The Abdus Salam
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for Theoretical Physics

6th Summer School on Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics: Artificial Intelligence and Climate Modelling | (SMR 4067)

05 May 2025 - 16 May 2025
ICTP, Trieste, Italy

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P01

Abstract Abstract template for the 12th Workshop on the Theory and Use of Regional Climate Models

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[2] *Department of Astronomy and Meteorology, Omdurman Islamic University, Sudan*

This study focuses on the Eastern Sahel, where climate extremes and water scarcity place immense pressure on decision-makers and local communities. Climate projections indicate an increase in summer precipitation, characterized by higher intensity but reduced frequency of extreme precipitation events. Additionally, a delayed onset and cessation of the rainy season is expected. This study aims to identify the key drivers of these projected changes and understand the mechanisms governing precipitation variability in the region.

Our findings reveal that these drivers are also the primary sources of uncertainty among CMIP6 model projections. The study highlights key controls on Eastern Sahel precipitation and the uncertainties associated with them. North Atlantic SST warming enhances the meridional temperature gradient, strengthening the West African Monsoon (WAM) and increasing rainfall. However, model discrepancies introduce uncertainty, mainly due to differences in how models simulate the Atlantic Meridional Overturning Circulation (AMOC) and the Atlantic Cold Blob. Euro-Mediterranean and Eastern Mediterranean SSTs influence monsoon dynamics by enhancing moisture transport, suppressing the Harmattan wind, and reinforcing the Saharan Heat Low (SHL). The interhemispheric temperature gradient shifts the ITCZ northward, increasing moisture convergence. The SHL location and intensity regulate monsoon expansion, while Eastern Sahara surface air temperature increases the pressure gradient, further promoting the northward expansion of the ITCZ along the eastern Sahel.

This study aims to use these climatic controls as emergent observational constraints to refine model projections and reduce uncertainty in the magnitude of future Sahel wetting. By constraining key sources of inter-model spread, such as North Atlantic SST and SHL location, this approach will enhance confidence in regional precipitation forecasts, aiding climate adaptation and policy planning.

P02

Future Projection of Drought over North Africa using RegCM

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[2]*University of Vigo*

North Africa is one of the most water-scarce areas in the world. The Standardized Precipitation Index (SPI) is a widely used metric for characterizing meteorological drought on a range of timescales. The present study evaluates the future drought hazard in North Africa using the ICTP regional climate model (RegCM) running with RCP4.5 and RCP8.5 scenarios. Future precipitation values were used to calculate the SPI for the near future 2025-2050, based on the historical period of 1986-2005. The results indicate a projected decline in precipitation, leading to an increased risk of aridity across North Africa. The future projections using the SPI results show that the average index values will mostly be within the drought zone, indicating an intensification of drought severity. The research concludes that the increase in drought severity will significantly impact water resources, agriculture and food security among others.

P03

Abstract template for … BARLEY YIELD ESTIMATION IN RESPONSE TO FUTURE CLIMATE CHANGE IN BASONA WERANA WOREDA NORTH SHEWA ZONE OF AMHARA REGION, ETHIOPIA…

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2. Debre Berhan University, Collage of Agriculture and Natural Resource Science, Department of Natural Resource Management, Debre Berhan, Ethiopia.

This study examines the impact of future climate change on barley yields in the Basona Werana District using the DSSAT model, complemented by an analysis of climate extremes through ETCCDI indices. The research leverages historical weather data from the Ethiopian Meteorological Institute and future climate projections under SSP245 and SSP585 scenarios from the CMIP6 models. The study employs Mann-Kendall tests and annual trend analyses to assess changes in climate extremes. ETCCDI indices indicate significant trends in temperature extremes, with increases in indices such as TN90p, TX90p, TNx, and TXx, while indices like TX10p and TN10p show decreasing trends. Precipitation extremes present mixed trends with few significant changes. The DSSAT model, calibrated with experimental data from two barley cultivars, demonstrated strong performance with a root mean squared error (RMSE) of 0.162 t/ha, R^2 of 0.99, and d-index of 0.95 for calibration, and RMSE of 0.593 t/ha, R^2 of 0.833, and d-index of 0.887 for validation. Projected barley yields under SSP585 are expected to decline by 12.95% to 32.31% in the mid-century and by 17.39% to 43.14% by the end-century. Even under the medium emission SSP245 scenario, declines are projected to be 9.78% to 29.39% in the mid-century and 13.12% to 40.08% by the end-century. These results underscore the urgent need for adaptive measures in farming practices to mitigate the adverse effects of climate change and ensure the long-term viability of barley production in the Basona Werana District.

P04

Deep Learning Approaches for Bias Correction in WRF Model Outputs for Enhanced Solar and Wind Energy Estimation: Case Study in East and West Malaysia

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Accurate renewable energy forecasting is crucial for integrating wind and solar power into the grid, but the Weather Research and Forecasting (WRF) model often exhibits biases due to parameterization uncertainties and limited observational constraints [1]. Traditional bias correction methods struggle to capture nonlinear dependencies, leading to errors in wind speed and solar irradiance predictions [2]. This study applies deep learning techniques to enhance WRF model accuracy for renewable energy assessment in Malaysia. High-resolution WRF simulations were conducted with nested domains, and outputs were validated against ground-based observations. A hybrid deep learning framework combining convolutional neural networks (CNNs), long short-term memory (LSTM) networks, feedforward neural networks (FNNs), and recurrent neural networks (RNNs) was developed to correct biases in WRF-simulated wind speed and solar irradiance. The models were trained on historical datasets, incorporating meteorological variables to refine predictions, and performance was evaluated using RMSE and correlation coefficients. Results show that deep learning techniques significantly improve wind and solar energy estimations. This approach enhances the reliability of renewable energy forecasting, supporting better integration of wind and solar power into the energy grid, with potential applications in other regions facing similar meteorological challenges.

[1] Skamarock, W., Klemp, J., Dudhia, J., Gill, D., Liu, Z., Berner, J., Wang, W., Powers, J., Duda, M., Barker, D. & Others A Description of the Advanced Research WRF Model Version 4.3; No. *NCAR/TN556+ STR*. (2021), https://doi.org/10.5065/1dfh-6p97

[2] Bi, K., Xie, L., Zhang, H., Chen, X., Gu, X. & Tian, Q. Accurate medium-range global weather forecasting with 3D neural networks. *Nature*. **619**, 533-538 (2023,7), http://dx.doi.org/10.1038/s41586-023-06185-3

P05

Abstract Template for 6th Summer School on Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics: Artificial Intelligence and Climate Modelling

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Rainfall is one of the weather parameters that mostly affects human life and livelihood around the world. In the current context of climate change and variability, accurate rainfall prediction is essential for mitigating floods, managing water resources, and safeguarding lives, property, and economic endeavours. In the Republic of Benin, the majority of the population relies on agriculture that is dependent on rainfall. The study conducted by [1] examined the significance of seasonal climate forecasts for maize farmers in the Republic of Benin. The findings revealed that farmers highly value rainfall forecasts, particularly those that are accessible 1–2 months prior to the start of the rainy season.

This research focuses on accurately predicting monthly rainfall 2 months ahead for six geographically diverse weather stations across the Benin Republic using artificial neural network (ANN), particularly Multi-layer Perceptron (MLP) approach. For this purpose, twelve lagged values of atmospheric data were used as predictors. The models were trained using data from 1959 to 2017 and tested for four years (2018-2021). The proposed method was compared to Long Short-Term Memory (LSTM) and Climatology Forecasts (CF). The prediction performance was evaluated using five statistical measures: root mean square error, mean absolute error, mean absolute percentage error, coefficient of determination, and Nash-Sutcliff efficiency coefficient (NSE). Furthermore, Taylor diagrams, violin plots, box error, and Kruskal-Wallis test were used to assess the robustness of the model's forecast. The results revealed that MLP gives better results than LSTM and CF. The NSE obtained with the MLP, LSTM, and CF models during the test period ranges from 0.373 to 0.885, 0.297 to 0.875, and 0.335 to 0.845, respectively, depending on the weather station. Rainfall predictability was more accurate, with 0.512 improvement in NSE using MLP at higher latitudes across the country, showing the effect of geographic regions on prediction model results.

In summary, this research has revealed the potential of ANN techniques in predicting monthly rainfall two months ahead, supplying valuable insights for decision-makers in the Republic of Benin.

[1] Amegnaglo CJ, Anaman KA, Mensah-Bonsu A, Onumah EE and Gero FA Contingent valuation study of the benefits of seasonal climate forecasts for maize farmers in the Republic of Benin, West Africa. Climate Services 6, 1–11 (2017).

P06

Machine Learning and Climate Resilience: A Multidisciplinary Approach to Assess Human Health Response to Climate Change and Heat Stress

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Understanding and enhancing climate resilience is crucial in the face of rising global temperatures and increasing extreme weather events. In this work, we present a novel framework that leverages multidisciplinary data and advanced machine learning (ML) techniques to assess human health responses to climate change and heat stress. Our approach integrates meteorological data, climate health indicators, and climate model projections from CMIP (Coupled Model Intercomparison Project) to develop a comprehensive and data-driven understanding of climate resilience.

We employ state-of-the-art ML algorithms, including supervised learning models such as Random Forest, Gradient Boosting, and Support Vector Machines to identify patterns and predict health outcomes under different climate scenarios. The framework also utilizes high-resolution meteorological data from the ERA5 reanalysis dataset and atmospheric composition data from the Copernicus Atmosphere Monitoring Service (CAMS), providing robust and detailed environmental inputs for model training and validation.

This interdisciplinary methodology allows us to assess the impacts of heat stress on human health with unprecedented accuracy, offering insights into vulnerability and adaptive capacity at different scales. By combining health, climate, and environmental data with powerful ML techniques, this study provides a valuable tool for policymakers and researchers to develop targeted and effective resilience strategies.

Through this poster, we aim to share our innovative framework, discuss preliminary findings, and explore opportunities for collaboration to advance climate resilience research.

Keywords: climate resilience, Machine Learning, Heat stress, Health response

P07

Developing a Novel Meteorological Dataset for the High Mountain Asia Region Using Geospatial Techniques and Machine Learning Algorithm: A Case Study of the Hunza River Basin, Pakistan

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Accurate meteorological datasets are critical for climate modeling, hydrological simulations, and disaster risk assessment, particularly in data-scarce regions like the High Mountain Asia (HMA). This study aims to develop a novel, high-resolution temperature and precipitation dataset for the Hunza River Basin, Gilgit-Baltistan, Pakistan, using a machine learning-based approach. Multiple satellite, reanalysis, and modeled datasets—including ERA5, MERRA-2, CHIRPS, PERSIANN, MODIS, GLDAS, and Landsat-based Land Surface Temperature (LST) were acquired and preprocessed using the official data portals and Google Earth Engine cloud computing platform. The datasets were compared against in-situ ground station data for the past 30 years to assess their correlation and biases. A supervised machine learning algorithm was trained to optimize the relationship between available coarser resolution products and observed data, ensuring better representation of local climate patterns. The algorithm was validated using a cross-validation approach, and the most accurate ensemble product was selected. Results indicate that the ensemble dataset significantly reduces biases found in individual datasets, improving correlation with in-situ observations. The newly developed dataset offers higher spatial and temporal accuracy, making it suitable for climate modeling and hydrological simulations. This methodology provides a scalable framework that can be extended to other river basins across Pakistan, facilitating improved hydro-climatic assessments. The study also enhances the understanding of climate variability and supports disaster preparedness, water resource management, and policy-making in climate-sensitive regions by addressing data scarcity in mountainous regions,

Keywords: High Mountain Asia (HMA), Machine Learning, Novel Meteorological Dataset, Geospatial and Google Earth Engine (GEE), Hydro-Climatic Assessment

P08

USING AI PREDICTION MODELS FOR CCS MONITORING AND RISK IN (NEAR) SURFACE AND MARINE MONITORING

ABSTRACT

The rapid advancement of artificial intelligence (AI) technologies has opened new frontiers in environmental monitoring and risk assessment, particularly in the context of Carbon Capture and Storage (CCS) initiatives. This study explores the application of AI-based prediction models for monitoring and assessing risks associated with CCS activities in both near-surface and marine environments. The integration of AI algorithms enables real-time analysis of complex datasets, facilitating a comprehensive understanding of the dynamic interplay between CCS operations and the surrounding ecosystems.

In the near-surface realm, the study focuses on leveraging AI to predict potential environmental impacts associated with underground carbon storage, considering factors such as ground deformation, gas migration, and subsurface fluid interactions. The AI models are trained on historical data to enhance accuracy in predicting potential hazards, providing early warnings and enabling timely mitigation strategies.

In the marine environment, the research extends to the development of AI-driven predictive models for monitoring the impact of CO2 injection and storage on marine ecosystems. By analyzing diverse datasets, including water quality parameters, marine life distribution, and seabed conditions, the AI algorithms contribute to a nuanced understanding of the short- and long-term effects of CCS activities on marine biodiversity and ecosystem health.

Furthermore, the study integrates risk assessment methodologies into the AI framework to quantify and prioritize potential threats associated with CCS operations. This holistic approach ensures a systematic evaluation of environmental risks, incorporating uncertainties and variability inherent in both near-surface and marine settings.

The findings of this research not only contribute to the advancement of AI applications in environmental monitoring but also provide valuable insights for policymakers, industry stakeholders, and regulatory bodies. By harnessing the power of AI for predicting and mitigating risks associated with CCS initiatives, this study contributes to the development of sustainable and responsible carbon management practices, paving the way for a more environmentally conscious and secure future.

P09

Abstract

This study proposes a methodology for selecting global climate models (GCMs) from the Coupled Model Intercomparison Project phase 6 (CMIP6) on the basis of their ability to simulate characteristics of mean and extreme precipitation over North-East Africa and Arabia. The seasonal climatology, annual rainfall cycles, and spatial and temporal variability (as documented by five Expert Team on Climate Change Detection and Indices [ETCCDI]ETCCDI indices) of twenty-five GCMs have been assessed against rain gauge observations and seven gridded rainfall products. Most of the GCMs simulate reasonably well the climatology of mean rainfall (annual and seasonal totals and number of rainy days). Large discrepancies are found in the reference products for some indices related to rainfall intensity (SDII, P95 and R95ptot), which is a major concern for the validation of GCMs. For these indices, we evaluate whether historical CMIP6 simulations fall within the uncertainty range of the rainfall estimates. Ten CMIP6 models are finally retained based on their ability to reproduce the geography and seasonality of mean and extreme rainfall. They tend to have a higher spatial resolution, although there is no systematic relationship between resolution and skill. Overall, the selected CMIP6 models perform better than the rest of the models over Djibouti The selected CMIP6 models perform better, not only at the regional scale (by construction), but also, and more meaningfully, at the local scale of the Republic of Djibouti (located at the interface of the two regions, serves as a valuable test for evaluating the robustness of the selection) (particularly for the March-to-May rainy season), although local climatic features such as those observed in the coastal area remain imperfectly resolved.

Keywords: Global Climate Models; Historical simulations; Mean and extreme rainfall; North-East Africa, Arabian Peninsula; Djibouti

P10

Evaluation of COSMO-CLM Model Parameter Sensitivity in the Study of Extreme Events across the Eastern Region of India

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The present study aims to identify the parameters from the Consortium for Small-scale Modelling in CLimate Mode (COSMO-CLM) regional climate model that strongly controls the prediction of extreme events over West Bengal and the adjoining areas observed between 2013 to 2018. Metrics, namely Performance Score (PS) screen out the most persuasive parameter on model output. Additionally, the Performance Index (PI) measure the reliability of the model and Skill Score (SS) establishes the model performance against the reference simulation leading to the optimization of the model for a given variable. In this study, parameter screening for four output variables such as 2m-temperature, surface latent heat flux, precipitation and cloud cover of COSMO-CLM is accomplished. For heat wave simulations, 2m-temperature and surface latent heat flux are explored whereas cloud cover and precipitation are examined for extreme rainfall events. A total of 25 adjustable parameters representing the following parameterization schemes: turbulence, land surface process, microphysics, convection, radiation and soil. Out of the six parameterization schemes, the scaling factor of the laminar boundary layer for heat (rlam_heat) and the ratio of laminar scaling factors for heat over sea and land (rat_sea) from the land surface process is sensitive to SLH, TP. The exponent to get the effective surface area (e_surf) from the land surface has a large impact on 2m-temperature. A few parameters from microphysics (cloud ice threshold for auto conversion), convection (mean entrainment rate for shallow convection) and radiation (parameter for computing the amount of cloud cover in saturated conditions) play a significant role in producing TP, and TCC fields. It is evident from the results that the parameter sensitivities on model performance depend on the choice of the meteorological field. Furthermore, in almost all input model parameters, the model performance reveals the opposite character in different domains for a given meteorological field.

P11

Effects of Solar Radiation Modification on Temperature Variability Over Ghana

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[2] *University of Cape Coast*

Africa is experiencing significant climate challenges, particularly in southern West Africa (SWA), where extreme weather events are increasing. This study focuses on Ghana during the harmattan period (December-February) from 1990 to 2020, a time characterized by sub-Saharan dust intrusions. Using data from satellite remote sensing (Merra 2, PM2.5) and ground-based observations from the 22 synoptic stations of the Ghana Meteorological Agency, the study analyses solar radiation, temperature, and dust concentration trends. Temporal trends were identified, with seasonal decomposition revealing overarching trends, seasonal variations, and residuals. Cross-correlation analyses highlight time lags influencing interactions among solar radiation, temperature, and dust concentration. Spatial correlation analyses, combined with land use and land cover data, provides insights into anthropogenic and environmental influences on spatial patterns. The study's findings may emphasize the complexity of climate dynamics in Ghana during the harmattan season, crucial for climate resilience, environmental management, and informed decision-making. These insights lay a foundation for future research and policy in climate science and sustainable development.

[1] A. Sunnu, G. Afeti, & F. Resch, J. Atm Res. 87(1), 13–26 (2008).

[2] N. Yusuf, S. Tilmes, & E. Gbobaniyi J.Aerosol Sci. 151, 105625 (2021).

P12

Assessment of a Planetary Boundary Layer Scheme in a Global Model and Perspectives on AI-based Parameterization

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The planetary boundary layer (PBL) plays a crucial role in numerical weather prediction and climate models by mediating the exchange of momentum, heat, and moisture between the surface and the free atmosphere. However, PBL parameterizations often introduce uncertainties, especially in long-term climate simulations. This study evaluates the performance of a PBL scheme in the UTGAM global model using single-column and baroclinic-wave life cycle experiments.

In the GABLS1 single-column experiment, two vertical coordinate systems (sigma-theta and sigma-pressure) and different vertical resolutions were tested against Large Eddy Simulation (LES) benchmarks. Results show that simulated turbulent diffusion of heat and momentum was higher than LES references, emphasizing the need for improved parameterization. Increasing vertical resolution and refining the placement of the first model level closer to the surface improved performance but did not fully resolve discrepancies.

In idealized baroclinic-wave simulations, adding PBL parameterization led to a reduction in eddy kinetic energy and a delay in reaching peak intensity. The boundary layer also altered surface pressure structures differently in the two baroclinic-wave life cycles (LC1 and LC2), suggesting a non-uniform impact of PBL processes on synoptic-scale dynamics. Tracer transport analysis revealed that PBL depth critically affects mass exchange between the boundary layer and the free atmosphere, with different responses in LC1 and LC2.

While these results demonstrate the importance of PBL processes in large-scale atmospheric models, challenges remain in capturing turbulent exchanges accurately. Given recent advancements in AI/ML-based parameterizations, data-driven approaches could offer new possibilities for improving PBL turbulence representation and uncertainty quantification. Exploring such techniques could refine boundary layer dynamics in global and regional climate models, making AI-enhanced modeling a promising direction for future research.

Keywords: Boundary layer parameterization, numerical modeling, AI/ML in climate modeling, baroclinic-wave dynamics

P13

Assessing the Impact of Climate Change on Groundwater Levels and Salinity Intrusion Using AI-Based Hybrid Models

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Groundwater resources are increasingly vulnerable to climate change, with potential consequences including fluctuations in water levels and salinity intrusion. This study develops and implements hybrid AI models to predict groundwater behavior under different climate change scenarios in key aquifers in Iran. By integrating machine learning techniques such as neural networks and decision trees with traditional numerical models, the study evaluates the sensitivity of aquifers to changes in temperature, precipitation, and sea-level rise.

The results highlight spatial and temporal variations in groundwater levels and identify regions at high risk of salinity intrusion. Additionally, the proposed models demonstrate improved prediction accuracy compared to standalone physical models, particularly over decadal time scales. The findings provide a robust framework for decision-makers to develop adaptive management strategies for sustainable groundwater use in the face of climate change

P14

Advancing Precipitation Modeling in the Yucatán Península: Integrating Ice-Nucleating Particle*Data into RegCM5*

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Abstract

This study enhances precipitation modeling accuracy over the Yucatán Peninsula by incorporating region-specific observational data on ice-nucleating particles (INPs) into cloud microphysics parameterizations within regional climate models (RCMs). By adjusting these parameterizations to align with measured INP concentrations, the research aims to refine the representation of heterogeneous ice nucleation—an essential process in ice crystal formation and precipitation evolution. Preliminary simulations conducted with the RegCM framework indicate that rainfall projections are highly sensitive to modifications in cumulus and microphysics schemes, demonstrating the potential of localized parameter tuning to better capture tropical precipitation patterns. While these findings highlight the crucial role of INP-induced processes in cloud formation, the study underscores the need for broader regional assessments to fully quantify the influence of such parameterizations on climate predictions in tropical environments like the Yucatán. This work contributes to improving model accuracy, fostering more reliable climate projections to support resilience planning in vulnerable areas.

Mapping Climate Change Hotspots in Sindh Using Deep Learning Techniques

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Climate change poses significant challenges worldwide, with Sindh, Pakistan, being particularly vulnerable due to rising temperatures, extreme weather events, and environmental degradation. This project employs advanced deep learning techniques to identify and analyze climate change hotspots in Sindh, providing critical insights into areas most at risk. Using convolutional neural networks (CNNs) and recurrent neural networks (RNNs), the research processes historical climate and environmental data to detect patterns and predict future trends. Additionally, socio-economic and demographic factors such as population density and vulnerability indices are incorporated to assess potential impacts on local communities.

The study's findings highlight the regions in Sindh requiring immediate adaptation and resilience measures, supporting policymakers and stakeholders in prioritizing resources and developing targeted strategies to mitigate climate change effects. This research not only contributes to understanding climate change impacts but also serves as a foundation for informed decision-making and sustainable development in the province.

P16

Quantifying the Relative Contributions of CCN and IN to Extreme Monsoon Rainfall

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The Indian summer monsoon, characterized by extreme rainfall events during June–September, frequently leads to severe natural hazards such as floods, causing significant societal and economic impacts. Accurate prediction of heavy rainfall remains critical for mitigating these risks. While the influences of large-scale circulation, water vapor availability, and topography on monsoon convection are well-documented, the role of aerosol-cloud interactions in modulating extreme precipitation remains poorly understood. Aerosols, acting as cloud condensation nuclei (CCN) and ice nuclei (IN), significantly influence cloud microphysics, precipitation processes, and the hydrological cycle, thereby intensifying weather and climate variability. Mixed-phase clouds, which are particularly sensitive to aerosol effects, play a crucial role in regulating the Earth's radiation budget but are challenging to model due to complex processes such as ice nucleation and hydrometeor growth.

This study employs the Weather Research and Forecasting (WRF) model coupled with a triple-moment microphysics scheme to investigate aerosol-cloud interactions in Indian summer monsoon precipitation. High-resolution simulations of monsoon depression events are conducted under contrasting aerosol scenarios—clean continental and urban (polluted) conditions—with model outputs evaluated against observational data. Sensitivity experiments reveal that polluted conditions amplify extreme precipitation and updraft intensities through enhanced ice-phase processes and the formation of larger snow and graupel hydrometeors. These findings underscore the critical role of aerosol concentrations in modulating extreme rainfall via intricate microphysical, thermodynamic, and dynamical interactions.

Furthermore, the study highlights how uncertainties in aerosol representation contribute to errors in quantitative precipitation forecasts (QPF). By elucidating these mechanisms, this research offers novel insights into the variability of monsoon rainfall and provides actionable knowledge to improve the predictability of extreme precipitation events during the Indian summer monsoon season.

P17

Data-Driven Analysis of Summertime Large-Scale Flow Regimes Linked to Consecutive Dry Days over Norway in the IFS Model

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Skilful sub-seasonal prediction of weekly consecutive dry days (CDDs) can benefit a wide range of sectors, including agriculture, energy, and wildfire management. However, such tailored forecast products are often lacking in current state-of-the-art AI and numerical weather prediction (NWP) models, particularly at the sub-seasonal timescale. This highlights the need for data-driven post-processing approaches that leverage our current understanding of atmospheric predictability at the S2S timescale to generate useful forecasts.

Previous study[1] found that upper-level jet patterns can be linked to the occurrence of heatwaves in the North Atlantic sector. Building on this, we aim to construct a model using a Bayesian framework that combines observational data and NWP representations of upper-level jet patterns, conditioned on the local climatology of CDDs, to produce skilful probabilistic forecasts of CDDs at a leadtime of 2-4 weeks. Assessing the capability of current state-of-the-art ensemble NWPs in capturing these jet patterns is essential for developing such a model.

In this study, we evaluate the performance of ECMWF-IFS in predicting dominant upper-level jet patterns at a 2–4 week lead time. First, we identify large-scale flow regimes associated with CDDs over southern Norway using ERA5 reanalysis data. We find systematic change in probability distribution of weekly CDDs, conditioned on specific jet patterns. These same clustering methods are then applied to ECMWF-IFS (cycle 48r1) S2S forecasts. We assess the alignment between predicted jet-pattern clusters and the ERA5-based ground truth using a range of probabilistic verification metrics.

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P18

A Machine Learning Framework for predicting daily-averaged sea level anomaly and surface currents with a lead time of 3 days

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Short-term prediction of sea level anomaly (SLA) and ocean surface currents are generally carried out using state-of-the-art dynamical models. In this study, we present a univariate machine learning framework using Long Short Term Memory (LSTM) [1] networks that forecasts daily-averaged SLA three days ahead of time over the north Indian Ocean, incorporating a novel methodology using randomized input features to remove the phase lag misalignment in predictions. The SLA forecasts exhibit accuracies reaching that of reanalyses from data assimilated ocean models. The 3rd day forecasted daily-averaged surface currents are thereafter predicted using forecasted SLA and forecasted winds. Unexpectedly, the skills of the 3rd day forecasted surface currents are comparable with the best available reanalyses. We demonstrate that the short-term forecast of daily-averaged SLA and surface currents can be approached as a collection of localized low dimensional independent univariate systems, thereby reducing computational costs by large margins.

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Abstract template for 6th Summer School on Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics: Artificial Intelligence and Climate Modelling

Future climate assessment in the Mediterranean using downscaled CMIP6 model output

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The Mediterranean has ben labeled as a ”climate change hot spot” as a result of the anthropogenic increase in greenhouse gas concentrations and aerosol forcing. The increase in warming and decrease in rainfall as a result will have dire consequences on a region where climate change has a great impact on the socioeconomic situations and relies heavily on rainfall. Drought and heatwaves in the Mediterranean region are analyzed under two climate scenarios during the wet season (ONDJFM) and dry season (AMJJAS) to provide an assessment of the impact anthropogenic climate change will have on the Mediterranean and how that will affect urban environments and coastal communities, especially in countries that do not necessarily contribute a large amount of CO_2 emissions but may feel the largest impacts because the Mediterranean warms at a rate higher than the rest of the world. Using ten high-resolution climate models and two climate emissions scenarios (SSP2-4.5 and SSP5-8.5), precipitation and air-temperature data is analyzed in the Mediterranean, including in the Middle East and North Africa countries, a region typically omitted from previous Mediterranean climate studies. The data used in this study comes from the Bias Correction Constructed Analogues with Quantile mapping reordering dataset, which takes the CMIP6 Global Climate models and downscales them from 1° to 0.25° removing the uncertainty and biases that comes with the coarse resolution, and improving the accuracy of predicting extreme events such as droughts and heatwaves. As expected, larger impacts are observed in the high emissions scenario (SSP5-8.5) and during the dry season for both droughts and heatwaves. Comparing the wet season to the dry season droughts, there is a northward shift in the positive signal as most of the values are seen over the Mediterranean Sea in the wet season and over the northern Mediterranean and Europe in the dry season. For the heatwaves, the dry season shows a response stronger than the one observed by the wet season by nearly 2-3 times and there is a strong signal located over the Mediterranean Sea during the dry season that is not see during the wet season.

P20

3D Latent heating structure over the Indian Summer Monsoon region through the eyes of TRMM/GPM

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Latent heat (LH) released /absorbed within the atmosphere is a dominant propellant to tropical circulation in scales ranging from mesoscale to planetary. Based on the vertical distribution of particle growth and fallout mechanism LH profiles are divided into convective and stratiform types, displaying mid – and upper-level heating peaks, respectively. The relative stratiform portion of a cloud cluster determines its overall implication on momentum redistribution, circulation strength and pattern. Summer monsoon circulation is the dominant planetary-scale circulation in our domain. All the entrants of a monsoon circulation have a different time scale of occurrence progress, lifespan, and interaction. Discernibly their tropospheric dynamics and thermodynamics properties diverge. In this context, LH, an energetic equivalent to precipitation, is a useful tool for studying those distinct characteristics. Since the advent of TRMM in 1997 and the ongoing GPM project we have a unique opportunity to study spatio-temporal distribution of latent heating over the tropics has been readily available. Alongside this, it also provides the convective stratiform separation of these LH profiles. This study compares two algorithms – CSH (convective Stratiform Heating) and SLH (Spectral Latent Heating) in emulating 3-dimensional LH distribution over the Indian Summer Monsoon region through the TRMM to GPM transition era. The result shows the systematic bias of the CSH algorithm to capture the lower-level convective heating peak at a comparably lower height than SLH. While GPM SLH simulates the upper-level deep-stratiform peak at a greater height than CSH and TRMM SLH. As the algorithm was modified for GPM, Convective enhancement in SLH and lower-level convective suppression in CSH became very noticeable. The study also employs the same algorithms to study salient features of the Indian Summer Monsoon for over two decades. Interestingly, the observed heating pattern for LPS in the recent decade has seen convective heating dominance in the CSH algorithm, which cannot be ascribed to the algorithm's innate biases. This disparity may arise due to the thermodynamic properties of organized cloud clusters in recent decades or contingent on the cases studied.

P21

Effect of stratospheric aerosol injection on marine heatwave events off the coast of South Africa

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How to mitigate the negative effects of global warming is one of the most challenging issues of our time. Stratospheric Aerosol Intervention (SAI) may help reduce these effects, but its impact on extreme sea surface temperature events like marine heatwaves (MHWs) remains uncertain, particularly in productive areas such as the Agulhas Bank (AB) in the southern coast of South Africa. This study aims to investigate to what extent the SAI can mitigate the impacts of global warming on MHW metrics (frequency, duration, intensity, and cumulative intensity) in the AB. We used ARISE-SAI-1.5 simulations, aimed to limit the future global mean surface temperature to 1.5°C above pre-industrial levels, to calculate the MHW metrics and compare them to those of the SSP2-4.5 simulations under global warming. Our results show that, under global warming, MHW frequency, duration and intensity are projected to increase with the maximum increase up to 150%, 200%, and 15%, respectively. Under the SAI, the changes in these metrics are mitigated; specifically, in the AB region. To understand these decreases, we applied a machine learning approach, the self-organizing map to the MHW events south of South Africa matching those covering 95% of the AB region in both the ARISE-SAI-1.5 and SSP2-4.5 simulations. The results reveal nine dominant patterns of MHW intensity, with SAI offsetting climate change impacts in certain patterns, especially those with cooling propagation from the south and west toward the AB region, potentially benefiting the productivity of the South African coast.

P22

Development of a Digital Twin for Dynamic Simulation and Optimization of Electric Vehicle Charging Demands

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As Electric Vehicle (EV) adoption accelerates, optimizing the charging infrastructure is crucial for balancing user satisfaction, energy efficiency, and financial viability. Unlike previous static modeling, this study developed a digital twin based on an agent-based decision-support approach for dynamic simulation and optimization of EV-charging interactions to enable scenario-based analysis. We used a university campus in Hanoi, Vietnam, to evaluate operational policies, EV charging station configurations, and the energy sources for charging electricity. The interactive dashboard enables seasonal analysis, revealing a 25% drop in solar efficiency from October to March and wind power contributing under 5% of demand, underscoring the need for adaptive energy management strategies. The simulation results revealed that notification systems of newly available charging slots significantly boost user satisfaction, while gasoline bans and idle fees improve slot turnover with minimal complexity. Optimization algorithms directly integrate into the system to determine the near-optimal mix of fast (30kW) and standard (11kW) chargers with solar energy, balancing energy efficiency, profitability, EV demand, while significantly reducing computation time. This digital twin allows optimal development of EV charging stations and will be a powerful tool for EV charging infrastructure.

P23

Drought Forecasting in the Indo-Gangetic Basin Integrating Climate Variables and Advanced Hybrid Machine Learning Techniques

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Drought, a complex and recurring global hazard arising from hydrometeorological processes, can lead to significant agricultural damage and economic losses. In the last couple of decades, climate change, CO_2 emission, and anthropogenic activities have heightened the risk of fluctuations in precipitation and its spatiotemporal variation. Future climate projections indicate that the intensity and frequency of drought will increase across various regions of the earth throughout the ongoing century. The resulting water shortage and agricultural losses have become serious threat to many countries including India. To address the limitations of drought indices solely based on remote sensing or climate data, researchers are increasingly using advanced mathematical regression and machine learning techniques that combine meteorological and remote sensing data to improve drought prediction, though studies in India often overlook climate projection datasets[1,2]. Consequently, region-specific monitoring with these datasets is essential for accurately predicting drought and mitigating its adverse impacts. This study aims to predict drought conditions in the Indo-Gangetic Plain of India by analyzing critical meteorological variables, including temperature, precipitation, and Potential Evapotranspiration (PET). Statistical downscaling techniques will be employed utilizing both observed data and outputs from Global Climate Models (GCMs) to project drought occurrences. Hybrid ML models integrate the strengths of multiple methodologies to improve the accuracy of time series predictions[3,4,5]. This research will deliver reliable predictions of the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Agricultural Standardized Precipitation Index (ASPI) over multiple time scales—specifically 1, 3, 6, and 12 months—through the use of advanced hybrid machine learning models, including SVM-POA, ANFIS-Wavelet, and ANN-MHA. These models are effective as they combine different models to capture diverse aspects of data. Iterative tuning of model parameters is crucial for enhancing both efficiency and predictive performance. Moreover, integrating optimization algorithms with these methods creates a more robust framework, thereby increasing the accuracy and reliability of forecasts. The models will be thoroughly evaluated using various statistical indices (RMSE, BIAS, WI, CI) to assess their effectiveness for both short-term and long-term drought forecasting. This study will assist policymakers in developing targeted policies, contingency plans, and mitigation strategies to the specific drought conditions of any region, thereby reducing the adverse effects.

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P24

Super-Resolution Deep Learning for Downscaling CORDEX-SEA 0.25° Precipitation and Temperature Projections over Indonesia: A Comparative Analysis of SRCNN and EDSR Models

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High-resolution climate projections are crucial for understanding the impacts of climate change on Indonesia's complex urban areas. However, the resolution of the Coupled Model Intercomparison Project Phase 6 (CMIP6)-based Coordinated Regional Climate Downscaling Experiment - Southeast Asia (CORDEX-SEA) regional dataset, with a resolution of 0.25° (25 km), remains too coarse for local applications. This study aims to enhance the spatial resolution of CORDEX-SEA CMIP6 climate projections to ≤0.1° (10 km) through the application of super-resolution deep learning techniques employing two distinct architectures: Super-Resolution Convolutional Neural Network (SRCNN)[1] dan Enhanced Deep Super-Resolution (EDSR)[2]. The research focuses on rainfall and surface temperature variables, with validation using the Multi Source Weather (MSWX) observational dataset [3]. he downscaling process incorporates historical data and future projections based on Shared Socioeconomic Pathways (SSPs) scenarios. To assess the efficacy of the models, various statistical metrics are employed, including mean squared error (MSE), peak signal-to-noise ratio (PSNR), structural similarity index measure (SSIM), and learned perceptual image patch similarity (LPIPS) on MSWX data. The anticipated outcome is a model capable of accurately reconstructing local climate patterns, particularly in urban areas, focusing on rainfall and temperature extremes. A comparative analysis between SRCNN and EDSR will reveal the advantages of each model in handling the spatial variability of rainfall and temperature in Indonesia. The findings of this study are anticipated to provide a scientific foundation for climate adaptation planning, including mitigating floods, droughts, and other hydrometeorological disaster phenomena. The current stage of the research involves the processing of data and the training of models. Preliminary results indicate substantial advancements in spatial resolution and congruence with MSWX observations.

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P25

The Use of Laboratory Experiment to Better Understand Post-Wildfire Processes on Soil Sealing for Hydrological Fluxes in Complex Terrain

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University of Wyoming; Department of Civil and Architectural Engineering and Construction Management

UW College of Engineering and Physical Sciences, Civil and Architectural Engineering and Construction Management

INTRODUCTION

- There's an escalating trend in the occurrence of wildfires in the United States:
- Wildfires drastically alter soil properties and hydrological processes, mainly through ash deposition and soil sealing effects.
- Complex terrain and varying topography add another dimension to understanding post-fire watershed behavior.
- The formation of ash layers plays a crucial role in determining surface runoff and erosion patterns in burned environments.

Goal

Investigate how the presence of ash after the first rainfall impacts the hydraulic properties of soil.

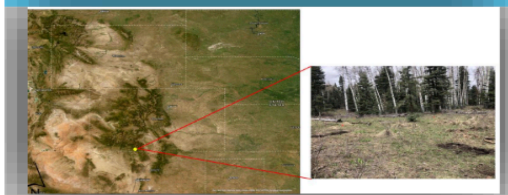
Hypothesis

The surface ash erosion rates would increase with steeper slope angles.

Objectives

- Quantify how slope angles (θ) influence ash erosion and surface retention during rainfall events.
- Determine the impact of retained ash on the field-saturated hydraulic conductivity (K_{fs}), saturated hydraulic conductivity (K_s), and water repellency (R) of the soil-ash interface after rainfall simulation.
- How water retention behavior changes at the ash-soil interface.

STUDY AREA



Description

The proposed research site is at Banded Peak ranch located in the small mountain community of Chromo, Archuleta County, Colorado.

Elevation and coordinates

8460ft and 37.11°, -106.69°

Vegetation / forest type:

Montane forest with Ponderosa pine, spruce-fir, and quaking aspen , Engelmann spruce, Douglas-fir, white fir, aspens. Etc.

Hydrology

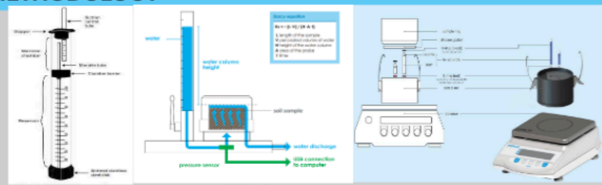
Primary tributary to the Colorado river.

Why this site:

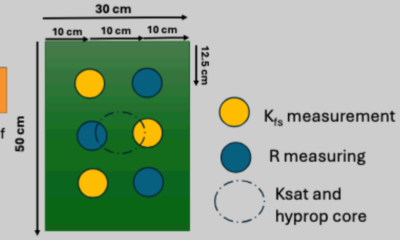
Research conducted here will inform land management practices seeking to balance ecological health with sustainable use of resources in the broader region

METHODOLOGY

Experimental design flowchart showing the distribution and treatment of soil samples for hydraulic conductivity analysis. The study includes Control A (n=3) and Control B (n=3) with varying burn and ash conditions, and an Experimental group (n=18) with burn and ash treatments. All samples underwent rainfall simulation followed by measurements of saturated (Ksat) and unsaturated (SWRC) hydraulic conductivity testing. The flowchart illustrates the systematic approach to evaluate the effects of burning and ash addition on soil hydraulic properties

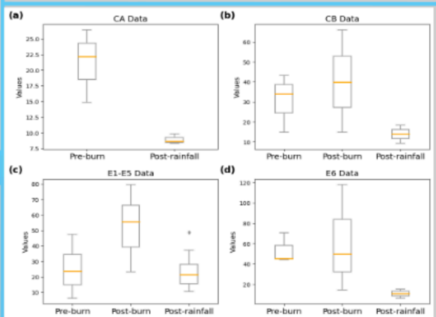


Laboratory instruments from METER Group used for hydraulic measurements: mini-disk infiltrometer for field infiltration, KSAT system for saturated conductivity, and HYPROP for soil water retention curves.

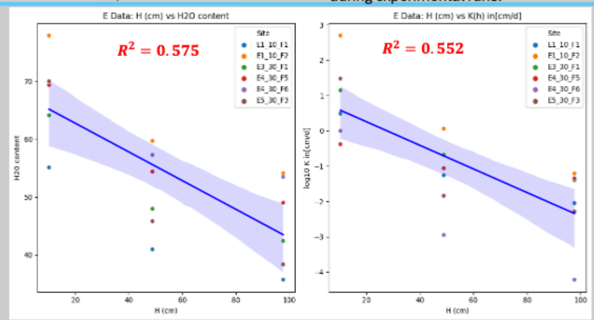


Schematic representation of the flume setup, highlighting sampling locations and instrumentation points.

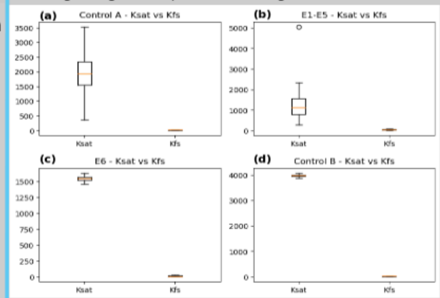
Laboratory rainfall simulator setup with protective blue tarp for containment during experimental runs.



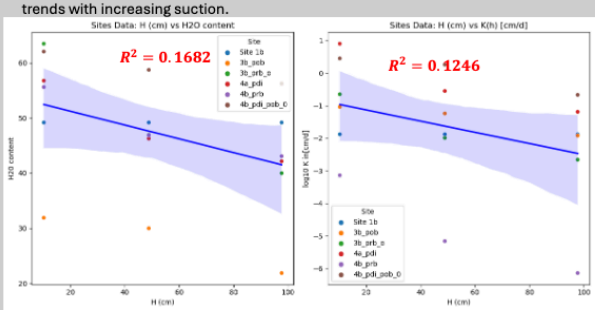
Box plots comparing soil hydraulic properties across three experimental phases (pre-burn, post-burn, and post-rainfall) for control samples (CA, CB) and ash-treated samples (E1-E5, E6), showing changes in response to burning and rainfall events.



Water retention (left) and hydraulic conductivity (right) curves as a function of suction head (H) for ash-treated samples (E1-E5), showing characteristic decreasing trends with increasing suction.



Box plots comparing saturated hydraulic conductivity (Ksat) and field-saturated hydraulic conductivity (Kfs) measurements across control (CA and CB) and experimental (E1-E5, E6) tests.



Relationship between suction head (H) and water content (left) and hydraulic conductivity (right) across different experimental sites, showing decreasing trends with increasing suction as indicated by the regression lines.

DISCUSSION

Pre-burn Conditions:

Samples exhibited K_{fs} values consistent with established references demonstrating typical baseline characteristics.

Post-burn Effects:

The burning process significantly increased K_{fs}, with several samples showing approximately twice their pre-burn state.

Post-rainfall Response:

Additional increases in hydraulic conductivity were observed following initial rainfall exposure.

Water Repellency

High-intensity burning resulted in no detectable hydrophobic layers on the surface. This absence of water repellency persisted through subsequent rainfall events.

Water Retention Properties

Ash-Soil Interface:

Ash-soil samples demonstrated:

- Enhanced water absorption rates
- Higher volumetric water content compared to non-ash samples
- Limited water retention capacity despite increased initial absorption

Erosion Analysis

Variation in slope angles showed no significant correlation with ash erosion rates, suggesting other factors may be more influential in erosion dynamics.

CONCLUSION

- Steeper slopes do not entirely contribute to the ash erosion
- There's an increase in hydraulic conductivity immediately after high-intensity fires and no repellency.
- K_{fs} and K_s in the same soil have a wide difference in magnitude.
- Ash plays a significant role in the absorption of water.
- Tho ash has good water retention properties, it loses water rapidly and gradually as seen from the Hyprop

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Study of Extreme Weather Events in the Central Himalayan Region through Machine Learning and Artificial Intelligence

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This study focuses on various machine learning approaches for analysing extreme weather events in Uttarakhand, India, based on meteorological data and aerosol properties. We aim to acquire a comprehensive understanding of the incidents and attributes of extreme weather events in the central Himalayan Region. we employ cutting-edge methodologies, including Random Forest, Support Vector Machines (SVM), Artificial Neural Networks (ANN), and General Regression Neural Networks (GRNN), Specifically, we implemented a Random Forest model to predict rainfall events in the Srinagar Garhwal region, utilizing parameters such as temperature, humidity, wind direction, and wind speed. This model serves as an early warning system for environmental management and disaster preparedness. The model's efficacy was assessed through rigorous evaluation metrics, including the Mean Absolute Error (MAE), Coefficient of Determination (R^2), and Root Mean Square Error (RMSE). The Srinagar rainfall model, with 100 trees, demonstrated a delicate balance between complexity and performance, excelling with RMSE 2.74, MAE 1.39, and R^2 0.57. However, increasing the number of trees to 1500 reduced the performance and increased the errors (RMSE 3.02, MAE 1.54 & R^2 0.46). In future work, we plan to incorporate more ground-based and satellite meteorological data, including parameters such as solar radiation, pressure, dew points, and higher data resolution (1 minute) to enhance model efficiency. Additionally, we aim to apply SVM, ANN, and GRNN to further study extreme weather events over Uttarakhand. This interdisciplinary approach provides valuable insights into extreme weather patterns in Uttarakhand, contributing significantly to the understanding of extreme weather events in the central Himalayan Region. It supports efforts for sustainable environmental management and disaster resilience.

Keywords: Metrological Parameters, Central Himalayan Region, Random Forest Model, RMSE, MAE, FFNN, Learning models

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ERBIL POLYTECHNIC UNIVERSITY

The Abdus Salam International Centre for Theoretical Physics

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Climate Dust Storm Pollution in Erbil's Kurdistan

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ABSTRACT

Rising temperatures and declining precipitation levels exacerbate environmental stressors, contributing to the intensification of drought conditions, the expansion of desertification, and the increased frequency of sandstorms. This study conducted a comprehensive analysis of dust storm samples collected from Erbil, employing Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to detect the presence and concentrations of heavy metals, including cadmium (Cd), nickel (Ni), chromium (Cr), mercury (Hg), lead (Pb), zinc (Zn), manganese (Mn), copper (Cu), cobalt (Co), iron (Fe), and arsenic (As). The research further assessed the potential health risks associated with exposure to these heavy metals through ingestion, inhalation, and dermal contact, with a particular focus on both adult and pediatric populations.

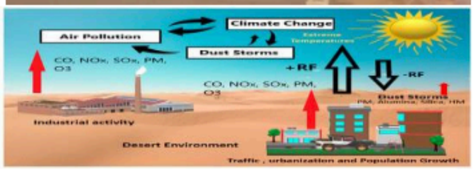
The findings underscored that children exhibit heightened susceptibility to the adverse effects of heavy metals (HMs) and polycyclic aromatic hydrocarbons (PAHs), attributable to the mineralogical and morphological characteristics of these particulates. Given that children's immune systems are inherently more vulnerable compared to those of adults, their exposure to such contaminants presents an elevated risk of developing severe health complications. Consequently, the study underscores the critical necessity of prioritizing vulnerable demographic groups, particularly children, when evaluating the health implications of dust storm pollution. Additionally, the study quantified the deposition rates of dry dust across various sampling sites and adjacent regions, revealing accumulation levels ranging from 5 to 9.1 times higher per square meter over a two-month observation period. This substantial accumulation not only highlights the pervasiveness of dust deposition but also suggests its potential role as a reservoir for chemical pollutants and heavy metals, which may exacerbate environmental contamination.

Furthermore, the investigation determined that the analyzed parameters of both indoor and outdoor dust compositions remained within globally recognized acceptable thresholds. Although the findings indicate that the dust composition in Erbil and its surrounding areas does not exhibit excessive contamination relative to international benchmarks, the study emphasizes the imperative for sustained environmental monitoring and the implementation of preventive interventions to mitigate long-term public health risks.

Indoor and Outdoor Dust Deposition

An experiment conducted in Erbil and surrounding areas evaluated dust accumulation as a significant form of indoor and outdoor air pollution. The study highlighted the serious impact of particulate matter on environmental conditions and emphasized the need for comprehensive programs to assess and control air pollution in the region. Given the limited studies on dust deposition in Iraq, coupled with recent drought conditions, this research underscores the growing importance of monitoring airborne particulates. The results stress the urgency of implementing strategies to address air quality issues, particularly in areas like Kurdistan, where air pollution remains a significant concern. The study's findings reveal the pressing need for effective measures to safeguard public health and mitigate environmental degradation caused by particulate pollution.

This study systematically evaluates indoor and outdoor dust deposition in Erbil, focusing on particulate accumulation and its enavironmental implications. Quantitative analysis revealed dust deposition rates ranging from 5 to 9.1 times higher per square meter over a two-month period, The presence of these elements suggests potential risks to public health through ingestion, inhalation, and dermal contact, particularly among vulnerable populations such as children. Comparative assessments indicate that dust composition remains within globally acceptable thresholds, though continuous monitoring and preventive interventions are recommended. Furthermore, increased dust deposition correlates with regional climate trends, exacerbating environmental burdens such as desertification and air quality deterioration. These findings highlight the necessity of integrated air quality management strategies to mitigate long-term health and environmental consequences.



A schematic picture of climate change and air pollution interactions in a desert regions.

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Abstract template for Smr 4067 Activity Title "Advancing Flood Frequency Prediction Under Climate Change Using Machine Learning and Hybrid Optimization with CMIP6 Global Climate Models"

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Introduction

Flood frequency prediction is a critical component of hydrological risk management, particularly in the context of climate change. The increasing intensity and frequency of extreme weather events, driven by global warming, demand innovative approaches to model and predict hydrological changes. Global Climate Models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) provide robust datasets for understanding climate impacts, but their coarse resolution necessitates advanced downscaling techniques for localized analysis [3].

Machine learning (ML) methods, such as Support Vector Machines (SVM) and Artificial Neural Networks (ANN), have emerged as effective tools for downscaling GCM outputs, offering precision in nonlinear relationships between large-scale climate predictors and localized hydrological responses [1,2]. However, these methods are sensitive to parameter tuning and input preprocessing, where hybrid optimization algorithms like Whale Optimization Algorithm (WOA) have demonstrated substantial potential for performance enhancement [5].

Objectives

This proposal aims to develop a hybrid framework that integrates CMIP6 GCM outputs with advanced machine learning and optimization techniques to:

1. Downscale precipitation and temperature data with enhanced accuracy using hybrid ML models.
2. Simulate river discharge under historical, near-future, and far-future climate scenarios.
3. Quantify uncertainties in flood frequency analysis using robust statistical techniques, including ANOVA and fuzzy logic.

Methodology

1. **Data Acquisition and Preprocessing**
    - Climate projections from CMIP6 GCMs, such as IPSL-CM6A-LR, GFDL-ESM4, and UKESM1-0-LL, will be obtained.
    - Observational datasets of precipitation, temperature, and discharge from globally distributed hydrological stations will serve as ground truth.
    - Preprocessing will involve Wavelet Transform (WT) to decompose complex time-series data, reducing noise and enhancing feature extraction [5].
2. **Downscaling Framework**
    - The framework will integrate Least Squares Support Vector Machines (LSSVM) optimized with WOA for parameter tuning. This hybrid model has demonstrated superior performance in capturing nonlinear relationships.
    - Models will be trained and validated using a combination of historical climate data and GCM outputs [4].
3. **Flood Frequency Analysis**
    - Hydrological models will simulate discharge for historical, near-future (2020–2040), and far-future (2070–2100) periods.
    - Log-normal distribution and return period analysis will be applied to identify flood risks under various scenarios.
4. **Uncertainty Quantification**

- Uncertainty will be evaluated through ANOVA to assess the contribution of GCMs, downscaling methods, and hydrological models.
- Fuzzy logic methods will provide additional robustness by quantifying uncertainty distributions.

Expected Outcomes

1. Improved accuracy in flood frequency predictions under CMIP6 scenarios.
2. Insights into the impacts of climate change on hydrological extremes, enabling better planning and adaptation strategies.
3. Quantified uncertainty to guide decision-making in water resource management.

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Enhancing Forest Fire Susceptibility Prediction with Modified AlexNet: A Case Study in Central Kalimantan, Indonesia

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Forest fires have resulted in losses in ecological, social and economic aspects. Indonesia is one of the countries with frequent forest fires. The most significant forest fires in Indonesia occur on peatlands. To prevent forest fires and reduce the level of losses in the event of forest fires, it is necessary to develop prediction map of potential forest fire susceptibilities. In recent years, the Convolutional Neural Network (CNN) method has become a state-of-the-art deep learning algorithm and is widely implemented in various fields including computer vision. Therefore, this study proposes a spatial prediction model for forest fire susceptibility by adding peat depth data combined with topography, human influence, climate and vegetation data. Furthermore, the results of the data fusion are modeled using a modified Alexnet based on CNN. The proposed model is also compared with common machine learning algorithms, namely Random Forest (RF), Gradient Boosting Machine (GBM), and Support Vector Machine (SVM) and Deep Neural Network (DNN). As a case study used data on forest fires in Pulang Pisau, Central Kalimantan from 2014 to 2019 and 11 variabels supporting forest fires derived from the factors causing forest fires. Finally, the performance of the model was tested using several statistical methods, namely accuracy test, Area Under Curve (AUC) and Wilcoxon Signed Rank Test (WSRT). The result is that the Alexnet architecture modification produces the outstanding accuracy performance (0,94) compared to RF (0,90), DNN (0,89), GBC (0,89), SVC (0,89). In addition, the statistical difference test shows that the proposed model is different from the comparison model. These results conclude that CNN is able to outperform the benchmark model, therefore it can be used as an alternative model for predicting forest fire susceptibility index.

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Mapping Climate Change Hotspots in Sindh Using Deep Learning Techniques

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Climate change poses significant challenges worldwide, with Sindh, Pakistan, being particularly vulnerable due to rising temperatures, extreme weather events, and environmental degradation. This project employs advanced deep learning techniques to identify and analyze climate change hotspots in Sindh, providing critical insights into areas most at risk. Using convolutional neural networks (CNNs) and recurrent neural networks (RNNs), the research processes historical climate and environmental data to detect patterns and predict future trends. Additionally, socio-economic and demographic factors such as population density and vulnerability indices are incorporated to assess potential impacts on local communities.

The study's findings highlight the regions in Sindh requiring immediate adaptation and resilience measures, supporting policymakers and stakeholders in prioritizing resources and developing targeted strategies to mitigate climate change effects. This research not only contributes to understanding climate change impacts but also serves as a foundation for informed decision-making and sustainable development in the province.

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Change in precipitation pattern over South Asia in response to the trends in regional warming and free-tropospheric aerosol loading

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The pre-monsoon precipitation patterns over South Asia are undergoing significant changes due to regional warming and increased free-tropospheric aerosol loading [1,2]. This study investigates the spatiotemporal variability of pre-monsoon rainfall using reanalysis datasets (ERA-5, GPCP), remote sensing observations (MODIS aerosol optical depth (AOD), NOAA outgoing longwave radiation (OLR)), and statistical modeling. Traditional climate models struggle to capture the complex interactions between aerosols, atmospheric dynamics, and cloud microphysics, necessitating the integration of AI/ML techniques for improved prediction and trend detection. We apply machine learning algorithms to analyze precipitation anomalies, focusing on how aerosols influence (if any) cloud formation, rainfall variability, and convective processes. A multivariate regression framework incorporating aerosol optical depth (AOD), water vapor, wind, low-level relative humidity, and temperature is used to identify key drivers of precipitation variability.

Our findings reveal that while warming enhances atmospheric moisture-holding capacity, it does not uniformly lead to increased heavy rainfall. Instead, the interplay of water vapor, aerosols, and circulation changes results in a complex precipitation response. High aerosol loads, particularly over the Bay of Bengal (BoB) and northeastern India (NEI), have led to rainfall suppression by altering cloud properties and reducing convective strength. Conversely, northwestern India (NWR) has experienced an increase in rainfall, likely due to reduced aerosol loading and more favorable thermodynamic conditions. The study also finds a shift in precipitation types, with a decline in high-intensity rainfall events replaced by more frequent low-intensity events, particularly over oceanic regions like the Arabian Sea (AS).

The results challenge the traditional “dry gets drier, wet gets wetter” [3] paradigm by showing that precipitation responses depend on multiple interacting factors beyond moisture availability . These findings underscore the need for improved regional climate modeling, integrating both numerical and AI/ML approaches to predict precipitation changes in a warming world better. Future work should focus on incorporating AI techniques for enhanced uncertainty quantification and hybrid modeling approaches that can bridge observational data with numerical simulations.

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Contrasting Features of Active and Break Spells During Flood and Drought Years of the Indian Summer Monsoon

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This study explores how intraseasonal rainfall patterns differ between flood and drought years during the Indian summer monsoon. Using daily rainfall data from the Indian Meteorological Department (IMD) for 1979–2020, we examine active (high rainfall) and break (low rainfall) phases over Central India (21°–26°N and 72°–85°E). Our analysis shows that active spells occur more frequently in flood years (4.6 events per year) than in drought years (2.3 events per year), though both typically last 3–4 days. In contrast, break spells are not only more frequent in drought years (3.9 events per year) but also longer, lasting 6–7 days or even over 10 days, compared to just 3–4 days in flood years (1.2 events per year).

Mean sea level pressure (MSLP) patterns reveal key differences. In flood years, positive pressure anomalies travel northwest from the Bay of Bengal, whereas in drought years, they move northward and become stagnant over Central India, restricting active spells. Similarly, break spells in flood years show westward-moving MSLP anomalies, while in drought years, these anomalies remain stationary or shift northward.

Monsoon intraseasonal oscillations (ISOs) behave differently between flood and drought years. Flood years are dominated by high-frequency ISOs (HF-ISOs) moving westward, while drought years exhibit strong low-frequency ISOs (LF-ISOs) propagating poleward. Over 90% of active and break spells align with HF-ISOs in flood years and LF-ISOs in drought years. Total column water (TCW) analysis further reveals that dry air intrusion from mid-latitudes is more pronounced in drought years, prolonging break periods.

To better understand these variations, we introduce a novel moisture budget decomposition that accounts for seasonally persistent components of daily anomalies. This approach highlights that the advection of mean moisture gradients by mean winds plays a crucial role, enhancing rainfall in flood years but suppressing it in drought years. Additionally, K-means clustering of LF-ISO and HF-ISO variance identifies four distinct clusters representing different patterns of intraseasonal variation. The cluster with the strongest LF-ISO and weakest HF-ISO variance experiences the lowest seasonal rainfall (92% of the long-term mean), while the cluster with the most intense HF-ISO activity sees the highest rainfall (112% of the long-term mean). These seasonally persistent patterns influence monsoon low-pressure systems, wind fields, and dry air intrusions, ultimately shaping seasonal rainfall.

Finally, we assess the potential of machine learning models to classify pentads as active, neutral, or break phases, evaluating their prediction skills. This study highlights the contrasting behavior of active and break spells in flood and drought years, emphasizing the role of ISOs, atmospheric circulation, and thermodynamic processes in shaping monsoon variability.

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Enhancing the prediction skill of monsoon intraseasonal oscillations: a deep learning approach

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The Monsoon Intraseasonal Oscillation (MISO), characterized by a 30-60-day northward-propagating mode of rainfall anomalies over India, plays a crucial role in modulating active and break spells during the Indian summer monsoon. These quasi-periodic oscillations are essential for understanding monsoon variability, which directly impacts agriculture, water resources, and disaster management in the region. Accurate forecasting of MISO is vital for enhancing sub-seasonal to seasonal (S2S) predictions, mitigating the effects of variability, and providing actionable information for farmers, policymakers, and planners. In this study, we utilized high-resolution (0.25° x 0.25°) daily precipitation data from the TRMM/GPM satellite to derive MISO indices (MISO1 and MISO2) through extended empirical orthogonal function (EEOF) analysis of 25 years of rainfall anomalies over the Indian region (June–September). The resulting time series of these indices were then used to develop a forecasting model with deep learning techniques. Specifically, we adopted a Transformer-based architecture, which effectively captures long-range dependencies in time-series data. The model was trained to predict MISO indices for the period 2018–2022, with forecast lead times extending up to 18 days. Results indicated that the Transformer model significantly outperformed traditional numerical weather prediction (NWP) methods, demonstrating superior predictive skill and reliability in forecasting MISO. These findings highlight the potential of advanced deep learning models to enhance S2S predictions of complex atmospheric phenomena like MISO, paving the way for more accurate and timely forecasts of monsoon activity.

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Forced Response in the Mean State and Interannual Variability of the Indian Summer Monsoon in Future Projections

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The Indian summer monsoon (ISM) is a complex system that plays a crucial role in the climate of South Asia. Here, we used Community Earth System Model 2-Large Ensemble (CESM2-LE) simulations to explore the forced response in the mean state and interannual variability of the ISM in future projections. This single-model initial-condition large ensemble is useful for studying the effect of natural variability and forced response in a coupled ocean-atmosphere climate system. The model could fairly reproduce the mean state and interannual variability of the ISM during historical periods (1980-2009). The strengthening of monsoon circulation during excess rainfall years and a weakening during deficient years are also well simulated by the model. It is also noticed that though low-level jet stream shows a weakening during deficit monsoon years, it has more eastward extension, up to the western Pacific Ocean, compared to excess monsoon years. In simulations for future years, the mean structure of both the low-level jet stream and the tropical easterly jet stream becomes weaker compared to historical years. However, the precipitation pattern shows an enhancement in the near future (2030-2059) and far future (2070-2099) periods.

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Investigating Large Scale Hydrologic Changes and their Causes relevant for key sectors using Earth System Data Cubes

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The Anthropocene has significantly altered Earth's hydrological systems, affecting water availability for human societies, agriculture, economies, and ecosystems both globally and locally [1, 2]. This research proposal aims to assess large-scale hydrological changes and attribute them to shifts in climatic patterns or direct anthropogenic modifications of land and water use. This investigation leverages innovations in hydrological science and technology, employing expansive and harmonized datasets to identify patterns of hydrological change and their driving factors [3].

Our steps in our research are: selecting relevant hydrological and explanatory variables; identifying global data sources; validating the data; aggregating data to an annual scale; constructing an Earth system data cube; identifying co-occurring temporal patterns across hydrological variables; and attributing causes to these changes. The selection of critical variables will be guided by existing literature [4] and sector-specific studies.

A crucial part of the project involves the identification and utilization of explanatory variables to understand the causes of hydrological changes. This project will look at changes induced primarily by climate, land use, and water use in a hierarchical manner. While there are hierarchies of hydrological models [5], hierarchical climate modeling approaches need to be developed [6,7]. This approach requires radiative convective equilibrium, intermediate complexity [8], and Earth system models, allowing us to attribute changes to different climatic processes.

These datasets will be harmonized to create an analysis-ready Earth system data cube [9]. This cube will facilitate the detection of trends, anomalies, and nonlinear changes within the hydrological system. Advanced statistical techniques [10] and archetype analysis [11] will be utilized to elucidate spatial and temporal co-occurrences of hydrological changes.

Ultimately, this research aims to holistically address the question of whether the hydrological cycle is regionally accelerating or decelerating due to climate and environmental changes, identifying possible tipping points [12]. The study's findings promise to strengthen knowledge of hydrological dynamics under changing climatic conditions, offering valuable insights into managing global water resources effectively and sustainably. The methodological advancements proposed here could set a new standard for comprehensive hydrological analyses and their applications across various domains.

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High-resolution CMIP6 downscaled dataset of temperature and precipitation over Tunisia

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Climate change and related issues become of a high importance due to their associated ecological, economic and social effects. Regarding the amplified challenges such as the increased frequency of extreme meteorological events, water scarcity and loss of biodiversity, initiatives for collaborative work to develop tailored climate services to help different socio-economic sectors become more resilient and minimize climate-driven risks become of paramount importance. High quality climate data is therefore required to provide reliable climate services.

In this context, production of high-resolution climate projections become mandatory for many applications and impact assessments studies. In response to this need in Tunisia, this study constructs a new precipitation and temperature daily dataset for Tunisia, at a high spatial resolution of $0.1° \times 0.1°$, based on the outputs global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) and the European Centre for Medium-Range Weather Forecasts Reanalysis 5 (ERA5) dataset. Daily temperature and precipitation data from 18 GCM models for the historical (1981-2014) and future simulations (2015-2100) for two shared socio-economic pathways SSP (SSP2-4.5 and SSP5- 8.5) is used. The Bias Correction and Spatial Disaggregation (BCSD) method is adopted to bias-correct monthly GCM simulations using observation data, then temporally disaggregate them into daily data. The bias-corrected data have an ERA5-based mean climate and interannual variance, but with a non-linear trend from the ensemble mean of the 18 CMIP6 GCM models. Our evaluation suggests that the bias-corrected data demonstrates good performance and are of better quality than the individual CMIP6 GCMs in terms of the climatological mean, interannual variance and extreme events.

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Linking of tropical waves and sub-daily rainfall events over Central Africa.

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Tropical waves (TWs) have the potential to serve as sources of predictability for sub-seasonal to seasonal forecasting in Central Africa (CA). This study systematically compares the influence of seven different TWs on rainfall events across CA. The historical scarcity of data in numerous regions of Africa, especially in Central Africa, has significantly limited a clearer picture of the regional variability of rainfall. Here, for the first time, we use high spatial resolution and sub-daily timescale rainfall events records to objectively evaluate how tropical waves influence rainfall events. The wet event (WE) are defined as consecutive half-hourly rainfall >=0.1 mm /30 min utilizing IMERG data (2001 - 2022) regardless of the season. The WEs are dynamically clustered into six canonical storm types (STs), mostly discretized by their duration, but also their mean and maximal intensity. The relationship between tropical waves (TWs) and STs was assessed firstly at a local scale using conditional probabilities on reference longitude. At 10°E, high-frequency waves such as westward inertion-gravity (IG1), Tropical Disturbances (TD), and Kelvin waves are most frequent and associated with STs. Moving eastward to 20°E, Kelvin, TD, and IG1 waves remain the most common and are associated with STs. Further east, at 30°E, the dominant waves shift to Kelvin, Madden-Julian Oscillation (MJO), and Equatorial Rossby (ER) waves, which are most common and associated with STs. The modulation of Tws waves reveals that wet phases amplified the activity of high-frequency waves (such as Kelvin, TD, IG1, and mixed Rossby gravity waves) and suppressed them during dry phases in sub-daily rainfall as they passed through the study area. In contrast, low-frequency waves, including the MJO and ER, had the weakest effect. These influences were particularly strong on intense and long-lasting storm types (ST #3-6).

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Evaluation of the Pangu-Weather Model for Indian Summer Monsoon Prediction: A Case Study for 2023 and 2024

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The recent advancements in AI-based weather forecasting models, such as the Pangu-Weather model, have opened new possibilities for improving short-to-medium-range predictions. This study evaluates the performance of the Pangu-Weather model in predicting key atmospheric variables air temperature, mean sea level pressure (MSLP), and wind fields—during the Indian Summer Monsoon (ISM) seasons of 2023 and 2024. The model outputs are compared against reanalysis datasets and observational records to assess its predictive skill in capturing monsoon circulation patterns, regional temperature variations, and pressure anomalies.

Preliminary results indicate that the Pangu-Weather model demonstrates high accuracy in short-term predictions 120 hours but exhibits biases in extended forecasts. The evaluation also highlights regional disparities in temperature predictions and variations in model skill across different lead times, time of initialization, and years. By quantifying these biases and assessing the model's overall reliability, this study provides insights into the potential of AI-driven forecasting for monsoon prediction and its applicability for operational forecasting. The findings contribute to the ongoing efforts to refine AI-based climate models and enhance monsoon predictability using hybrid approaches.

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Interannual Variability in Indian Summer Monsoon wind circulation in the changing climatic change

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The objective of this proposed study is to investigate the monsoon circulations during the Indian summer monsoon period and to examine the impact of climate change on these monsoonal circulation patterns. The most important circulation patterns like the Low Level Jet (LLJ) in the lower troposphere and Tropical Easterly Jet (TEJ) in the upper troposphere are investigated using observations and model data. The corss-sectional view of these synoptic scale features at a given location within the monsoon zone is investigated during ISM months (June, July, August and September) using seventeen years (2006-2023) of high resolution GPS radiosonde observations over a sub-tropical observation site Gadanki, India. The detailed characteristics of horizontal wind fields like TEJ peak strength, height and width over a given grid/location will be estimated daily during monsoon months and then averaged for peak monsoon months July and August to represent the seasonal mean. The seasonal mean time series of TEJ characteristics are subjected to multi-variate regression analysis to extract the dominance of natural variability's like QBO, ENSO and solar cycle. The residual time series is then subjected to linear regression to estimate the long term trend in TEJ strength and spatial extent. In addition, the forward moving regression will be performed to find the point of origin that make the change in trend. The relation between TEJ characteristics and monsoon rainfall and tropical cyclones will be delineated. Finally, the future projections in TEJ characteristics are examined with the help of CMIP model outputs. Further, the machine learning methods like XGboost method is used to predict TEJ peak speed and spatial distribution and the prediction are tested with suitable metric. The present study focuses on these monsoon circulations in the changing climate by utilizing long term observations, reanalysis and CMIP climate projects.

Keywords: Monsoon Circulation, Low Level Jet, Tropical Easterly Jet, Machine Learning

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P40

A Deep Learning Model for rainfall and drought prediction

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Africa is highly affected by severe floods and persistent droughts which affect people and the economy at large. The primary climate issues facing Africa include widespread drought, extreme heatwaves, desertification, flooding in certain regions, changing rainfall patterns, rising sea levels along coastlines, and overall increased vulnerability to the impacts of climate change, particularly impacting food security and livelihoods due to the continent's reliance on agriculture. Most people in Africa rely on farming as their primary source of income and without advance information about weather and climate during different seasons of the year it has become very difficult to know what crop the farmers should grow. To minimize on the loses by the farmers, there is need to come up with smart systems for predicting rainfall intensity and drought times. This work developed a Deep learning model for weather prediction to support farmers in knowing rainfall intensity and expected water levels as well as guidance on the best suit crop to plant for each season.

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Abstract template for Performance-based evaluation of NMME and C3S models in forecasting the June-August Central African rainfall under the influence of the South Atlantic Ocean Dipole

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In this study, hindcasts from eight Copernicus Climate Change Service (C3S) and three North American Multi-Model Ensemble (NMME) operational seasonal forecast systems, based on dynamical climate models, are employed to investigate the influence of the South Atlantic Ocean Dipole (SAOD) on the predictive skill of Central Africa (CA) rainfall. The focus is primarily on the June-July-August season for 1993-2016. The findings reveal that, when regionally averaged, all models exhibit positive skill in predicting CA rainfall, except for the Geophysical Fluid Dynamics Laboratory (GFDL-SPEAR) model. Notably, there are significant spatial variations in skill across different regions. Model performance is particularly low (high) in the Central African Republic and Congo Basin (Gabon and Chad) and tends to deteriorate with increasing lead-time. Models that demonstrate a strong connection between SAOD and CA rainfall tend to exhibit better predictive skills in forecasting rainfall, in contrast to models with weaker connections. This leads to a significant in-phase relationship between the predictive skills of rainfall and the strength of the SAOD-rainfall connection among the models. Furthermore, the atmospheric circulation responding to SST forcing associated with the El Niño-Southern Oscillation exerts a significant influence on the robust atmospheric circulation associated with the climatological mean of SST over the SAO. This suggests that mean state bias in the SAO/equatorial Pacific region plays a role in modulating the strength of the simulated SAOD-CA rainfall connection and, consequently, the prediction skill of CA rainfall. In general, both NMME and C3S models appear to be valuable tools capable of providing essential seasonal information several months in advance. These insights can aid decision-makers in the region in making informed decisions regarding adaptation and mitigation measures.

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Validation of Pollution Proxy Indicators Using Personal Exposure Air Quality Data from 3 Sub-Saharan African Countries

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Abstract

Poor air quality is a major global health risk, yet characterizing air pollution exposure remains challenging in resource-limited settings due to sparse monitoring networks. Proxy air quality indicators offer a viable alternative however, these require validation for use in different settings. This study evaluated the Weighted Road Network Density (WRND), the Euclidean distance from the highways (EH), and the Euclidean distance from the main roads (EM) as proxies for particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) exposure using personal expoure data .The personal exposure data used was collected by 500 women carrying low-cost personal exposure bags in the PRECISE project in Gambia, Kenya and Mozambique. Correlation tests, cluster analysis, spatial autocorrelation, and regression modelling were applied to validate the indicators. The analysis showed that WRND had a moderate positive correlation with $PM_{2.5}$ in Mozambique ($r = 0.30$), but weak relationships in Kenya ($r = 0.02$) and Gambia (Spearman correlation, $r = 0.10$). NO_2 was negatively correlated with road proximity, with EH showing negative correlations in Kenya ($r = -0.010$) and Mozambique ($r = -0.20$).Cluster analysis inidcated No_2 hotspots in areas with high WRND, particularly in Kenya and Gambia. On the contrary, $PM_{2.5}$ showed greater spatial variability, The regression results showed that WRND was the strongest predictor of $PM_{2.5}$, with Support Vector Machines (SVM) achieving the best performance in Gambia ($R^2 = 0.586$, RMSE = 38.024 µg/m³), while a multivariate SVM model in Mozambique provided the highest predictive precision ($R^2 = 0.336$, RMSE = 52.82 µg/m³) for modelling NO_2 using combined variables. Best overall performance modelling PM2.5 using the combined proxies was found in Mozambique using the GAM model (R^2=0.556 ,RMSE= 30.699 µg/m³).Regression results confirmed that machine learning models, especially SVM and Generalized additive models (GAM), outperformed traditional regression methods, emphasizing the importance of nonlinear approaches for exposure assessment. These findings support the use of proxy indicators in modelling pollution exposure but highlight the need for additional environmental variables to improve the predictions of $PM_{2.5}$ and NO_2. Future research should integrate meteorological and satellite-derived data to improve air quality assessments and guide policy interventions in sub-Saharan Africa.

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Climatology of ITCZ Breakdown Events and their Impact on East Pacific Tropical Cyclogenesis

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The Intertropical Convergence Zone (ITCZ) is a key component of the general circulation of the atmosphere, where the trade winds from both hemispheres converge near the equator, leading to significant convective activity near the ascending branch of the Hadley cell [1]. While often considered a relatively stable process on seasonal timescales, one important feature of the ITCZ on a weekly timescale is its breakdown, a process characterized by the disintegration of a stable band of convection (and relative vorticity anomalies) into individual disturbances. ITCZ breakdowns are triggered by two main pathways: the interaction of the ITCZ with easterly waves (EWs) and barotropic instability that causes the band to oscillate and ultimately split into individual vortices[2,3,4]. Previous research has shown the significance of breakdowns for Tropical Cyclone (TC) genesis[5]. However, research has not yet quantified the relative importance of the generation of seeds — weakly-rotating convective clusters (precursors of TCs) — from ITCZ breakdown as compared to other seed pathways, such as easterly waves arising from baroclinic instability.

In this work, we construct a dataset of ITCZ breakdown events for the Eastern North Pacific (ENP) using reanalysis and OLR satellite data from 2000 to 2010. We are developing a 3D Convolutional Neural Network trained in high-resolution data (e.g., precipitation from MSWEP) to detect breakdowns for the entire climatology (1980-2024). Preliminary results show that seeds developing from ITCZ breakdowns have a stronger low-level circulation and a deeper bottom-heavy vortex structure than seeds coming from EWs. However, ITCZ breakdown seeds are more susceptible to entrainment due to a drier middle troposphere than EW seeds. Additionally, we are performing climate simulations (using the MPAS-Atmosphere model), altering the topography (removing the Andes mountain) to modify the ITCZ morphology in the basin, producing a straighter ITCZ that is less prominent to break[2], and quantifying the impacts on seasonal mean TC statistics.

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Multi-Forcing Impacts on Temperature Extremes over Africa: Anthropogenic, Aerosols, Natural, and Solar Influences Under Higher Emission Pathways

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Abstract

Extreme temperatures pose significant threats to various sectors across Africa, potentially disrupting livelihoods, ecosystems, and socioeconomic development. This study presents projected changes in mean and extreme temperatures over Africa from 1960 to 2100 under different Shared Socioeconomic Pathway (SSP) scenarios, employing the Relative Contribution Percentage (RCP) metric and analyzing fast and slow climate system responses. Our analysis reveals a shift towards more frequent and intense warm days and nights across the continent as emission scenarios intensify. The severity of this increase is directly linked to the respective emission pathway. Under SSP585, the highest emission scenario, warm night frequency (TN90p) could increase by up to 80% continent-wide by 2100, while the low emission scenario (SSP126) projects a more modest increase of 27%. Regional variations in vulnerability to temperature extremes are significant. West and North Africa show the highest projected increases in TX90p and TN90p across most emission scenarios. In contrast, East and Southern Africa exhibit relatively lower increases, particularly for TX90p. Our attribution analysis indicates that greenhouse gas (GHG) forcing is the dominant driver of observed and projected temperature extremes, with relative contributions of 120% and 117% to TX90p and TN90p trends, respectively. Aerosol forcing partially offsets this warming effect, with relative contributions of -73% and -70% to TX90p and TN90p trends. The study introduces a novel vulnerability trajectory analysis, revealing that even under the lowest emission scenario (SSP126), all African regions face increasing climate vulnerability over time. By 2060, most regions under SSP370 and SSP585 scenarios reach a normalized vulnerability of 0.6, indicating significant risk to various sectors and population groups. Our findings underscore the pressing need for substantial emissions reductions and locally adapted strategies to address the severe impacts of climate change on African communities and their agriculture. Even if global warming is limited to 1.5°C per the Paris Agreement, vulnerable African populations and agricultural sectors still face prolonged periods beyond safe temperature thresholds. This research contributes to a more nuanced understanding of climate change impacts in Africa by providing detailed regional projections and attribution analyses. It highlights the urgent need for both ambitious global mitigation efforts and region-specific adaptation strategies. While achieving the 1.5°C target remains vital, tailored adaptation measures involving local communities and agricultural sectors are crucial to shield Africans from unavoidable climate risks driven by past and future emissions.

Keywords: Socioeconomic, Attribution, Greenhouse gas, Vulnerability, Emissions

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Enhancing Heavy Rainfall Forecasting in High-Resolution Regional Models Over West Africa for Operational Application.

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Abstract

Flash floods in West Africa, caused by heavy rainfall and exacerbated by a global rise in temperature, are posing increasingly severe socioeconomic consequences. This study uses binary analysis, unsupervised machine learning, and recent evaluation metrics to improve West African heavy rainfall forecasts. The aim is to provide an operational forecasting tool to improve the deterministic COSMO model's rainfall forecasts. It conducts a comprehensive analysis of eight High Impact Weather (HIW) events that occurred during the peak of the West African boreal summer monsoon from 2015 to 2022. The study focuses on four crucial synoptic variables: the mean sea level pressure (MSLP), the African Easterly Jet (AEJ), the African Easterly Waves (AEWs), and the convective available potential energy (CAPE), all of which are integral to operational forecasting in West Africa. Using the COSMO model these variables are simulated and merged with European Centre for Medium-Range Weather Forecasting (ECMWF) ERA-5 reanalysis data for the period August 2001 to 2022.

The refined binary rainfall forecast patterns derived from each synoptic clustering processes are aggregated to produce a probability-based rainfall forecast. Two primary statistical metrics are used to evaluate the quality and dependability of clustering-based rainfall forecasts and compare them to COSMO model predictions and satellite-derived Integrated Multi-satellite Retrievals for the Global Precipitation Measurement mission (GPM_IMERG) rainfall observations.

The results indicate that, regardless of the specific weather event, each synoptic clustering procedure generates unique rainfall forecast attributes. In addition, the generated probability forecasts capture the observed spatial distribution of heavy rainfall over West Africa, particularly west of the prime meridian. The correlation between individual and combined forecasts of synoptic clusters and actual rainfall exhibits distinct patterns across West Africa, with stronger correlations observed west of the prime meridian. Although the correlation with the COSMO model is generally high, the combined clustered forecast demonstrates a stronger correlation when compared to the individual synoptic clusters, as the CAPE-clustered rainfall displays the weakest correlation.

The incorporation of the fractions skill score (FSS) with varying neighbourhood sizes highlights the distinctive contributions of each synoptic cluster and the ensemble method. While rainfall from the MSLP clustering exhibits the strongest FSS over West Africa, the CAPE clustering exhibits the strongest FSS over the East of the prime Meridian, and the COSMO model demonstrates the strongest FSS across the West. To the West of the prime meridian, the FSS from the ensemble of all synoptic clusters is stronger than the individual synoptic cluster at a neighbourhood size of 10km.

In addition, the study identifies that each synoptic cluster and the ensemble have distinct minimum spatial scales at which the rainfall forecast is deemed accurate (FSS > 0.5). Nevertheless, the results indicate that rainfall from the AEJ-AEW cluster east of the prime meridian has the smallest spatial scale for acceptable skill.

This study concludes with valuable insights regarding the improvement of severe rainfall forecasting in West Africa. This study alights on the unique characteristics of synoptic clustering in enhancing rainfall forecasts by employing unsupervised machine learning techniques and evaluating forecast quality with a variety of metrics.

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Regional-scale spatio-temporal variability of precipitation and its relationship to atmospheric patterns over central Europe

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This study explores the spatio-temporal variability of precipitation and its underlying large-scale atmospheric processes using EURO-CORDEX regional climate model (RCM) simulations, ERA5 reanalysis datasets, and E-OBS daily gridded observational precipitation data during 1980-2010. The analysis is conducted only for the summer and winter seasons. The focus of the analysis is primarily on anomalous precipitation patterns, which are identified from days with at least three consecutive days of precipitation (denoted as active spells). It is found that both the RCMs and ERA5 accurately represent the observed anomalous precipitation patterns. Inter-model variability in precipitation intensity during active spells and the number of spells among the RCMs is noted. The occurrence of active spells of precipitation during the summer season is associated with a trough-ridge dipole pattern (i.e., a trough centered over the Alpine region and a ridge located around the North Atlantic). During the winter season, active spells appear to be linked to the positive phase of the North Atlantic Oscillation (NAO), with the trough located around the Nordic region. These patterns promote the transport of moisture-laden warm air originating from the Atlantic Ocean toward central Europe, leading to precipitation due to convergence. The analysis suggests that the synoptic-scale pattern drives and maintains moisture transport during the active spells of precipitation.

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Parametric sensitivity of E3SM in the presence of aleatoric, observational, and structural uncertainty

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The atmospheric component of the Energy Exascale Earth System Model (E3SM) contains numerous new characteristics in the physics parameterizations. It becomes quite difficult to comprehend the behaviors of the models and to tune the parameters due to the complicated nonlinear interactions among the additional elements. To better understand the model behaviors and physics, we plan to conduct 263 short simulations (3 years) in which 45 parameters carefully selected from parameterizations associated with cloud processes, convection-precipitation, and aerosols were perturbed simultaneously using the Latin hypercube sampling method. As Climate models are too expensive to undergo iterative optimization procedures, a machine learning emulator is used that can map model parameters to the subset of model output. In this study we use our 263 ensemble members to train and test the Gaussian Processes, Random forests, Convolutional Neural Net (CNN) emulator. This computationally efficient emulator is then used to obtain an estimate of the optimal value of the parameters that best matches observations when comparing a subset of model output.

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Daily Rainfall Prediction at JakartaMeteorological Station Using Artificial Neural Network

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Weather forecasting is essential to support various societal activities. Accurate weather forecasts require the knowledge and experience of weather forecasters, supported by weather modeling technology. In this study, a rainfall modeling approach using Artificial Neural Networks (ANN) was conducted at the Jakarta Meteorological Station. The process of creating the ANN model requires training data based on past weather conditions. The data used for training the ANN model consisted of daily weather data from January 2011 to December 2019, which was then tested using case studies from January to August 2020. Variations in the model were created based on the type of input and the number of hidden layers to understand the impact of different predictor data used. The ANN model was constructed using a three-layer approach consisting of an input layer, a hidden layer, and an output layer. The comparison of these models was evaluated using the correlation coefficient (R) and the mean absolute error (MAE) to determine the best model. The results of the study showed that rainfall prediction using input parameters of daily weather conditions, including air temperature, air humidity, and sunshine duration, achieved a correlation coefficient (R) of 0.4–0.5 and a mean absolute error (MAE) of 9.7–9.8 mm. On the other hand, when the model was built using rainfall data from previous days as input parameters, the correlation coefficient (R) was only 0.1–0.3, with a mean absolute error (MAE) of 11.3–12.3 mm. These findings indicate that the better predictors for daily rainfall prediction using Artificial Neural Networks are surface weather condition parameters.

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Abstract for Missing Values in Climate Dataset of Pakistan

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This research tackles the serious problem of missing data in climate data sets, a common problem in climate studies, especially in countries such as Pakistan where gaps in data make it difficult to model and predict climate accurately [1]. Missing data in climate records, usually due to sensor failure, transmission errors, or missing observations, can result in biased results and unreliable predictions [2]. To address this, we suggest a comparison of state-of the-art imputation methods such as Multiple Imputation by Chained Equations (MICE) and K-Nearest Neighbors (KNN), with deep learning-based methods such as Generative Adversarial Networks (GANs)and Recurrent Neural Networks (RNNs) [3]. These methods are compared using the Pakistan Weather Dataset on Kaggle, which comprises historical climate data such as temperature, precipitation, humidity, and wind speed.

The research uses a holistic assessment framework, using measures like Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and data reconstruction accuracy to evaluate the performance of every method [4]. The initial findings are that deep learning-based methods, especially GANs, are superior to conventional methods like MICE and KNN in learning intricate temporal and spatial patterns from climate data [5]. However, MICE is still a strong option for datasets with lower missing rates, whereas KNN performs better on smaller datasets with less complex structures [6]. Hybrid methods integrating deep learning with conventional methods also demonstrate potential in enhancing imputation precision for largescale climate data sets [7].

This study adds to the existing knowledge of missing data imputation within climate science and provides useful suggestions for researchers as well as policymakers in Pakistan [1]. This study identifies the most efficient imputation methods that will improve the precision of climate models, leading to more well-informed decision-making for adaptation and mitigation interventions in the region [2].

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P50

Machine Learning-Based Assessment of Solar Radiation Potential in Southern Algeria

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Abstract

Accurate estimation of solar radiation is a critical parameter for designing and evaluating solar energy systems. In recent years, various machine learning techniques have been developed to enhance forecasting accuracy using diverse input attributes. This study focuses on predicting horizontal global solar radiation for the next day based on a combination of meteorological and geographical inputs. Gaussian Process Regression (GPR) and Least-Square Support Vector Machine (LS-SVM) models with different kernel functions were employed and compared to identify the most suitable forecasting approach. The research was conducted in the southern Algerian region of Ghardaia, utilizing five years (2013–2017) of historical meteorological data from the Renewable Energies Research Unit (URAER) in Ghardaia. The results indicate that all proposed models yield comparable performance in terms of statistical evaluation metrics. Moreover, while all models demonstrated acceptable computational efficiency, the GPR model stood out for its lower computational cost compared to the other machine learning techniques.

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Use of AI/ML in Improvement of Cloud Fraction Parametrization in Rapid Radiative Transfer Model (RRTM)

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The Indian Summer Monsoon Rainfall significantly influences the agricultural productivity, water resources, and overall socio-economic stability of South Asia. The Monsoon Mission Coupled Model (MMCFS-v2) employs the RRTM for its radiative transfer calculations. The Rapid Radiative Transfer Model (RRTM), originally developed by AER, Inc. (Mlawer et al., 1997), calculates radiative parameters using Cloud fractions from grids. This simplification inherently limits the accuracy of radiative flux calculations. To address the limitations of traditional RRTM methods, we developed a machine learning (ML) model designed to predict cloud fractions as continuous values within each grid box. We have trained our model for 37 synoptic vertical layers to accommodate atmospheric pressures, utilizing ERA5 reanalysis data and incorporating key predictor variables such as temperature, wind speed, relative humidity, and cloud water content. To enhance generalization and mitigate biases associated with the inherent ordering of the data, we implemented a shuffling process during the training phase. This ensures that the model is exposed to a diverse and representative sample of conditions, thus facilitating balanced learning and improving its performance across various weather scenarios. Upon testing the trained model with unseen data, we observed a bias close to 0.1, indicating strong predictive performance in estimating cloud fractions. This ML approach significantly advances the capabilities of traditional RRTM methods by overcoming the limitations associated with cloud fractions. As a result, it enhances the accuracy of radiative calculations, particularly in complex atmospheric systems, such as monsoons.

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AI-Powered Hybrid Climate Modeling: Enhancing Accuracy and Computational Efficiency in Regional Climate Projections

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Accurate regional climate projections are essential for effective climate adaptation and disaster risk management in Pakistan, a country highly vulnerable to extreme weather events such as heatwaves, monsoons, and droughts. This study aims to develop a hybrid AI-driven climate modeling framework that integrates machine learning techniques with General Circulation Models (GCMs) to enhance climate projections at a regional scale.

The methodology consists of four key steps: (1) Data Collection & Preprocessing, where historical climate data from Pakistan Meteorological Department (PMD), reanalysis datasets (ERA5, CMIP6), and remote sensing sources (MODIS, TRMM) are standardized and prepared for model training; (2) AI Model Development, where Convolutional Neural Networks (CNNs) for spatial pattern recognition and Recurrent Neural Networks (RNNs)/Long Short-Term Memory (LSTM) models for temporal dependencies in climate variability, along with bias correction techniques to refine GCM outputs; (3) Downscaling & Model Optimization, where AI-driven statistical downscaling techniques enhance the resolution of coarse climate projections, transfer learning adapts models to Pakistan-specific climate data, and ensemble modeling improves prediction robustness; and (4) Case Study & Validation, where AI-driven projections are tested on extreme weather events and validated using historical climate records, satellite observations, and performance metrics (RMSE, MAE, correlation coefficients).

The expected outcomes of this research include the development of an AI-powered hybrid climate model that significantly improves regional-scale climate projections for Pakistan, enhances the accuracy of extreme weather event predictions, and reduces computational costs compared to traditional climate models. The findings will contribute to data-driven climate adaptation policies and disaster management strategies in Pakistan, providing a more reliable foundation for policymakers and climate scientists to address the growing challenges of climate change.

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Simulating extreme temperature events: a case study of the abnormally hot January 2023 conditions over southern Africa

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Between 9 and 23 January 2023, southern Africa experienced a prolonged period of abnormally high temperatures linked to an unusually strong Botswana High. ERA5 reanalysis data reveals that daily temperature anomalies across the subcontinent reached up to 5°C above average, with the most extreme conditions observed over central-western regions. In Kakamas, Northern Cape, at least five farmworkers tragically lost their lives to heat stress during this period. Recognising the dangers posed by extreme heat events and the need to improve understanding and forecasting of such occurrences, this study evaluates the Weather Research and Forecasting (WRF) model's ability to simulate the temperatures and atmospheric circulation patterns associated with this event. The WRF model simulation was initialised using 6-hourly Climate Forecast System version 2 (CFSv2) reanalysis data for the period 3–31 January 2023. Model outputs at 8 km resolution were evaluated against ERA5 reanalysis data and Agricultural Research Council (ARC) temperature records. Results indicate that the WRF model successfully captured 2 m temperature magnitudes comparable to observations and reproduced the atmospheric circulation patterns driving the extreme heat event. This study provides insights into the mechanisms underpinning abnormally hot conditions and demonstrates the utility of the WRF model in simulating such events. These findings can contribute to enhancing forecasting capabilities for heatwave events over southern Africa, supporting early warning systems and risk management strategies. Importantly, this work underscores the value of developing weather and climate services such as a heat stress early warning system tailored to protect farmworkers.

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Spatio-Temporal Modeling using Machine Learning Approach for Forecasting of Rainfall at West Java

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In this study we proposes the development of spatio-temporal model using machine learning approach. We integrated the Generalized Space Time Autoregressive Integrated Moving Average (GSTARIMA) and Deep Neural Network (DNN), we called the GSTARIMA-DNN model. We used the residual of GSTARIMA model to be input in the DNN and applied the model to forecast a rainfall observation in West Java region. We used big data for climate phenomena from NASA POWER based on Data Analytics Lifecycle method. The result show that the GSTARIMA(0,1,1)-DNN model gave a Mean Absolute Percentage Error (MAPE) is smaller then the GSTARIMA(0,1,1) model. The hybrid model GSTARIMA-DNN have a valuable insights for advancing the spatio-temporal model to support the 13th pillar of Sustainable Development Goals (SDGs).

Key words: Big Data, GSTARIMA-DNN, Data Analytics Lifecycle, Rainfall, SDGs

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Tropical Cyclone Forecasting with Global Machine Learning Weather Prediction Models: Strengths and Weaknesses

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Machine Learning Weather Prediction (MLWP) systems are emerging as powerful alternatives to traditional Numerical Weather Prediction (NWP) models, offering comparable forecast accuracy at a fraction of the computational cost. However, they need rigorous validation before they can replace NWP systems in operational settings. This study systematically evaluates four leading MLWP models—GraphCast, PanguWeather, Aurora, and FourCastNet—by comparing their tropical cyclone (TC) forecasts against observational data and state-of-the-art NWP models across global ocean basins. The results show that MLWP models perform well in predicting TC tracks, with average errors of less than 200 km at 96-hour lead times. However, they tend to underestimate TC intensity, consistently predicting lower maximum sustained wind speeds than NWP models and real-world observations. A deeper analysis suggests this intensity bias stems from limitations in the training datasets used to develop MLWP models, emphasizing the crucial role of data quality. On the dynamical side, these models effectively capture TC movement, accurately simulating absolute vorticity patterns and advection processes. They also replicate the characteristic vertical warm core structure of TCs, though with weaker thermal anomalies. Among the four models, Aurora stands out, delivering the most accurate and well-rounded forecasts compared to GraphCast, PanguWeather, and FourCastNet.

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OHC interannual variability over SIO during the monsoon season and its mechanism

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Ocean Heat Content (OHC) plays a crucial role in influencing weather patterns and climate. However, its interannual variability in the Tropical Indian Ocean over a long time periods remains underexplored. This study examines OHC variability using century-long reanalysis data from the SODA dataset (1871–2010). To ensure data reliability, we compared SODA with other reanalysis and analysis products (EN4, ISHI, GECCO-3, and ORSS5) over their common period, finding correlations of 0.77, 0.78, 0.72, and 0.65, respectively. Seasonal analysis reveals that the standard deviation of OHC is highest during summer (7×10^{22} J/m²). Based on this, years with OHC anomalies greater than one standard deviation are classified as strong years, while those below one standard deviation are weak years. We identified 25 strong and 21 weak years. Composite analysis of OHC anomalies shows anomalies ranging from (3.5 to 4.5) $\times 10^{19}$ J/m², with 95% significance over 10˚S to 20˚S and 50˚E to 80˚E. The vertical temperature anomaly profile remains positive throughout the 700 m column in strong years and negative in weak years. Additionally**,** D20 (~20m), SSHA (~0.9m), and chlorophyll anomalies exhibit coherent variability with strong and weak OHC years. To understand the mechanisms behind OHC variability, we analysed net heat flux anomalies but found no significant role. Instead, wind stress anomalies revealed an anticyclonic circulation during strong years and a reverse pattern during weak years over 10˚S to 20˚S and 80˚E to 110˚E. Furthermore, the correlation between the time series of wind stress curl anomalies and OHC anomalies in the region is 0.40**,** with a 99% confidence level. Examining the influence of global SST anomalies, we found a 0.7 correlation with SST in the Indian Ocean, significant at 95%, on wind stress curl over the study region, suggesting a local wind forcing role in OHC variability. Additionally, we observed a positive correlation with the southwest Indian Ocean and a negative correlation with the southeast Indian Ocean, both significant at 95%, indicating the role of the Indian Ocean Dipole (IOD)**.** To further assess the role of the IOD, we calculated correlations between wind stress curl and three regions: the IOD box, the SIOD box, and our identified region of maximum correlation**.** We found a 0.42 significant correlation with the IOD box, a weak and non-significant -0.16 correlation with the SIOD box, and the highest correlation of 0.46 in our defined region (-30˚S to 0˚S, 50˚E to 85˚E, and -15˚S to 0˚, 100˚E to 120˚E). Hence present study concludes that the interannual variability of summer monsoon OHC over the SIO is largely driven by the local wind forcing, which impact the SSH, D20 and chlorophyll over the region.

Application of CMIP6 models in the simulation of heatwave over different meteorological subdivisions of India?

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With rising global temperatures, extreme weather events have become more frequent, intense and of longer duration. CMIP6 GCMs provide improved climate simulations that need robust evaluation for historical period for reliable future projections. The present study assesses the ability of bias corrected CMIP6 14 Global Climate Models (GCMs) in simulating heat wave over India for March–June during the historical period (1951–2014). Heat waves were identified using IITM criteria. Model biases were removed using variance scaling bias correction method that showed higher correlation (0.93) and lower root mean square error (2.15) and improvement in approximating the inter-annual variability as well as spatial patterns as observed maximum temperature after bias correction. Evaluation of model performance for 95th and 99th percentile maximum temperature and heatwaves showed that most of the models simulate these extremes similar to observation. Northwestern, Central and South-central regions recorded highest number of heatwaves with a frequency of 50 heatwave days/decade, which were captured by the most of the GCMs varying in decadal frequency over the region. Among the GCM, although all models were found competent, ACCESS-ESM1–5, MPI-ESM1–2HR and MRI-ESM2–0 models were found to be the best performing models for extreme indices and heat wave simulation over India. The study will aid to the current understanding of CMIP6-GCMs performances over the different meteorological subdivisions of India and pave way for future projection of heat waves as well as reduction in uncertainty among the models.

Keywords: CMIP6, Heat wave, Global Climate Model, Climate Change, Extreme temperature

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Enhancing Climate Downscaling with GANs: Improving Realism and Physical Consistency in Storm Prediction

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Abstract

High-resolution storm downscaling is essential for improving precipitation forecasts, flood risk assessment, and climate resilience planning. Traditional downscaling techniques including statistical and convolutional neural network (CNN)-based approaches often struggle to capture fine-scale storm structures, leading to spatial inconsistencies and the loss of critical storm features [1]. While dynamical downscaling methods offer higher fidelity, they are computationally expensive and often infeasible for large-scale applications across the globe [2]. Generative Adversarial Networks (GANs) have recently emerged as promising tools for enhancing spatial resolution in precipitation modeling [1, 2]. However, most existing GAN-based downscaling methods primarily focus on intensity reconstruction, often neglecting accurate delineation of dry-wet boundaries [1,2]. This limitation reduces their effectiveness in hydrological modeling and disaster prediction. To address these challenges, we propose a novel two-step GAN-based downscaling framework that enhances both the realism and physical consistency of high-resolution storm reconstructions. Our approach integrates Wasserstein Generative Adversarial Networks (WGANs) with U-Net architectures, ensuring accurate dry-wet classification while preserving storm intensity variations and spatial coherence. A key innovation of our approach is the incorporation of a hard constraint that explicitly enforces dry regions to remain dry after downscaling. This constraint prevents the generation of spurious precipitation, leading to a physically consistent transition between dry and wet areas and ensuring alignment with fundamental atmospheric principles. Taking advantage of a model trained on dry/wet binary classification, our approach provides a robust mechanism to statistically correct the probability of zero precipitation in high-resolution downscaled storm images and can be applied as a post-processing tool to improve the reliability of various downscaling techniques. Improving the spatial representation of precipitation fields, our proposed framework offers substantial benefits for hydrological modeling, flood prediction, and climate impact assessments, ultimately improving operational weather forecasting and extreme event preparedness.

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Abstract

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Atmospheric Rivers (ARs) are elongated corridors of concentrated atmospheric moisture. They transport water vapour from tropical and subtropical regions towards the poles [1]. They are responsible for significant precipitation and extreme weather events in the West Coast of USA and part of Europe [2]. Accurate detection and reliable tracking of these transient atmospheric structures remain challenging due to their dynamic nature. ARs frequently exhibit complex behaviours such as splitting into multiple streams, merging with other moisture plumes, and fragmenting into smaller systems. These characteristics, combined with their rapid evolution and interaction with topography, make them difficult to predict and model accurately [2].

We have developed an improved grid-based algorithm (model) specifically designed to detect and track ARs. The model employs inflated-area masks around identified AR objects, allowing continuous of tracking even when AR objects break apart temporarily. The model maintains track of AR objects, even during fragmentation events by retaining and applying pre-fragmentation masks. This ensures consistent tracking of the AR objects throughout their entire lifecycle, until they either dissipate or merge with other AR systems. The model utilises reverse tracking to identify the genesis points (spatial and temporal coordinates) of AR events. Meanwhile, forward tracking is used to analyse their evolution, interactions, and eventual dissipation.

Additionally, the model can be used to understand how AR features are influenced by extratropical cyclones and other climatic patterns. We use binary labels to categorise climate features as AR or non-AR objects, which can be utilised for extensive analysis. Thereby, it enhances the overall understanding of AR interactions, dynamics, and lifecycle.

Preliminary results from our model indicate improved continuity and robustness in detecting and tracking AR features compared to previous methods [1], [3], particularly in handling the tracking of fragmented AR objects.

Future work includes integrating machine learning techniques to generate reliable AR forecasts and to provide further insights into how AR extremes influence and impact surrounding environments. These forecasts will be systematically validated against state-of-the-art forecasting systems, such as Microsoft's Aurora model, to identify strengths, limitations, and areas for further refinement.

Keywords: Atmospheric Rivers (ARs), Detection, Tracking, Inflated-Area Masks, AI/ML, Forecasting

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Monitoring Polar Stratospheric Clouds in the Post-CALIPSO Era: A Machine Learning Approach

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The Ozone layer, located at the lower stratosphere, made life on Earth's surface possible by absorbing harmful ultraviolet radiation. However, anthropogenic emission of ozone-depleting substances (ODS) has led to seasonal depletion of the ozone layer forming recurring ozone holes over Antarctica each polar winter. By the late 20th century, this depletion posed an existential threat to life on Earth's surface. In response, the Montreal Protocol of 1987 initiated a global phaseout of ODS, leading to gradual recovery of the ozone layer, with full restoration projected by the 2060s. Until then, the ozone hole continues to form during every polar winter whose size and duration are modulated by the polar stratospheric cloud (PSC). The ongoing global warming scenario is expected to increase the PSC areal coverage by the coupled effect of the stratospheric cooling and enhanced water vapor transport from the troposphere to the stratosphere and thus could possibly retarding the ozone recovery process itself.

For these reasons, the PSC dynamics are closely monitored using a lidar onboard CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) satellite, but its decommissioning in August 2023 has created a critical void in PSC research. With no follow-up CALIPSO mission, this loss severely obstructs our ability to monitor the PSC and its response to climate change, posing a serious setback to climate and atmospheric research.

In this challenging scenario, we propose retrieving key PSC information such as its composition, areal, and volume coverage using reanalysis and satellite datasets with machine learning techniques, specifically Decision Tree. Our trained Decision Tree model effectively identifies PSC presence and composition with reasonable accuracy, providing a valuable dataset to supplement CALIPSO's observations and ensuring continued monitoring of PSC dynamics in a changing climate.

The Western Himalayan Precipitation Regimes and Ecosystem Dynamics Under Climate Change

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ABSTRACT

The arid and high-altitude region of Ladakh in the Western Himalayas exhibits particular vulnerability to climate change due to its unique cold desert ecosystem. Recent increases in rainfall events have raised concerns about agricultural impacts and natural hazards like flash floods and landslides. This study analyzes rainfall patterns in Ladakh over a 90-year period (1932-2021) using India Meteorological Department (IMD) gridded rainfall data. The analysis employs multiple temporal scales - tricadal (30-year) and decadal (10-year) - to examine seasonal rainfall variations across pre-monsoon, monsoon, post-monsoon, and winter periods. Statistical significance of trends was assessed using non-parametric Mann-Kendall (MK) and Sen's slope tests, complemented by Ordinary Least Squares (OLS) regression and MK sequential analysis for overlapping time segments. The Precipitation Concentration Index (PCI) was used to quantify rainfall variability. Results reveal distinct temporal patterns across the study period. The tricadal analysis identifies higher pre-monsoon rainfall during T1 (1932-1961), followed by reduced monsoon and post-monsoon precipitation in T2 (1962-1991) and T3 (1992-2021). The PCI values indicate consistent and highly concentrated rainfall patterns, suggesting potential for extreme weather events. Decadal analysis revealed rainfall fluctuations that may be attributed to broader climate cycles. These findings have significant implications for developing climate-resilient infrastructure, early warning systems, and adaptive strategies for agriculture, water resource management, and ecosystem services in the region.

Keywords: Ladakh, Rainfall Variability, Mann-Kendall Sequential Test, Gridded Data, Climate Change

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[2] A. Author, B. Coauthor, J. Sci. Res. **17**, 7531 (2013).

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Prediction of Temperature for the Indonesian Maritime Continent Using Machine Learning

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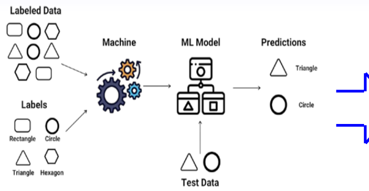
Agency for Meteorology Climatology and Geophysics [BMKG], Indonesia

Abstract

The Maritime Continent is situated in the world's most active convective zone, its tem re is extremely unusual. Since the early 20th century, scientists have been drav this distinctiveness. This region's temperature variability is thought to be the chaotic aspect of climate variability and is highly complex.

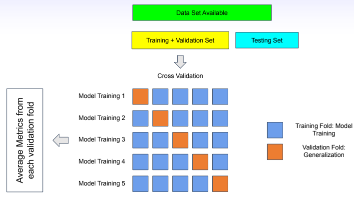
This study uses data from 117 Meteorological Stations to predict the temperature in 2025. Each meteorological station uses ten machine learning methods to predict the temperature in 2025. Furthermore, an analysis of the best method is carried out at the Station. Finally, the results of the best methods from each station are used to predict the temperature in Indonesia.

Using machine learning to forecast temperature for the Indonesian Maritime Continent entails applying sophisticated algorithms to examine past weather data and additional environmental variables.



Type Of Machine Learning

- Linear Regression
- Logistic Regression
- KNN
- Decision Tree
- Random Forest
- Bagging
- AdaBoost
- XGBoost
- Gradient Boosting
- SVM



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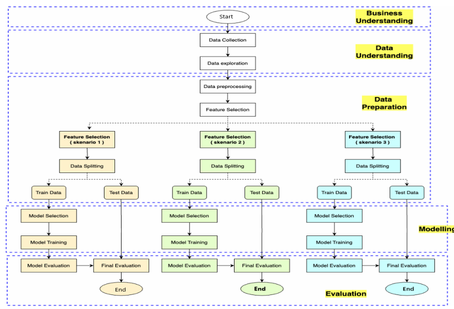
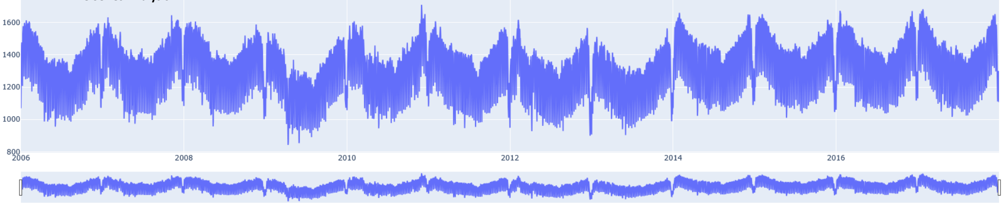
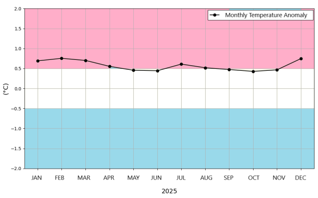
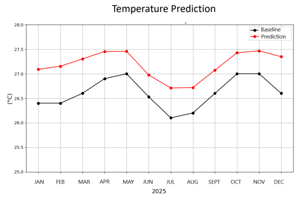


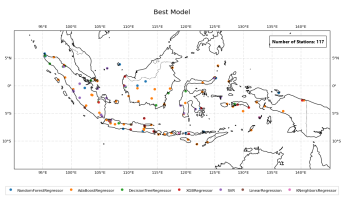
Time Series Analysis



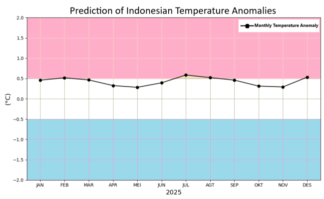
Error Based

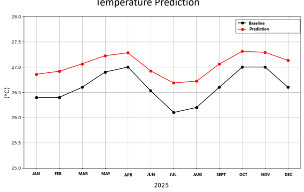


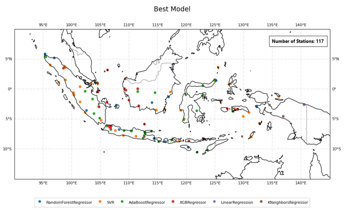




Taylor Base







Results and discussions

- Overview of the processes is consisting of data collection, data preprocessing, feature selection, model selections, training the model and validation and testing.
- Predicting temperature for the Indonesian Maritime Continent using machine learning involves the application of advanced algorithms to analyze historical weather data and other environmental factors.
- The ten methods used are linear regression, logistic regression, KNN, decision tree, random forest, bagging, Adaboost, XGBoost, gradient Boosting and SVM. All methods were used at 117 meteorological stations for 2025 temperature prediction, the results of which had different performances at each station.

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Analysis of Extreme Rainfall in Bengawan Solo Watershed

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Natural catastrophes including floods, droughts, and intense heat waves can be brought on by climate change. Floods could be caused by large volumes and heavy rainfall. Extreme weather that made it difficult or inaccurate to analyze the current weather was one of the causes of the flooding incident in the Bengawan Solo River Area. Analysis of extreme weather and climate change on the Bengawan Solo river is still limited. This study aims to analyze extreme rainfall in Bengawan Solo using a statistical approach. To look for variations in the distribution of rainfall in this area, rainfall data from 25 rainfall stations will be analyzed. This research uses daily rainfall data from 2000 - 2023. The research region's temporal trends show variation in the results, in which most extreme rainfall indices are highly fluctuating with a slight upward trend during 24 years. It is expected that this research's findings may aid in classifying regions with heavy rainfall and assist relevant parties in developing disaster mitigation strategies.

Inspired neural networks model for efficient prediction of future climate change

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Climate models are reliable mathematical representations of climate systems usually expressed as computer codes. These models are reliable as they are constructed based on the physical laws such as conservation of mass, energy and momentum coupled with useful observations. In this contribution, a trained neural network is built to predict future climate. The current model reproduces accurately useful aspect of current climate. Our simulations are assessed by comparing our results with observations of the atmosphere, ocean, cryosphere and land surface.

[1] Liuyi Chen, Bocheng Han, Xuesong Wang,et al, Applied Sciences 13 (21), 12019, 2023

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A Preliminary Study on Precipitation Forecasting Using a Random Forest Model Over Uttarakhand, India

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Machine learning (ML) techniques are increasingly being utilized to enhance weather and climate predictions, offering new avenues for improving forecast accuracy and computational efficiency [1], [2]. In this study, an attempt has been made to apply a Random Forest (RF) model for precipitation forecasting using IMD reanalysis data over Uttarakhand, India—a region highly prone to natural calamities due to its unique and complex topography, which consists of both Himalayan mountainous terrain and low-lying land regions. Given the region's susceptibility to extreme weather events such as heavy rainfall, cloudbursts, and landslides, accurate precipitation forecasting is crucial for disaster preparedness and mitigation.

The RF model is trained on key meteorological variables to identify nonlinear relationships and patterns in precipitation trends, providing a data-driven alternative to traditional numerical models. The performance of the RF model is evaluated across different temporal and spatial scales to assess its forecasting skill, reliability, and generalization ability which are critical for improving confidence in climate-scale applications[3], [4].

Overall, this study explores the potential of integrating AI-driven approaches to enhance precipitation prediction capabilities, particularly in topographically diverse and disaster-prone regions like Uttarakhand [5]. The findings contribute to the ongoing discourse on the role of machine learning in climate science, highlighting the advantages and challenges associated with AI-based precipitation forecasting. This research underscores the importance of leveraging data-driven techniques alongside physical models to improve climate resilience and support informed decision-making for weather-related risk management.

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[5] P. Kainthura and N. Sharma, "Hybrid machine learning approach for landslide prediction, Uttarakhand, India," *Sci Rep*, vol. 12, no. 1, p. 20101, Nov. 2022, doi: 10.1038/s41598-022-22814-9.

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Abstract

Climate variability and climate change are significantly impacting many poor countries, whose primary economic activities rely heavily on climate-sensitive sectors with little adaptive capability. This study analyzes the trends, spatiotemporal variability and anomalies of precipitation and temperature in the Central Ethiopian Regional State (CERS). A monthly precipitation data from Climate Hazards Group Infrared Precipitation Station (CHIRPS) and Climate Research Unit (CRU-TS4.08) temperature gridded dataset for the period of 43 years (1981-2023) were used. To examine temperature and precipitation characteristics, descriptive statistics were employed. These include the Mann-Kendall (MK) test, Standardized Anomaly Index (SAI), and Empirical Orthogonal Function (EOF). The result indicates that there are distinct seasonal patterns in precipitation and temperature. The Kiremt season (July to September) contributes 57.7% of the annual rainfall, whereas the Bega season (October to January) and the Belg season (February to May) account for 10.70% and 32%, respectively. There is no statistically significant increase in precipitation for the Kiremt, Belg and Bega seasons at the p=0.05 level. However, monthly precipitation showed a significant increasing trend in September and November at the same level of significance. EOF analysis identified three main modes of variability: The first three EOFs explained 84.23% and 92.16% of total variance in Kiremt and Belg season precipitation, respectively. Significant warming trends over the study period were found by temperature analysis. All seasons experienced an increase in the minimum, mean, and maximum temperatures. In line with the patterns of global climate change, anomalies in yearly temperature showed a shift from primarily less severe years in the early 1980s to continuous rising in recent decades. To increase resilience and minimize the impacts of climate variability and climate change, this study recommends the necessity of localized and implementable climate adaptation methods.

Key Words: Spatiotemporal variability; precipitation; temperature; Central Ethiopia Regional State; Empirical Orthogonal Function

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Investigating Role of Loss Functions in Bias Correction of Satellite Precipitation Estimates Guided by Environmental and Terrain Variables

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Accurate precipitation estimation is essential for understanding weather systems, managing water resources, and analyzing ecological processes across varying spatial and temporal scales. This task becomes particularly challenging in regions where orographic effects play a dominant role. The complex topography influences key meteorological variables, shaping precipitation patterns in ways that ground-based observations often fail to fully capture due to their limited spatial and temporal coverage. While advancements in satellite-based precipitation datasets have improved estimates in complex terrains, significant biases persist in regions with pronounced topographic influences. A key challenge in data-driven machine learning-based bias correction lies in the choice of loss functions, which directly influence model performance and the physical consistency of corrected precipitation estimates.

This study investigates the dependency of satellite-based quantitative precipitation estimates (QPEs) on different loss functions conditioned by static topographic and dynamic meteorological variables, focusing on the IMERG Final Run product from the Global Precipitation Measurement (GPM) mission. We validate our findings using the India Meteorological Department's (IMD) gridded daily rainfall data. By employing a Convolutional Neural Network (CNN), we assess the impact of integrating static features (elevation, slope) and dynamic variables (such as relative humidity, integrated precipitable water content) into precipitation bias correction models. We examine the working of commonly used loss functions such as Mean Squared Error (MSE), which tends to over-penalize large errors. Alternative loss functions, including Mean Absolute Error (MAE), Huber loss, and quantile loss, are explored to assess their ability to improve bias correction performance. Our results indicate that certain loss functions enhance the preservation of precipitation variability in orographic regions while reducing systematic biases, leveraging deep learning techniques to interpret model behavior and regional climate characteristics. This study provides insights into the role of loss function selection in bias correction models and contributes to improving the accuracy and reliability of satellite-based quantitative precipitation estimates.

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[2] A. P. Barros, M. Arulraj, Adv. Glob. Change Res. **69**, Remote Sensing of Orographic Precipitation (Springer, Cham, 2020). https://doi.org/10.1007/978-3-030-35798-6$_6$

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Models of climate change: tools for science outside of the measurement practices

Simulations in science can be used in several ways: to confirm certain signature values, to predict possible phenomena, to better characterize an existing phenomenon with few data points or simply to explore the effects of different factors in an experiment. Simulations, in general, serve many purposes to better secure the scientific exploration of experimental methodologies and measurement practices. They describe how we should explore the world and what type of things we should be able to see if our measurement practices are right. Nonetheless, the way that we evaluate these different models depends on several different factors that are not necessarily the same values applied in other scientific practices. The following essay will explore how the use of models for prediction of climate change patterns should not only be evaluated based on how precise the values that it predicts are but also by its contribution to the development of pedagogical tools that improve our relationship with the environment. Although in this second aim we should not regard the prediction as measurements, they should not be regarded as unscientific, on the contrary, they demonstrate the dual characterization of the scientific phenomena as a natural and artificial kind.

For this purpose, I will begin by describing what a simulation is, how it can be considered a measurement and how climate change models may enter in this definition. I will then explain how these models may contribute to the development of policies and why the use of hypothetical scenarios to justify a policy over another may be outside of the scope of the measurement practices. I will then proceed to explain the role of these models in the process of answering a diverse range of needs and purposes and how these purposes might seem more like ongoing processes that end up affecting the construction of the model, consequently having an essential part in the way we interact with the predicted values.

Simulations are used for several purposes. One example of the use of these simulations is the creation of signatures. This is “the practice of justifying claims to detect new phenomena by running computer simulations of the detection process” (Tal, 2011, p. 118), in other words, to represent the already existing measurement practice to verify what should be the data pattern that one should obtain if the conditions are optimal. This use permits scientists to rule out other possible reasons that could lead to the data obtained in the experiment because it permits the evaluation of several hypotheses and, finally, contributes to our security of the existence of the phenomenon being studied. It is important to notice, these signatures “serve not merely to contrast empirical data with theoretical consequences, but also to validate empirical detection methods” (Tal, 2011, p. 118), this is, it is not only a way of demonstrating that the theory behind the measurement might be plausible but that the methodology used it is adequate.

Tal mentions that, since the evidence of the simulation contributes to two things (testing the reliability of the model and testing the qualitative match between the prediction and the actual data), one could argue in favor of their use in very specific contexts. One needs to have certain equations, mathematical relations, and initial conditions to evaluate the model and, furthermore, to evaluate the methodology. This could be interpreted as part of the epistemic iteration that Chang establishes in the justification structure: the evaluation of the predicting model and the evaluation of the measurement practice with reference to the true experimental values obtained. It is only using these values that one can assess the validity of the signature and so computer-simulated signatures provide very little insight into detailed dependencies between different factors inside of the experiment. This is because the complexity of the algorithm makes the relation between input and output impossible for humans to track.

Moreover, the computer simulations are tailored to a particular intervention and experimental design and so it cannot be used to further explain other methodologies.

Nonetheless, because these can be used to show contrasting scenarios and create counterfactual evidence of the existence of a phenomenon, computational signatures can be used to evaluate the impact of certain factors over an outcome (even though they cannot completely explain their dependency). For example, for environmental purposes it might be useful to justify certain policies over others by demonstrating how much impact one could make by manipulating one of the factors affecting climate change. If one could use the computational signature to infer the main factors contributing to the general decay of the environment, one could then justify the policies that concentrate on these factors. An example of this can be seen in the Climate Change 2023 Synthesis Report by the IPCC where it is stated that carbon emissions might affect the sea level and, consequently, by 2050 the extreme sea level events that occurred once per century will be up to 30 times more frequent (IPCC, 2023, p. 80). This relation between one specific factor and how it might reinforce a natural tendency contributes to the better decision-making process of policy makers.

Because the objective of this use is not to directly calculate the effect in the measurements of the climate, it is possible that the best model is not the one that fits the data from the future. In other words, the way that we evaluate our reliance on the model is not based on the comparison with the values of the phenomena that has not yet occurred because we do not have access to those values but on the effect that these discrepancies could generate to better reinforce a policy. In this line, “It is possible that the model that will best answer the question of interest is not the one with the best fit to the data” (Taper, Staples, & Shepard, 2008, p. 359), it is possible that the signature created is used to answer a different question than that of the direct measurement and the concrete values in nature. Even if this model cannot be proven to be precise in its calculations, even if the initial conditions change and the model does not appear to be reliable for further predictions, it might be the best model as it appears to suffice one important objective.

We have encountered two problems. If the models or signatures cannot be compared to the data because this data is not available, should we consider the predictions to be measurements? Furthermore, if one utilizes these models to justify certain actions in policies, how do we account for consistency and reliability of these predictions if they are based on possible scenarios and not phenomenological realities? And, consequently, one might also wonder how these two problems are intertwined. If one is willing to accept that "measurement" may be a term used even in situations in which we are not directly in contact with the phenomenological entities but justify using certain policy over other based on what should be robust measurements, we might restrict the argumentation power of the scientific predictions to fulfil the objective of making a change in the environment and, therefore, interfere with the model.

To answer the first problem, it is important to revise the definition of measurement and measurement practice. According to van Fraassen, a methodology or a given practice is considered a measurement if there is a theory that permits its confirmation. Moreover, "the question, whether a given procedure counts as a measurement at all, requires a theoretical answer: the question can only be answered completely relative to a theory" (van Fraassen, 2012, p. 779). Theories permit the understanding of the object being measured, how the technique might influence this procedure, the relevance of certain factors, among others. In this line, a model that generates signatures might only be called measurement if it is programmed with certain regulations and theories and if the outcome is a quantity that one could later observe or that it is going to somehow exist in nature in the future.

Although there is a need to have one specific quantity that must be measured in a practice, there is also a recognition of the difficulty of precisely obtaining the specific values regarding this quantity. This is why van Fraassen (2012) mentions that

> for a procedure to qualify as a simultaneous joint measurement of quantities A and B, the theory would (according to the criterion displayed above) have to imply that the probabilities of its outcomes match the joint probabilities assigned to A and B. (p. 780)

To have certain probabilities and not exact values contributes to the description of the difficulty of predicting climate. The climate models are constructed using several models because scientists are trying to recreate several different phenomena at the same time "— encompassing the atmosphere, oceans, sea ice, and land surface—and the equations of interest are ones that represent the transport of mass, energy, moisture, and other quantities by processes within the system" (Parker, 2017, p. 986). The simulation of these quantities carries out certain uncertainty and so, by using several different parts and trying to merge them all, calculating the uncertainty of the values they produce is very hard and many times unproductive. The measurements made by these simulations are then subject to a high and many times difficult-to-calculate uncertainty.

For climate models in specific, the use of probability density functions seems to be encouraged. This allows models to calculate a range of possible values for certain measurements, but it also assigns certain probability to each of the values that one gets. Parker (2017) mentions that

> if scientists cannot say precisely what would occur under a given emission scenario, decision makers would at least like to know the range of outcomes in which the actual

> outcome is expected to fall and which outcomes within that range are most plausible. (p. 993)

In this way, we are permitting predictions to have a wider or a narrower uncertainty and, consequently, to call many different values predicted by the model a measurement. Computational models or signatures permit the measuring of certain phenomena and, even if uncertainty is carried from model to model, as long as the outcome may be explained by theory, we can always acknowledge it as a measuring practice.

The problem, as mentioned before, is to recognize what it is really being measured. Although climate models can give highly-probable significant values, while trying to justify certain policy over other one would like to know the difference or the impact of one factor over another in imaginary scenarios. For example, one would like to know the impact of replacing all carbon plants with solar panels versus replacing all carbon plants with a mixture of solar panels and wind towers or, even in certain scenarios, the impact of doing any replacement at all versus not doing any changes. Because we are simulating two different scenarios (one in which one applies certain policy and one in which we do not), it would also be reasonable to say that one is a measurement and the other one is not because one is shaped to simulate conditions that are not yet existent and that includes many other economic and social contributions that can affect the development of the measurement. Consequently, the calculation of the impact of an action over another is not a measurement either, since it is not possible to compare one measurement with a hypothetical data point. To justify certain action over another it is not possible to use measurements because the point of reference being used is something that might never happen if the initial conditions remain the same. It is because the object can be modified by an external factor like human intent that the measurement itself cannot be robust.

There is also a possibility to call of these hypothetical scenarios measurements and it is to have a wide range of possible measured values obtained in the modelling and, so, to say that one can compare the measurements with different uncertainties. If one accepts that all the array of values in the prediction might be called a measurement, one only needs to make the model more uncertain, more imprecise, and then cover a wider range of possible values that can be obtained. Nonetheless, this would be useless for two motives: it conflicts with the definition of measurement, and it affects our reliance of the model. By modifying certain values in the model, we are including another set of theories that could explain one value or another. According to van Fraassen, "a theory cannot be less likely to be true (or empirically adequate) than any of its stronger extensions" (van Fraassen, 2012, p. 782), in other words, although we might have a wide array of possible outcomes from a model there is always one value or prediction that it is going to have more "theoretical background" and if it is this theoretical background what gives meaning to the value obtained then only this value can be called a measurement. This is not to say that the other values obtained from the model are not in a sense measurements, "when a theory is still weak there can in general be very little or even no evidence relevant to its support" (van Fraassen, 2012, p. 782) and by having some value being predicted we are also permitting these theories to be supported. The problem relies on how strong the theory is, how probable is to obtain a measurement over another, and in which sense we might call each of the predicted values a strong or a weak measurement.

Not only is there a problem with differentiating between the different types of measurements that could come from this practice but that there is not a theoretical tool that could allow us to compare them and call it a measurement itself. In other words, knowing the distinction between different values in the array of predictions, there is no theory that relates or that contributes to the comparison of two different values predicted. Moreover, it is not possible for us to account for the comparison of two values that are not measurements in the same strict sense since one must be accompanied by a more robust interpretation of equations and initial conditions than the other one. We lack the tools to extrapolate a significant value from these two data points in the simulations since they are based on different structures. The justification of applying one policy over another cannot be said to be based on a measurement of its effect over the climate over another policy. Nonetheless, this does not necessarily entail that the model is not capable of providing meaningful information that could guide our preferences.

It is also important to understand how making the model less precise affects our perceived reliance over it. By increasing the uncertainty of the model to fit more possible measurement values, we are also permitting other interpretations of the data results as, for example, not having the adequate measurement techniques or the adequate theories to better calculate the values needed. When the values being predicted will eventually be used in a non-scientific environment which is not necessarily informed about the mathematical descriptions of the uncertainty values and so might interpret these as an error, as doubtfulness, or simply as incapacity to fully grasp the value. Parker (2017) mentions that

> When the uncertainty under investigation is structural uncertainty, then the space of possibilities instead ranges over model structures—simulation algorithms to be implemented on machines with specified precision and so forth—and the task of systematic uncertainty analysis begins to look overwhelming indeed. (p. 990)

And it is in this inclination, general perception of how uncertainty works, that allowing to have a big uncertainty might be understood as "not being capable" and so that it "might not be completely true". Lack of robustness when having the opportunity to have a more robust answer might not contribute to the better understanding of the data to guide decision making processes like choosing a policy.

Now, regarding the second problem mentioned, to better guide how and why should we rely on computational models we should understand the different ways we are using them and adjust our standards and requirements according to these different uses. According to Parker, to better evaluate a model we should differentiate between two types of adequacies: the ones associated to success in a particular instance and the ones associated with reliability in a type of use. Regarding the first one, "a model to be adequate-for-purpose, it must stand in a suitable relationship not just with a representational target T but with a target T, user U, methodology W, circumstances B, and goal P jointly" (Parker, 2020, p. 464). Adequacy for purpose means that in a specific context the model can predict specific values. This is similar to the description of Tal's signatures which only represent a specific experimental methodology. On the other hand, "scientists often will be interested in whether a model is ADEQUATE_C in a context in which it is actually used; we might call this its *adequacy-in-practice* for P" (Parker, 2020, p. 463). This type of adequacy permits a variety of instances to be explained by the same model while the delimitation of the context is respected. In this line, a model may be adequate in practice for a variety of different purposes as each purpose may have different circumstances.

We tend to value climate models only as instruments that should be reliable to predict our role in the changes in climate in very specific scenarios. We expect these models to be adequate in practice, this is, to precisely determine the different influences of factors under our control that lead to climate change in different places using many methodologies. Nonetheless, to judge these models with these criteria seems inadequate. Signatures become reliable because they show us counterfactual evidence, this is, they are valuable as insofar they can represent different scenarios and permitting us judge which option minimizes the possible bad consequences of our contributions. The reliability of the model does not come from the precision we get over one prediction but from the capacity to process information in a way that shows all the different things that could occur based in our inaction or certain particular actions. In this sense, we might say the model fits the purpose if it generates de pedagogical labor of describing the scenarios in a way that they would generate an impact on the people. In Parker words, “A tool M is FIT$_X$-FOR-P if and only if it is ADEQUATE$_X$-FOR-P” (Parker, 2020, p. 463) but fitness admits degrees. Because it admits degrees it allows us to evaluate how well can the model generate an effect on the people.

More specifically, signatures should be adequate based on their capacity to generate pedagogical and impactful predictions in a wide range of scenarios. This, specifically to generate the most change in the society and to better improve the way we discuss, and we deal with climate change. The purpose, although might initially seem to be controversial, is not to have the most accurate predictions of our influence in in the environment. The higher purpose is, without leaving aside scientific rigor and good practices, to motivate certain emotional and social responses towards our actions regarding climate. This is not to say that we should encourage sensationalism because “even once the purpose is specified, the features that will facilitate the achievement of that purpose can vary, depending on the user, methodology, the circumstances of use, and perhaps even the type of model being employed” (Parker, 2020, p. 467). We do not want to create alarmist values based on propaganda. We want to understand the public (the user) of these data and include them in the way we are evaluating the fitness of the models. To say that these models are more adequate it is to say that they present a reality in a better manner, that they show the difference between taking care of the environment or not, in a convincing and pedagogical way.

By including this secondary use of the models, we are permitting the evaluation of signatures outside from the measurement practices. Since we recognize that we are not aiming to capture a specific value, we are recognizing how these models can serve a purpose that is not tested by comparing the predictions with specific experimental data. This does not follow from Tal's signatures because we cannot follow the iterative process by evaluating specific data and because we are not trying to adequately assess the existing of future phenomena with exactitude. Additionally, this does not follow van Fraassen's rules of measurement and is not bounded by the restrictions imposed by the scientific theories. "After all, adequacy (not perfection) is all that is really needed, and it is plausible that the structures of today's models are adequate for some predictive purposes of interest" (Parker, 2017, p. 991), this is, to better generate the actions and the changes that we are interested in.

The relation between these two ways of addressing a same model might seem controversial. On one hand we recognize these models as possible instruments of measurement and so we try to evaluate them according to the theoretical representation of certain phenomena and how these phenomena relate to different factors. On the other hand, we acknowledge how "climate models should be evaluated with respect to their adequacy for the purpose of revealing real possibilities about (particular aspects of) future climate change, rather than for the purpose of giving predictions to within specified margins of error" (Parker, 2020, p. 473) and so we do not try to achieve certain robustness but value their flexibility and their completeness. The controversy between these two purposes, I think, comes from not recognizing science as a social enterprise and not only a natural and unbiased goal. Climate change is only one example of how our interaction with the experimental world affects it and how it, consequently, ends up affecting us. This phenomenon, just like civil wars, "is not something 'just there' in nature, like a hydrogen atom or a birch tree or the planet Jupiter. It is not what is called a 'natural kind'"

(Cartwright & Runhardt, 2014, p. 268). This indicates that there is not a particular way in which the expression and the understanding of the phenomena can only be traced to specific consequential factors of natural processes. By recognizing our interference on natural processes and factors we are also recognizing the dual characterization of the phenomenon and, so, it is less controversial to think about two different ways of understanding the evaluation of the models that predict these changes in the climate.

The model might serve different purposes and, although some purposes do not seem to be entirely scientifical, they permit the continuation of science and serve a purpose to the scientific investigation. Nonetheless, this does not mean to sacrifice scientific development and values since although "including that information would almost certainly increase the "humanistic" values of the text and might conceivably breed more flexible and creative scientists, it would inevitably detract from the ease of learning the contemporary scientific language" (Kuhn, 1961, p. 168), more specifically for the example shown before, it will detract people from understanding the real meaning of uncertainty values. Not regarding them as measurements does not deprive them as tools capable of sustaining scientific investigations, nonetheless, it does not indicate how to better achieve the pedagogical purposes of the models and so it is necessary to start including new values in the way we address the models without eliminating the existing ones. How to adequately frame the predictions and the values for a wider public should continue to be investigated.

In conclusion, models can be used for several purposes in science. Although these data models could in principle be called measurements as they respond to a specific theoretical background, the reality is that the complex modelling processes tend to make these predictions more complex and, therefore, no specific value in the prediction can be said to be exactly a prediction of what might occur. This can be seen, for example, in the modelling of the climate and the impact of human activity in its progression. By trying to model different imaginary scenarios we must sacrifice the conception of measurement used in the original signatures, nonetheless, this does not make the use of the models less scientific because it might encourage the use of less precise values to better achieve a specific purpose. “In the end, perhaps the best option would be to step back and reconsider what sort of depiction of uncertainty is most appropriate for each predictive variable of interest” (Parker, 2017, p. 996). When the phenomena being studied is constitutive of an ongoing process affected by human activity that cannot be controlled or adequately predicted, we should look towards values in social science to better comprehend how to value these models. Because these can used for pedagogical purposes, one might value models that are not as strict or robust but that permit a pedagogical approach to the subject and are aligned with other scientific purposes. Without the judging the model as “(just) a matter of how accurately and completely a model represents a target, where the ideal limit is a perfect and complete representation” (Parker, 2020, p. 458) we are permitting other types of tools of practices to contribute to the development of science.

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Prediction of Pre-Monsoon Temperature of Varanasi Using Machine Learning and Deep Learning Techniques

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Accurate temperature forecasting is essential for understanding climate changes. While natural factors, including seasonal variations, solar radiation, affect global temperatures, long-term trends are predominantly influenced by anthropogenic factors. Univariate modeling offers the advantage of using historical data points and their behaviour to make future predictions without taking into account any additional variables, thereby minimizing data complexity. In this study, two network-based models, Multi-Layer Perceptron (MLP) and Long Short-Term Memory (LSTM); one kernel-based model, Support Vector Regression (SVR), and one tree-based model, Random Forest (RF) regression have been applied. These models are employed to forecast daily maximum temperature using univariate time series analysis over the pre-monsoon season of Varanasi, a densely populated city of Uttar Pradesh, India. Based on the various performance metrics such as Root Mean Square Error (RMSE), Mean Absolute Error (MAE), R^2 score, and correlation coefficient, models have been compared and evaluated. The results demonstrated that SVR achieved the highest R^2 score (0.801) and correlation (0.897), while LSTM recorded the lowest RMSE (1.673) and MAE (1.213). The findings conclude that both SVR and LSTM demonstrate significant potential for accurate temperature forecasting by achieving high accuracy and minimizing errors over Varanasi.

Keywords: Univariate time series; Deep learning; Long short-term memory; Temperature forecasting; Support vector machine.

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Benefit of convection permitting climate model simulations in the representation of extreme precipiation in Central Europe: A case study

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Extreme precipitation events can cause significant damage, often triggering floods or landslides that result in economic losses and fatalities in affected region. The IPCC (2021) report highlights that global economic losses due to extreme weather events, including floods, droughts, and storms, have increased sevenfold from the 1970s to the 2010s [1]. This study analysed the 2002 Central European flood was a catastrophic natural disaster that caused intense rainfall, combined with saturated soils and overflowing rivers, leading to extensive flooding affecting mainly Germany, Austria, the Czech Republic, and Hungary [2, 3, 4]. Simulating extreme rainfall events at regional and local scales remains a challenge due to limitations in the spatial and temporal resolution of climate models, particularly in capturing precipitation intensity and distribution. To address this, high-resolution regional climate models (RCMs) with explicit convection, known as convection-permitting (CP) models, have been employed to improve the representation of deep convection without relying on parameterization schemes [5,6]. This study evaluates the performance of the latest version of RegCM5 [7] in simulating two consecutive extreme rainfall events (6–7 and 11–13 August 2002) over Central Europe, with a specific focus on the Czech Republic. Simulations at 12 km and 3 km resolutions were conducted with incorporating the sensitivity of planetary boundary layer (PBL) schemes, namely Holtslag and UW and dynamical cores (MM5 and MOLOCH) respectively. The findings reveal significant discrepancies in the 12 km RCM simulations, particularly over Central Europe, where the model struggles to accurately capture the spatial distribution and intensity of extreme precipitation. Overall, convection-permitting (CP) models exhibit a marked improvement over 12 km RCM simulations, demonstrating their ability to resolve finer-scale convective processes critical for extreme rainfall events. Among the CP schemes, CP-MM5_UW and CP-MOL_UW show the best agreement with observations, suggesting that the combination of the UW boundary layer scheme with CP dynamics enhances the model's ability to capture extreme precipitation. These results underscore the importance of CP-RCMs in simulating extreme precipitation events and their potential applications in climate adaptation, infrastructure development, and policy planning to mitigate associated risks.

Key words: Convection-permitting models, extreme precipitation, RegCM5, planetary boundary layer schemes, Central Europe.

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Semi-Automated Detection of Glacial Lakes: A Tool for GLOF Hazard Monitoring

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Glacial Lakes, evolve as the glaciers retreat, owing to the shifting climate patterns, presenting serious threats of Glacial Lake Outburst Floods (GLOFs) jeopardising the ecosystems and communities downstream. The purpose of evaluating possible risks and putting mitigation plans into action, monitoring these lakes are essential. This study proposes a combination of remote sensing data and geospatial analysis tools to put forward a semi-automatic approach for extracting glacial lakes. The method combines classification algorithms with satellite images, including Sentinel-2 and Landsat, to accurately locate and outline glacier lakes in Chamera and Tapovan-Joshimath Catchment. For ensuring the accuracy in challenging terrains like the Himalayas, this methodology combines automatic thresholding algorithms and spectral indicators such as the Normalised Difference Water Index (NDWI), which are augmented by subjective validation techniques. The results clearly reflect how the efficiency of the methodology in detecting glacial lakes while saving time and effort when compared to completely manual methods. Additionally this framework makes it easier to establish temporal datasets is also made easier by this semi-automatic approach, which makes it possible to monitor lake changes and pinpoint high-risk areas for GLOFs. Future research will concentrate majorly on improving the glacial lake detection accuracy at snow and cloud covered peaks with machine learning models and further automating the procedure.

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Understanding the Possible Relationship Between the Stratospheric QBO and the Indian Summer Monsoon

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The stratosphere has been identified as an important source of predictability for a range of processes on subseasonal to seasonal (S2S) time scales by various pathways. One of them is an equatorial pathway in which the QBO (Quasi Biennial Oscillation) is a dominant phenomenon. The QBO has a downward propagating easterly and westerly zonal wind pattern dominant in the lower and middle stratosphere bounded vertically (between 100 hPa and 10 hPa) and meridionally (between 10 N and 10 S), which has approximately 28 months of periodicity. The QBO phase influences the Boreal Wintertime convections of eastward propagating ISO (Intra-seasonal Oscillations) called MJO (Madian Jullian Oscillations). MJO is found to be more organized and persistent during the Easterly phase of the QBO. Even MJO prediction skill is enhanced by a couple of days in the easterly phase of the QBO. This study evaluates to what extent the QBO impacts the Indian monsoon in perspective of the northward propagating ISO called MISO (Monsoon Intra-seasonal Oscillations) during Boreal summer. When QBO phases are identified by Empirical Orthogonal Function method. It is noted that Easterly phase of the QBO enhances the Indian Monsoon and its intraseasonal oscillation convection phases over the Indian land region. Contrarily, in the QBO westerly phase.

DOWNSCALING CMIP6 SEA LEVEL RISE PROJECTIONS FOR INDONESIAN COASTAL AREAS USING AI-BASED METHODS

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Indonesia, as an archipelagic nation, is highly vulnerable to sea level rise driven by climate change. Coastal communities face increasing risks, including coastal erosion, saltwater intrusion, and severe flooding. High-resolution sea level projections are essential for effective adaptation and mitigation strategies.

In this study, artificial intelligence (AI) and machine learning (ML) techniques are used to downscale sea level rise forecasts for Indonesian coastal areas from the Coupled Model Intercomparison Project Phase 6 (CMIP6). To improve the spatial resolution of CMIP6 sea level projections to a finer scale (<25 km), Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) models will be used. This will align with reanalysis datasets like NASA's Sea Surface Height data. Considering recent research on the efficacy of AI-based techniques for sea level projection, the performance of CNN and LSTM models will be compared in order to identify the best technique for downscaling sea level data [1,2].

The outcomes of the AI-based downscaling and projection process will be interactively shown via a web-based platform that makes use of the Python streamlit module. This platform will give academics and policymakers an easy-to-use interface while enabling users to dynamically investigate anticipated sea level rises across various coastal regions and climatic scenarios. For Indonesia's coastal adaptation planning, this work intends to promote more precise and useful sea level rise assessments by combining cutting-edge AI-driven downscaling approaches with interactive visualization.

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Understanding the Physical Mechanisms Driving the Spatial Variability of Indian Monsoon Rainfall During El Niño Years: Insights from Climate Model Sensitivity Experiments

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El Nino Southern Oscillation (ENSO) is known to have a significant influence on the Indian summer monsoon, typically associated with widespread reduced rainfall over India during its positive phase. However, observational analysis reveals a distinct spatial variability in this response, with the central Indian region not exhibiting robust negative correlation with ENSO. Our analysis reveals that the onset and persistence of El Niño significantly influence the spatial variability of Indian monsoon rainfall. To better understand this variability, we examine sea surface temperature (SST) composites during ENSO years, which indicate notable SST modifications (due to the prolonged persistence of El Nino) beyond the canonical ENSO pattern—such as a warmer Indian Ocean and cooler SST anomalies both north and south of the ENSO region.These SST modifications could play a crucial role in altering monsoon dynamics and rainfall distribution across India. To assess their impact, we propose sensitivity experiments using current climate models, systematically modifying SST patterns to isolate their influence on monsoon rainfall. Through these experiments, we aim to improve the understanding of ENSO-monsoon interactions and identify potential mechanisms responsible for the observed spatial variability of Indian rainfall. This study will contribute to refining model representations of monsoon teleconnections and improving seasonal prediction capabilities.

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ABSTRACT

This study investigated the performance of the North American Multi-Model Ensemble (NNME) and Copernicus Climate Change Service (C3S) seasonal forecast models and the role of forecast domains and initialization lead time in predicting June-September (JJAS) and February-May (FMAM) seasonal rainfall and temperature in Ethiopia for the period 1994–2016 using CHIRPS and CRU temperature datasets using the Pearson correlation, Relative Operating Characteristics (ROC), and Ranked Probability Skill Score (RPSS) measures. The results show good performance of CanSIPS-IC3, ECMWF-SEAS5, DWD-GCFS2P1, CMCC-SPS3P5 and METEOFRANCE8 in forecasting rainfall in the JJAS season over the central, northeastern, northern, northwestern and pocket areas in the eastern Ethiopia compared to GFDL-SPEAR, RSMAS-CCSM4, NASA-GEOSS2S and NCEP-CFSv2. During the FMAM season, the CanSIPS-IC3, ECMWF-SEAS5, DWD-GCFS2P1, CMCC-SPS3P5 and METEOFRANCE8 models show higher skill in the southeastern, southern, central, and eastern Ethiopia compared to RSMAS-CCSM4, NASA-GEOSS2S and NCEP-CFSv2. The 1-month lead time forecasts exhibit a better skill compared to the 2-month lead time forecast. The tropical domain showed the best skill in the JJAS and FMAM seasonal rainfall forecasts. The models perform better in predicting temperature compared to rainfall. SPEAR, CCSM4, CFSv2, GEOSS2S, GCFS2P1, and SPS3P5 models exhibit better skill for JJAS seasonal temperature. SPEAR, CanSIPS-IC3, SEAS5, CFSv2, GEOSS2S, GCFS2P1, and SPSv3P5 models display higher skill for FMAM seasonal temperature across most portions of Ethiopia, especially in the western half. The study demonstrates the added value in objective seasonal prediction of rainfall and temperature over Ethiopia through the appropriate consolidation of multimodel ensemble members, the predictor domain, and the initialization lead time for important sectoral applications in the country.

KEYWORDS: Ethiopia; Forecast; Model Evaluation; Predictor domain; Lead time, global model