First steps of a historical storm track model based on climate reanalysis data for understanding the spatial footprint of recorded storm impacts

Pierre Pouzet [1], Ayyoub Frifra [2, 3], Mohamed Maanan [3]

[1] Univ Angers, Nantes Université, Le Mans Université, CNRS, Laboratoire de Planétologie et Géosciences, LPG UMR 6112, 49000 Angers, France

[2] Department of Geomorphology and Geomatics, Scientific Institute, Mohammed V University in Rabat, Morocco

[3] UMR CNRS 6554 LETG – Littoral, Environnement, Télédétection, Géomatique, Université de Nantes, France

Abstract: In the context of climate change, understanding extratropical storm dynamics is crucial for anticipating risks related to sea-level rise, as coastal hazards are expected to be more frequent in the future decades. This study presents the first steps of an innovative storm track reconstruction model based on wind gusts from ERA5 reanalysis data, instead of relying solely on atmospheric pressure. By focusing on wind intensity, the model prototype enables the identification of "impact trajectories" that align more closely with observed damage along the French Atlantic coastline. The methodological framework includes four main steps: ERA5 data processing, high-wind structure detection, trajectory modeling and smoothing, and interactive mapping. To validate the approach, seven major historical storms were analyzed: Xynthia (2010), Lothar and Martin (1999), Daria and Herta (1990), the 1987 "Great Storm", and the February 1974 event. The modeled tracks were compared with geomorphological records (sedimentary deposits and dendrochronology) and historical sources such written documents and newspapers, revealing strong spatial consistency. Results highlight the value of combining climate reanalysis data with environmental archives to better understand past storm dynamics. This interdisciplinary approach may enhance the temporal depth of storm reconstructions and can be applied to pre-instrumental periods. The early stage of this model offers significant potential for assessing long-term changes in storm patterns and shall contribute to improved projections of future coastal hazards in the ongoing context of climate change.

Keywords: GIS, extreme events, storm track, coastal flooding, environment, climate reanalysis data.

1. Introduction

1.1 Coastal flooding and storm dynamics knowledge regarding climate change

In the ongoing context of climate change, coastal extreme events are emerging as a major environmental challenge. According to the latest findings from the Intergovernmental Panel on Climate Change (IPCC), rising sea levels could ultimately displace up to 280 million people worldwide (Pörtner et al., 2019). The International Union for Conservation of Nature (IUCN) reports that nearly 60% of the global population resides within 150 km off the coast, making coastal flooding a persistent and significant threat to these communities. As they are mainly caused by atmospheric surges produced by climatological events such as storms or hurricanes, the understanding of these climatological phenomena must be further strengthened. While the impact of climate change on tropical cyclones is well documented, its effects on extratropical storms remain uncertain (Masson-Delmotte et al., 2021).

The IPCC has observed a poleward shift in extratropical storm trajectories in both hemispheres over recent decades but emphasizes the challenges in predicting how rising greenhouse gas emissions will influence these storms in the future (Wang et al., 2006). At present, the only widely accepted consequence is the increase in associated precipitation (Semmler et al., 2004). Although extreme coastal events in Europe are becoming more frequent due to global mean sea-level rise, the long-term climatological dynamics of European storms that may cause coastal flooding remains poorly understood (Frifra et al., 2024a).

1.2 Understanding the link between storm damage recorded and their historical tracks

To address this gap, historical storm records are essential. As an example, a new digital approach based on a 1996–2015 dataset has been applied to predict storm characteristics and occurrences in Western France (Frifra et al., 2024b). In the line with these new methods, this study aims to improve the precision of historical storm reconstruction by assessing their past trajectories using reanalysis data. Geomorphological methods, such as sedimentology and dendrochronology (Pouzet et al., 2018), have been used to understand short- and long-term storm variability in western France, supplemented by detailed written archives. These environmental methods extend storm chronologies back several decades or even centuries, providing greater temporal depth for predictive models. However, the accuracy of dating decreases with the age of the archives, increasing uncertainty for older records. To address this limitation, climate reanalysis data are used to improve dating precision and identify specific weather and/or marine parameters that played key roles in generating the environmental impacts recorded in geomorphological archives (Pouzet and Idier, 2024).

Now this new study explores the potential of reanalysis data to understand how historical storms have impacted both physical and societal environments in coastal and then continental areas thanks to their trajectory estimations. Using ERA5 ocean-atmosphere data (Hersback et al., 2020) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), we present new methodologies to apprehend the evolution of historical storm activity in western Europe. These approaches are tested on major storms that impacted French coastal environments during the XIXth and the XXth centuries, within the temporal scope of the ERA5 reanalysis data. The storm tracks of historical events that caused geomorphological marks detected in the environment are estimated based on their wind gust records. Spatial analysis tools, utilizing GIS techniques, is employed to understand the overall extent of the most intense winds per storm. The early stage of this model helps identify potential physical and societal impacts of historical storms and refines historical spatial storm parameters, including their precise "impact trajectories".

1.3. The importance of wind gusts to reconstruct historical storm tracks

Most studies regarding storm tracks are based on a trajectory of the low-pressure center displacement (e.g. Priestley et al., 2020a; Graff and LaCasce, 2012; Feser et al., 2015 or Chang, 2017), however, choosing the lowest pressure value as a meteorological parameter to model storm track may not be relevant if we want to link them to recorded storm impacts. As an example, we choose the intense 2010 Xynthia storm that deeply affected low-lying coastal cities with significant floodings (Chauveau et al., 2011) and continental areas with intense wind gusts recorded (Haidu et al., 2019). As seen in the Figure 1 modified and traduced from Genovese et al., 2012, a clear intense-wind path of intense winds can be estimated south-eastern to the center of the low-pressure system (blue dashed arrow). This observation highlights the fact that the most intense wind gusts, extracted from Météo-France data were not recorded in the center of the storm (by its common definition based on its pressure). Intense wind gusts are not strictly correlated to the air pressure, and this observation proves that using the low-pressure system as the parameter to model storm tracks may not be the most interesting choice to assess ancient storm trajectories and cross them with their coastal and continental impacts recorded. In consequence, we choose to model our storm tracks as *"storm impact trajectory"* based on maximum wind gust records rather than the typically applied low-pressure minimum values, to estimate the path that underwent the most intense storm damages.

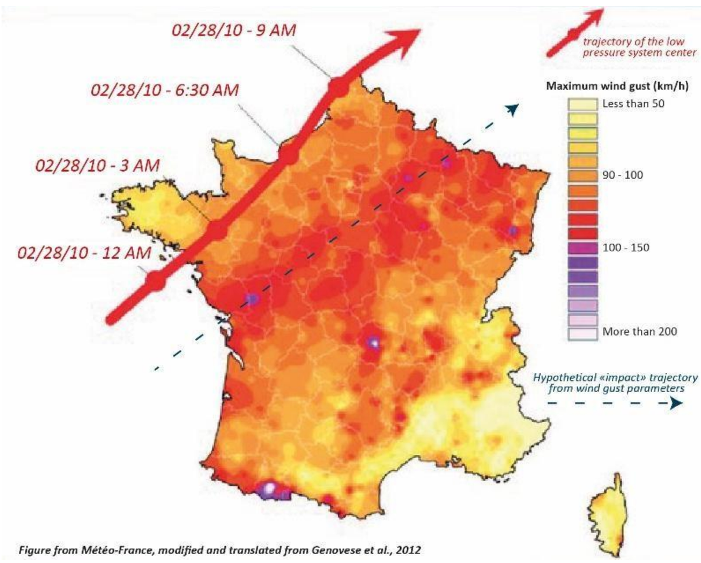

Figure 1. Maximum wind gust recorded from Meteo-France during the 2010 Xynthia storm and comparisons of the "low-pressure system" and "impact" trajectories. Figure traduced and modified from Genovese et al., 2012.

2. Methods

2.1 Spatial modeling framework for storm trajectories based on ERA5 wind gust data

To recreate historical storm tracks and assess storm activity in Western Europe, we developed the first steps of a spatial modeling framework based on ERA5 reanalysis wind gust data. The methodology adopted is divided into four major steps (Figure 2): ERA5 wind gust data retrieval and preprocessing, detection of high-wind storm structures, modeling and smoothing of storm trajectories, and interactive mapping of storm tracks. The spatial model prototype was tested on the main storms that affected the French coastal environments in the XXth and XXIth centuries, and it was developed in Python using open-source tools and geospatial libraries, ensuring reproducibility and adaptability to different study areas and temporal scales.

2.1.1. ERA5 wind gust data retrieval and preprocessing

The ERA5 reanalysis dataset, created by the European Centre for Medium-Range Weather Forecasts (ECMWF) as a component of the European Union's Copernicus Climate Change Service, is used to accomplish the study's goals. ERA5, which spans the years 1950 to the present, is the fifth generation of atmospheric reanalysis generated by ECMWF (Bell et al., 2021). ERA5 offers hourly estimates of the global atmosphere, land surface, and ocean waves at a horizontal resolution of 31 km, which represents a major improvement compared to its predecessors, such as ERA-Interim, which had fewer assimilated observations and a coarser spatial resolution of 78 km. Due to its greater temporal and spatial resolutions, ERA5 can capture far finer details of atmospheric phenomena than earlier global reanalysis (Bell et al., 2021; Hersbach et al., 2020).

The variable "instantaneous 10-meter wind gust" was specially used in this investigation to identify high-intensity wind events. Therefore, the Climate Data Store (CDS) Application Programming Interface (API) was used to obtain hourly wind gust data from the ERA5 reanalysis archive. The data extraction procedure was automated so that users may choose the temporal coverage (year, month, start and finish dates) and geographical extent (bounding box determined by minimum and maximum latitudes and longitudes). The downloaded dataset was then preprocessed to allow for effective manipulation of multidimensional meteorological variables, as well as creating a visualization that highlights the geographical distribution and progression of wind gusts throughout the specified storm periods.

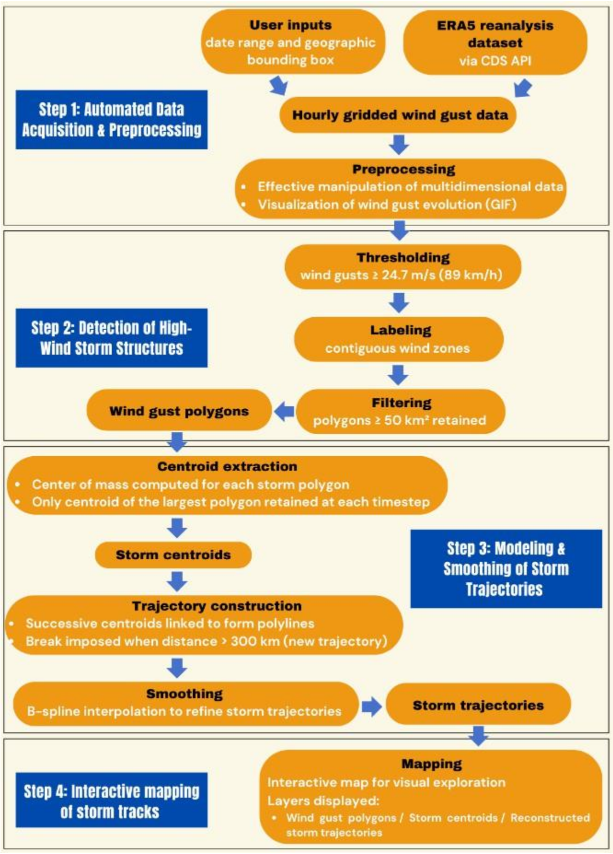

Figure 2. Workflow of the spatial modeling framework for storm trajectories

2.1.2. Detection of high-wind storm structures

The second step in this research consists of extracting severe wind occurrences that indicate storm activity using wind gust thresholding and storm cell detection. Therefore, we employed a threshold of 24.7 m/s (89 km/h), which represents the lowest wind speed for storm-force conditions (scale 10/12) as described by the Beaufort scale (Gliksman et al., 2023). Grid cells that exceeded this threshold were transformed into binary masks at each hourly time step and then labeled into distinct storm zones using connected-component labeling. For each identified storm wind zone, the geographical extent was determined by calculating the number of impacted grid cells and converting it into area units (km^2) using the ERA5 grid's spatial resolution. The study only included regions with a surface area of 50 km^2 or more, ensuring that small, isolated, or transient gusts are excluded from the analysis. The resulting identified storm cells were saved as polygons that delineate the storm impact region at each time step. Finally, the dual criteria of intensity and geographical footprint applied in the study guarantees that the discovered structures correspond to synoptic-scale wind disturbances normally associated with extratropical storms striking western France.

2.1.3. Modeling and smoothing of storm trajectories

Following the extraction of storm structures, the next stage was to rebuild the temporal evolution of storm systems. The center of mass was calculated for each detected storm polygon at a certain time step. Among the observed storm cells, the centroid with the biggest surface area was chosen as the main storm core for that hour. These centroids act as geographical proxies for the sites of greatest wind intensity and, when sequenced chronologically, provide the foundation for modeling the storm's track.

The centroids were linked in temporal order to create polylines, which produced coherent storm tracks. However, a quality control step was put in place to avoid the incorrect linking of several storm systems by adding a break to the trajectory when the geodesic distance between two consecutive centroids surpassed 300 km. This threshold was set using physical restrictions affecting storm motion. While tropical storms may maintain wind speeds of 62 to 117 km/h, extratropical storms, which are the primary storm systems of interest in this study, often spread at a slower rate (Frifra et al., 2024b). As a result, a 300 km/h threshold indicates a generous upper limit, above which the identified centroid is more likely to be a distinct storm system or atmospheric depression. Two fundamental principles served as the basis for this filtering criterion: preserving the geographic continuity of a coherent storm system across consecutive time steps and preventing the artificial merging of spatially disconnected storm structures. Thus, a new trajectory was started when this threshold was surpassed, guaranteeing the separation of discrete meteorological events.

B-spline interpolation was used as a smoothing procedure to further refine the produced trajectories and reduce noise related to sudden directional shifts (Lim, 1999; Ishida, 1997). This technique produces more realistic and continuous storm trajectories by attenuating sudden variations while maintaining the centroid path's general structure. The final output consists of smoothed polylines that accurately depict the spatiotemporal evolution of high-wind storm systems over the research region.

2.1.4. Interactive mapping of storm tracks

To facilitate additional geospatial analysis inside common GIS platforms, the framework's last step involved exporting all generated spatial outputs, including wind gust polygons, storm centroids, and reconstructed trajectories, in shapefile format. Additionally, an interactive mapping interface was created utilizing the Ipyleaflet package in a Jupyter Notebook environment to improve the interpretability and exploration of storm development patterns. This tool provides interactive layer control and enables dynamic visualization of storm-related features over satellite base maps. Users can control the visibility of centroids, polygons, and trajectories, as well as investigate individual centroid markers using pop-up windows that provide timestamps and geographical coordinates. The interactive interface allows for straightforward visual examination and improves quality control during the detection and trajectory reconstruction process. The interface was also implemented as a web application, allowing users to engage with the storm mapping tool directly via a web browser, eliminating the necessity for a Jupyter environment.

2.2 Storm impacts from environmental multi-sources

2.2.1. The use of geomorphological archives to detect environmental imprints

Several geomorphological approaches have been deployed over the last decades to push back the temporal boundaries of storm chronologies into pre-instrumental periods using environmental proxy data and historical sources. Sediment-based analyses, such as the identification of overwash deposits, coarse clastic layers, or geochemical anomalies in coastal archives (e.g., lagoons, marshes, or estuaries), are frequently used to infer high-energy storm events. These approaches have been deployed over the French Atlantic Coast at the Petite Mer de Gâvres (Pouzet et Idier 2024) and the Traicts du Croisic lagoons (Pouzet et al., 2018). Sedimentological imprints detected from these studies are spatialised in a GIS database to see if they fit with the storm paths estimated by the storm track model prototype.

New approaches deployed in dendrochronology were also considered, as it has been recently used to record intense wind impacting the tree tilting that can be detected thanks to the tree-rings size variation analyses. As one tree ring refers to a vegetative season, the ring counts is then used to date back the historical storms that may cause the tree growth disturbance. This new method has been tested in the Pen Bron dune stand (Pouzet et al., 2018) and then specified in the Pointe d'Arcay coastal forest (Pouzet et al., 2025 in press). These impacts have also been considered in the spatial analyses to understand if the storm track paths of the model is accurate.

2.2.2 Historical archives analysed to understand socio-economic implications

In parallel, historical climatology plays a complementary role by incorporating archival records such as chronicles, administrative documents, and early instrumental data to document storm impacts and societal responses over the past centuries (Athimon & Maanan, 2018). Multidisciplinary frameworks, though still underdeveloped in some regions, offer valuable insights into storm frequency, magnitude, and spatial patterns over long timescales, particularly when instrumental records are absent or fragmentary (Pouzet et al., 2019). The historical component is grounded in a systematic analysis of diverse archival materials, including: (i) documents from libraries and archives, (ii) narrative sources (chronicles, diaries, memories, etc.), and (iii) old maps. These documents come from financial records and post-disaster assessments to barometric observations and press articles and are conserved in local archives (Athimon & Maanan, 2018). These sources provide descriptive and observational data on extreme weather events, including accounts of storm characteristics, associated damages, and the societal responses and adaptations they elicited (Pouzet et al., 2019; Athimon & Maanan, 2018). Meteorological data such from Meteo France storm archives were also considered to complement the information.

Prior to their integration into a long-term reconstruction of storm and submersion events, these data underwent critical evaluation, validation, and standardization within a dedicated database to facilitate cross-referencing (Athimon, 2021). To assess the reliability of individual documents, attention was given to the context of their production and if the identity and status of the author is known, if he witnessed the event, and the institutional or administrative framework in which the source was generated. Where possible, cross-verification between independent sources was conducted to improve the accuracy and completeness of each event record (Athimon et al., 2016).

3. Results

3.1 Trajectory model validation with the Xynthia storm

We choose the well documented 2010 Xynthia storm to validate the trajectory model prototype with ERA5 wind gusts data. Figure 3 presents the results of the storm path determined by the model (yellow polygons) from consistent winds highest that 24.7 m/s (89km/h) in a minimum surface of 50km². The pink dots were determined as the centroids of each path for each timestep, from midnight to 3 PM during the passage of the storm. Then, the blue line is the trajectory estimated as the smoothed line that connects each centroid.

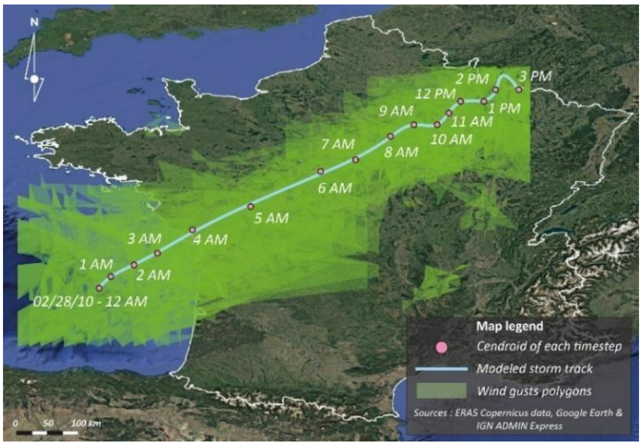

Figure 3. Storm track model prototype results for the 2010 Xynthia storm

These results are consistent with the hypothetical "impact" trajectory from wind gusts parameters as it strictly follows the path of the highest winds recorded by Metéo-France (blue dashed arrow of the Figure 1, traduced and modified from Genovese et al., 2012). The areas that were the most impacted in the Atlantic coastlines were centred on the Vendée, with impacts from the Loire-Atlantique in the north to the Charente-Maritime and the Gironde at the south during the early morning. Then the main impact trajectory strokes the Northern Nouvelle-Aquitaine and the southern Pays de la Loire, the Centre-Val de Loire and the southern Ile-de-France in the late morning; to end mostly in the Bourgogne-Franche-Comté and the Grand Est administrative regions in eastern France around noon.

3.2 Modelling historical storms trajectories that impacted coastal environments

We then integrated to the model ERA5 wind gusts data to the main storms that impacted the French Atlantic coastlines : the highly mediatized Lothar and Martin 1999 storms; Daria and Herta 1990 storms, the two most impacted events over the four storms that struck the area during the winter 1990 ; the 1987 significant event that was called *"Ouragan"* or *"Great Storm"* as it deeply leave a mark on people living on the coastlines ; and the February 1974 storm as an older and less documented storm example that we also found on geomorphological archives (Pouzet and Idier, 2024; Pouzet et al., 2025 in press). Figure 4 presents each storm trajectory obtained from wind gusts ERA5 data integrated in our model prototype.

https://doi.org/10.5194/isprs-archives-XLVIII-4-W17-2025-263-2026

Figure 4. French storm track from ERA5 wind gusts data model for the most impacting recent events of the late XXth century

The latest storm tested is the one that presents the southernmost trajectory. It begins around 10 AM the 27th of December 1999 off the coast of Aquitaine, to end near the Alps at 6 AM the 28th of December. The day before, the Lothar storm also struck a large part of France, with a trajectory at its center starting at noon of the coasts of Vendée until the Burgundy region in the late morning. According to the numerous damages recorded, these two events were locally called the *"Storms of the Century"* as they induced significant wind destruction and floods over the coastlines; with nearly 100 deaths recorded over France and an estimated financial damage reaching nearly 7 billion euros (Gerard and Lang, 2019). Figure 4 shows that these two events follow a general W-E direction.

Daria and Herta are two intense storms that occurred during the particularly stormy 1990 winter that also undergone Vivian and Weibke events. In early February, Herta begins its path near the Pays de la Loire coasts in the morning of the 3rd of February to follow a SW-NE direction and end in the evening near the Luxembourg border. Later in the year, the Daria event was shorter but also highly impacted and crossed Brittany from west to east from the late morning of the 25$^{th\ of}$ January to end the early afternoon in Normandy. A dozen deaths were recorded after these storms and the only Daria event caused nearly 6.8$ Billion economic loss (valued at 1992 prices) according to Dorland et al. (1999).

A few years later, the October 1987 storm was considered as one of the most powerful storms that struck the European coastlines. Starting its French impact track (it also deeply impacted Britain) the 15th at 9 PM near the Groix Island, it ends off the Manche's coastlines the morning after following a clear SW-NE direction. From its intensity that was never seen in the last 250 years in England and the significant forest loss (Mitchell and al., 1989), It has been called *"The Great Storm"*, and nearly 15 deaths were recorded in French Brittany. The last storm studied is the February 1974 storm, also following a SW-NE path starting from Britanny at 9 AM on the 11th of February to reach the Hauts-de-France region during the evening of the same day. Well documented, this storm was still particularly impacting for the Northern France as several beaches and wind destruction were recorded (Le Cornec et al., 2012).

3.3 February 1974 and 1999 Martin wind tracks crossed with storm impacts recorded near the French coastlines

The February 1974 and Martin 1999 storm paths modeled were selected to be crossed with geomorphological archives extracted near the French Atlantic coast and historical data delved in local archive centers as they are two distinct cases (Figure 5). First, their directions are not consistent as the Martin storm follows a W-E path and the 1974 storm follows a SW-NE direction. They reflect the main principal trajectories of extratropical storms such as the Z2 (1974) and Z3 (1999) paths estimated by Lozano et al. (2004). Then, the Martin 1999 storm mainly impacted southern France and the 1974 storm struck the north of the country.

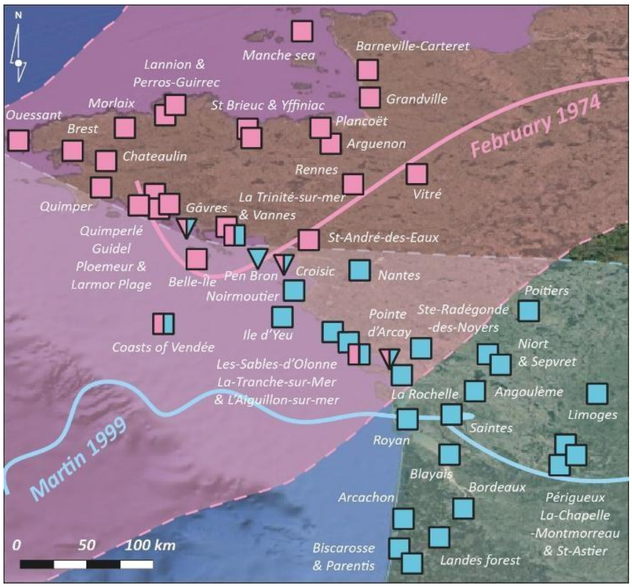

Figure 5. February 1974 (pink) and Martin 1999 (blue) examples of storm tracks modeled from wind data; crossed with geomorphological (triangle) and historical (square) archives of impacts recorded near the coastlines.

During the 1974 storm, most geomorphological and historical impacts were recorded on the Britanny coastlines, with also a few impacts in western Normandy and in Pays de la Loire. This storm let a sedimentological impact in the Petite mer de Gâvres (Pouzet and Idier, 2024) and Traicts du Croisic (Pouzet et al., 2018) lagoons; and in the Pointe d'Arcay dune stand (Pouzet et al., 2025 in press); all exemplified in the Figure 5 with pink triangles. In addition, numerous newspapers reported significant wind damage (Brest, Belle-Île, Châteaulin, etc.), river floods (such as in Morlaix, Plancoët or Vitré) and intense marine conditions inducing coastal breaches (Vannes, Guidel, Barneville, l'Aiguillon-sur-Mer, etc.) and a disruption of maritime traffic in the Manche Sea and in Ouessant where a shipwreck is reported ; they are all indicated as pink squares in Figure 5. In addition, Le Cornec et al. (2012) work also proposed a summary of the intense impacts of this event on Brittany that confirmed that this storm has deeply impacted north-western France. As indicated by Figure 5, the spatialization of these impacts near the coastlines are consistent with the storm track modeled in the pink line, as they are in the "impact" path polygon (transparent pink flat color).

The second 1999 storm called Martin was one of the most powerful storms that impacted the country (Ulbrich et al., 2001). Geomorphological impacts (in blue triangles in the Figure 5) were recorded in a large part of the French coastlines, from southern Brittany (Gâvres, see Pouzet and Idier, 2024) to the Pays de la Loire (Croisic, see Pouzet et al., 2018) in sedimentological records; and in dendrochronological archives in the Pen Bron (Croisic, see Pouzet et al., 2018) and Pointe d'Arcay (Pouzet et al., 2025 in press) dune stands. Written historical documents (blue squares on the Figure 5) are very rich for this storm, and they reflect the intense damages recorded over a large part of western and southern France. For example, a total of 26.1 million m^3 of wood were downed in the Landes forests during the two storms of December 1999 (Cucchi and Bert, 2003). The Blayais nuclear central was flooded after the passage of the storm, and severe wind damage was recorded (such as uprooted trees, damaged bell towers, toppled cranes) in important cities such as Nantes, Bordeaux, Périgueux, Niort, Poitiers and Limoges. A large part of the Atlantic coastline, from southern Brittany (Vannes) to the Aquitaine region undergone intense marine conditions such as Noirmoutier, La Rochelle, Royan and Arcachon. As indicated by Figure 5, the spatialization of these impacts in western and southern France are consistent with the storm track modeled in the blue line, as they are also located in its "impact" path polygon (transparent flat blue color).

4. Discussion & Conclusion

4.1 Strengths and limitations of storm impacts recorded linked to their modeled tracks

Generally, the storm tracks modeled and exemplified with the February 1974 and Martin 1999 storms shows a good fit with impacts recorded near the coastline. Anyway, several limitations of this study can be discussed. First, ERA5 wind gusts are recognized to be slightly underestimated compared to observations (Gandoin and Garza, 2024). Consequently, the path spatial extends (2.1.2 section) may also be slightly underestimated. Concerning the geomorphological impacts recorded, back barrier washover deposits generally occur when both intense weather and marine conditions are recorded (Pouzet and Idier, 2024). Consequently, storms that produce high winds but those that do not cross high tide conditions may be missed in sedimentological archives. Therefore, this approach is more effective with storms that cause significant coastal damage from a crossing of intense marine and weather conditions. On the contrary, dendrochronological archives are more fully linked to wind gusts records as they directly impact the tree ring growth (Pouzet et al., 2025 in press). They may be a better environmental proxy to cross with these wind impact trajectories. Concerning historical records, it is also important to keep in mind that it is very difficult to remain exhaustive and that the spatialization of storm damage may also be influenced by the archives sites that have been delved. A storm like the Martin 1999 storm*, "one of the storms of the century"* may also have impacted the entire southern France. However, it remains impossible today to identify impacts for each affected city.

Most research on storm tracks in the literature depends on sea-level pressure minima (e.g., Priestley et al., 2020a; Graff and LaCasce, 2012; Feser et al., 2015) or vorticity-based identification from reanalysis datasets (Neu et al., 2013). Although these methods effectively detect large-scale synoptic systems, they may neglect localized wind effects or underestimate storm severity during periods of weak pressure gradients. Conversely, the current model prototype employs ERA5 wind gust data to rebuild storm paths grounded on surface wind extremes, providing a more immediate correlation to observable damage and environmental impacts. This approach facilitates also enhanced separation between successive storm occurrences, as seen by the 1999 Martin and Lothar storms.

This study demonstrates that climatic reanalysis data is essential for understanding historical storm dynamics recorded during the reanalysis timespan, confirming the hazardousness of these storms in relation to current coastal issues. Combining reanalysis data with geomorphological archives is crucial, and in future research, extending climatic reanalysis datasets to earlier periods could provide critical insights for interpreting geomorphological data, as sedimentological and dendrochronological archives now offer storm records spanning millennia. By obtaining more accurate and ancient historical data through these methods, future models will be able to make precise predictions in the context of ongoing climate change. Given the high uncertainty surrounding extratropical storm dynamics, this research addresses a major contemporary issue.

4.2 Perspectives for the development of the storm track model prototype regarding climate change science

This model prototype will be submitted for further development in the future months. A limitation regarding the trajectory polylines angles will be implemented to better identify the successive storms that can occur consecutively on the same day or in two days in a row. This is the case for the 1999 storms that struck the French Atlantic Coastline in late December, the geodesic distance of 300 km allowed for cutting the trajectory between the end of the first storm in the east of France and the beginning of the second in the southwest. However, a third low-pressure system started just after the second storm a few kilometers north to the end of the second storm, thus producing a right angle at the end of the trajectory. It may be useful to introduce this additional angle condition to better isolate each storm from their beginning to their end.

In addition, the interactive interface developed in this study was deployed as a web application, allowing wider audiences to examine storm trajectories and associated features directly via a web browser without needing a Jupyter setup, therefore, improving the accessibility outside of the development environment. The application is publicly available at the following URL: https://mybinder.org/v2/gh/AyoubFrifra/storm-map/HEAD?urlpath=voila/render/storm_map.ipynb or via the corresponding GitHub repository, which includes a launch badge: https://github.com/AyoubFrifra/storm-map/tree/main

Future efforts will focus on developing this prototype into a more sophisticated web-based geospatial platform. The envisioned tool would enable users to designate temporal ranges and geographical regions of interest, automatically activating the storm detection and trajectory reconstruction process in real time. The proposed tool will democratize access to climate hazard modeling, permitting researchers, planners, and decision-makers to analyze severe wind occurrences with minimum technological overhead dynamically. As it can be applied in every region, it should also be used to estimate tropical storm dynamics.

Moreover, the present study focuses on recent XX^{th} century data as meteorological information is available, but a deeper timespan may offer longer-trend links between climate and storm dynamics that may be used for future prospective scenarios. While most reconstructions of historical storm tracks focus on the recent past (*e.g.* Rogers, 1997; Ulbrich and Christoph, 1999; Priestley et al., 2020b) *i.e.*, since the use of meteorological data and reanalysis, it remains impossible today to evaluate the evolution of these physical processes over long timescales. To extend this kind of analysis to older periods, these geomorphological and historical archives recorded in the environment and discussed in this paper may be used (Pouzet and Maanan, 2020). The adaptation of these early stages of our storm track model to the last millenary with the implement of ancient geomorphological and historical impact spatial databases will thus provide a crucial millenary temporal depth to understand the processes influencing storm formation along the French Atlantic coast. Future innovative objectives will be understanding of how these stormy tracks evolved during different climatic periods such as the Little Ice Age and the Medieval Warm Period (Lamb, 1965), to ascertain whether a latitudinal migration is observed, and if so, what the ocean-climatic causes might be. Understanding the evolution of past trajectories and their influences over the long term also provides insights into the future evolution of these dynamics, thereby better protecting coastal societies against future weather-marine hazards.

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