Non-linear radiative response to patterned global warming due to convection aggregation

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Motivation

The **Green's Function (GF)** approach promises insights into the **pattern effect** using the linear sum of the responses to localized SST perturbations

$$\Delta\bar{R} = \sum_x \frac{\partial \bar{R}}{\partial \mathrm{SST}(x)} \cdot \Delta\overline{\mathrm{SST}(x)}$$

to predict the change in top of atmosphere radiative fluxes (R) for an arbitrary geographical pattern of SST changes. Question:

Is the additivity condition satisfied?

Non-additivity of the TOA radiative flux responses

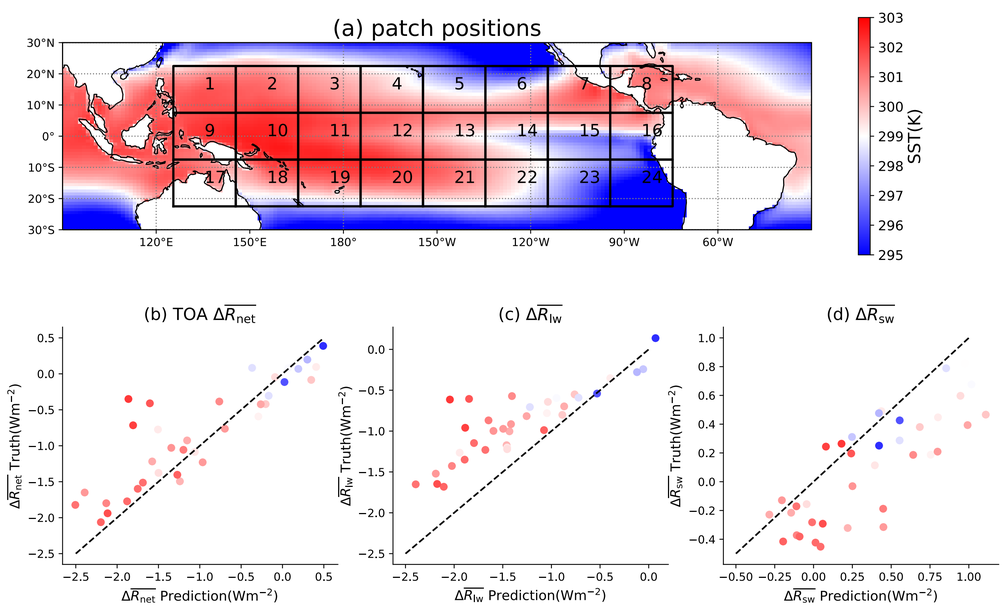

Fig.1: (a) Climatological annual mean SST of base simulation, and grid for SST perturbations. (b) – (d) Green's function prediction (x-axis) and model result (y-axis) for the warming of two adjacent patches of total, longwave and shortwave TOA flux perturbation.

Simulations with GFDL's AM4 atmospheric GCM show (SST+4K):

(i) SST warming in **warm patches** has **stronger** radiation response.

(ii) Two adjacent patches $\mathrm{SST} + 4\mathrm{K}$, **linear superposition** (prediction by the GF approach) **overestimates** the true response. Warmer patches have larger errors.

(iii) Partial **cancellation of errors** between $\Delta\overline{R_{\mathrm{lw}}}$ and $\Delta\overline{R_{\mathrm{sw}}}$.

The role of large-scale convection aggregation

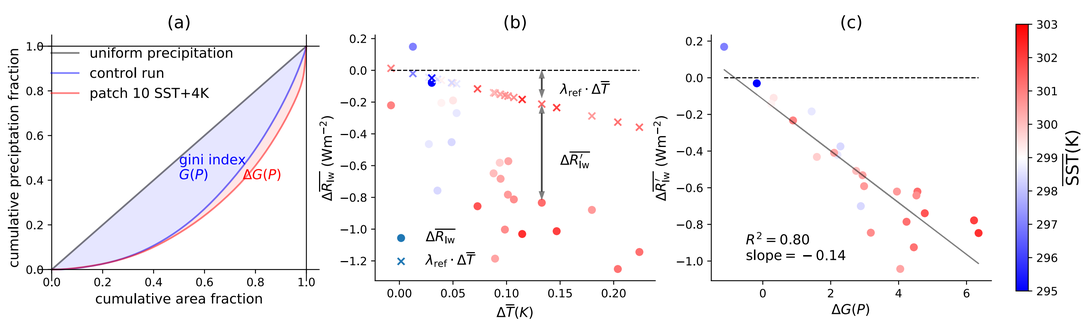

Fig.2 (a) Schematic of tropical rainfall Gini index $G(P)$. (b) Longwave radiation response to single patch $\mathrm{SST} + 4\mathrm{K}$ perturbation, decomposed as $\Delta\overline{R_{\mathrm{lw}}} = \lambda_{\mathrm{ref}} \cdot \Delta\bar{T} + \Delta\overline{R_{\mathrm{lw}}'}$, where $\lambda_{\mathrm{ref}} = -1.6\mathrm{Wm}^{-2}$ is the longwave feedback in $4 \times \mathrm{CO}_2$ simulation, and $\Delta\overline{R_{\mathrm{lw}}'}$ is the "pattern effect". (c) $\Delta\overline{R_{\mathrm{lw}}'}$ is linearly related to Gini index change $\Delta G(P)$ representing convection aggregation response.

The **Gini index** of tropical rainfall $\boldsymbol{G(P)}$ measures the **spatial unevenness** of rainfall and **convection aggregation** strength. We find:

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

Longwave radiation response to single patch $\mathrm{SST} + 4\mathrm{K}$ perturbation $\Delta\overline{R_{\mathrm{lw}}}$ is dominated by $\Delta\overline{R_{\mathrm{lw}}}'$ (departure from $4 \times \mathrm{CO}_2$ scenario):

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

$\Delta\overline{R_{\mathrm{lw}}}'$ is caused by convection aggregation response (mid tropospheric drying and high cloud reduction).

Conclusions

The GF approach **fails** for **large** SST warming perturbations (**i.e. future global warming**) due to the **non-additivity** of **convection aggregation responses**.

Convection aggregation is also responsible for the **outsized response** to **patterned** global **warming**. Accurate estimation of **climate sensitivity** requires **accurate estimation of convection aggregation**, which is **beyond the scope of linear methods like GF.**

Non-additivity of convection aggregation responses

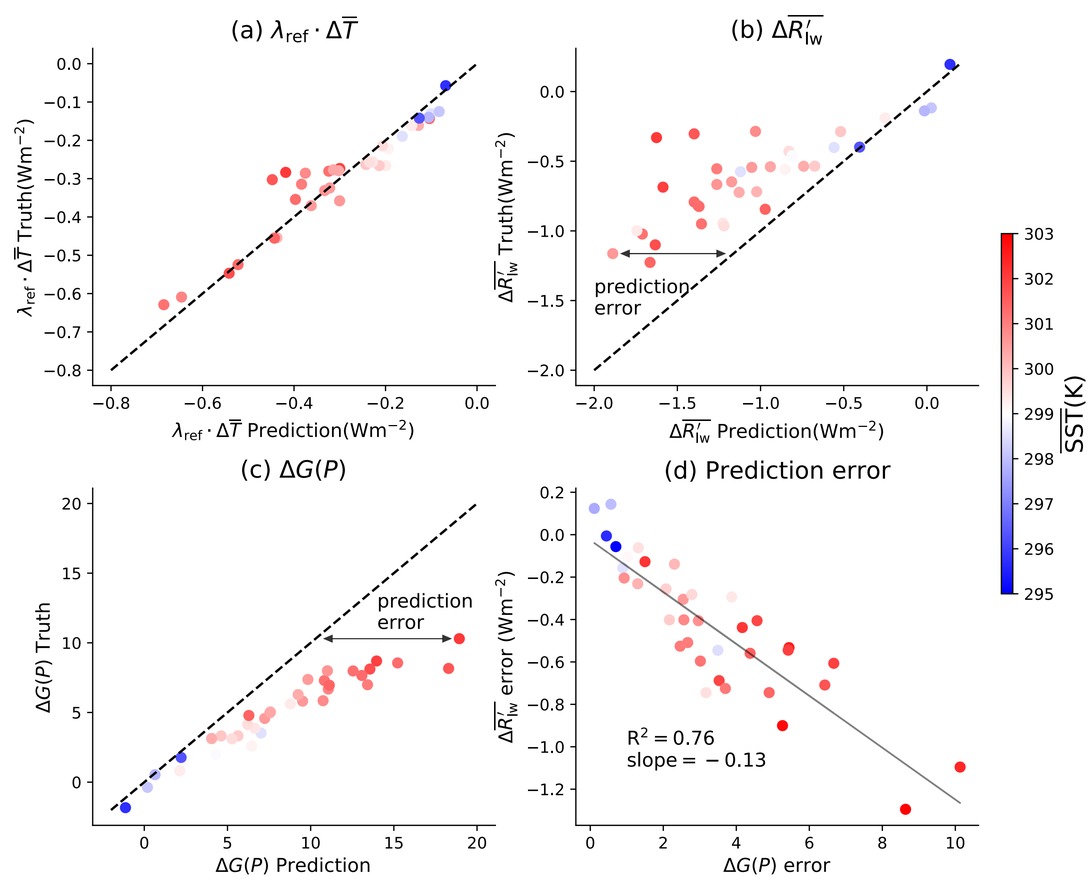

Fig.3 Prediction v.s. truth for (a) $\lambda_{\mathrm{ref}} \cdot \Delta\bar{T}$; (b) $\Delta\overline{R_{\mathrm{lw}}}'$ and (c) $\Delta G(P)$. **(d) The prediction error of $\Delta\overline{R_{lw}}'$ as function of precipitation Gini index change $\Delta G(P)$.**

The GF approach **prediction error** in $\Delta\overline{R_{\mathrm{lw}}}$ is dominated by error in $\Delta\overline{R_{\mathrm{lw}}}'$, which is caused by **prediction error in convective aggregation $\boldsymbol{\Delta G(P)}$.**

Dependence of non-additivity on patch size

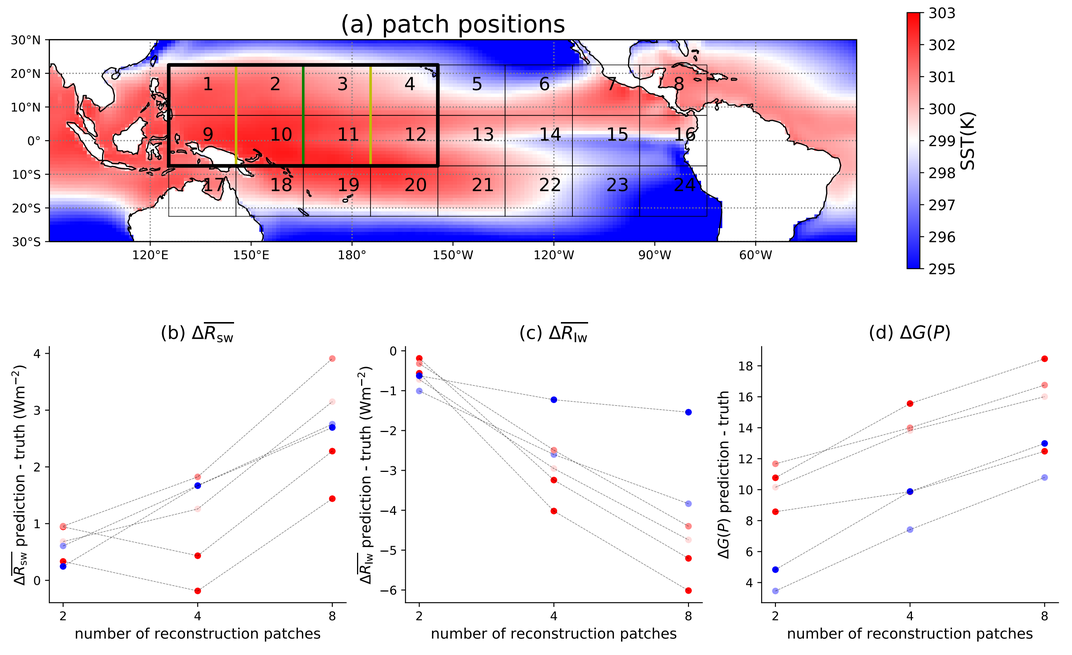

Fig.3 GF prediction of changes following an SST perturbation in an 8-patch area (a), based on linear sum of responses to 8 single patch, 4 two-patch, and 2 four-patch responses; for (b) shortwave and (c) longwave radiation, and (d) the precipitation Gini index.

The GF approach error is **larger** for **smaller** (or equivalently, **more**) patches. **The GF approach is not valid.**