Analysis of Climate Feedback Processes: Local vs. Non-Local Effects

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Introduction

A feedback loop occurs when a system has a fraction of its output fed back into the system as input. There are many feedbacks in the climate system. These feedbacks govern how the climate reacts to perturbation such as an increase in atmospheric CO2. It is important to analyze these feedbacks to understand their strengths and the ways in which they interact.

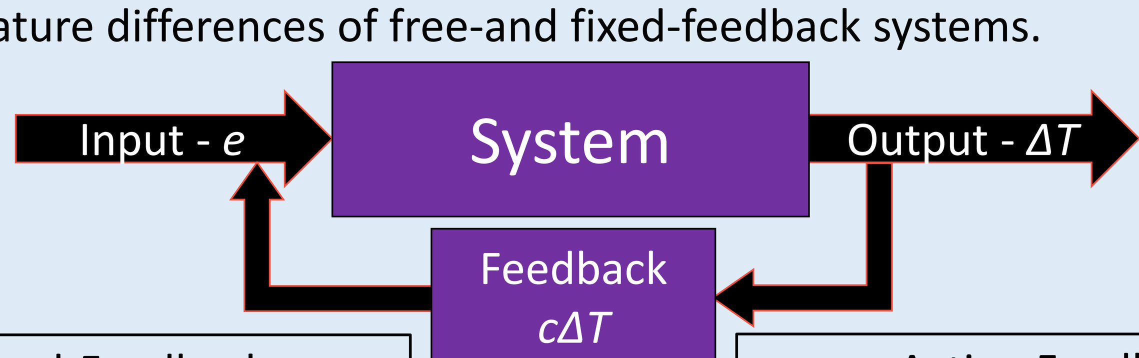
In the climate modeling context an applied forcing (e = W/m^2) results in a temperature change (DT = K). Feedback processes can be positive or negative, adding to or suppressing the initial forcing. This is important because positive feedbacks amplify and negative feedbacks suppress the initial input.

- Ice-Albedo (SA) Feedback – Albedo describes amount of light an object reflects
  - If Earth cooled and ice grew, Earth would cool more due to ice's Albedo
- Water Vapor (WV) Feedback – WV heats due to its greenhouse effect
  - If Earth warmed, WV content in air would rise and heat Earth more

This study analyzes these two feedbacks using two different models.

Feedback Analysis

Adding energy to a system with fixed or no feedbacks will result in a base temperature change (ΔT_0). A feedback loop feeds part of the output ($c\Delta T$) into the system as input. The strengths of the feedbacks are commonly studied using ratios of temperature differences of free-and fixed-feedback systems.



Fixed-Feedback: Climate Sensitivity - $\lambda_0 = \frac{\Delta T_0}{e}$

Active-Feedback: Feedback Sensitivity - $\lambda_\alpha = \frac{\Delta T_\alpha}{e}$

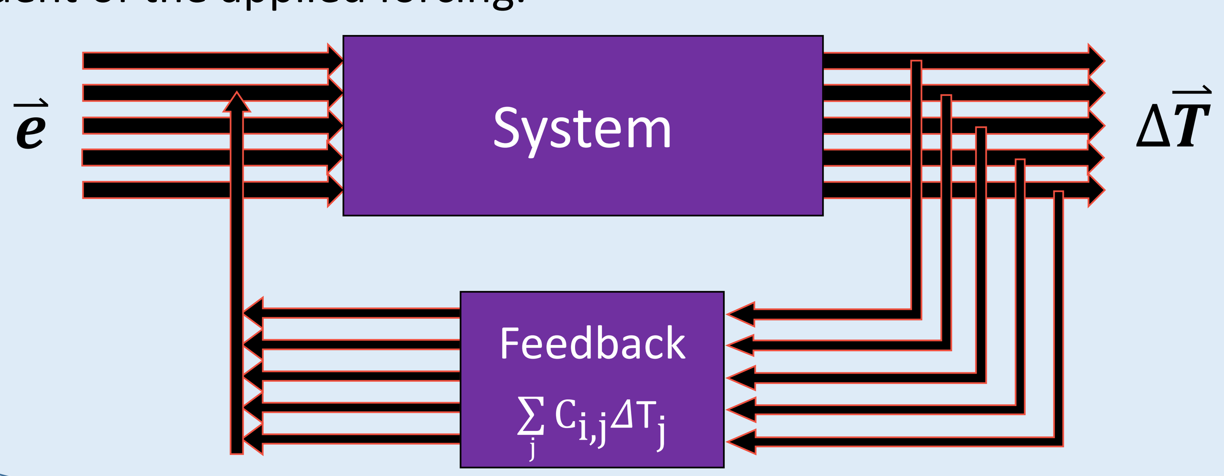
Gain (g) = $\frac{\Delta T_\alpha}{\Delta T_0}$

$g > 1 \leftrightarrow$ Positive
$0 < g < 1 \leftrightarrow$ Negative

The visual above is a 0D model in which Earth would be one single average temperature. Earth has zones each with their own temperature and if we want to have a higher resolution we will have more then one sensitivity and gain.

A Matrix Approach to Feedbacks

Due to heat transport mechanisms a forcing to one cell will affect other cells within Earth and an applied equatorial forcing will yield a different gain and sensitivity then an applied polar forcing. Thus we define matrices which are independent of the applied forcing.



These gain matrices can be computed by finding the sensitivity matrices

$$\boxed{\begin{array}{c}\Delta\vec{T}_\alpha = \Lambda_\alpha \vec{e} \\ \Delta\vec{T}_0 = \Lambda_0 \vec{e}\end{array}} \longrightarrow \boxed{\Delta\vec{T}_\alpha = \Lambda_\alpha \Lambda_0^{-1} \Delta\vec{T}_0} \longrightarrow \boxed{G_\alpha = \Lambda_\alpha \Lambda_0^{-1}}$$

The gain matrix can tell us if a feedback is a local (L) or non-local (NL) process. The diagonals of the gain matrix tells us if how much the feedback has an effect locally and the non diagonals of a row tell us how much effect a feedback has locally from non-local areas.

Models

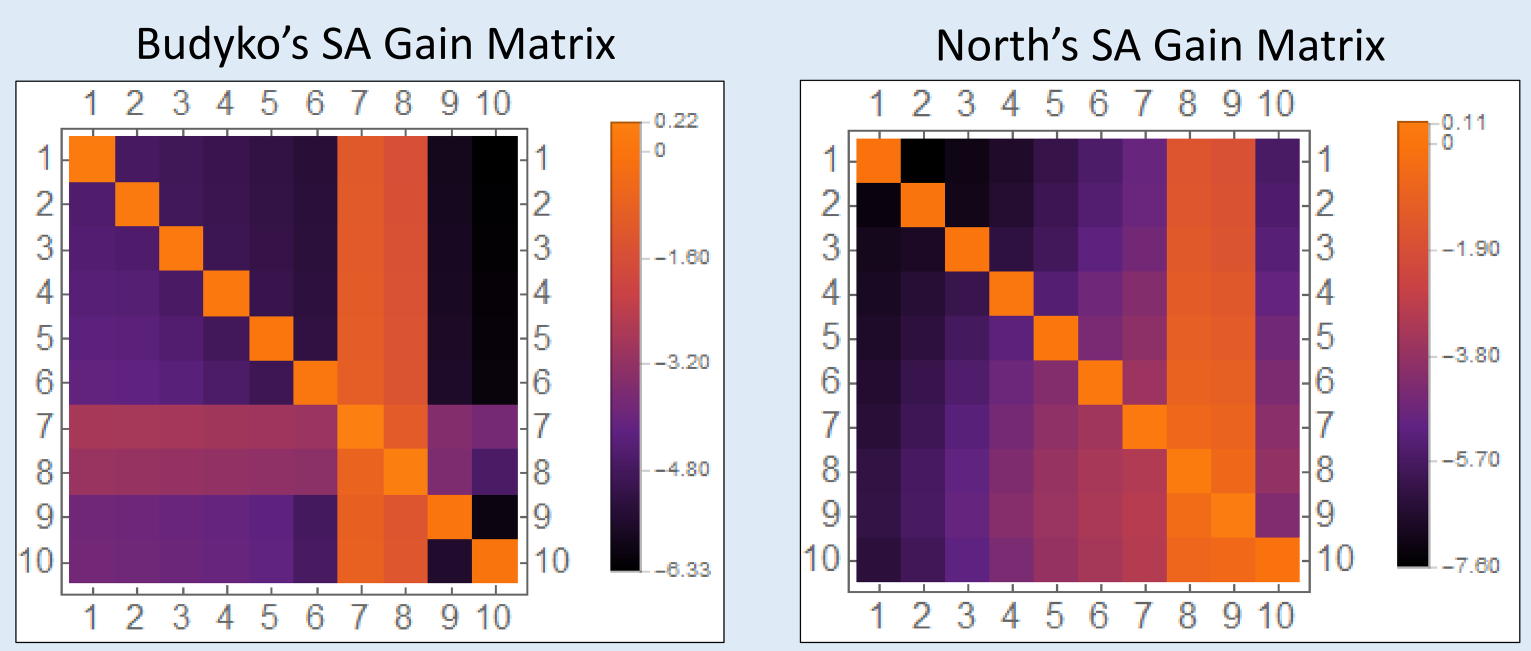
The two models used in this analysis were two similar 1D energy balance models from Budyko and North. Both use an energy balance equation with the difference being the heat transport term, which creates a system of differential equations.

$$\underbrace{H_i}_{\text{Specific Heat Capacity}} \frac{dT_i}{dt} = \underbrace{R_i(\vec{T})}_{\text{Surface Energy Balance}} + \underbrace{F_i(\vec{T})}_{\text{Heat Transport Term}} + \underbrace{e_i}_{\text{External Forcing}}$$

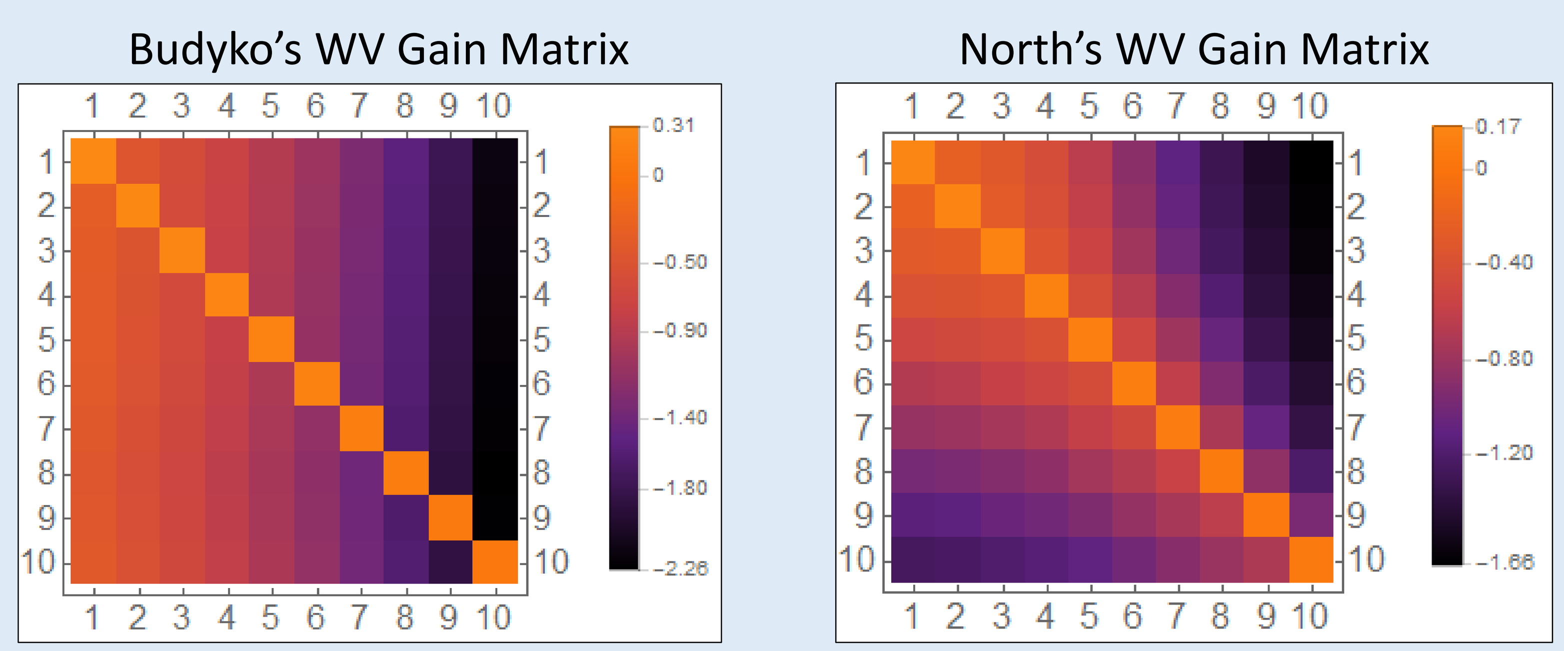
T_i = Temperature of *i*th Cell

Results

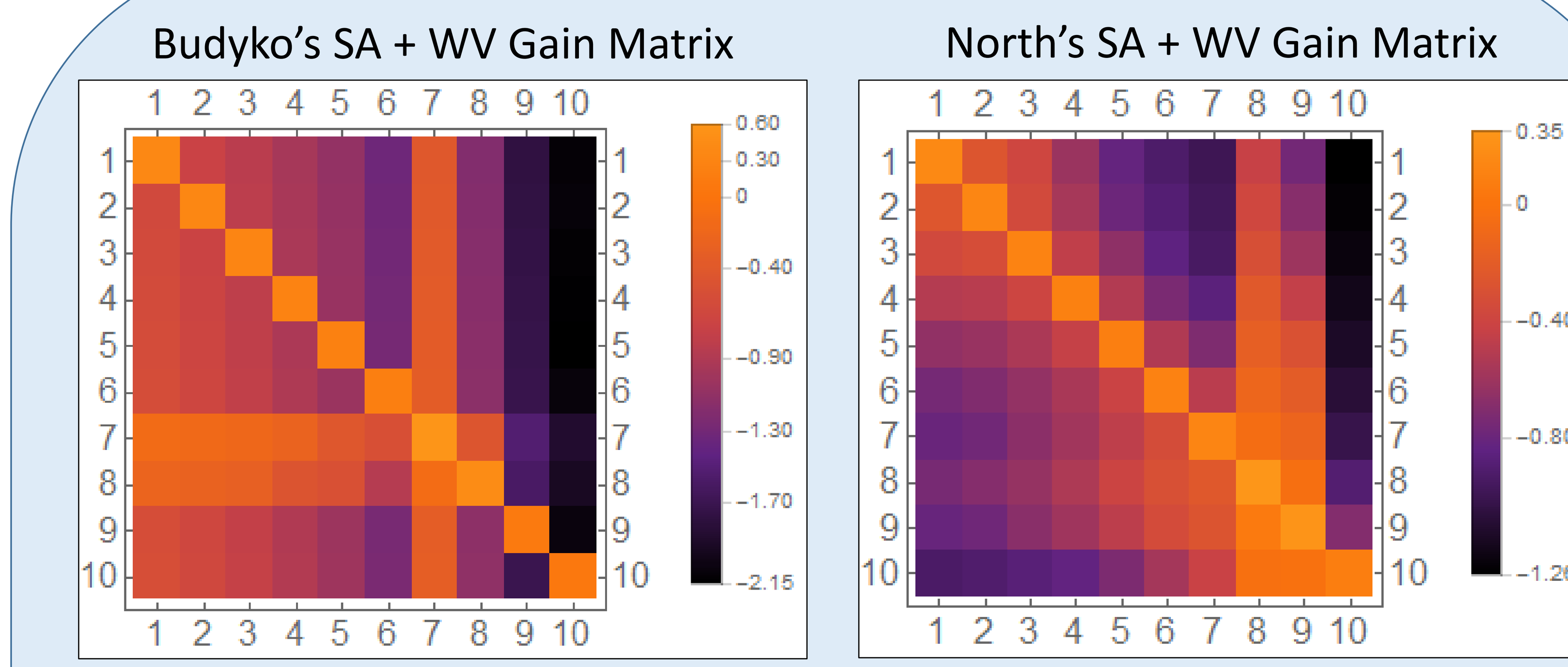
Gain matrices are computed for the SA feedback, WV feedback, and SA + WV for each model. They are similar with only a few differences between each.



Both have the strongest NL effect near the ice line. The NL effects contributing to the ice line regions are higher all around in Budyko's.

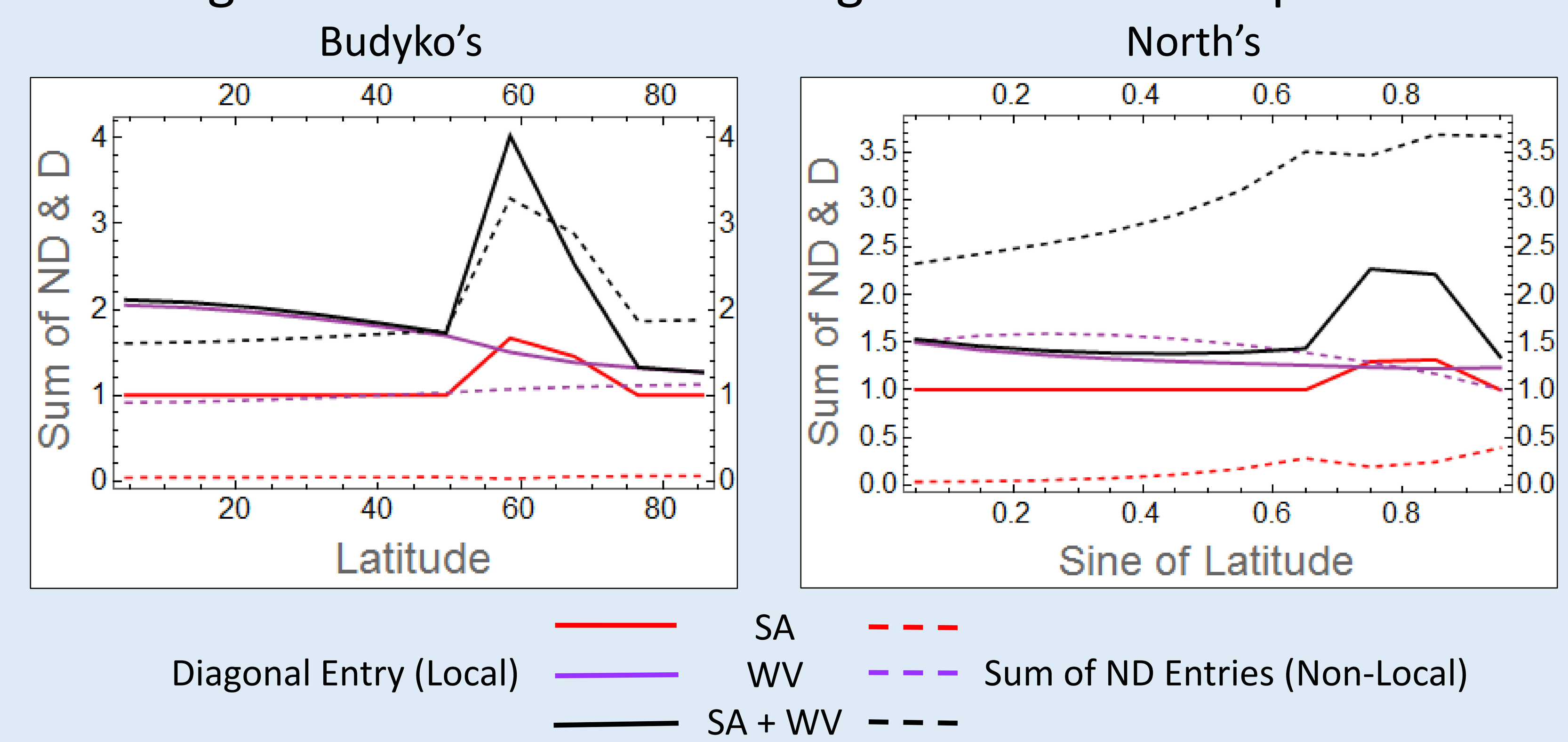


Budyko's WV has it's NL effects strengthen towards the equator. North's NL effects are strongest in neighboring cells and toward the equator as well.



Both the SA + WV gain matrices are mixes of the main features of the single SA and WV Gain Matrices

Diagonal and Sum of Non-Diagonal Entries Comparison



Both of these show how the feedback processes of the SA and WV are different being the SA is more of a local feedback where as the WV seems to have more of a non-local contribution. These figures also point to the importance of the parametrization used for heat transport. They also show how interactions between feedbacks are difficult to interpret and could be a whole other topic of study.

References

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