ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
2 February 2026

REVISED
22 March 2026

ACCEPTED FOR PUBLICATION
31 March 2026

PUBLISHED
15 April 2026

LETTER

Attributing precipitation, wind and socioeconomic exposure in Hurricane Melissa (2025)

Davide Faranda[1,2,3,*], **Gabriele Messori**[4,5,6], **Carmen Alvarez-Castro**[7] and **Stella Bourdin**[2,8]

[1] Laboratoire des Sciences du Climat et de l'Environnement (LSCE/IPSL), CNRS, Université Paris-Saclay, Gif-sur-Yvette, France
[2] Laboratoire de Météorologie Dynamique (LMD/IPSL), École Normale Supérieure, Ecole Polytechnique, PSL Research University, Paris-Palaiseau, France
[3] London Mathematical Laboratory, London, United Kingdom
[4] Department of Earth Sciences, Uppsala University, Uppsala, Sweden
[5] Swedish Centre for Impacts of Climate Extremes (climes), Uppsala University, Uppsala, Sweden
[6] Department of Meteorology, Stockholm University, Stockholm, Sweden
[7] Physical, Chemical and Natural Systems Department, Pablo de Olavide University, Seville, Spain
[8] Department of Physics, University of Oxford, Oxford, United Kingdom
[*] Author to whom any correspondence should be addressed.

E-mail: davide.faranda@lsce.ipsl.fr

Keywords: attribution, tropical cyclones, vulnerability and exposure, climate extremes

Supplementary material for this article is available online

Abstract

Hurricane Melissa reached Category 5 intensity in the Caribbean Sea in late October 2025, becoming the strongest hurricane on record to make landfall in Jamaica. Here, we assess the influence of anthropogenic climate change and natural variability on the hurricane's precipitation and wind hazards. We apply the ClimaMeter analogue-based attribution protocol to ERA5 reanalysis, complemented by a track-based constraining approach. We find that events similar to Melissa are up to 15 mm d^{-1} wetter and are associated with winds up to 10 km h^{-1} stronger in today's climate compared with a counterfactual past. Both correspond to an ∼10 % intensification of the hazards. These results indicate that human-driven climate change amplified Melissa's precipitation and strengthened its large-scale wind environment. At the same time, natural variability likely modulated the Hurricane's trajectory and development. We further integrate the meteorological attribution with an exposure analysis, combining hazards with population and gross domestic product per capita at purchasing power parity. We find that almost 5 million people and USD 35 billion in economic assets were located in areas where Melissa's precipitation and wind hazards were intensified by ongoing climate change. This underscores the growing contribution of anthropogenic climate change to climate risk amplification.

1. Introduction

The increasing frequency and intensity of several categories of extreme weather events are among the most visible and impactful effects of climate change [1]. However, the fact that there is an increasing trend in a given extreme event category need not imply that all individual extreme events of that type are modulated by climate change. Extreme event attribution aims to provide such information, by assessing the influence of human-induced climate change relative to natural variability in the occurrence and intensity of specific extreme events [2–4]. A wide range of different attribution approaches exist, including methods based on numerical modelling, extreme value statistics and analogues [5–8]. In this study, we adopt the latter approach, as detailed below, for the case of 2025 Hurricane Melissa.

Severe tropical cyclones, called hurricanes in the North Atlantic Ocean, are among the most socioeconomically devastating weather extremes globally. It is estimated that such cyclones have caused over $ 1.5 trillion in economic damage and over 7000 deaths worldwide over the past 45 years [9].

Detecting and attributing recent changes in hurricane frequency and intensity remains challenging. In the Atlantic, a statistically significant increase has been observed in the proportion of Category 4–5 hurricanes, but not in the mean intensity of all storms [10]. Regarding seasonality, observations suggest an extension of the Atlantic hurricane season, with more early-season hurricanes [11]. Looking to future climate change, changes in the overall frequency of Atlantic hurricanes remain uncertain, yet it is likely that the proportion of major hurricanes will increase [12–15]. Several analyses have additionally found increases in the precipitation related to tropical cyclones, consistent with thermodynamic expectations. In some cases, these exceed those predicted by the Clausius–Clapeyron relationship, suggesting additional dynamical influences [16, 17]. Only a few studies have attempted to attribute individual hurricanes to human-induced climate change, using probabilistic or storyline-based approaches [6, 18, 19]. Most of these studies focused on precipitation and found that climate change contributed to making rainfall more extreme.

Analogue-based attribution is a storyline approach that compares the hazards associated with similar meteorological conditions in different climate periods. In this framework, a 'factual' period representing the current climate is compared with a 'counterfactual' past period with weaker anthropogenic forcing. This method relies entirely on observations or reanalysis data, allowing for rapid and reproducible attribution analyses without the need for ad-hoc numerical climate simulations. Such approach has been applied successfully to heat waves and other mid-latitude extremes [20–27], but less so to tropical systems. Moreover, when attributing cyclonic systems, it is important to encompass cyclone track information in the attribution. To this effect, [28] recently developed a track-based analogue framework that conditions directly on tropical cyclone tracks.

In this paper, we combine the ClimaMeter analogue-based attribution protocol [27] with the track-based analogue approach of [28], to attribute Hurricane Melissa, which struck the Caribbean in October 2025. We first quantify how meteorological environments similar to Hurricane Melissa have changed between a present climate and a counterfactual past. Second, we cross the meteorological information with population and gross domestic product (GDP) data to quantify the people and assets exposed to meteorological hazards intensified by climate change.

2. Data and methods

2.1. ClimaMeter attribution protocol

The ClimaMeter protocol performs a detection and attribution analysis of weather extremes using reanalysis data and a factual versus counterfactual comparison [27]. We consider a recent period strongly affected by climate change (1987–2023, factual) relative to a past period with a weaker climate change footprint (1950–1986, counterfactual). We use ERA5 reanalysis [29] at 0.5° horizontal and daily temporal resolution and compute anomalies with respect to the 1950–2023 climatology.

For Melissa we define a 10 by 10° box approximately centred on the location of the cyclone as it approached Jamaica and made landfall on the island: [80°W–70°W, 12°N–22°N], and focus on the months of August to November, which match the Atlantic hurricane season. We define 27 and 28 October 2025 as the event dates. For each event date we select the 40 best analogue days in the factual and counterfactual periods, based on the Euclidean distance of standardized sea-level pressure (SLP) anomalies. Composite present minus past differences are computed for SLP, 10 m wind speed, daily precipitation and 2 m temperature. These differences provide the climate-change signal for Melissa-like meteorological environments. Following previous work, we compute the analogue quality Q as the average Euclidean distance between the event and its 40 analogues. We then compare the value of Q to the distribution of average distances of each of the 40 analogues from its own 40 analogues. For Melissa, Q points to comparatively poor analogue quality. This suggests that conclusions should be interpreted with caution, as SLP-based analogues do not necessarily capture storm structure or intensity. Following the ClimaMeter protocol, we also examine the distributions of the El Niño–Southern Oscillation (ENSO), the Pacific decadal oscillation (PDO) and the Atlantic multidecadal oscillation (AMO) indices on analogue dates in the two periods to document the possible influence of natural variability on the results of the analogue analysis. The indices for the three modes of variability are derived from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature dataset, version 5. The ENSO and AMO indices are obtained from the Royal Netherlands Meteorological Institute Climate Explorer https://climexp.knmi.nl/start.cgi (last access: 12 July 2024). The PDO time series is retrieved from the National Centers for Environmental Information of the NOAA https://www.ncei.noaa.gov/ (last access: 12 July 2024), where the most up-to-date version is provided.

2.2. Track-based analogue analysis

In addition to identifying SLP-based analogues, we also apply a method introduced in [28] that defines analogues as storms whose tracks resemble that of Melissa within a fixed spatial tolerance. This method works as follow (see [28] for more details):

(i) All data is interpolated to a 1-hourly frequency.

(ii) We find all TC points in a given catalogue that are within d_{LF} of Melissa's landfall point ($d_{LF} =$ 1000 km for IBTrACS, and 300 km for the other catalogues). If several points belong to the same cyclone, we keep only the closest.

(iii) For each of these points, we extract the trajectory of the corresponding cyclone 24 h before the closest point to landfall. We then compute a mean pointwise great-circle distance from Melissa's track.

(iv) Only tracks whose distance is below a threshold (2° GCD for all catalogues, except IBTrACS for which we use 3° GCD) are kept as analogues. Note this is different from the ClimaMeter approach, where a fixed number of analogues is selected.

This approach mitigates three issues: the underrepresentation of storm intensity and structure in ERA5, the rarity of observed hurricanes, and the sensitivity of SLP-based distances to absolute pressure minima and spatial co-location. We use four track catalogues: observational data from IBTrACS [30], synthetic tracks generated by the Columbia Hazard model [31, CHAZ] driven by ERA5, following the configuration used by previous studies [32], tracks produced by the MIT-Open TC downscaling model [33], again driven by ERA5, and the SEAS5-20 C hindcast dataset produced by ECMWF [34, 35].

The common period for IBTrACS, CHAZ and MIT-Open is 1950–2019. Moreover, IBTrACS is generally considered reliable in the North Atlantic from 1950 onwards, although there is evidence of a discontinuity at the start of the satellite era [36, 37]. We thus split the data into 1950–1984 (counterfactual) and 1985–2019 (factual). SEAS5-20 C forecasts are initialised in May and November each year during 1901–2010 using CERA-20 C initial states [38]. TCs are detected by the TRACK algorithm [39]. We retain June–November tracks from the first forecast year for May initializations. This ensures that the cyclones are not inherited from initial conditions. To take advantage of the full length of the reforecasts, we use 1901–1955 as counterfactual and 1956–2010 as factual. Differences in external forcing and internal variability across the different period splits that we use are acknowledged; our aim here is methodological consistency and sample enlargement rather than a single unified trend estimate across all catalogues.

Once analogue sets are identified for each catalogue and period, we evaluate changes in wind hazards conditional on track similarity. We are not able to analyse precipitation changes since this variable is not present in all the datasets we used. Among these datasets, only SEAS5-20 C includes precipitation. However, since it is based on the same IFS model as ERA5, but at lower resolution, we expect it to perform less well than ERA5 for this purpose and we therefore do not include it.

2.3. Significance calculation and sensitivity testing

To determine whether map composite differences between the two analysis periods are significant, we apply a bootstrap procedure across analogues and determine a significance threshold at each grid point. This corresponds to 5% at each gridpoint, but since we are performing multiple tests, the true significance level is likely higher and we do not assign a specific significance level to this test. For scalar metrics such as maximum wind and rainfall at urban points we report median differences with percentile confidence intervals based on 10 000 bootstrap resamples.

For track-based analogues, a t-test for difference in means between the counter-factual and factual analogues' maximum wind speed is performed, at the 5% significance level.

Sensitivity tests include varying the number of analogues, and the date used for the analysis in the ClimaMeter protocol, and varying d_{max} for the track-based analogues (see supplementary material and supplementary figures S2–S4).

2.4. Socioeconomic exposure

We quantify socioeconomic exposure to precipitation and wind hazards enhanced by climate change by crossing event-day hazard masks with spatially gridded population and GDP data over the domain used in section 2.1. Population data are derived from the Global Human Settlement Layer for 2025 and regridded at 0.5° spatial resolution [40], and GDP per capita from a global gridded dataset at the same resolution [41].

First, we compute detrended and deseasonalized daily anomalies of precipitation and 10 m wind relative to the 1950–2023 reference climatology, to remove long-term and seasonal variability. A 2 d moving average is applied, and the anomaly on the event day is retained. A quantile threshold of 0.95 is then used to define a binary hazard mask, and connected hazard areas smaller than 4 gridpoints are removed. Based on the significance testing for differences between precipitation and 10 m wind maps of analogues in the two periods, we next identify gridcells in which the hazards have intensified in the current climate compared to the past. We then calculate population and GDP totals over all grid cells within the event hazard mask and additionally for grid cells within that mask at which the hazards have intensified in the present climate. Finally, we compute the ratio of total exposure to the event to exposure to increased hazards. We use the same 2025 exposure fields in both cases to isolate the contribution of hazard changes under present-day socioeconomic conditions.

2.5. Event overview

Hurricane Melissa underwent rapid intensification in the Caribbean Sea in late October 2025, reaching Category 5 intensity with sustained winds exceeding 175 mph (282 $km\,h^{-1}$) and a minimum central pressure below 920 hPa. The storm originated from a tropical wave that departed the African coast on 17th October, gradually organizing as it crossed the central Atlantic. Melissa rapidly strengthened south of Hispaniola under highly favourable conditions for cyclogenesis: very warm sea-surface temperatures above 30 °C, high ocean heat content across the western Caribbean, and weak vertical wind shear associated with a well-defined upper-level anticyclone. These factors enabled a near-exponential intensification phase between 24th and 26th October, with the maximum intensity reached while the storm was located south of Jamaica.

The hurricane's large circulation extended several hundred kilometres from the centre, with hurricane-force winds recorded over most of Jamaica and tropical-storm-force winds as far as eastern Cuba and Haiti. According to the World Meteorological Organization, Melissa may be the strongest storm to strike Jamaica in the 21st century. Hurricane Melissa brought extremely heavy rainfall to Jamaica, with total accumulations exceeding several hundred millimetres in parts of the island, contributing to widespread flash flooding and landslides. The storm made landfall with some among the highest sustained winds on record for an Atlantic hurricane, causing severe structural damage and power outages affecting hundreds of thousands of customers. The slow translation speed of the cyclone, combined with continuous moisture convergence along the eyewall, contributed to the high precipitation totals.

Satellite and reanalysis products indicate that the storm evolved in an environment of positive sea-surface temperature anomalies of 0.5°C–1.0 °C relative to the 1991–2020 climatology, linked to a neutral phase of the ENSO. Upper-tropospheric divergence over the central Caribbean and a strong Madden–Julian Oscillation pulse provided additional dynamical support for intensification. The storm's eventual recurvature towards the northwest was influenced by the weakening of the subtropical ridge over the western Atlantic, while interaction with a mid-latitude trough led to gradual weakening after 28th October.

ERA5 data show a deep low-pressure centre to the South of Jamaica, with a pronounced cyclonic structure consistent with a tropical storm and negative SLP anomalies reaching –25 hPa (figure 1(a)). We also find positive temperature anomalies over oceanic regions, locally in excess of +1.5 °C and localized negative anomalies up to –2 °C over Jamaica and Hispaniola (figure 1(e)). Daily precipitation exceeded 100 mm near the eyewall, and surface wind anomalies surpassed 80 $km\,h^{-1}$, concentrated along the southern coast of Jamaica and the adjacent sea (figures 1(i) and (m)).

3. Results

3.1. Changes in hazard intensity

3.1.1. ClimaMeter

The ClimaMeter attribution protocol provides a dynamical and thermodynamic perspective on Hurricane Melissa (figure 1).

Comparison between analogues in past and present periods shows widespread warmer and wetter conditions across the basin. We specifically find an increase of up to +1 °C throughout the storm environment (panel h), while precipitation changes (panel l) display localized increases up to +15 $mm\,d^{-1}$. Similarly, windspeed changes (panel p) display positive anomalies up to +10 $km\,h^{-1}$ over the core of the event. This points to storms similar to Melissa producing stronger winds and heavier rainfall in the present climate than in the past. SLP differences (panel d) show a slightly deeper low, although the SLP is subject to considerable aliasing due to the fact that different analogues will have low pressures centred at different locations. Nonetheless, the changes are consistent with greater storm intensity under present conditions.

Additional diagnostics on analogue quality, predictability, persistence, seasonality, and frequency trends are shown in supplementary figure S1 (see [8] for details on the metrics used). The large-scale indices of climate variability shown in figure S1, namely ENSO, AMO and PDO, reveal that analogue events in the present period are preferentially associated with positive values of ENSO and AMO, higher than in the past, and negative values of the PDO, lower than in the past. This is a combination favourable to enhanced Caribbean convection [42–44].

3.1.2. Track-based analogue analysis

In IBTrACS, few analogues are found (figures 2(a) and (e)). They either go eastward or northward, but none has a sharply curving path similar to Melissa (red track in the figure). The analogues' wind speeds are, on average, 7 $m\,s^{-1}$ stronger in the present period compared to the past period (figure 3(a)). However, the wide confidence interval due to the limited sample size does not allow us to rule out that the difference might be due to chance (figure 3(e)). Using the CHAZ catalogue, which contains more tracks, we find more analogues compared to IBTrACS, all of them making landfall or passing very close to Jamaica, and some of them having a similar curvature to Melissa (figures 2(b) and (f)). The factual analogues' wind speeds are, on average, 1 $m\,s^{-1}$ higher in the present period compared to the past (figure 3(b)). However, even in this case the wide confidence interval does

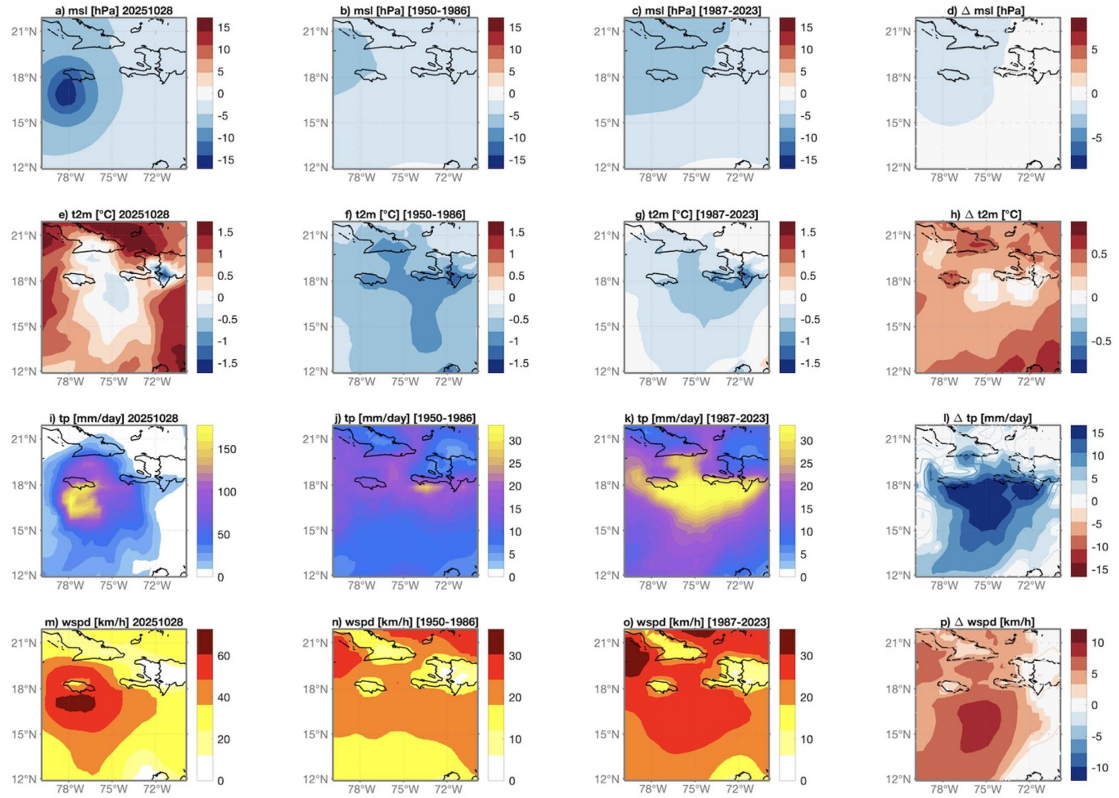

Figure 1. ClimaMeter attribution diagnostics for Hurricane Melissa, based on ERA5 reanalysis for the 27th and 28th October jointly. Panels (a), (e), (i), (m) show the event-days anomalies in SLP (msl), 2 m temperature (t2m), and averaged values of daily precipitation (tp) and windspeed (wspd), respectively. Panels (b), (f), (j), (n) display the corresponding composite means for the past (1950–1986) analogue period, and (c), (g), (k), (o) for the present (1987–2023) period. Panels (d), (h), (l), (p) show the present minus past differences. Only significant differences (see section 2.3) are displayed.

not allow us to rule out that the difference might be due to chance (figure 3(e)). The very large number of tracks in the MIT catalogue allows us to find a very large number of good analogues that go through or close to Jamaica, several of which follow a similar direction to Melissa (figures 2(c) and (g)). The factual analogues' wind speeds are, on average, 3 m s^{-1} higher in the present period compared to the past (figure 3(c)). Thanks to the very large number of analogues, the confidence interval reduces so that we are able to identify a significant positive change in maximum wind speed (figure 3(e)). Using SEAS5-20 C, which covers the entire last century, we find a reasonable number of analogues for Melissa (figures 2(d) and (h)). Due to SEAS5-20 C tracks being produced by a dynamical model with a comparatively low resolution, the maximum wind speeds in the analogue tracks are lower than for the other catalogues. The analogues' wind speeds are, on average, 1 m s^{-1} higher in the factual period compared to the counter-factual (figure 3(d)), but the confidence interval crosses the zero line, which means we cannot rule out the hypothesis that there might not be a change (figure 3(e)). To conclude, all catalogues suggest an intensification of winds associated with hurricanes like Melissa, and one of them indicates a statistically significant changes. This is in partial agreement with the ClimaMeter protocol, which displays a widespread and significant increase in windspeeds.

3.2. Socioeconomic exposure to intensified rainfall and wind during Hurricane Melissa

Having quantified how climate change may have modified Melissa's meteorological hazards, we now assess how these changes translate into human and economic exposure. The aim is to isolate the effect of anthropogenic climate change by keeping exposure fixed at present-day levels. Using 2025 population and GDP for both factual and counterfactual cases, the approach does not reconstruct past socioeconomic conditions but measures how much of the current exposure lies in areas where hazards have intensified. Accounting for changing population and GDP would instead address the joint role of hazard changes and socio-economic changes.

Figure 4 shows the spatial distribution of log-population and log-GDP exposed to extreme rainfall and wind during Hurricane Melissa. Although most of the Caribbean domain that we consider is sea, both rainfall and wind affected densely populated or economically active regions on the main Caribbean islands (continuous blue contours). For rainfall, 34.47% of the domain area experienced event-day

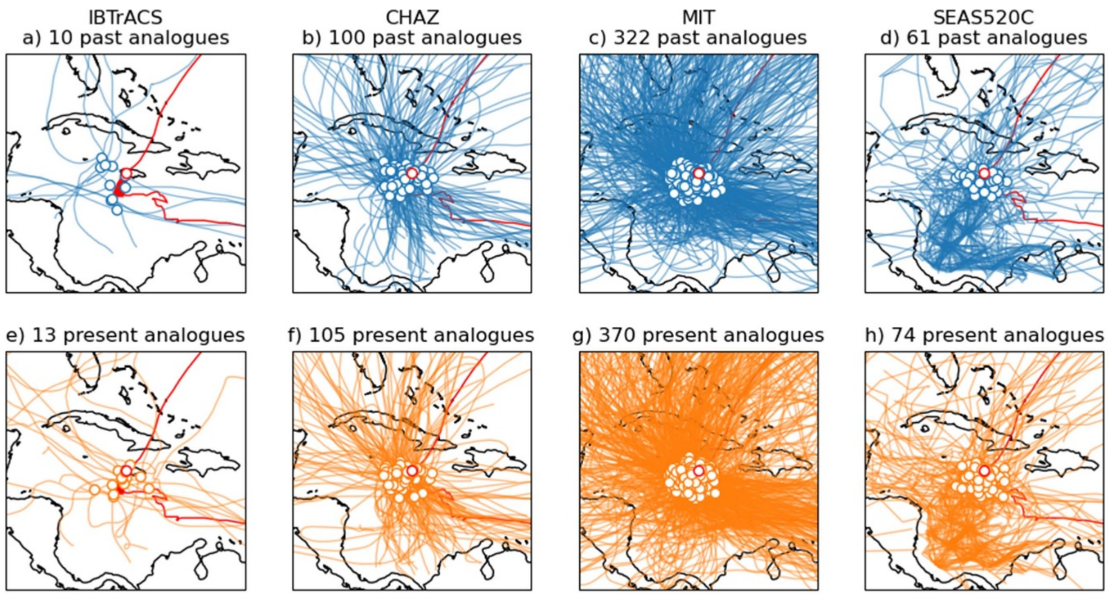

Figure 2. Melissa's track (red) and analogue tracks in the past (blue, panels (a)–(d)) and present (orange, panels (e)–(h)) periods, using the track-based analogue method. The red circle shows the position of Melissa's landfall, and the blue and orange circles represent the closest point to Melissa's landfall position for each of the analogue tracks. The numbers of analogues found is indicated on top of each panel.

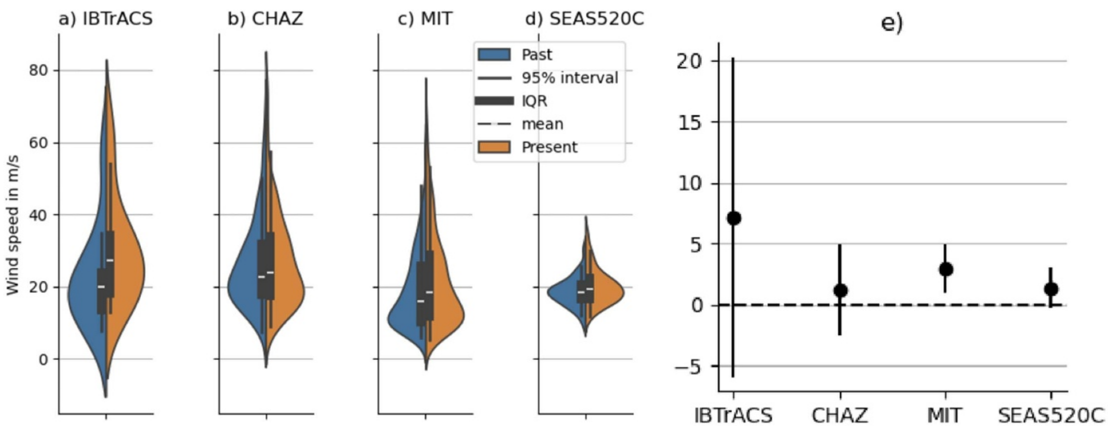

Figure 3. Distributions of wind speeds for past (blue), and present (orange) analogues of Melissa, in each of the four track catalogues (a)–(d). Change in mean wind speed among Melissa's analogues between the past and present periods, in each track catalogue (e). The error bars in (e) show 95% confidence intervals for a t-test for difference in means.

anomalies above the 95th percentile hazard threshold (see section 2.4), and 31.29% showed intensification in the present climate (dashed black contours). This corresponds to approximately 6.05 million people affected, of whom 5.87 million (97.0%) were exposed to stronger rainfall in present than in past Melissa analogue events. The corresponding economic exposure reached 40.40 billion USD, with 39.70 billion USD (98.4%) located in areas with intensified hazards.

Wind exposure displayed a comparable pattern: 39.00% of the domain area was affected by strong winds, with 38.78% showing intensification. The total affected population amounted to 4.84 million, of which 4.72 million (97%) were located in regions where wind intensity has increased in the present climate. The corresponding affected GDP totalled 40.11 billion USD, with 34.66 billion USD (86%) within zones with intensified wind hazards.

Overall, these results indicate that nearly all the population and economic assets affected by Hurricane Melissa were situated in areas where both rainfall and wind have become more intense under current climate conditions. This highlights the growing contribution of anthropogenic climate change to exposure—and presumably impacts—associated with the amplification of tropical cyclones in the Caribbean region.

3.3. Attribution statement

The ERA5-based ClimaMeter analysis points to human-driven climate change having amplified Hurricane Melissa's precipitation and wind intensity.

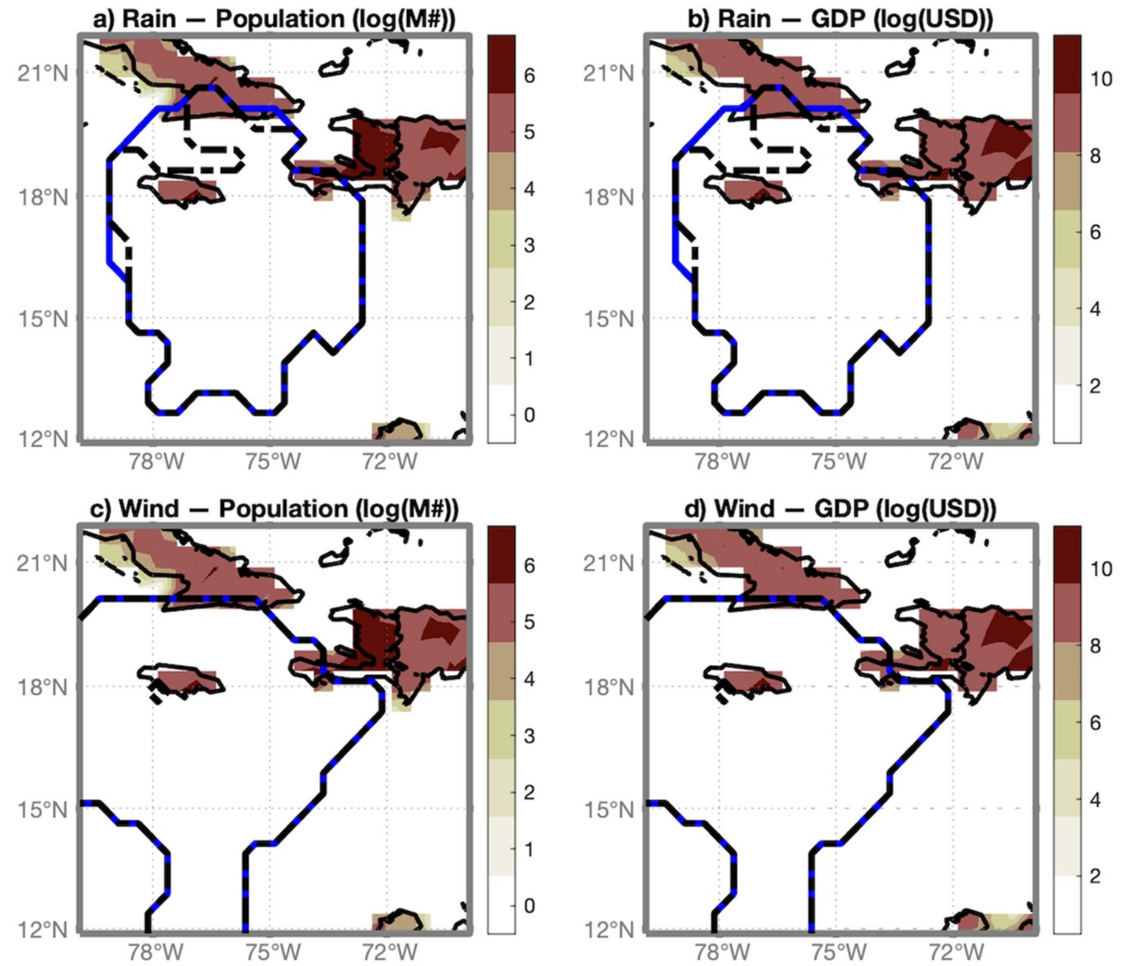

Figure 4. Spatial distribution of log-population (a), (c) and log-GDP (b), (d) in the analysis region. Continuous blue contours show regions exposed to extreme rainfall (a), (b) and wind (c), (d) during Hurricane Melissa. The black dashed contours indicate areas where the hazard intensity has increased in the present climate compared to the past.

This is reflected in a statistically significant strengthening of the wind and precipitation environments associated with Melissa-like circulation patterns. However, the analysis of natural variability indicates that ENSO, PDO and the AMO potentially played a role in modulating the event. Moreover, due to Melissa's unique nature, the ClimaMeter SLP analogues are of poor quality, limiting confidence in the attribution results. Track-based attribution indicates predominantly positive, yet mostly non-significant changes in mean wind intensity. The two attribution approaches, which build on different aspects of Hurricane Melissa, are therefore in reasonable agreement.

The exposure analysis, based on results from the ClimaMeter protocol, shows that millions of people and economic assets worth tens of billions of dollars were exposed to hazards which were likely made more severe by anthropogenic climate change.

3.4. Limitations

Both attribution methodologies used in this study present limitations. The ClimaMeter protocol is based on ERA5, which underestimates hurricane intensity and inner-core gradients. Moreover, the selection of analogues based on SLP does not guarantee that the analogues are themselves tropical cyclones, and may miss relevant aspects of storm structure. This is particularly true for Melissa, which was a highly unusual event in the ERA5 dataset (figure S1(a)). The above motivates complementing the ClimaMeter protocol with a track-based approach. Moreover, the quantification of the role of natural variability is based on changes in the index values of three large-scale modes of climate variability, but does not account for known spatial variations in the effects of these modes on climatic conditions.

The track-based approach relies on observed best tracks and modelled tracks. The first are affected by changes in observing systems, and present a limited sample size, while synthetic catalogues depend on model design and environmental drivers. In both cases, the attribution relies on point-based estimates of maximum wind speed that depend strongly on storm-core representation, detection thresholds, and model or observational resolution, all of which can produce large sampling uncertainties. Moreover, the distance threshold d_{max} presents a trade-off between analogue quality and sample size, and results can be sensitive to this choice in track-sparse regions.

The lack of analysis of precipitation in the track-based approach is an additional limitation. This is because precipitation is not available in all catalogues, and the only catalogue that includes it, SEAS5-20 C, has a relatively coarse resolution. The precipitation attribution thus relies on the ClimaMeter analogues and ERA5 alone, which is both have limitations in tropical convective environments.

Finally, our exposure estimates rely on static population and GDP which we regrid to the comparatively coarse resolution of the reanalysis data that we used. We thus do not capture fine-scale exposure or short-term population and economic dynamics. Since exposure is held fixed at 2025 levels, our results isolate the contribution of hazard changes under present-day socioeconomic conditions. Moreover, the exposure does not provide any direct information on impacts, as we lack information on the vulnerability of the exposed populations and economic assets.

Nonetheless, the ClimaMeter and track-based approaches provide broadly consistent results. Both point to climate change having intensified the meteorological hazards associated with Melissa, albeit with lower increases and mostly with a lack of statistical significance for the track-based approach. ClimaMeter evaluates changes in the large-scale synoptic environment using homogenized reanalysis fields, which are sensitive to thermodynamic intensification (e.g. warmer SSTs, moister boundary layer) and large-scale circulation anomalies that favour stronger surface winds. This is fundamentally different from the point-based estimates of maximum wind speed used in the track-based approach. This difference makes the minor discrepancies between the two methods unsurprising. Indeed, the results from both approaches are consistent with a scenario in which the background environment favours strengthened hazards under anthropogenic warming, yet we hypothesize that catalogue-based storm-core metrics remain too variable to reflect these changes robustly.

4. Conclusion

We applied the ClimaMeter analogue-based attribution protocol, combined with a track-based analogue approach, to Hurricane Melissa (October 2025), and complemented the meteorological attribution with an analysis of population and GDP exposure. Our analysis indicates that events similar to Melissa are up to 15 mm d^{-1} wetter, and occur within wind environments up to 10 km h^{-1} stronger today than in the pre-1987 climate. The track-based analogue approach suggests weaker and less robust wind increases than those inferred from ClimaMeter, reflecting methodological limitations of both approaches and uncertainties in constraining storm-core intensity.

The intensification of wind and precipitation that we identify is consistent with theoretical expectations and with the thermodynamic influence of human-induced climate change, and qualitatively aligns with other rapid attribution studies conducted in the aftermath of Hurricane Melissa [45]. The exposure analysis shows that almost 5 million people and 35 billion USD in assets were located in areas where hazards were intensified in the current climate.

Hurricane Melissa illustrates how human-driven climate change may increase the intensity and potential impact of Atlantic tropical cyclones. Integrating physical attribution with exposure information can support quantifying risk amplification, communication, preparedness, and adaptation planning in highly exposed regions.

Acknowledgments

We acknowledge funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 101003469 (XAIDA), the ANR Project PowDev (Strategic Development of the Power Grids of the Future, ANR-22-PETA-0016), the ANR Project Templex (ANR-23-CE56-0002), the ANR Project TRACCS, Transformer la modélisation du climat pour les services climatiques (ANR-22-EXTR-0005, Extending), and the Swedish Research Council Vetenskapsrådet (2022-06599).

Data availability statement

ERA5 data are available from the EU-funded Copernicus Climate Change Service (C3S) Climate Data Store on regular latitude-longitude grids at $0.25° \times 0.25°$ resolution: https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset, accessed on 2026-04-07.

Population and GDP data are available from the Global Human Settlement Layer at: https://human-settlement.emergency.copernicus.eu, accessed on 2026-04-07.

Supplementary Text and Figures available at https://doi.org/10.1088/1748-9326/ae5992/data1.

Conflict of interest

The authors declare no competing interests nor conflicts of interest. No human or animal data have been used in this study.

Author contributions

Davide Faranda 0000-0001-5001-5698
Conceptualization (equal), Funding acquisition (equal), Investigation (equal), Methodology (equal), Validation (equal), Visualization (equal), Writing – original draft (equal), Writing – review & editing (equal)

Gabriele Messori 0000-0002-2032-5211
Conceptualization (equal), Funding acquisition (equal), Methodology (equal), Writing – original draft (equal)

Carmen Alvarez-Castro 0000-0002-9958-010X
Methodology (equal), Writing – original draft (equal)

Stella Bourdin
Methodology (equal), Visualization (equal), Writing – original draft (equal)

References

[1] Seneviratne S *et al* 2021 Weather and climate extreme events in a changing climate *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (*Book section 11*) V ed Masson-Delmotte *et al* (Cambridge University Press) pp 1513–765 (available at: www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter11.pdf)
[2] Meredith E P, Semenov V A, Maraun D, Park W and Chernokulsky A V 2015 *Nat. Geosci.* **8** 615–9
[3] Otto F E L 2016 *Nat. Clim. Change* **6** 342–3
[4] van Oldenborgh G J *et al* 2021 *Clim. Change* **166** 13
[5] National Academies of Sciences and Medicine and Division on Earth and Board on Atmospheric Sciences and Committee on Extreme Weather Events and Climate Change Attribution 2016 *Attribution of Extreme Weather Events in the Context of Climate Change* (National Academies Press)
[6] Reed K A, Wehner M F and Zarzycki C M 2022 *Nat. Commun.* **13** 1905
[7] Meyer J, Neuper M, Mathias L, Zehe E and Pfister L 2022 *Hydrol. Earth Syst. Sci.* **26** 6163–83
[8] Faranda D, Bourdin S, Ginesta M, Krouma M, Messori G, Noyelle R, Pons F and Yiou P 2022 *Weather Clim. Dynam.* **3** 1311–40
[9] Delforge D, Wathelet V, Below R, Lanfredi Sofia C, Tonnelier M, van Loenhout J A F and Speybroeck N 2025 *Int. J. Disaster Risk Reduct.* **124** 105509
[10] Kossin J P, Knapp K R, Olander T L and Velden C S 2020 *Proc. Natl Acad. Sci. USA* **117** 11975–80
[11] Truchelut R E, Klotzbach P J, Staehling E M, Wood K M, Halperin D J Schreck C J III and Blake E S 2022 *Nat. Commun.* **13** 4646
[12] Knutson T *et al* 2020 *Bull. Am. Meteorol. Soc.* **101** E303–22
[13] Knutson T R, Chung M V, Vecchi G, Sun J, Hsieh T L and Smith A J 2021 Climate change is probably increasing the intensity of tropical cyclones *Report Tyndall Centre for Climate Change Research Tyndall Centre for Climate Change Research Report* (available at: https://tyndall.ac.uk/)
[14] Balaguru K, Xu W, Chang C-C, Leung L R, Judi D R, Hagos S M, Wehner M F, Kossin J P and Ting M 2023 *Sci. Adv.* **9** eadf0259
[15] Vecchi G A, Landsea C, Zhang W, Villarini G and Knutson T 2021 *Nat. Commun.* **12** 4054
[16] Liu M, Vecchi G A, Smith J A and Knutson T R 2019 *NPJ clim. Atmos. Sci.* **2** 38
[17] Yang Y and Toumi R 2025 *Environ. Res. Lett.* **20** 074013
[18] van Oldenborgh G J, van der Wiel K, Sebastian A, Singh R, Arrighi J, Otto F, Haustein K, Li S, Vecchi G and Cullen H 2017 *Environ. Res. Lett.* **12** 124009
[19] Keellings D and Hernández Ayala J J 2019 *Geophys. Res. Lett.* **46** 2964–73
[20] Yiou P, Jézéquel A, Naveau P, Otto F E, Vautard R and Vrac M 2017 *Adv. Stat. Clim. Meteorol. Oceanogr.* **3** 17–31
[21] Jézéquel A, Yiou P, Radanovics S and Vautard R 2017 *Bull. Am. Meteorol. Soc.* **99** S76–S79
[22] Faranda D, Vrac M, Yiou P, Jézéquel A and Thao S 2020 *Geophys. Res. Lett.* **47** e2020GL088002
[23] Messori G, Bevacqua E, Caballero R, Coumou D, De Luca P, Faranda D, Kornhuber K, Martius O, Pons F and Raymond C *et al* 2021 *Bull. Am. Meteorol. Soc.* **102** E774–81
[24] Ginesta M, Yiou P, Messori G and Faranda D 2023 *Clim. Dyn.* **61** 229–53
[25] Faranda D and Alberti T 2026 *Atmos. sci. lett.* **27** e70016
[26] Faranda D, Messori G, Jezequel A, Vrac M and Yiou P 2023 *Proc. Natl Acad. Sci.* **120** e2214525120
[27] Faranda D *et al* 2024 *Weather Clim. Dynam.* **5** 959–83
[28] Bourdin S, Camargo S J, Lee C Y, Lin J, Vrac M, Ayar P V and Faranda D 2025 *Environ. Res. Lett.* **20** 024042
[29] Hersbach H *et al* 2020 *Q. J. R. Meteorol. Soc.* **146** 1999–2049
[30] Gahtan J, Knapp K, Schreck C, Diamond H J, Kossin J P and Kruk M C 2024 *NOAA National Centers for Environmental Information* vol 10
[31] Lee C Y, Tippett M K, Sobel A H and Camargo S J 2018 *J. Adv. Model. Earth Syst.* **10** 223–41
[32] Emanuel K, Ravela S, Vivant E and Risi C 2006 *Bull. Am. Meteorol. Soc.* **87** 299–314
[33] Lin J, Rousseau-Rizzi R, Lee C Y and Sobel A 2023 *J. Adv. Model. Earth Syst.* **15** e2023MS003686
[34] Johnson S J *et al* 2019 *Geosci. Model Dev.* **12** 1087–117
[35] Weisheimer A, Befort D J, MacLeod D, Palmer T, O'Reilly C and Strømmen K 2020 *Bull. Am. Meteorol. Soc.* **101** E1413–26
[36] Kossin J P, Knapp K R, Olander T L and Velden C S 2020 *Proc. Natl Acad. Sci.* **117** 11975–80
[37] Chen B F, Chen B, Lin H T and Elsberry R L 2019 *Weather Forecast.* **34** 447–65
[38] Laloyaux P *et al* 2018 *J. Adv. Model. Earth Syst.* **10** 1172–95
[39] Hodges K, Cobb A and Vidale P L 2017 *J. Clim.* **30** 5243–64
[40] Schiavina M *et al* 2022 *Luxembourg: Publications Office of the European Union*
[41] Kummu M, Taka M and Guillaume J H 2018 *Sci. Data* **5** 1–15
[42] Park J H and Li T 2019 *Clim. Dyn.* **52** 5345–60
[43] Aiyyer A and Thorncroft C 2011 *J. Clim.* **24** 2846–59
[44] Rodríguez-Fonseca B *et al* 2016 *Atmosphere* **7** 87
[45] Clarke B et al 2025 Climate change enhanced intensity of hurricane Melissa, testing limits of adaptation in Jamaica and eastern Cuba (available at: https://hdl.handle.net/10044/1/125306)