



Research Article

Has the Anthropocene affected the frequency and intensity of tropical cyclones? Evidence from Mascarene Islands historical records (southwestern Indian Ocean)

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ABSTRACT

We present a historical record of landfalling tropical cyclones (TCs, 85 events) over the Mascarene Islands (southern Indian Ocean) since the 17th century to evaluate interannual-to-decadal-scale changes in past TC variability, from the cooler Little Ice Age (LIA) to the present warming world, and to contextualize present and future changes in risk estimates. For the Mascarene Islands, we observe a mean fourfold increase in regional landfalling TCs, beginning around 1940. Before this date, the historical TC data exhibit clear decadal cycles, which mirror solar radiative forcing. This historical record demonstrates how enhanced understanding of past variability can improve baseline risk estimates of TCs making landfall in the SW Indian Ocean basin.

1. Introduction

Understanding future changes in tropical cyclones (TCs) and associated storm surges is a significant challenge for assessing, planning and mitigating against the impact of climate change on natural environments and coastal anthroposcapes. Tropical cyclones are weather events affecting tropical, sub-tropical and mid-latitude regions, and they consistently rank among the world's deadliest and costliest natural hazards (Mendelsohn et al., 2012; Peduzzi et al., 2012; Seo and Bakken, 2016). From 2000 to 2018, the impacts of TCs led to >186,000 deaths worldwide and affected a further >423 million with total damages exceeding US\$ 858 billion (EM-DAT, 2020). Many of these socio-economic problems have been compounded by relative sea-level rise and global change (Woodruff et al., 2013; Horton et al., 2018; Oppenheimer et al., 2019; Vousdoukas et al., 2020), and the threat of TCs sits uneasily with high coastal population densities and seaboard megacities

(Reed et al., 2015; Garner et al., 2017), particularly in developing countries (Hallegatte et al., 2013; Neumann et al., 2015).

Although climate change is one of several factors likely to affect the future evolution of damage by TCs, the link between their activity and global warming is unclear and widely debated (Sobel et al., 2016; Walsh et al., 2016; Knutson et al., 2019, 2021; Wu et al., 2022). TCs respond to latent heat fluxes from the underlying ocean surface and observational records suggest that variations in Sea Surface Temperatures (SST) drive changes in their activity (Emanuel, 2005; Webster et al., 2005; Bender et al., 2010). Nonetheless, key knowledge gaps remain with regards to TC behavior in a warming world (Mann et al., 2017), due in part to regional disparities in TC dynamics and tracks. Furthermore, our understanding is hindered by limitations in the temporal length and quality of observational records, which are mostly constrained to the satellite era, hampering both trend detection and attribution (Kossin et al., 2013; Magee and Verdon-Kidd, 2019). Within this context, careful analysis of

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Fig. 1. Location map of the Mascarene Islands.

the data in individual ocean basins and their interpretation in terms of the local modes of natural variability is needed to probe the mechanisms responsible for variations in TC characteristics. An analysis of the lifetime maximum intensity of TCs in various basins for a two-decade period spanning 1989–2009 elucidated modest increasing trends (Kossin et al., 2013). The study found that trends at the level of some individual basins were more transparent. For instance, for the North Atlantic (increases) and Western North Pacific (decreases) manifested highly significant trends at the 95% confidence level. More modest upward trends were observed for the South Pacific and South Indian Ocean basins. Insufficient data for the Eastern North Pacific and the North Indian basin meant that robust conclusions could not be drawn. In other studies, relating specifically to the South Indian basin, Holland and Bruyère (2014) reported an increasing trend in the number of intense TCs that they attributed to global warming at the 99% confidence level. These findings are largely supported by Malan et al. (2013) who elucidated, for the Southwest Indian Ocean, an increased occurrence of severe storm days (category 3 or greater) since the 1990s, although the study found that the total number of cyclones decreased.

TCs are a recurring phenomenon in the SW Indian Ocean, most frequent during the cyclone season spanning November to April (Terry et al., 2013). A study by Mavume et al. (2009) found that an average of 12.5 cyclones formed annually in the SW Indian Ocean over the period 1980–2007. 85% of these events were constrained to November–April (the cyclone season). Over the same period, the number of intense tropical cyclones increased from 36 during 1980–1993 to 56 during 1994–2007. TCs frequently reach landfall on the islands of Mauritius and Réunion and can cause severe damage and societal disruption. Satellite imagery reception issues and a paucity of digital imagery before the late 1990s mean that there are inconsistencies in the TC data base for the SW Indian Ocean before this period, hampering long-term trend analysis. The short nature of the observational record motivates the use of historical time series to probe decadal-to-centennial TC trends in the area. Within this context, the volume of the available archives for the southern Indian Ocean is a corollary of the major strategic interest that the Mascarene Islands represented for European colonial powers. British

and French historical archives from the Mascarene archipelago are particularly detailed (Garnier and Desarthe, 2013) and their quality and the continuity of observing capabilities over time renders the data reliable for long-term trend analysis.

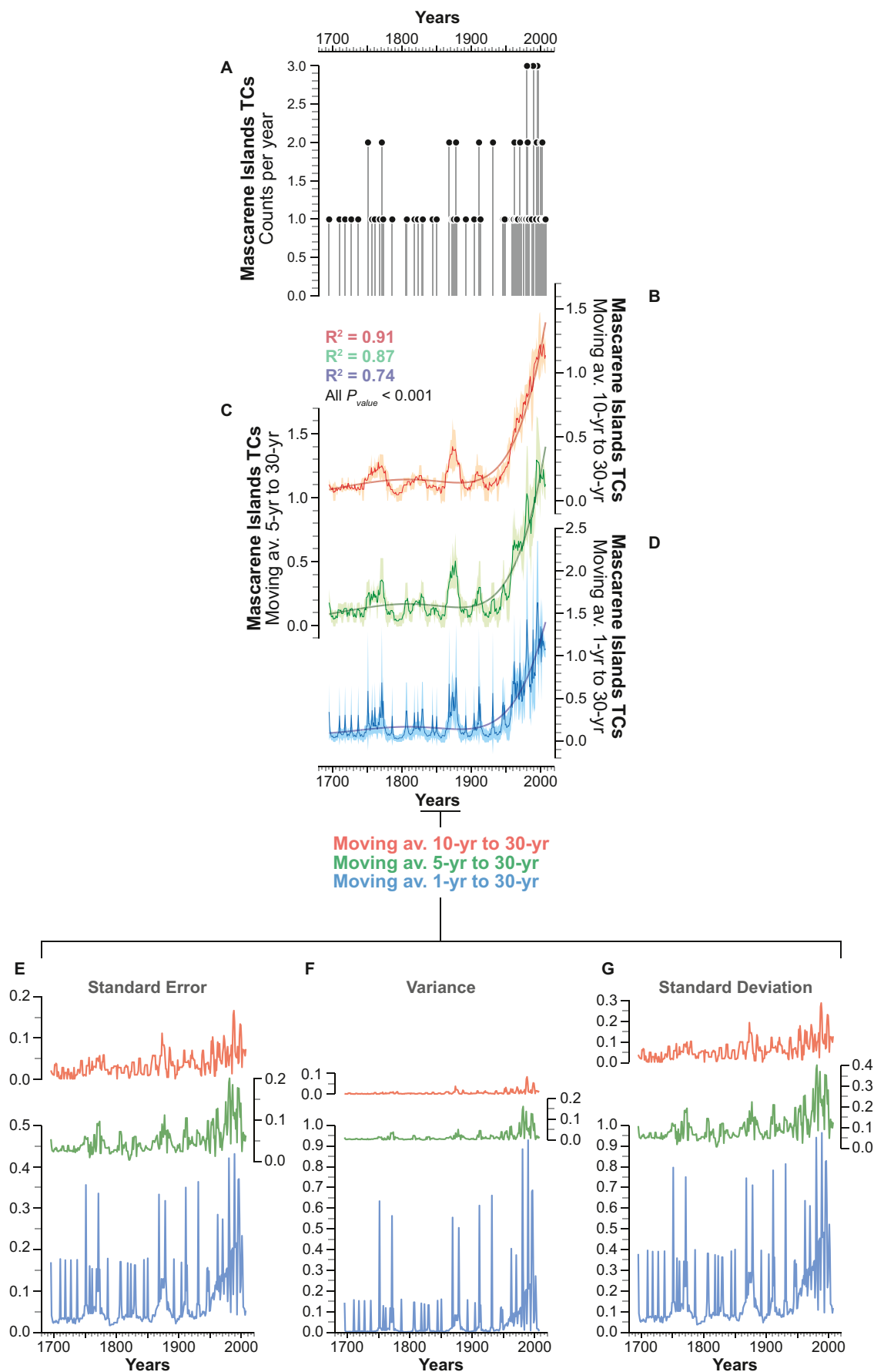
The main objectives of this study may be defined as follows:

- 1) To extend the observational record for landfalling TCs in the SW Indian Ocean back over the last ~300 years using an exceptionally long documentary time series from the Mascarene Islands. This time series constitutes the longest historical record of TC activity in the Southern Hemisphere.
- 2) To compare and contrast decadal-to-centennial-scale trends in landfalling TCs with high-resolution palaeoclimate records.

Addressing these objectives will provide information on the role of well-calibrated historical for studying long-term TC dynamics in the SW Indian Ocean basin and for a better understanding of how past variability can improve the baseline risk estimate of TCs making landfall over the Mascarene Islands. Historical data are key to informing adaptation and to compare climate change projections.

2. Methods

Geostationary satellite data only became available in the SW Indian Ocean in 1998. To understand the drivers of TC changes in a warming world, their recent activity needs to be placed in a longer-term temporal framework, data potentially furnished by palaeotempestology (Chenoweth and Divine, 2008; Callaghan and Power, 2011; Trouet et al., 2016). Here, we report an exceptionally long documentary time series from the Mascarene Islands (Fig. 1) to extend the observational record for landfalling TCs in the SW Indian Ocean back over the last ~300 years (Fig. 2). We characterized landfalling TC activity (frequency and intensity) over the Mascarene archipelago using a comprehensive documentary compilation of 85 TCs recorded in British and French historical archives, between 1695 and 2007 (Garnier and Desarthe, 2013). The volume and quality of the archives for the SW Indian Ocean result from



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Fig. 2. A. Frequency of Mascarene Islands TCs by year. We used 20-year sliding sums of TC frequency in order to minimize the purely random variability that dominates the historical time series at high frequencies, while retaining most of the variability at decadal and longer periods. To illustrate this, we calculated three sets of averages and associated confidence intervals: (B) 10-year to 30-year, with averages of 10-year +20-year +30-year moving averages; (C) 5-year to 30-year, with averages of 5-year +10-year +20-year +30 year moving averages; and (D) 1-year to 30-year, with averages of 1-year +5-year +10-year +20-year +30 year moving averages. Associated (E) standard errors; (F) variance; and (G) standard deviations associated with the three sets of averages.

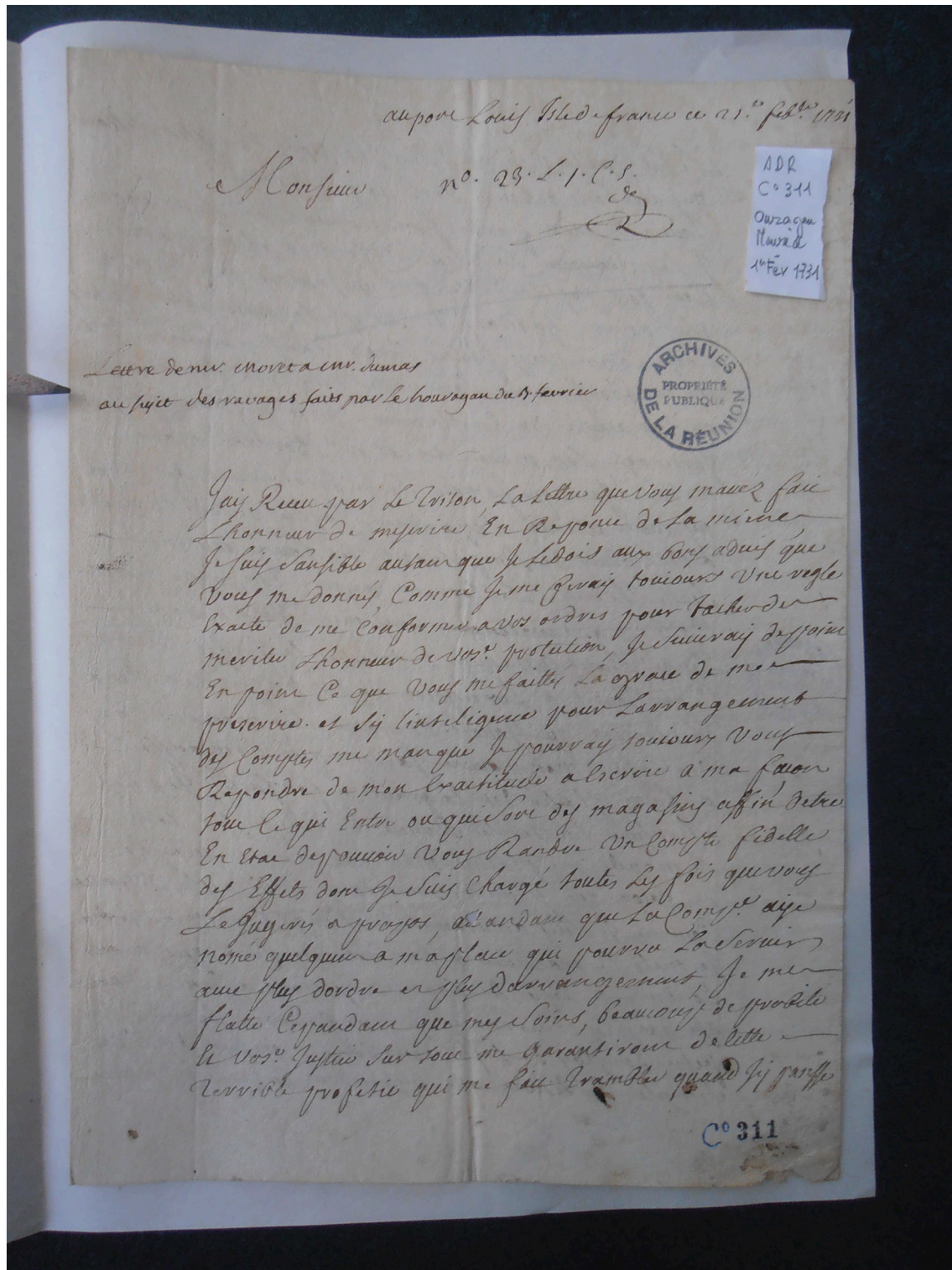


Fig. 3. Letter from the governor of Ile de France (present-day Mauritius) at Port-Louis detailing the damage caused by the TC of the 3rd February 1731. Departmental archives of La Réunion, C 311 (photograph: E Garnier).

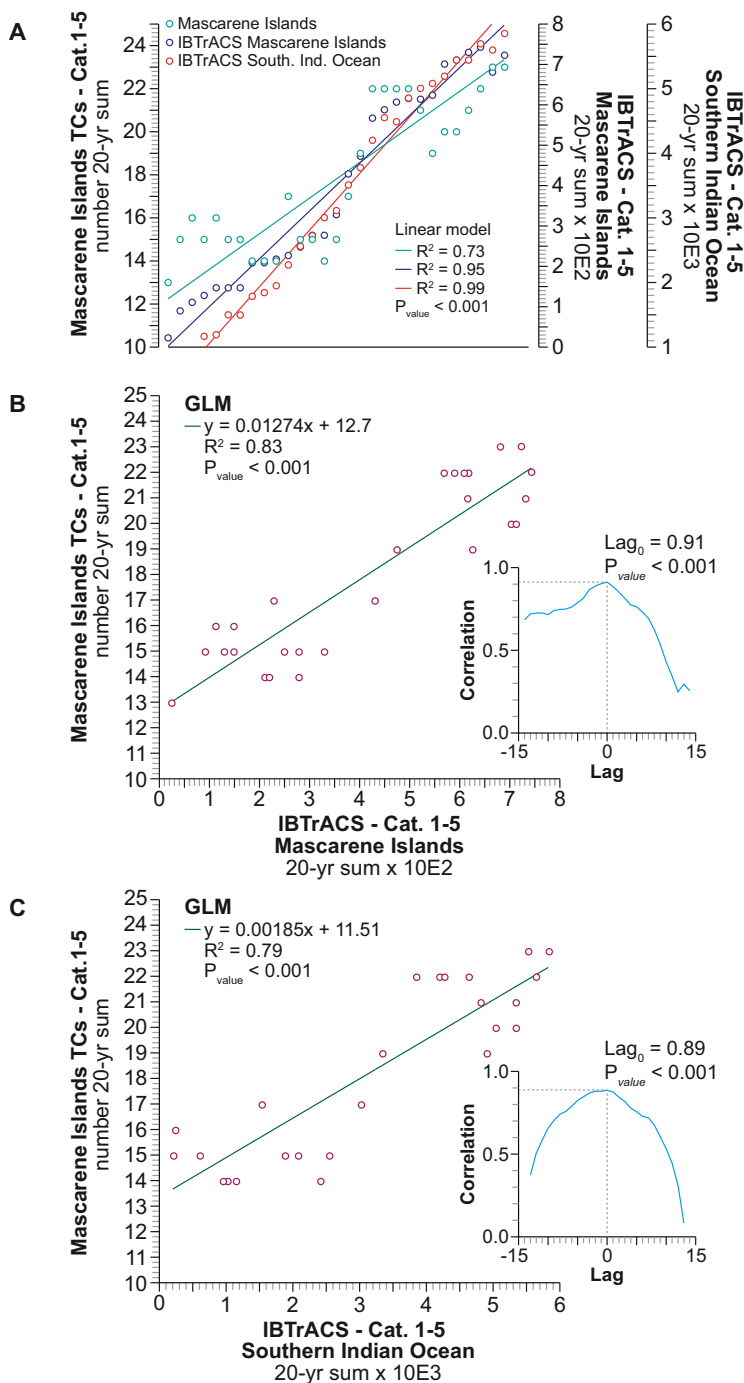


Fig. 4. A. Comparison of Mascarene Island category 1–5 TCs (green) with IBTrACS TC data for the Southern Indian Ocean and IBTrACS (red) TCs passing in proximity to the Mascarene Islands (blue; coordinates = 51 to 65 E and 15.30 to 21 S). B. Generalized Linear Model (GLM) of Mascarene Island category 1–5 TCs and IBTrACS TCs passing in proximity to the Mascarene Islands. C. GLM of Mascarene Island category 1–5 TCs and IBTrACS TC data for the Southern Indian Ocean. For the period since 1960, the two IBTrACS data series show statistically significant correlation with the historical Mascarene data ($\text{Lag}_0 = 0.91$ for IBTrACS Mascarene Islands and $\text{Lag}_0 = 0.89$ for IBTrACS Southern Indian Ocean). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the major strategic interest that the Mascarene Islands represented for British and French colonial powers. Shipping logs were not included in our analysis, to avoid problems of data quality linked to changing densities of shipping traffic through time. Nonetheless, one potential source of error could relate to the lower confidence of historical records to reconstruct lower-intensity events due to diminished levels of infrastructure damage. Most of the documents derive from handwritten colonial archives (e.g. Fig. 3) kept in La Réunion, Mauritius and the national archives in Aix-en-Provence (France) and Kew (UK). For both islands, the authors are representatives of the French West India Company, its administrators and the governors of the two islands.

Before the French Revolution (1789), the TC records primarily constitute the correspondence of the East India Company (1700 to 1789). These voluminous archives are not specifically devoted to TCs

but rather to the management of maritime trade and the region's sugar plantation economy. Nonetheless, the records regularly mention extreme weather events and catastrophes, particularly TCs.

After the French Revolution (1789) and the Napoleonic wars, these documents were drafted by the director of the French Ministry of the Interior French prefects, local representatives of the French government, the General Council (local assembly), the Gendarmerie for La Réunion (formerly “Ile Bourbon”) and by British officials of the Colonial Office and of the Secretary of State for the Colonies after British conquest of “Ile-de-France” (Mauritius) in 1810. These documents systematically report precise climate information from Meteorological Offices on the islands, including the chronology, temperature, pressure and wind speeds of each event. The authors also describe the damage caused to buildings, trees, local infrastructure and crops. Furthermore, the records

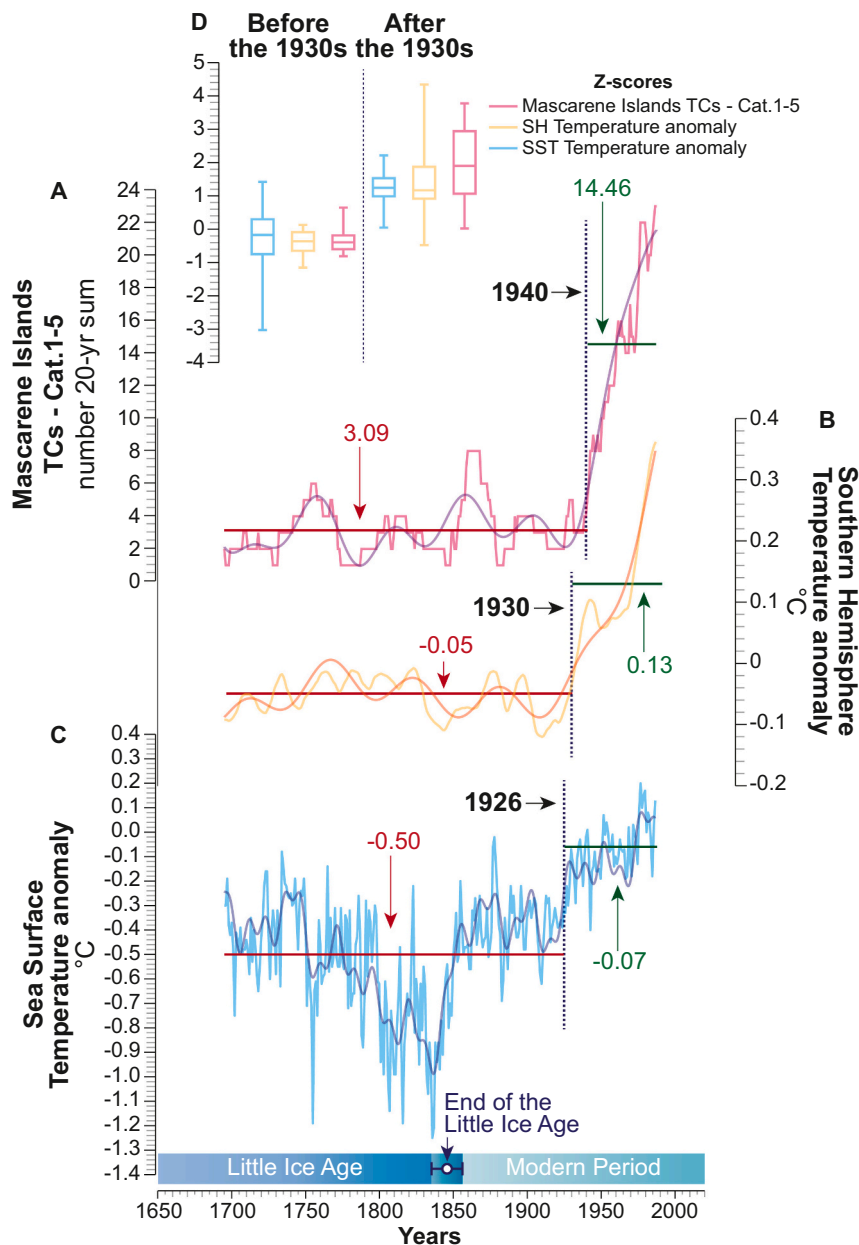


Fig. 5. A. Historical record of TC frequency (20-year moving sum) on the Mascarene Islands; B. Southern Hemisphere Temperature anomalies (Neukom et al., 2014). The anomalies are relative to the 1961–1990 temperature average; and C. Indian Ocean SST anomalies (Tierney et al., 2015). The anomalies are relative to the 1961–1990 SST average. We homogeneity tests (SNHT) on all three datasets to identify trend changes in the time series. Each discordant period is categorized by red and green lines and the mean value for each discrete period is given. D. Boxplots of all three datasets for the periods before and after the 1930s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mention the estimated costs of TC damage and aid measures taken by the government in London. The administrative archives are further complemented by the colonial press of the period. For La Réunion (French overseas territory), historical records also improved with the development of republican centralism, translated by a proliferation of locally-based administrations (Governor, Conseil Général, colonial Gendarmerie, forestry commission). Finally, other printed and online archives were also studied, mainly the Meteorological Offices of the islands and the colonial written press, in particular *The Mercury*, *The Brisbane Courier* and *The Straits Times Weekly Issue*. In addition to meteorological and social data (deaths, destruction), newspaper photographs of large TCs began in 1892.

We argue that the quality and the continuity of observing capabilities on the Mascarene Islands, which were continuously inhabited during the study period (Dundas, 1801), renders the data reliable for long-term trend analysis. The records include descriptions of TC rainfall, damage to fleets at anchor in regional ports, deaths and destruction of crops and sugar refineries (Walter, 1910). The damage wrought by TCs often

affected the fragile economy of the islands. For example, famine and disease were commonplace following the natural disasters.

For this study, landfalling TCs were classified into five groups based on the Saffir-Simpson scale criteria (Saffir, 1973; Simpson and Saffir, 1974). The scale is particularly well suited to the historical sources and descriptions outlined above. Events were assigned to the five Saffir-Simpson groups using twelve different criteria: (i) meteorological details; (ii) state of the sea; (iii) surge; and damage to (iv) people, livestock; (v) infrastructure; (vi) buildings (slave huts, colonial houses, barracks, stone churches, stone stores and Governor's Palace); (vii) plantations; (viii) ships; (ix) landscapes; (x) trees; (xi) power and water; and (xii) social and economic consequences.

As a measure of observing capacities over time, we compared and contrasted the landfalling TC data from the Mascarene Islands with regional trends elucidated in the IBTrACS database (Fig. 4). We extracted two regional time series from the database: (i) IBTrACS TC data for the Southern Indian Ocean; and (ii) IBTrACS TCs passing in proximity to the Mascarene Islands (coordinates = 51 to 65 E and 15.30

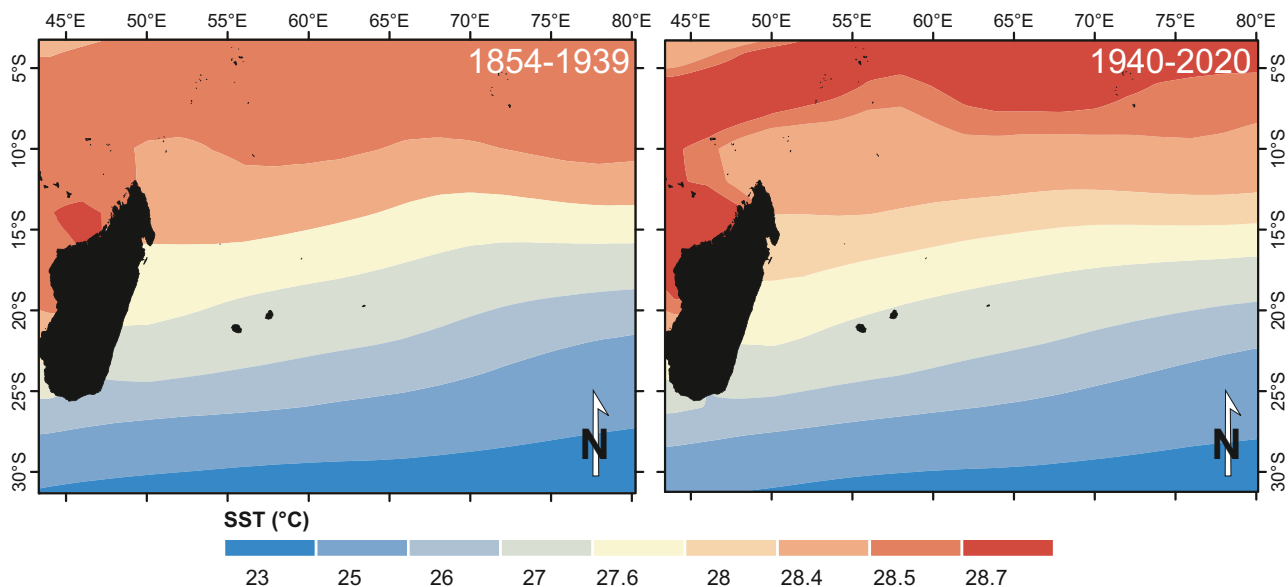


Fig. 6. Geography of SST temperatures over the SW Indian Ocean (average cyclone season SSTs) for the period 1854–1939 (A) and 1940–2020 (B). Data are from the NOAA OI SST V2 High Resolution SST Dataset and highlight the extent of ocean warming during the Great Acceleration.

to 21 S). For the period since ~1960, when at least once-a-day satellite pictures became regularly available, the two IBTrACS data series show statistically significant correlation with the historical Mascarene data ($\text{Lag}_0 = 0.91$ for IBTrACS Mascarene Islands and $\text{Lag}_0 = 0.89$ for IBTrACS Southern Indian Ocean). Despite the inherent challenges in interpreting long-term historical records, these trends give us confidence in the overall reliability of the historical TC data from the Mascarene Islands for long-term trend analysis and understanding the decadal to secular drivers of TC activity. We furthermore insist that the data series focuses solely upon land-based historical records so as to avoid problems related to changes in shipping densities, traffic and trade routes.

20-year sliding sums of TC frequency were employed in order to minimize the purely random variability that dominates the historical time series at high frequencies, while retaining most of the variability at decadal and longer periods. We compared and contrasted the TC data with various high-resolution palaeoclimate datasets including: (1) Indian Ocean SSTs (Tierney et al., 2015); (2) SH temperatures (Neukom et al., 2014); and (3) sunspot numbers (SILSO, 2021).

All data were analyzed using XL-Stat2019 (<https://www.xlstat.com/fr/>) and the software package PAST, version 2.17c and 4.03 (Hammer et al., 2001). Homogeneity tests (SNHT) were applied to the time series to detect shifts in long-term dynamics. Each discordant period is categorized and its average is indicated. Longer-term trends in the time series were probed using a “smoother” transform with a moving average as the basic function (20-yr was selected as trends) and sinusoidal model (Pvalue < 0.001).

Sinusoidal regressions were employed to model periodicities in the time series (the Pvalue, based on an F test, gives the significance of the fit). The sinusoidal series have been cross-correlated to ascertain the best temporal match. The correlation coefficient is then given, focusing on the Lag_0 value (with +0.50 and – 0.50 as significant thresholds).

3. Results and discussion

The compiled documentary evidence yields an annual resolution record of landfalling TC variability that spans the 17th century to 2007. This period is particularly interesting for understanding the drivers of TC activity because it spans both the cool global temperatures of the Little Ice Age (e.g. low solar irradiance) and the global warming of the 20th and 21st centuries (e.g. human-induced change). The recent Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean

and Cryosphere in a Changing Climate concluded that much of the global surface temperature increase over the past half century is probably underpinned by increases in anthropogenic greenhouse-gas concentrations (Pörtner et al., 2019). As a test of the influence of multidecadal changes in ocean warmth on TCs, we compared the historical time series with Indian Ocean SSTs (Tierney et al., 2015) and Southern Hemisphere (SH) temperatures (Neukom et al., 2014). Fig. 5 shows the frequency of landfalling TCs for the period 1700 to 2007, plotted against Indian Ocean SSTs and SH temperatures. TC frequency is plotted as a 20-year sliding sum so as to emphasize decadal-scale oscillations. For the Mascarene Islands, the reconstruction shows that there have been on average 4.9 TCs per 20 years over the entire study period. Indian Ocean temperatures have increased by ~1 °C since the maximum cooling of the Little Ice Age. These data are corroborated by results from the NOAA OI SST V2 High Resolution SST Dataset. Fig. 6 maps the geography of SST temperatures over the SW Indian Ocean (average cyclone season SSTs) for the period 1854–1939 and 1940–2020 and underscores the extent of ocean warming during the Great Acceleration. This trend is mirrored by SH temperatures which show a ~0.4 °C rise during the same period. The tests of homogeneity (SNHT), shown in Fig. 5, underscore a major break in TC frequency beginning around 1940, consistent with two broad phases. Before 1940, TC frequency varied between 1 and 8 TCs per 20 years, with a mean value of 3.1. After 1939, these frequencies rose significantly with between 4 and 23 TCs/20 years, and a mean of 14.2. The tests of homogeneity show that the 1940 change-point date for landfalling TC frequency lags ~10–14 years behind the articulation point for rising SH temperatures and Indian Ocean SSTs, consistent with inertia in the atmosphere-ocean system and TC response to warming. Beyond 1940, we note increases in SSTs (average decadal increase of 0.04 °C after 1940) and SH temperatures (average decadal increase of 0.15 °C). Significantly, 1940 appears to represent a turning point in the climate system beyond which natural climate cycles were superseded by human-induced warming (Fig. 7).

At longer temporal lengths, we found that the cycles of TC activity manifest phasing with sunspot numbers for the period 1700 to 2000 ($\text{Lag}_0 = 0.85$; Fig. 8). Precise solar-TC mechanisms are complex (Hodges et al., 2014) – furthermore, long time-series of TC response to radiative forcing are lacking – but our reconstruction supports a decadal to secular-scale link between warming/cooling of regional sea surface temperatures by solar activity and TC frequency over the Mascarene Islands. This premise is reinforced by a positive correlation between

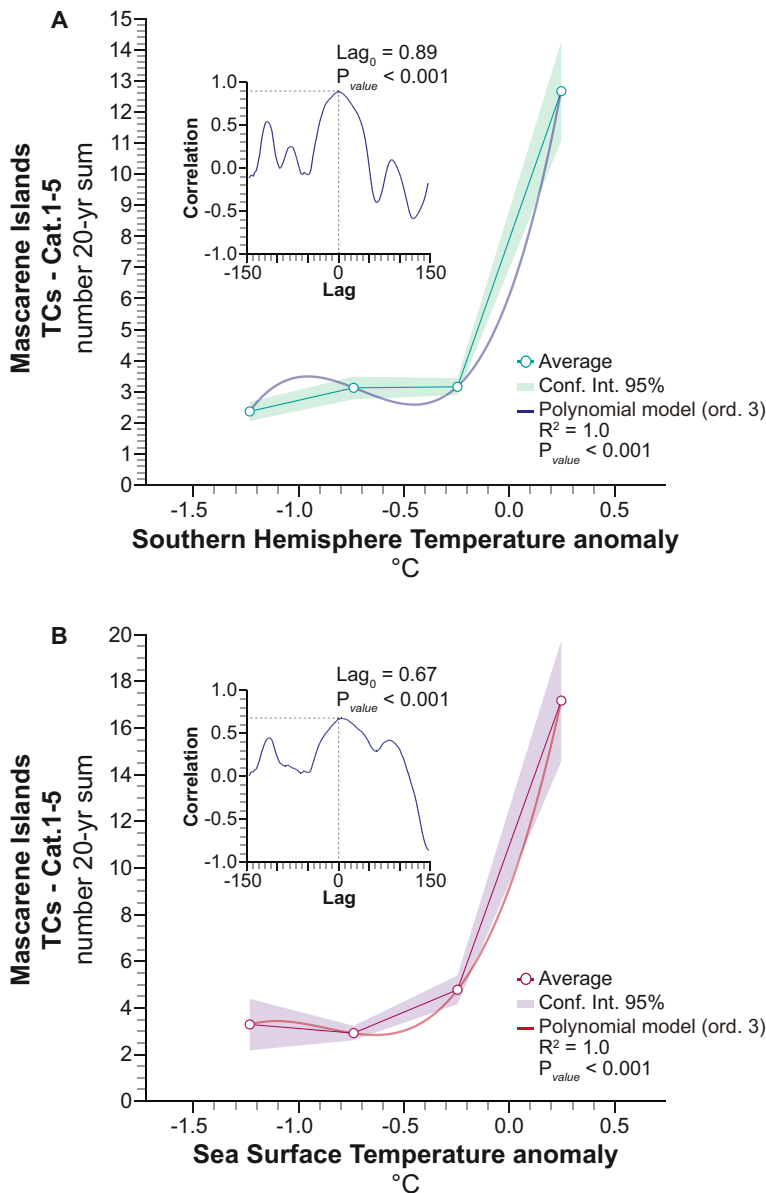


Fig. 7. TC frequency compared and contrasted with Southern Hemisphere temperature anomalies and Sea Surface Temperature anomalies. A. Number of TCs versus a gradual increase in temperature anomalies in the Southern Hemisphere. The average values are shown by blue line and dots. Each dot is associated with a confidence interval (95%). The correlation between the two time-series is highlighted by a cross-correlogram (Pvalue < 0.001). B. Number of TCs versus a gradual increase in Sea Surface Temperature anomalies. The average values are denoted by a purple line and dots. Each dot is associated with a confidence interval (95%). The correlation between the two time-series is highlighted by a cross-correlogram (Pvalue < 0.001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Southern Indian Ocean SSTs and sunspot numbers ($r = 0.56$, $p = 0.0001$), although the correlation figure indicates that other physical factors, for which we do not have regional proxy time series, have also affected Mascarene Islands cyclogenesis and intensification during the study period. Our findings are corroborated by an investigation of historical TCs in the Caribbean (Trouet et al., 2016), which linked a 75% decrease in regional TC activity between 1645 and 1715 to the reduced solar irradiance of the Maunder Minimum and its effects on local sea surface temperatures and cyclogenesis.

We also assessed the relationship between cyclone frequency and intensity because the latter has the potential to enhance the impacts of sea-level rise on TC-related inundation extremes in coastal areas (Timmermans et al., 2017). There is emerging evidence for an increase in the global proportion of category 4 or 5 TCs in recent decades (Knutson et al., 2010, 2019; Pörtner et al., 2019). Fig. 9 plots the moving 20-year sums of category 1–3 and 4–5 TC events. The data and plot show that TC frequency and intensity exhibit different features in their interannual and decadal variations over the study period. The entire times series is characterized by an average of 2.74 category 1–3 TCs and 2.2 category

4–5 TCs per 20 years. Since 1940, there has been a fourfold increase in category 1–3 TCs (20-year average = 10.57 events) and a 67% increase in category 4–5 TCs (3.67 events). Our regional reconstruction implies that there has been an increase in the frequency of landfalling Mascarene TCs since the 1940s, particularly with regards to the frequency of less intense TC categories. This is largely consistent with studies from other basins suggesting that TC frequency and intensity have been increasing (e.g. Kossin et al., 2013; Emanuel, 2015; Bhatia et al., 2019). Nonetheless, the frequency of less intense events over the Mascarene Islands appears to be evolving at a more rapid rate than more intense category 4 and 5 events, underscoring the geographic complexities in understanding regional-scale TC cyclogenesis and the extrapolation of regional models to the global scale. For the Mascarene Islands, it appears that diverse local factors (e.g., other modes of regional climate variability, atmospheric dynamics, vertical wind shear, oceanic upwelling, land interactions) can be detrimental to local TC intensities and therefore hamper confidence in future forecasting. For instance, modes of climate variability such as ENSO are known to have a strong regional influence on the spatial pattern and frequency of TC genesis in the

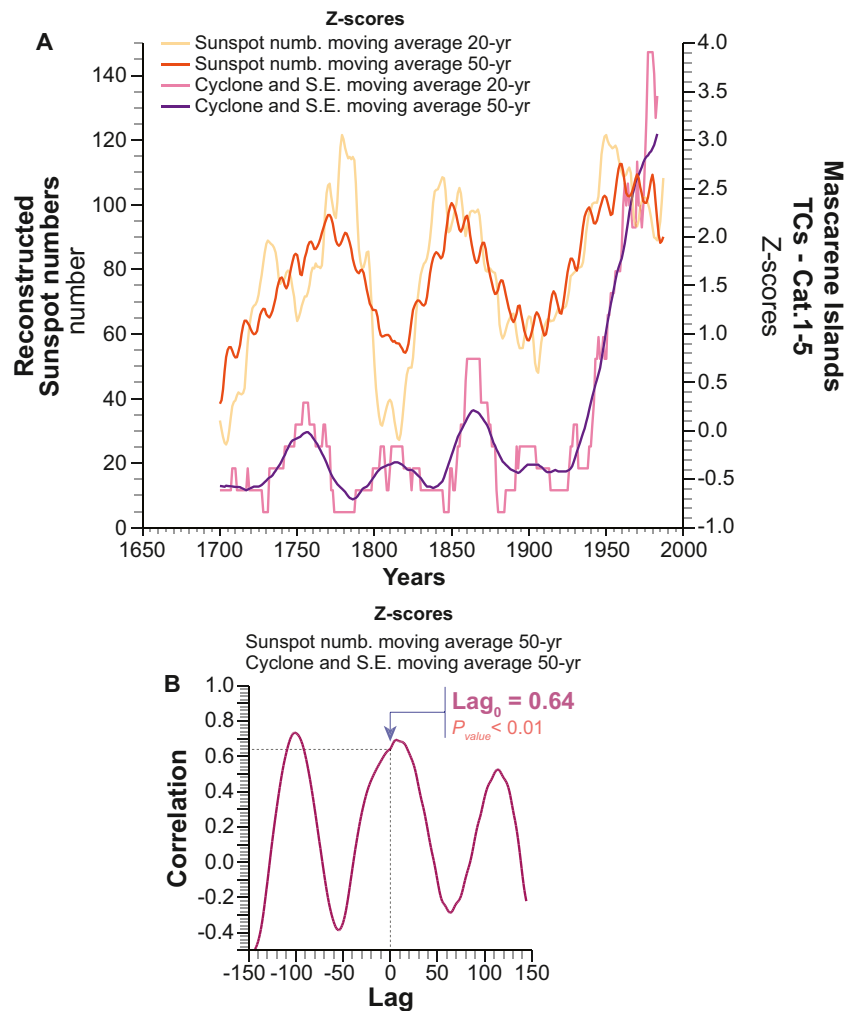


Fig. 8. A. Mascarene Islands TCs (pink = moving average 20-yr and purple = 50-yr moving average) versus reconstructed sunspot numbers (yellow = 20-yr moving average and red = 50-yr moving average). B. Cross-correlation between Mascarene Islands TCs and reconstructed sunspot numbers (50-yr moving averages). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

southern Indian Ocean (Camargo et al., 2007; Ash and Matyas, 2012; Lin et al., 2020) by either modifying the spatial patterns of TC genesis and/or affecting the geography of cyclone movement. Recent observational records show that TCs originating in the regions 54°E–73°E, and following westward and southwestward trajectories, are generally associated with a cool or neutral ENSO phase and a positive Subtropical Indian Ocean Dipole (SIOD) mode (Ash and Matyas, 2012). Conversely, during El Niño and when the SIOD is negative, the regional ocean–atmosphere patterns strongly favor a shift of Tropical Temperate Troughs (TTTs) over the southwestern Indian Ocean coincident with the warm Sea Surface Temperature Anomaly pool. In this situation, the TTTs are positioned to frequently steer TCs away from inhabited areas on the western rim of the basin.

4. Conclusion

Climate change is one of several factors likely to affect the future evolution of TCs and the damage that they generate. Using a > 300-year historical record, our results show that there has been variability in TC activity over the Mascarene Islands at decadal timescales but that an increasing trend in landfalling TCs since the second half of the 20th

century could be related to anthropogenic-driven processes that have superseded background climate variability. Historical observations are particularly useful tools to reconstruct natural disasters such as TCs because they focus on extreme events rather than climatic averages. We believe that the quality and the continuity of observing capabilities over the Mascarene Islands, which were continuously inhabited during the study period, renders the data reliable for long-term trend analysis and overcomes the problems of shipping-log data which can be hindered by changing traffic densities through time. Documentary archives from other TC basins, particularly land-based records with continuous and high-quality observing capabilities, are key to furthering our understanding of TC driving mechanisms, magnitudes, and frequencies, beyond the limits of current observational series that suffer from short temporality. Despite caveats relating to the use of indirect evidence to reconstruct quantitative variables, such records can contribute to improving the quality of climate-change projections and for developing robust hazard assessments and adaptation strategies, at both present and future timescales.

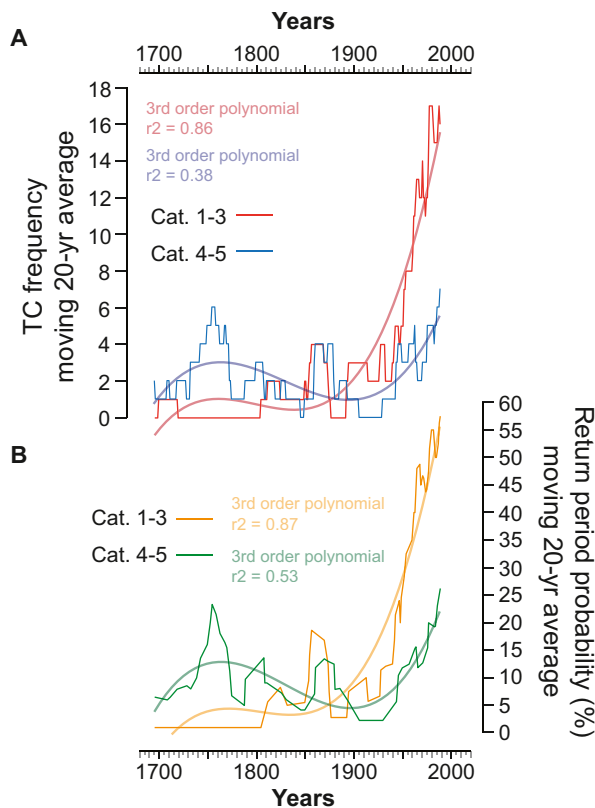


Fig. 9. A. Moving 20-year frequencies of TCs grouped into categories 1–3 (red curves) and 4–5 (blue curves). B. Smoothed (moving 20-year window) return period probabilities for category 1–3 (orange curves) and 4–5 (green curves) TCs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Author contributions

N.M., D.K. and E.G. jointly conceived the study and contributed equally to the manuscript. E.G. compiled the historical TC data. N.M. and D.K. curated the various datasets and performed the statistical analyses. M.P. performed GIS analyses. N.M., D.K. and E.G. analyzed all data and prepared the manuscript, with all authors discussing results and commenting on the manuscript at all stages of production.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloplacha.2022.103933>.

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