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INVESTIGATING THE IMPACT OF ATMOSPHERIC VOLCANIC AEROSOL INJECTION ON WATER AND ENERGY BALANCE USING EARTH SYSTEM SIMULATIONS

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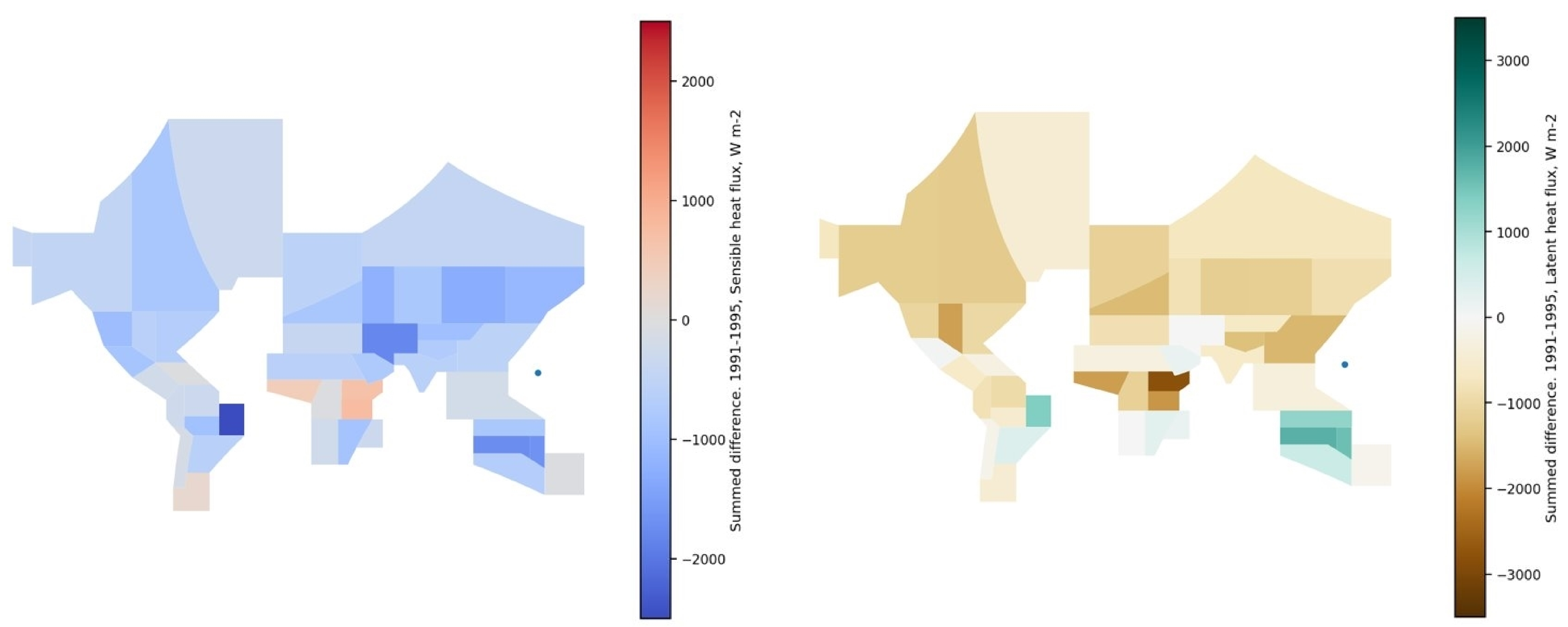
When Volcanoes Change the Climate

Large volcanic eruptions, like the 1991 Mt. Pinatubo eruption, can significantly perturb global climate by injecting aerosols which influence incoming and outgoing radiation and lead to changes in precipitation, cloud cover, and temperatures. Understanding these disruptions is crucial, especially for regions stressed by climate change.



Cumulative difference between factual and counterfactual sensible and latent heat by IPCC region,1991-1995. the approximate location of Mt. Pinatubo is shown by a blue dot

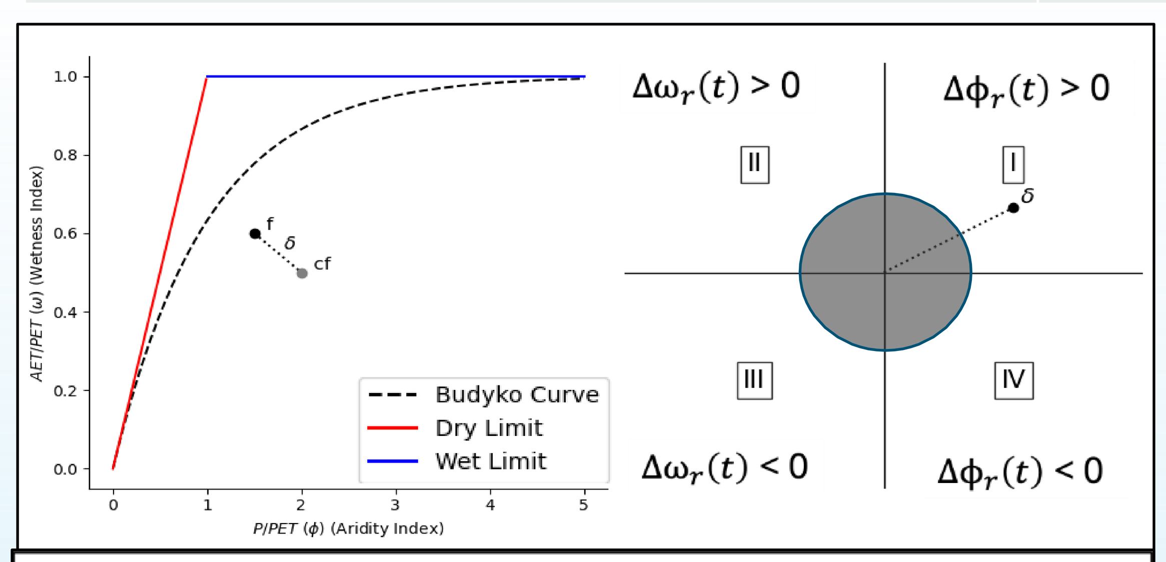
Modeling the Unseen: The Counterfactual Approach

To analyze the impact of large eruptions, we model the counterfactual scenario—if the eruption did not occur.. The Energy Exascale Earth System Model (E3SM) was run with (Factual f) and without (Counterfactual cf) Mt. Pinatubo aerosol injections. We calculated 1991-1995 weekly sums and means for variables in each IPCC reference region (Iturbide et al. 2020) using 15 replicates (r).

Equations

The Budyko ratios between precipitation (P), potential evapotranspiration (PET), and actual evapotranspiration (AET) are:	$\phi = \frac{P}{PET} \quad \omega = \frac{AET}{PET}$
The Budyko curve can be expressed as:	$\omega = 1 - e^{-\phi}$
We use the Energy Only PET where Rn is the net radiation, G is the ground heat flux, and λ is the latent heat of vaporization:	$PET = \frac{Rn - G}{\lambda}$
We then calculated the differences of each ratio between the factual and counterfactual scenarios for each replicate for week t:	$\Delta\phi_r(t) = \phi_{f,r}(t) - \phi_{cf,r}(t)$ $\Delta\omega_r(t) = \omega_{f,r}(t) - \omega_{cf,r}(t)$

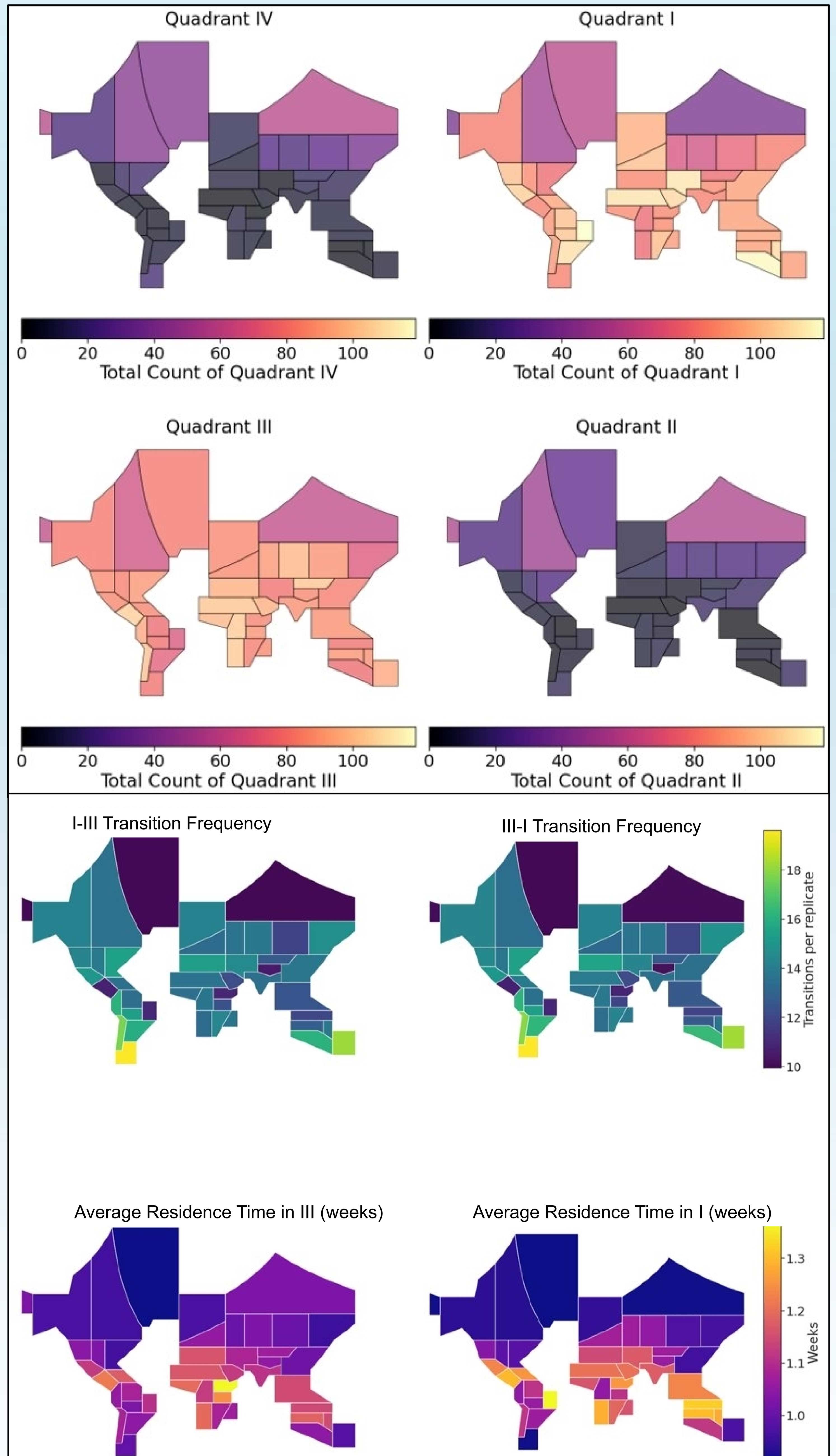
The Budyko Framework: Pinatubo's global impact



The Budyko space (left) and differences between Factual f and Counterfactual cf is represented as ô. On the right, this is represented in terms of the z-score delta of ϕ and ω. The grey zone represents non-significant movement (delta < 1).

The Budyko framework provides a method to analyze the effects of volcanic eruptions on ecological systems by examining the balance between water and energy (Budyko & Miller, 1974). Changes in the Budyko ratios, known as movement in the Budyko space, can indicate significant ecological shifts.

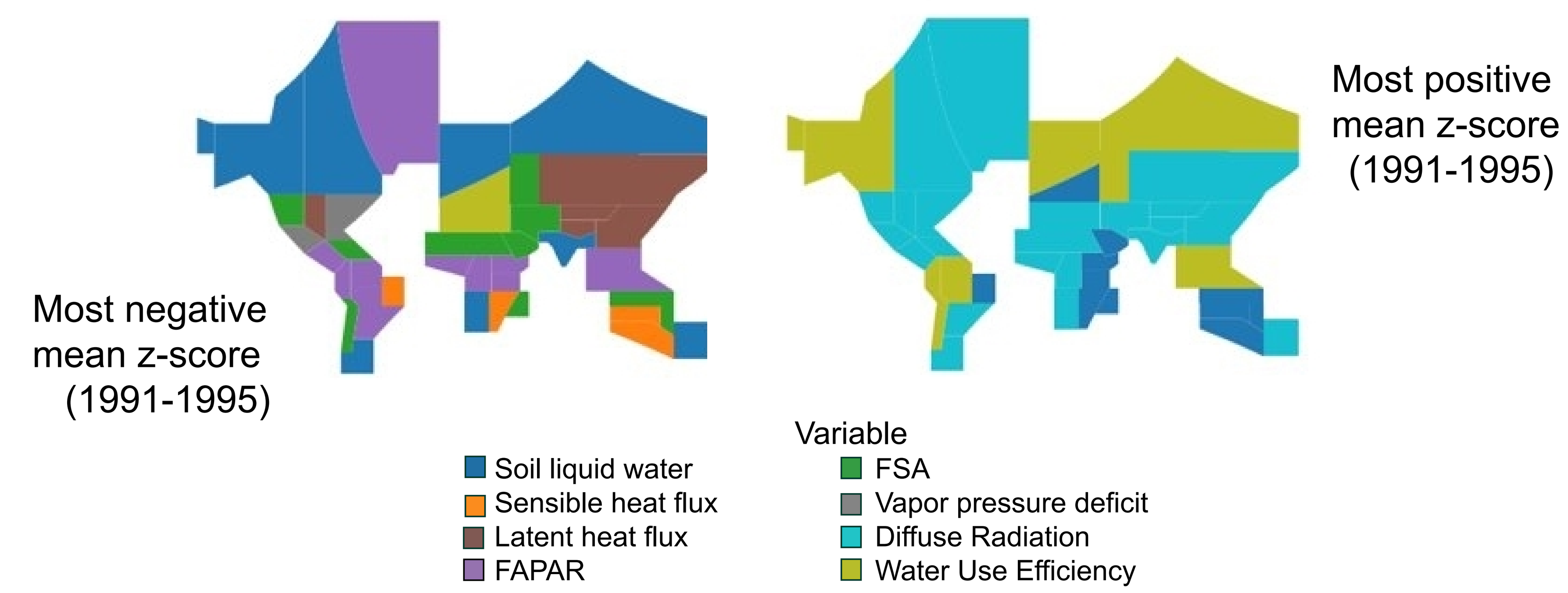
Regional shuffling: Movement in Budyko Space



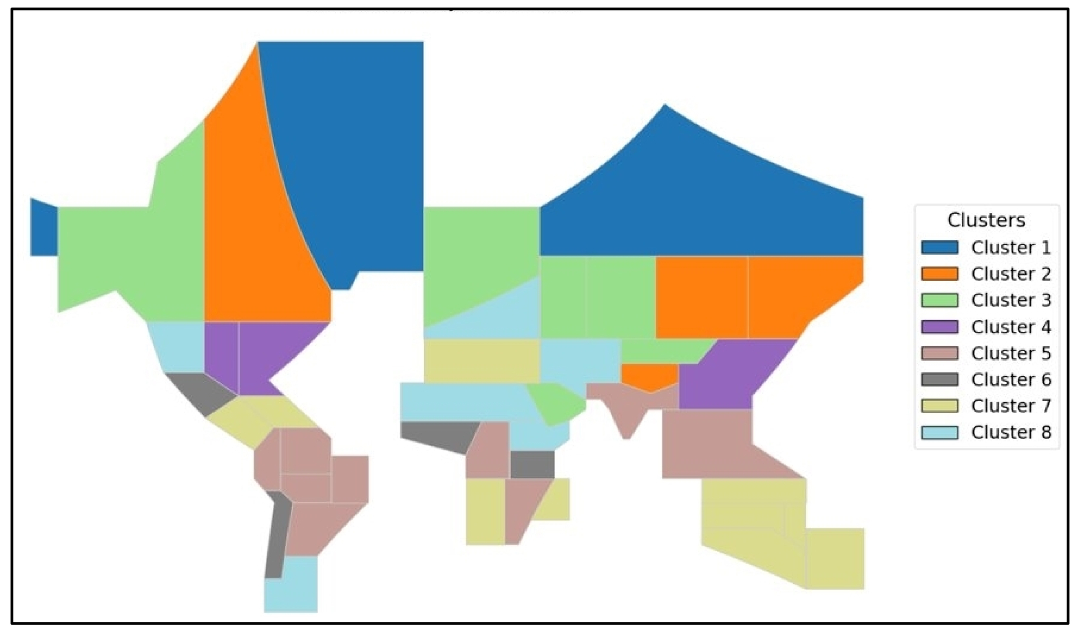
Counts per quadrant (top), and counts of I-III and III-I quadrant transitions with average residence time (weeks) in quadrant I and III (bottom), with more transitions suggesting more oscillations between quadrants during the 1991-1995 period, and longer residence times indicating slower oscillations into or out of those quadrants.

Climate impacts during Budyko space anomalies

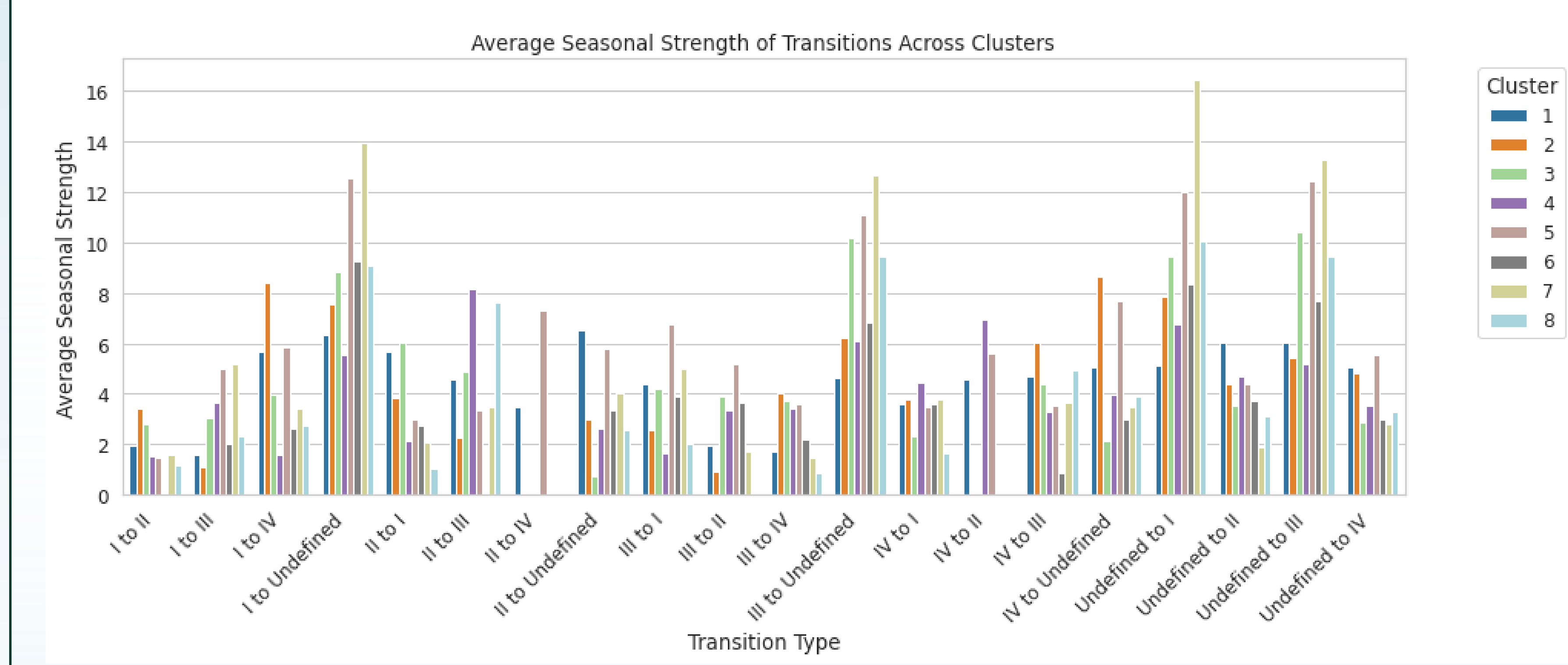
Movement in the Budyko space identifies when Mt. Pinatubo's effects exceeded background noise. While the most common positive impact was an increase in diffuse radiation, polar regions experienced reduced soil water and equatorial regions experiencing decreased photosynthesis



Global effects, regional similarities



Hierarchical clustering of regions by residence time and frequency of shifts between quadrants (left). Seasonal decomposition of transitions (with moving averages, below), where average seasonal strength is the average periodicity in months of each transition for each cluster.



Conclusions: The Lasting Effects of Pinatubo

The Pinatubo eruption significantly altered ecohydrology. Southern hemisphere regions oscillated between high and low quadrants, while equatorial zones remained in these quadrants for longer. This shuffling suggests that the continental location of regions is key to understanding how future eruptions may buffer some regions from climate change while exacerbating impacts in others. Changes in diffuse radiation, soil water, and water use efficiency were associated with these shifts, highlighting the complex interplay of variables in response to eruptions.

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Iturbide, M., Gutiérrez, J. M., Alves, L. M., Bedia, J., Cerezo-Mota, R., Cimadevilla, E., ... & Vera, C. S. (2020). An update of IPCC climate reference regions for subcontinental analysis of climate model data: definition and aggregated datasets. *Earth System Science Data*, *12*(4), 2959-2970.