The SST pattern effect on OLR: the role of large-scale convective aggregation

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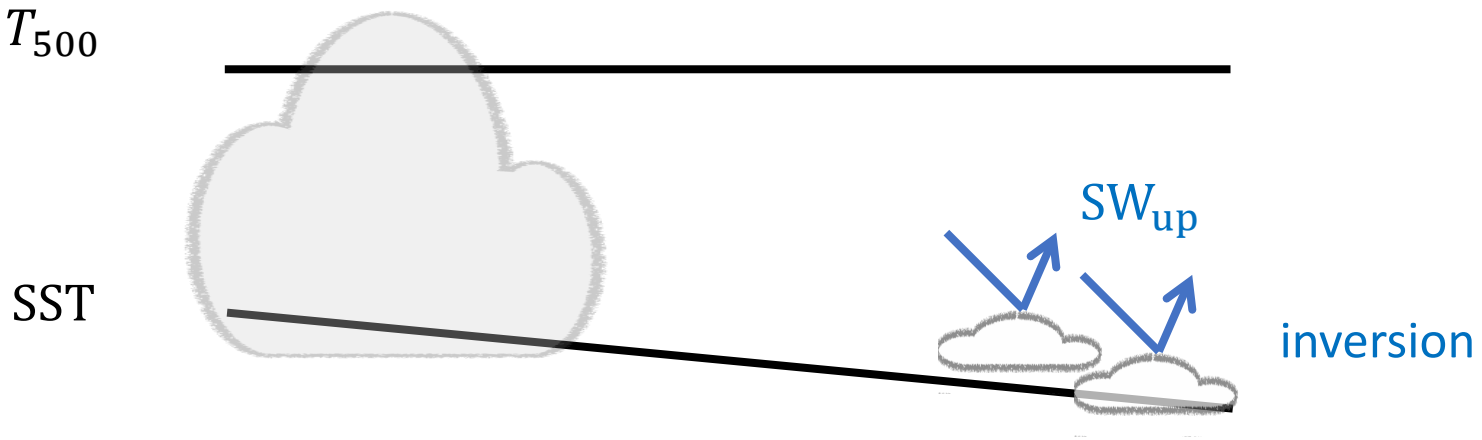
Jun. 5th

Collaborators: Stephan Fueglistaler, Bosong Zhang, Chenggong Wang

The SST pattern effect – shortwave radiation



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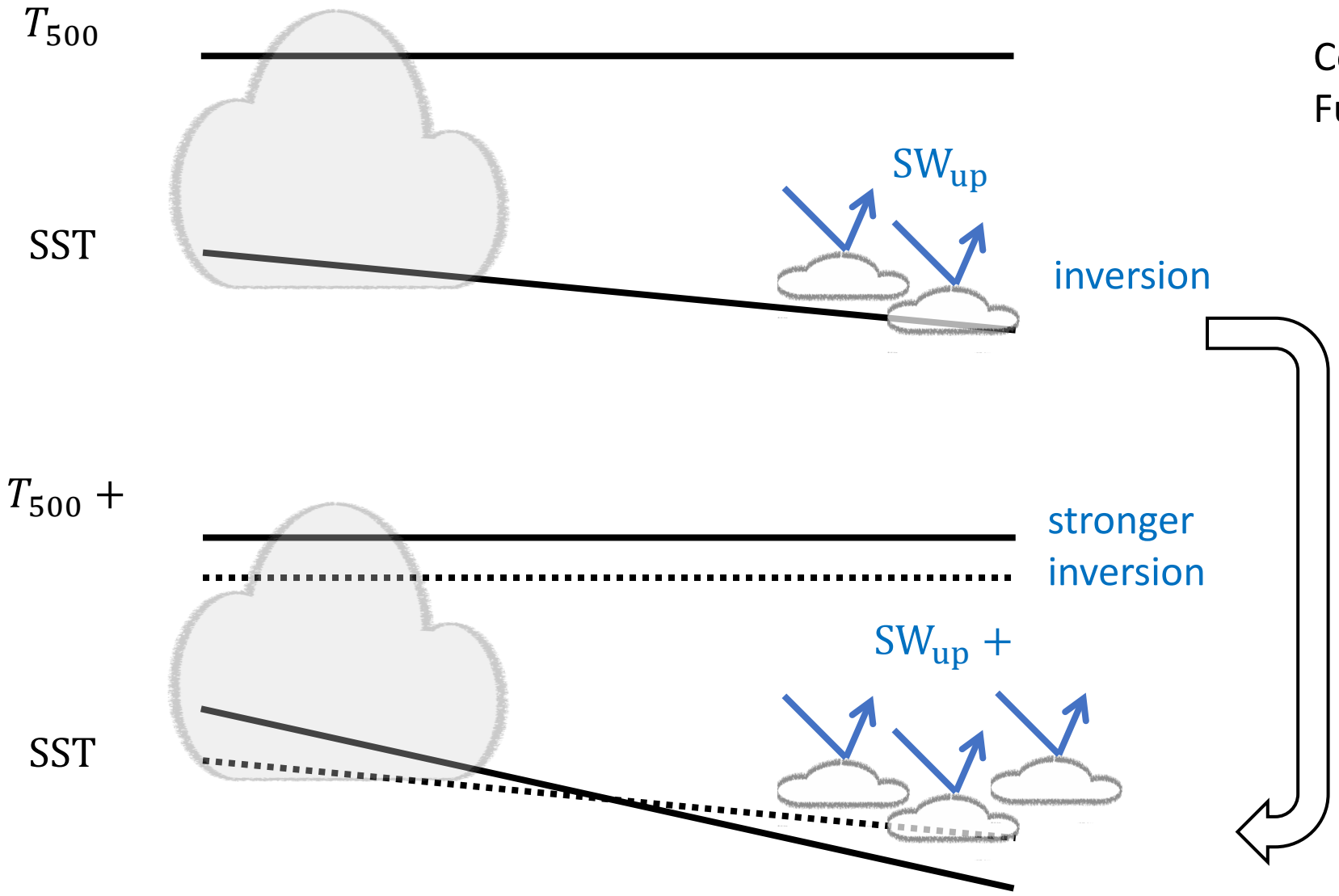
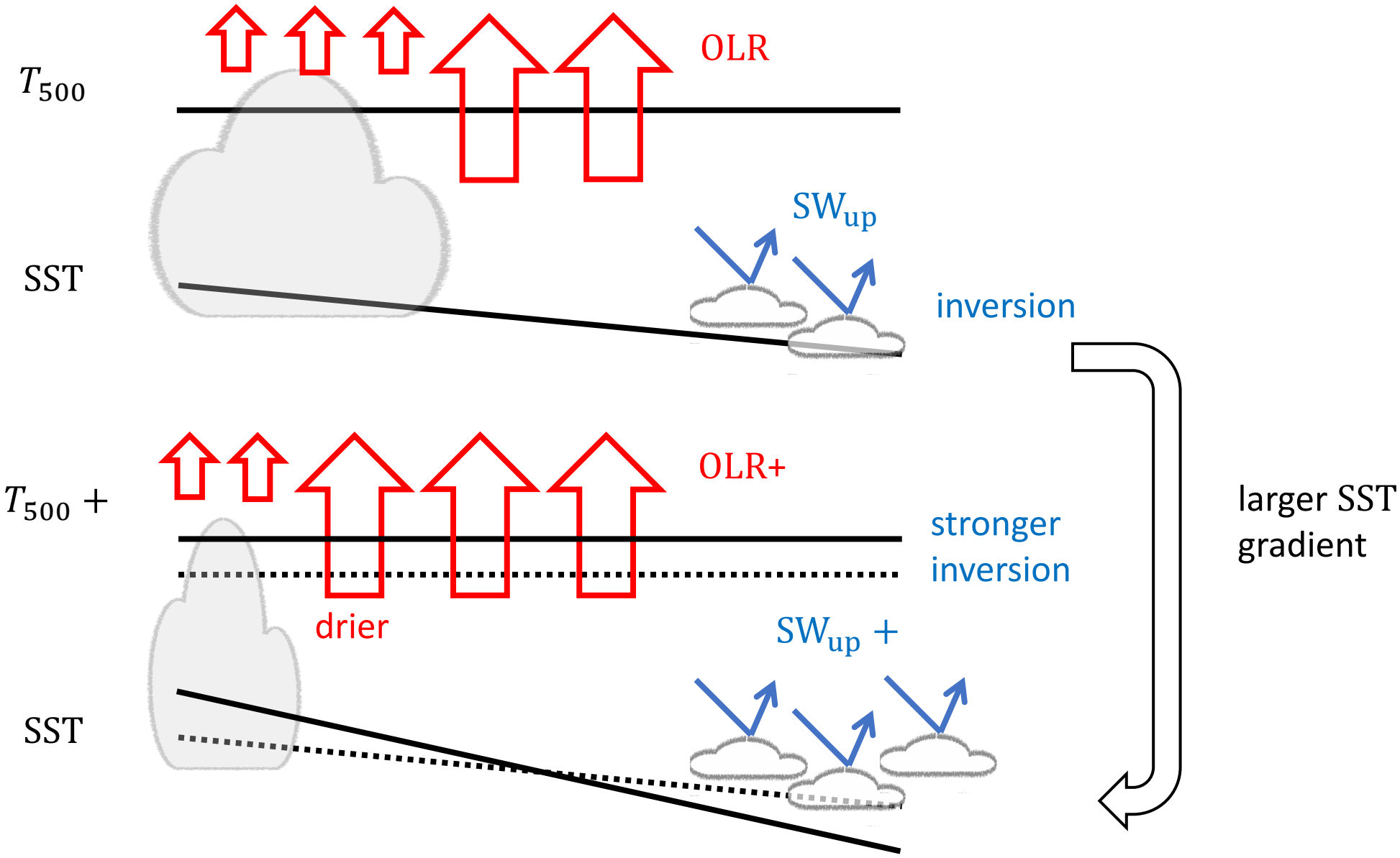


Ceppi & Gregory, 2017, *PNAS*
Fueglistaler 2019, *GRL*

larger SST gradient

The SST pattern effect – longwave radiation



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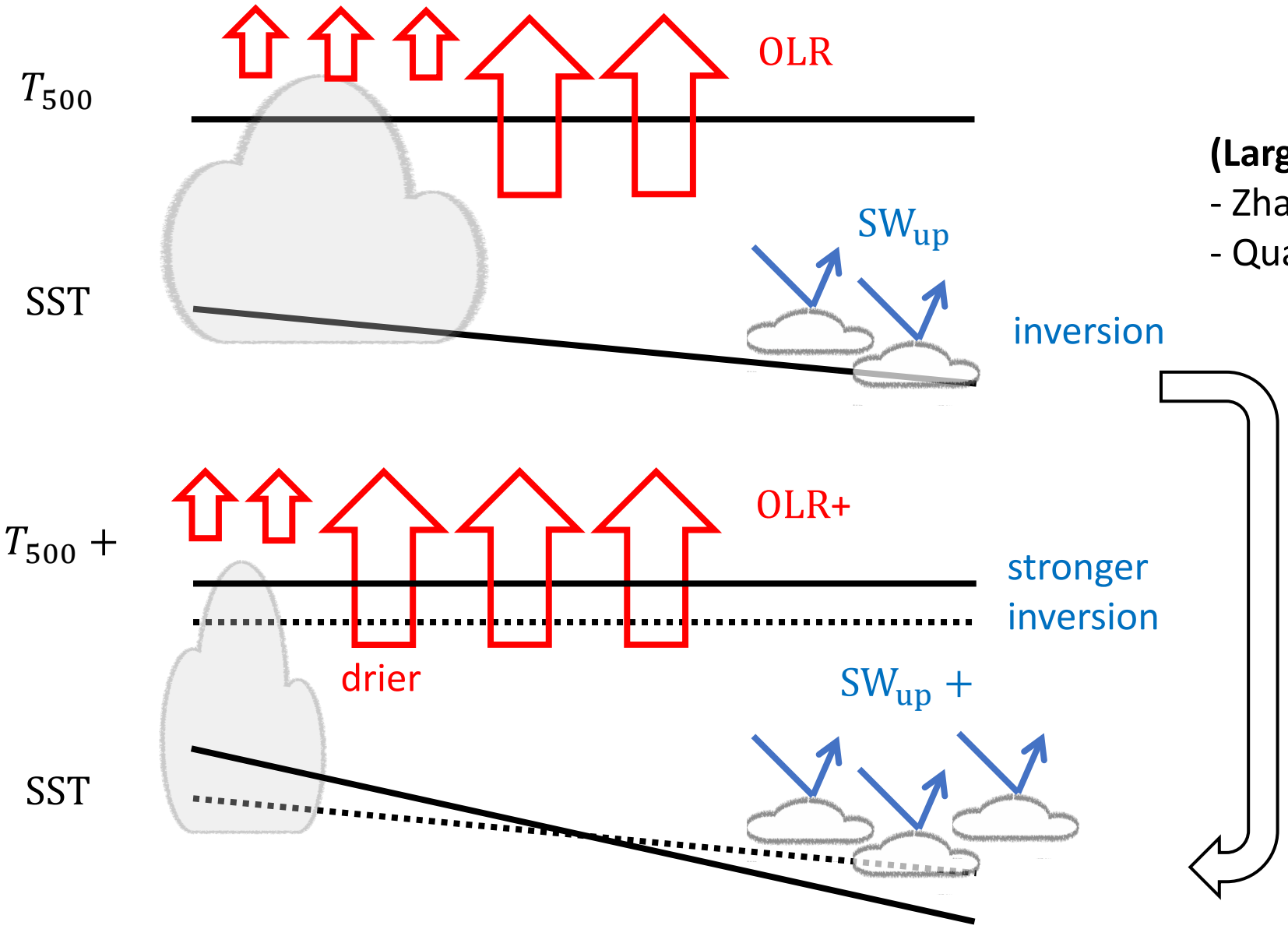
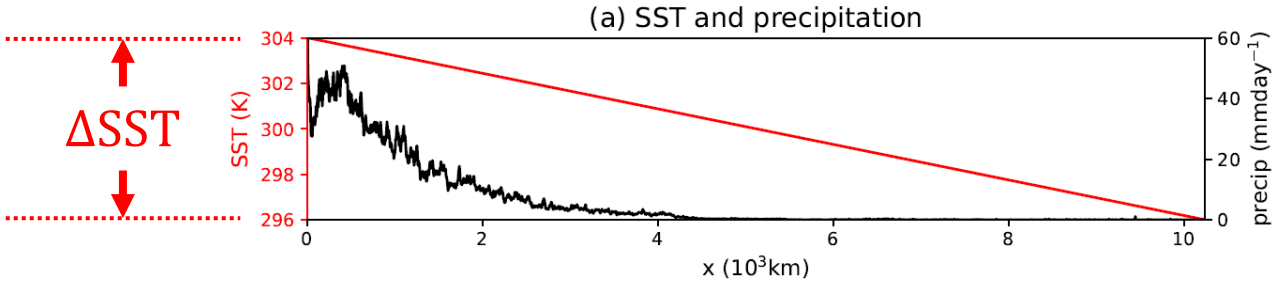


(Large-scale) convection aggregation
- Zhang & Fueglistaler, 2020, *GRL*
- Quan et al., 2024, *under review*

Stronger convection aggregation → larger OLR: mechanism



Cloud-resolving model - SAM
2-D (x-z) mock Walker circulation
Prescribed linear SST
Perturb ΔSST

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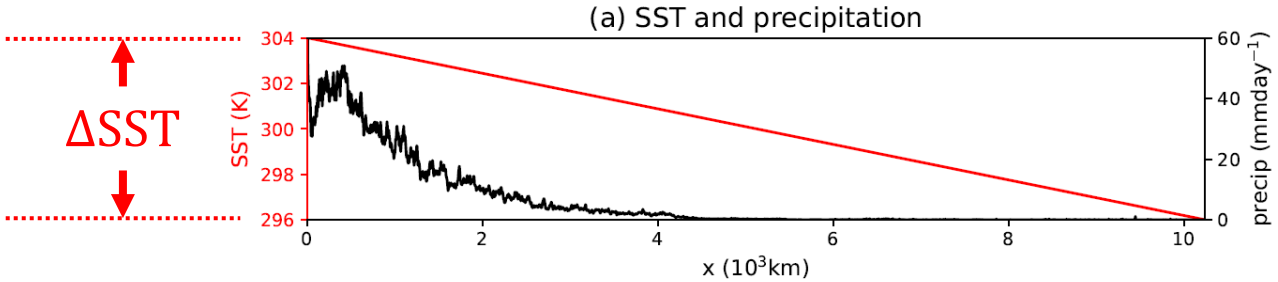

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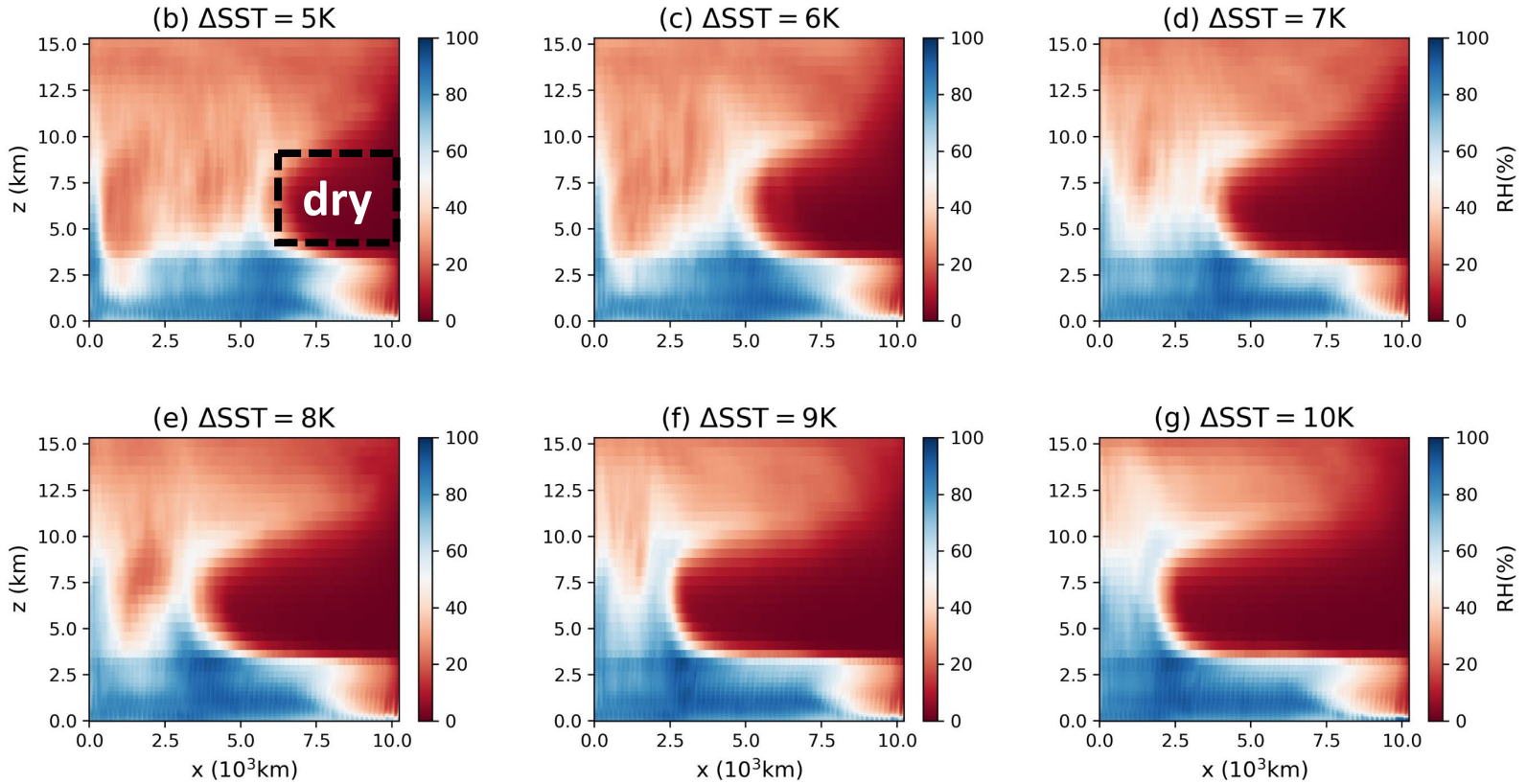
$\mathrm{RH}(x,z)$ for different ΔSST



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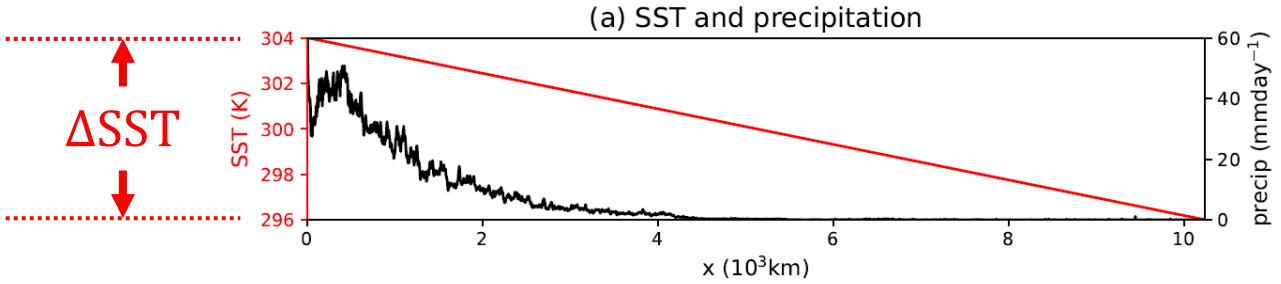

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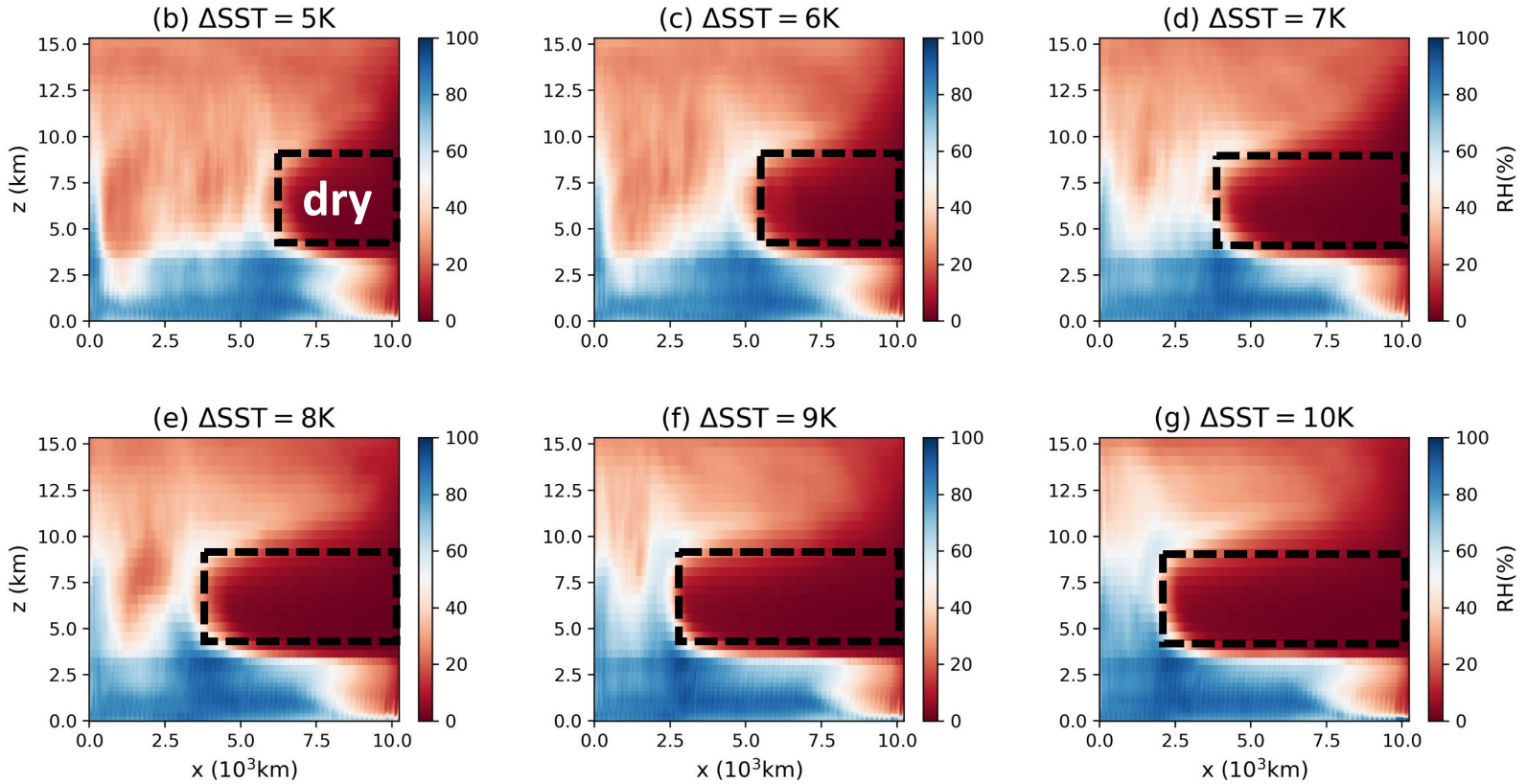


Larger ΔSST
⇩
Stronger convection aggregation
⇩
Dry subsidence region expansion
⇩
Larger OLR

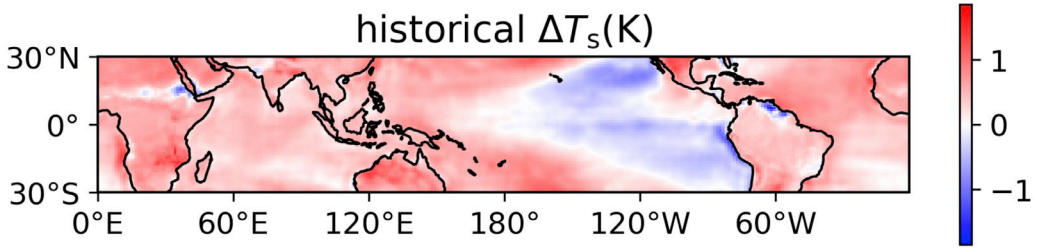
Large-scale convection aggregation is important for climate change

1. Historical (1980-2010) SST pattern effect on OLR is comparable to reflected shortwave radiation because of convection aggregation strengthening.

2. The non-additivity error in the SST Green's Functions approach is explained by the non-additivity of convection aggregation.

Historical SST pattern effect on OLR comparable to reflected SW

uniform: GFDL-AM4, uniform SST+4K
historical: SST perturbation = 1980 - 2010 SST trend × 30yr



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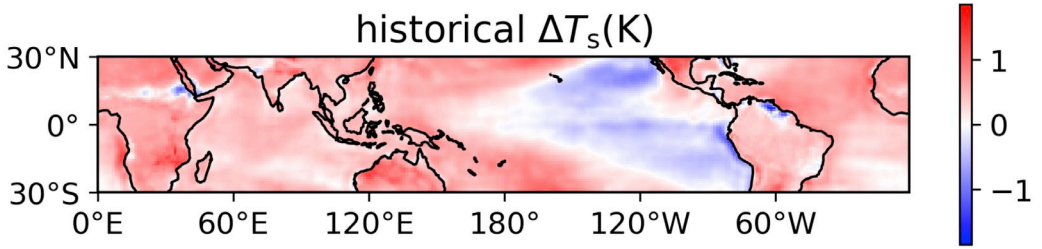

Tropical (30°S ~ 30°N) average responses, normalized to 1K mean surface warming

	$\frac{dSW_{up}}{d\overline{T_s}}$	$\frac{dOLR}{d\overline{T_s}}$	$\frac{dT_{500}}{d\overline{T_s}}$	$\frac{dLCC}{d\overline{T_s}}$	$\frac{dCRH}{d\overline{T_s}}$	$\frac{dHCC}{d\overline{T_s}}$
uniform	-0.21	1.69	1.44	$-0.46\%/K$	$0.27\%/K$	$-0.19\%/K$
historical	1.72	3.14	1.95	$1.51\%/K$	$-0.62\%/K$	$-1.10\%/K$
difference	$+1.93$	$+1.45$	$+0.55$	$+1.97\%/K$	$-0.89\%/K$	$-0.91\%/K$
(historical – uniform)			500hPa T	Low cloud	Column RH	High cloud

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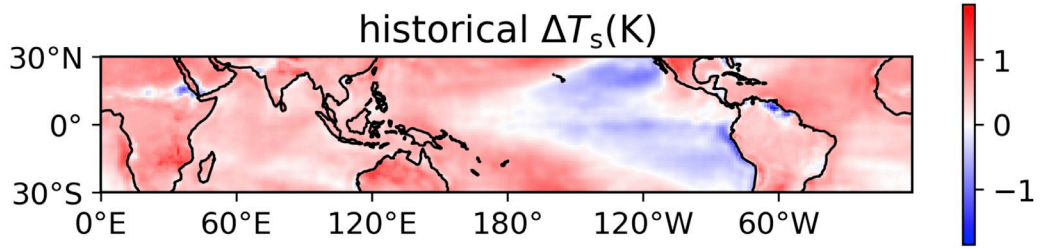

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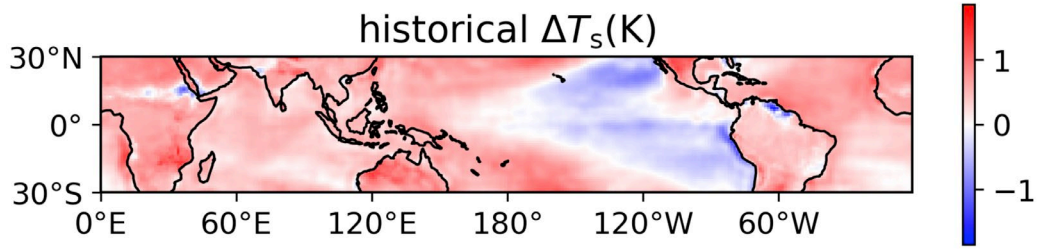

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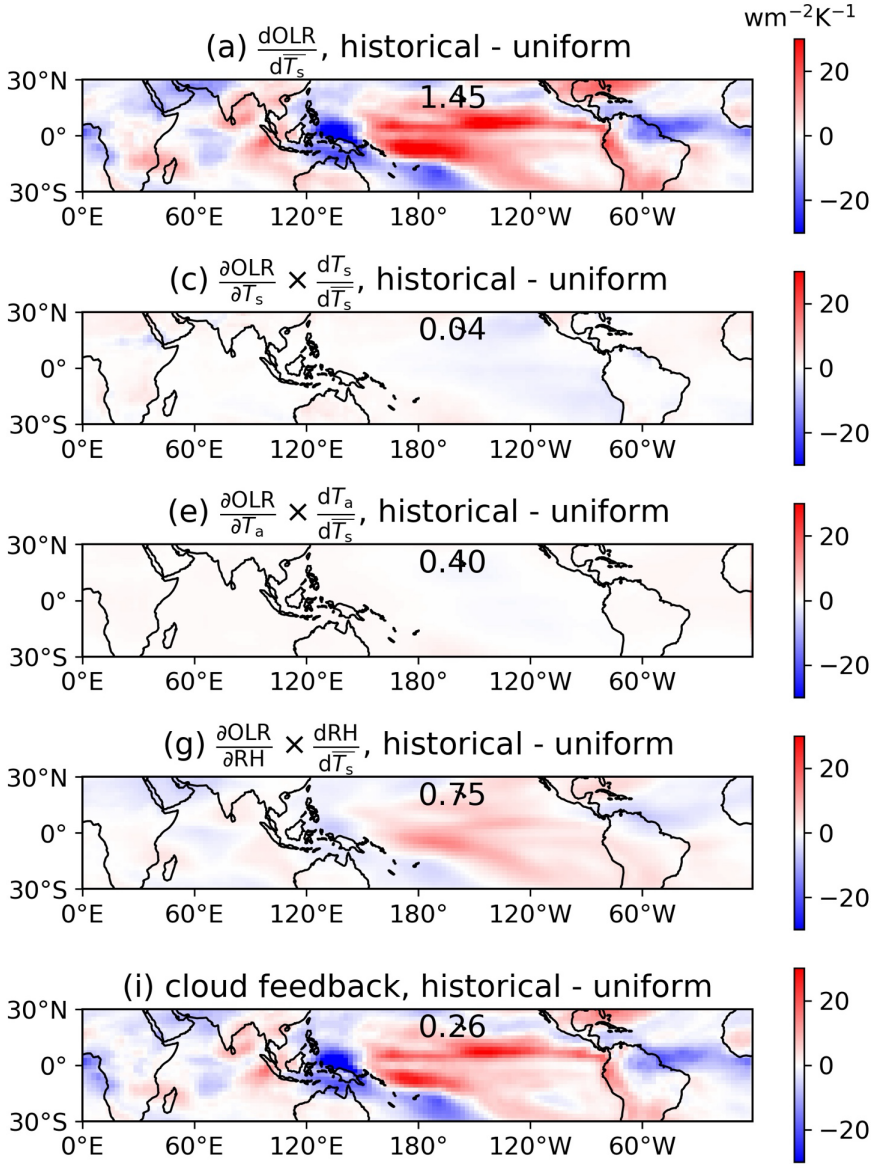
Historical SST pattern effect on OLR due to convection aggregation



$\frac{dOLR}{d\overline{T}_s}$

$\frac{dOLR}{\partial T_s} \cdot \frac{dT_s}{d\overline{T}_s}$

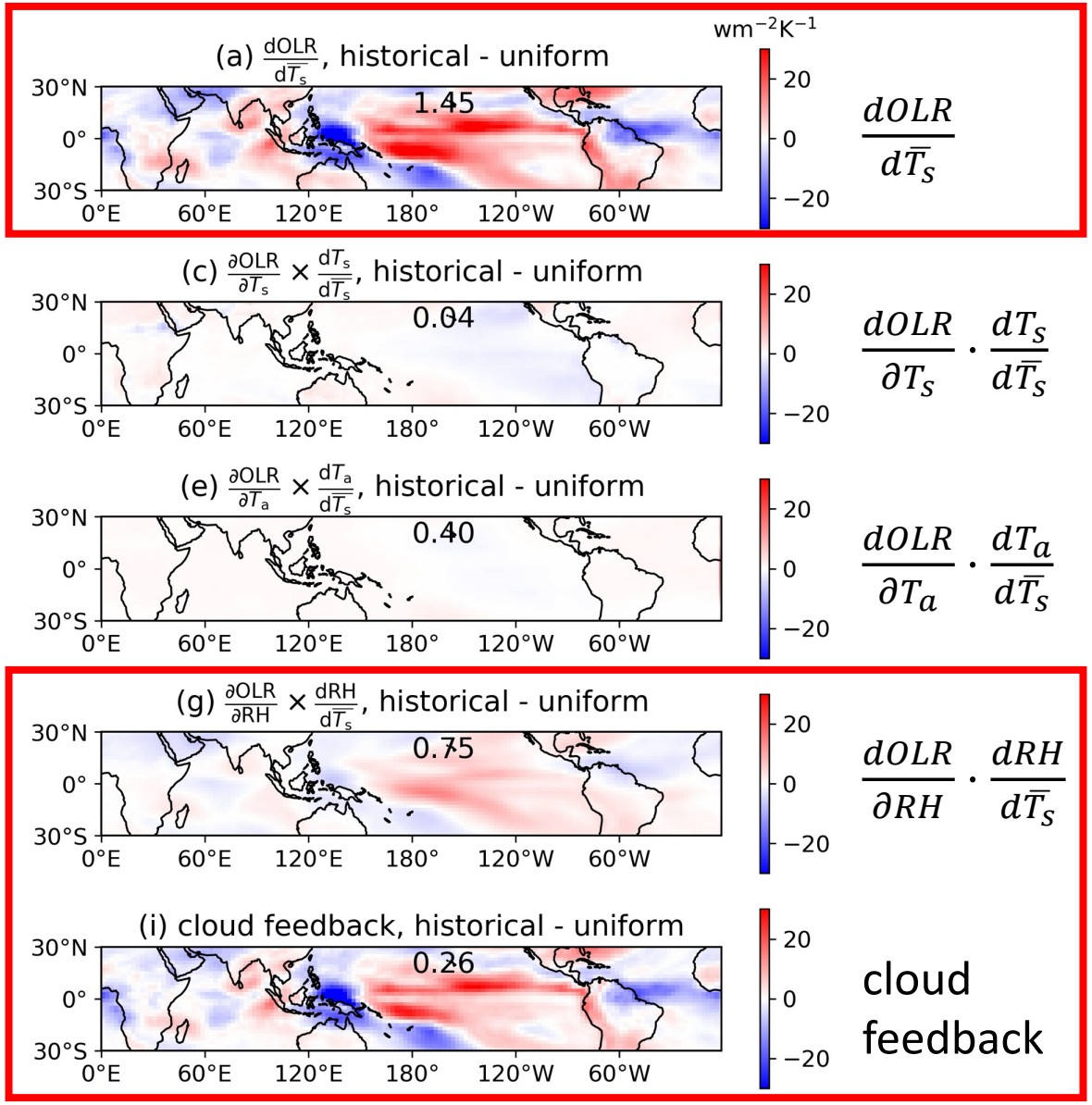
$\frac{dOLR}{\partial T_a} \cdot \frac{dT_a}{d\overline{T}_s}$

$\frac{dOLR}{\partial RH} \cdot \frac{dRH}{d\overline{T}_s}$

cloud feedback

(Figures show historical – uniform)

Historical SST pattern effect on OLR due to convection aggregation



$\frac{dOLR}{d\overline{T_s}}$

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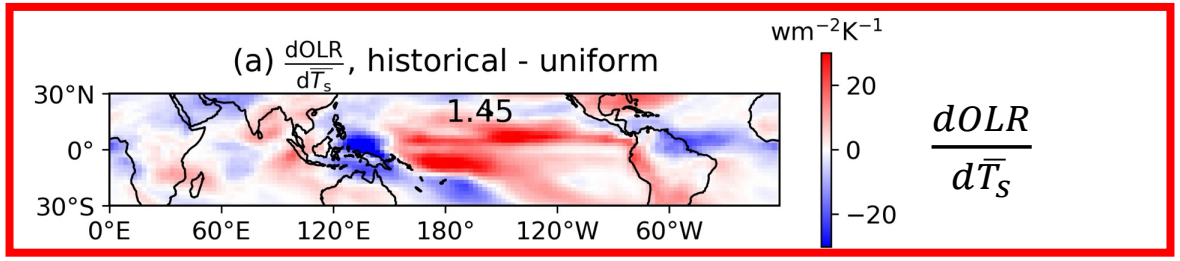
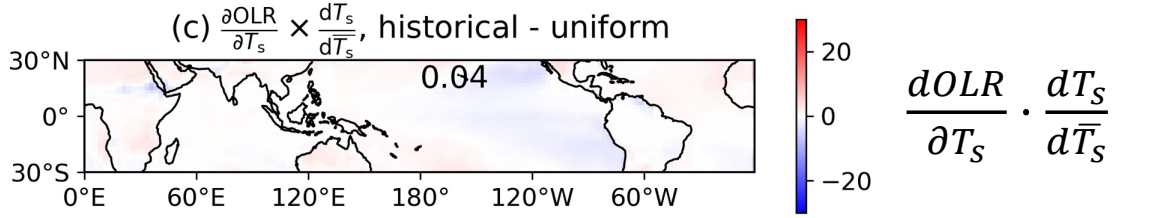
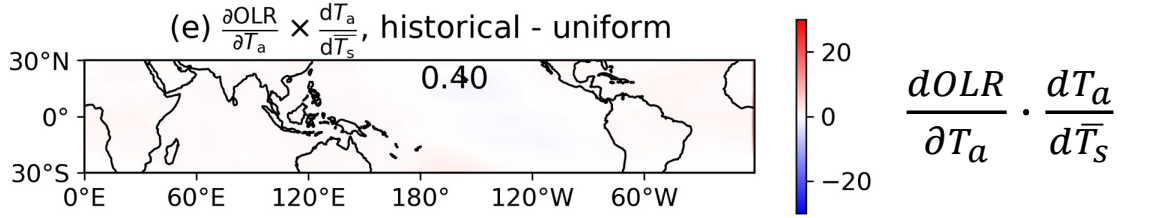


$$\frac{dOLR}{d\overline{T}_s}$$



$$\frac{dOLR}{\partial T_s} \cdot \frac{dT_s}{d\overline{T}_s}$$



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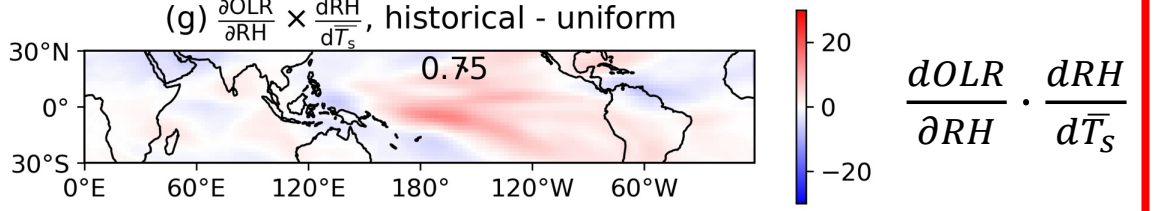

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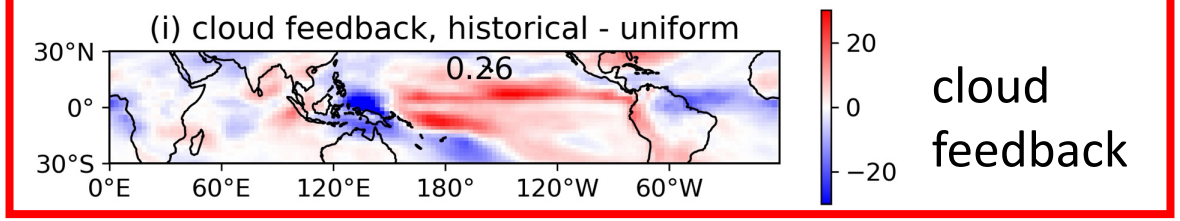

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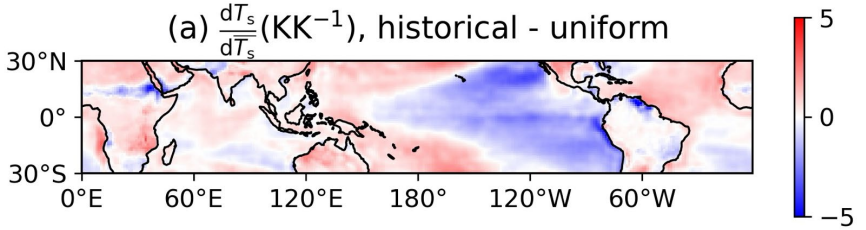
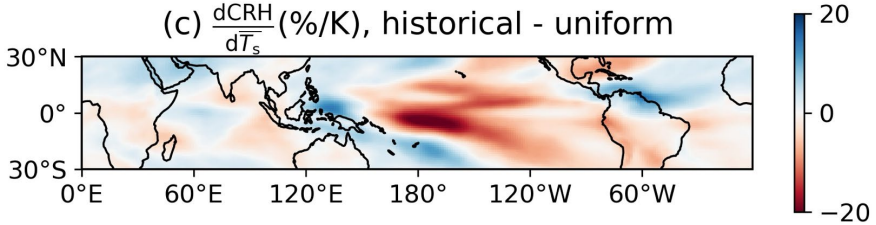
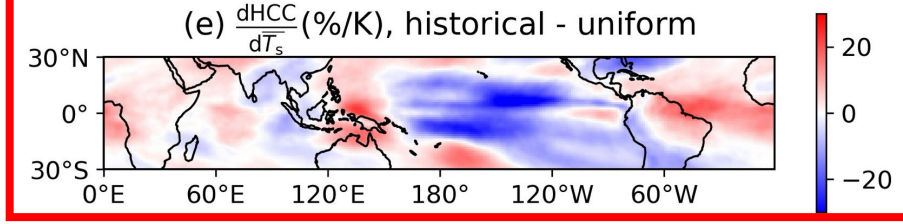


ΔT_s

convection aggregation



Column RH



High cloud

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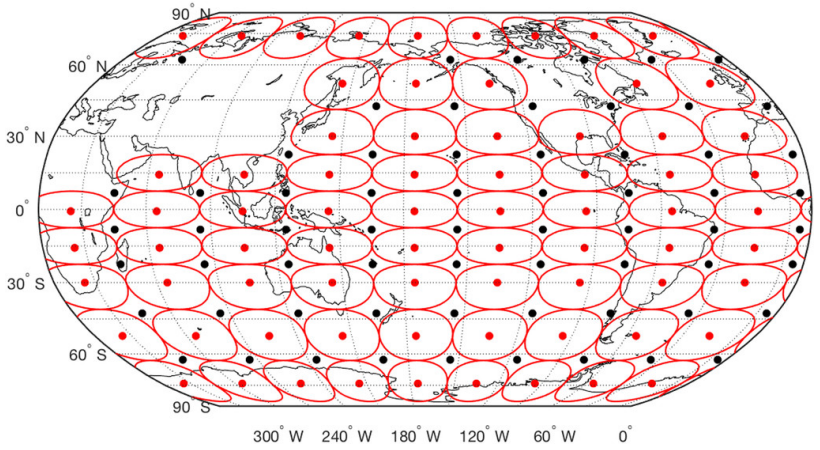
2. The non-additivity error in the SST Green's Functions approach is explained by the non-additivity of convection aggregation.

The SST Green's functions (GF) approach

$$\Delta\bar{R} = \sum_j \frac{\partial \bar{R}}{\partial \mathrm{SST}_j} \Delta \mathrm{SST}_j$$



Dong 2019

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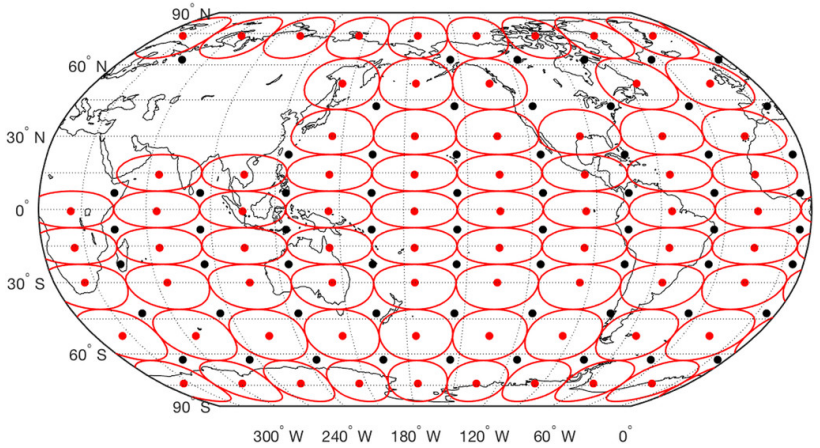
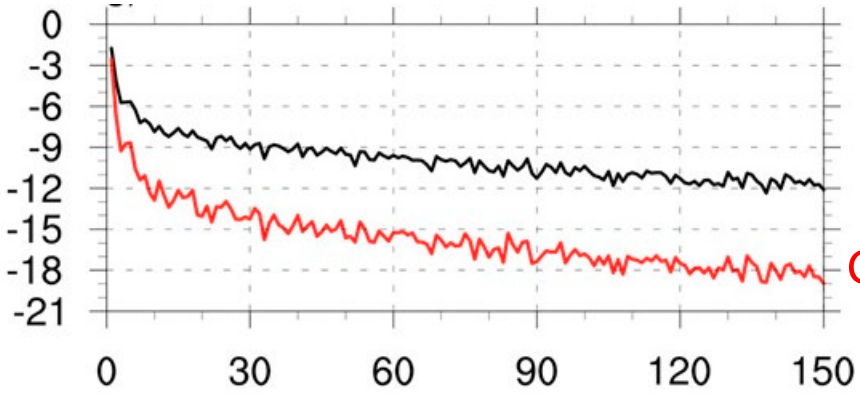


Dong 2019

AGCM ← SST warming in 4xCO_2 GCM

Y: $\Delta\overline{R_{lw}}$



Truth (4xCO_2 run)

GF reconstruction

X: year

Zhang et al., 2023, *JCLI*

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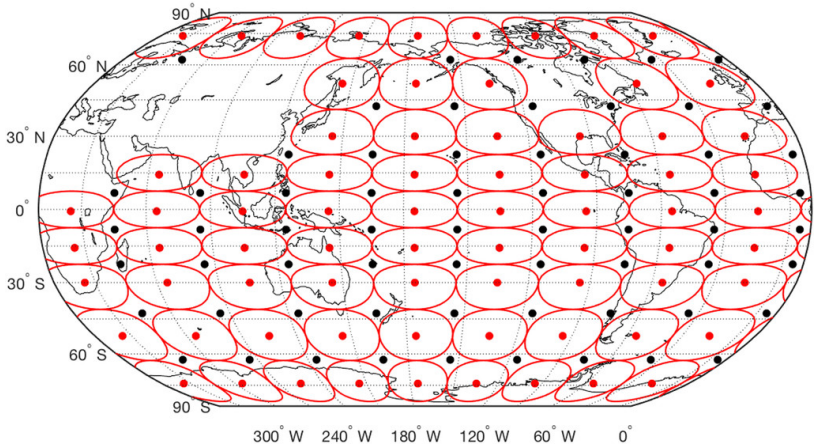

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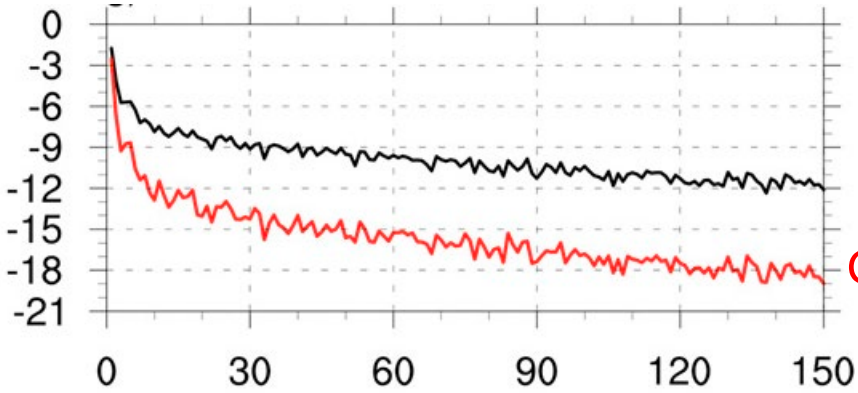

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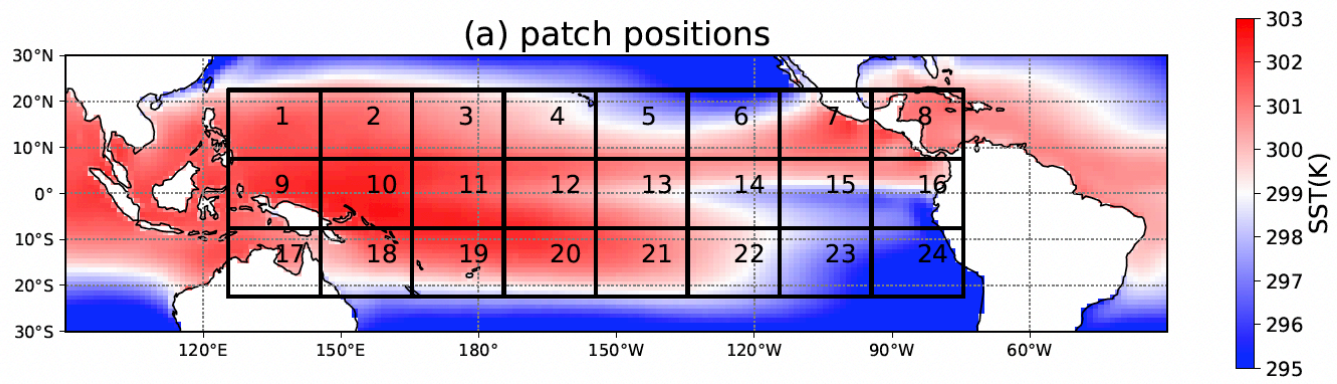
$$\Delta\bar{R}(\Delta\mathrm{SST}_1, \Delta\mathrm{SST}_2, \dots) \neq \Delta\bar{R}(\Delta\mathrm{SST}_1, 0, 0, \dots) + \Delta\bar{R}(0, \Delta\mathrm{SST}_2, 0, \dots) + \cdots$$

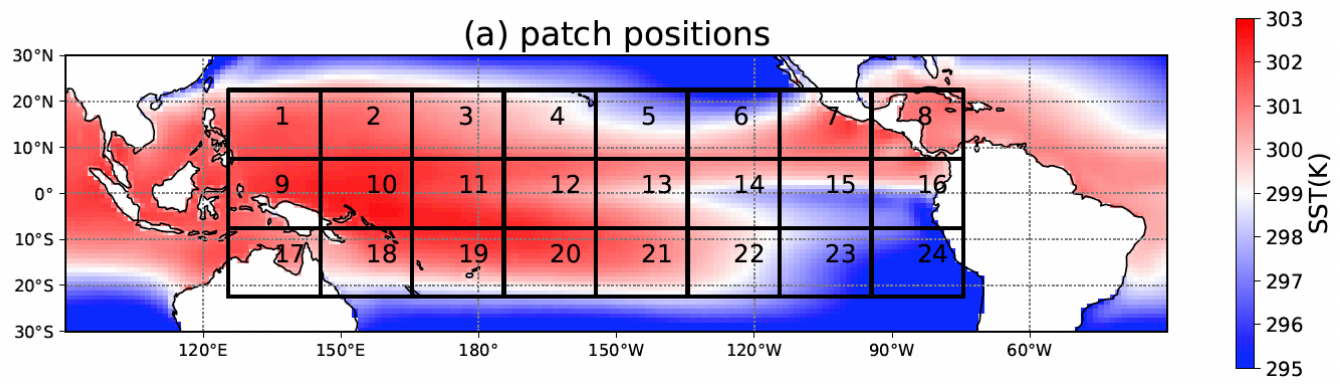
Question: Why is OLR response overestimated by linear sum?

Two-patch combination: Linear sum overestimates OLR



AM4, SST+4K perturbation in **two adjacent** tropical Pacific patches (37 combinations in total)

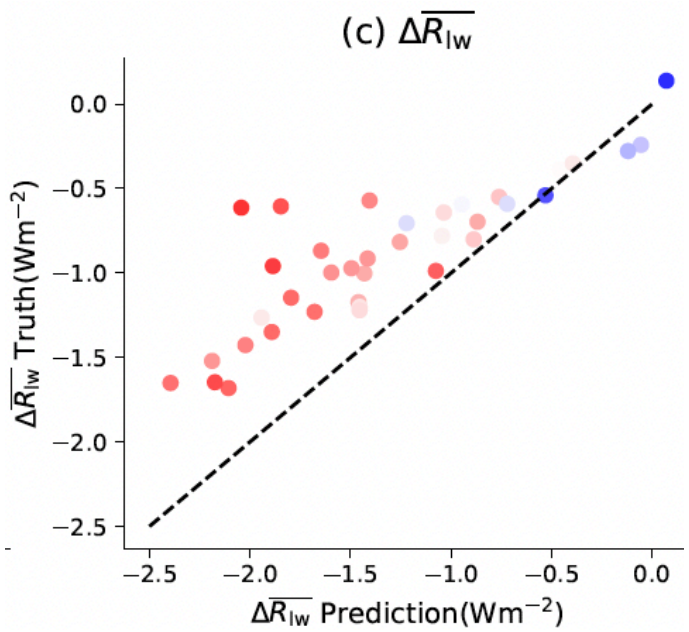
Two-patch combination: Linear sum overestimates OLR



AM4, SST+4K perturbation in **two adjacent** tropical Pacific patches (37 combinations in total)

Y: actual response

$\Delta\bar{R}(\Delta\mathrm{SST}_i, \Delta\mathrm{SST}_j)$

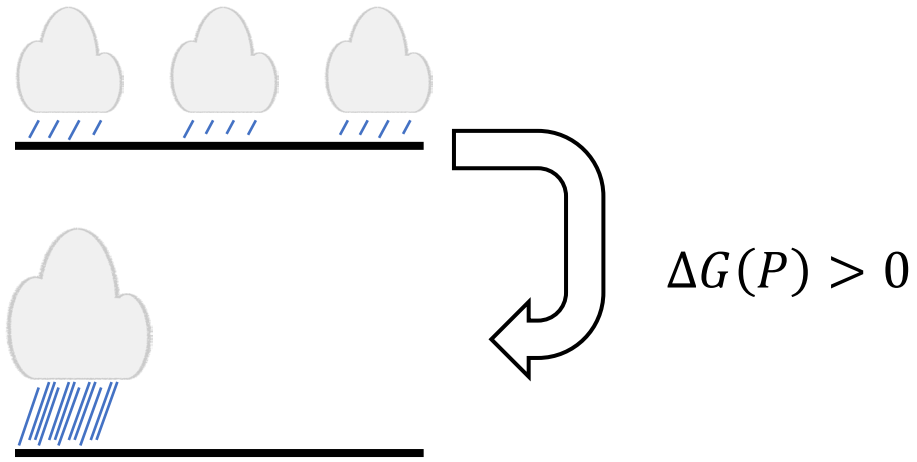


Color: average SST of two patches

X: linear sum

$\Delta\bar{R}(\Delta\mathrm{SST}_i, 0) + \Delta\bar{R}(0, \Delta\mathrm{SST}_j)$

OLR overestimation ← convection aggregation overestimation



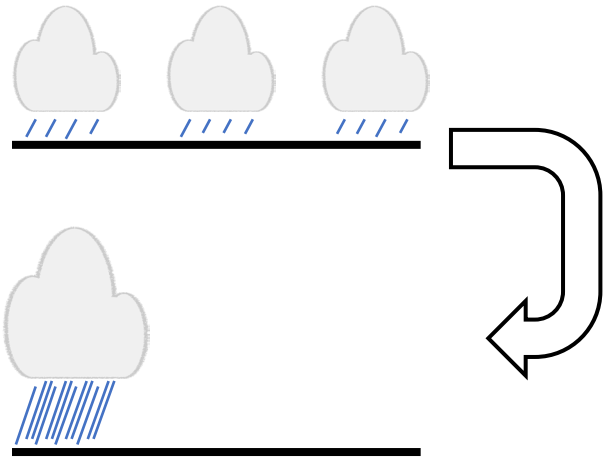
$\Delta G(P) > 0$

Tropical rainfall Gini index: $0 < G(P) < 100$
If $\Delta G(P) > 0$:

- Precipitation more spatially uneven
- Convection more aggregated

- Zhang & Fueglistaler, 2020, *GRL*

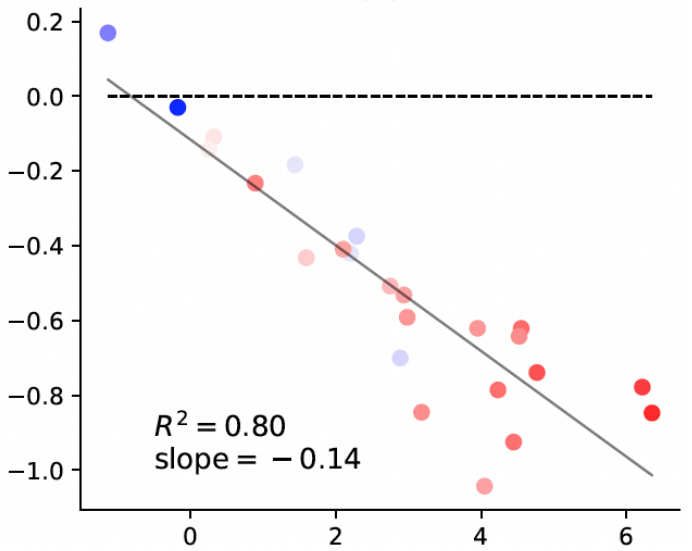
OLR overestimation ← convection aggregation overestimation



$\Delta G(P) > 0$

single patch SST+4K

Y: $\Delta\overline{R_{lw}}'$



X:$\Delta G(P)$

Tropical rainfall Gini index: $0 < G(P) < 100$

If $\Delta G(P) > 0$:

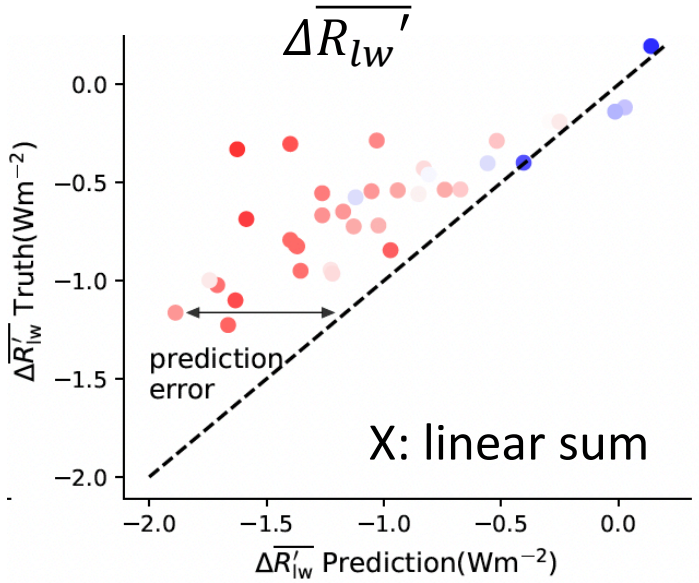
- Precipitation more spatially uneven
- Convection more aggregated

$\Delta\overline{R_{lw}}' \propto \Delta G(P)$

- Zhang & Fueglistaler, 2020, *GRL*

OLR overestimation ← convection aggregation overestimation

Y: actual response



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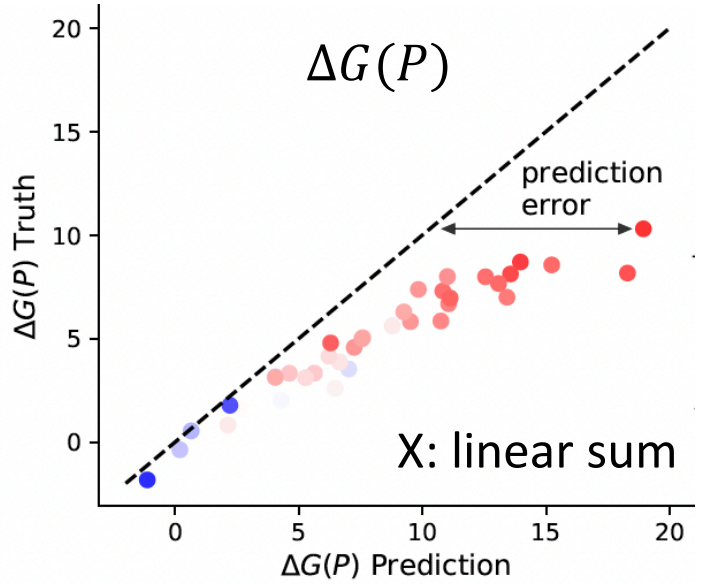

two adjacent patches SST+4K

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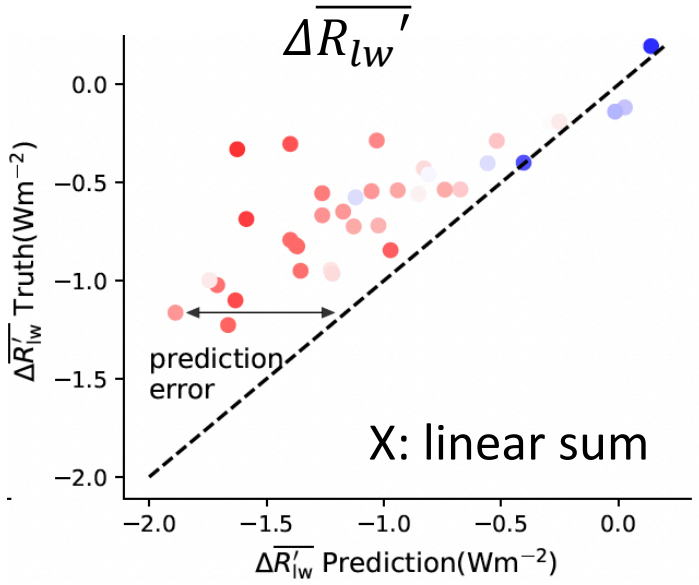

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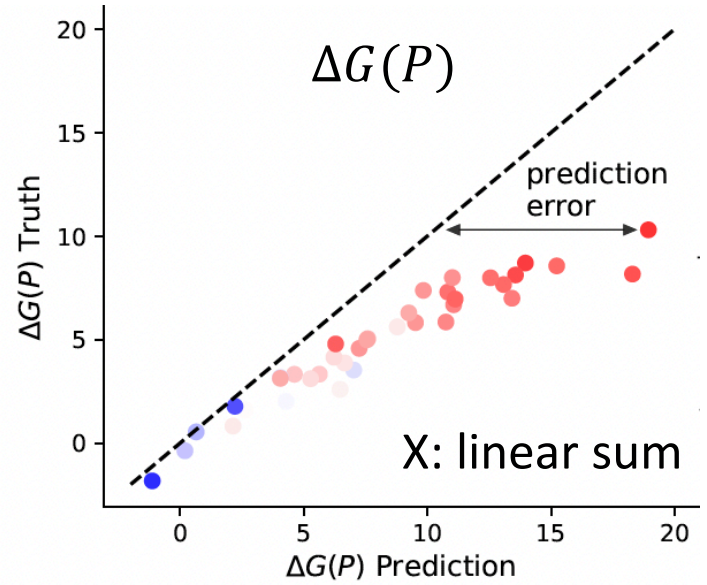

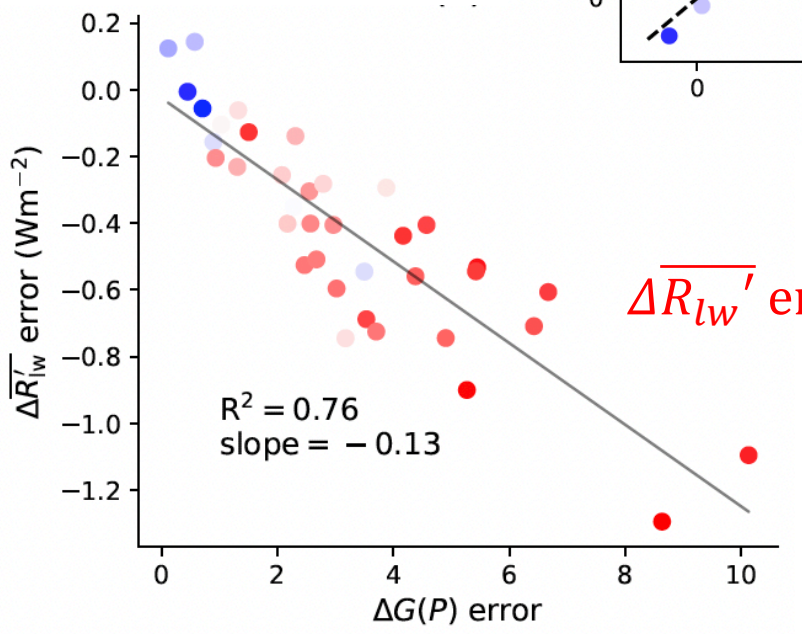

$\Delta\overline{R_{lw}}'$ error $\propto \Delta G(P)$ error

OLR overestimation ← convection aggregation overestimation

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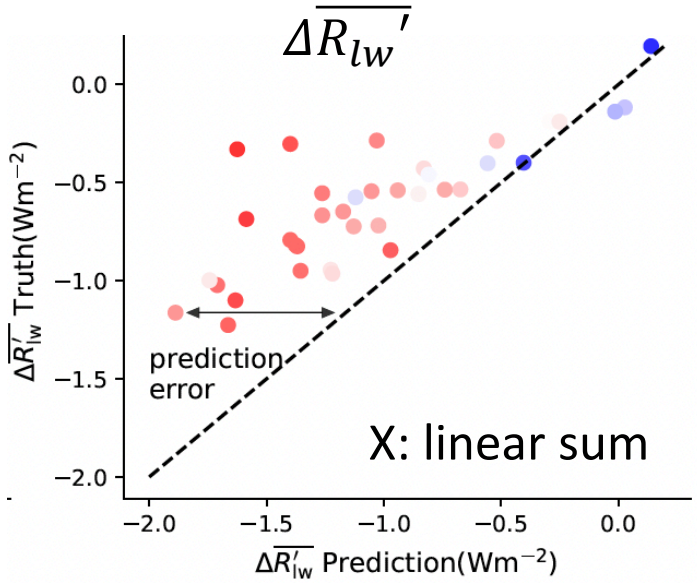
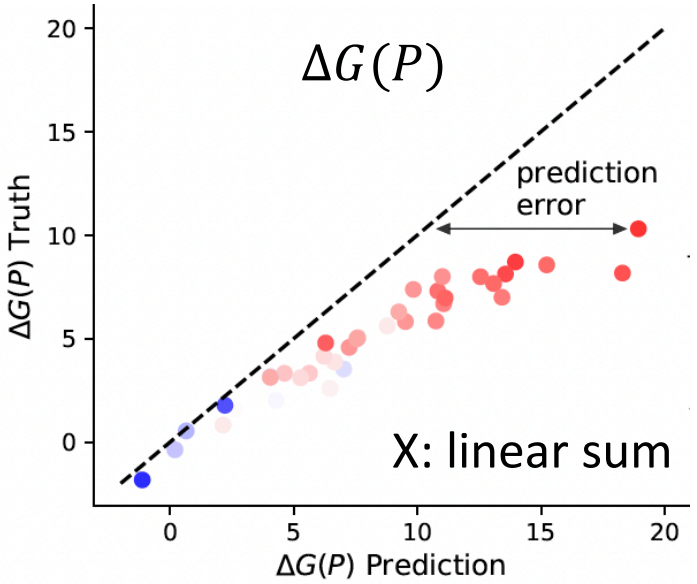


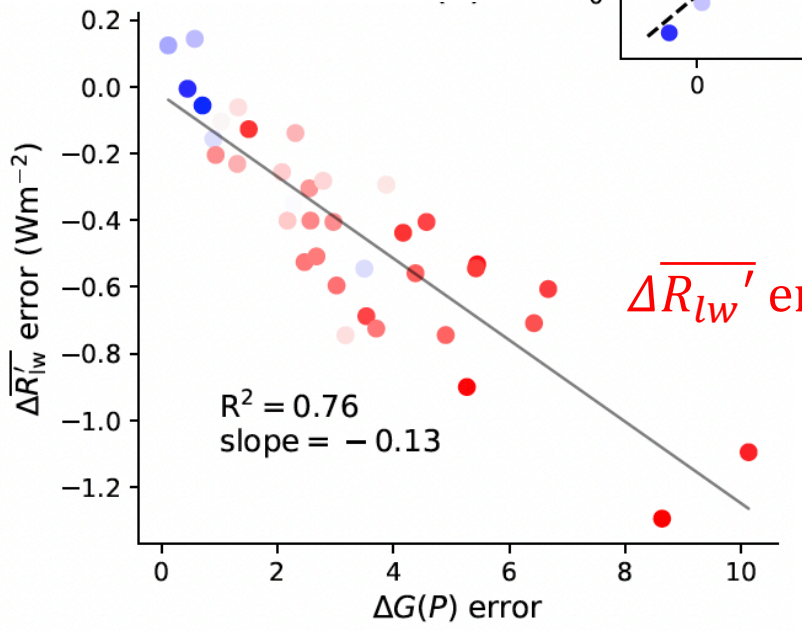
two adjacent patches SST+4K

Why is convection aggregation response overestimated by linear sum?

- non-additivity in circulation response
- Quan et al., 2024, *under review*

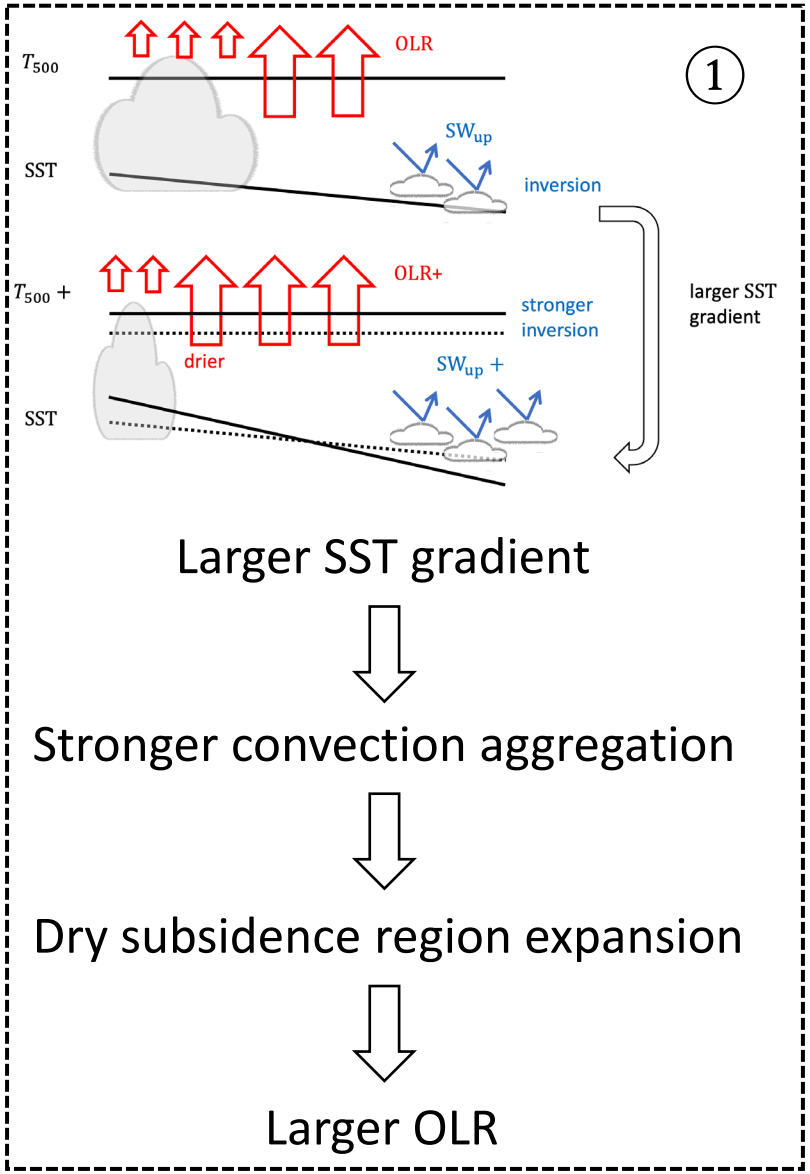
Y: actual response



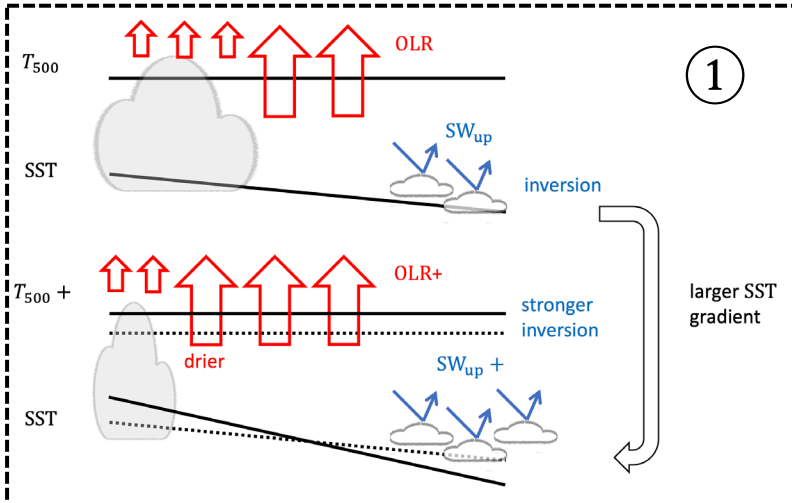


$\Delta\overline{R_{lw}}'$ error $\propto \Delta G(P)$ error

Summary


T_{500}
OLR
①
SW_{up}
SST
inversion
T_{500} +
OLR+
stronger inversion
larger SST gradient
drier
SW_{up} +
SST
Larger SST gradient
Stronger convection aggregation
Dry subsidence region expansion
Larger OLR

Summary



Larger SST gradient

⇩

Stronger convection aggregation

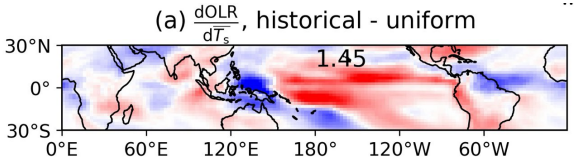
⇩

Dry subsidence region expansion

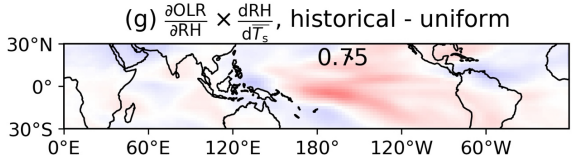
⇩

Larger OLR

② $\frac{dOLR}{d\overline{T_s}}$



≈



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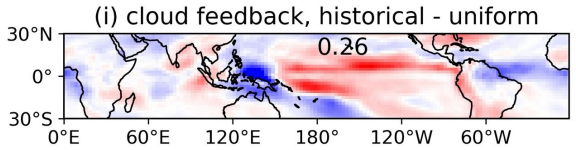
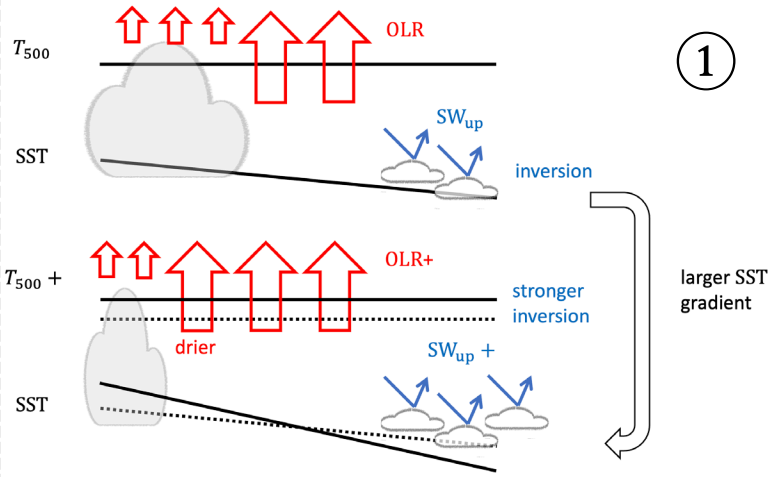


$\frac{dOLR}{\partial RH} \cdot \frac{dRH}{d\overline{T_s}}$

cloud feedback

Historical (1980-2010) SST pattern effect on OLR is comparable to reflected SW because of convection aggregation strengthening.

Summary



Larger SST gradient

⇩

Stronger convection aggregation

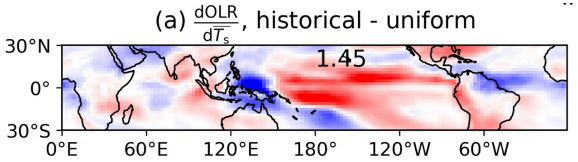
⇩

Dry subsidence region expansion

⇩

Larger OLR

② $\frac{dOLR}{d\overline{T_s}}$



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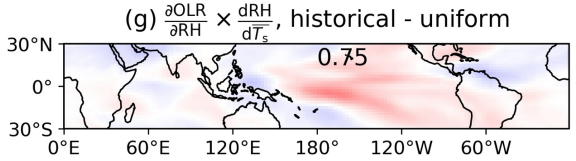

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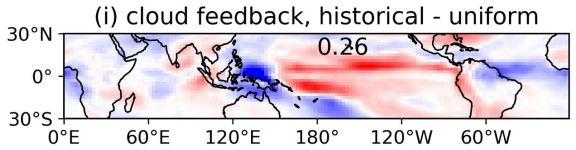
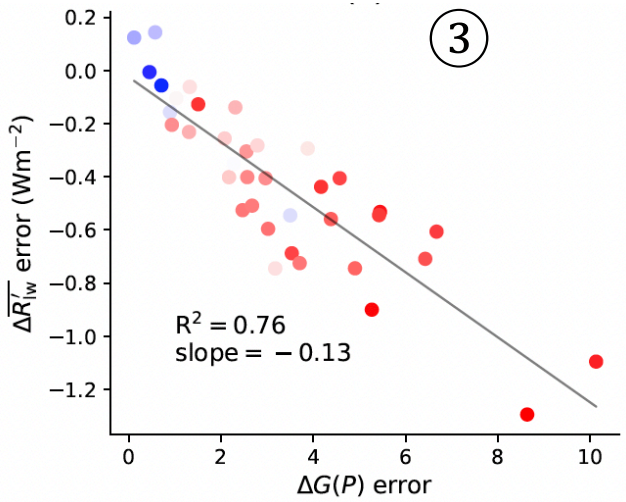


$\frac{dOLR}{\partial RH} \cdot \frac{dRH}{d\overline{T_s}}$

cloud feedback

Historical (1980-2010) SST pattern effect on OLR is comparable to reflected SW because of convection aggregation strengthening.

③



$\Delta\overline{R_{lw}}'$ error $\propto \Delta G(P)$ error

The non-additivity error in the SST Green's Functions approach is explained by the non-additivity of convection aggregation.

Thanks!

Preprint & Contact me:
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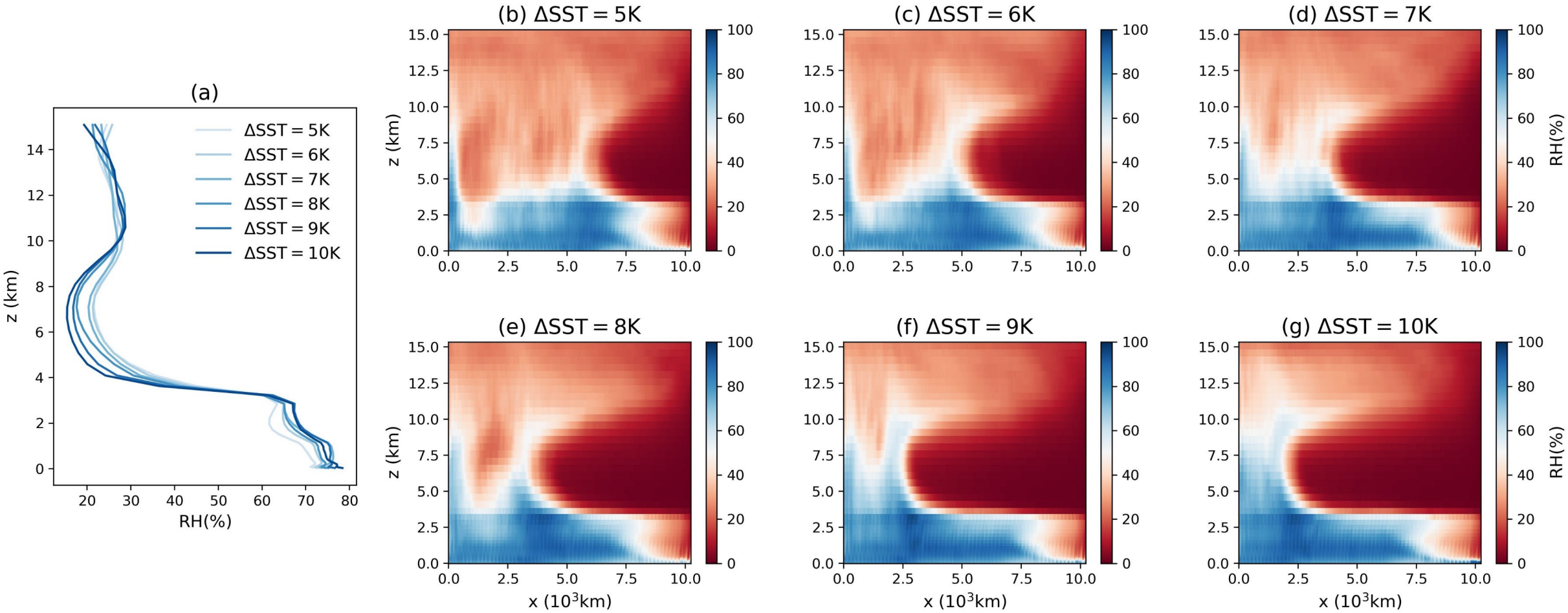
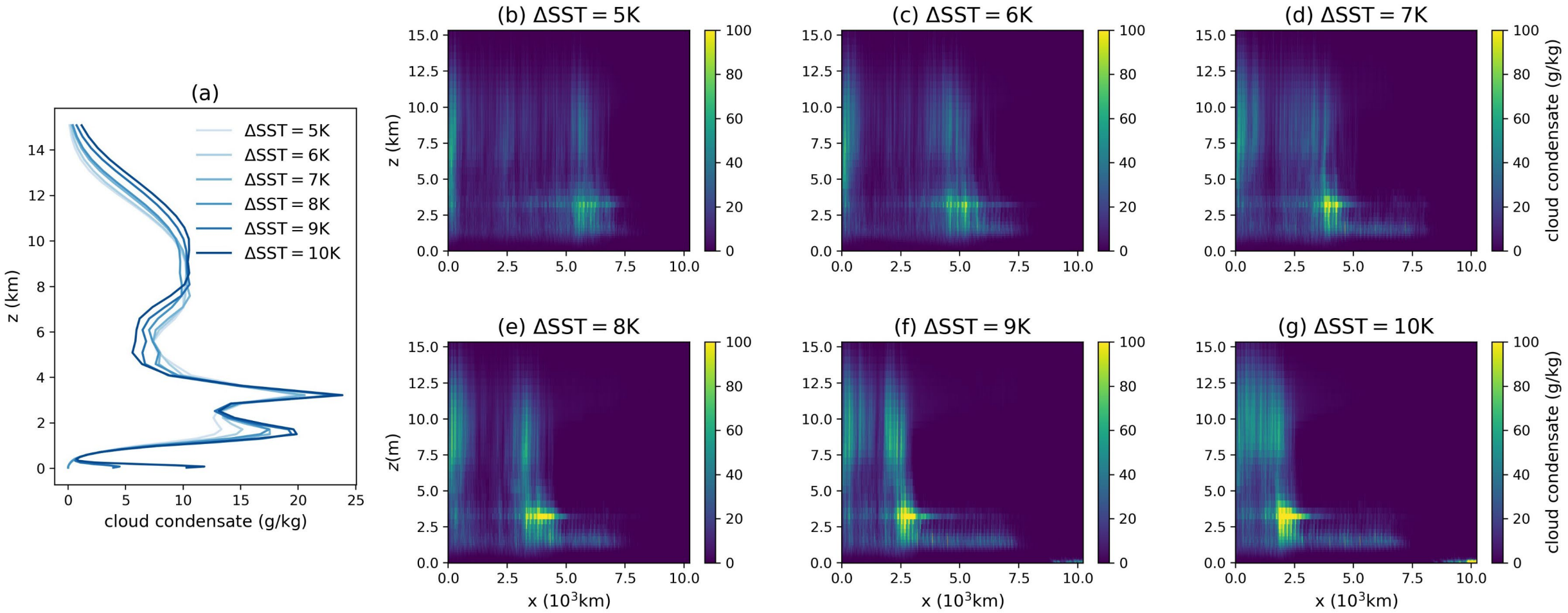
https://heng-quan.github.io

Stronger convection aggregation → larger OLR: mechanism



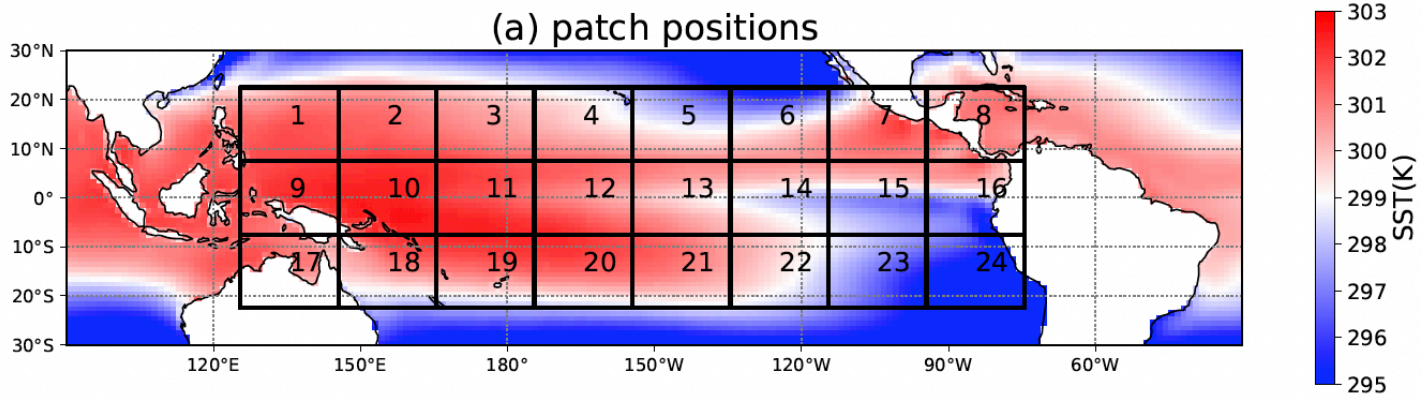
$\mathrm{RH}(x, z)$ for different ΔSST

Stronger convection aggregation → larger OLR: mechanism

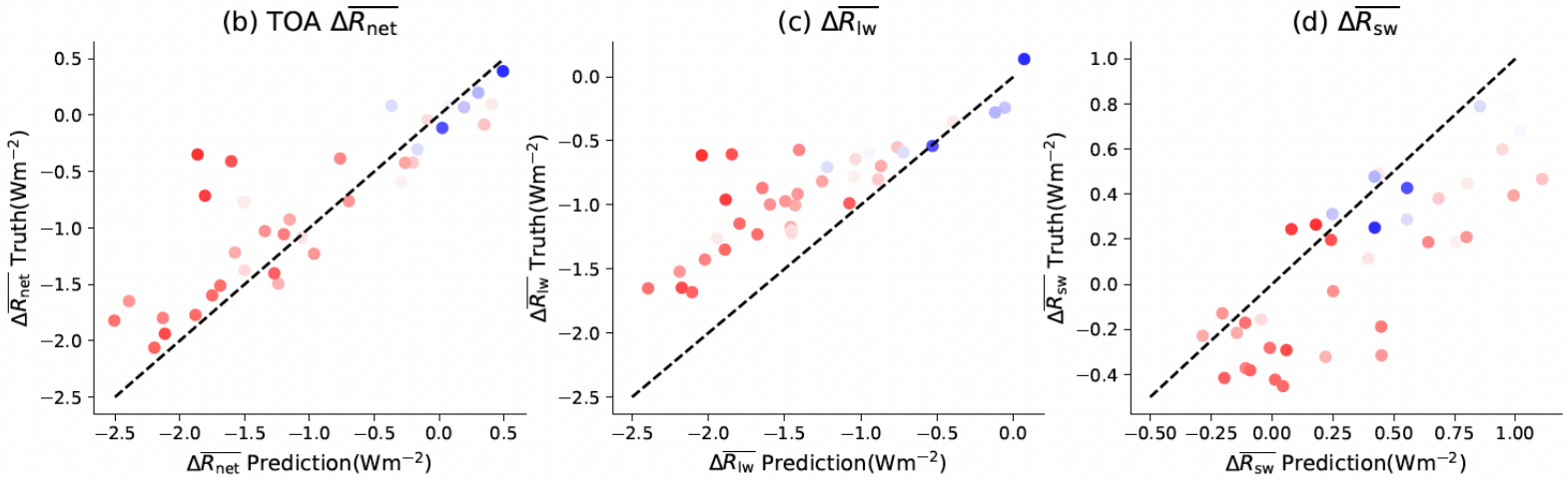


Cloud condensate mixing ratio for different ΔSST

Linear sum overestimates TOA radiation responses

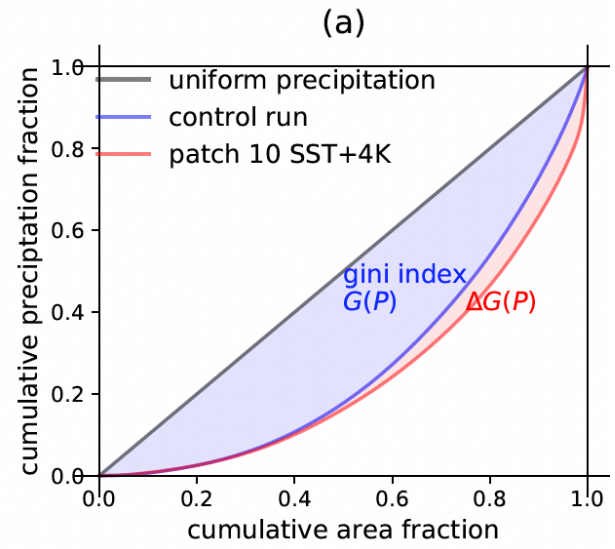


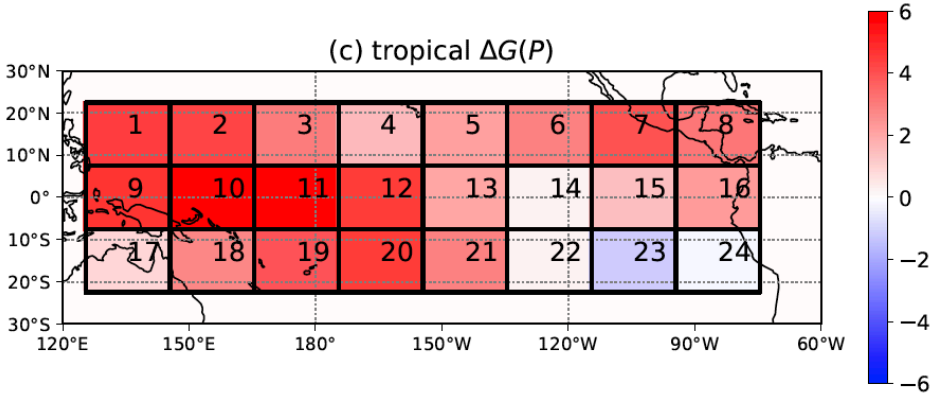
AM4, SST+4K perturbation in **two adjacent** tropical Pacific patches (37 combinations in total)



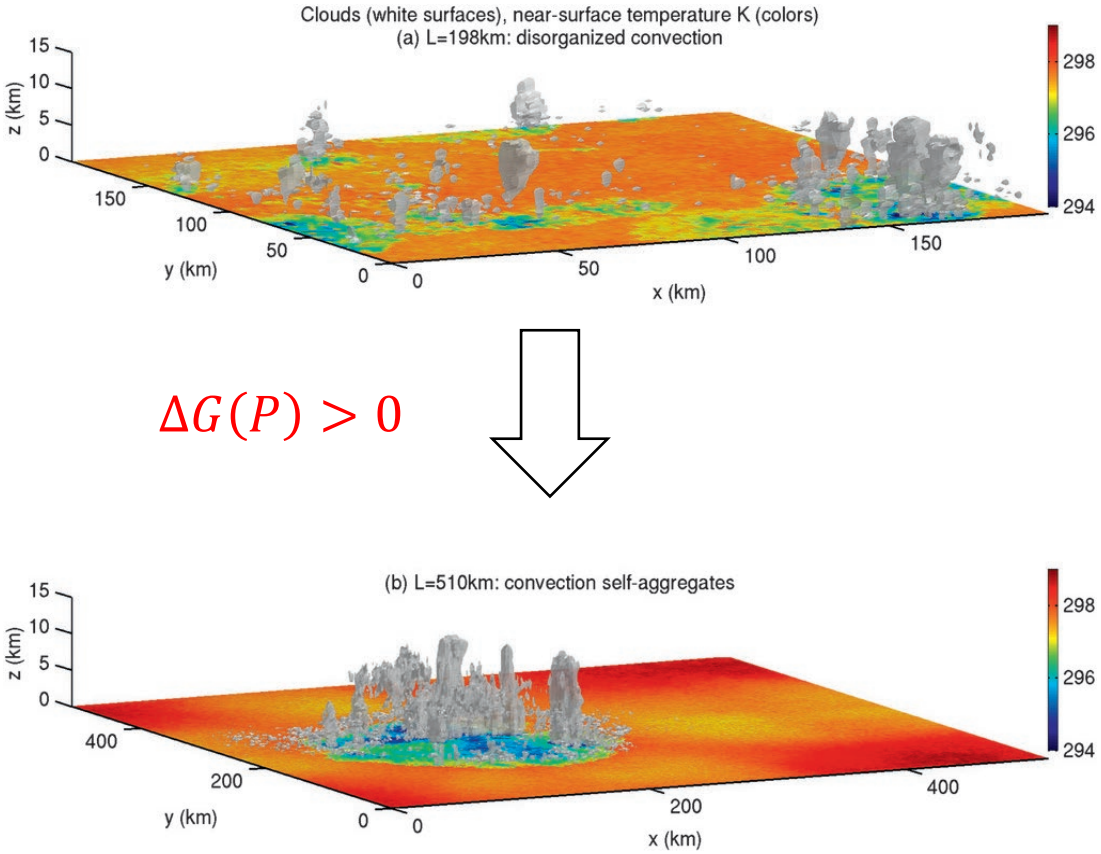
$$\Delta\overline{R_{\text{net}}} = \Delta\overline{R_{\text{lw}}} + \Delta\overline{R_{\text{sw}}}$$

Gini index measures large-scale convection aggregation strength





single patch SST+4K $\Delta G(P)$ responses

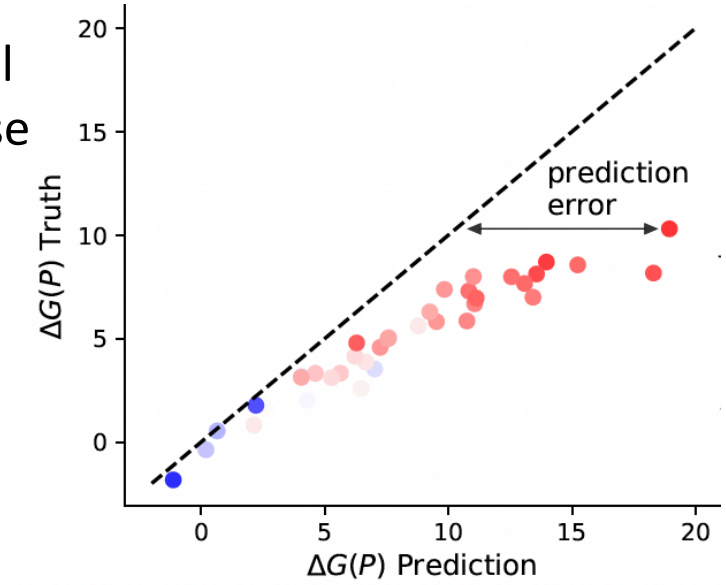


$\Delta G(P) > 0$

Muller & Held, 2012

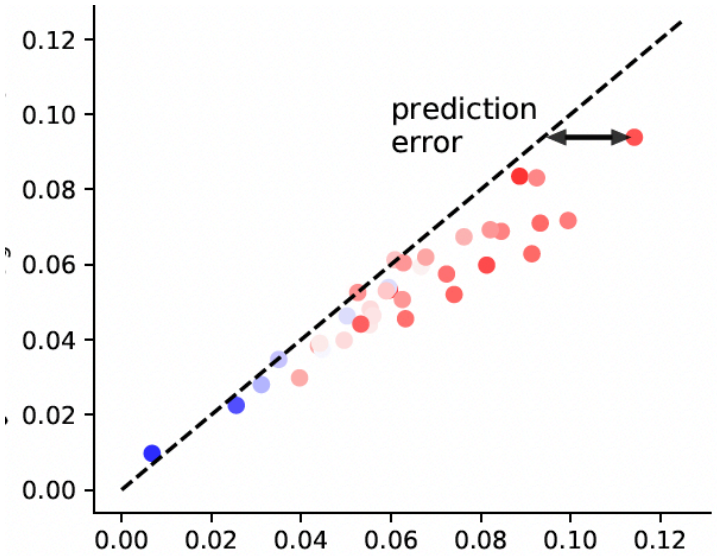
convection aggregation overestimation ← circulation overestimation

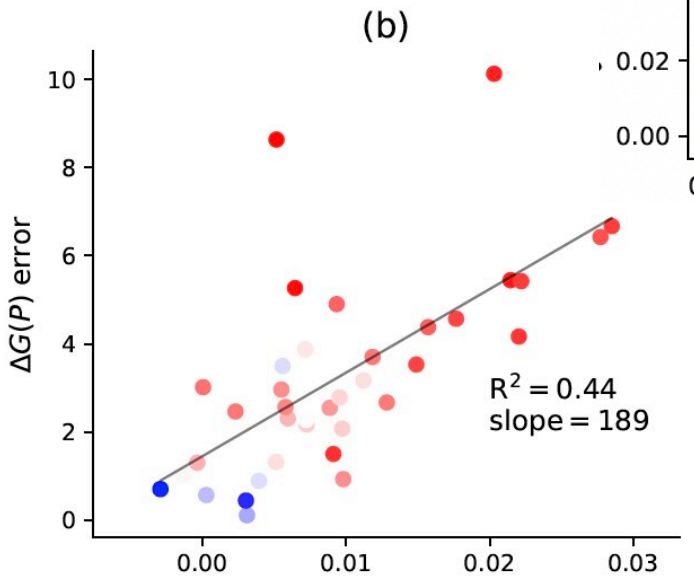
Y: actual response



two adjacent patches SST+4K

Y: actual response

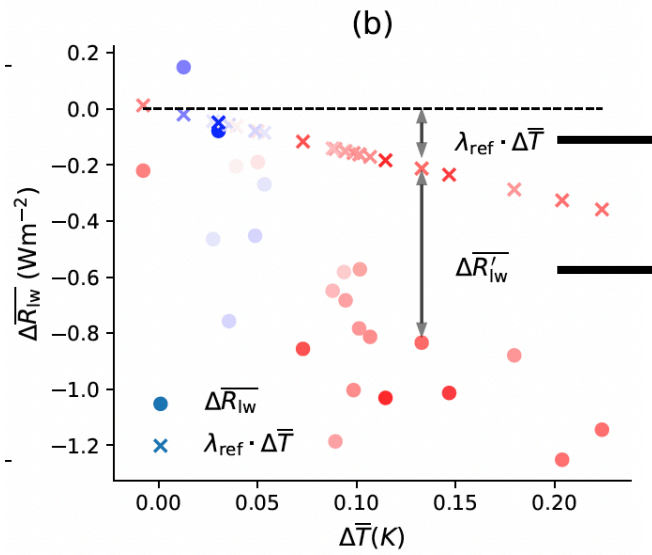




$\Delta G(P)$ error $\propto -\int \nabla \cdot (\Delta \vec{u} q) \frac{dp}{g}$ error

$-\int \nabla \cdot (\Delta \vec{u} q) \frac{dp}{g}$ error in perturbed region

Longwave radiation response attributed to convection aggregation

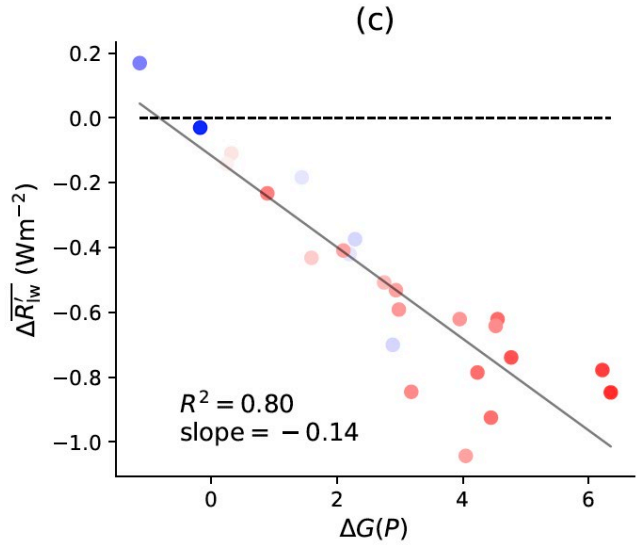


$\lambda_{\mathrm{ref}} \cdot \Delta\overline{T}$ due to mean surface warming

$\Delta\overline{R_{\mathrm{lw}}}'$ due to convection aggregation (dominant)

$$\Delta\overline{R_{\mathrm{lw}}} = \lambda_{\mathrm{ref}} \cdot \Delta\overline{T} + \Delta\overline{R'_{\mathrm{lw}}}.$$

(single patch SST+4K)

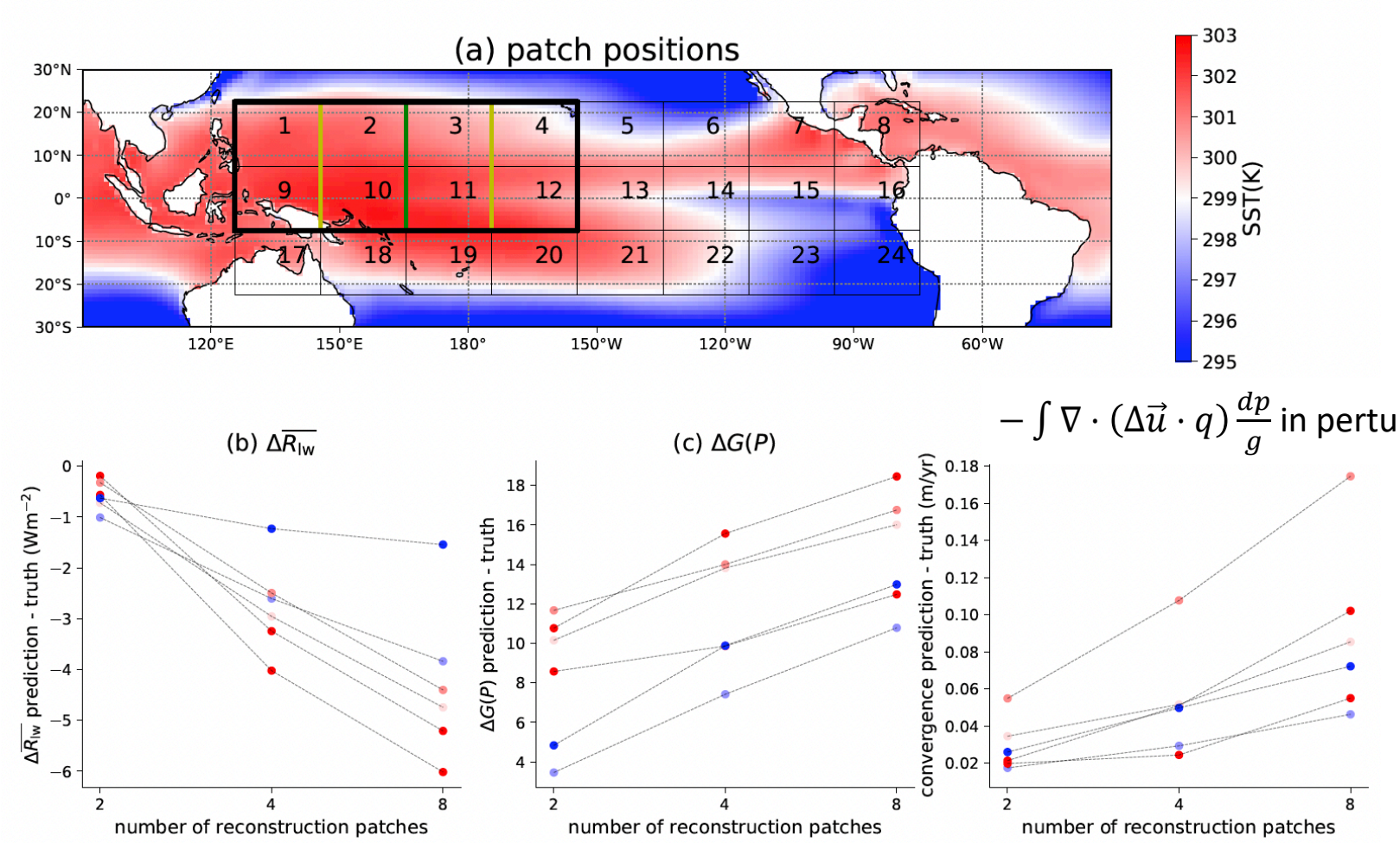


$\Delta\overline{R_{lw}}' \propto \Delta G(P)$

Stronger convection aggregation
→ mid-troposphere drying & high cloud reduction
→ Stronger longwave radiative cooling

Bony 2020, Wing 2020, Zhang 2021

More (/smaller) patches → larger errors



$-\int \nabla \cdot (\Delta\vec{u} \cdot q)\frac{dp}{g}$ in perturbed region (m/yr)

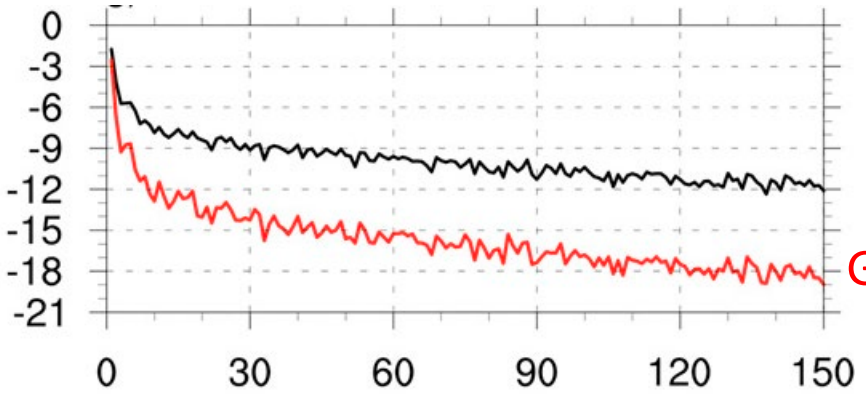
Y: Prediction error

X: Number of reconstruction patches

The failure of the Green's Functions approach

AGCM ← SST warming in 4xCO_2 GCM

Y: $\Delta\overline{R_{lw}}$

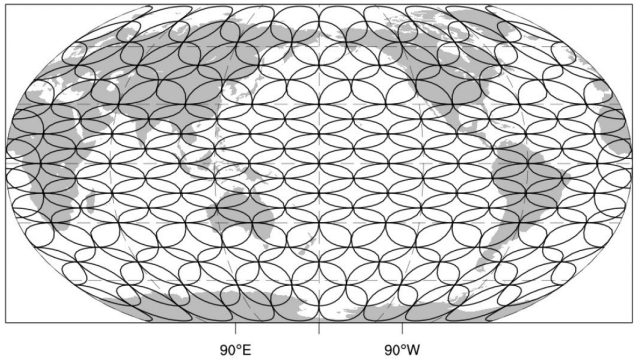


Truth

GF reconstruction

Zhang 2023

X: year



	AM4 Control	AM4 4×CO_2	GF reconstruct
tropical $G(P)$	43.9	42.0	74.3
$\overline{\text{MTH}}$(%)	43.1	43.0	34.8
$\overline{\text{HCC}}$(%)	37.8	37.5	30.2

The Green's Functions approach fails in AM4 4xCO_2 radiation reconstruction due to the overestimation of convection aggregation