Analyzing the Indian Summer Monsoon Through Perturbed Parameter Ensembles

Anthony Guzmán[1], Kyle McEvoy[2], Qingyuan Yang[3], Brian Medeiros[4], Greg Elsaesser[3,5]

[1]University of Southern California, [2]University of California - Los Angeles, [3]Columbia University, [4]National Center for Atmospheric Research, [5]NASA Goddard Institute for Space Studies

Abstract

Indian summer monsoon rainfall is important to the livelihood of a substantial portion of the world's population. However, monsoon predictions are limited in accuracy since their rainfall characteristics are dependent on small-scale physics processes that are not fully understood and represented in climate models. To begin understanding how monsoon rainfall depends on physics processes in climate models, we analyzed a perturbed parameter ensemble (PPE) of the CESM2-CAM6 model, where each PPE member is characterized by different physics parameter settings which in turn impacts the climate and rainfall of each member. Using the rainfall data from all PPE members, we develop a multiple linear regression model to assess whether there are any significant relationships between the physics parameters choices and the intensity of the monsoon rainfall cycle. We hope that our findings will contribute to an increased understanding and representation of the Indian monsoon in climate models, given the importance climate model predictions play in informing society of the expected changes in rainfall patterns as the climate warms.

Introduction

The Indian summer monsoon (ISM) is one of the most impactful climate phenomena which affects about 1.5 billion people who live on the subcontinent of India. Arrival of the monsoon winds is crucial, as 60% of the Indian population is dependent on the winds due to their impact on the agricultural sector. However, given the complexity of the atmospheric environment, it is difficult to predict how the summer monsoon will look from year to year. Many studies have attempted to untangle the inherent chaotic nature of the ISM, looking at its relationship with El Nino Southern Oscillation and the local topography (most notably the Tibetian plateau), however the dynamics of this air-ocean coupled system remain mostly unresolved.

This study attempts to untangle the dynamics of the ISM through perturbed parameter ensembles, a technique which involves running simulations of a model multiple times (in this case the CESM2-CAM6 model), each with a different set of parameters. The goal is to determine how much each parameter affects the overall output of each simulation.

Methodology

262 parameter ensembles of the CESM2-CAM6 model were created to simulate conditions for both large-scale and convective precipitation globally. The area of study was limited to the following coordinates: 8°4' north to 37°6' north latitude and 68°7' east to 97°25' east longitude. This area encapsulates all of the Indian subcontinent, and includes some of the local oceans. The data was analyzed in three ways: land only, ocean only, and then land + ocean. The reasoning behind this was to determine if there were any behaviors between the two environments that could possibly have been masked if analyzed together. Because each of the parameters have different ranges of values that they can be set to, we standardized each of the parameters to a scale of 0 to 1, in order to make it easier to compare each parameter. Finally, we placed each of the parameters into a multiple linear regression model to determine if any of the variables had a strong correlation with the amount of precipitation which was observed in the model. Separate models were created for both convective (PRECC) and large-scale (PRECL) precipitation. For each parameter, the effects from both PRECC and PRECL seem to cancel each other out, so separating the two from each other was crucial to determine which parameters were influential in the creation of monsoon events.

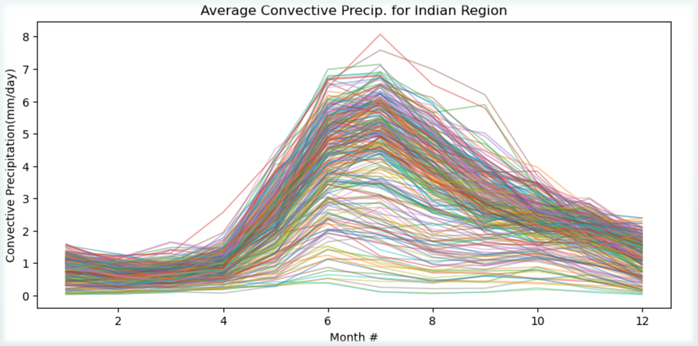


Figure 1. Time series depicting the mean annual precipitation over three years for all 262 ensembles conducted. Each line represents a distinct ensemble, and captures the impact of both PRECL and PRECC on both land and ocean combined. Of importance are the peaks in June and July, which are the data points used in our regression analysis.

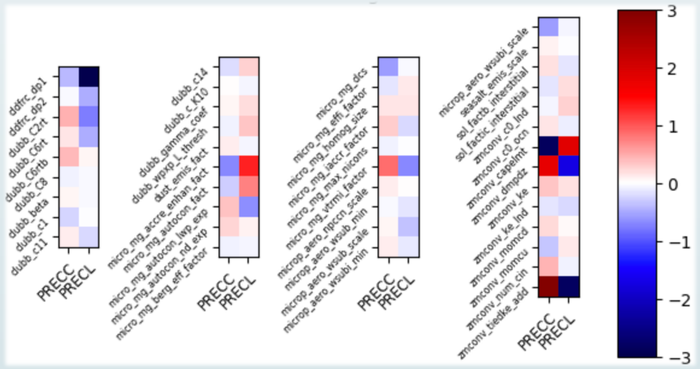


Figure 2. Correlation heatmap for most of the 43 parameters used in the simulations for land and ocean partition. Intensity of color refers to the magnitude of the regression slope calculated..Of importance are the parameters zmconv_tiedke_add, zmconv_dmpdz, and zmconv_capelmt. Not depicted are the heat maps for the ocean and land partitions separately. These charts depicted the same behaviors as in the land + ocean partition.

Results

After creating our regression model, we have found three parameters that seemed to contribute the most to the amount of rainfall observed within each model simulation. "Zmconv_capelmt", "zmconv_dmpdz","zmconv_tiedke_add". All three variables relate to atmospheric convection mechanisms that occur in the model, which is expected, since the monsoon is created and sustained through convection. "Zmconv_capelmt" represents the minimum threshold value of convective available potential energy needed to sustain deep convection. "Zmconv_dmpdz" refers to the air parcel fractional mass entrainment rate, in other words, the rate at which mixing between air parcels and the surrounding air occurs. "Zmconv_tiedke_add" controls the initial convective parcel perturbation, also known as the magnitude of difference between air parcels to initiate the beginning of the convection process. Our land + ocean model for convective precipitation had an R^2 value of 0.77, while our model for large-scale precipitation had an R^2 value of 0.74.

Conclusion

Our findings demonstrate that atmospheric variables associated with convection processes are the most influential factors in determining annual precipitation during the Indian summer monsoon. These processes, which involve the vertical movement of heat and moisture within the atmosphere, are critical to the formation and distribution of monsoonal rainfall. However, the inherent complexity of convection, particularly its interaction with other large-scale atmospheric and oceanic systems, highlights the need for further investigation. To advance our understanding of the ISM, future research should focus on the microphysics of convection processes which remain underexplored in current studies.

It is also important to acknowledge that our climate model does not account for certain critical factors, such as land-use changes, deforestation, and the release of greenhouse gas emissions, all of which are known to influence the monsoon system. These anthropogenic drivers are becoming increasingly relevant as human activities continue to alter the Earth's climate, contributing to shifts in temperature, atmospheric circulation, and moisture availability. While such factors have yet to be extensively studied in the context of the SIM, their growing impact underscores the need for an integrated approach that combines natural and human-induced influences.

Although our results underscore the importance of convection processes, it is essential to recognize that these variables do not operate in isolation. Instead, they interact with a complex web of interconnected factors, including oceanic circulation patterns (such as ENSO events), local topography, and human-induced changes to the environment. Understanding the interplay of these elements is vital for building more accurate predictive models of the monsoon system and addressing the challenges posed by its variability. A more holistic approach that incorporates both physical processes and anthropogenic influences will be crucial in improving monsoon forecasting and mitigating the impacts of its variability on agriculture, water resources, and livelihoods across the Indian subcontinent.

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