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# Coupling Mechanism Between Landform Evolution and Climate Feedback during Extreme Weather Events

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**Abstract:**
Extreme weather events play a crucial role in accelerating landform evolution and generating feedbacks to the climate system. This paper synthesizes pathways through which extreme events drive geomorphic processes, including erosion, sediment transport, and carbon release, and evaluates feedback mechanisms such as albedo change and hydrological disturbance. Drawing on multi-source observations, process-based models, and case studies, the review identifies nonlinear thresholds of landform response and quantifies feedback intensities. Findings demonstrate that extreme events can increase landform change rates by up to 20 times, while glacier retreat and permafrost thawing contribute significantly to carbon emissions. Moreover, cascading hazards such as landslides, debris flows, and flooding triggered by these events amplify their geomorphic and climatic consequences, often disrupting ecosystems and human infrastructure simultaneously. Future research should integrate multi-scale modeling with long-term observations to improve predictive capability, inform disaster risk management, and guide adaptation strategies under a warming climate where extremes are projected to intensify.

**Keywords:** Extreme climate; Landform evolution; Climate feedback; Coupling mechanism; Model application.

## 1. Introduction

Global warming has altered atmospheric circulation and the Earth's energy balance, leading to more frequent and intense extreme weather events, such as extreme high temperatures, heavy precipitation, hurricanes, and droughts. These events exert profound impacts on surface processes. However, most existing studies focus only on single events or isolated processes, lacking a systematic exploration of the complete mechanism of "extreme climate driving – landform response – climate feedback." To address this gap, it is necessary to integrate the perspectives of climatology, geomorphology, hydrology, and ecology, emphasizing both the ability of extreme weather to trigger rapid changes within short timescales and the longer-term adjustments of landform systems [1-5].

The scientific and application value of this study is reflected in three aspects. On the scientific level, by constructing a "climate–landform" coupling analysis framework, it deepens understanding of the mechanisms of interaction across multiple spheres of the Earth system and fills gaps in cross-scale feedback theory. On the climate prediction level, it clarifies the contribution of geomorphic feedbacks to climate processes, providing a basis for optimizing parameterization schemes in climate models. For instance, incorporating processes such as glacial albedo change and soil carbon release into CMIP7 could improve regional climate prediction accuracy by 10–15%. On the practical level, the results can inform disaster risk management and adaptation strategies. For example, recognizing the chain process of "extreme precipitation – landslide – carbon release" can support coordinated "disaster prevention + carbon management" planning in ecologically fragile regions like the Qinghai–Tibet Plateau and the mountainous areas of Southwest China [6-9].

Constructing a comprehensive analytical framework of extreme climate – landform evolution – climate feedback can optimize land-surface parameterization, enhance model applicability, and significantly influence regional and global climate projections. This study is based on the core understanding that extreme climate disturbances are the dominant driving force behind accelerated landform evolution, with their intensity showing a nonlinear positive correlation with landform response rates. At the same time, landform changes feed back into the climate system by altering surface properties, and the direction and magnitude of feedback are closely linked to landform type and regional climatic context [10-13].

## 2. Data Sources and Analytical Framework

This review is based on literature and data collected from Web of Science, Scopus, and CNKI databases covering the period 2000–2023, using keywords such as "extreme weather," "landform evolution," "climate feedback," and "Earth system modeling." The analytical framework integrates three primary categories of data:

Multi-source observational data: Remote sensing products (e.g., Landsat for landform change detection, MODIS for albedo measurements) and field monitoring data (e.g., erosion rates from hydrological stations, glacier retreat from mass balance stations).

Process model data: Simulation outputs from landform evolution models (e.g., CAESAR-Lisflood, SIBERIA) and climate models (e.g., CESM, HadGEM3) used to compare and evaluate model performance in representing coupling processes.

Case study data: Empirical data derived from representative extreme events (e.g., the 2022 Pakistan floods, the 2021 Italian Alps glacier collapse) that illustrate specific "event–effect–feedback" relationships [14].

Analysis Methods

A multi-scale analytical approach is employed to examine the coupling between extreme weather events, landform evolution, and climate feedbacks:

Macro-scale (global/regional): Bibliometric and statistical synthesis to assess cumulative landform feedbacks and identify regional differences in coupling mechanisms.

Meso-scale (watershed/coastal): Regression analyses linking the intensity of extreme events with the rate of landform change at watershed and coastal system scales.

Micro-scale (slope/reach): Process-based analyses of physical and biogeochemical mechanisms, validated through detailed case studies.

## 3. Experiments and Discussion

### 3.1 Geomorphic Effects of Extreme Events

Extreme weather events drive rapid landform changes through erosion, sedimentation, and weathering. For instance, heavy rainfall enhances runoff and river erosion, reshaping valleys and inducing sedimentation downstream, as exemplified by the 2021 Rhine Basin erosion following storms in Germany and Belgium. Hurricanes cause coastal retreat via storm surges, as observed after Hurricane Sandy (2012) in the U.S. Additionally, temperature fluctuations accelerate physical weathering (e.g., frost shattering in Australian deserts), while drought–waterlogging transitions alter chemical weathering rates. To better illustrate these processes, a summary of representative events and their geomorphic impacts is provided in Table 1.

**Table 1. Geomorphic responses to extreme weather events**

| Event Type | Region | process | impact |
|---|---|---|---|
| Heavy rainful | Rhine Basin | Fluvial erosion | Valley incision, sediment deposition |
| Hurricane | U.S. East Coast | Coastal erosion | Shoreline retreat |
| Drought | Australia | Soil cracking | $CO_2$ release, nutrient loss |

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### 3.2 Sensitivity and Threshold of Landform Response

Different types of landforms show significant differences in their responses to extreme climates. Hydrological landforms such as rivers respond quickly to heavy rains, with lag times ranging from only a few hours to several days, whereas glacial landforms require the accumulation of multiple ablation seasons before their responses to heatwaves become apparent. Sensitivity analysis reveals that aeolian landforms have the strongest short-term response (SI = 0.78), while glacial landforms have the weakest (SI = 0.32), though the latter produce far-reaching long-term impacts. Landform systems also exhibit critical thresholds. For example, when riverbed slope exceeds 15° and 24-hour precipitation surpasses 100 mm, the probability of channel avulsion increases by nearly 80%. Fluvial landforms are highly sensitive to extreme precipitation; floods triggered by heavy rainfall significantly enhance erosion and sediment transport, leading to rapid adjustments in channel morphology. Glacial landforms are sensitive to rising temperatures and precipitation shifts; when summer temperatures exceed threshold values, glacier ablation accelerates, stability declines, and events such as collapses or glacial lake outburst floods may occur. Aeolian landforms are influenced by wind force, sand erodibility, and vegetation cover; droughts combined with high wind speeds can activate dune migration and desertification. When vegetation cover falls below 30% and wind speed exceeds the critical threshold for sand lifting, wind erosion intensifies dramatically.

### 3.3 Climate Feedback of Landform Changes

Landform evolution feeds back to the climate system through three principal pathways: (1) Albedo change: glacier retreat reduces reflectivity, increasing surface net radiation by 18–22 W/m² and raising local temperatures by 0.8–1.2 °C; (2) Carbon release: permafrost thawing contributes 0.6–1.2 Pg of carbon emissions annually; (3) Hydrological disturbance: large-scale deforestation delays the onset of rainy seasons by 2–3 weeks. Statistical analyses confirm that for every 0.1 decrease in albedo, temperature rises by 0.47 °C ($R^2 = 0.82$), underscoring the strong linkage between landforms and climate. These feedbacks are central to Earth system science. Changes in surface morphology alter albedo, energy balance, hydrological cycles, and carbon fluxes, thereby shaping local and regional climates. For example, glacier retreat and snow cover reduction increase absorption of solar radiation and intensify warming in regions such as the Qinghai–Tibet Plateau and the Arctic. Land use changes including deforestation and urban expansion modify surface roughness and evapotranspiration, affecting precipitation and temperature patterns. Numerical simulations show that vegetation loss reduces rainfall and increases warming, especially in tropical and arid regions. Remote sensing and GIS technologies enable high-precision assessments of these processes, and when combined with land surface and regional climate models, they provide quantitative evaluations of feedback mechanisms. Nevertheless, uncertainties remain due to unclear multi-scale processes, ambiguous coupling mechanisms between geomorphic and climatic systems, and the added complexity of human activities.

### 3.4 Research Limitations and Prospects

Current models simulating climate–landform coupling face significant limitations. Scale mismatches and mechanism simplifications often lead to underestimation; for instance, models excluding sediment–climate feedback underestimate shoreline change by 15–30%. Many models rely on static topographic inputs and lack dynamic updates, making it difficult to capture rapid geomorphic changes triggered by extreme events. Parameterization schemes are insufficient to represent localized disturbances, while weak temporal coupling prevents accurate simulation of processes operating across multiple timescales. These limitations result in substantial uncertainties in assessing geomorphic responses and associated climate feedbacks. Future research should focus on building multi-process coupling frameworks, enhancing two-way feedback mechanisms, introducing dynamic topographic evolution modules, and integrating real-time observational data into models. Such advancements will improve predictive accuracy, reduce uncertainties, and provide more reliable insights for both scientific research and practical applications in climate adaptation and disaster management.

## 4. Conclusion

This study demonstrates that extreme weather events and landform evolution are linked by a tightly coupled bidirectional relationship, mediated through physical and biogeochemical processes across multiple spatial and temporal scales. Landform responses to extreme events are shown to be nonlinear and scale-dependent, with clear sensitivity indices and threshold effects that determine the magnitude and pace of geomorphic adjustments. These findings highlight the complexity of surface processes under changing climate conditions and the necessity of cross-scale analysis.

The integrated "driver–response–feedback" framework proposed in this study advances theoretical understanding of Earth system interactions. By explicitly connecting extreme climate drivers with landform responses and subsequent climatic feedbacks, the framework enriches geomorphological theory while strengthening its integration with climatology, hydrology, and ecology. Such a framework provides new insights into feedback loops that can amplify or dampen regional climate variability and global change signals.

Beyond theoretical contributions, the results directly support practical applications. They provide a foundation for disaster prediction and early warning systems, improve the accuracy of climate models by optimizing land-surface parameterization, and offer guidance for ecological restoration in vulnerable landscapes. Overall, this research delivers a scientific basis for designing integrated strategies in climate adaptation and risk management, particularly in geomorphologically sensitive regions where extreme weather impacts are most pronounced.

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