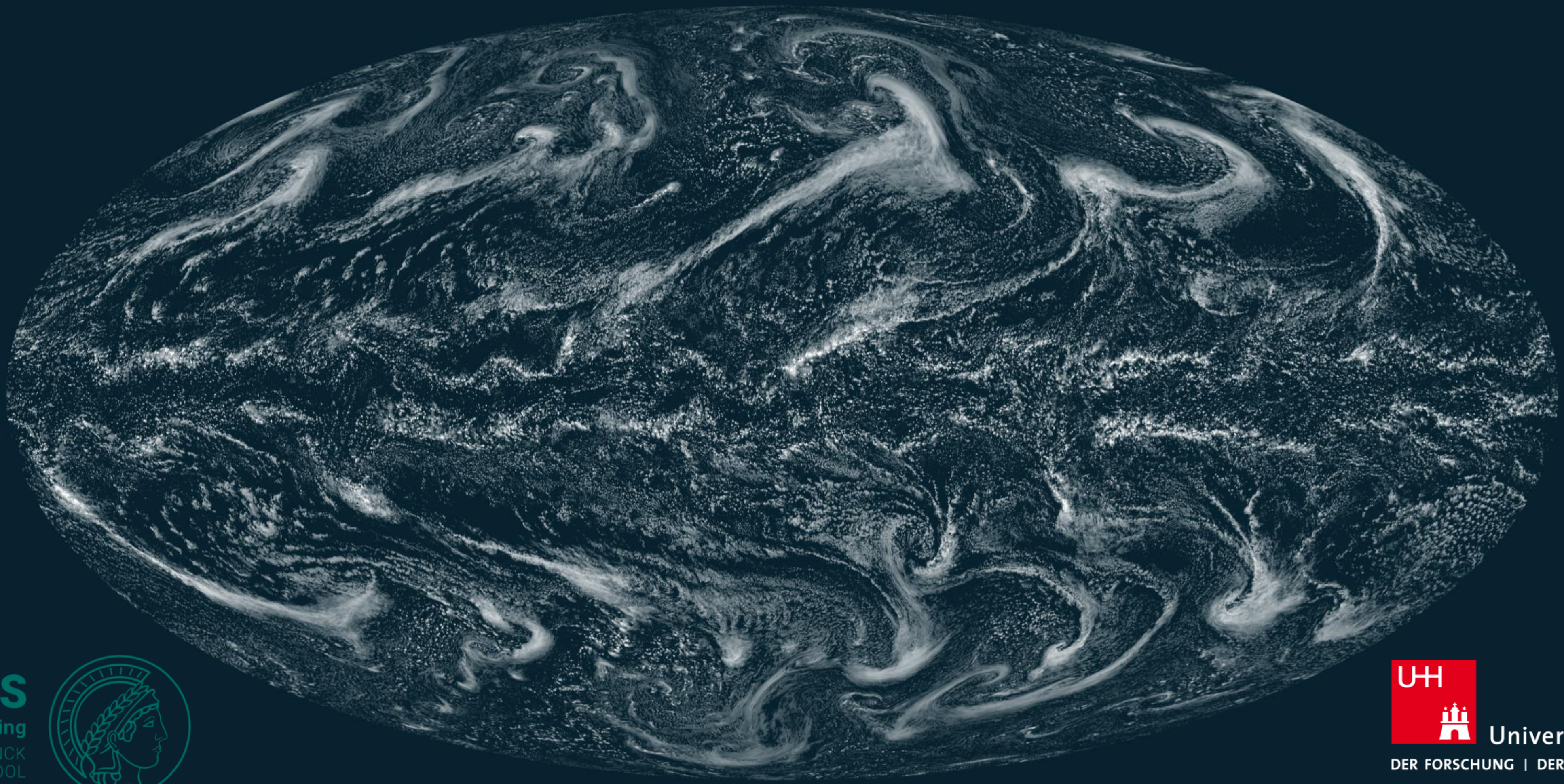
Why the Tropical High-Cloud Feedback is Positive

Jakob Deutloff, Julia Windmiller, Stefan A. Bühler, Ann Kristin Naumann



IMPRS on Earth System Modelling
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

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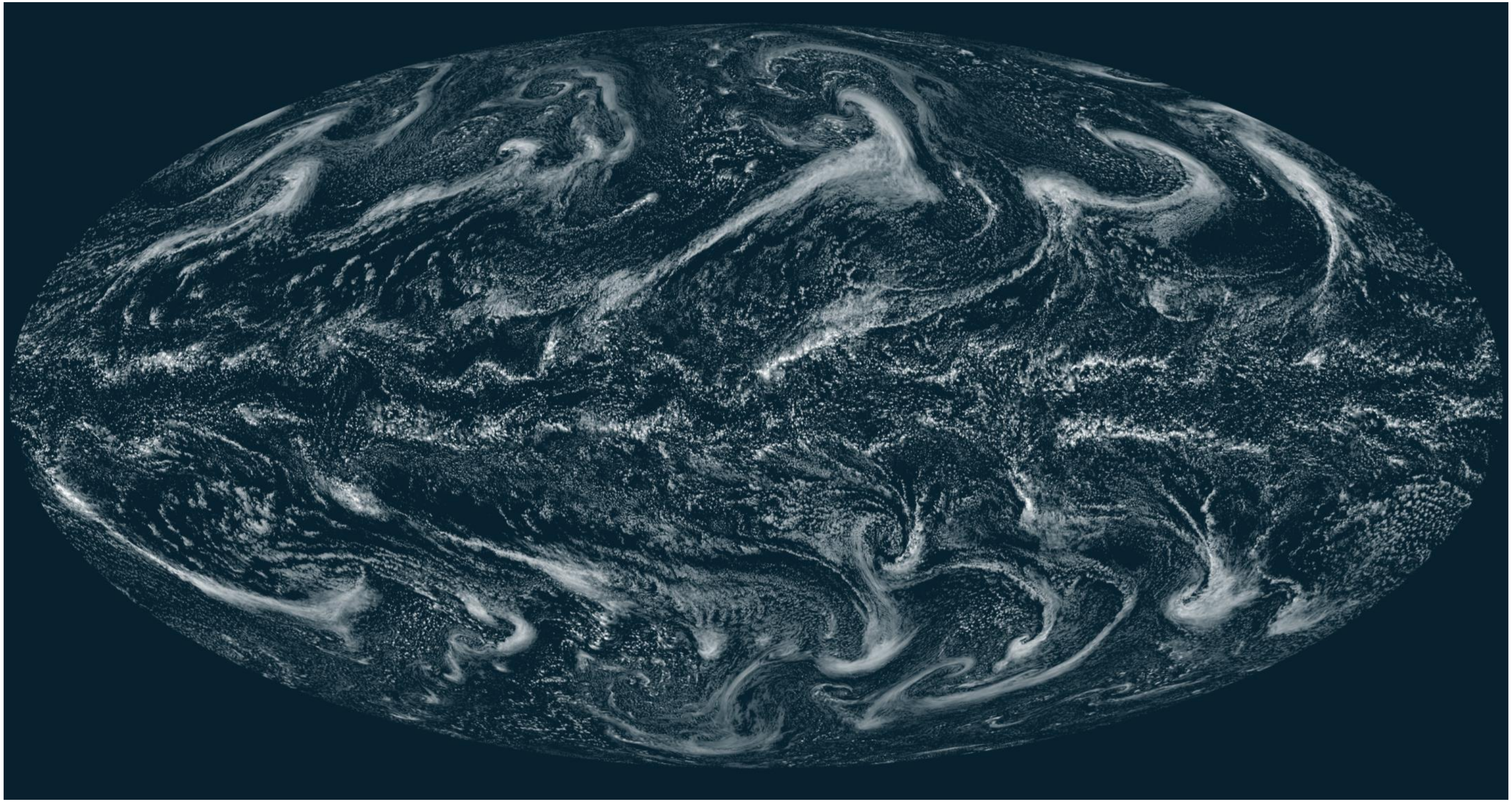
AQUAPLANET ENSEMBLE



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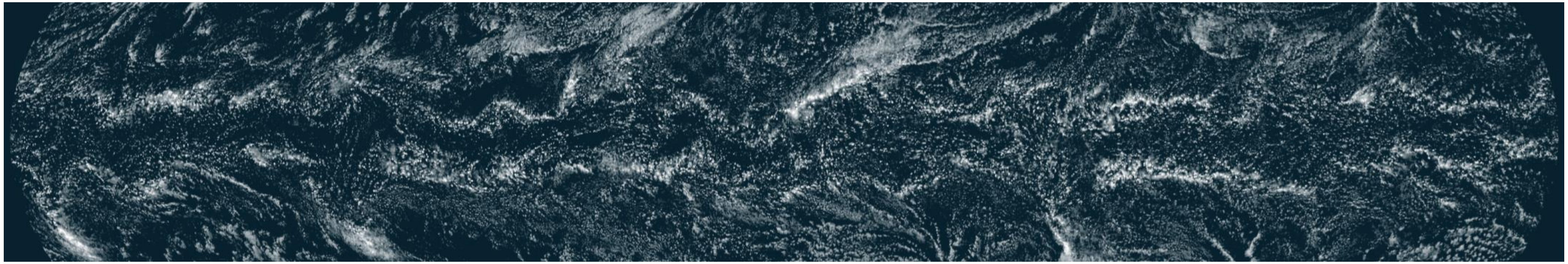

20° N

20° S

Setup:

- ICON Sapphire without convective parameterization (Hohenegger et al., 2023)
- Interactive ozone (Cariolle and Teyssèdre, 2007)
- Three months of simulation at 5 km horizontal grid spacing

Three Simulations:

- Control
- +2 K
- +4 K

HIGH-CLOUD RADIATIVE EFFECT AS FUNCTION OF IWP

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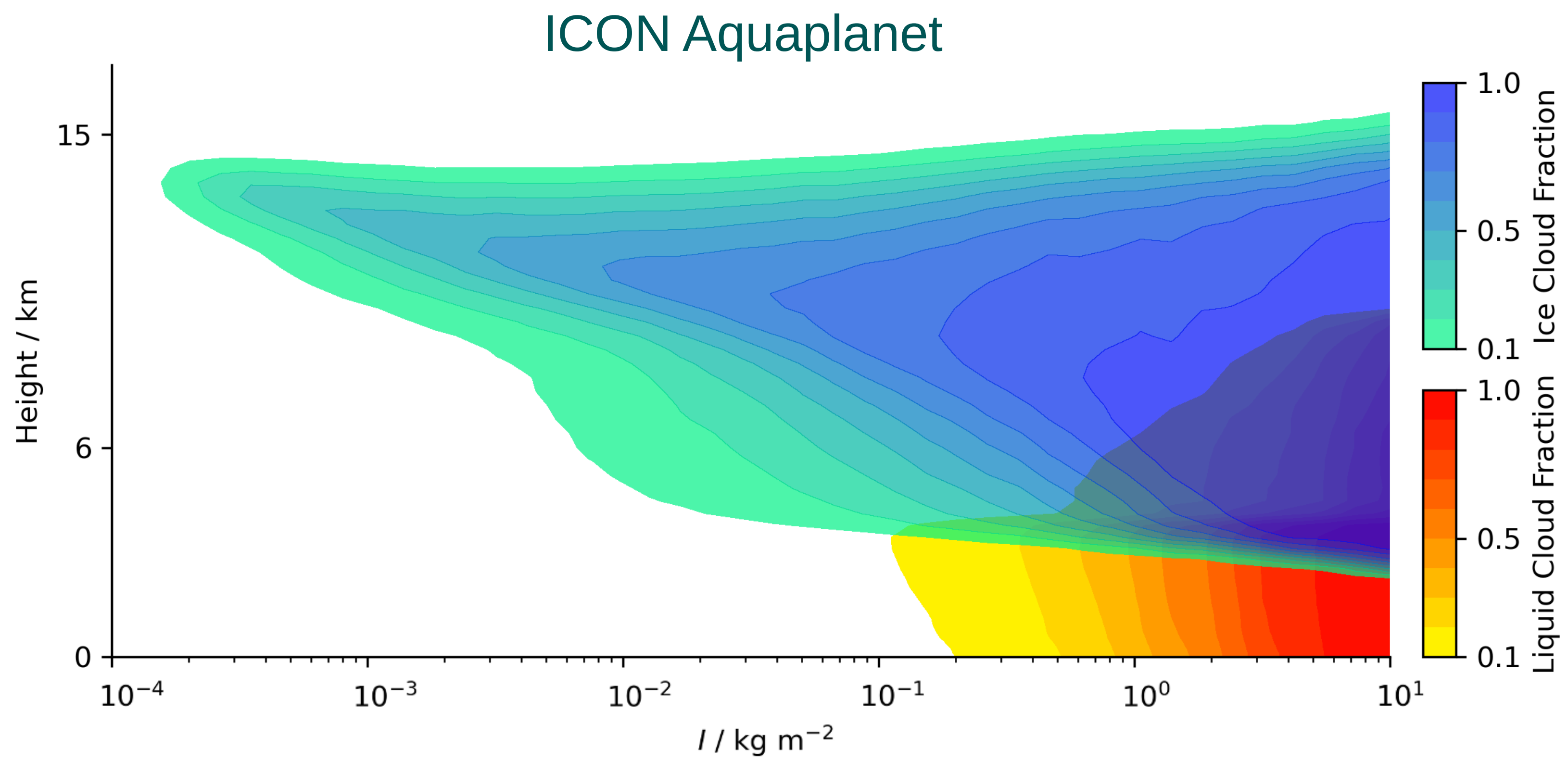

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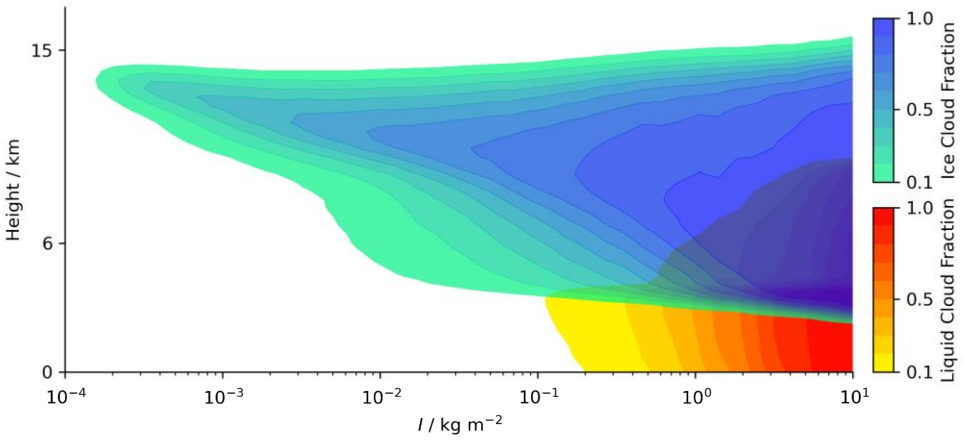

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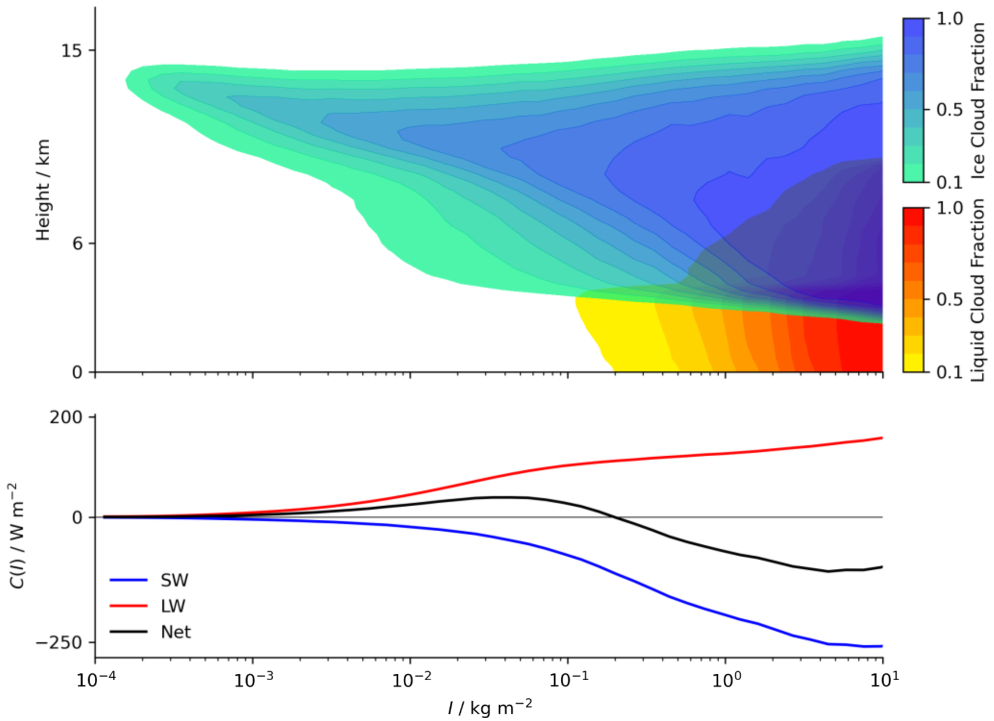


I / kg m^{-2}

Intuitive understanding of cloud radiative effect (CRE):

- Thin clouds warm
- Thick clouds cool

Thin clouds are more frequent than thick ones:

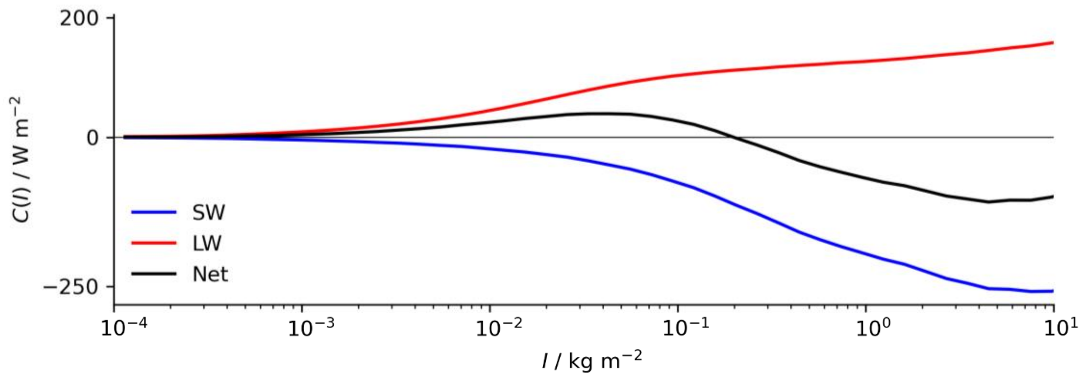
- Mean CRE is positive in ICON (3.7 $\mathrm{W\,m^{-2}}$)

High resolution enables ice water path perspective:

- Satellite observations (Berry and Mace, 2014; Gasparini et al., 2019)
- Idealized simulations (Sokol et al., 2014; Gasparini et al., 2025)

HIGH-CLOUD FEEDBACK WITHIN THE IWP FRAMEWORK

Change in Cloud Radiative Effect



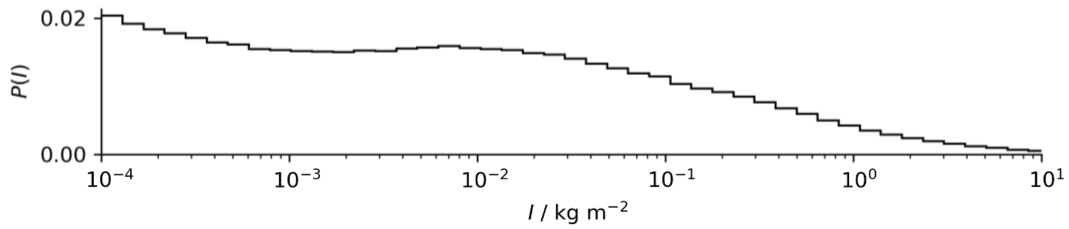
FAT / PHAT (Hartmann and Larson, 2002; Zelinka and Hartmann, 2010)

- ➢ LW *C(I)*

Shift in daily cycle of convection (Gasparini et al., 2021)

- ➢ SW *C(I)*

Change in IWP Frequency

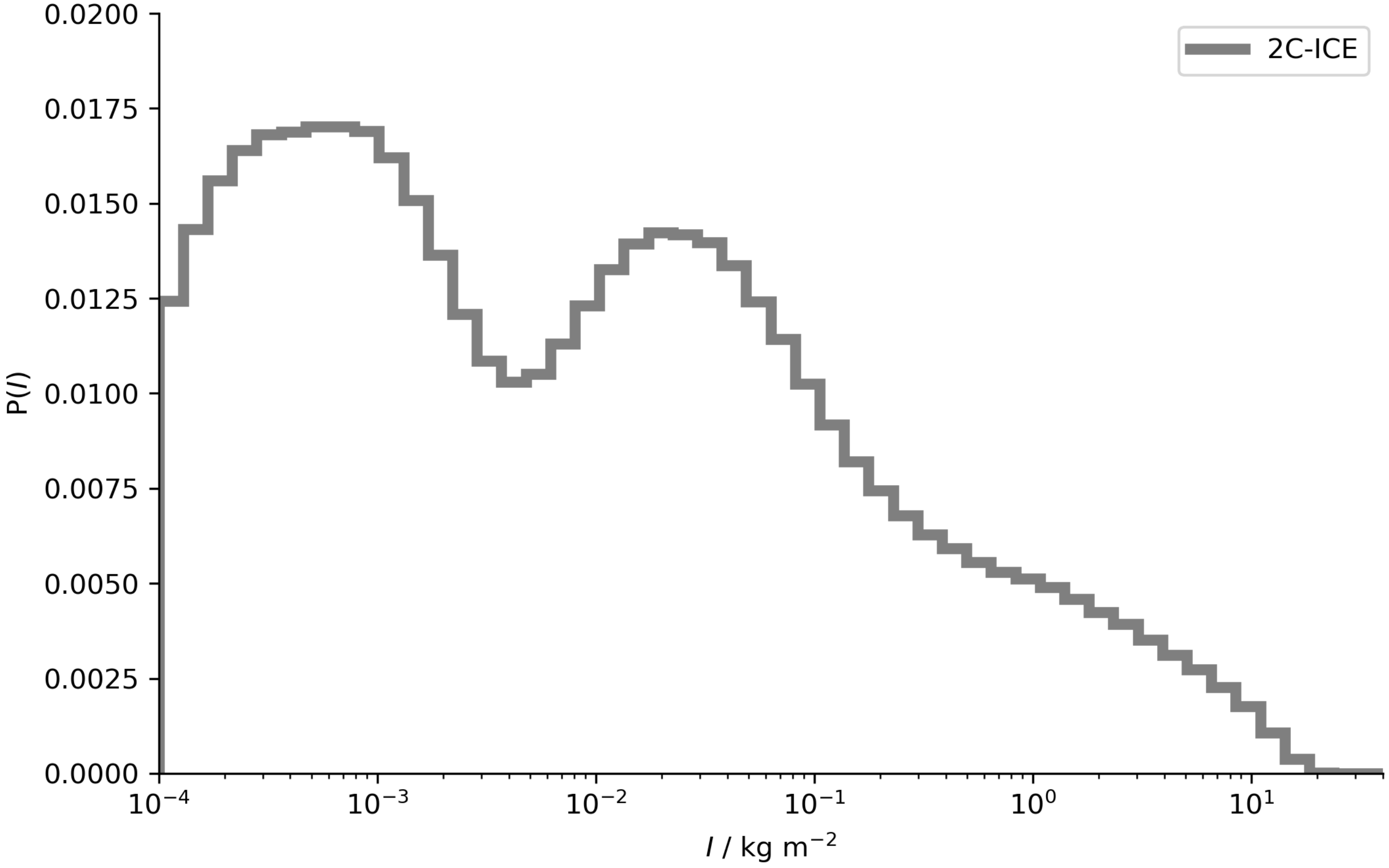


Stability Iris (Bony et al. 2016)

- ➢ Anvil thinning found by Sokol et al. (2024)

Albedo Feedback (McKim et al. 2024)

FREQUENCY OF HIGH CLOUDS IN THE TROPICS



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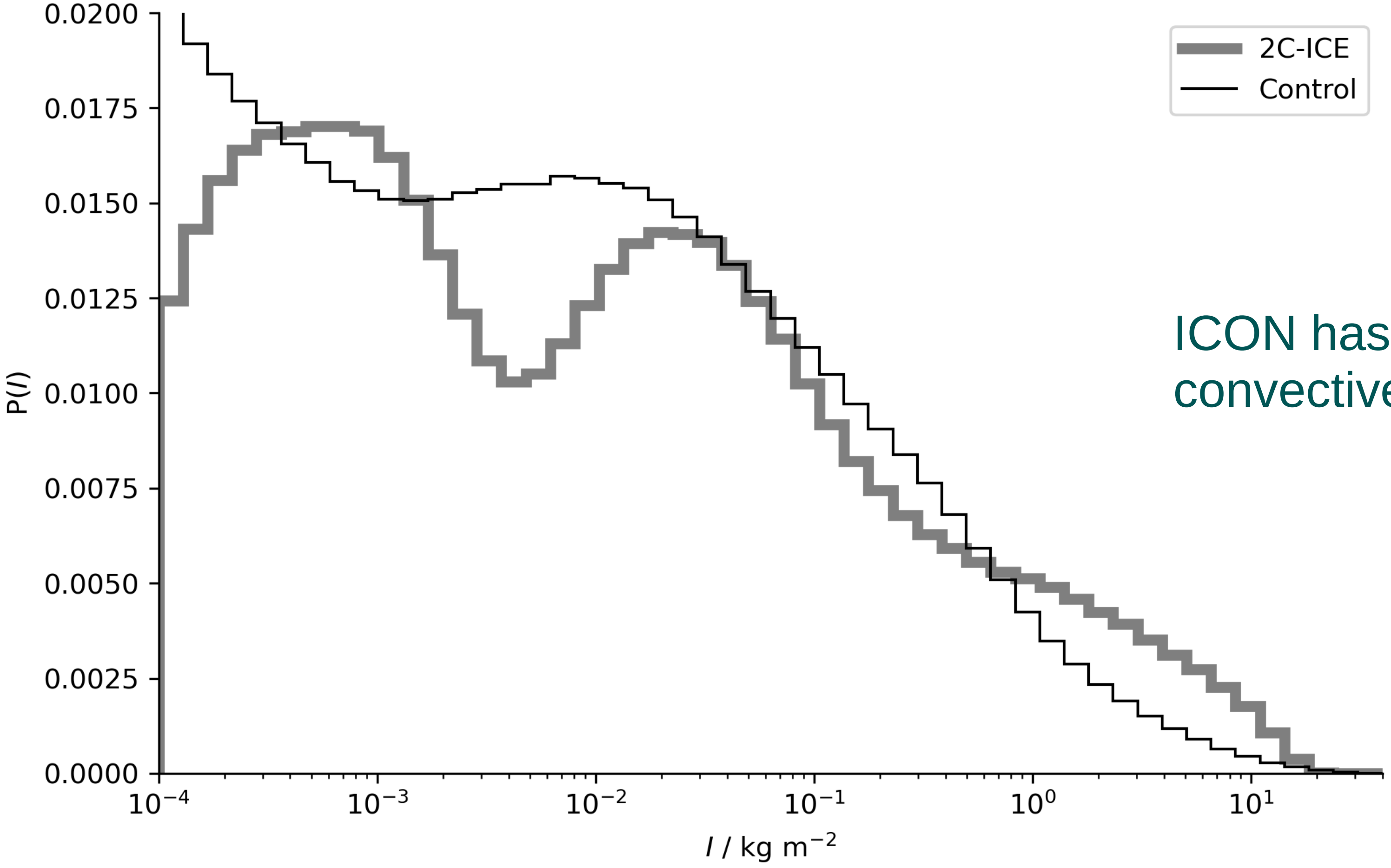

ICON has too little deep convective clouds

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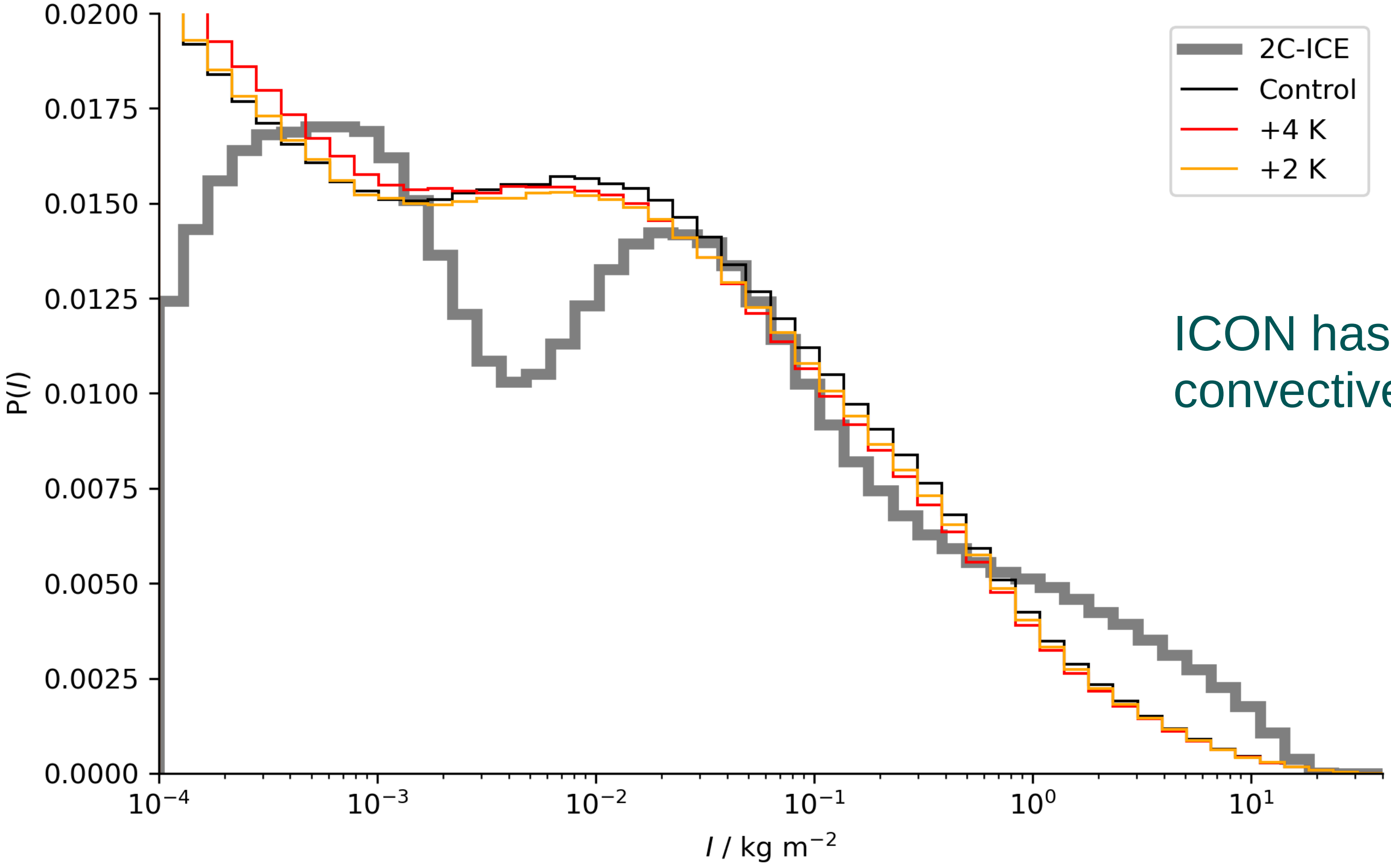
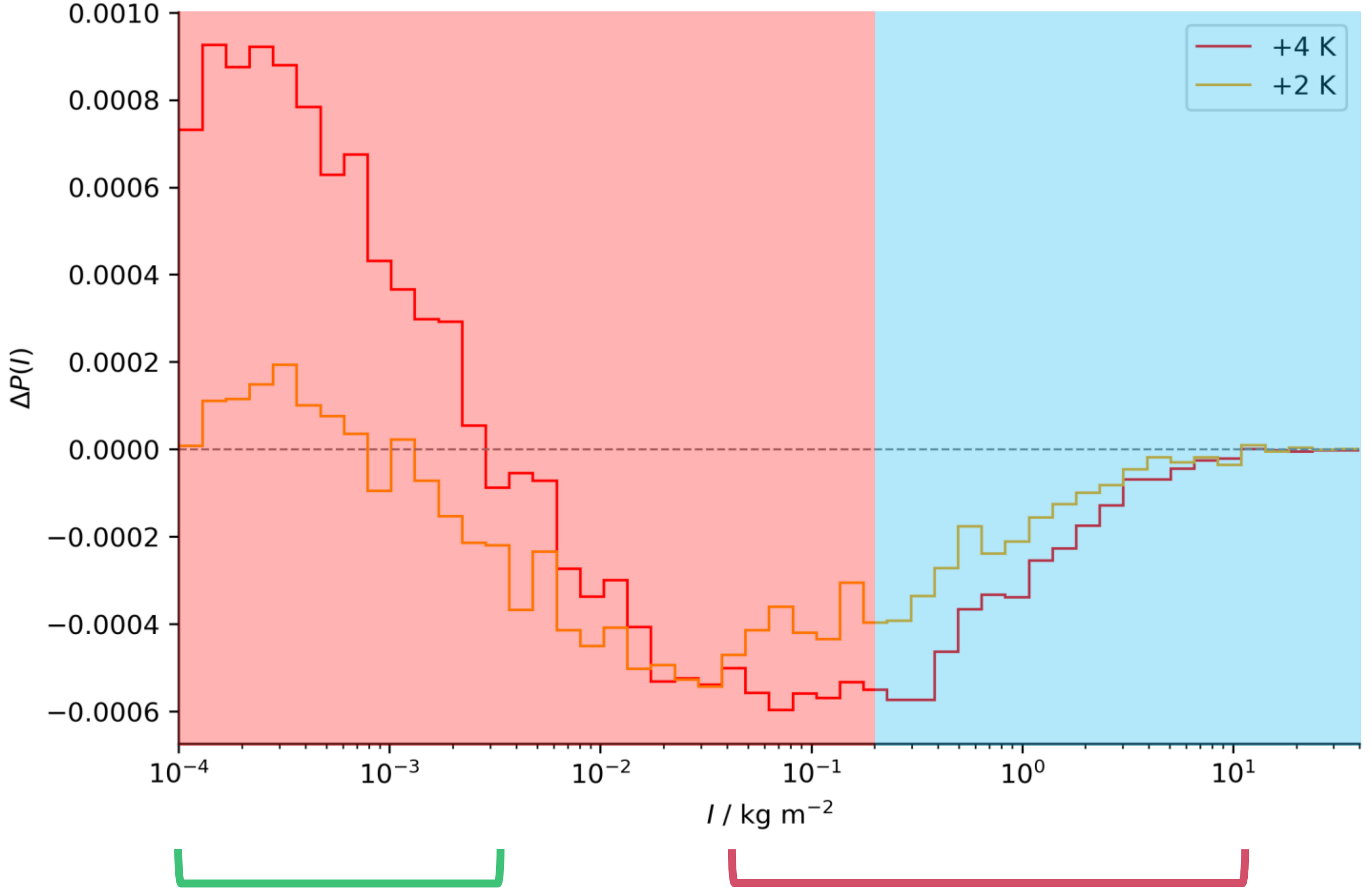


ICON has too little deep convective clouds

REDUCTION OF ANVIL CLOUDS AND INCREASE OF THIN CIRRUS WITH WARMING



Driven By Stability Iris?

Two counteracting responses to warming:

- Decrease of intermediate thickness clouds
- Increase in cirrus clouds

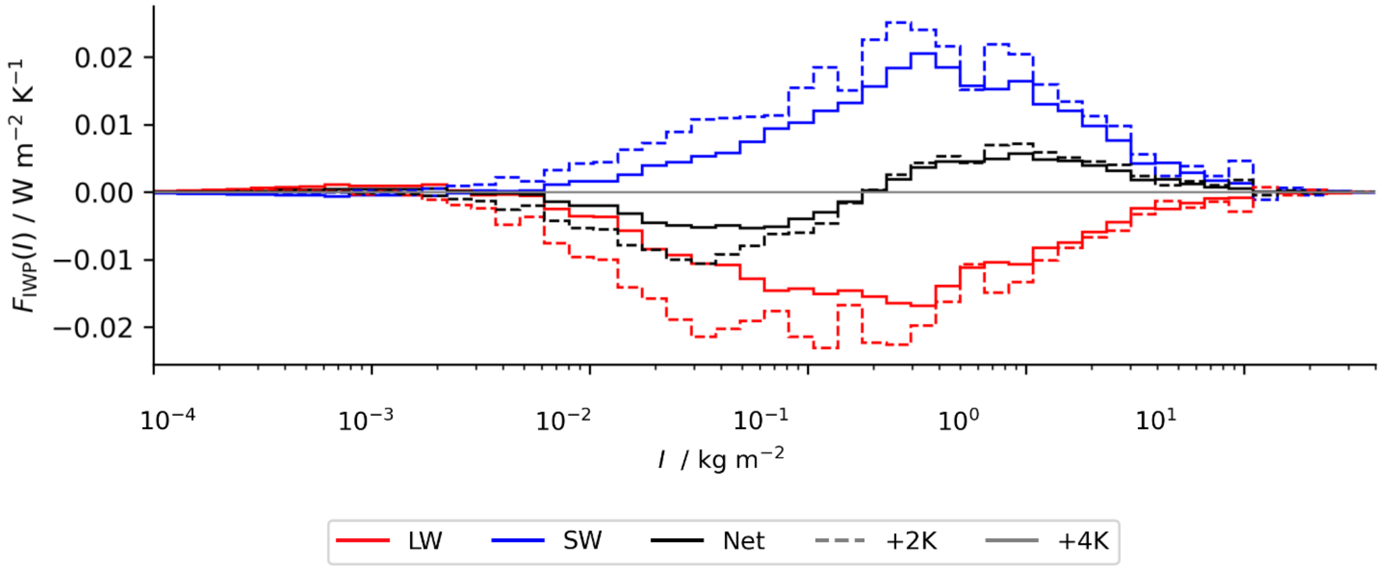
HIGH CLOUD FREQUENCY FEEDBACK IS NEAR NEUTRAL

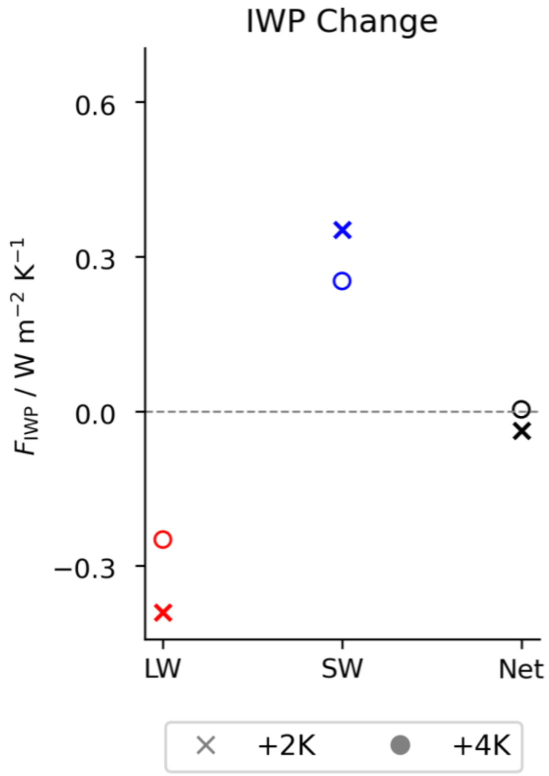
$$\mathrm{F_{IWP}(I)} = \frac{\mathrm{C(I)} \cdot \Delta P(I)}{\Delta T_\mathrm{s}}$$

$$F_\mathrm{IWP} = \sum_I F_\mathrm{IWP}(I)$$

$F_\mathrm{IWP}(I)$ Feedback from change in IWP frequency

ΔT_s Increase in surface temperature





STABILITY IRIS MECHANISM EXISTS

$$C \sim CSC = \partial_z \left(\frac{H}{\Gamma_{\mathrm{d}} - \Gamma} \right) = \partial_z \left(\frac{\text{Radiative Cooling}}{\text{Stability}} \right)$$

Γ_d: Dry Adiabat
H: Clear Sky Radiative Heating Rate
Γ: Lapse Rate
C: High-Cloud Fraction

STABILITY IRIS MECHANISM EXISTS – BUT IS WEAK

$$C \sim CSC = \partial_z\left(\frac{H}{\Gamma_\mathrm{d} - \Gamma}\right) = \partial_z\left(\frac{\text{Radiative Cooling}}{\text{Stability}}\right)$$

Γ_d: Dry Adiabat

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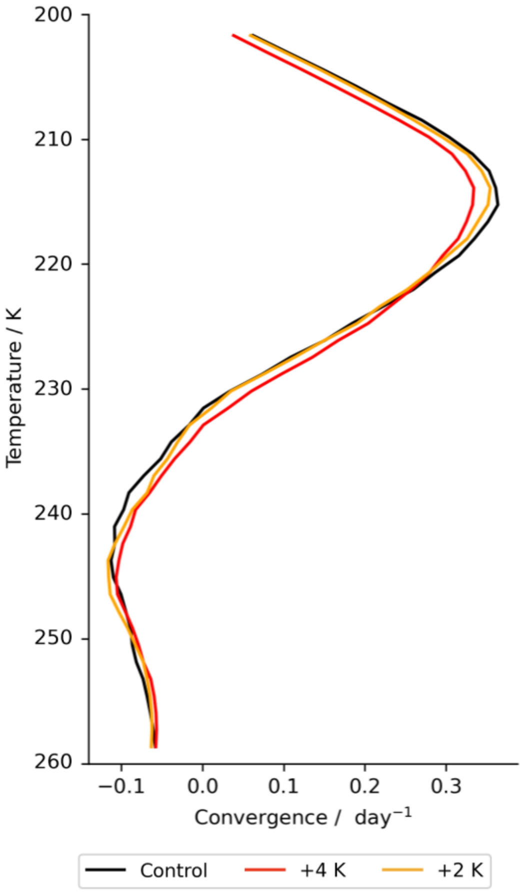
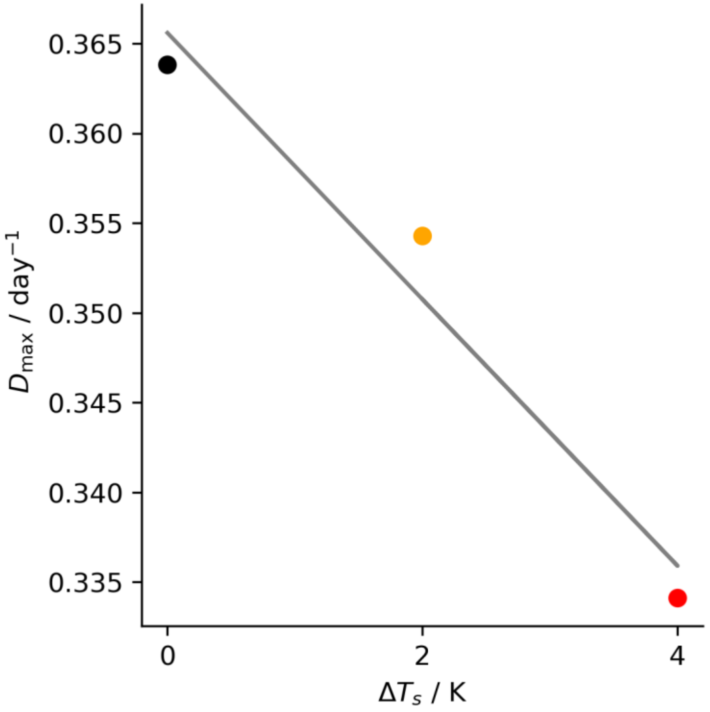
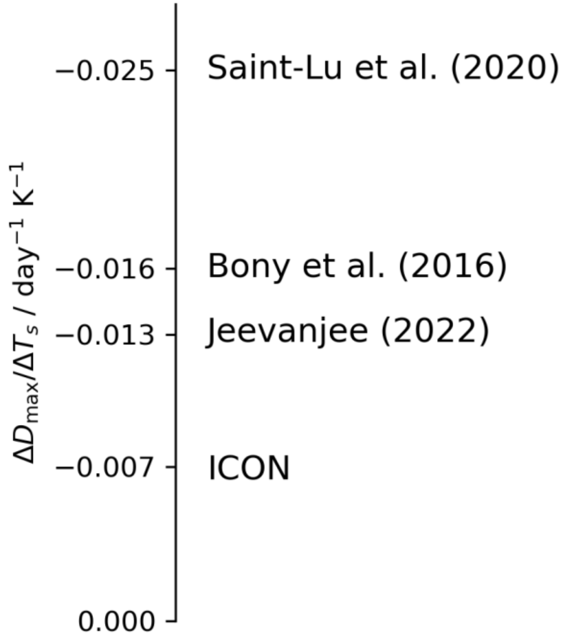
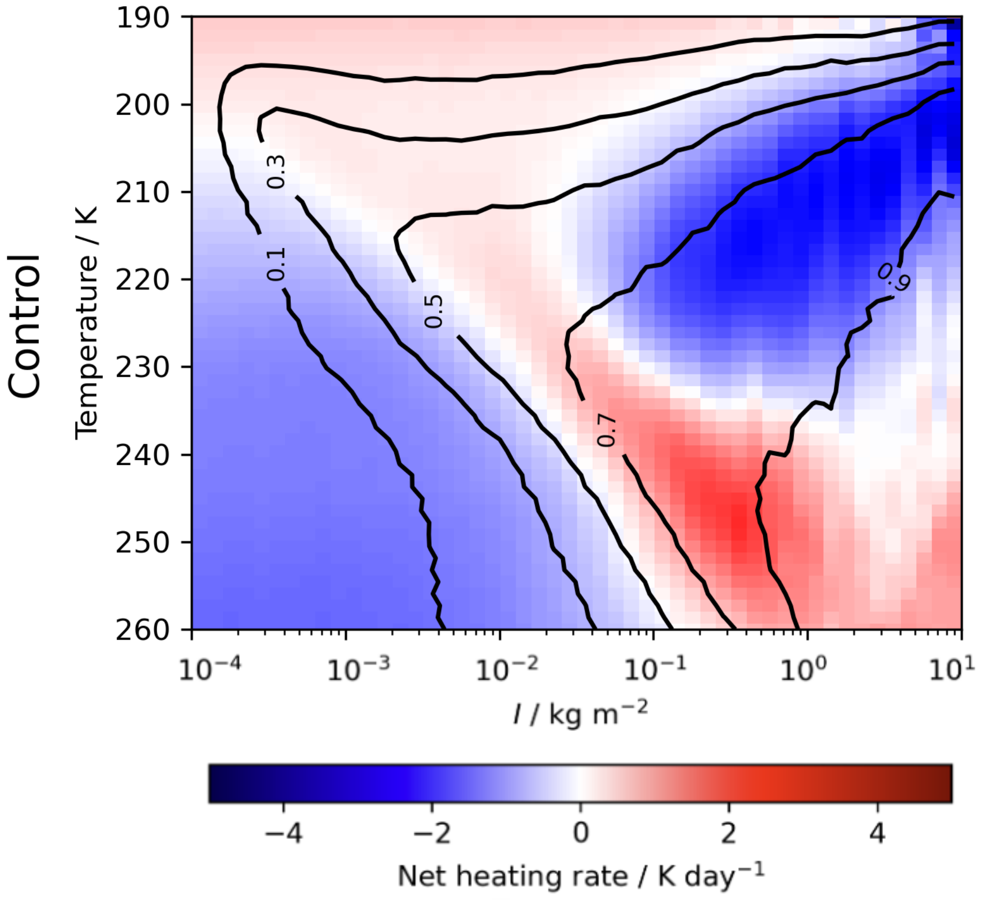


Maximum Convergence D_{max}





INCREASE IN CLOUD RADIATIVE HEATING MIGHT CAUSE CHANGES IN HIGH CLOUD FREQUENCY



- Heating Dipole for intermediate thickness clouds
- Heating throughout for cirrus

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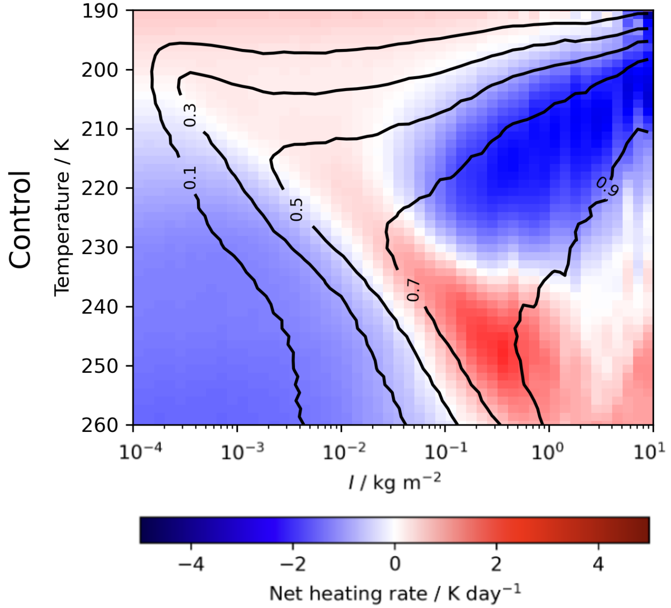
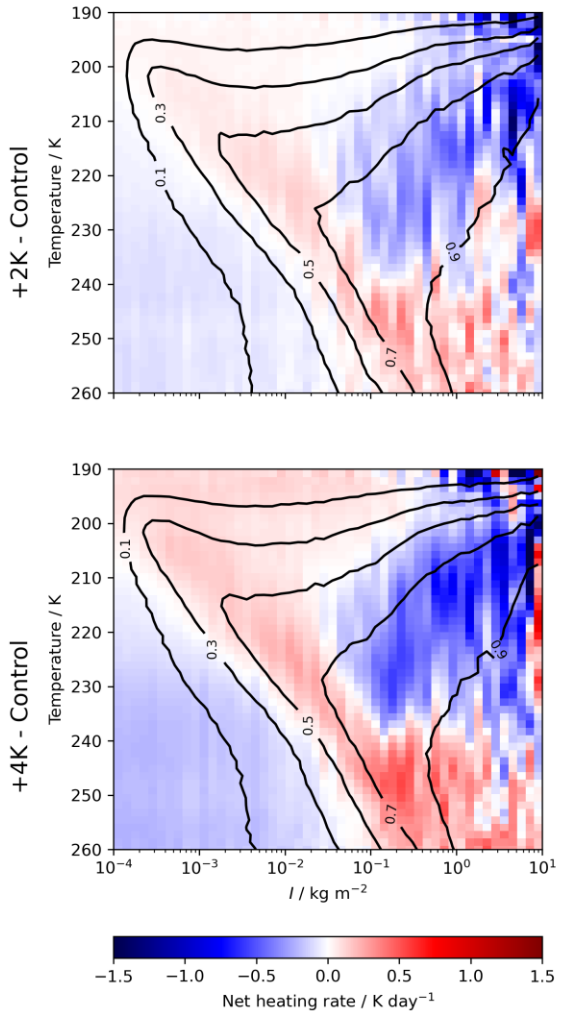
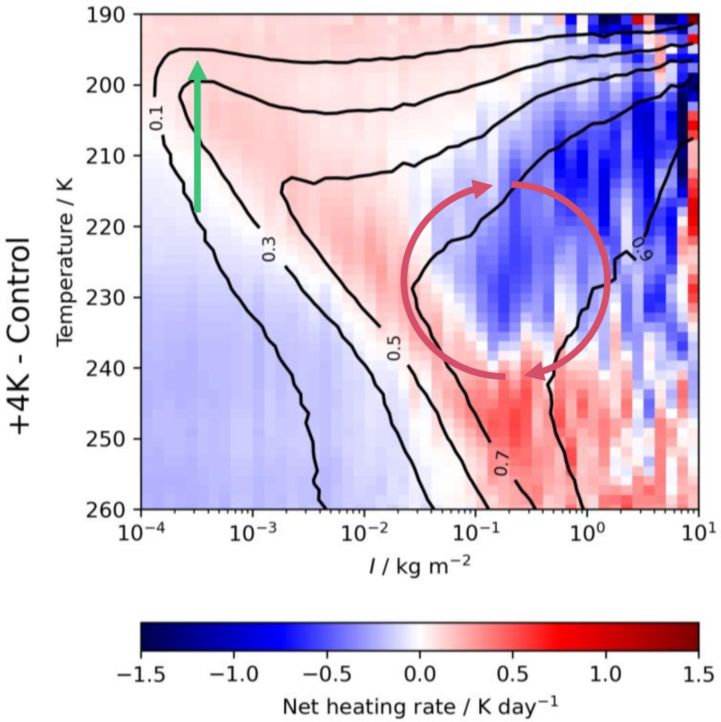


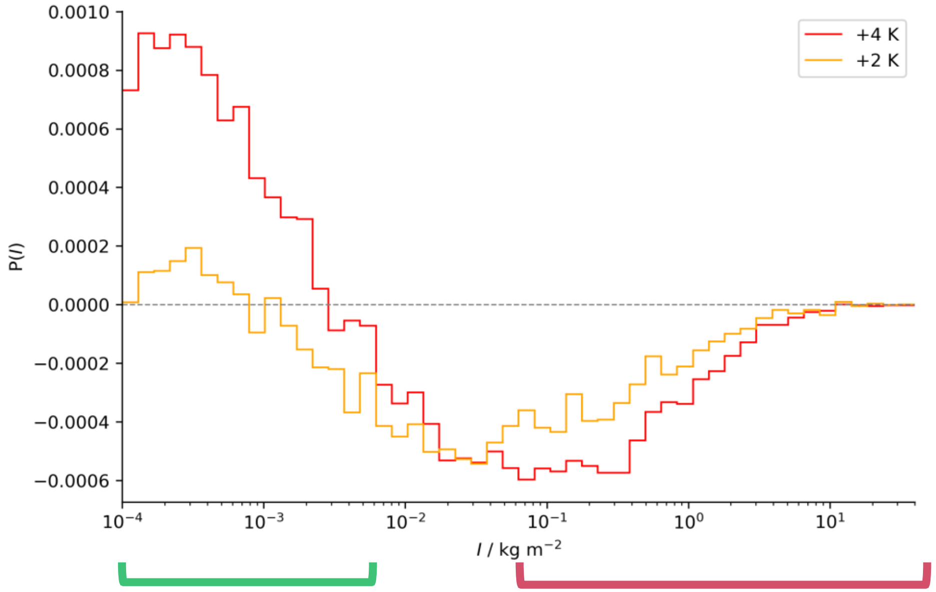


- Heating Dipole for intermediate thickness clouds
- Heating throughout for cirrus

  - Both intensify with surface warming
  - Result of lower density as clouds rise to lower pressure with surface warming (Gasparini et al., 2024)

INCREASE IN CLOUD RADIATIVE HEATING MIGHT CAUSE CHANGES IN HIGH CLOUD FREQUENCY





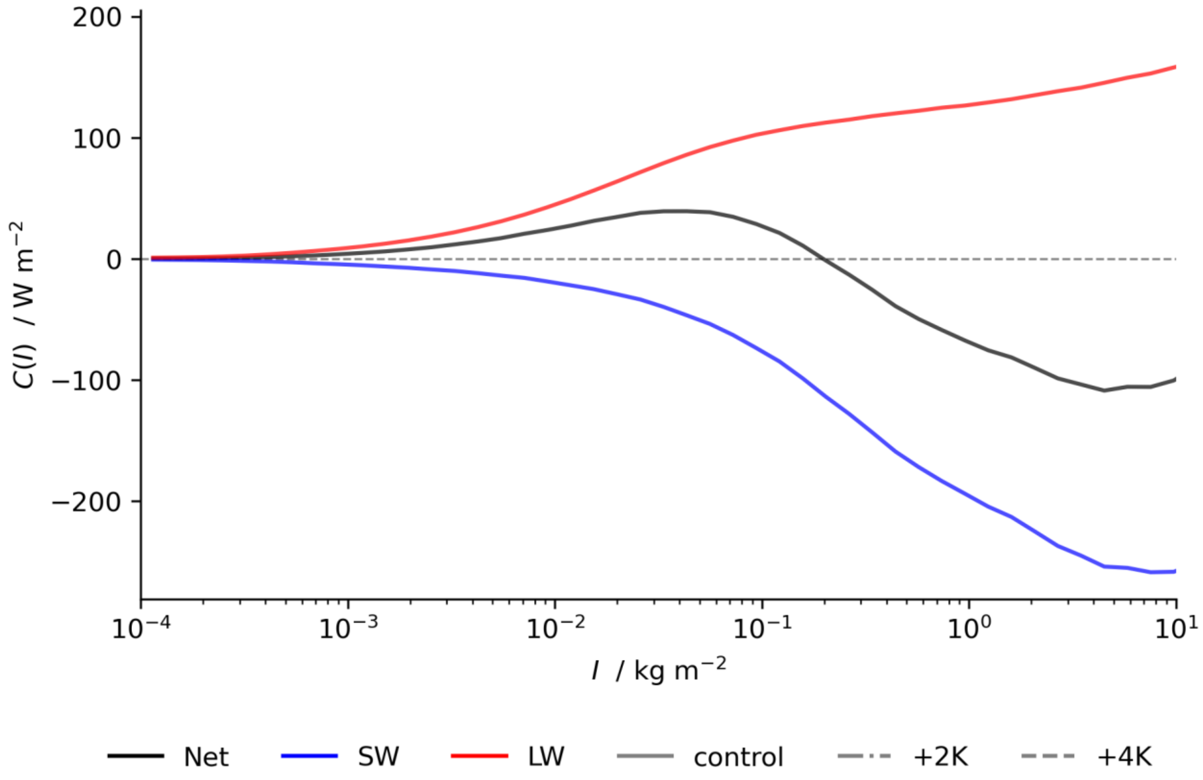
Increased Heating dipole for intermediate thickness clouds

➔ Decrease Cloud Lifetime
Hartmann et al. (2018)

Increased Heating of Cirrus

➔ Increase Cloud Lifetime
Gasparini et al. (2022)

CHANGES IN HIGH-CLOUD RADIATIVE EFFECT



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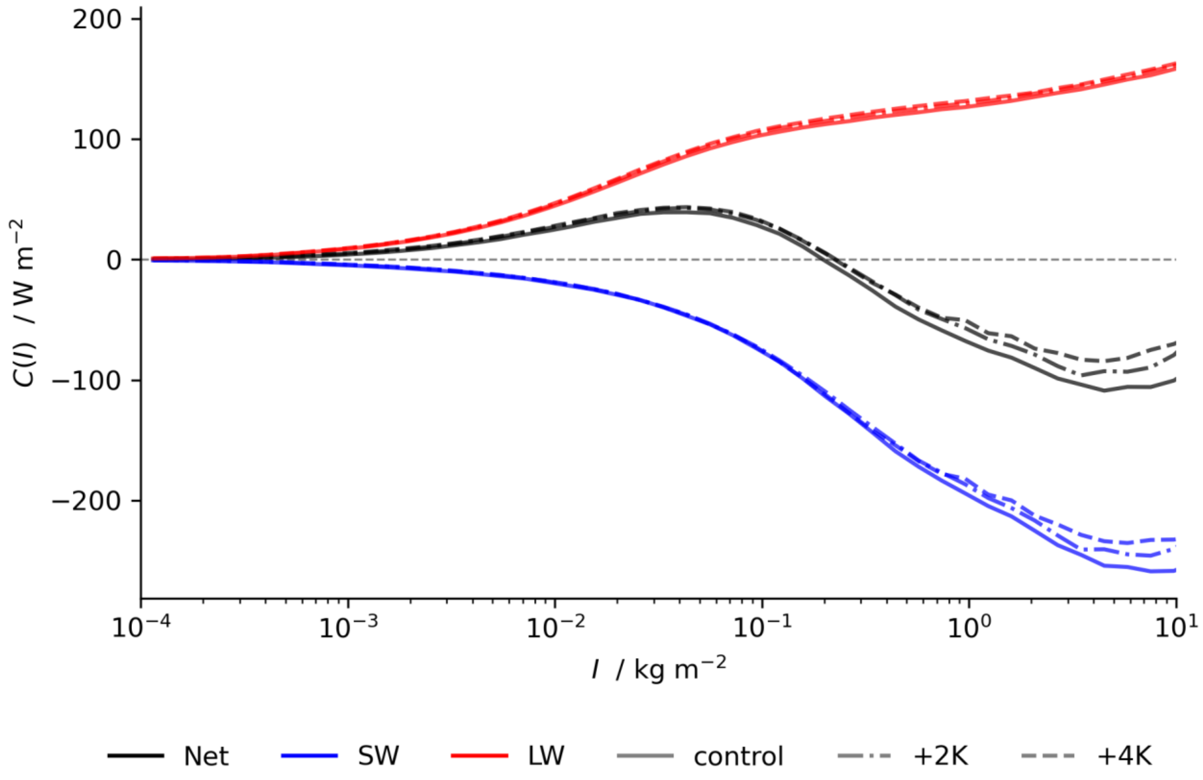

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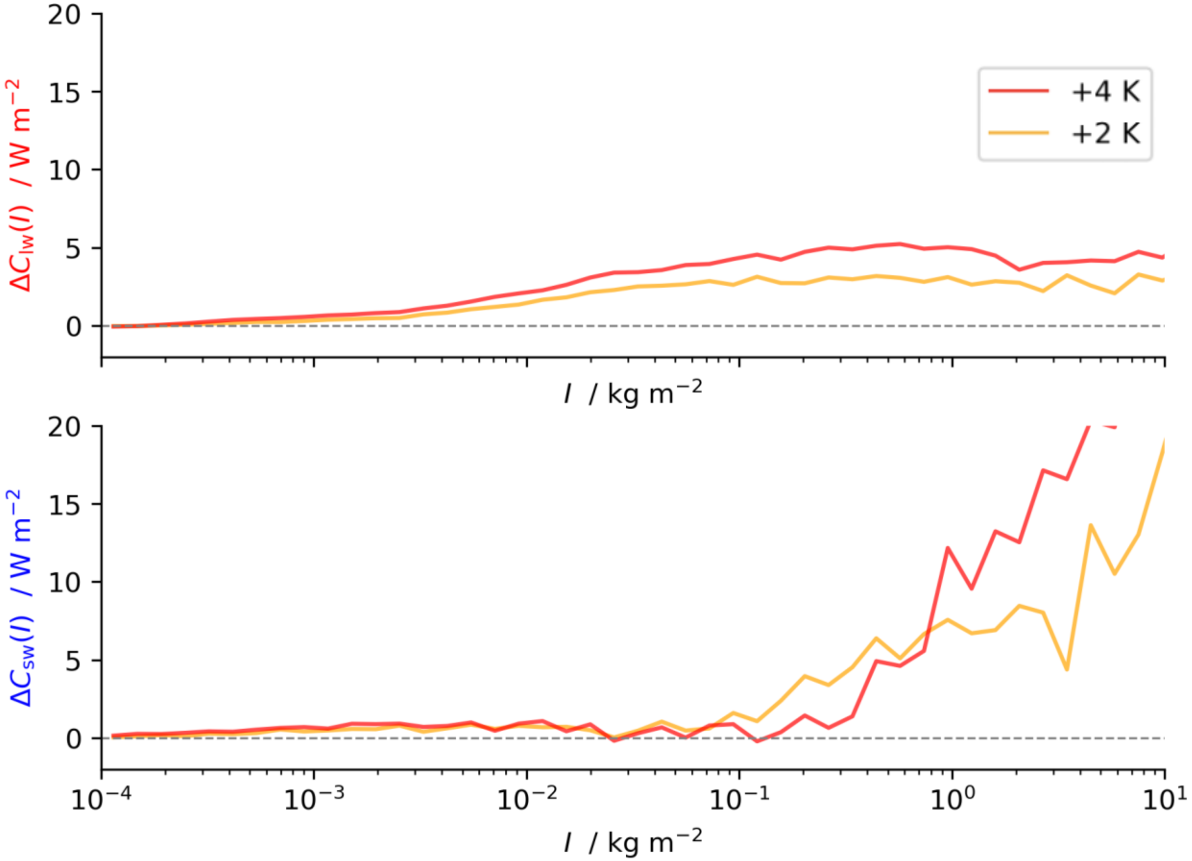


SW and LW cloud radiative effect become more positive with surface warming

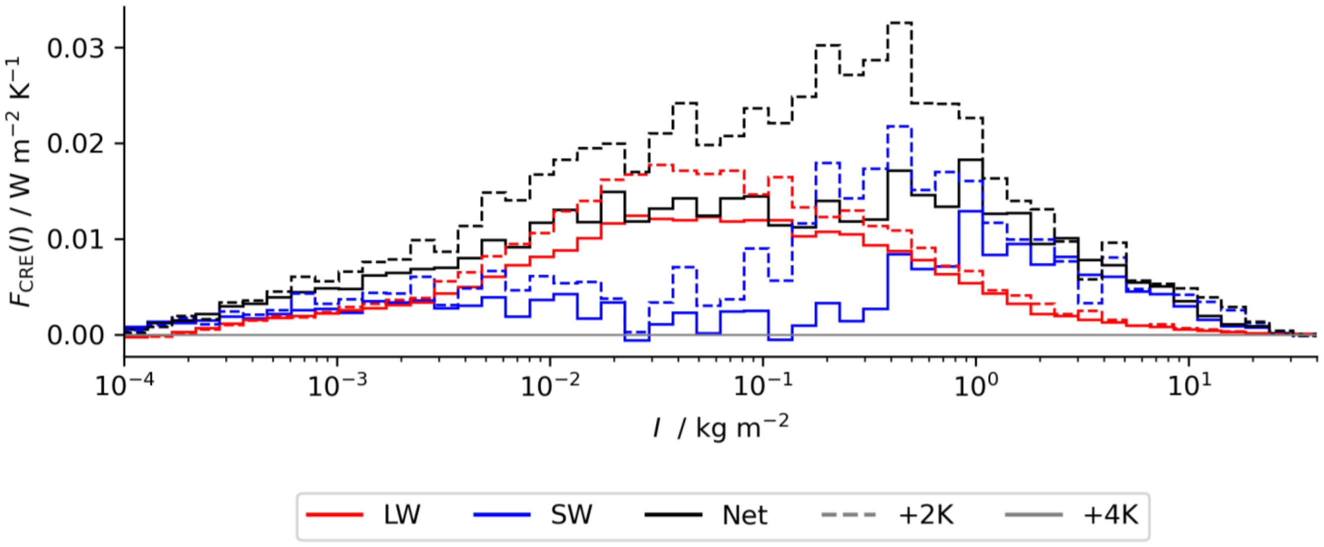
WEIGHTED CRE CHANGE AND FEEDBACK

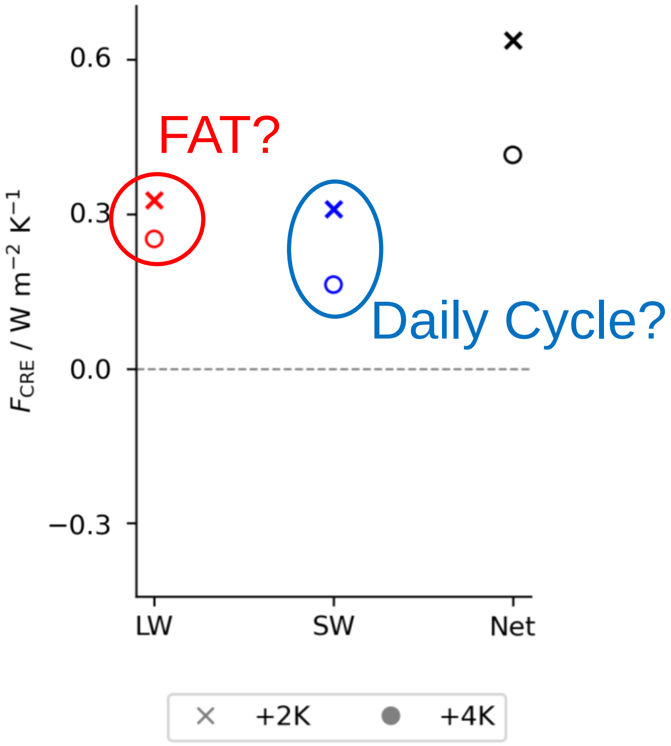
$$\mathrm{F_{CRE}(I)} = \frac{\Delta \mathrm{C(I)} \cdot P(I)}{\Delta T_s}$$

$$F_{\mathrm{CRE}} = \sum_I F_{\mathrm{CRE}}(I)$$

$F_{\mathrm{CRE}}(I)$ Feedback from change in CRE

ΔT_s Increase in surface temperature



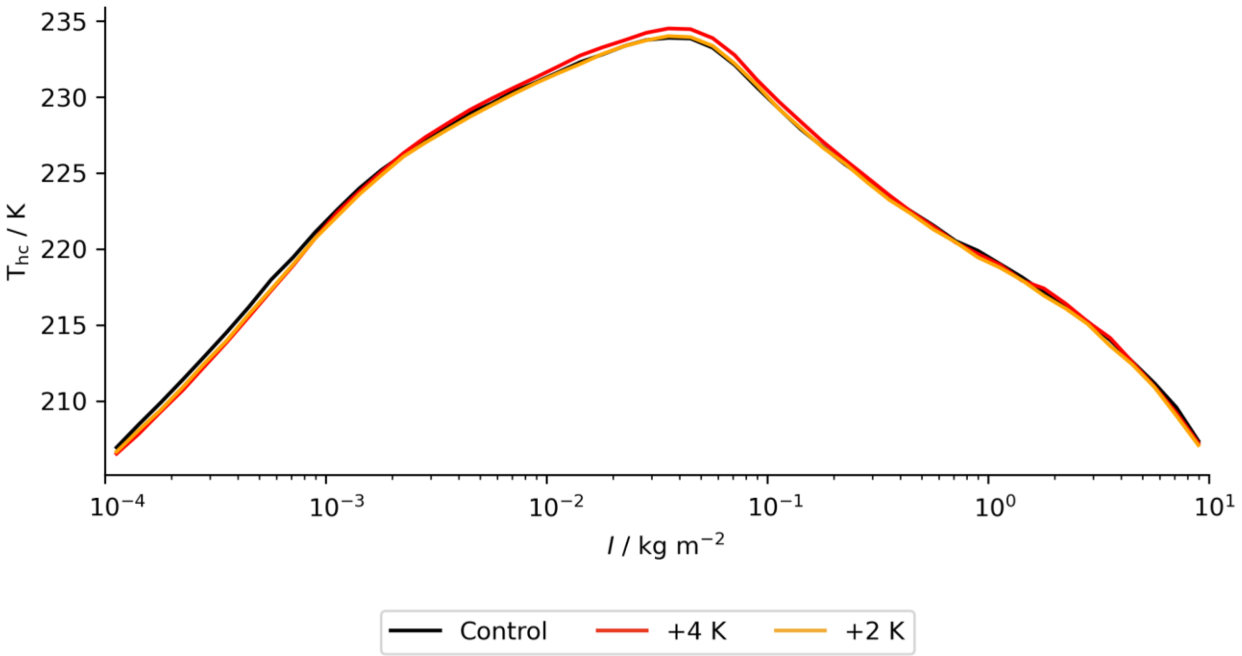


FAT HOLDS IN ICON

$$T_{\mathrm{hc}} = \min\left(T_{bright}, T\Big|_{\max(IWC)}\right)$$

T_{bright}: Brightness temperature

$T|_{\max(IWC)}$: Temperature at maximum ice water content



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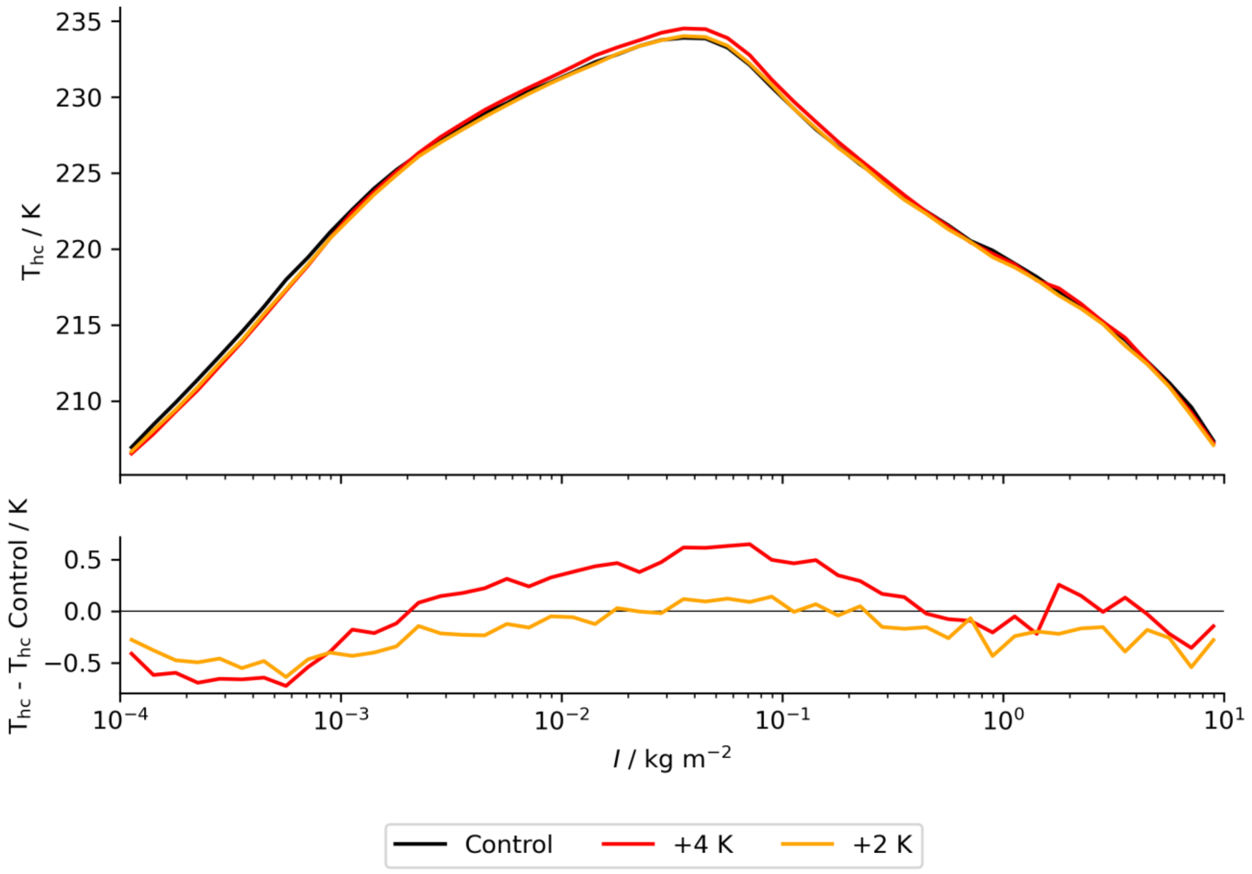
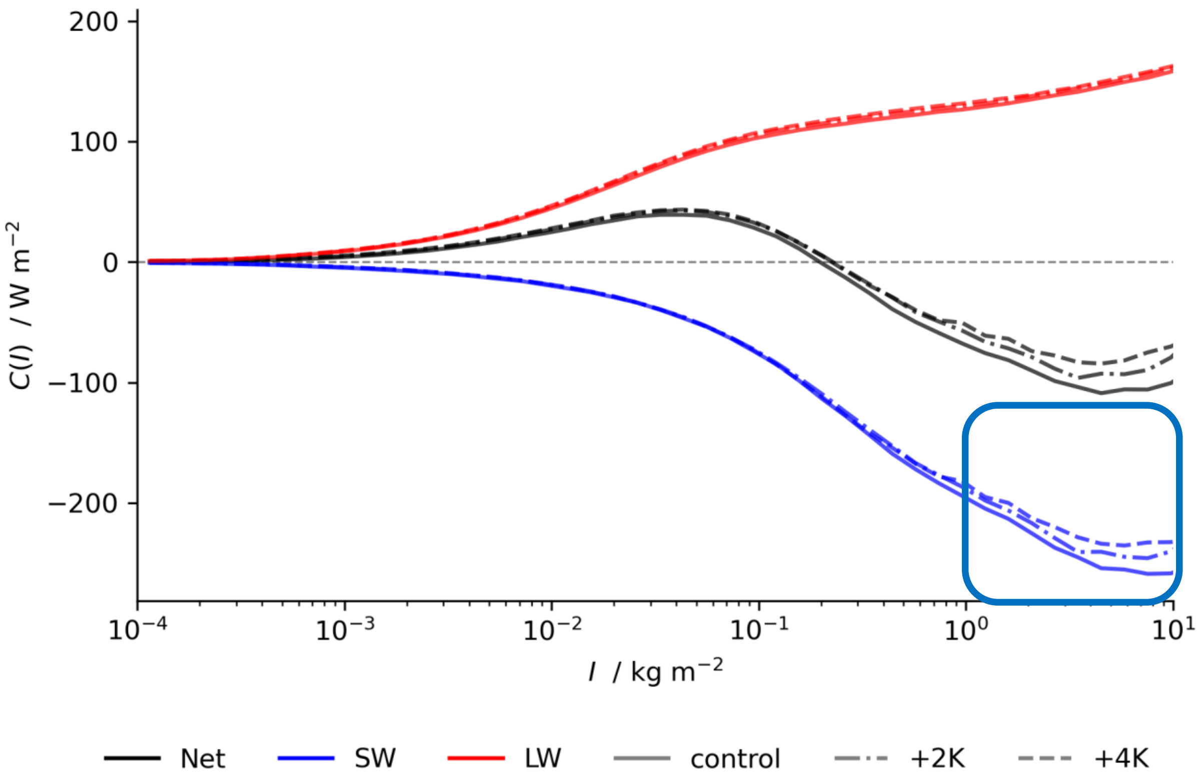


Mean high-cloud temperatures:

Control:	223.7 K
+2 K:	223.4 K
+4 K:	223.4 K

SHIFT IN DAILY CYCLE DECREASES SW *C(I)*



Decrease in SW *C(I)* is most pronounced for $I > 1\ \mathrm{kg\ m^{-1}}$

Decrease of incoming SW radiation:

Control:	430 W $\mathrm{m^{-2}}$
+2 K:	415 W $\mathrm{m^{-2}}$
+4 K:	406 W $\mathrm{m^{-2}}$

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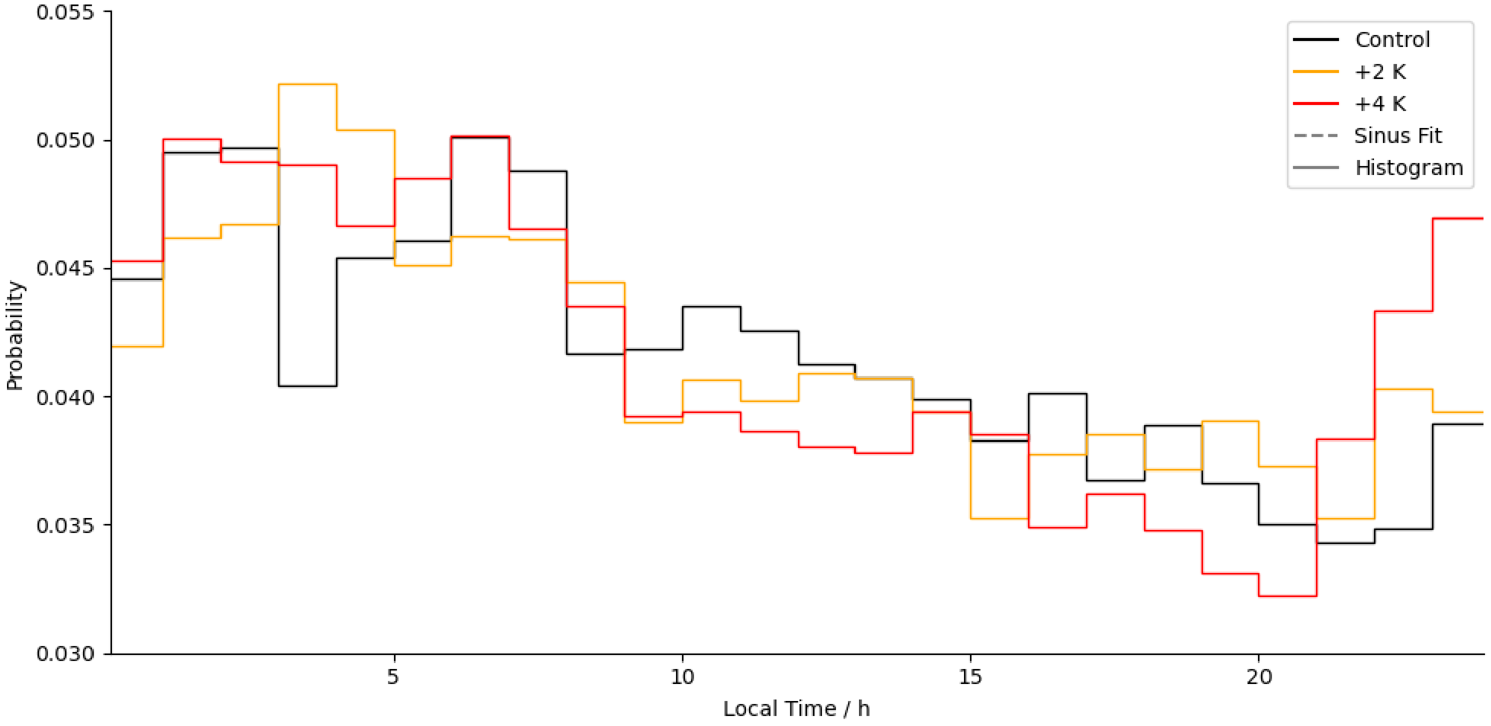

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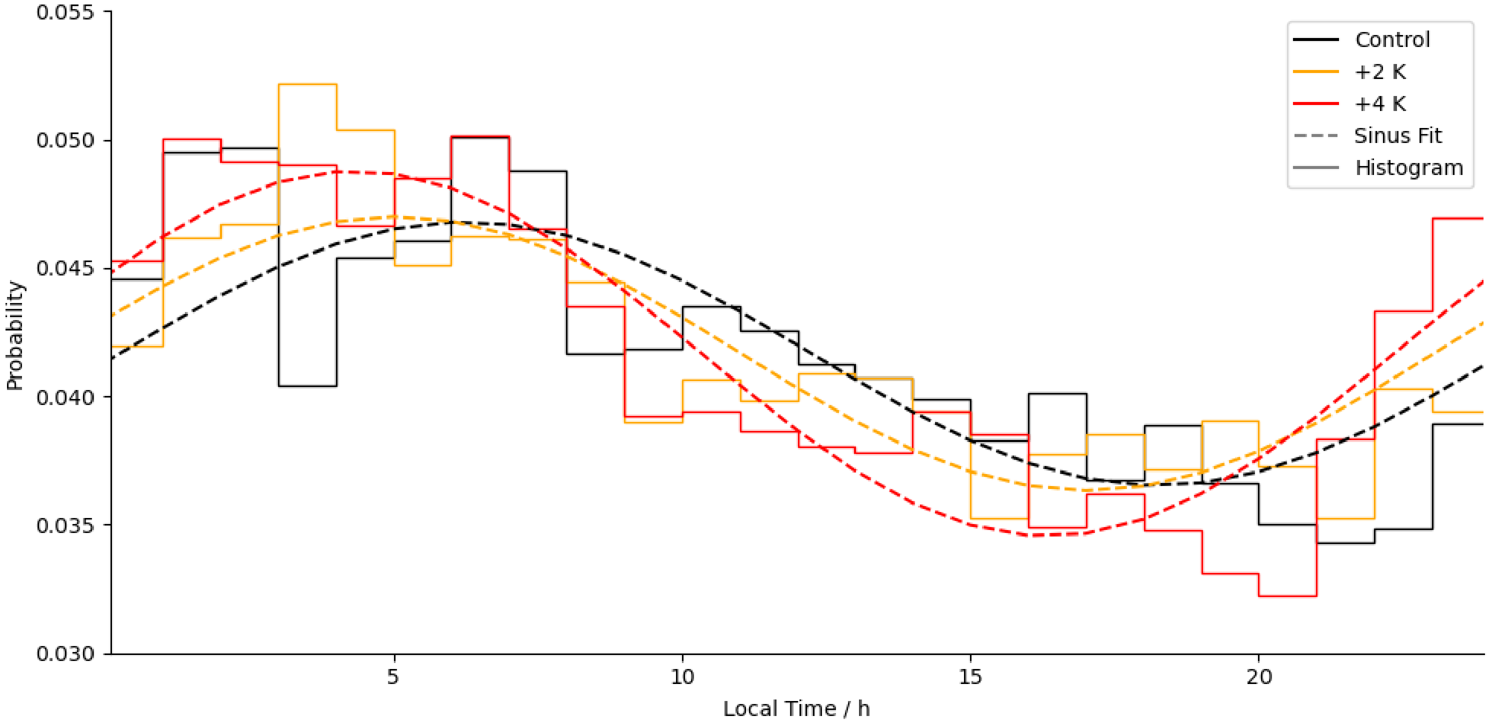

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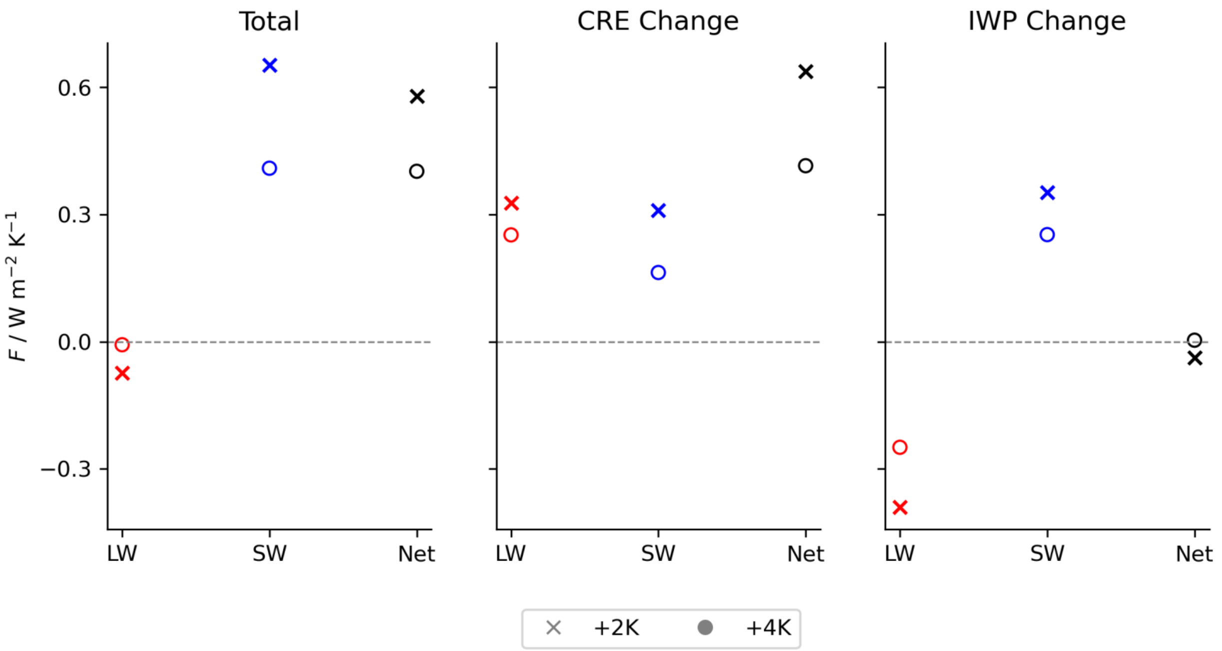
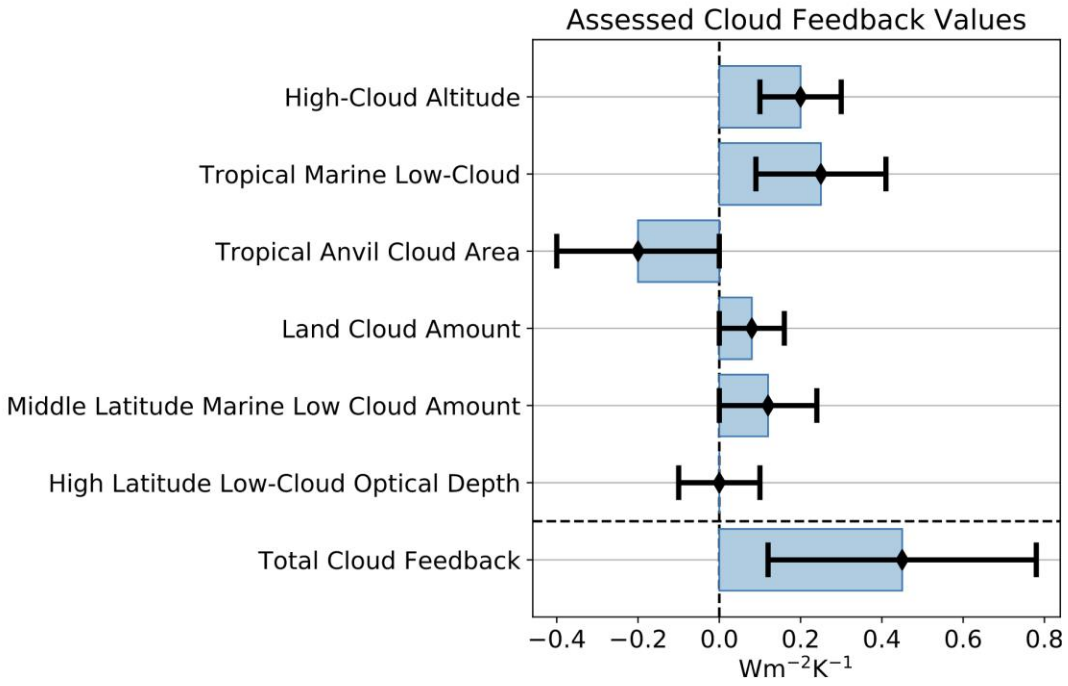
Daily cycle of convection shifts to earlier times

THE HIGH CLOUD FEEDBACK FROM ICON IN PERSPECTIVE

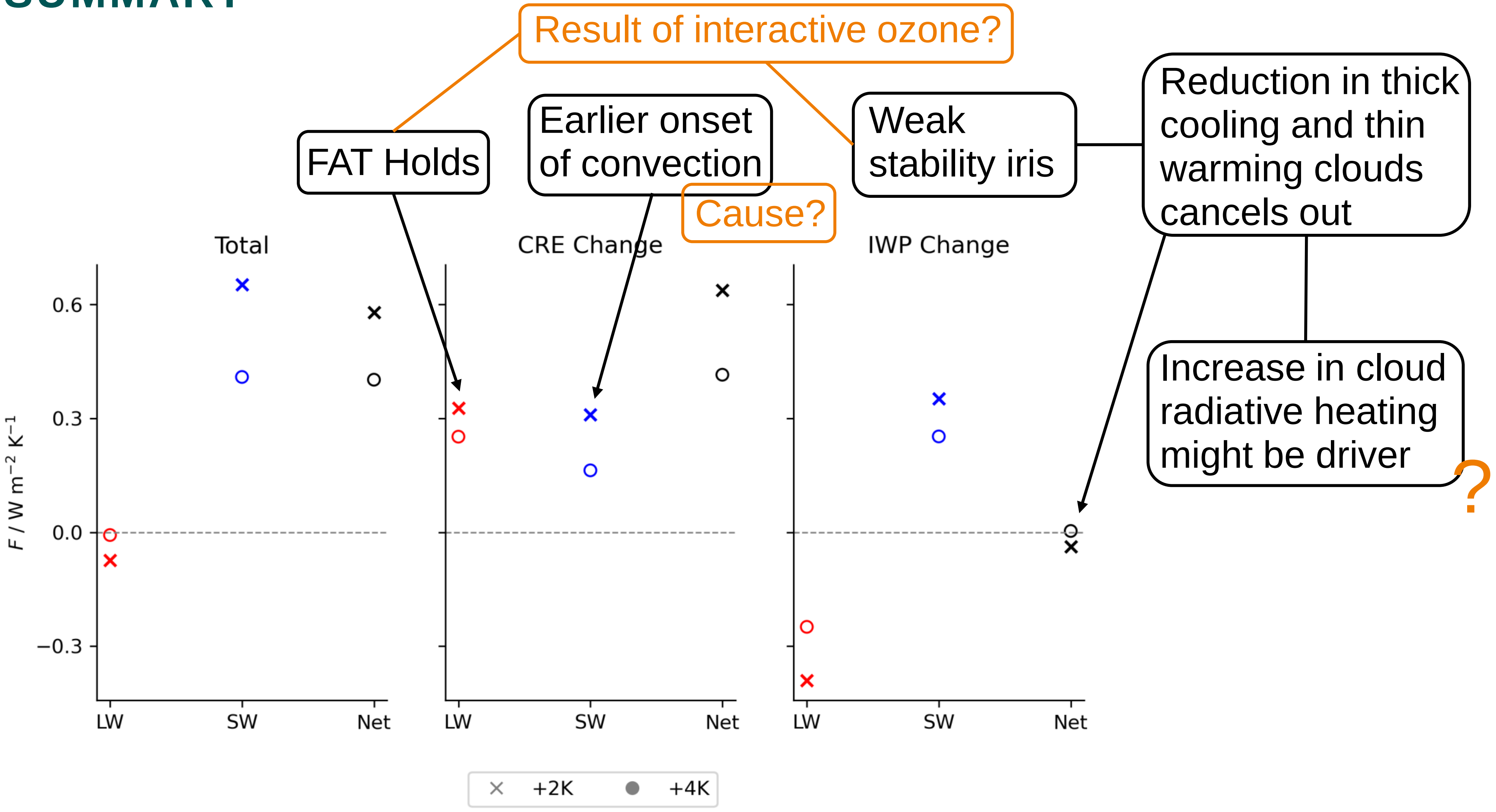




Sherwood and Webb et al. (2020)

- Altitude feedback from ICON at high end of uncertainty range
- Area and albedo feedback from ICON close to zero
- Positive feedback from shift in daily cycle with the same order of magnitude as altitude feedback

SUMMARY



Result of interactive ozone?
FAT Holds
Earlier onset of convection
Cause?
Weak stability iris
Reduction in thick cooling and thin warming clouds cancels out
Increase in cloud radiative heating might be driver
?
Total
CRE Change
IWP Change
F / W m^{-2} K^{-1}
0.6
0.3
0.0
−0.3
LW
SW
Net
+2K
+4K

WHAT CAUSES WEAK STABILITY IRIS?

$$C \sim CSC = \partial_z\left(\frac{H}{\Gamma_\mathrm{d} - \Gamma}\right) = \partial_z\left(\frac{\text{Radiative Cooling}}{\text{Stability}}\right)$$

Γ_d: Dry Adiabat H: Clear Sky Radiative Heating Rate
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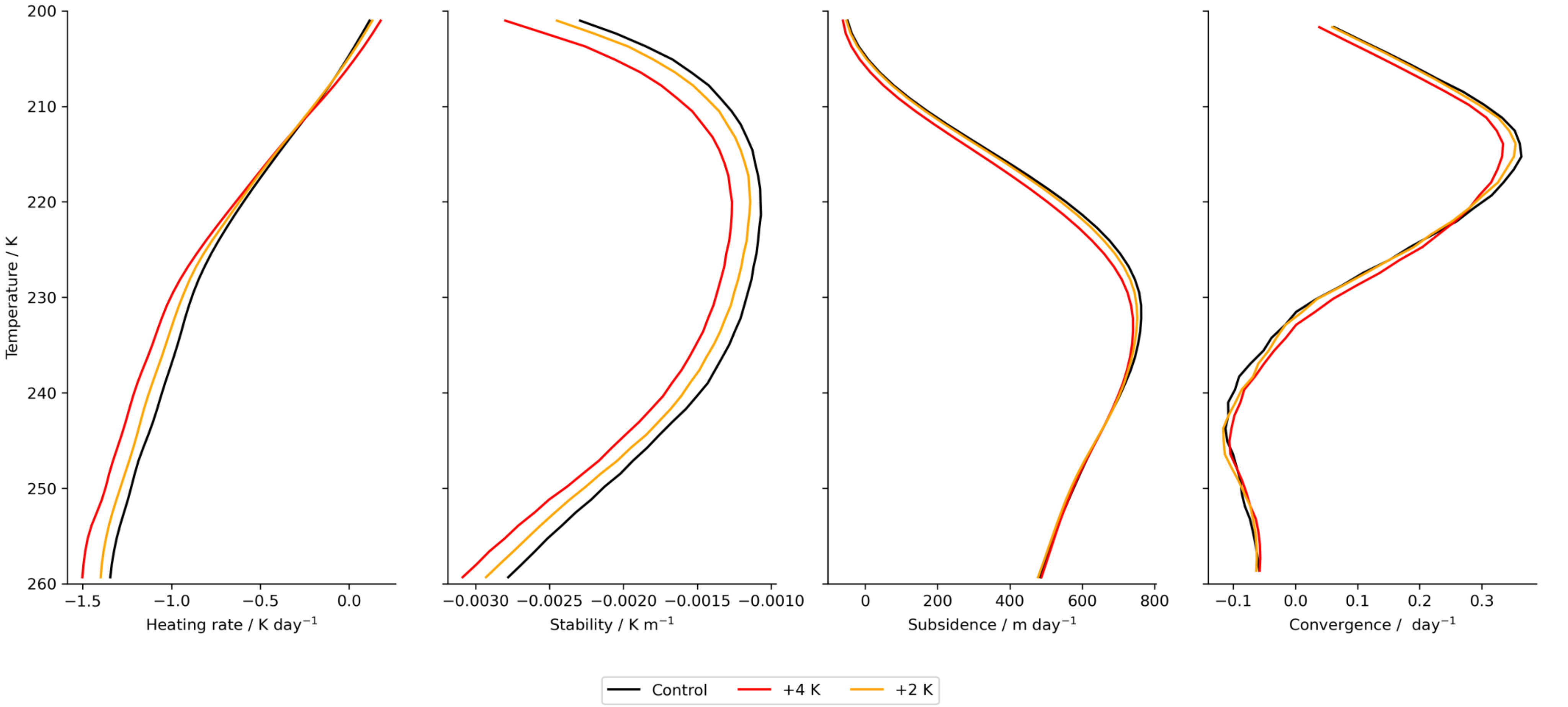

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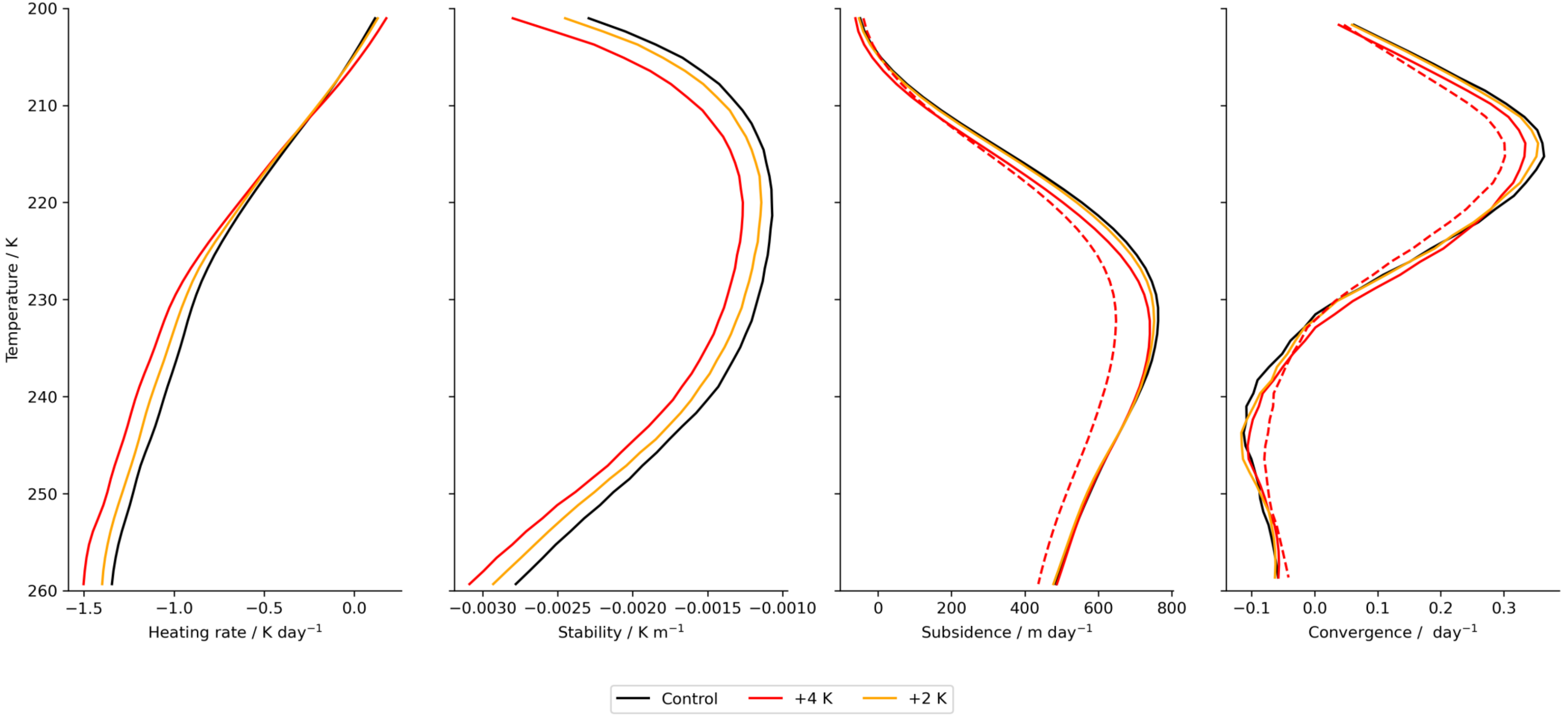

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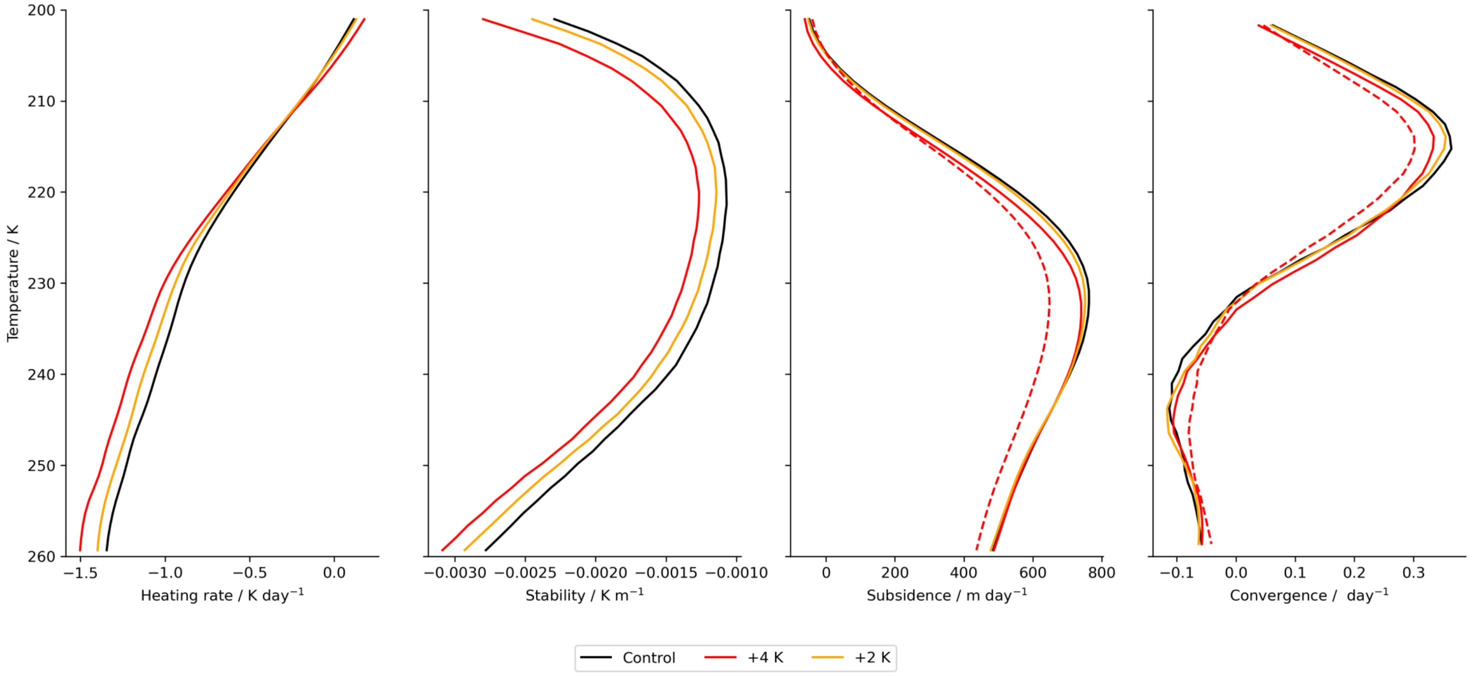


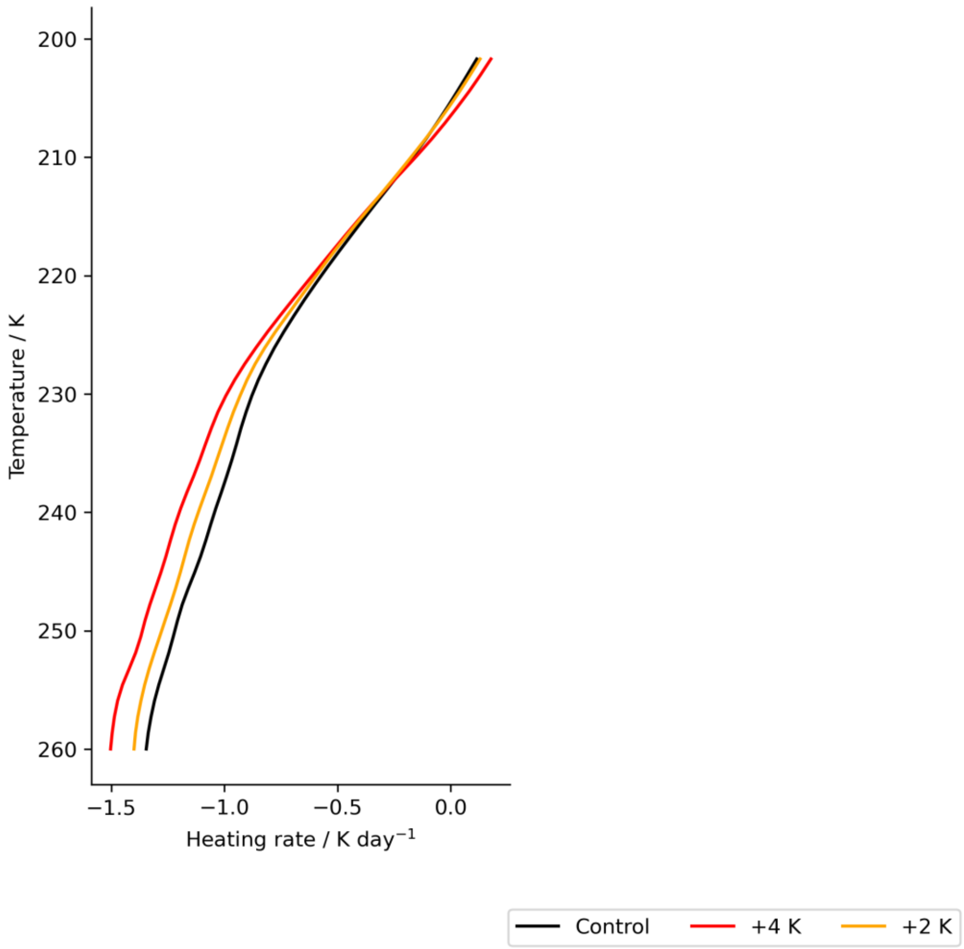
Increase in clear sky cooling counteracts increase in stability

Also found by Bony et al. (2016), but less strong

INCREASE IN CLEAR SKY COOLING DUE TO LOWER DENSITY

$$H = \frac{1}{\rho c_p} \frac{dF}{dz}$$

ρ: Density
c_p: Heat Capacity
F: Radiative Flux
H: Heating Rate



1. Flux divergence invariant to surface temperature (Jeevanjee and Romps, 2018)
2. Increase in clear sky cooling due to density reduction (Gasparini et al., 2024)

Speculation: Prescribed ozone might result in bias towards stronger stability iris due to decreased clear sky cooling