DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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灾害、风险、预测、防治

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Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

Debris flows and climate dynamics in natural areas of Eastern Cuba

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Abstract. Debris flows are triggered by intense rainfall and are often associated with tropical cyclones. Preceding precipitation, as one of the determining factors for debris flow occurrence, is a variable of interest in assessing the risk of debris flows triggered by such events. In this research, we conducted an initial analysis of the effects that local climate dynamics can have on the likelihood of debris flow occurrence in conserved natural zones. We utilized a landslide inventory to identify five topoclimates where concentrations of debris flows exist in the natural areas of eastern Cuba. For each of these topoclimates, we analyzed the evolution of local climate characteristics, as well as water and bioclimatic balances, across the following time series: 1970–2000, 2000–2040, 2040–2060, 2060–2080, and 2080–2100, considering two shared socioeconomic trajectories. Our results show that the monthly rainfall distribution throughout the year in high-risk debris flow zones will remain relatively stable under the studied scenarios, with a slight decrease in soil saturation occurring during the central months of the hurricane season. However, in topoclimates with a significant proportion of debris flows, a steep reduction in available water within ecosystems is anticipated for most of the hurricane season, potentially mitigating the danger posed by debris flows in the area. Furthermore, the increase in temperature favors atmospheric water vapor in a positive feedback loop, which increases precipitation intensity, especially during severe rainfall events, consequently altering the conditions of occurrence of landslides.

Key words: *topoclimates; debris flows; climate change; hydrologic balance; severe weather events*

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Селевые потоки и динамика климата в природных зонах Восточной Кубы

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Аннотация. Селевые потоки вызываются интенсивными дождями и часто связаны с тропическими циклонами. Предшествующие осадки, как один из определяющих факторов возникновения селевых потоков, являются переменной, представляющей интерес для оценки риска селевых потоков. В данном исследовании мы провели первоначальный анализ влияния местной динамики климата на вероятность возникновения селей в охраняемых природных зонах. Использовалась инвентаризация оползней, чтобы определить пять топоклиматов, к которым приурочены селевые потоки в природных зонах Восточной Кубы. Для каждого из этих топоклиматов проанализирована эволюция местных климатических характеристик, а также водных и биоклиматических балансов в следующих временных рядах: 1970–2000, 2000–2040, 2040–2060, 2060–2080 и 2080–2100 гг. учитывая две общие социально-экономические траектории. Наши результаты показывают, что ежемесячное распределение осадков в течение года в зонах высокого селевого риска останется относительно стабильным в рамках изученных сценариев, с небольшим снижением насыщения почвы, происходящим в середине сезона ураганов. Однако в топоклиматах со значительной долей селевых потоков ожидается резкое сокращение количества доступной воды в экосистемах на протяжении большей части сезона ураганов, что потенциально смягчит опасность, которую представляют селевые потоки в этом районе. Кроме того, повышение температуры благоприятствует образованию водяного пара в атмосфере по принципу положительной обратной связи, что увеличивает интенсивность осадков, особенно во время сильных дождей, и, как следствие, изменяет условия возникновения оползней.

Ключевые слова: *топоклиматы, селевые потоки, изменение климата, гидрологический баланс, суровые погодные явления*

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Introduction

Debris flows are commonly associated with episodes of intense rainfall, with the intensity of precipitation being one of the most relevant factors in their occurrence [*Pospehov et al., 2023*]. However, other characteristics of the rainfall regime, such as prior precipitation, are also factors to consider when predicting the occurrence of debris flows [*Zhang et al., 2014*]. Consequently, the behavior of other climate elements and related phenomena resulting from the interrelationships of the climate system, especially those related to the hydrological cycle, become relevant in the context of climate variability and change [*Green et al., 2017; Zaitchik et al., 2023*].

While the majority of the research related to climate change impacts on the probability of debris flow occurrence refers to alterations in rainfall regimes [*Jakob, 2022; Lin et al., 2022*], these studies have generally focused on global and regional scales in heavily anthropized environments. Analyzing climate characteristics with a local focus, such as that provided by topoclimate research [*Atkinson, 2003*] in mountains with a predominance of natural areas, can provide relevant information for the planning of risk reduction strategies and adaptation to climate change for local stakeholders.

Debris flows can have significant impacts both on the natural environment and on society [*Fan et al., 2020*]. In relatively preserved natural areas, however, debris flows can be considered natural phenomena to which endemic species have adapted throughout their evolution. Nevertheless, the reduction in preserved areas, the expansion of invasive species, and anthropic pressure have turned massive debris flow events into a cause for concern from a biodiversity conservation perspective.

An example of an atmospheric event known to trigger massive debris flows is tropical hurricanes in the insular Caribbean. Eastern Cuba hosts one of the largest biodiversity reserves in the insular Caribbean. It is home to the Cuchillas del Toa Biosphere Reserve, a World Heritage Site notorious for its biodiversity in the insular Caribbean, with the highest number of endemic taxa in this region [*Gallardo-Toirac et al., 2023*]. This region records the highest rainfall values of the island, with intense rainfall events during the months of October and

November, often associated with the influence of tropical cyclones [*Peña-de la Cruz et al., 2013*].

In meteorological sciences, the concept of climate dynamics encompasses the behavior and interrelation of the components of the climate system and their evolution, including human impact. This research analyzes the temporal dynamics in the topoclimates of eastern Cuba, where debris flow events triggered by tropical hurricanes have been recorded. In this context, climate dynamics are considered the evolution of the atmosphere subsystem at a local scale and its relationship with the hydrological regime in two human impact scenarios.

Methods and data

The study was conducted in the natural areas of Eastern Cuba (Fig. 1). This region is sparsely populated, with a significant proportion under conservation. Cuban humid forests predominate in the area, in which the average annual precipitation reaches 2200 mm. The relief is abrupt, with steep slopes known locally as “cuchillas”. The elevations are relatively low, averaging 360 m above sea level.

An inventory of landslides carried out after hurricane Matthew [*Pospehov et al., 2023*] was used as a reference to identify the areas with the highest danger of debris flow events. Hurricane Matthew was a high-intensity tropical cyclone that moved through the Atlantic and the Caribbean, reaching a maximum of 5 on the Saffir-Simpson scale. In Cuba, Hurricane Matthew made landfall on October 4, 2016, at 18:00 local time on the south coast of the eastern mainland in a north–northwest direction and category 4 on the Saffir-Simpson scale. During October 5, 6, and 7, accumulated rainfall of up to 700 mm was recorded in some areas of the region under the influence of its feeder bands [*Stacy R. Stewart, 2017*]. This hurricane caused catastrophic damage to the infrastructure and vegetation of the area, which was valued at 2430.8 million pesos by the Cuban government.

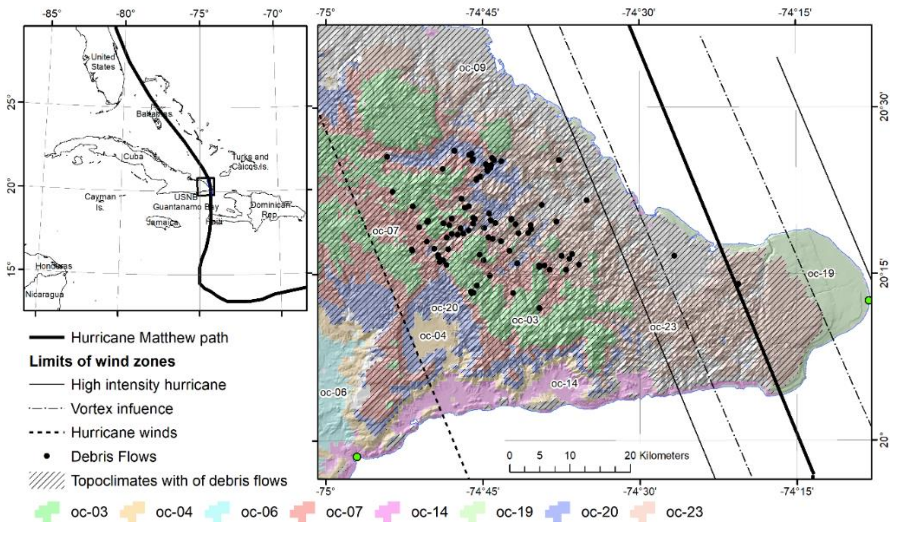

Fig. 1. Map of the study area, topoclimates, and debris flows recorded in the area. The limits of the hurricane wind intensities are shown as a reference. The locations of the debris flows were taken from Pospehov et al. [*2023*]. Source: prepared by the authors

The topoclimates were delineated using patterns of local climate types according to complex climatology theory [*Piotrowicz and Ciaranek, 2020*]. Similar patterns of diurnal cycles of temperature and relative humidity were identified for the rainy (PLL) and less rainy (PPLL) periods in the area. Each topoclimate is a cluster from a dimensional reduction of the patterns made with a deep autoencoder. The topoclimates that recorded debris flow events during the hurricane were selected for this study. The evolution of local climatic characteristics and water balance for each climate reference and future climate terms was analyzed.

The analysis and evolution of topoclimates were determined using two climatic elements: temperature and precipitation. Climatological series from 1970–2000, used as a reference period, and from 2040, 2060, 2080, and 2100 were used. For the medium-term climate (MT) scenario, the 2040–2060 series was used, and the 2080–2100 series was used for the long term (LT) scenario. The source of climatological data used was the WorldClim v2.1 product [*Fick and Hijmans, 2017*]. A set of five global climate models (MCG) with a history of use in the Caribbean region included in the CMIP6 [*Eyring et al., 2016*] was selected: HadGEM3, MIROC6, MPI-ESM1-2-HR, FIO-ESM-2-0, and BCC-CSM2-MR.

Two shared socioeconomic pathways (SSPs) [*Riahi et al., 2017*] were considered to consider the human impact on the evolution of the future climate. These pathways were selected based on current trends according to Hausfather and Peters [*2020*]: SSP2-4.5 was the most trending pathway, and SSP5-8.5 was the most negative extreme. The Bioclim package implemented in R language v3.0 [*Serrano-Notivoli et al., 2022*] was used for the hydrological balance analyses.

Results and discussion

The intersection of the topoclimates and debris flows allowed the identification of five topoclimates in the eastern region of Cuba prone to debris flows (Table 1). The analysis focused on the oc-20, oc-23, oc-07, and oc-03 topoclimates. The oc-09 topoclimate does not present a significant number of events.

Table 1. Debris flows recorded for each topoclimate, debris flows count, from [*Pospehov et al., 2023*]

Topoclimate	Debris flows
oc-20	25
oc-23	29
oc-07	21
oc-03	17
oc-09	2

The topoclimates associated with debris flows are similar in the rainfall regime, with maximum values occurring between the months of May, September, and October (Fig. 2).

According to the Walter-Lieth climogram of those topocliamtes, the evolution of the average monthly accumulated rainfall will remain relatively stable. However, a disturbance related to the impoverishment of the relative minimum values of the month of July within the summer period is expected. This decrease was accentuated in the oc-20 topoclimate for the SSP5-8.5 trajectory (Fig. 2). The increase in the monthly average temperature is consistent in all the terms and trajectories analyzed.

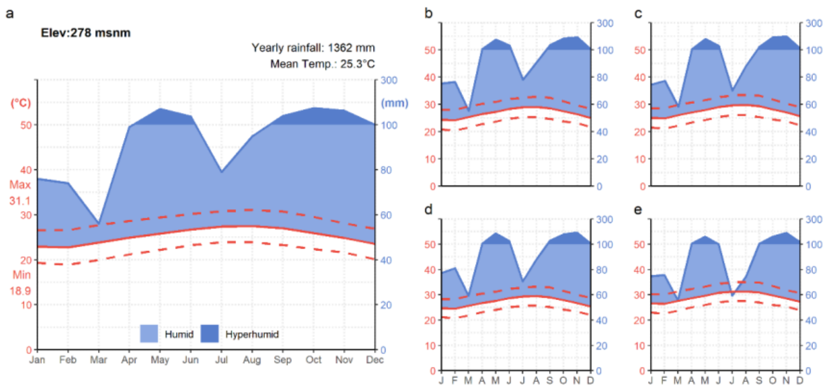

Fig. 2. Walter-Lieth climogram for the oc-20 topoclimate. a – reference period; b – SSP2-4.5 MT; c – SSP2-4.5 LT; d – SSP5-8.5 MT; and e – SSP5-8.5 LT. Source: prepared by the authors

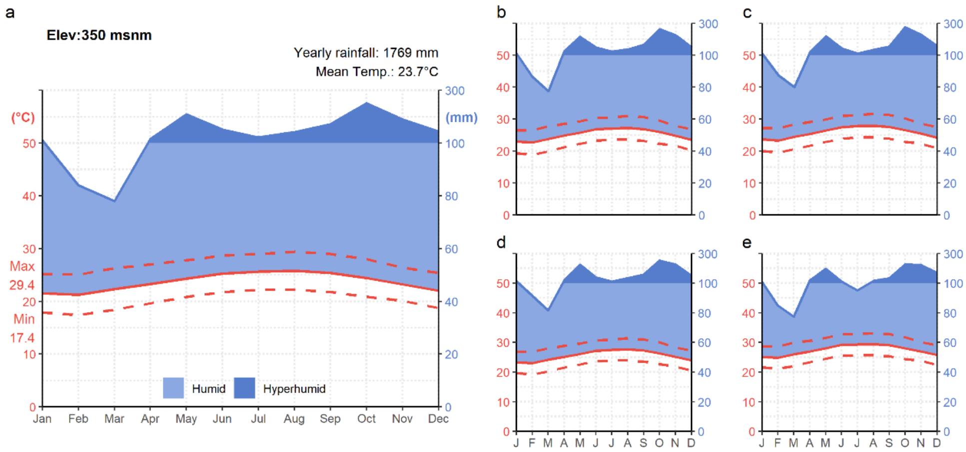

Fig. 3. Walter-Lieth climogram for the oc-23 topoclimate. a – reference period; b – SSP2-4.5 MT; c – SSP2-4.5 LT; d – SSP5-8.5 MT; and e – SSP5-8.5 LT. Source: prepared by the authors

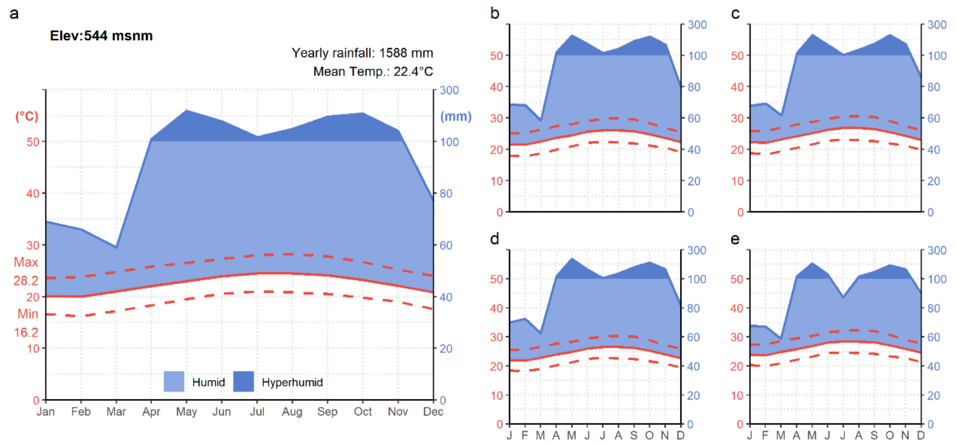

Fig. 4. Walter-Lieth climogram for the oc-07 topoclimate. a – reference period; b – SSP2-4.5 MT; c – SSP2-4.5 LT; d – SSP5-8.5 MT; and e – SSP5-8.5 LT. Source: prepared by the authors

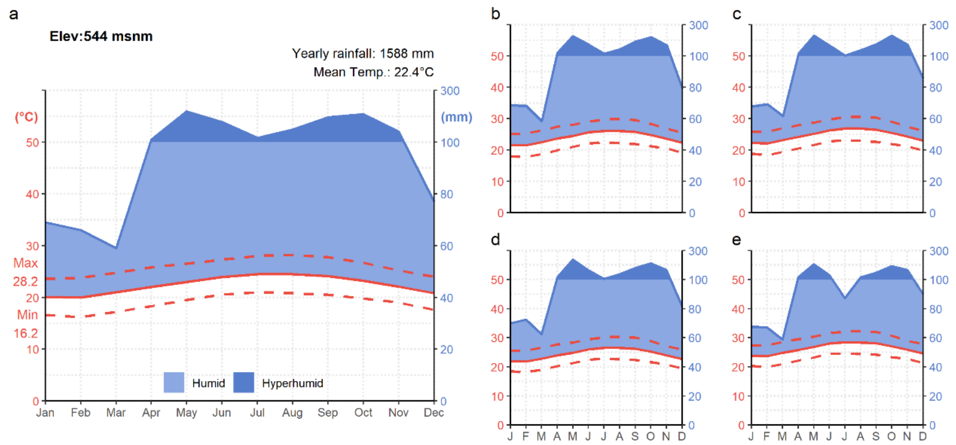

Fig. 5. Walter-Lieth climogram for the oc-03 topoclimate. a – reference period; b – SSP2-4.5 MT; c – SSP2-4.5 LT; d – SSP5-8.5 MT; and e – SSP5-8.5 LT. Source: prepared by the authors

The results of the climate projections are consistent with the steady increase in average temperature values for all future terms and trajectories (Fig. 6*a*). This result corroborates, at a local scale, the conclusions of other studies and the IPCC for the Caribbean region [*IPCC, 2023; Taylor et al., 2018*].

In the case of average accumulated precipitation values, the results indicate a small increase in the medium term and a trend toward the recovery of current values in the long term in the SSP2-45 trajectory. Notably, this trend is much stronger in the SSP5-8.5 trajectory for all topoclimates (Fig. 6*b*), in which a significant decrease in total rainfall is expected. However, it should be noted that several authors have highlighted greater uncertainty in the rainfall prediction of GCMs [*Centella-Artola et al., 2020*]. Additionally, the greatest disturbances in precipitation resulting from climate change are expected to be concentrated in extreme hydrometeorological events, such as severe drought episodes alternating with intense rainfall events [*Taylor et al., 2018*]. These disturbances may not be reflected in the average monthly and interannual precipitation accumulations analyzed in this study.

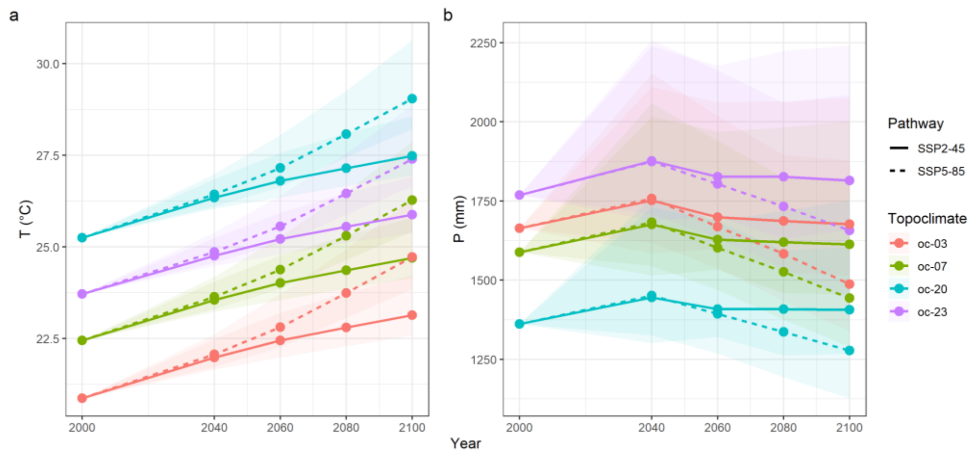

Fig. 6. Projection of the elements of the topoclimates associated with the landslides: a – temperature; b – precipitation. Prepared by the authors

The water balance analysis revealed that the oc-23 topoclimate evolved from experiencing two months of soil water deficit to experiencing 3 to 7 months of water deficit, with the last occurring under SSP5-8.5 LT. This increase in water deficit is associated with the summer period (Figs. 7*b–e*), except for SSP5-8.5. The evolution is similar for the oc-07 and oc-03 topoclimates after two months of soil water deficit in the reference period, albeit in different months (Figs. 9*a* and 10*a*). However, the oc-03 topoclimate presents a different distribution of water deficit for the reference period, and the oc-07 topoclimate may evolve toward more severe water deficit in SSP5-85 LT.

The water balance of the oc-20 topoclimate shows that there are 7 months with negative feedback in the hydrological cycle during the current climate period. This topoclimate evolves from these 7 months with water deficit in the reference period to a generalized water deficit with only short periods of water recharge in both trajectories for the ST period (Figs. 8*b*, *d*). The difference in the evolution of the water balance for this topoclimate despite having similar rainfall regimes to the others is associated with the difference in the current and projected temperature values (Fig. 6*a*), which is positively correlated with evapotranspiration [*Zaitchik et al., 2023*].

These water balance results highlight the relevance of the temperature increase in the evolution of the topoclimates and its impact on the soil water cycle, a variable of great interest for the study of debris flows.

All the topoclimates of eastern Cuba prone to debris flows triggered by intense rainfall events showed similar changes in their water balance, except for the oc-20 topoclimate. They are characterized by a deficit of water availability associated with the PPLL, and relatively low rainfall accumulates in the summer. In the specific case of oc-20, only in short periods during the months of May, October, and November are soil water recharged. This topoclimate presents a significant decrease in water availability, which increases and becomes very marked in both periods and in the SSP under study (Fig. 8).

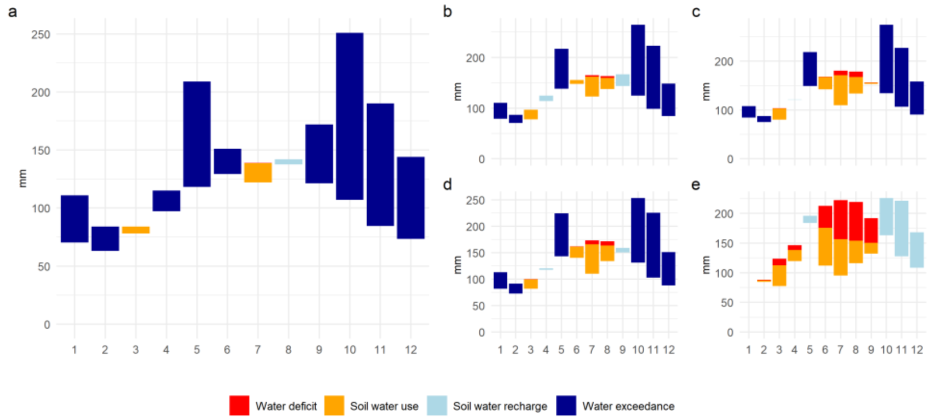

Fig. 7. Water balance of the oc-23 topoclimate. a – reference period; b – SSP2-4.5 MT; c – SSP2-4.5 LT; d – SSP5-8.5 MT; and e – SSP5-8.5 LT. Source: prepared by the authors from the BioClim results

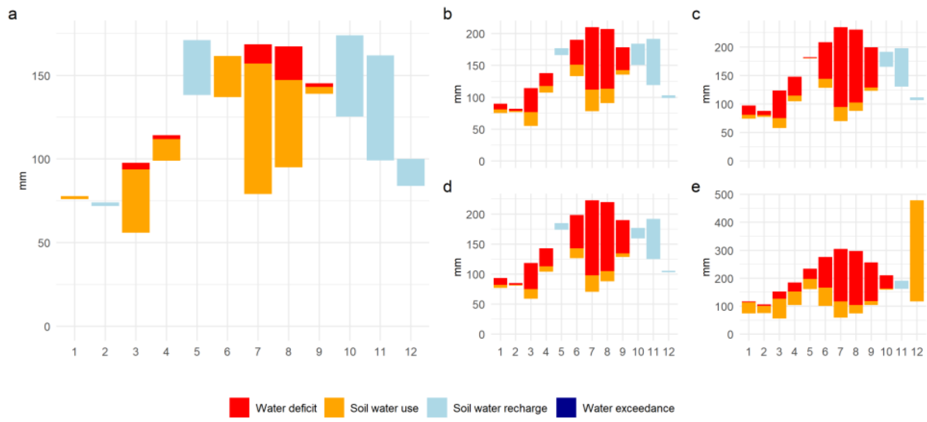

Fig. 8. Water balance of the oc-20 topoclimate. a – reference period; b – SSP2-4.5 MT; c – SSP2-4.5 LT; d – SSP5-8.5 MT; and e – SSP5-8.5 LT. Source: prepared by the authors from the BioClim results

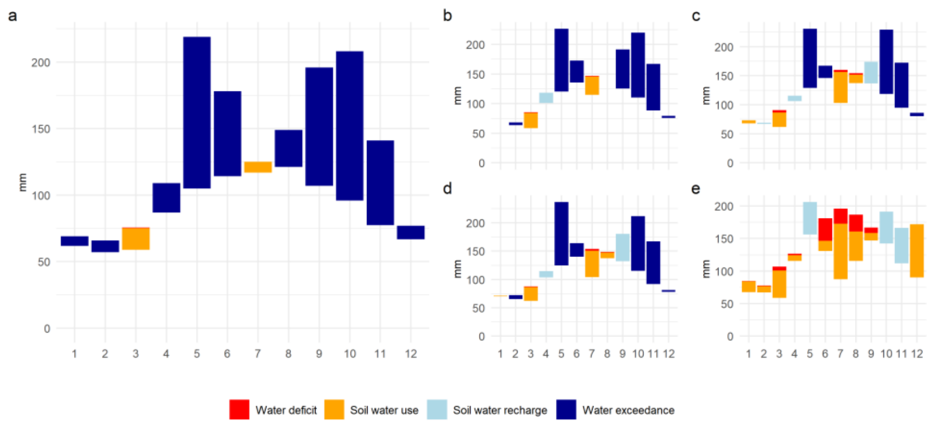

Fig. 9. Water balance of the oc-07 topoclimate. a – reference period; b – SSP2-4.5 MT; c – SSP2-4.5 LT; d – SSP5-8.5 MT; and e – SSP5-8.5 LT. Source: prepared by the authors from the BioClim results

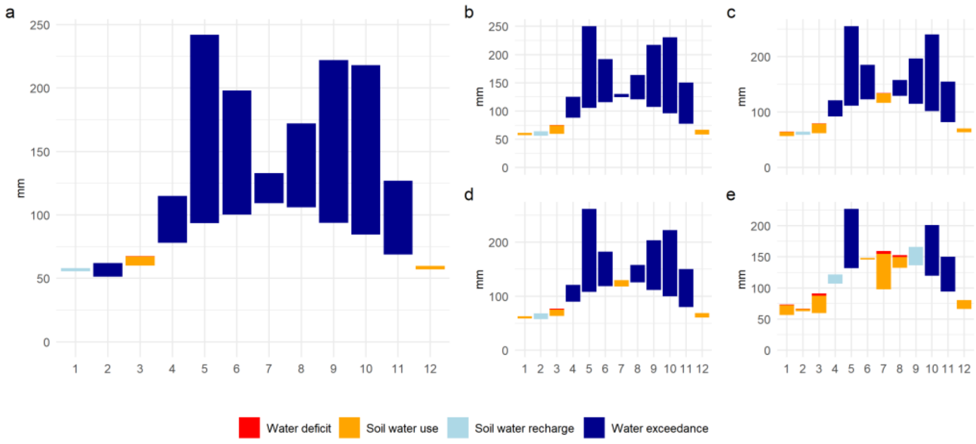

Fig. 10. Water balance of the oc-03 topoclimate. a – reference period; b – SSP2-4.5 MT; c – SSP2-4.5 LT; d – SSP5-8.5 MT; and e – SSP5-8.5 LT. Source: prepared by the authors from the BioClim results

These results show that the projected increase in interannual rainfall accumulation in the MT does not translate to greater water availability, which is expected to decrease across socioeconomic pathways. These conclusions confirm the findings of studies affirming that on tropical islands such as Cuba, an increase in temperature favors an increase in water vapor, creating positive feedback since water vapor is a greenhouse gas [*Buis, 2022; Chia & Lim, 2022*]. However, this increase in precipitation will especially reflect in severe events such as those associated with hurricanes. The second statement, referring to the decreasing volume of water in the soil in the topoclimates associated with debris flows, agrees with the findings of researchers such as Zaitchik et al. [*2023*], who associated the increase in global evapotranspiration with changes in moisture availability in terrestrial regions. The projected increase in water loss due to evapotranspiration will cause disturbances, sometimes counterintuitive, in the hydrological cycle. In both cases, these trends could influence the probability of debris flows occurring in preserved natural areas of tropical island regions.

Conclusions

The results of this study show that the rainfall distribution in areas at risk of debris flows in conserved regions of eastern Cuba will remain relatively stable throughout the year, with a decrease in the minimum accumulation during the summer period and in periods with little rainfall. Climate projections predict that increasing rainfall will accumulate in the medium term and that there will be a negative deviation in the long term, which is very pronounced in the SSP5-8.5 trajectory. However, a notable increase in the water deficit in the soil is expected, which is associated with increases in temperature and evapotranspiration. The projected increase in temperature favors atmospheric water vapor in a positive feedback loop, which will increase precipitation intensity, especially during severe rainfall events, consequently altering the conditions of occurrence of landslides.

The results of this research could inform further analysis of the probability of occurrence of landslides in preserved natural areas of tropical regions.

Acknowledgments

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References

Atkinson, B.W. [2003]. The climate near the ground, sixth edition, R. Geiger, R. H. Aron and P. Todhunter, Rowman and Littlefield Publishers, Lanham, MD, USA, 2003. No. of pages xviii +584. ISBN 0-7425-1857-4. International Journal of Climatology, 23(14), 1797–1798. https://doi.org/10.1002/joc.967

Centella-Artola, A., Bezanilla-Morlot, A., Taylor, M.A., Herrera, D.A., Martinez-Castro, D., Gouirand, I., Alpizar, M. [2020]. Evaluation of Sixteen Gridded Precipitation Datasets over the Caribbean Region Using Gauge Observations. Atmosphere, 11(12), 1334. https://doi.org/10.3390/atmos11121334

Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J., and Taylor, K.E. [2016]. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development, 9(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937–2016

Fan, X., Dufresne, A., Siva Subramanian, S., Strom, A., Hermanns, R., Tacconi Stefanelli, C., Xu, Q. [2020]. The formation and impact of landslide dams – State of the art. Earth-Science Reviews, 203, 103116. https://doi.org/10.1016/j.earscirev.2020.103116

Fick, S.E., and Hijmans, R.J. [2017]. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology, 37(12), 4302–4315. https://doi.org/10.1002/joc.5086

Gallardo-Toirac, C., Martínez-Zorrilla, A.J., Valdés-Pérez, J.A., and Salabarría -Fernández, D. [2023]. The System of National Reserves in Cuba: Conserving biodiversity and ecosystem services. In Family Farms and the Conservation of Agrobiodiversity in Cuba (pp. 15–24). Retrieved from https://www.taylorfrancis.com/chapters/edit/10.4324/9781315183886-16/

Green, J.K., Konings, A.G., Alemohammad, S.H., Berry, J., Entekhabi, D., Kolassa, J., Lee, J.-E., and Gentine, P. [2017]. Regionally strong feedbacks between the atmosphere and terrestrial biosphere. Nature Geoscience, 10(6), 410–414. https://doi.org/10.1038/ngeo2957

Hausfather, Z., and Peters, G.P. [2020]. Emissions – the ‘business as usual’ story is misleading. Nature, 577(7792), 618–620. https://doi.org/10.1038/d41586-020-00177-3

IPCC. [2023]. AR6 Synthesis Report: Climate Change 2023 — IPCC. Retrieved from https://www.ipcc.ch/report/sixth-assessment-report-cycle/

Jakob, M. [2022]. Chapter 14 – Landslides in a changing climate. In T. Davies, N. Rosser, and J. F. Shroder (Eds.), Landslide Hazards, Risks, and Disasters (Second Edition) (Second Edition, pp. 505–579). https://doi.org/10.1016/B978-0-12-818464-6.00003-2

Lin, Q., Steger, S., Pittore, M., Zhang, J., Wang, L., Jiang, T., and Wang, Y. [2022]. Evaluation of potential changes in landslide susceptibility and landslide occurrence frequency in China under climate change. Science of The Total Environment, 850, 158049. https://doi.org/10.1016/j.scitotenv.2022.158049

Peña-de la Cruz, A., Moya-Álvarez, A. S., and Delgado-Téllez, R. [2013]. Patrones Sinópticos que generan lluvias intensas que producen inundaciones en el municipio de Baracoa. Revista Cubana de Meteorología., 19(2).

Piotrowicz, K., and Ciaranek, D. [2020]. A selection of weather type classification systems and examples of their application. Theoretical and Applied Climatology, 140(1–2), 719–730. https://doi.org/10.1007/s00704-020-03118-2

Pospehov, G. B., Savón, Y., Delgado, R., Castellanos, E. A., and Peña, A. [2023]. Inventory Of Landslides Triggered By Hurricane Matthews In Guantánamo, Cuba. GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY, 16(1), 55–63. https://doi.org/10.24057/2071-9388-2022-133

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O’Neill, B. C., Fujimori, S., Tavoni, M. [2017]. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Serrano-Notivoli, R., Longares, L. A., and Cámara, R. [2022]. Bioclim: An R package for bioclimatic classifications via adaptive water balance. Ecological Informatics, 71, 101810. https://doi.org/10.1016/j.ecoinf.2022.101810

Stacy R. Stewart. [2017]. HURRICANE MATTHEW (No. AL142016). National Hurricane Center.

Taylor, M. A., Clarke, L. A., Centella, A., Bezanilla, A., Stephenson, T. S., Jones, J.J., Campbell, J. D., Vichot, A., and Charlery, J. [2018]. Future Caribbean Climates in a World of Rising Temperatures: The 1.5 vs 2.0 Dilemma. Journal of Climate, 31(7), 2907–2926. https://doi.org/10.1175/JCLI-D-17-0074.1

Zaitchik, B.F., Rodell, M., Biasutti, M., and Seneviratne, S.I. [2023]. Wetting and drying trends under climate change. Nature Water, 1(6), 502–513. https://doi.org/10.1038/s44221-023-00073-w

Zhang, S., Yang, H., Wei, F., Jiang, Y., and Liu, D. [2014]. A model of debris flow forecast based on the water-soil coupling mechanism. Journal of Earth Science, 25(4), 757–763. https://doi.org/10.1007/s12583-014-0463-1