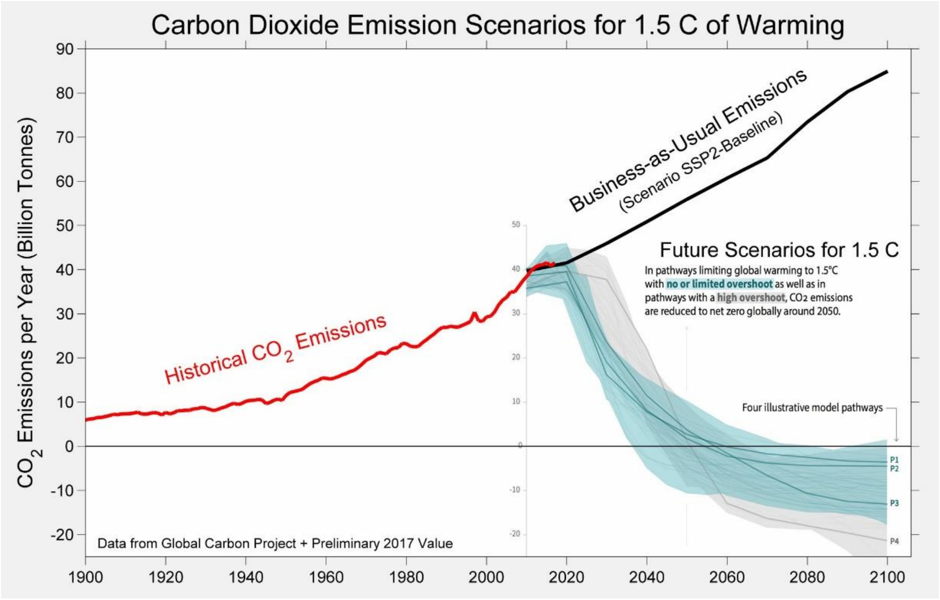
[Climate Projection]



Grise and Davis (2020)

Reversibility of the climate system

- For effective climate mitigation, knowledge of the climate system responses and reversibility to CO_2 removal is essential.

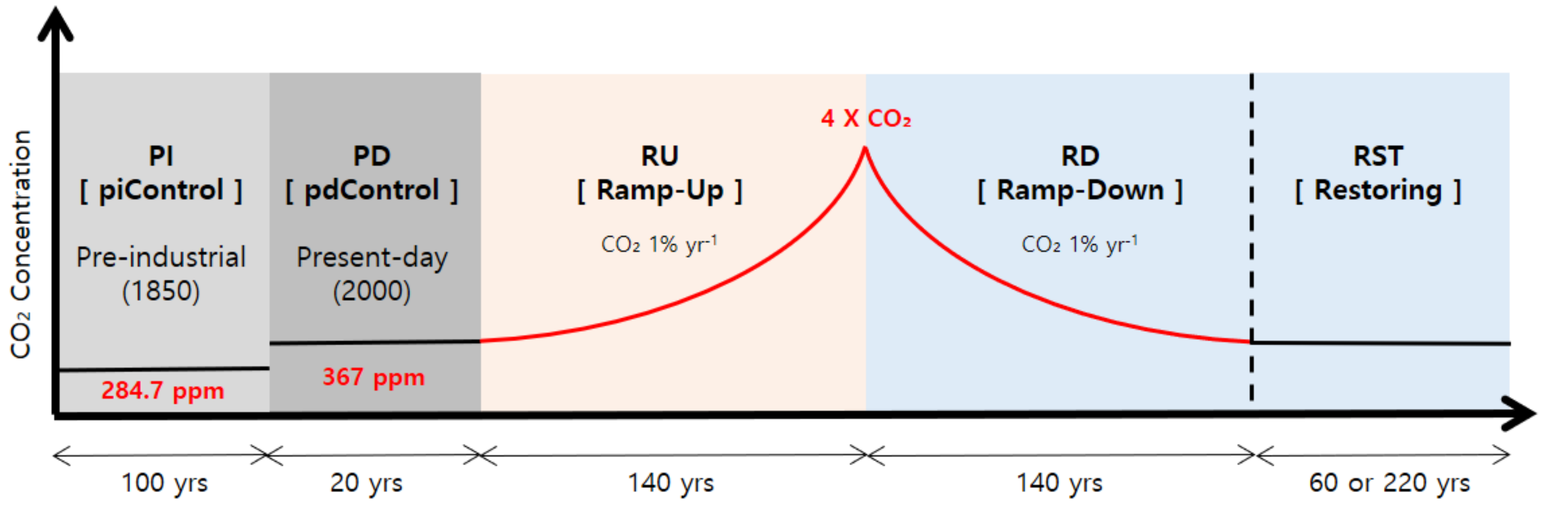


IPCC (2018)

Does HC edge exhibit the reversibility when CO_2 increases and then decreases?

Data and Methods

CO_2 removal experiments



Data	Institution	Model	Ensembles	Resolutions (nlat X nlon X nlev)	Initial CO2 concentration
CESM-LE	NCAR	CESM 1.2.2	28 ensesmbles	192 X 288 X 19	367 ppmv (2000 year)
CMIP6	CSIRO	ACCESS-ESM1-5	r1i1p1f1	144 X 192 X 19	284.7 ppm (1850 year)
	CCCma	CanESM5	r1i1p2f1	64 X 128 X 19	
	NCAR	CESM2	r1i1p1f1	192 X 288 X 19	
	NOAA-GFDL	GFDL-ESM4	r1i1p1f1	180 X 288 X 19	
	MIROC	MIROC-ES2L	r1i1p1f2	64 X 128 X 19	
	NCC	NorESM2-LM	r1i1p1f1	96 X 144 X 19	
	MOHC	UKESM1-0-LL	r1i1p1f2	64 X 128 X 19	

HC width & edge

$$\psi 500 = \frac{2\pi a \cos\varphi}{g} \int_{10\mathrm{hPa}}^{500\mathrm{hPa}} \overline{[v]}\, dp$$

HC edge

; the zero-crossing latitude of 500hPa mass streamfunction

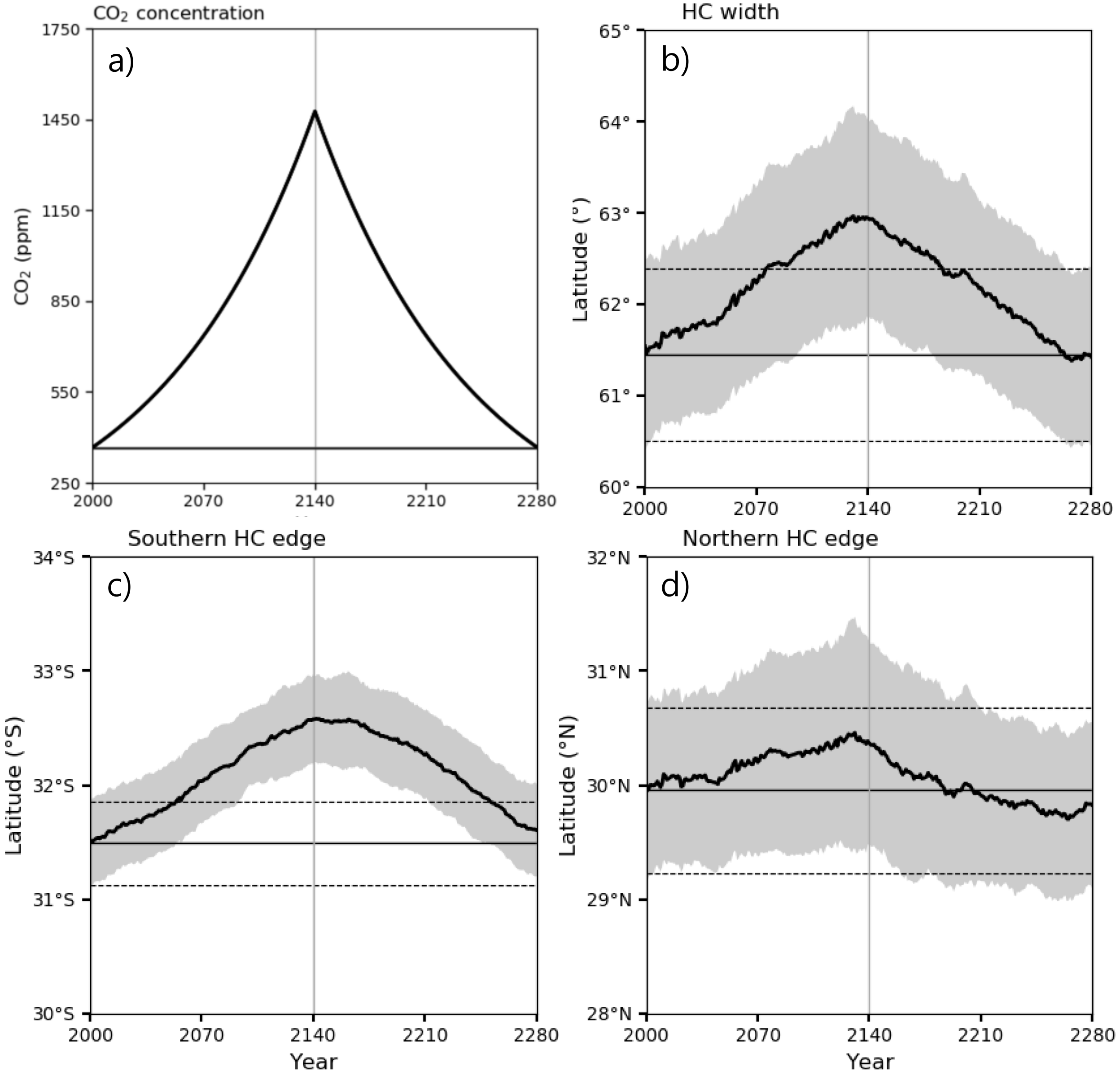
HC width

; the range of latitude between Southern and Northern HC edges

Global Dryness Index

; the frequency of the occurrence of dry months defined as a month where the monthly rainfall is less than 0.1 mm/day (Lau and Kim, 2015)

Changes of Hadley cell edges to the CO_2 forcing



HC width ≡ SH HC edge ~ NH HC edge

Lines: ensemble mean
Shadings: 1-std ranges across the ensembles
(Smoothed with a 11-yr running mean)

- While the HC-width change is symmetric in response to the increase and decrease of CO_2, **the HC edges in southern and northern hemispheres exhibit less- and over-recovery after CO_2 removal**.

What controls the HC responses to the CO_2 forcing - Baroclinicity

Baroclinicity criterion

$$C = \frac{f^2}{\beta g H} \frac{(U_{500} - U_{850})}{(\theta_{500} - \theta_{850})/\Theta_0}$$

(between 20 ~ 40ºLat) Philips (1954)

$$\delta A = A_{EXP} - A_{PD}$$

$$\delta C_{all} = \delta \left[\frac{f^2}{\beta g H} \frac{(U_{500} - U_{850})}{(\theta_{500} - \theta_{850})/\Theta_0} \right]$$

$if\ \delta(U_{500} - U_{850}) = 0,$

$$\delta C_{st} \approx -\frac{f^2}{\beta g H} \frac{(U_{500} - U_{850})_{PD}\, \delta(\theta_{500} - \theta_{850})}{(\theta_{500} - \theta_{850})^2_{PD}/\Theta_0}$$

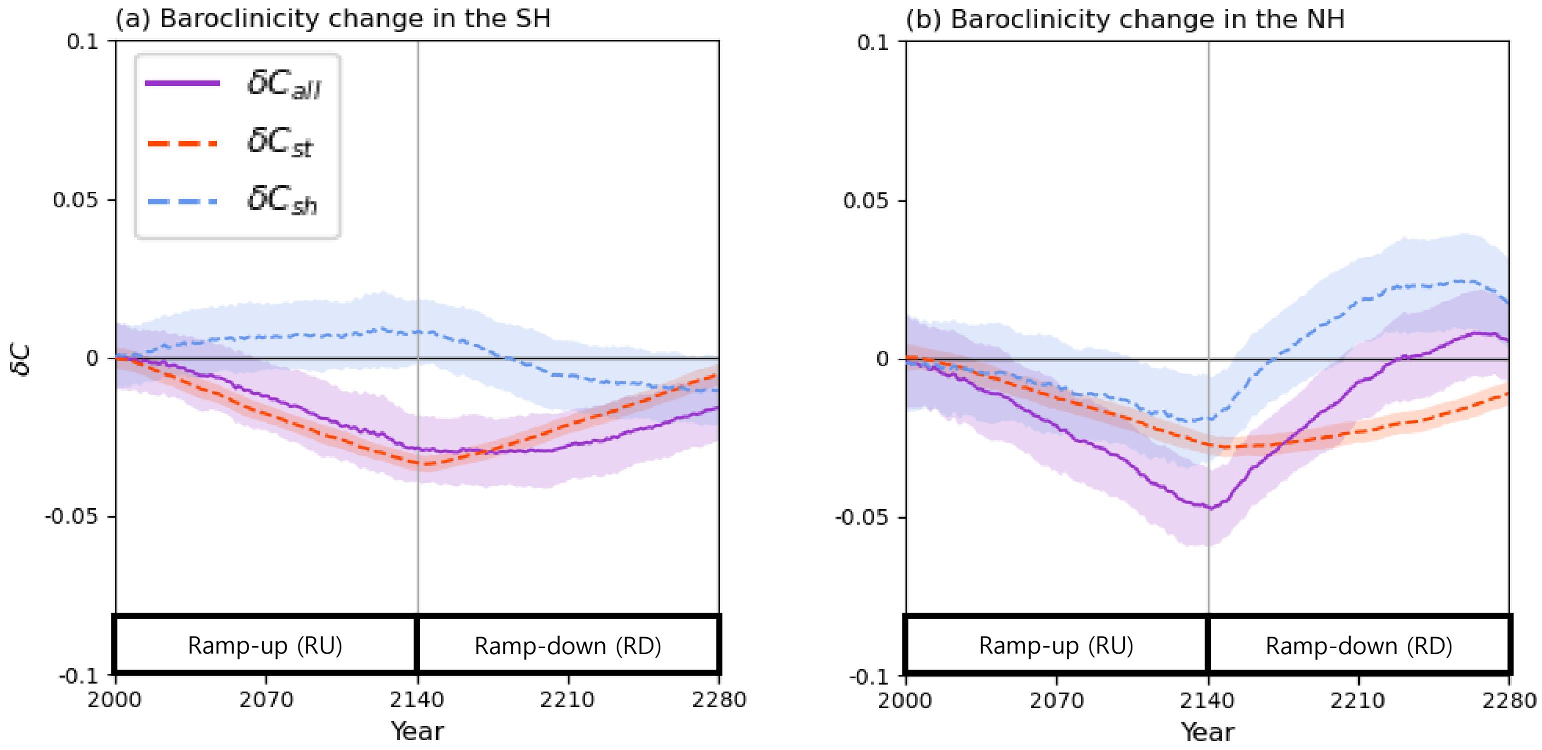
$if\ \delta(\theta_{500} - \theta_{850}) = 0,$

$$\delta C_{sh} = \frac{f^2}{\beta g H} \frac{\delta(U_{500} - U_{850})}{(\theta_{500} - \theta_{850})_{PD}/\Theta_0}$$

decreasing baroclinicity	increasing static stability decreasing wind shear

HC cell poleward shifts

Baroclinicity response

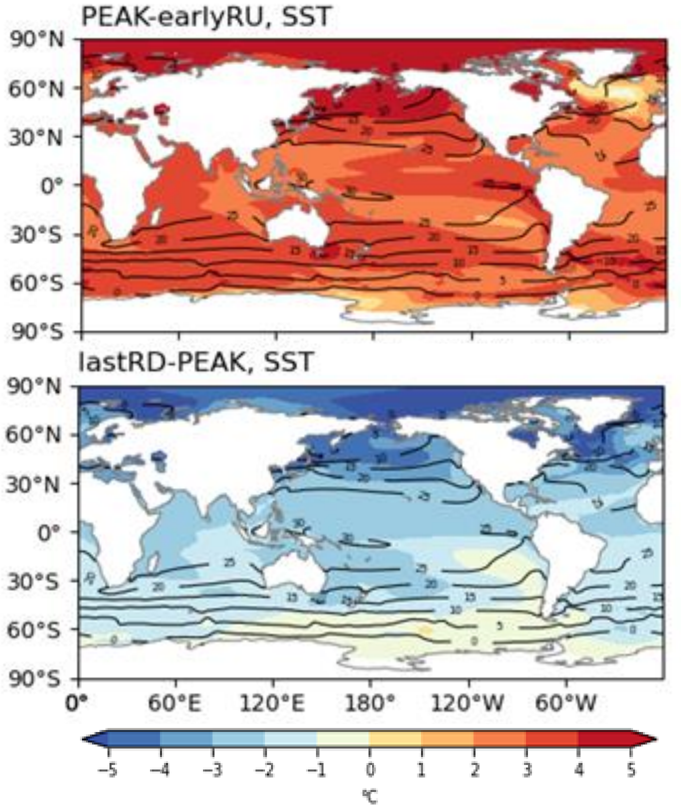


Lines: ensemble mean
Shadings: 1-std ranges across the ensembles
(Smoothed with a 11-yr running mean)

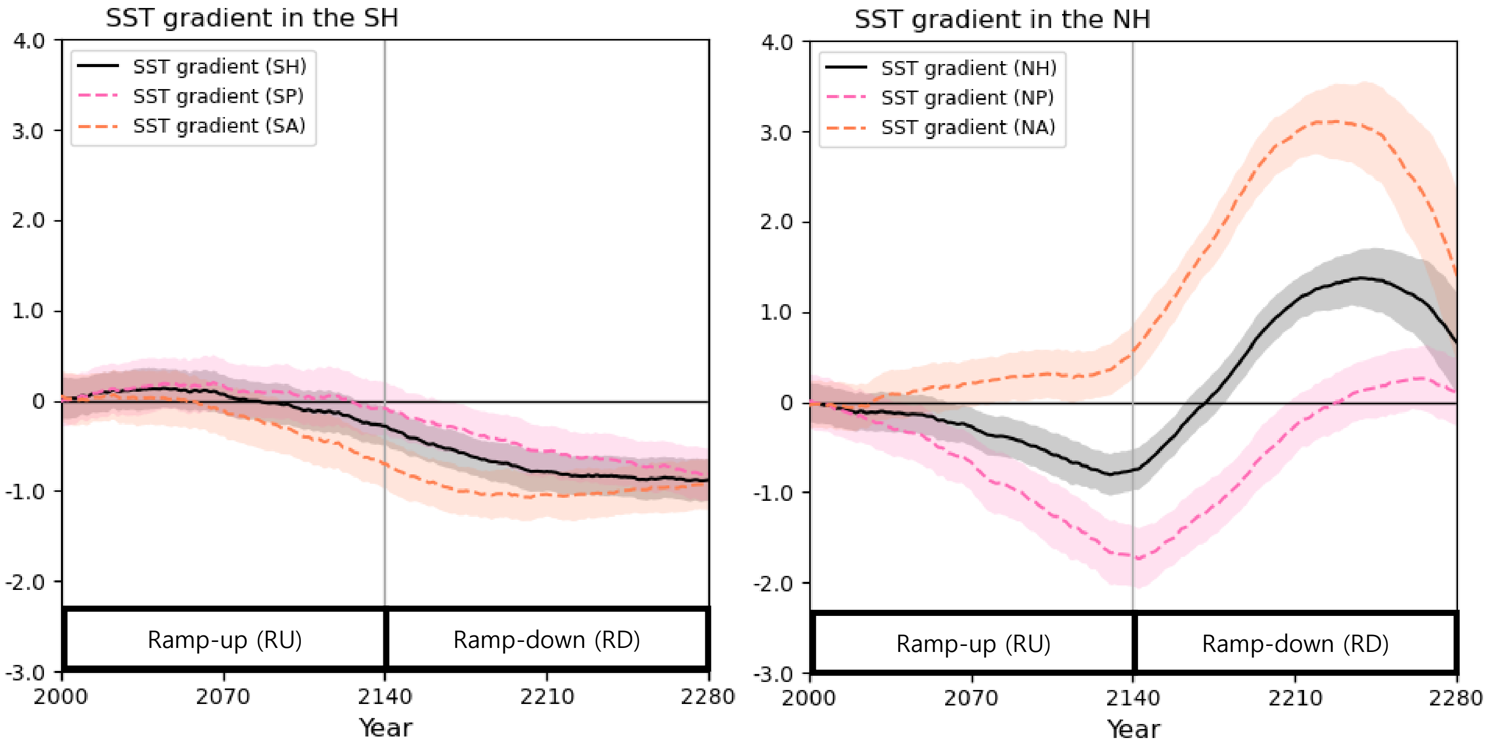
- While the baroclinicity due to the static stability monotonically changes in both hemisphere, the changes of the **baroclinicity due to the vertical wind shear exhibits a distinct hemispheric asymmetry.**

What controls the HC responses to the CO_2 forcing - SST

SST distribution



SST gradient

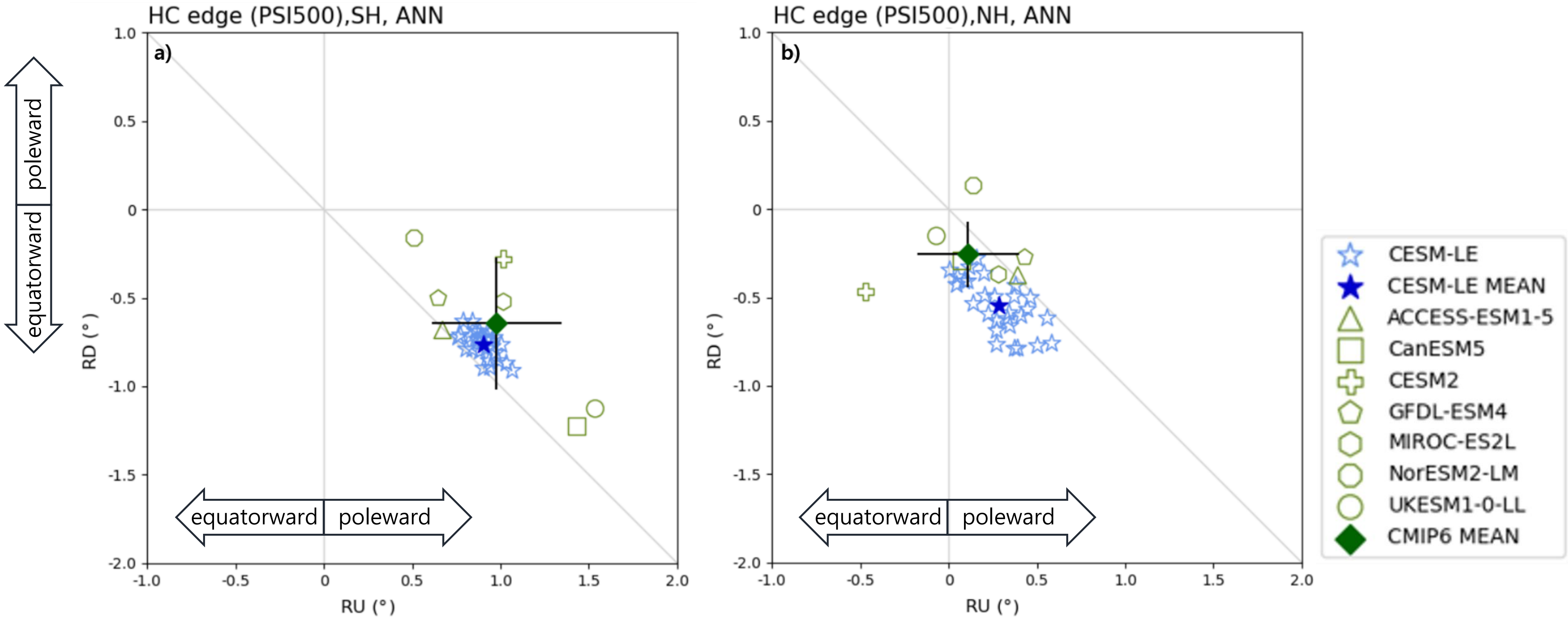


line: ensemble mean
shading: 1-std ranges across the ensembles
(smoothed with a 11-yr running mean)

SP: 130˚E–80˚W, SA: 70˚W–20˚E
NP: 120˚E–90˚W, NA: 70˚W–20˚E

- **The SST gradient over North Atlantic** may be relevant to a rapid recovery of the vertical wind shear in NH, resulting in the hemispheric asymmetry of the HC-edge changes.

Generalize the results of the CESM-LE with CMIP6 models



- The multi model mean of the CMIP6 models also shows the poleward and equatorward shifts during RU and RD periods, respectively.
- **The linear relationship between the RU and RD periods implies the symmetric change of HC edge.** However, its northern counterpart does not show the relationship, which means **the irreversible change of the NH HC edge.**

Conclusions and Discussion

The poleward shifted HC edges in both hemispheres in warming climate do not return to their present-day states after CO_2 removal with a hemispheric asymmetry.

The irreversible HC edge changes are associated with wind shear change induced by the irreversible ocean change after CO_2 removal.

Multi model mean of CMIP6 also shows the poleward and equatorward shift during RU and RD period.