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

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Tuning and climate sensitivity of the EC-Earth global climate model with simulation of synthetic radiances

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This PhD research focuses on enhancing the tuning methodology of the EC-Earth global climate model to reduce biases and refine our understanding of climate sensitivity. A novel approach is adopted, targeting the radiative responses across the far-infrared spectrum to assess tuning impacts. Using a spectral emulator (the COSP-sigma-IASI module), comparisons between simulated and satellite-measured radiances will provide insights into model biases and feedback mechanisms.
Currently, the research is directed at developing a software framework capable of analyzing variations in outgoing longwave radiation (OLR) at the top of the atmosphere (TOA) related to specific climate feedbacks under different tuning setups. The initial analysis uses synthetic spectral kernels to reproduce the radiative response based on variations in model variables, applied to outputs from EC-Earth simulations performed without online radiative response simulation, while varying a range of tuning parameters. Initial analysis focuses on broadband kernel-derived monthly OLR variations, laying the groundwork for further refinement using high-resolution spectral kernels.
Future work will expand these methods to evaluate the full spectral radiative sensitivity under varied tuning setups and scenarios. This interdisciplinary approach aims to contribute an innovative perspective to climate model validation and enhance our ability to attribute spectral biases to specific atmospheric processes.

"Enhancing Sub-seasonal Forecast Accuracy in Saudi Arabia: WRF Sensitivity Analysis of Moisture and Energy Dynamics during the April 2024 Rainfall Events"

Abstract:

Subseasonal rainfall forecasting remains a significant challenge in arid regions like Saudi Arabia, where extreme weather events, such as flash floods, can have profound socio-economic impacts. This study evaluates the performance of various microphysics and cumulus parameterization schemes within the Weather Research and Forecasting (WRF) model to improve rainfall prediction across Saudi Arabia during the period from March 30 to April 26, 2024. Twelve model configurations were analyzed, with the top-performing schemes identified as Thompson microphysics paired with Kain-Fritsch cumulus parameterization, WSM6 microphysics with Kain-Fritsch cumulus parameterization, and Purdue Lin microphysics with Kain-Fritsch cumulus parameterization. Model performance was assessed based on rainfall bias, upper-atmospheric circulation patterns at 200 hPa, and temperature advection at 700 hPa.

The results indicate that the Thompson, WSM6, and Purdue Lin microphysics schemes, each combined with Kain-Fritsch cumulus parameterization, exhibited the lowest biases. These configurations underestimated rainfall by 15-20% during heavy precipitation events and overestimated rainfall by 10-12% under dry conditions. While all configurations accurately captured 200 hPa circulation patterns, temperature advection accuracy declined notably during the fourth week of the study period. These findings highlight the critical role of selecting appropriate parameterization schemes tailored to the unique climatic conditions of arid regions. By providing insights into moisture and energy dynamics, this study advances subseasonal forecasting capabilities and contributes to improved weather prediction accuracy in arid environments.

Keywords: Subseasonal forecasting, WRF model, rainfall prediction, parameterization schemes, Saudi Arabia, bias analysis, moisture dynamics, energy dynamics, arid regions.

P03

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Keywords: Subseasonal forecasting, WRF model, rainfall prediction, parameterization schemes, Saudi Arabia, bias analysis, moisture dynamics, energy dynamics, arid regions.

P04

High-Resolution Anthropogenic Emission Inventories with Deep Learning in Northern South America

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Abstract: Air quality in northern South America suffers from significant challenges due to limited high-resolution emission inventories and a lack of detailed atmospheric studies. This study leverages high-resolution nighttime light data from SDGSAT-1 and multisource remote sensing information with deep learning techniques to downscale emission inventories, providing a robust framework for simulating urban air quality. Integrating satellite-derived data with meteorological inputs, we use the WRF-Chem model to capture pollutant dynamics, validated against SISAIRE ground station measurements. Results show improved spatial and temporal accuracy in pollutant estimations, notably for PM_{10} and NO_2, emphasizing anthropogenic and natural influences, such as urbanization and biomass burning. This research underscores the importance of targeted policy interventions to address air quality issues in rapidly urbanizing regions, presenting a replicable approach to enhance global emission inventories and public health outcomes.

P05

Moist equatorial Rossby waves

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Our research is focused on large-scale westward propagating quasi-biweekly oscillations (QBWO) in the global tropics. In boreal summer, these waves show significant activity in southeast Asia and the western Pacific Ocean. In boreal winter, the highest activity shifts slightly south-eastward but remains in the west Pacific region. Due to their westward propagation, once formed, these waves can influence weather conditions in southeast Asia, western Pacific, Indonesian, and Indian regions. In fact, these large-scale systems can influence cyclones/depressions, intense/suppressed rainfall events, and regional temperature changes.

Composites from multiple decades of data reveal the structure of the different variables associated with the waves. These show significant differences between circulation and convection structures in different regions in the tropics. The moisture activity modifies the theoretically predicted structure of the equatorial Rossby waves [1] in relatively moist regions such as the west Pacific, the Indian region, etc. Specifically, convection maintains a slight lag from the circulation center instead of the expected quadrature lag in these regions [2]. To understand the dynamics and convection of the systems, we performed vorticity and moisture budgets on the composites. The vorticity budget usually shows the beta effect as a primary controller of the tendency. Vortex stretching is also present throughout the rotational gyre and plays a role in moist regions. The moisture budget shows contributions of different terms, depending on the composite region. Generally, horizontal advection plays a vital role in the moisture tendency; but vertical advection also contributes significantly in relatively moist regions of the tropics.

The phase speed of these waves is westward, ranging from 5-7 m/s. Contrary to the theory, the group velocity is eastward, from 0.5-3.5 m/s, indicating a systematic eastward flux of energy via these waves. We are assembling these observed features to develop a better understanding of the QBWO. In fact, due to the intricate relationship among moisture, precipitation, and dynamic variables, in addition to traditional analysis, we plan to use tools from machine learning to resolve complicated phenomena in this moist dynamical system.

[1] T. Matsuno, Journal of the Meteorological Society of Japan. Ser. II, 44(1):25–43, (1966).
[2] Y. Nakamura and Y.N. Takayabu, Journal of the Atmospheric Sciences, 79(1):247–262, (2022).

P06

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

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In this work we apply a deep learning UNet-based regional model emulator, recently developed and thoroughly tested over a region centered over the Southern France [1], to the complex terrain of Subtropical Chile (26ºS-34ºS). The study region exhibits marked climate gradients associated with a decreasing influence of the Pacific Ocean from the coast to the inlands and with topographic effects of the Andes Mountains reaching 6000 m.a.s.l.

The emulator is trained using a 150-years simulation of the CNRM-ALADIN regional climate model (RCM) configured for the North-Central Chile at a 12km resolution and driven by the CNRM-ESM2-1 CMIP6 global climate model (GCM) under the historical and SSP5-8.5 scenarios over 1950-2100. The emulator performance is evaluated based on an independent CNRM-ALADIN simulation driven by the same GCM but under SSP3-7.0 (2015-2100). Three less sophisticated downscaling methods are used as benchmarks: (i) a simple interpolation to the target resolution with an elevation adjustment based on the lapse-rate from CNRM-ALADIN RCM; (ii) multiple linear regressions using the same predictors as UNet and (iii) constructed analogues.

The results show that the UNet emulator is able to accurately reproduce the high-resolution spatio-temporal variability and changes of the RCM-simulated near surface temperature over the complex terrain of subtropical Chile, although in most cases it tends to underestimate the cold and hot extremes. In general, the performance of the emulator is weaker a) in autumn-summer than in winter-spring, and b) over mountains above ~3000m.a.s.l. and over a narrow coastal strip than over more inland coastal regions and valleys, suggesting an important role of regional to local phenomena (e.g. near-costal SST, marine low clouds, snow cover etc.) controlling the near-surface temperature in these seasons/regions.

Motivated by practical applications, we further discuss advantages and limitations of two training strategies for predictors/predictand over the study region: RCM/RCM or so-called "perfect model framework" which uses predictors from the upscaled RCM and GCM/RCM which uses predictors from the driving GCM.

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P07

Learning Subseasonal-to-Seasonal Global Ocean Forecasting on a Hierarchical Triangle Mesh

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The accuracy of medium-range weather forecasts has steadily improved over time[2]. However, effective risk mitigation for extreme weather events depends on longer-range predictions. Subseasonal-to-seasonal forecasts help bridge this gap and have traditionally relied on ensembles of physics-based atmosphere-ocean coupled simulations[7]. Recently, data-driven models have emerged as a strong alternative[4, 5], but they lack an explicit representation of the ocean, which becomes crucial at these timescales[6, 3, 8]. To address this limitation, we introduce a data-driven model for global subseasonal-to-seasonal ocean forecasting using graph neural networks[1]. We outline the rationale behind our architectural choices and present enhancements inspired by finite element methods to handle irregular domains more effectively.

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P08

On the underestimated Indian Ocean teleconnections to the northern extra-tropics in seasonal forecast models

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Recent studies show that the October Indian Ocean Dipole (IOD), rather than El Niño Southern Oscillation (ENSO), leads to strong Indian Ocean precipitation anomalies in early Winter, which results in a Rossby wave response that propagates through the extratropical Northern Hemisphere, eventually impacting the North Atlantic Oscillation (NAO). Although seasonal prediction systems reproduce the teleconnection patterns reasonably well, they underestimate the amplitude of the signals. Our study investigates the potential sources of these reduced teleconnection signals to northern extra-tropics, particularly to NAO. These weak signals could be arising from a multitude of factors, including biases in the forcing, basic state, incorrect eddy-mean flow interaction, etc. Using a simple Linear Baroclinic Model (LBM), we analyze whether these discrepancies, at least partially, could arise from the basic state or the forcing over the Indian Ocean. Running the LBM with basic state and forcing from the ECMWF seasonal hindcast dataset SEAS5 shows a more zonally trapped Rossby wave response, while running it with ERA5 basic state and forcing shows a more meridional propagation of the Rossby wave. This could be due to the stronger South Asian Jet (SAJET) in SEAS5 than ERA5. The impact of the differences in forcing is less clear. Using an intermediate complexity atmospheric general circulation model (AGCM), we further investigate the sensitivity to forcing and jet in modulating the extratropical circulation response to Indian Ocean heating. Despite the possibility of errors arising from multiple factors, understanding whether forcing in the source region and/or model climatology plays a role in producing such reduced signals could pave the way towards improving the seasonal forecast for early boreal winter.

P09

Abstract

On the use of ANN in Drought Forecasting across Vietnam: A hybrid model approach using regional climate modelling

for

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

Dao Nguyen-Quynh Hoa [1] , **Pham Quang-Nam** [1], **and Phan Van-Tan** [1]

This document is the template for contributed abstracts (posters and/or talks) and gives the guidelines for preparing and submitting abstracts for the *6th Summer School on Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics: Artificial Intelligence and Climate Modelling* to be held online from *5th May 2025* to *16th May 2025*.

Drought is one of the most pervasive and complex natural hazards, with significant impacts on ecosystems, agriculture, and communities, particularly in Vietnam. The study constructed a hybrid model to explore the sensitivity of drought forecast over Vietnam, utilizing ANN architectures in bias-correction procedures of regional climate models, RegCM and clWRF. The resulting 6-month scale Standardized Precipitation Evapotranspiration Index (SPEI-6), which is then processed through two different multi-model ensemble approaches: a simple averaging method (ENS) and a more complex ANN architecture (CTL), forming the basis of our two experimental setups. CTL consistently outperformed ENS, demonstrating stronger drought predictive skills. CTL effectively captured the spatio-temporal distribution of SPEI-6, showing high accuracy at a 1-month lead time. Its performance is promising, particularly in regions with complex climate patterns like the Central of Vietnam (R4 and R5), though discrepancies in predicting SPEI-6 amplitudes become slightly evident at 5-month lead time. The geographic extent analysis further supports CTL's strengths in short-term forecasting, highlighting its utility in early warning systems and immediate drought response planning. Nonetheless, the decrease in accuracy at extended lead times underscores the need for model refinement. The study contributes to the growing body of literature on ANN-based drought forecasting, emphasizing the potential and limitations of these models in the context of Vietnam.

P10

Numerical modeling of the stability of the George V Land (East Antarctica) continental margin: interplay between glacio-isostatic adjustment and ice sheet dynamics over the past Late Pleistocene interglacials.

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Geological records and morphological features of the George V Land continental margin (East Antarctica), located in front of the Cook Ice Shelf and Ninnis Glacier, indicate that the ice sheet over the Wilkes Subglacial Basin (WSB) has been subject to significant fluctuations, making it one of the most dynamic sectors of East Antarctica over its glaciological history. The scarcity of geophysical, glaciological, oceanographic, and geological data limits a comprehensive assessment of the instability potential of this region, both in the past and in the future. The paleo-climatic context is crucial for understanding the interactions between ice sheet stability and external forcing factors, providing key insights into potential future responses of the Antarctic Ice Sheet to ongoing climate change. Stratigraphic records and multi-beam data highlight a complex sedimentary system extending from the continental shelf to the slope, characterized by turbiditic deposits and extensive marine sediment slides. These features are likely shaped by the interplay between bathymetry, ice sheet dynamics, and glacio-isostatic adjustment. This study investigates whether the observed sedimentary architecture has been influenced by glacio-isostatic adjustments linked to the advance and retreat of the Antarctic Ice Sheet in the WSB since the Last Glacial Maximum, as well as during key Late Pleistocene transitions from glacial to interglacial periods (MIS 11 and MIS 5). These interglacials present distinct characteristics: MIS 11 was prolonged but moderately warm, while MIS 5 was shorter yet marked by higher temperatures. The research is conducted within an iterative framework, employing a series of numerical models that integrate ice sheet dynamics, glacio-isostatic adjustment, as well as the influence of shifting climatic patterns and oceanic dynamics for both periods, allowing for a refined understanding of their interplay over time and their impact on sedimentary processes.

P11

Exploring the Dynamics of Climatological Mean Monsoon Using a Machine Learning Based Empirical Leading Order Analysis

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The global monsoon circulation, which governs the subtropical rainband, can be interpreted as a manifestation of the seasonal migration of tropical overturning circulation (Hadley cell). However, the dynamics of regional monsoons is additionally controlled by zonal asymmetries occurring from land sea distribution, zonal gradients in sea surface temperature, and other stationary wave forcings. Despite its importance, the dynamics of regional monsoons remain poorly understood. Here, we demonstrate, using a machine learning guided empirical leading order analysis, emergence of distinct dynamical regimes that describe the complex evolution of regional monsoons. Conservation of angular momentum plays an important role in our understanding of the climatological and zonal mean picture of monsoon. It suggests, during the solstitial seasons the dominant balance in the momentum budget comes from the mean meridional circulation and the advection of mean zonal wind by the divergent wind. However, for regional monsoons the resulting angular momentum budget now includes many terms arising from the drivers mentioned above. We deploy an unsupervised machine learning algorithm to find the dominant balances in the momentum budget. This enables us to find spatio-temporal clusters characterized by distinct balances in the momentum budget and to study how they evolve throughout the seasonal cycle. The inherent stochastic nature of the algorithm is leveraged to find the robustness of the identified clusters. Entropy is used to measure uncertainty for the clusters recognized by the algorithm. The algorithm is successfully applied to idealized simulations with varying complexities ranging from aquaplanet to different distributions of land-sea-topography. Consistent with zonal mean theory, resulting clusters capture the dominant tropical overturning. However, zonal asymmetries result in additional clusters with distinct dynamical regimes

Half-day (daytime and nighttime) precipitation extremes in China: Changes and attribution from 1981 to 2022

Shibo Fang [1], **Jiahao Han** [1,2] , **Xiaomao Lin**[3] , **Zhanhao Zhang**[1] , **Man Li** [1]， **Yanru Yu**[1]， **Wen Zhuo**[1] **and Xinyu Wang**[1]

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Increased atmospheric water vapor pressure due to the warming climate has led to more frequent and extreme precipitation events, which has resulted in incalculable losses. The hydrothermal circulation suggests that extreme daytime and nighttime precipitation patterns can have many distinct consequences, ranging from changes in various scale hydrological cycles to social security concerns. However, the spatio-temporal patterns of daytime and nighttime precipitation events remain underexplored, lacking quantitative analysis. Therefore, our study analyzed daily precipitation data (including 24-h, daytime, and nighttime) from 1981 to 2022 across China to investigate extreme precipitation patterns at a half-day scale (daytime and nighttime). Fourteen monthly extreme indices associated with atmospheric circulations and sea surface temperatures were examined to clarify precipitation distribution patterns using random forest and optimal fingerprinting techniques.

The main findings are: (1) A clear upward trend was found in cumulative precipitation, intensifying the frequency of extreme precipitation events. Notably, the increase in both accumulated 24-h precipitation and the rate of nighttime precipitation exceeded the rate of daytime precipitation between 1981 and 2022. This trend became more pronounced as precipitation events became more extreme. (2) Most regions in China exhibited an increasing trend in both cumulative precipitation days and total precipitation, particularly in the North China Plain, although the Yunnan-Guizhou Plateau saw significant decreases in both variables. (3) Extreme precipitation events were primarily driven by changes in the different types of the Subtropical High (Western Pacific, South China Sea, and Northern Hemisphere Subtropical High), along with the typhoons southeast of the Hu Huanyong line. These findings enhance the understanding of hydrothermal exchange processes and extreme precipitation, providing a useful basis for climate change adaptations in China.

All the details could be find in［1］

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P13

Two or three minutes to midnight? Tropical ice loss following Amazon tipping points

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In this work, we present our research about the possible impacts of widespread Amazon deforestation on Andean Tropical climate that controls glacier mass balance. Tropical South America is a region where strong climate impacts on hydrological, ecological, and socioeconomic systems are occurring[1]. While iconic Andean environments provide critical water resources to sustain ecosystems downstream, large river basins such as the Orinoco and the Amazon sustain unique endemic landscape assemblages that in several cases remain untouched by direct human activities[2]. Recent research reveals significant impacts of anthropogenic global climate change and local human activities over the tropical Andean cryosphere and the Amazon rainforest. In the case of the Amazon rainforest, research suggests that when land cover change grows above certain threshold, this forest will undergo a critical transition to a landscape with large areas becoming savanna. This Amazon tipping point (ATP) can result from the interaction of global warming, deforestation, and fires[3], triggering an abrupt and self-perpetuating process of further warming, drying and savannization[4]. In this study, we are using numerical climatic simulations considering current and projected land cover scenarios[5], the Weather Research and Forecasting Model[6] and an energy mass balance model applied to glaciers of the Cordillera Blanca, Peru (10ºS). Results to date modelling 2 years suggest a puzzling outcome after the ATP. Under Amazon deforestation, the atmosphere aloft glacierized Andean becomes drier, with stronger and more zonally oriented wind speed. This leads to less accumulation above the regional Equilibrium Line Altitude and less ablation below. Thus, it seems that after the ATP glacier mass balance becomes less sensitive to temperature, leading to negative feedbacks that might slow down ice loss. These processes have not been tested under climate change scenarios and thus it remains to be seen whether the ATP under global warming strengthens or weakens the temperature-mass balance coupling. Tackling this question becomes relevant since decoupling may mean that tropical glaciers could maintain certain hydrological function despite increasing warming; otherwise, shrinkage enhancement by the ATP may speed-up ice loss and trigger worse consequences on water resources than previously thought. During the presentation, we will discuss results of ongoing experiments and the potential for accelerating this research via integrating numerical modelling and artificial intelligence techniques.

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P14

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

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Precipitation in Argentina presents diverse characteristics due to the country's vast territory. Given its impact on key economic sectors such as agriculture, livestock, and energy production, improving its predictability one month in advance has become increasingly relevant for planning and decision-making. In this context, this study develops a monthly precipitation forecast for Argentina using an ensemble approach that integrates multiple machine learning techniques, including multiple linear regression (MLR), generalized additive models (GAM), support vector machines (SVM), and artificial neural networks (ANN). Based on accumulated precipitation data from 91 weather stations across Argentina for the period 1981–2020, we analyzed key climate drivers such as sea surface temperature, geopotential height at various atmospheric levels, precipitable water, and zonal and meridional wind at 850 hPa. The statistical models were initially trained using data from 1981 to 2015, followed by an iterative process where the training period was extended yearly to predict the subsequent year. Ensemble models explaining at least 50% of the precipitation variance for each methodology and region were selected, and their performance was assessed using verification metrics such as standard deviation (SD) and root mean square error (RMSE). Notably, machine learning techniques, particularly ANN and SVM, outperformed other methods, achieving the best RMSE scores. This was especially evident in Patagonia, a region where precipitation is scarce and water availability is crucial for various activities. Additionally, a tercile-based precipitation forecast is being conducted in a pre-operational framework. Preliminary results suggest that the ensemble approach provides skillful predictions, particularly in northern Andean regions during January and in Patagonia during July. These findings highlight the value of integrating machine learning techniques with reanalysis data to improve monthly precipitation forecasting in Argentina. Future work will focus on evaluating the potential advantages of using alternative sources for precipitation predictors and assessing the forecast's skill under the current neutral El Niño–Southern Oscillation (ENSO) conditions.

P15

Monthly precipitation forecasting in the eastern Amazon

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The eastern Amazon has one of the most critical mining complexes in the world. This economic sector is highly impacted by weather conditions, mainly precipitation [1]. Therefore, monthly precipitation forecasting is crucial for planning activities in this region. Usually, numerical, dynamic and statistical models make these forecasting, but machine-learning (ML) models have recently significantly advanced in this area [2]. This study uses different statistical and ML models (ARIMA, ARX, ARMAX, ARIMAX, RNN, LSTM, GRU, CNN-1D and XGBoost) to predict the monthly precipitation in two regions in North Corridor (the mining supply chain corridor, mines, railway, and port, in eastern Amazon), one in southeastern Pará state (mine region), and another near São Luis (a coastal city in west of northeastern Brazil). Most of these methods use exogenous variables in their formulation, and it is known that this region is affected by some teleconnections, such as El Niño – South Oscillation, Tropical Atlantic Gradient and South Atlantic Gradient [3,4]. In this case, we choose the sea surface temperature in regions representing these phenomena: equatorial Pacific (Nino1+2, Nino3, and Nino4), tropical Atlantic (tropical north Atlantic and tropical south Atlantic) and south Atlantic (south-north Atlantic and south-south Atlantic), in addition to temperature at 2 m and zonal and meridional wind at the chosen point, as exogenous variables. The strongest correlation between precipitation and exogenous variables (with the 1-month lag) occurs between April and October (most of these months are part of the dry season of the chosen region). The time-series cross-validation analysis indicates that the CNN model provided the best fit for the training series in the mine region, with average RMSE (avRMSE) values ranging from 28.59 to 112.92 throughout the months. In contrast, ARIMA performed better in the coastal region, achieving avRMSE values between 15.41 and 166.05. For the independent series analysis, the CNN model achieved RMSE values ranging from 20.31 to 84.81 in the mine region. In contrast, ARIMA yielded RMSE values between 15.58 and 189.59 in the coastal region, closely matching the best-performing model from June to January. The results show that there isn't the best model for all areas and all months, and to obtain better results, it is necessary to evaluate different methods for each area of interest.

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P16

Understanding Extreme Precipitation over the Himalayas Using High-Resolution Regional Earth System Modelling

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The Himalayas, with their intricate topography and highly dynamic climate, present significant challenges for accurately simulating extreme precipitation events in regional climate modelling and prediction. This study evaluates the performance of a Regional Earth System Model (ROM) in capturing such events over Himachal Pradesh, a region particularly vulnerable due to its altitude-sensitive climate and rugged terrain. The ROM simulations, driven by ERA-Interim reanalysis data, were conducted at a horizontal resolution of 0.22° x 0.22° for the period 1980–2017. Key precipitation indices, including Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), and the 99th percentile of daily precipitation, were analysed seasonally. ROM displays high skill in capturing CDD and CWD indices, but exhibits positive precipitation bias for the 99th percentile index. As a future objective, this research will extend to the application of the high-resolution ICON model, marking its first use in this topographically complex and data-sparse region. ICON's quasi-uniform grid structure and demonstrated performance over Europe motivate its selection for this study. Furthermore, we propose the integration of advanced AI/ML techniques to correct model biases and enhance the reliability of extreme precipitation simulations over the Himalayas.

Keywords: Extreme Precipitation, Himachal Pradesh, ROM, ICON

P17

Abstract template for poster

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Abstract

The Atlantic Niño, the leading mode of interannual variability in the tropical Atlantic, exhibits low prediction skill but the reasons are not fully understood. Here we frame its predictability on the basis of the underlying mechanisms: the canonical Atlantic Niño events are governed by dynamics similar to the El Niño/Southern Oscillation, featuring strong coupling between deep atmospheric convection and oceanic variability, which is lacking in non-canonical events. Observational analysis reveals that the canonical events are preceded by a strong La Niña-like pattern in the tropical Pacific. These events are predictable up to six months in advance using a 51-member ensemble operational seasonal forecast system. The non-canonical events are scarcely predictable; however, they lead the emergence of a Pacific La Niña-like variability. These findings provide a new framework to disentangle the two-way connection between the equatorial Atlantic and Pacific Oceans and improved seasonal climate prediction across the tropics.

P18

Statistical Downscaling of Multiple Atmospheric Variables over Europe using a Super-Resolution Transformer

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High-resolution climate projections are crucial for understanding regional climate impacts, but current global climate models are limited by their coarse resolution. Downscaling methods address this limitation by bridging the gap between global-scale and regional-scale data. Recently, empirical downscaling approaches utilizing deep learning have shown promising results [1].

This study introduces SwinFSD [2], an empirical downscaling model adapted from the state-of-the-art super-resolution model SwinFIR, designed to downscale 20 atmospheric variables from the ERA5 [3] reanalysis dataset to the high-resolution CERRA [4] dataset. Additionally, we present DECADL [2], a downscaling dataset that enables training and evaluation of SwinFSD across Europe using both gridded CERRA data and station-based observational data [5, 6].

SwinFSD achieves good results, demonstrating strong performance in evaluations against CERRA data and station-based observations across Europe. Furthermore, we evaluate the model's generalization capabilities on regions outside the training domain, assessing its ability to partially generalize to new regions.

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Abstract for the 6th Summer School on Theory, Mechanisms, and Hierarchical Modelling of Climate Dynamics

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Atmospheric gravity waves (GWs) are buoyancy waves generated by topography, convection, frontal systems and jets [1]. As altitude increases and density decreases, the GW amplitudes grow until they reach their maxima, breaking and depositing momentum and energy into the atmosphere. This process influences global atmospheric dynamics, coupling the lower and upper atmosphere [2, 3]. Therefore, understanding the dynamics of gravity waves, as well as their interactions with atmospheric chemistry, wind fields, and climate, is crucial for improving the accuracy of global and regional models [1]. Since much of the gravity wave spectrum is too fine to be resolved at current model resolutions, models rely on parameterisations to approximate their effects on the circulation [1]. Assessing the ability of models to simulate changes in the mesosphere and lower thermosphere (MLT) remains a challenge, primarily due to limited global observations of GWs at high altitudes. The MATS (Mesospheric Airglow/Aerosol Tomography and Spectroscopy) satellite, launched in November 2022, addresses this data gap. By measuring O_2 airglow and sunlight scattered from noctilucent clouds, MATS aims to provide a global 3D dataset on GW spectra climatology using tomography and spectroscopy [4]. By comparing MATS data with outputs from numerical weather and climate models such as the Japanese Atmospheric General circulation model for Upper Atmosphere Research Data Assimilation System (JAGUAR-DAS) and WACCM, my research aims to evaluate how well current models represent the chain of wave processes to reproduce the GW properties observed in the MLT. This will ultimately enable improvements in gravity wave parameterisations (GWPs). While my research does not directly involve artificial intelligence (AI), I am interested in exploring how AI techniques could improve GWPs, as they are becoming increasingly relevant in atmospheric modelling. Recent advances in machine learning (ML) offer promising improvements in GWPs. [5] demonstrated that U-Net convolutional neural networks can estimate orographic GW parameters, accurately predicting 3D wind fluctuations and momentum flux amplitudes. Another study by [6] used ML to emulate the non-orographic gravity wave drag scheme in the IFS forecasting model, successfully reproducing the Quasi-Biennial Oscillation. Attending this summer school would provide valuable insight into AI/ML applications in climate modelling, particularly their potential to improve the representation of GWs in models.

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P20

Understanding multi-millennial variability in the Southern Ocean

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Temperature reconstructions from Greenland and Antarctica during glacial times show anti-phased oscillations which are assumed to be connected to changes in ocean circulation patterns. However, the research focus of most studies is set to the Northern Hemisphere, connecting Dansgaard-Oeschger (DO) events to changes of the Atlantic Meridional Overturning Circulation (AMOC). Meanwhile, in the Southern Ocean (SO), millennial-scale oscillations, driven by changes in the formation of deep water, have been found in different climate model simulations, yet the exact mechanism leading to these changes is still not fully understood. These oscillations, diagnosed by the strength of Antarctic Bottom Water (AABW) formation, have been simulated under warmer climate conditions and also in experiments with additional freshwater input to the North Atlantic. Here we present results of multi-millennial experiments with the fast Earth system model CLIMBER-X and the coarse resolution General Circulation Model (GCM) CM2Mc in which the AMOC is collapsed by freshwater forcing in the north Atlantic and convection is eventually triggered in the SO. We aim to find the drivers of convection onset in the SO and the subsequent strengthening of AABW by analysing the changes of temperature and salinities in both models. Between the two models, we compare how the dynamics of features such as sea-ice, wind stress and thermodynamic ocean variables contribute to changes of SO convection and AABW formation. We also analyze additional sensitivity experiments with CLIMBER-X to explore which conditions lead to oscillations.

P21

Forecasting Extreme Weather Events in Ecuador using Neural Networks

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Heavy rainfall events or rains that trigger floods with economic and social consequences in Ecuador can be caused mainly by seasonal events such as El Niño, sub-seasonal events such as the Madden Julian Oscillation, or mesoscale convective systems that develop in a few hours [1, 2]. Given the significant influence of extreme rainfall, it is essential to have a system for forecasting extreme rain that will help prepare more effectively to face this threat and mitigate its impact. Although the application of neural networks in weather forecasting has been going on for almost two decades, in recent years, the application and development of algorithms have advanced at a dizzying pace [3, 4]. However, in Ecuador, there are few studies on applying neural networks to weather forecasting and much less on forecasting extreme rainfall events, which are events with social and economic consequences of significant impact. In addition, the complexity of predicting extreme events, given the chaotic behavior of the atmosphere, is still well known. Although global and mesoscale meteorological models are currently used for weather forecasting, it is still complex to forecast the amount of precipitation with such precision and in such advance that they can help prevent the effects they may cause. For this reason, applying new neural network algorithms is of great interest.

This study uses various neural network techniques to analyze a ten-year time series of meteorological data. Firstly, an exploratory data analysis is performed to observe the relationship between the variables: rainfall, average, minimum, and maximum temperature, average relative humidity, solar radiation, wind speed, and cellophane. The study then proceeds to implement a neural network for extreme events. Extreme Learning Machines (ELM) [5] are used for multilayer perceptrons among different types of training methods due to their superior computational speed compared to conventional gradient backpropagation. ELM shows competitive results in comparison to other classical training methods. Its computational efficiency in training outperforms classifiers and regression approaches such as Support Vector Machines (SVM) or Multilayer Perceptron (MLP) algorithms.

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P22

Representation of Tropical Intraseasonal Variability in AI Models

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Intraseasonal variability is a prominent component of variability in the tropical atmosphere. Key modes of tropical intraseasonal variability (TISV), such as Convectively Coupled Equatorial Waves (CCEW) and the Madden-Julian Oscillation (MJO), present significant forecasting challenges due to their nonlinear and multiscale nature. The increasing demand for accurate and timely weather forecasts has driven the integration of AI into Numerical Weather Prediction, particularly for short to medium-range weather forecasting. Leveraging AI models to improve the representation and prediction of TISV holds promise for enhancing the accuracy of extended-range forecasts, particularly in the tropics, which remains a significant challenge due to the complex variability of the tropical atmosphere.

In this study, we evaluate the representation of TISV modes using three state-of-the-art AI models — PanguWeather, GraphCast, and FourCastNet V2. Wheeler-Kiladis plots generated from the model outputs show some power in the Kelvin wave and Rossby wave domains, along with strong power in the MJO band. To assess whether the power captured by the models reflects physically meaningful structures, we analyse the representation of Kelvin waves, Rossby waves, and the MJO in the models. For Kelvin waves, all the three models exhibit eastward-propagating disturbances between 5°N and 5°S, with strong zonal wind patterns resembling Kelvin wave disturbances but phase velocities in the range of 4–7 m/s. The models generally reproduce the tilted vertical structure of Kelvin waves in at least one variable, such as specific humidity or temperature anomaly, with the magnitudes of anomalies across variables consistent with documented studies. For Rossby waves, all the models capture westward-propagating gyres around 10°N/S, with phase speeds of approximately 5–6 m/s, aligning with documented value. Most models reproduce the correct phase of anomalies in at least one variable, although some fail to capture the expected vertically upright structure. For the MJO, all three models exhibit a large-scale eastward-propagating disturbance with strong zonal flow. However, none of the models capture the gyres typically associated with the MJO.

Thus, our results suggest that these models do capture some of the physical characteristics of the TISV modes examined in this study. Future work includes creating a composite of events to obtain more robust results and case study analyses to evaluate how these models compare with real-world observations.

P23

The Convective Exchange Matrix, a new diagnostic tool, reveals the impact of climate change on convective transport

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Atmospheric moist convection is adapting due to the rising surface temperatures. It can be expected that changes in the convection properties influence the associated convective transport. Deep convection comes along with extremely high vertical wind velocities, leading to a redistribution of trace species with implications for the composition of the upper troposphere and the (photo-)chemistry and the radiation budget. Consequently, convective transport has feedback on the climate. We developed a new tool, the convective exchange matrix, and implemented it in the global chemistry-climate model EMAC (ECHAM/MESSy Atmospheric Chemistry) to investigate the changes in convective transport patterns within the observed global warming. The convective exchange matrix displays the air mass transport between all model levels and allows us to study the convectively induced transport from all inflow levels to all possible outflow levels unaffected by other processes. Furthermore, the turbulent mixing in and out of convection in the CVTRANS (ConVective tracer TRANSport) submodel was updated within the MESSy setup because the former versions did not handle the turbulent detrainment and entrainment between the environment and the up-/downdraft sufficiently well. Now, the turbulent mixing is in line with the underlying convection parameterisation, the Tiedtke-Nordeng scheme. Historical climate simulations were performed from 1979 to 2020 applying the new version of CVTRANS. The use of the convective exchange matrix enables the examination of the changes in convective transport in comparison to the trends in occurrence and strength of different convection types. Deep convection occurs less frequently on average between 2011 and 2020 compared to the 1980ies. Although deep convection penetrates higher in the latter time period, this cannot compensate for the reduction in deep convection occurrence and, overall, less material is transported from the planetary boundary layer to the upper troposphere. However, more air mass is transported to the highest levels affected by convection. Furthermore, the large scale subsidence strengthens in these altitudes. Moreover, a shift in the downdrafts towards higher starting levels emerges from the simulations. We conclude that the simulations indicate a statistically significant change in the convective transport due to climate change in this 41-year time period.

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

Detection of extreme precipitation events in global climate models using ML

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The Intergovernmental Panel on Climate Change (IPCC) (AR5, AR6 [1]) states with high confidence that precipitation extremes are increasing in both frequency and intensity due to climate change. These extreme precipitation events, whether long-lasting or short but intense, can have significant societal and economic impacts, including loss of life, damage to infrastructure and disruption to agriculture. Understanding and predicting these events is therefore crucial for climate adaptation and risk management.

Extreme precipitation modelling requires high resolution to capture the localised and short-term nature of such events. Two common approaches to increasing resolution are statistical downscaling and dynamical downscaling, each of which has its own strengths and limitations. Dynamical downscaling provides explicit modelling and should better capture local processes. In addition, robustness is required in a changing climate, and dynamical downscaling does not assume stationarity in the relationship between the components of the climate system, but simulates the interactions between them. However, running continuous high-resolution climate models is computationally expensive compared to statistical downscaling. The aim of this research is to optimise the cost of running high-resolution climate models only for detected extreme events from a global climate model (GCM).

Our approach investigates event-based dynamical downscaling, in which extreme precipitation events are detected from the fields of the coarse-resolution GCM, EC-Earth2, and then downscaled with the regional climate model (RCM) HCLIM ALADIN. To detect an extreme precipitation event in the GCM, a Convolutional Neural Network model is used. Its performance is evaluated using the Fractions Skill Score (FSS) for different seasons and predictor variables. The ML-based detection model was trained using supervised learning on sets of daily GCM variables as inputs and a daily extreme precipitation mask from the RCM as ground truth.
Initial results in a northern European area indicate promising capabilities for ML-based detection, especially in the cold season when extreme precipitation events are more distinct. The ML detection model increases the efficiency of extreme precipitation analysis and enables better assessment, climate adaptation strategies and risk mitigation.

Keywords: extreme events, precipitation, ML-based, CNN

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P25

Controls on the convective environment in the Lake Victoria region and their interactions with large-scale climate variability: machine learning approach

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The Lake Victoria region is inhabited by over 40 million people and is a major source of food, water and economic activity in East Africa. As the intertropical convergence zone passes by, this region experiences two rainy seasons that result in extreme precipitation events and flash flooding. Over 80% of extreme rainfall around Lake Victoria is produced by mesoscale convective systems (MCSs), which are characterised by organised convection spanning a few hundred kilometres, and often lasting several hours. Here, we tracked 4,811 MCSs between 2014 and 2019 that moved over Lake Victoria and lasted longer than 3 hours. A clustering algorithm was applied to identify different types of MCSs crossing this region: cross-lake storms that initiate overnight East Africa time, lake-to-land storms that initiate in the morning, and land-to-lake storms that initiate in the afternoon. We examined conditions of the local environment leading to the development of these storms to link them to larger scale climate variability, such as the Madden-Julian Oscillation, El Niño–Southern Oscillation and Indian Ocean Dipole. Our analysis is used to inform a machine learning model that predicts the probability of a given storm type occurring over this region in order to improve predictions of high-impact weather over the lake.

P26

Elevation dependent effects of precipitation on river discharge at different spatio-temporal scales

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The link between climate extremes and river floods is complex and greatly affected by regional characteristics. River discharges are highly dependent on elevation and size of catchment in mountainous regions. This study explores the effects of orography on the precipitation-discharge relationship in the Greater Alpine Region (GAR). We make use of daily discharge data and several reanalysis and observation datasets. The region is stratified into low (LE), and high (HE) elevation categories to assess variations in discharge responses. The correlation of discharges with precipitation at HE shows stronger relationship during the autumn season (September-November, while LE exhibits a stronger association in summer (June-August). Coarser resolution (>0.25°) datasets show degradation of the association of precipitation with river discharge at both elevation categories, although with a larger sensitivity of HE to decreasing spatial resolution (i.e. 0.10° to 1° degree) as compared to the LE category. Significant sensitivity to spatio-temporal scales is found also in the intensity and duration of the climate extremes (ETCCDI indices) and their relationship with discharges in the GAR. This study emphasizes the advantages of high-resolution, multi-scale approaches to understand the intensity and duration of climate extremes and their impacts on river discharges. An improved framework integrating climate and orographic indices is essential to identify the complex relationships governing flood extremes in the GAR. The improved framework will contribute to the development of diagnostic tools and enhance the skill of future flood extreme projections by climate models.

P27

Revisiting Indian Ocean interannual variability and its dependence on the Pacific Ocean.

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In this study, we focus on characterizing the modes of seasonal and interannual variability in the Indian Ocean and its connections to the Pacific basin, analyzing the main spatial correlation patterns such as the Indian Ocean Dipole (IOD) [1] in both reanalysis and ad hoc model experiments.

The independence of the IOD and even its existence were questioned from its discovery [2], and we put forward new analysis to certify how much of the pattern variance depends on other modes like ENSO, and how much is instead dependent on the internal dynamics of the Indian Ocean.

We then revisit the accuracy of previous simple statistical models [3, 4] and test their significance as a null hypothesis for the variability of the basin.

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P28

Characterizing Temperature Extremes and their relationship with Land-Atmosphere Interactions in the Mediterranean Using Deep Learning: Insights from Past and Future Climate Data

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Temperature extremes, among others climate extremes, are becoming a growing concern for both researchers and policymakers due to their significant and devastating impact on socio-economic sectors (such as agriculture), infrastructure, ecosystems and human health. Recent trends indicate an increase in the frequency and intensity of extreme temperature events, particularly in the Mediterranean region, which is highly vulnerable to climate change [1]. According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report [2], the Northern Hemisphere is experiencing more frequent and intense weather extremes, leading to greater economic and human losses. Understanding and quantifying temperature extremes, both historically and under future climate scenarios, is crucial for developing strategies to mitigate these impacts and strengthen resilience.

To gain deeper insights into potential changes in the frequency, duration, and intensity of heatwaves in the Mediterranean region, we apply a novel approach developed within the InterTwin project. Rather than relying on traditional statistical methods, this study employs a generic machine learning (ML) framework based on Convolutional Variational Auto Encoders (CVAE), enabling a more efficient and scalable analysis of extreme temperature events. The unsupervised anomaly detection approach identifies anomalies by measuring reconstruction errors (the difference between the original and reconstructed images). To assess the robustness of this method, we compare the results against traditional statistical techniques using extreme temperature indices defined by Expert Team on Sector-Specific Climate Indices (https://climpact-sci.org/indices/). Heatwaves are analyzed based on summer daily maximum temperature from the Regional Climate Model EBU-POM, with a horizontal resolution of 0.5°. EBU-POM, developed at the Faculty of Physics, University of Belgrade, is a part of the Med-CORDEX framework within the CORDEX international initiative. Additionally, heatwaves are examined for both past and future climate conditions up to 2100, following the RCP8.5 climate scenario. Given the strong influence of land-atmosphere interactions on climate extremes in the Mediterranean region, where soil moisture affects air temperature [3], we also assess the correlation between land-atmosphere coupling metrics and heatwave characteristics in past and future climates.

This approach highlights the potential of machine learning in climate research, offering more efficient and scalable methods for analyzing climate extremes in the Mediterranean region, particularly in handling large time series from climate ensembles.

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Investigation of aerosol effects on diurnal cycle of precipitation amount, frequency and intensity over Central Africa

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Abstract

Regional climate is affected by a wide variety of aerosols which modify through their radiative effects the precipitation distribution. In this article, the effects of aerosols, mainly dust aerosols on diurnal cycle of precipitation amount, frequency and intensity are investigated over central Africa by using the latest version of the Abdu Salam ICTP regional climate model coupled with the Community Land Model 4.5 as land surface scheme. Two sets of experiments have been conducted (one with aerosols interaction with dynamics and thermodynamics processes and another without this interaction) for a 10-year study period (2002–2011) and the Fourier transformation is used to study the 24-h cycle. In order to clearly understand spatial differences in RegCM experiments over central Africa, three subregions have been considered according to their land cover and climate characteristics. Our results indicate that the pattern of simulated aerosol optical depth (AOD) is well represented particularly northward of the study region compared to AOD from moderate resolution imaging spectroradiometer (MODIS) even if some differences in terms of magnitude are reported. The aerosols' effects on diurnal cycle are generally not similar to those found in the amplitude and phase. The result pointed out that over the Sahelian region, atmospheric aerosol in general and dust in particular always induced a positive effect on diurnal cycle (increase the magnitude of the cycle) of precipitation intensities and in precipitation amount and precipitation frequency as well. But, the change is opposite in terms of amplitude and peak time over some subregions. It appears that the forcing of aerosols in solar radiation as well as in latent heat flux leads to the changes in the amplitude of the precipitation amount during the DJF and JAS seasons particularly during daytime. The changes in amplitude of the precipitation frequency are not consistent even if the corresponding phase always tends to increase by up to 5 h.

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

Title: Application of machine learning in simulating river flow over the Faleme basin (Senegal)

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Abstract

Hydrological systems have been considerably impacted by climate variability and climate change. Several studies have provided abundant evidence that water resources over West African Basins were highly affected by climate change [1, 2, and 3]. These studies used the traditional approach in climate change impact studies on water resources which consist of forcing hydrological models (HM) by climate variables to simulate river discharge. However, in recent years, advanced methods such as machine learning (ML) techniques have emerged in the field of hydrological modelling and forecasting [4]. The main objective of this work is to simulate river flow over the Faleme basin (Senegal). In this current study, we use the Long Short-Term Memory (LSTM) to simulated river discharge at Kidira outlet from 1981 to 2010; the Adam Optimizer were used. I use several data such as river discharge, rainfall, potential evapotranspiration, actual evaporation, temperature, soil moisture, where 80% of the data is used for training and the remaining 20% for testing. Two experiences have been done. First, river discharge (at the main outlet in downstream) was considered as target variable and the others as features. As for the second experience, I use the same target variable (river discharge) at the same station hydrometric station, but for the features variables, I use only river flows from two upstream stations. The preliminary results show that under both experiences, the river flow signal is quite well simulated, particularly under the second experience which better performance. For the first experience, the efficiencies are: NSE: 0.528, 0.5359, for nse_loss, and huber_loss, respectively. As for the second experience, the efficiencies are: NSE: **0.7156, 0.6944** for nse_loss, and huber_loss, respectively. However, under both cases, the machine learning model underestimates the magnitudes of the river discharge. The next steps will be to do Hyperparameter tuning before doing river flow forecasting. Furthermore, the output of the machine learning model will be compared with simulations from hydrological models.

Keywords: river flow, machine learning, simulation, Senegal

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Circulation patterns in subtropical South America: associations with rainfall anomalies and modes of climate variability

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This work presents a climate diagnosis and evaluation framework focused on cross time-scale interactions of circulation patterns (CPs) over subtropical South America (83°W-40°W and 10°S-40°S) during the 1979-2023 period. To achieve this, we develop a machine-learning algorithm that classifies the daily 850 hPa wind fields from ERA5 into dominant CPs. The workflow includes: (i) standardization of zonal and meridional wind components, (ii) dimensionality reduction using Empirical Orthogonal Functions, and (iii) k-means clustering. Once classified, the CPs are analyzed in relation to daily rainfall anomalies and key climate variability modes.

Using the Silhouette index, seven CPs that capture the seasonality of daily circulation in the region were identified. Among them, two CPs are characteristic of summer, one of winter, one of transition seasons, two of all seasons except summer, and one occurs throughout the year. The CPs exhibit anomalies associated with cold fronts passages and cyclonic/anticyclonic activity over the oceans and tropical-continental regions. All CPs are linked to rainfall anomalies across different parts of the study area, explaining the spatial variability of precipitation over the region. Notably, those associated with cold fronts strongly promote positive rainfall anomalies east of the Andes. Additionally, it is observed that circulation anomalies over the Pacific play a key role in generating rainfall anomalies in central Chile.

The seasonal and annual frequency time series shows how CPs occurrence is related with modes of climate variability. Particularly, the CPs related to spring rainfall anomalies in south-eastern South America show significant correlation mainly with El Niño Southern Oscillation indices. To a lesser extent, relationships were also found with the Indian Ocean Dipole, Pacific Decadal Oscillation, Southern Annular Mode, and Tropical South Atlantic indices across different seasons.

Results of this work provides a basis to assess state-of-the-art high-resolution simulations from a process-based perspective, which will provide useful climate information for the region.

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A data-driven approach for wildfire risk modelling in Southern Europe

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Wildfires are one of the most devastating natural disasters with wide impacts across economic sectors and society in Europe. Modeling wildfire risk remains a complex challenge, particularly as predictions of fire risk often rely on weather-based operational indices, such as the Fire Weather Index (FWI) which exclude key factors such as human activities and other ignition sources. In addition, it is unclear how wildfire risk will evolve in the future under different climate scenarios.

The study shows how data driven models can be used to combine human, topographic, land cover and weather data to quantify wildfire risk in Southern Europe on a 10 x 10 km grid at a daily resolution. Four classification machine learning models are trained on a historical fire record from 2008 to 2023, obtained from the European Forest Fire Information System (EFFIS). The best performing model is a Random Forest (RF) model with an AUC of 0.95 and F1 score of 0.89.

The RF model is first validated by comparing the model output run using weather variables from the ERA5-land reanalysis to the historical fire record from EFFIS. The results show that the RF model can successfully identify high-risk fire regions both seasonally and daily and provides a more accurate representation of fire risk compared to the FWI. The model is subsequently run using future climate data (2081 – 2100) from the ClimEx2 regional climate model under the Shared Socioeconomic Pathways (SSP) 1 and SSP3 scenarios, showcasing its potential to evaluate fire risk under evolving climate conditions.

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Diffusion-Model Based Downscaling of Extreme Weather in Southern Europe

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High-resolution weather simulations provide valuable information about when and where natural disasters may occur, as well as precise estimates of climate change impacts. Large-scale climate models provide enormous amounts of atmospheric data, but these data are often produced at too coarse a scale to resolve key weather phenomena such as convective storms [1]. Recently, machine-learning based approaches to downscale—increase the resolution of coarse data—have shown considerable skill in producing high-resolution, realistic samples of atmospheric variables such as precipitation [1,2]. In this work, we employ a modified version of CPMGEM [2], a diffusion model, to create $0.1^{o} \times 0.1^{o}$ samples of hourly IMERG v7-Final [3] precipitation based on ERA5 [4] atmospheric variables on a $1^{o} \times 1^{o}$ grid. When training on these data, we withhold the top 1 percentile of precipitation, as well as the dates in which Medicanes—tropical-like cyclones which occur in the Mediterranean Sea—happened to evaluate this models' ability to produce samples of extreme precipitation when it has not seen them during training. Additionally, we retrain this model using future atmospheric conditions from a regional climate model in order to evaluate this model's ability to capture the climate change signal and quantify the frequency of future severe weather.

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Causality in the interaction between extratropical storm tracks, atmospheric circulation, and Arctic sea ice loss

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Using ERA5 data from 1980 to 2023, we investigated the relationship between extratropical storm tracks, atmospheric circulation patterns, and sea ice area (SIA) in three key Arctic regions. Building on causality approach of [1], we considered two distinct conditions: (1) the Arctic sea ice driving the atmosphere (ice-driven winters – IDWs) and (2) the atmosphere driving the Arctic sea ice (atmosphere-driven winters – ADWs). This categorization was based on the sign of SIA and surface turbulent heat flux anomalies in the Barents-Kara Sea (BKS), Baffin Bay, Davis Strait, and Labrador Sea (BDL), and Chukchi-Bering Seas (CBS). In contrast to [1], who focused on sea level pressure and surface air temperature (which provide only insights into surface conditions), we analyzed geopotential height at 850 hPa**.** This allowed for a better understanding of circulation above the boundary layer. We also examined the 1000-500 hPa geopotential thickness, which is a key component of the lower troposphere's thermal profile. Moreover, to explore the relationship between storm tracks and sea ice, we extended our analysis to include track density and mean intensity, computed by tracking positive V850 wind, which serves as a proxy for the northward transport of warm and moist air on the eastern side of cyclones.

Our findings show that in IDWs, reduced SIA has a minor effect on extratropical storm tracks. However, we observed significant mid-tropospheric cooling over Asia (around 55ºN), which aligns with the effects of reduced ice in the BKS during IDWs. The mechanism behind this connection may be better understood by examining potential vorticity dynamics (e.g. [2]). While based on surface temperature analysis, [1] concluded that the loss of sea ice in the BKS has minimal influence on cold winters in Asia. This emphasizes the importance of considering the entire tropospheric temperature profile to capture the impact of sea ice loss. In contrast, during ADWs, the BKS and CBS regions experience amplified surface warming and SIA loss due to storm-induced intrusion of warm and moist air, with sea ice loss in the BKS contributing to strengthening Ural blocking. While cyclone-induced heat and moisture intrusion is prevalent, we found no significant trend in track density or mean intensity of positive V extrema in the North Atlantic sector of the Arctic, suggesting that changes in atmospheric circulation are unlikely to be the primary driver of recent sea ice loss in the BKS (e.g. [3]).

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Abstract for Poster Presentation

NUMERICAL METHODS FOR FINE-GRAINED RECONFIGURABLE COMPUTING CLUSTERS

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Field-Programmable Gate Arrays (FPGAs) have emerged as a transformative computational technology for high-performance computing systems, offering adaptability, power efficiency, and parallel processing capabilities. However, harnessing the collective computational power of FPGA clusters remains a challenge due to the lack of standardized methodologies and automation tools. Fine-grained reconfigurable supercomputing offers a promising avenue to address this challenge by enabling customized computational models, pervasive distributed memory architectures, and non-standard numerical representations.

This research addresses this gap by developing novel numerical methods tailored for fine-grained reconfigurable computing clusters, leveraging a prototype FPGA-based supercomputing platform: HyperFPGA developed at the ICTP Multidisciplinary Laboratory. We construct a class of two-derivative IMplicit-EXplicit Runge-Kutta (TD-IMEX RK) time integrators, to improve stability and accuracy in solving nonlinear partial differential equations PDEs with application in air-pollution, fluid-structure interactions and wave propagation models.

Hence, this project aims to develop a novel theory leveraging Field Programmable Gate Arrays (FPGAs) to optimize numerical simulations of the Advection-Diffusion-Reaction (ADR) equation focusing on compartmentalizing the implementation, the approach will create logical units to efficiently handle various mathematical operations required in the TD-IMEX RK methods. This FPGA-based strategy is expected to significantly enhance computational efficiency, reduce execution time, and enable large-scale real-time simulations of complex PDEs.

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Evaluating the sensitivity of the AI IGP-UHM model to initial conditions

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The AI IGP-UHM model [1] predicts El Niño using recent climate information and would be expected to take advantage of precursors identified in previous research, such as the high probability of strong El Niño events based on the E Index in January when the central equatorial Pacific wind stress anomaly (τ_{xc}) in the previous August exceeds a critical value [2]. In this study, the sensitivity of the AI IGP-UHM model to selected precursors is evaluated. While the model forecasts for the period 1981–2023 approximately reproduce the empirical relationship between τ_{xc} in August and E in the following January, in a single experiment, after neutralizing or even artificially inverting the τ_{xc} value for August 1982, 1997, and 2015, the prediction of the El Niño events of 1983, 1998, and 2016 by the model presented very low sensitivity, implying that its training did not allow it to identify this precursor as a necessary condition for El Niño. The most relevant predictor for the AI model was identified as the sea surface temperature (SST') anomaly in the core region of the E pattern. In another experiment similar to the first one, but this time neutralizing said SST', the prediction for 2016 was neutral, but for 1983 and 1998 it continued to predict El Niño. From the control AI outputs, we "discover" a reasonable causal network using the PCMCI technique [3]. However, the same AI model with perturbed initial conditions (e.g. reversed central equatorial Pacific zonal winds in August 1982, 1997 and 2015) results in a very different model causal network (e.g. disregards zonal wind as predictor). These preliminary results suggest that the AI IGP-UHM model does not capture the causal physical relationships as expected from a numerical climate model, which warns us of the need to maintain a critical position of AI models, especially regarding their performance in novel situations.

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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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Improving S2S Prediction in Indonesia using Machine Learning Approach

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Subseasonal to Seasonal (S2S) prediction have recently received significant attention due to their ability to bridge the gap between short-term weather predictions and longer-term seasonal forecasts. Since 2015, the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) have been utilizing forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF), specifically focusing on the 10-day scale subseasonal forecasts. This research aims to evaluate the effectiveness of the ECMWF model in predicting ten-day rainfall patterns in Indonesia. ECMWF hindcast data from 1996 to 2021 is utilized for analysis. The ground truth is established by combining BMKG station observations and rain gauge data with Global Satellite Mapping of Precipitation (GSMAP) data. The assessment of ECMWF's performance employs regression analysis and a three-class classification method, using quantile one and three thresholds for each grid point. The results highlight ECMWF's proficiency in capturing rainfall patterns, as evidenced by strong correlations, minimal bias, low Mean Absolute Error (MAE), reduced Root Mean Square Error (RMSE), high accuracy rates, and favorable F1 scores—particularly for the initial ten-day forecast period. However, performance decreases as the forecast lead time increases. Seasonally, ECMWF have an outperformed accuracy during the June-July-August (JJA) period, with comparatively lower accuracy during the December-January-February (DJF) period. Geographically, the forecast performance is notably better in the Java and Bali-Nusa Tenggara regions compared to other areas, while Papua consistently exhibits lower predictive accuracy. Overall, this study sheds light on the capabilities and limitations of the ECMWF S2S model in forecasting subseasonal to seasonal rainfall patterns across Indonesia

Keywords: Machine Learning, S2S Forecast

Short-to-medium lead seasonal precipitation forecasting in Ceara, northeastern Brazil, using an interpretable machine learning model

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This study employs TelNet [1], an interpretable machine learning sequence-to-sequence model, for short- to medium-lead seasonal precipitation forecasting in the state of Ceará, northeastern Brazil. The model uses past seasonal precipitation values and climate indices to predict an empirical precipitation distribution at each grid point in the target region for the next six overlapping seasons. TelNet features a simple encoder-decoder-head architecture, allowing it to be trained with limited samples, as is often the case in climate forecasting. The state of Ceará is a prominent region in seasonal forecasting studies due to its high predictability. TelNet's probabilistic performance is thoroughly evaluated and compared with state-of-the-art dynamical models. The training, validation, and test sets are resampled multiple times to estimate the uncertainty associated with a small dataset. Results show that TelNet ranks among the most accurate and calibrated models, outperforming the dynamical model in several initialization months and lead times. Analysis of TelNet's variable selection weights indicates that the gradient of SST anomalies in the tropical Atlantic Ocean is often the most important feature, followed by the Oceanic Niño Index—findings aligned with previous studies.

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Transferring Knowledge Across Regions: Domain Adaptation for Km-Scale Super-Resolution

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Downscaling is crucial for enhancing the spatial and temporal resolution of weather and climate projections, facilitating more accurate regional impact assessments and supporting informed decision making, water management and risk modeling. Super-resolution (SR) models, where low-resolution inputs are transformed into high-resolution outputs for variables such as temperature, humidity, pressure, and precipitation, have been effective in weather and climate downscaling when trained on regional data [1][3][4]. The ability of these downscaling models to generalize across diverse regions remains uncertain. To our knowledge, no studies have explicitly tested the transferability of these models across diverse topographic and climatic conditions. Domain adaptation [5][2] has been successfully implemented to address the challenge of training a model in a data distribution (source domain) and applying it to a related but different data distribution (target domain). This study compares different domain adaptation techniques to improve the generalization of SR models across different regions. Specifically, we coarsen a 10-year, storm-resolving COSMO simulation over Europe, reducing the horizontal grid spacing to approximately 18 km (source) before downscaling it back to the original 2.2 km resolution (target). To improve model generalization across unseen topographical conditions, we implement domain adaptation techniques evaluating the performance through tailored spatial evaluation metrics. We hypothesize that domain adaptation leads to superior generalization across diverse terrains, improved data efficiency, and better convergence, outperforming standard techniques such as Dropout and Batch Normalization. The goal is to learn transferable mapping, allowing high-quality data from well-studied regions to enhance predictions in data-sparse areas. Additionally, we believe that this approach may facilitate the discovery of more general relationships between mesoscale and storm-scale thermodynamic environments, improving the broader applicability of deep learning-based downscaling methods.

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Spatiotemporal of drought characteristics during 1981-2022 and its impact on Madagascar's vegetation cover

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This study aims to assess the spatiotemporal characteristics of drought in terms of its duration, frequency, severity, intensity over Madagascar during 1981-2022. Additionally, the relationship between the Standardized Precipitation Index (SPI) and the Normalized Difference Vegetation Index (NDVI) during 2000-2022 were analyzed, which aims to represent the impact of drought on vegetation over the studied area. Drought assessment was computed on the timescales of 3, 6, and 12 months (i.e. SPI-3, SPI-6, and SPI-12, respectively) and accompanied by seasonal and annual analyses. While the relationship between SPI and NDVI was assessed through vegetation change analysis based on selected SPI time-periods and the correlation analysis. The findings reveal that drought events have become more intensified over the southern part of the country and consecutive during the most recent past (2017 to 2022). Links between the drought occurrence and vegetation changes are perceived. The increase in vegetation losses is linked to the occurrence of continuous negative values of seasonal and annual SPI. While, the existence of smaller negative values of the wet season SPI is connected to more vegetation degradation during the wet season. The NDVI-SPI relationship is confirmed through the statistical significance correlation found between NDVI anomaly and SPI, especially over southern Madagascar.

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Tropospheric gravity waves in the subtropics: Optical detection on low cloud decks

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Internal gravity waves with wavelengths of tens to hundreds of kilometers are frequently seen as ripples on high-resolution geostationary satellite animations of subtropical stratocumulus decks. To systematically detect and characterize these waves, several satellite data fields are employed. Daytime visible reflectance images have high contrast, with units of reflected insolation relevant to climate impacts. IR brightness temperature is available day and night, but requires high-pass filtering and contrast enhancements. The divergence of low cloud tracking winds, retrieved via Particle Image Velocimetry (PIVdiv), is a scalar field independent of those radiative quantities. Water vapor channel time differences show wave vertical displacements at midlevels.

In any given image array, Matlab's Cauchy continuous wavelet transform detects packets of elongated phase crests and projects them into 10 logarithmic half-wavelength bins between 20-500 km, with angle discrimination of about 15 degrees, all on a 5 degree coarse geographical mesh. Cross-wavelet analysis probes for connections between pairs of images. Time pairs of the same field lead to estimates of wave propagation speed. Cross spectra of PIVdiv and radiative brightnesses help to quantitatively relate wave modulations of cloudiness to the vertical displacement of PBL top where the clouds reside. Connecting low level cloud signals to midlevel water vapor signals allows us to estimate vertical wavelength, allowing an independent check against propagation speed via the dispersion relation.

Preliminary wave rose maps, generated for the southeast Pacific during October–December 2023 reveal multiple source regions: synoptic jet-front disturbances in the South Pacific upper-level westerlies, intertropical convergence zone (ITCZ) convection, and orographic or thermal forcing from South America. We hypothesize that similar processes, plus tropical cyclones absent in this sample, drive similar wave activity in other basins and seasons.

The results may have several applications. Any novel observed signal stands as a challenge or target for high-resolution models. Wave sources inferred from these observations may usefully constrain estimates of physical and nonlinear processes in the atmosphere. Low cloud dependence on vertical velocity could have climate relevance, for instance case studies of strong waves have shown they can be rectified in closed to open cell transitions. If periodic waves are trackable for much longer than their inverse frequency, they could comprise a subtle source of surprisingly long predictability of convective initiation, coastal fog/clearing, or other local effects. Like all gravity waves, these redistribute zonal momentum via meridional and vertical fluxes, a process whose contribution to larger scale flows can now be estimated quantitatively.

By offering open-access wave data products, we hope to inspire collaborative efforts on all these application areas. By scaling up computations from 3 months in one region to many years around the globe, downgrading newer data to be comparable to older data as needed, we can build up a nearly global daily picture of tropospheric internal waves over the subtropical oceans through time. With so many degrees of freedom contributing to these high-resolution measurements, very subtle trends and differences should be detectable.

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Climatic Shifts in the Beas Basin: A Spatio-Temporal Analysis of Temperature and Precipitation Trends using TerraClimate Dataset

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Abstract

Understanding the spatio-temporal variations in temperature and precipitation is pivotal for evaluating the impacts of climate change, particularly in ecologically sensitive and topographically complex regions such as mountains.These variations influence the hydrological cycles, biodiversity, and human livelihoods, necessitating detailed assessments to develop targeted adaptation and mitigation strategies. The study was done over the Beas Basin in the Northwestern Himalayas, a region of high ecological and socio-economic significance analysing changes from 1980 to 2023, utilizing TerraClimate reanalysis datasets of 4 km resolution. The monthly, seasonal climatology of Temperature Maximum (Tmax), Temperature Minimum (Tmin) and Precipitation has been built over the basin, providing comprehensive insights into temporal patterns and spatial distributions of these variables.The statistical analysis used Mann-Kendell to identify the trends and shifts. The Pettitt test has been done to find out the point of abrupt change. The spatial trend analysis of Tmax and Tmin has been conducted on both monthly and seasonal scales, facilitating a detailed understanding of temperature dynamics. The results show that Tmax and Tmin have been increasing at rates of 0.02°C and 0.04°C (just double) per year, respectively, over 43 years in the Beas Basin, with the trends being statistically significant. These trends are statistically significant, emphasizing their importance in the context of long-term climate variability. The Long-Term Average (LTA) anomaly analysis for temperature variables exhibited a negative trend from the 1980-2000 period in a range of 0 to -1.5˚C indicating cooler-than-average conditions, and it is increasing in a range from 0 to +1.5 ˚C from 2001-2023 exhibited a warming trend. A notable abrupt change was identified by Pettitt's test in 1999 for the temperature across all five stations marking a critical shift in the region's climate regime. The lack of observatories necessitated the use of high-resolution datasets to ensure accurate analysis. This analysis develops our understanding of climate dynamics in the Beas Basin and highlights the broader implications of Climatic shifts in mountainous landscapes, emphasizing the importance of accurate and high-resolution data for effective climate modeling and regional planning. The findings highlight the importance of localized studies in addressing the challenges posed by climate change, offering guidance for policymakers and stakeholders to build resilience and ensure sustainable development in the region.

Keywords: Climatology, Spatial Trends, TerraClimate, Pettitt's Test, North Western Himalayas

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Improving Arctic Cloud Representation in Climate Models: The Role of Warm and Moist Air Intrusion

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The Arctic plays a critical role in global climate dynamics, yet climate models struggle to accurately represent Arctic clouds, leading to significant uncertainties in climate projections [1, 2]. Arctic amplification, characterized by rapid warming, is both influenced by and influences mid-latitude weather patterns, particularly through warm and moist air intrusions (WAMAI) [3]. These intrusions transport water vapor and aerosols that are essential for cloud formation, thereby altering the Arctic energy balance and affecting sea ice dynamics [4]. However, current climate models fail to capture the altered cloud characteristics associated with these intrusions, reducing their predictive accuracy . Understanding and accurately representing the microphysical responses of Arctic clouds to WAMAI is crucial for improving climate model reliability [5].

This research aims to address these limitations by investigating the physical processes governing Arctic cloud formation and evolution. Utilizing large-eddy simulations (LES) in conjunction with observational data from field campaigns such as ASCOS (The Arctic Summer Cloud Ocean Study), MOSAiC (Multidisciplinary Drifting Observatory for the Study of Arctic Climate), and ARTofMELT (Atmospheric Rivers and the Onset of Sea Ice Melt), we will identify the conditions leading to multilayer cloud formation and assess their microphysical responses on WAMAI.

By refining parameterization schemes, particularly in relation to vertical resolution and microphysical processes, this study aims to improve the representation of Arctic clouds in climate models. Given that clouds are a major source of uncertainty in global climate projections, enhancing their representation in Arctic models will lead to more reliable climate predictions on a global scale. This research will contribute to reducing uncertainties in climate projections and improving our understanding of Arctic cloud processes within the broader climate system.

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Machine Learning Prototyping for Hail Size Estimation in Germany

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Hail remains one of the least understood severe weather phenomena in Germany, posing significant challenges for forecasting and contributing to substantial economic losses, particularly in agriculture, infrastructure, and related insurance sectors. While the probability and frequency of hail occurrence have been studied, estimating hail size remains an open research question. The project HAIPI (Hailstorm Analysis, Impact, and Prediction Initiative) focuses on improving hail size estimates for hail events in Germany by integrating multiple datasets, including latest generation polarimetric radar products, crowd-sourced data, and numerical weather prediction (NWP) output.

Here we begin with an initial prototyping phase from the project in which we apply machine learning techniques, starting with a random forest approach to identify key input features relevant to hail size, which will be followed by neural networks for classification [1]. Special attention is given to crowd-sourced datasets from platforms such as the ESWD (European Severe Storms Database) and the DWD WarnWetter app, as well as to novel dual-polarization radar products (e.g., Z_{DR}, K_{DP}) and lightning data from the German national meteorological service (Deutscher Wetterdienst, DWD). Additionally, NWP products describing convective available potential energy (CAPE) and wind shear, along with other components of the DWD seamless forecast chain KONRAD3D, are incorporated to improve predictive capabilities.

Preliminary results from this prototyping phase with a random forest approach will be presented, highlighting the potential of integrating radar, NWP data, crowd-sourced observations, and machine learning methods to refine hail size estimation and forecasting.

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Enhancing Intra-city Scale Air Temperature Forecasting with Graph Neural Network

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Air temperature (T_a) varies significantly across different locations within cities due to local landscape and various anthropogenic influences, with critical implications for socioeconomic outcomes. While physics-based models often struggle to deliver fine-scale forecasts and tend to average out local variations, deep learning methods offer an alternative by directly leveraging local observations for training and prediction. However, weather patterns do not exist in isolation, necessitating consideration of broader-scale information in modeling approaches. Although large-scale information can capture weather propagation patterns, the potential benefits of information within smaller, intra-city scale observation networks remain unclear. In this study, we evaluated two types of graph-based models with different learning mechanisms alongside a location-independent model to explore the impact of spatial information. Our findings reveal that intra-city observation information remains effective but operates through an undirected mechanism. Furthermore, we introduce a novel framework that enhances graph construction and model configuration, leading to more robust forecasts. We also document detailed spatiotemporal performance patterns. With the increasing deployment of environmental sensors in urban areas, our approach offers a computationally efficient method for providing local-scale T_a forecasts.

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The Role of ENSO in Modulating Short-term Tropical SST Trends and Implications for Long-term Warming Patterns

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The pattern of tropical sea surface temperature (SST) warming in response to increasing greenhouse gas emissions plays a critical role in driving large-scale circulation and regional precipitation, as well as determining the magnitude of global-mean surface temperature rise. However, significant differences exist in the simulated tropical SST warming patterns over both short-term (1985-2014) and long-term (1930-2014) among models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6). It is expected that the model diversity in representing internal variability, particularly the El Niño-Southern Oscillation (ENSO) on interannual timescales, contributes significantly to the inter-model spread in SST warming patterns. To reduce the uncertainty in future climate projections, it is essential to separate the effects of internal variability and external forcing on SST warming patterns. In this study, we demonstrate a strong correlation between the simulated trends in the ENSO mode and the magnitude of SST gradient trend between the equatorial eastern and western Pacific, as well as a strong correlation between the ENSO trends and the magnitude of tropical-averaged SST trend over both periods of 30 and 85 years. To isolate the influence of ENSO on SST trends, we develop a simple yet effective method based on a modified Principal Component Analysis (PCA) method. Our results show that the observed cooling trend in the eastern Pacific during 1985-2014 is largely resulted from the trend in ENSO. Removing ENSO-related variations reduces the inter-model spread in the equatorial SST gradient trends by 64% (71%) and tropical-averaged SST trend magnitude by 18% (10%) for the short-term (long-term). Furthermore, the correlation between short-term and long-term warming patterns is significantly enhanced after removing ENSO effects. This finding suggests that accounting for ENSO's influence on short-term SST trends facilitates the inference of long-term warming patterns in response to external forcing, particularly given the limited observational records.

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Extreme Rainstorm in the Southern China Coastal Region: The Critical Role of Upper-level Wind Divergence Associated with the Subseasonal Variation of the South Asian High

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On September 7, 2023, the residual low-pressure system from Typhoon Haikui approached the Guangdong-Hong Kong-Macau Greater Bay Area (GBA), triggering an extreme precipitation event that broke historical records at multiple stations. From September 7 to 8, the 24-hour accumulated rainfall exceeded 200 mm, with Hong Kong experiencing rainfall rates surpassing 150 mm per hour. This unprecedented storm led to the issuance of the longest black rainstorm warning signal on record in Hong Kong. The extreme rainfall, which was not accurately forecasted in advance, resulted in severe urban flooding and widespread disasters. This study investigates the physical mechanisms driving the extreme rainfall by utilizing ERA5 reanalysis data, satellite observations, ground-based measurements, and the Weather Research and Forecasting (WRF) model. Our analysis reveals that the tropical easterly jet underwent fragmentation as the South Asian High shifted westward, coinciding with the southward extension of the trough in the subtropical westerlies. Simultaneously, the residual low-pressure center of Typhoon Haikui was positioned on the right-hand side of the tropical easterly jet's entrance, generating strong divergence at approximately 200 hPa. WRF simulations, both with and without nudging to ERA5 wind profiles, demonstrate that upper-tropospheric divergence played a critical role in initiating and sustaining the mesoscale convective systems responsible for the extreme rainfall. This study provides valuable insights for improving the forecasting of extreme precipitation events in the GBA, emphasizing the importance of upper-level atmospheric dynamics in such high-impact weather scenarios.

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Developing a deep learning model for high-resolution regional climate projection

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High-resolution precipitation projections with spatial and temporal coherence are crucial for understanding future climate change and assessing the local-scale impacts of extreme events. However, the high computational cost of traditional dynamical downscaling methods limits their resolution, simulation length, and capacity to represent uncertainty. Recent advancements in deep learning (DL) offer a computationally efficient alternative to traditional dynamical downscaling methods. A common limitation of existing DL-based approaches is their dependence on paired low- and high-resolution data, typically obtained by artificially coarsening high-resolution climate model outputs [1, 2, 3]. This raises concerns about the inheritance of systematic biases from the underlying climate models. Additionally, temporal dependency is often overlooked, which limits existing methods to daily time-scales that do not capture short duration high impact events that typically occur on sub-daily time scales.

Generative DL models offer a more flexible training framework and can potentially address the temporal alignment between low and high resolution data. They also enable the generation of ensembles, allowing for a better representation of uncertainty in downscaling climate projections. In this study, a diffusion-based generative framework is presented: the model is first trained on a spatially and temporally coherent km-scale observations-based reanalysis to learn fine-scale precipitation dynamics and is then conditioned on large-scale predictor fields during inference. The aim is to produce high-resolution precipitation fields that are spatially and temporally coherent, dynamically consistent with large-scale atmospheric states, and applicable to downscaling climate model outputs for future projections.

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