Modelling the Effects of Vegetation Change on Climatic Extremes over South Asia Using ICON-ESM

Abstract

Climatic extremes, including heatwaves, droughts, and intense precipitation events, are becoming more frequent and severe across South Asia. These extremes directly affect vegetation structure, productivity, and ecosystem functioning. At the same time, vegetation change can feed back onto the climate system by modifying carbon uptake, and land-atmosphere exchanges of energy and water (Figure 1). South Asia is particularly vulnerable to these interactions because of its strong monsoon dependence, dense population, intensive agriculture, and rapid land-use and land-cover change. However, the extent to which vegetation change amplifies or mitigates climatic extremes remains poorly understood.

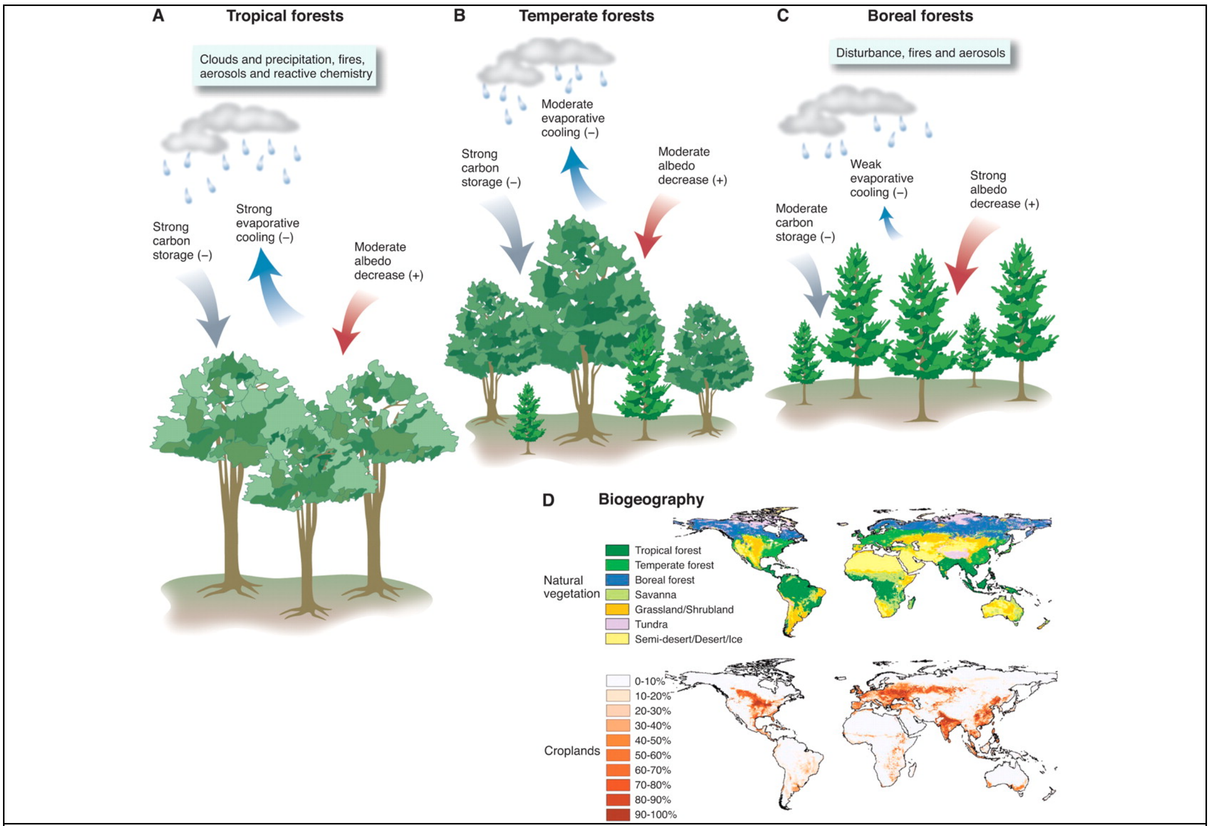

Figure 1: Vegetation-Climate Interactions. Adapted from (Bonan, 2008)

Observational datasets alone cannot fully isolate vegetation-climate feedbacks because vegetation and climate evolve simultaneously under the influence of land-use change, rising CO_2, nitrogen deposition, climate variability, and anthropogenic forcing. Therefore, controlled process-based model experiments are required to separate the effects of vegetation change from background climate variability and external forcing.

This project aims to investigate how vegetation change influences climatic extremes over South Asia using the ICON-ESM framework (Figure 2). The study will focus on the role of vegetation-driven changes in land-surface processes and their impacts on temperature extremes, precipitation extremes, drought conditions, and surface energy and water fluxes.

The key scientific questions that will be addressed are:

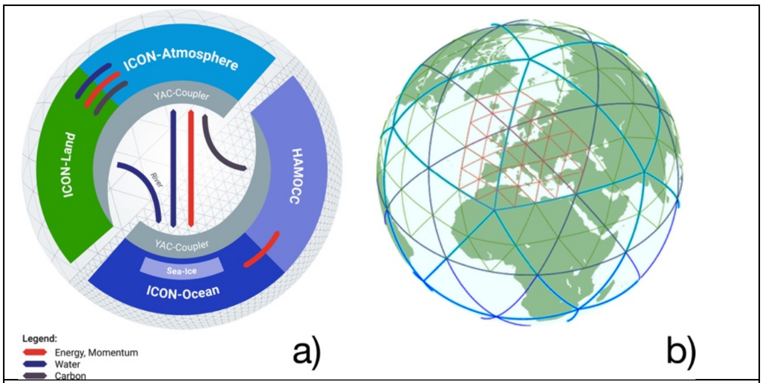

Figure 2: (a) Schematic representation of the model components of the ICON-ESM and (b) the construction of the grid through the bisection process. Adapted from (Jungclaus et al., 2022).

1. How does vegetation change modify land-atmosphere exchanges of energy, water, and carbon over South Asia?
2. To what extent do vegetation-driven changes in albedo, evapotranspiration, soil moisture, and surface roughness influence heatwaves, droughts, and precipitation extremes?
3. Does vegetation change amplify or mitigate climatic extremes under present-day and future climate conditions?
4. What are the relative contributions of CO_2 forcing, climate change, and vegetation change to future changes in climatic extremes?

The modelling strategy will include controlled sensitivity experiments designed to isolate the effects of vegetation change, CO_2 forcing, and climate variability. By comparing simulations with different vegetation and forcing configurations, the project will quantify the biophysical and biogeochemical pathways through which vegetation change affects regional climate extremes. The experiments will include a historical simulation for 1980-2014 and future scenario simulations under SSP3-7.0 and SSP5-8.5 using the ICON-ESM framework. These simulations require substantial computational resources because they involve high-resolution Earth system modelling, multi-decadal integrations, large regional domains, and high-frequency outputs of land-atmosphere fluxes and extreme climate diagnostics. Access to the DKRZ Levante high-performance computing system is therefore essential for performing the ICON-ESM experiments, managing large data volumes, and conducting robust process-based analysis.

The expected outcomes are:

1. improved understanding of vegetation-climate feedbacks over South Asia
2. quantitative assessment of the role of vegetation change in modulating heat, drought, and precipitation extremes
3. identification of the physical mechanisms linking vegetation change with surface energy and water fluxes
4. generation of a high-resolution model dataset for future studies on land-atmosphere interactions, climate risk, and regional climate adaptation.