Dynamics and Future Projections of Compound Ocean-Atmosphere Extremes in South Asia using High-Resolution Regional Earth System Modelling

Abstract

South Asia is among the world's most climatically vulnerable regions, facing rapidly intensifying compound ocean and atmospheric extremes. Its average temperature has risen by ~1.0°C between 2000-2019 compared to 1971-2000, surpassing the global trend and intensifying extreme temperature events, particularly in northern and central India (Dash et al., 2007; Basha et al., 2017; Rohini et al., 2016; Panda et al., 2017). This region has also experienced deadly heatwaves, leading to thousands of fatalities (Pattanaik et al., 2017). In addition to atmospheric heatwaves, marine heatwaves (MHWs) are emerging as major threats to marine ecosystems and climate systems (Kumar P et al., 2023; Oliver et al., 2019; Sen Gupta et al., 2020). Recent studies indicate that MHWs in the Bay of Bengal and Western Indian Ocean influence Indian monsoons, altering rainfall patterns (Saranya et al., 2022). Additionally, MHWs have been linked to the intensification of tropical cyclones, as seen with Cyclone Amphan (Rathore et al., 2022). The compounding effects of MHWs with other extreme events, like precipitation episodes, concurrent drought events, remain underexplored. Existing studies (Kumar et al., 2022) emphasise the need for high-resolution regional climate models. This project proposes a systematic investigation of these compound extremes events over the CORDEX-SA domain using the Regional Coupled Earth System Model ROM integrating atmosphere (REMO), ocean & sea ice (MPIOM), and marine biogeochemistry (HAMOCC) via the OASIS3-MCT coupler. These high-resolution simulations will be complemented by AI/ML-based downscaling and pattern recognition techniques to achieve km-scale projections. By simulating a high-resolution coupled regional climate model, the study improves simulation accuracy, while machine learning-driven downscaling and bias correction refine climate projections. This interdisciplinary approach advances scientific knowledge, enhances predictive capabilities, and informs targeted adaptation and mitigation strategies to protect ecosystems and societies.

To understand processes and address the key questions, this project uses a Regional Earth System Model ROM over the region. ROM will be configured over the CORDEX-SA domain with the atmospheric REMO having 27 hybrid vertical levels and oceanic MPIOM with 40 vertical layers. Three simulation sets are planned: a hindcast (ERA5 reanalysis from 1980-2020), and two future scenario runs (SSP3-7.0 and SSP5-8.5 from 2015-2100).

The computational setup involves multi-decadal, high-resolution coupled simulations over a large regional domain, generating substantial data volumes and requiring high-frequency output for process-based diagnostics. Such simulations demand efficient parallel scalability, high-throughput I/O, and large storage capacity, which are provided by the DKRZ Levante high-performance computing system. The strong integration of ROM within the DKRZ ecosystem further enables optimised workflows for model coupling, execution, and analysis.

Research Questions

- To quantify the frequency, intensity, and spatial distribution of compound ocean–atmosphere extremes (e.g., marine heatwaves coinciding with heatwaves, heavy rainfall, and droughts) across South Asia, with particular focus on the Bay of Bengal and Arabian Sea.
- To investigate how marine heatwaves in the northern Indian Ocean modulate large-scale circulation and influence variability and extremes of the South Asian monsoon system.
- To assess projected changes using ROM simulations in compound extreme events over South Asia under SSP3-7.0 and SSP5-8.5 scenarios, including shifts in their frequency, intensity, and co-occurrence patterns.
- To enhance the representation and prediction of compound extremes over South Asia using high-resolution coupled Regional Earth System Model (ROM) simulations combined with AI/ML-based downscaling and bias correction techniques.

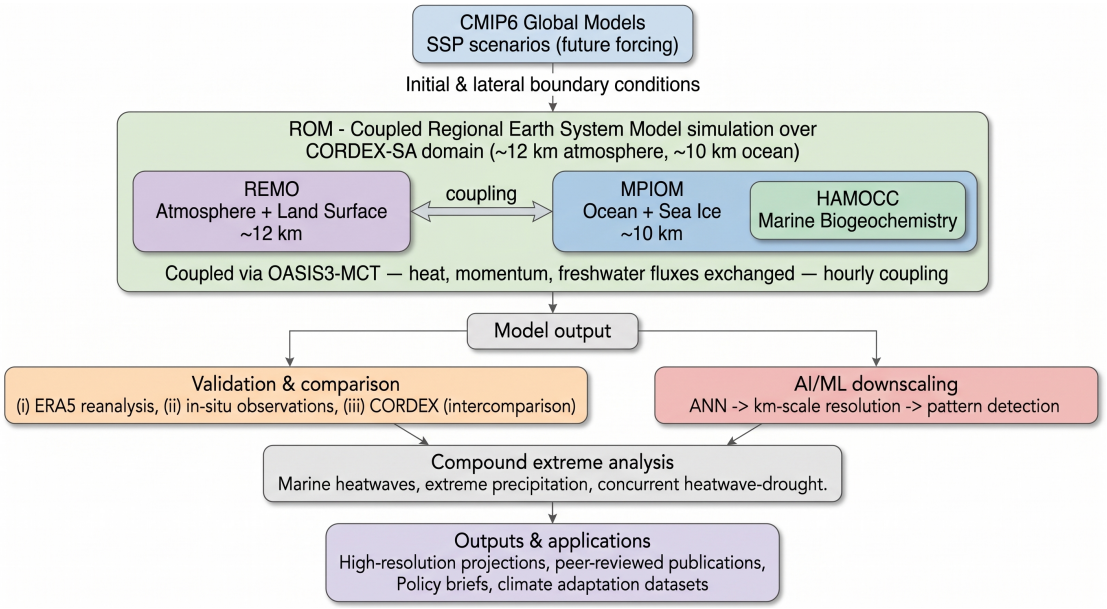

Fig 1: Graphical Abstract of the project

Expected Outcome

- Regional Earth System Modelling framework configuration over the CORDEX-SA domain.
- A high-resolution climatology of compound ocean–atmosphere extreme events over South Asia, including their frequency, intensity, duration, and spatial distribution.
- Better understanding of how marine heatwaves interact with the South Asian monsoon, and land–ocean processes to produce cascading climate extremes.
- Reliable projections of how compound extreme events may change under future warming scenarios, identifying regional hotspots of increasing climate risk.
- Improved regional climate projections through AI/ML-based downscaling and bias correction, enabling finer-scale representation of extreme events.