Simulating the Influence of the Agulhas Current on Cut-Off Low-Induced Flooding in KwaZulu-Natal, South Africa

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ABSTRACT

Cut-off low-induced floods are a threat to socio-economic activities in the KwaZulu-Natal (KZN) province of South Africa due to the associated landslides and high-impact disasters. When cut-off lows (COLs) track over southeastern Africa, they may interact with the Agulhas Current (AC). While studies have shown that the Agulhas Current plays a crucial role in rainfall over South Africa, there is no information on how the current affects floods over KZN, especially through COLs. The present study examines the impact of the Agulhas Current System (ACS) on COL-induced floods in KZN, with a focus on the specific event of the April 2022 Cut-Off Low. For the study, a flood prediction system called the Africa Flood Prediction System (AFPS) was developed by coupling atmospheric, hydrologic, and hydraulic models. First, we evaluate the AFPS model and quantify the sensitivity of COL-driven precipitation to ACS-modulated sea surface temperature anomalies and then evaluate how COL-driven rainfall propagates into basin-scale streamflow response. Thereafter, we assess how precipitation and streamflow translate into flood extent and inundation dynamics.

Results show that the AFPS provides credible simulations of the COLs and their associated extreme rainfalls, peak streamflow, and flood hazards over KZN. Also, it demonstrates that ocean-modulated atmospheric forcing strongly induces rainfall intensity and spatial organisation, while hydrological and hydraulic responses exhibit nonlinear sensitivity to precipitation magnitude and timing. Although explicit ACS sensitivity experiments are applied only at the atmospheric level in this phase, the cross-scale evaluation establishes a robust baseline for forthcoming end-to-end flood sensitivity attribution. The findings highlight the importance of explicitly representing ocean–atmosphere interactions in flood prediction and risk assessment frameworks for coastal southern Africa.

KEYWORDS: Flooding, Cut-off low, Extreme rainfall, Agulhas Current, Atmosphere-ocean interaction, regional modelling, KwaZulu-Natal, Southern Africa.

1 INTRODUCTION

Cut-off lows (COLs) are recurrent synoptic-scale systems over southern Africa and are frequently associated with prolonged and spatially extensive rainfall. In KwaZulu-Natal, such systems have been responsible for several high-impact flood events (Holloway et al. 2010; Favre et al. 2013; Molekwa et al. 2014), including the catastrophic April 2022 disaster. The extreme rainfall of April 2022, which battered towns in the region, resulted in a catastrophic flood which left 40,000 people displaced, 88 people missing, and at least 443 dead (Thoithi et al. 2022; Grab and Nash 2023). Despite the regular occurrence of COLs, only a subset generates extreme precipitation (Molekwa 2013; Abba Omar and Abiodun 2020), indicating that regional-scale environmental controls play a decisive role in modulating rainfall intensity. Therefore, improving our understanding of various local-scale features in the vicinity of South Africa is essential for assessing their influence on COL-induced precipitation.

Previous studies have highlighted the importance of mesoscale interactions, including low-level jets, coastal mesolows and mesoscale convective systems, in shaping COL rainfall distribution (Jury 2015; Imbol Nkwinkwa et al. 2021; Thoithi et al. 2022). More recently, attention has turned towards the potential influence of the Agulhas Current System (Reason 2001; Rouault et al. 2002; Jury 2015), a warm western boundary current that enhances surface fluxes and onshore moisture transport. While observational and modelling studies suggest that the ACS may amplify storm systems along South Africa's east coast, its direct contribution to COL-induced flood has not been explicitly quantified. This study addresses this gap by isolating the influence of the ACS on a well-documented extreme COL event using the coupled atmosphere-hydrology-hydraulic model, with specific emphasis on implications for flood hazard assessment.

2 DATA AND METHODOLOGY

The analysis focuses on the April 2022 cut-off low that produced exceptional rainfall and flooding over KwaZulu-Natal. A top-down modelling framework was developed to simulate the April 2022 COL-induced flood event over KZN, integrating atmospheric, hydrological, and hydraulic components. Atmospheric simulations were conducted using the Model for Prediction Across Scales (MPAS), configured with variable-resolution meshes to resolve mesoscale circulation features over southern Africa and the adjacent southwest Indian Ocean. The model configuration enables explicit representation of moisture transport pathways associated with COL systems.

Hydrological simulations were performed using the Soil and Water Assessment Tool Plus (SWAT+) over the uMlazi River Basin, which experienced severe flooding during the April 2022 event. The model incorporates spatially distributed representations of land use, soil properties, topography, and river networks. Meteorological forcing was derived from MPAS precipitation outputs combined with reanalysis-based variables. A multi-month spin-up period was applied to stabilise soil moisture and groundwater storage before event-scale simulations. Model performance was evaluated against observed streamflow using standard statistical diagnostics, with emphasis on hydrograph timing, peak discharge magnitude, and overall flow dynamics.

Flood propagation and inundation dynamics were simulated using the Hydrology Engineering Centre's River Analysis System (HEC-RAS) hydraulic model over a critical downstream reach of the uMlazi River. Both observed and SWAT+-simulated hydrographs were applied as upstream boundary conditions to assess sensitivity to discharge magnitude and timing. Model outputs were evaluated against satellite-derived flood extent maps and post-event observational evidence. Additional idealised hydraulic experiments employing synthetic hydrographs were conducted to explore nonlinear floodplain responses to increasing peak discharge, providing a controlled framework for sensitivity assessment.

To assess sensitivity to oceanic forcing, a suite of idealised SST perturbation experiments is conducted over the Agulhas Current region using the MPAS model. These include a control simulation with unmodified SSTs, a cooling experiment that limits warm SST anomalies, and a warming experiment that amplifies them. This framework enables isolation of the ACS influence on moisture supply, latent heat fluxes and convective instability during the COL event.

3 RESULT AND DISCUSSION

3.1 Evaluation of the Coupled Modelling Framework

The AFPS framework was first evaluated by simulating the April 2022 cut-off low (COL) event in a component-wise manner, beginning with atmospheric processes and propagating the resulting forcing through hydrological and hydraulic components. This approach allows assessment of the internal consistency of the modelling chain before attribution or sensitivity analysis.

MPAS successfully captures the synoptic evolution of the April 2022 COL, including its cold-core structure, slow south-eastward progression, and the characteristic concentration of rainfall along the eastern flank of the system (Fig. 1). At coarse horizontal resolution, the model reproduces the broad-scale rainfall signal but exhibits spatially diffuse precipitation patterns and timing biases over KwaZulu-Natal. Increasing horizontal resolution to convection-permitting scales substantially improves the representation of low-level moisture convergence and orographically enhanced rainfall, resulting in more realistic coastal precipitation maxima. These results demonstrate that MPAS provides physically consistent atmospheric forcing suitable for downstream hydrological applications.

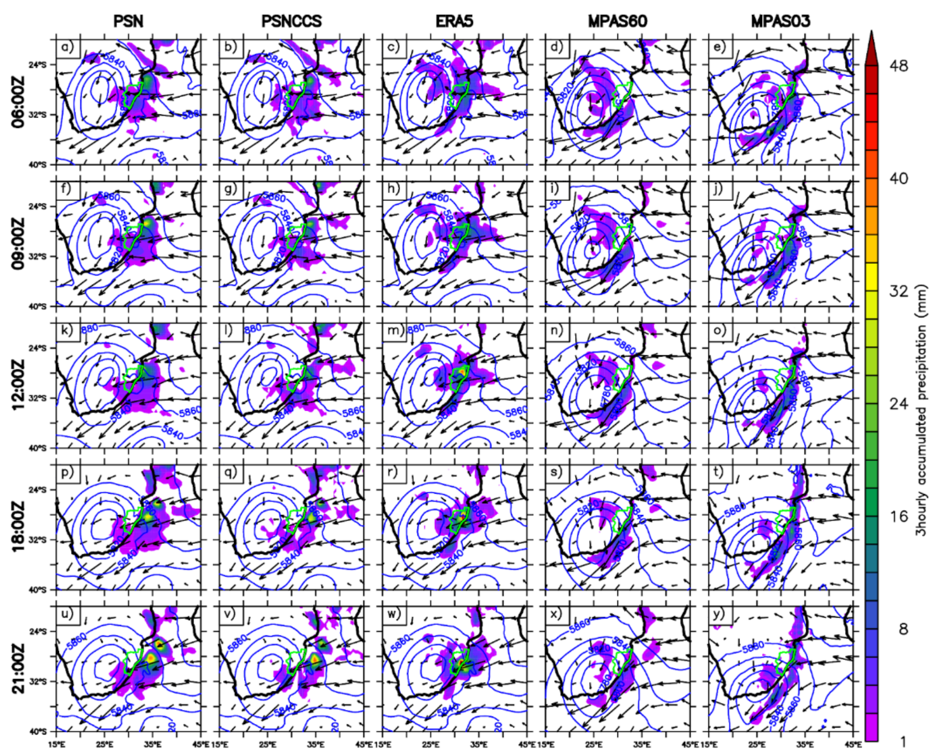

Figure 1: 500 hPa geopotential Height (blue contour; m), 850 hPa wind field (black vector; ms^{-1}) and the COL-associated 3-hourly accumulated precipitation (shaded, mm) as represented by the observation (PSN, PSNCCS), ERA5 reanalysis and MPAS simulations (MPAS60 and MPAS03). The green polygon represents the KwaZulu-Natal province of South Africa.

The simulated precipitation fields were subsequently used to force the SWAT+ hydrological model over the uMlazi River Basin. The simulated hydrographs reproduce the general timing and structure of observed streamflow, with peak discharge broadly coinciding with periods of extreme rainfall (Fig. 2). However, peak flows are systematically overestimated and exhibit secondary maxima, indicating sensitivity to biases in precipitation magnitude and temporal phasing. The combined precipitation–streamflow diagnostics (combined Figures 4.4 and 4.6) illustrate both the capacity of SWAT+ to translate mesoscale rainfall forcing into runoff and the importance of targeted calibration when coupling atmospheric and hydrological models.

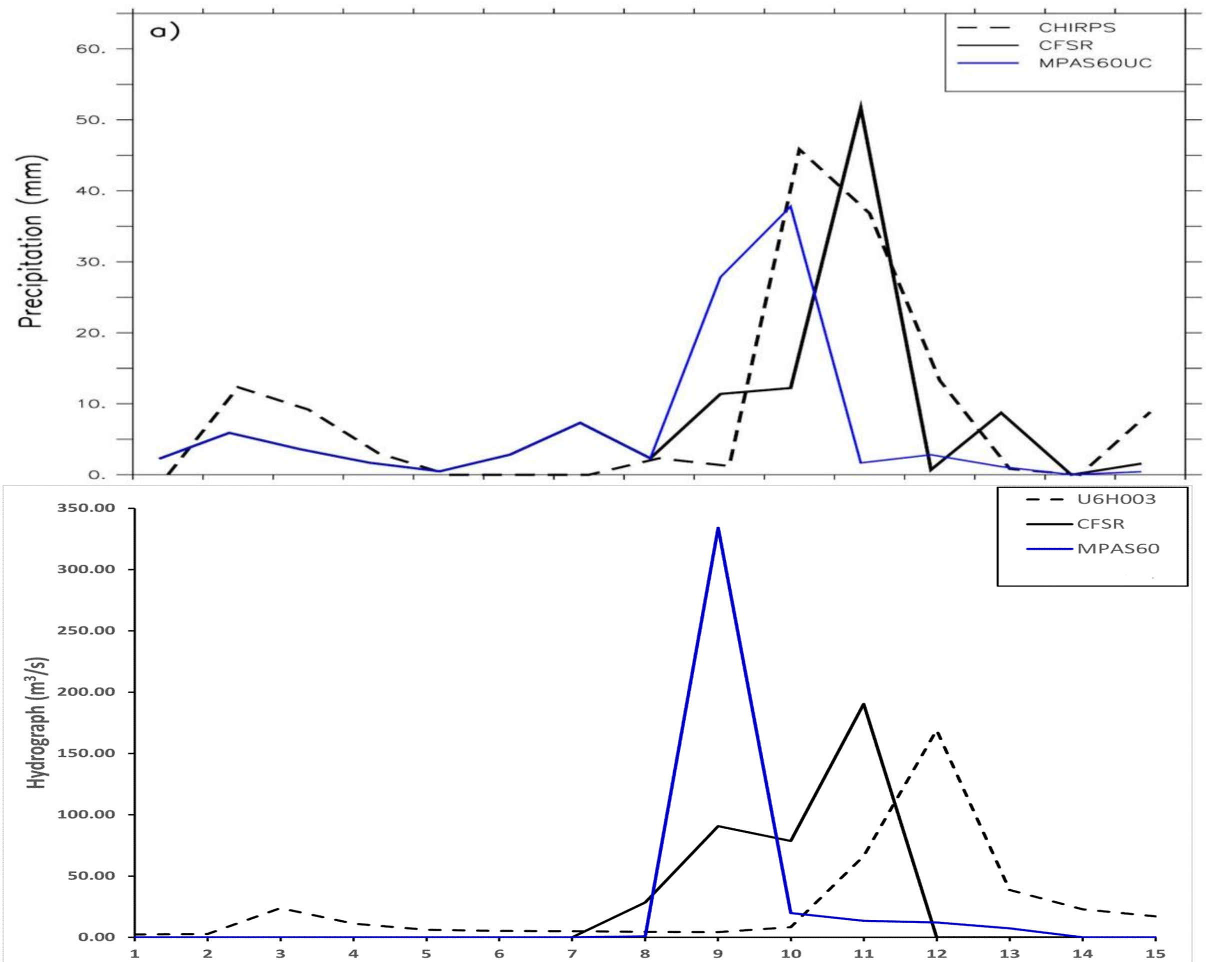

Figure 2: Temporal distribution of (a) daily precipitation over the study region from the period 1 - 15 April 2022 as depicted by CHIRPs, CFSR reanalyses, and MPAS 60 km simulation, and (b) daily hydrograph of SWAT+ initialised with CFSR and MPAS60 simulation.

Hydrological outputs were then passed to the HEC-RAS hydraulic model to simulate flood propagation and inundation over a vulnerable reach of the uMlazi River. Using both observed and SWAT+-derived hydrographs as boundary conditions, the model reproduces the main zones of flood inundation along the river corridor. Bias correction of simulated inflows improves agreement with satellite-observed inundation patterns, particularly along the main channel and adjacent low-lying floodplains. Nevertheless, inundation is underestimated in some urban areas, reflecting uncertainties in digital elevation data resolution and channel representation. Comparisons of observed and simulated flood extents and depths (Fig. 3) confirm that hydraulic outcomes are highly sensitive to upstream discharge magnitude and timing.

A key advantage of the sequential evaluation presented above is that it establishes confidence in the internal consistency of the coupled modelling framework, thereby providing a physically defensible basis for isolating and interpreting the influence of oceanic forcing on atmospheric processes.

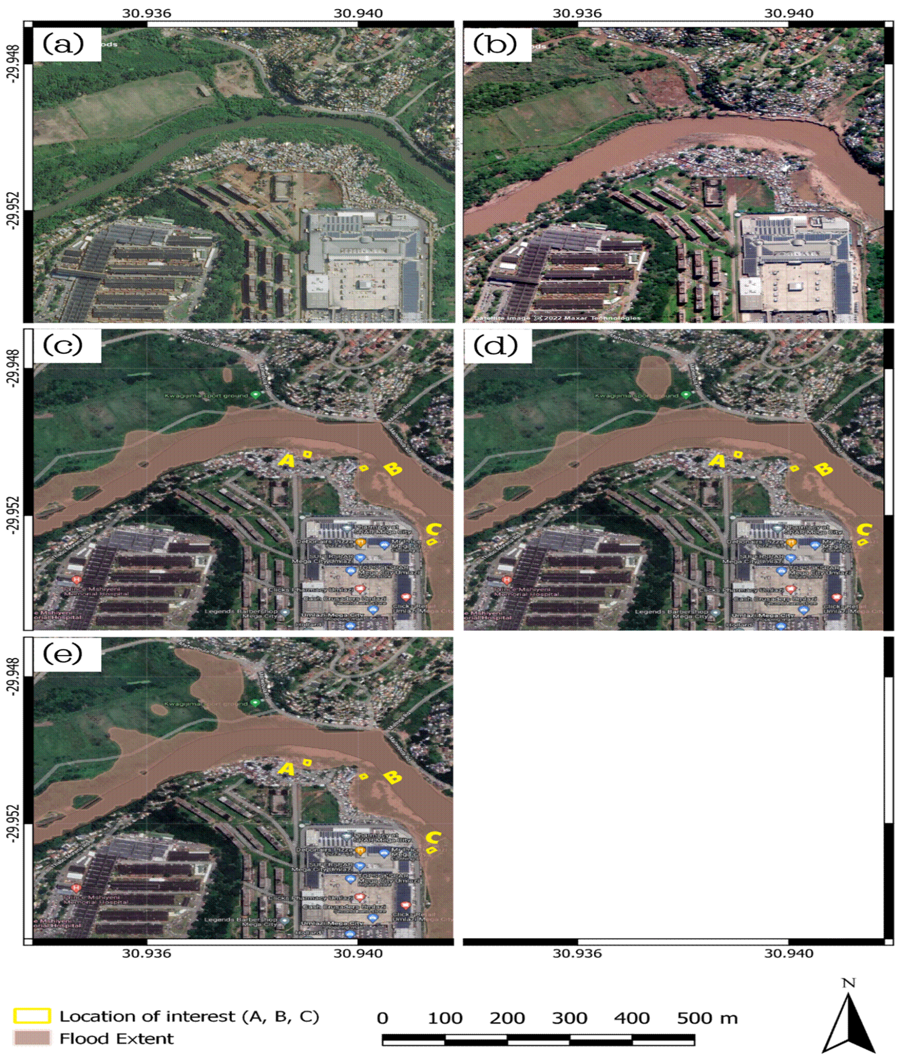

Figure 3: The map of the uMlazi area showing the area before the flood (a) and flood extent of the 10 -13 April 2022 flood as observed (b) and simulated with (c) U6H003, (d) CFSR, and (e) MPAS60 hydrographs. The yellow letters and small boxes indicate the locations of interest.

3.2 Sensitivity of COL-Induced Precipitation to the Agulhas Current System

Following evaluation of the coupled framework, sensitivity experiments were conducted to examine the influence of the Agulhas Current System (ACS) on COL-induced precipitation. Analysis of moisture fluxes confirms that the dominant moisture source for the April 2022 event originates over the southwest Indian Ocean, consistent with reanalysis diagnostics. Perturbations to ACS thermal conditions reveal a strong dependence of COL rainfall on oceanic forcing.

Cooling the Agulhas Current substantially weakens low-level moisture advection and surface latent heat fluxes, leading to a marked reduction in coastal rainfall and a displacement of convective activity offshore. In contrast, warming the current enhances near-surface moisture supply and convective buoyancy, resulting in increased coastal precipitation, although the inland rainfall response remains comparatively muted. This asymmetric rainfall response highlights nonlinear feedback between sea surface temperature anomalies, boundary-layer moisture availability, and convective dynamics. These results demonstrate that the Agulhas Current acts as an effective regulator of COL-induced rainfall intensity, with direct implications for flood forecasting in coastal and adjacent inland catchments.

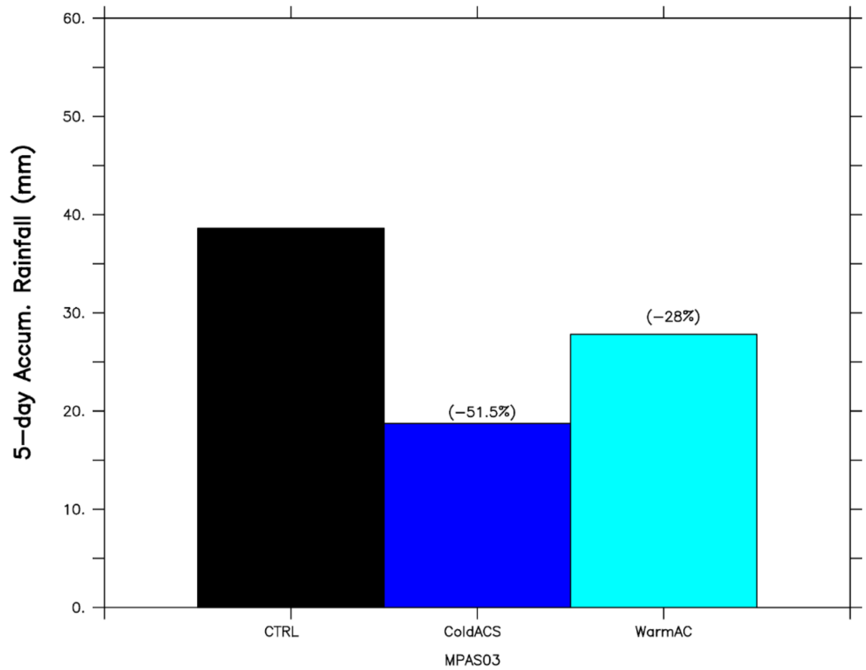

Figure 4: Accumulated precipitation (over 5 days from 8 - 12 April 2022) over the KwaZulu-Natal province (shown as green contour in Figure 1) as simulated in the control (CTRL; black bar) and the two scenarios (ColdACS; blue bar and WarmACS; cyan bars) for MPAS03. The values in brackets quantify the percentage error related to the control (CTRL) over the KwaZulu-Natal.

4 CONCLUSIONS

This extended abstract synthesises the first three objectives of a broader investigation into ACS–COL–flood interactions over KwaZulu-Natal. The results demonstrate that ocean-modulated atmospheric forcing substantially conditions extreme rainfall during COL events, while downstream hydrological and hydraulic responses exhibit nonlinear sensitivity to precipitation magnitude and timing. By establishing a coherent end-to-end modelling framework, the study provides a foundation for explicit attribution of ocean–atmosphere influences on flood hazards in coastal southern Africa. Ongoing sensitivity experiments will further quantify the role of the Agulhas Current in shaping flood risk and will be presented at the conference.

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