INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **35**: 3249–3261 (2015)
Published online 13 November 2014 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.4204

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Tropical cyclone activity over Madagascar during the late nineteenth century

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ABSTRACT: Tropical cyclones (TCs) represent the most significant natural hazard for the economy and population of Madagascar. Planning for the impacts of future cyclone strikes requires a detailed understanding of the frequency of destructive storms in the past. In this paper, we utilise historical documentary materials to construct an initial framework of TCs making landfall on Madagascar during the latter half of the 19th century. The study focuses on 1862–1900 as this is the period of most extensive documentary records. Accounts of storm damage contained within historical sources are used to reconstruct TC tracks over land, with details of wind damage converted into Fujita (F) Scale classes to classify TC intensity. A total of 20 TCs are identified, of which only 17 are included within the IBTrACS dataset for the southwest Indian Ocean. The TCs of 13–14 March 1872 and 28 January–1 February 1893 were the most destructive of the late 19th century, with F3+ levels of wind damage identified from historical accounts. We compare our results with data for TCs within the IBTrACS dataset that made landfall on Madagascar during the period 1970–2012. This comparison suggests that (1) fewer TCs made landfall during the 19th century compared with the post-satellite era, but that of these (2) a greater proportion appear to have crossed the northeast of the island. There is no significant correlation between numbers of landfalling TCs and either mean annual SOI or DMI. We conclude with a consideration of additional archival collections that may be used in future investigations to enhance our chronology.

KEY WORDS tropical cyclone; Madagascar; southwest Indian Ocean; 19th century

Received 31 March 2014; Revised 22 September 2014; Accepted 13 October 2014

1. Introduction

Tropical cyclones (TCs) – non-frontal synoptic scale low-pressure systems over tropical or sub-tropical waters with wind speeds in excess of 64 kt (119 km h^{-1}; 33 m s^{-1}) – are a significant and life-threatening natural hazard for populations in and around the southwest Indian Ocean (SWIO). Individual storms may cause disruption to shipping, but the most severe impacts occur when TCs pass near or make landfall on the inhabited islands and mainland at the western rim of the basin. Around 5% of TCs in the SWIO strike the southern African mainland. However, a far greater number make landfall on Madagascar, with 48 of the 64 landfalling TCs in the SWIO from 1980–2007 impacting upon the island (Mavume *et al.*, 2009). The dependence of rural Malagasy communities upon agriculture, alongside the lesser economic status of the country, make Madagascar particularly vulnerable to the strong winds, heavy rainfall, and storm surges associated with TC events (Brown, 2009).

Planning for the impacts of future TCs in Madagascar requires a detailed understanding of variations in the frequency, trajectory, and intensity of storms in the past. Such information is necessary to estimate TC return periods, identify climatic drivers, and facilitate disaster planning based on previous damage. NOAA's National Climatic Data Center, in combination with the World Data Centre, has developed the International Best Track Archive for Climate Stewardship (IBTrACS) dataset to collate information about tropical storms (see http://www.ncdc.noaa.gov/oa/ibtracs/). IBTrACS is arguably the most complete archive of TC best-track data (Knapp *et al.*, 2010) and provides trajectory data for the SWIO from 1848 onwards. However, the most reliable information only dates back to 1880 (Garnier and Desarthe, 2013) and it is unclear whether all TCs have been captured. Lists of historical TCs have been compiled for Mauritius (Padya, 1984), Réunion (Maillard, 1863; Mayoka, 1998), and the combined Mascarene islands (Garnier and Desarthe, 2013) but these do not

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extend to Madagascar. Records of historical TC strikes on Madagascar are available for 1889–1929 (Colin, 1913; Blosset, 1924; Poisson, 1930), but although these records include maps of estimated storm tracks based on early instrumental pressure data from Antananarivo, they give only a general indication of cyclone intensity. Again, it is unclear whether all TCs have been captured.

In the absence of long-term instrumental records for much of the island, historical documentary sources provide an invaluable resource for reconstructing past TC activity over Madagascar and for checking the validity of datasets such as IBTrACS. Methods involving the analysis of reports of storm damage within documents offer the best approach to estimating TC occurrence, intensity, and track over land (Boose, 2004). Information from historical sources has been used, for example, to construct chronologies of hurricane activity in the Caribbean (Millas, 1968; Caviedes, 1991; Boose *et al.*, 2004; García-Herrera *et al.*, 2007; Mock, 2008; Chenoweth and Divine, 2012), Atlantic (Mock, 2004; García Herrera *et al.*, 2005; Chenoweth, 2006; Glenn and Mayes, 2009) and eastern Pacific (Chenoweth and Landsea, 2004; Raga *et al.*, 2013), and typhoons in the western Pacific (Chan and Shi, 2000; Ribera *et al.*, 2008; Liu *et al.*, 2012); see Nash and Adamson (2014). However, despite a relative wealth of available historical material, no attempt has yet been made to explore TC damage reports for Madagascar.

This study presents an initial framework for the construction of a chronology of TCs making landfall on Madagascar during the latter 19th century. Focussing on the period 1862–1900, we use descriptions of storm damage contained within European missionary correspondence and other historical records to (1) identify individual TCs, and, where possible, reconstruct (2) their intensity, and (3) track across land. We compare our results against the IBTrACS dataset as well as records of cyclone landfall identified by Colin (1913) and Poisson (1930) using early instrumental data for Antananarivo, explore the possible controls on cyclone frequency and, finally, point towards additional sources that may be used in future investigations to enhance and extend our chronology.

2. Tropical cyclone climatology in the southwest Indian Ocean

On average, nine TCs develop in the SWIO per year, with the majority occurring during the November–April TC season (Reason, 2007; Chang-Seng and Jury, 2010a; Fitchett and Grab, 2014). Cyclogenesis in the region is sometimes organised by transient waves within a weak zonal flow, but is more often associated with periods of cyclonic vorticity created by meridional pulses of the Indian Monsoon (Jury and Parker, 1999; Chang-Seng and Jury, 2010b). The spatial pattern and frequency of TC genesis is affected by a range of large-scale, low-frequency modes of ocean-atmosphere variability, including the El Niño-Southern Oscillation (ENSO), Madden-Julian Oscillation (MJO), subtropical Indian Ocean Dipole (SIOD), and convectively coupled equatorial waves.

Correlation between ENSO and TC frequency in the Indian Ocean as a whole is weak (Jury, 1993; Kuleshov *et al.*, 2012). However, TC genesis is more frequent in the SWIO during El Niño phases (Ho *et al.*, 2006; Kuleshov *et al.*, 2008), to the extent that ENSO is used as a significant predictor of SWIO TC activity at weekly to monthly timescales (Leroy and Wheeler, 2008; Vitart *et al.*, 2010). Vitart *et al.* (2003) identify that zonal steering flow (averaged over 850–200 hPa across the tropical and subtropical SWIO) is more westerly (easterly) during El Niño (La Niña) phases. As a consequence, Mozambique is at greater risk of TC strike during La Niña, whilst TCs are more likely to re-curve east of Madagascar during El Niño (Jury and Pathack, 1991; Vitart *et al.*, 2003; Ash and Matyas, 2012). There are, however, flaws to this generalisation, with, for example, TC Favio making landfall on Mozambique in February 2007 during an El Niño year (Klinman and Reason, 2008). La Niña is also associated with an increased frequency of longer-lived and more intense TCs (Chang-Seng and Jury, 2010a).

The influence of the SIOD on SWIO TCs is less well understood, although it appears to interact with ENSO to influence TC trajectories (Ash and Matyas, 2012). Periods of cool (La Niña)/neutral ENSO and a positive SIOD mode are associated with TCs following west- and southwest-ward trajectories; these are more likely to make landfall on the western Indian Ocean rim. In contrast, when ENSO is in warm phase (El Niño) and SIOD in negative mode, TCs follow more south- and southeast-ward trajectories and frequently steer away from inhabited areas (Ash and Matyas, 2012).

Few studies have explored the links between the MJO and TC genesis. Bessafi and Wheeler (2006) identify a clear modulation signal associated with the MJO in the South Indian Ocean, due to the influence of the oscillation upon low-level vorticity and wind shear. Increased TC genesis occurs at times when the MJO produces anomalous westerlies equatorwards of 15°S across the whole Indian Ocean and enhanced convection in the east of the basin. TC passages are more frequent during MJO phases 2–4 (Ho *et al.*, 2006). The equatorial Rossby wave and, to a lesser extent, Kelvin wave also appear to modulate TC genesis through the large variations in vorticity associated with these waves (Bessafi and Wheeler, 2006).

3. Materials and methods

3.1. Documentary sources

As noted, this investigation focuses on the period 1862–1900. The 1860s represented a significant shift in the European presence on Madagascar, and hence the availability of European language records. Various European powers had established trading posts on the island in the centuries following the first Portuguese contact in 1500. However, it was not until the early 19th century, when the Merina King, Radama I, signed a treaty with

Table 1. Locations of historical archives and repositories visited for primary sources in this study, together with archive codes used to cite sources.

Name of archive	Key collections	Archive code
Archives Nationales, Paris, France	Hydrographical observations relating to coastal settlements in Madagascar	AN followed by catalogue details
Bodleian Library of Commonwealth and African Studies at Rhodes House, University of Oxford, UK	Society for the Propagation of the Gospel materials for Madagascar	USPG followed by catalogue details
British Library, London, UK	Various books, *Antananarivo Annual and Madagascar Magazine*, British Newspapers 1600–1950 (online), 19th Century British Newspapers (online)	Standard Harvard citation style for books and journal articles
Cadbury Research Library, University of Birmingham, Birmingham, UK	Church Missionary Society collection for Madagascar	CMS followed by catalogue details
Council for World Mission archive, School of Oriental and African Studies, London, UK	London Missionary Society materials for Madagascar	LMS followed by catalogue details
Friends House Library, London, UK	Documents from Quaker missionaries in Madagascar	FHL followed by catalogue details
Kew Gardens Archives, London, UK	19th century correspondence from botanists in Madagascar	KGA followed by catalogue details
The National Archives, London, UK	Various books, British Colonial Office materials	NA followed by catalogue details
Msunduzi Municipal Library, Pietermaritzburg, South Africa	19th century materials, including *Natal Witness* newspaper	MML followed by catalogue details
Norwegian Mission Society archive, Stavanger, Norway	Norwegian Mission Society materials for Madagascar	MHS followed by catalogue details

Britain abolishing the slave trade and admitting Protestant missionaries that European population numbers began to grow (Ellis, 1890; Campbell, 2005). The period of intensified contact ended in 1835 when Queen Ranavalona I repudiated this treaty and expelled non-nationals, including missionaries, from the island (Sharman, 1909). However, following her death in 1861, King Radama II allowed non-nationals to return. In 1863, his successor, Queen Rasoherina, introduced new laws permitting non-nationals to rent land, which led to the spread of missionary activity across the island. By the time of the declaration of Madagascar as a French Protectorate in 1890 and then Colony in 1896, written documents were being sent to Europe from almost all of the major seaports and inland settlements across the island (with the exception of the northeast which remained relatively sparsely populated).

The last decades of the 19th century also saw the publication of the earliest systematic meteorological data for Madagascar, based on recordings made by the Catholic missionary, Father Élie Colin, at the Ambohidempona observatory, Antananarivo, from 1889 onwards. These data were used to compile records of TCs crossing Madagascar by Colin (1913), Blosset (1924), and Poisson (1930). The first of Colin's annual reports (Colin, 1889) also contains monthly pressure, temperature, humidity, and rainfall data for Antananarivo for selected years back to 1872, recorded by various observers prior to his arrival on the island.

The most important collections used for this study were those of the London Missionary Society (LMS), Church Missionary Society, Friends Foreign Mission Association, and the Society for the Propagation of the Gospel (Table 1; Figure 1), who established, or re-occupied in the case of the LMS (Lovett, 1899), mission stations in the central plateau and east coast during the 1860s and 1870s (Beach and Fahs, 1925). Representatives of the Norwegian Mission Society established their first missions in 1867 and, by the 1890s, had stations across the centre, west, and south of the island (Uglem, 1979). The various collections include letters, diaries, personal papers, and quarterly/annual reports written by missionaries and sent back to their respective headquarters in Europe. These types of material are rich in descriptions of local weather, climate, and environment, and have been used to reconstruct rainfall (Endfield and Nash, 2002; Nash and Endfield, 2002a, 2002b, 2008; Kelso and Vogel, 2007; Nash and Grab, 2010; Neukom *et al.*, 2014) and cold season (Grab and Nash, 2010) variability on the southern African mainland.

Additional materials were consulted in the British Library (BL) and The National Archives (both London). Documents in these repositories included reports from, and official communications with, British resident agents, plus more general accounts of conditions in the country. Extensive use was made of the historical book collection at the BL, which includes editions of the first scientific journal for Madagascar, the *Antananarivo Annual and Madagascar Magazine*, which was published from 1875 onwards. Accounts of cyclone damage, particularly to shipping, were identified from the BL's online 'British Newspapers 1600–1950' and '19th Century British Newspapers' collections. Sir Joseph Hooker's correspondence with botanists travelling in Madagascar was consulted at the

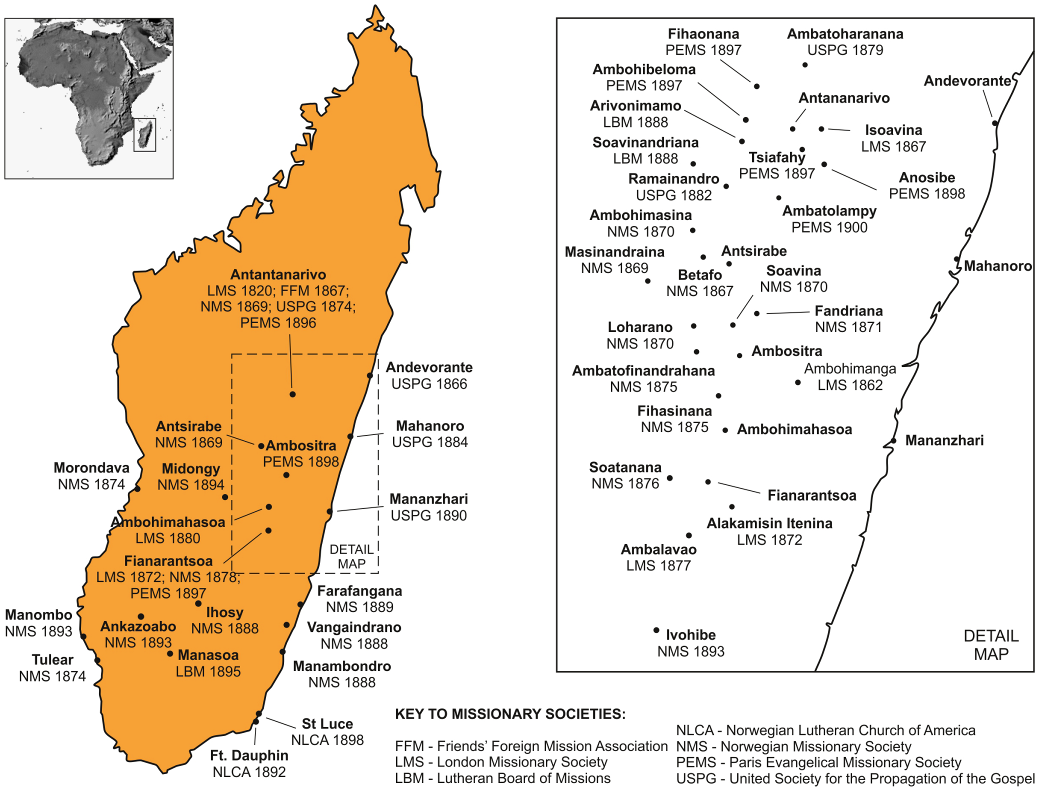

Figure 1. Locations of mission stations on Madagascar established prior to 1900 (Source: After Beach and Fahs, 1925).

Kew Gardens Archives (London). Hydrographical papers within the marine collection of the Archives Nationales (Paris) were also explored for geographic and other scientific observations about harbours and coastal settlements.

Collections of French missionary materials were not studied. In the case of Catholic missions, this is because the majority of 19th century mission stations were located in the same settlements as British and Norwegian Protestant societies (Werner, 1885), and hence add little additional spatial information for cyclone reconstruction. Missions operated by the Protestant Paris Evangelical Missionary Society were established following the onset of French colonial rule and only add detail for the last 4 years of the 1890s. For similar reasons, the small collections of materials relating to the Lutheran Board of Missions and Norwegian Lutheran Church of America missions (Figure 1) were not consulted. These collections remain an area for future investigation (see Section 7).

Early pressure and wind data were not included as part of our analyses, because all available data were used by Colin (1913), Blosset (1924), and Poisson (1930) in their compilations of TC activity from 1889 onwards. As we draw directly upon both Colin (1913) and Poisson (1930) to cross-check and validate our results, the use of the same instrumental data would introduce issues of circularity.

3.2. Reconstruction methods

Documents in each of the collections in Table 1 were studied, with all accounts of individual storms and any associated storm damage during the cyclone season recorded *verbatim*. Following Chenoweth (2007), analysis of the terms used by English, French, and Norwegian observers to describe wind force was undertaken to distinguish accounts of TC-force events from other categories of tropical storm. To establish the specific wind force terms used in the description of TCs crossing Madagascar, accounts of two late 19th century TCs identified by Poisson (1930) – those of 28–29 February 1892 and 28 January–1 February 1893 – were scrutinised in detail. These events were described by observers using terms including *hurricane*, *cyclone*, *coup de vent* (French: gust of wind), *ouragan* (French: hurricane or cyclone), *syklon* (Norwegian: cyclone) and *orkan* (Norwegian: hurricane) or variants thereof. In the subsequent analysis of accounts of all storms, only those events described by multiple observers using similar terminology (see Table 2), and which were accompanied by significant levels of damage, were classified as TCs. Storms described as *severe gales*, *severe storms,* and related terms (Table 2) were treated as tropical storms or lesser storm events. To avoid the potential misidentification of a severe localised storm (including storms described by observers as *whirlwinds*), only those storms identified by observers at multiple locations were classified as a TC.

For each TC, actual storm damage was mapped at the settlement level, because this was the scale at which damage was reported by European observers. Negative impacts of TCs included damage to buildings and vegetation caused by (1) strong winds, (2) freshwater flooding (associated with heavy rainfall), and (3) coastal flooding (following storm surges). Maps of storm damage were used to identify the approximate track of each storm.

Table 2. Typical English-, Norwegian-, and French-language wind force terms used by observers to describe tropical cyclones and other storm events.

Tropical cyclones	Tropical storms or lesser events
Hurricane	Storm (English and Norwegian)
Fearful hurricane	Violent storm
Grievous hurricane	Storm of rain and wind
Mighty hurricane	Severe storm
Severe hurricane	Heavy storm
Disastrous hurricane	Fearful storm
Hurricane	Heavy winds
Cyclone (English and French)	Perfect tempest
Violent cyclone	Very strong wind
Severe cyclone	Strong gales
Destructive cyclone	Half a hurricane
Ouragan	Sterk storm
Coup de vent	Heftig stormvind
Orkan	
Syklon	

From this information, TCs were classified qualitatively as one of four types (Figure 2), following the scheme devised specifically for historical TCs in Madagascar by Colin (1913) and illustrated in Poisson (1930). Under this scheme, Type I cyclones are those that typically track down the Mozambique channel and west coast of Madagascar before crossing the southern part of the island, Type II cross the northeast coast and exit in the east or southeast, Type III follow a similar pathway but enter the island along the east coast, and Type IV only affect the east coast. Note that this classification does not fully encompass TCs such as Leon-Eline and Jaya which caused extensive damage as they tracked across Madagascar in 2000 and 2007, respectively (Reason and Keibel, 2004).

Accounts of damage caused solely by strong winds were examined in more detail and used to estimate the severity of each TC. We utilised an approach widely adopted in the analysis of historical tropical storms (Boose *et al.*, 1994, 2001, 2004; Boose, 2004; Chenoweth, 2007), whereby wind damage was assessed according to the Fujita (F–) Scale (Fujita, 1971, 1987). This scale, originally designed to assess tornado damage, separates storms into classes defined by the extent of wind damage caused to a range of common cultural and biological features. Classes extend from 0 (minor damage) to 5 (severe damage resulting from the most intense storms).

Following the methodology developed by Boose (2004), a series of wind damage indicators was created specifically for use with historical materials from Madagascar (Table 3). These include varying degrees of damage to major and minor structures, trees, crops, and ships. Descriptions and drawings within historical sources were used to match building and vegetation types in 19th century Madagascar against those from Boose's original research in New England (USA) and Puerto Rico. With the exception of royal palaces and government buildings in Antananarivo, most indigenous buildings were made of wood or bamboo and roofed with rushes. Details for mission buildings were determined from the annual accounts of expenditure required of all missionaries. During the early part of the study period, most rural chapels were built of wood and rushes whilst major churches and larger buildings were constructed using sun-dried earth bricks. By the 1880s and 1890s, many larger buildings, including churches, were constructed using stone foundations and fired bricks. Damage reports could also be used to confirm construction methods. For example, in an account of wind damage in Antananarivo caused by the 20–23 February 1893 TC, the LMS missionary Rev. J. Mackay noted that:

> The verandah of the hospital was two-thirds blown down including the wooden gable roof over the middle with its pillars and arches of burnt brick … Our Station Church, as well

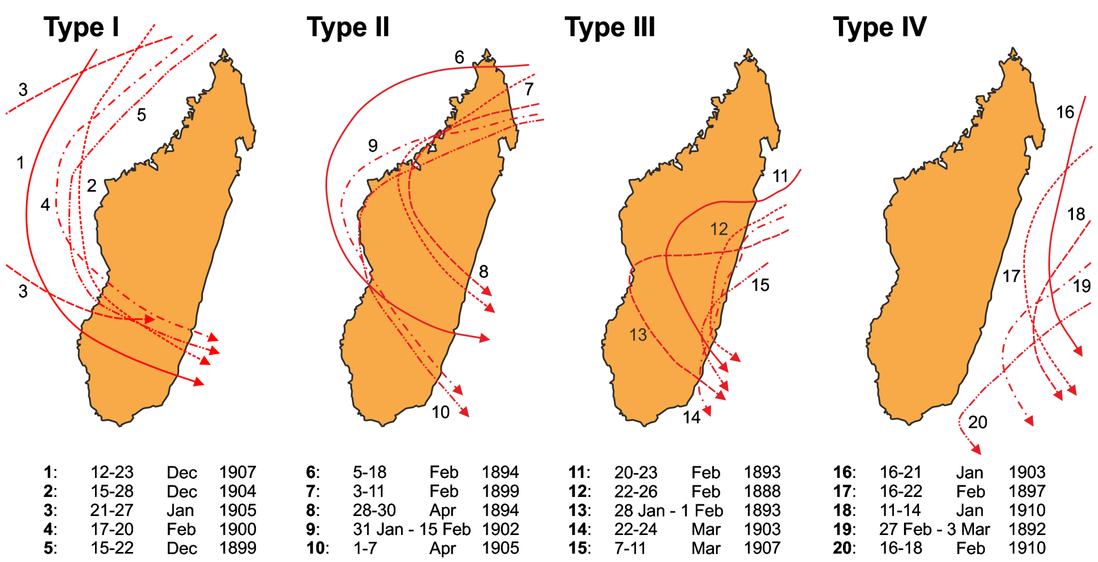

Figure 2. Tracks of selected tropical cyclones that made landfall on, or passed close to, Madagascar between 1888 and 1910 (Source: After Poisson, 1930). The tracks were first described by Colin (1913) and are used to classify cyclones into the four 'types' used in this study.

Table 3. Fujita Scale of wind damage modified for application to historical materials from Madagascar.

	F0 wind damage	F1 wind damage	F2 wind damage	F3 wind damage
Sustained wind speed	18–25 m s^{-1}	26–35 m s^{-1}	36–47 m s^{-1}	48–62 m s^{-1}
Trees	Branches broken, trees damaged	Trees blown down	Extensive blowdowns	Most trees down
Crops	Damaged or blown down			
Masonry buildings[a]	Minor damage	Roof peeled, windows broken, chimneys down	Unroofed	Blown down or destroyed
Wooden houses[b]	Minor damage	Roof peeled, windows broken, chimneys down	Unroofed or destroyed	3+ blown down or destroyed in same town
Churches, major buildings[c]	Minor damage	Unroofed, steeple blown down, damaged	Blown down or destroyed	
Barns, shacks, sheds, outbuildings[d]	Minor damage	Unroofed, blown down or destroyed		
Huts[e]	Damaged	Blown down or destroyed		
Masonry walls[f]	No damage	Blown down		
Small boats	Blown off moorings	Sunk		

Source: Developed using the approach in Boose (2004). [a]Normally well-built and constructed of either sun-dried earth bricks or, towards the end of the 19th century, fired bricks. [b]Normally well-built European dwellings constructed with a wooden frame and metal bracing. [c]Includes large buildings (schools, hospitals, sugar mills, commercial buildings) constructed of either wood or sun-dried earth bricks and sometimes rendered or plastered. Religious buildings described as chapels were assumed to be constructed using wood. [d]Normally constructed using wood and roofed with rushes. [e]Indigenous dwellings constructed using wood or bamboo and roofed with rushes. [f]Normally constructed of sun-dried earth bricks and sometimes rendered or plastered.

> as most of the wooden churches throughout Antsihanaka, was blown down … (LMS MAD Incoming Correspondence 24A-3-B, Rev. J. Mackay, Antananarivo, 6 March 1893)

Geographical variations in building styles needed to be noted. For example, according to Sibree (1888), it was not until after the accession of Queen Ranavalona II in 1868 that an '… ancient (and foolish) law or custom forbidding the erection of any building made of material other than wood, bamboo, or rush within the boundaries of the city proper … ' (p. 5) was rescinded, and brick buildings were constructed in Antananarivo.

The indicators in Table 3 only permit the classification of wind damage up to a value of F3. Where destruction of multiple masonry buildings and wooden houses was described in a single settlement, wind damage was categorised as F3+. It should be stressed that the Fujita scale is a measure of local wind damage only and is not directly equivalent to overall TC intensity. It is possible, for example, for an intense TC to have caused low levels of wind damage along the coast of Madagascar because it remained offshore.

4. Tropical cyclones making landfall on Madagascar in the late 19th century

Details of the date, range of reconstructed Fujita wind damage values and track of all TCs that made landfall on Madagascar between 1862 and 1900 are shown in Table 4. A total of 20 TCs were identified from historical records, with two storms making landfall during each of the 1887–1888, 1892–1893, 1893–1894, and 1899–1900 cyclone seasons. The available documentary evidence is sufficiently rich to permit the identification of the wind damage class for 16 storms and the cyclone type for 12 storms. Uncertainties in Table 4 arise where either the available descriptions of storm damage are limited or the spatial distribution of damage reports is insufficient to map complete cyclone tracks.

Two TCs during the late 19th century caused wind damage in excess of class F3: the events of 13–14 March 1872 and 28 January–1 February 1893. The wind damage map for the 1872 TC is shown in Figure 3, together with the approximate track of the storm as shown in the IBTrACS dataset. The distribution of damage indicates that the Type IV storm hit first at Ambodimanga on the east coast, before causing destruction and loss of life at the seaport of Tamatave (present-day Toamasina) and the coastal villages of Ivondrova, Andevoranto, and Mahanoro further south. A letter written by the SPG missionary, Rev. A. Chiswell, provides a graphic account of the impacts of the storm:

> A most heart rending calamity has befallen us. This afternoon I received one of our special messengers from Tamatave who brought the sad intelligence that a severe hurricane has passed near the town, completely destroying our church and printing house … The Roman Catholic church, a much larger one than ours and put up only 4 years ago, is as complete a wreck as our own. Our church at Ivondrova has been blown to atoms, and also the L.M.S. church at Andovoranto. The Consulate was saved but flooded. Nearly every native house has been blown down. The only

Table 4. Chronology of tropical cyclones making landfall on Madagascar, 1862–1900.

Year	Date[a]	Wind damage	Cyclone type	Areas affected	IBTrACS	Poisson (1930)
1865	16–18 February	F2	II	Tamatave, Antananarivo, and northeast	Y	N
1866	Unknown	–[b]	IV?	Info for Antananarivo area only	Y	N
1868	22–27 January	–[b]	II?	Info for Antananarivo area only	N	N
1872	13–14 March	F3+	IV	East coast	Y	N
1876	20–21 February	F3	III	Central and South-central Plateau	Y	N
1880	2–10 February	F1-F2	II	East coast, South-central Plateau, Morondava	Y	N
1884	29–30 January	F1-F2	I?	Info for Morondava area only	N	N
1885	24–25 February	F2-F3	II	North of island only	Y	N
1888	22–24 February	F2-F3	IV	East coast	Y	Y
1888	20 March	–[b]	II or III	Info for Antananarivo area only	Y	N
1890	17 December	–[b]	II, III or IV	Info for Antongil Bay area only	Y	N
1892	28–29 February	F3	III	Central Plateau and southeast	Y	Y
1893	28 January–1 February	F2-F3+	III	East/west coast, Central Plateau	Y	Y
1893	20–23 February	F2-F3	III	East coast and Central Plateau	N	Y
1894	5–10 February	F2	II?	Info for Betafo area only	Y	Y
1894	28–30 April	F2-F3	II?	Info for Diego Suarez and Nosy Be only	Y	Y
1898	25–28 February	F2	I or II	Info for Morondava area only	Y	Y
1899	3–11 February	F2-F3	II	North of island plus central east coast	Y	Y
1899	20–22 December	F1-F2	II	North, west coast and south	Y	Y
1900	17–20 February	F3	I	West coast and south only	Y	Y

The date, estimated Fujita Scale wind damage class, reconstructed cyclone type (indicative of storm track; see Figure 2) and areas affected are shown. The final columns indicate whether the storm is included in the NOAA IBTrACS dataset and/or mapped by Poisson (1930). [a]Date ranges are only given where historical documents provide sufficient evidence for precise date determination. [b]Unclassified due to insufficient detailed descriptions of wind damage.

> ship at Tamatave is wrecked. The Press I fear is injured and the paper is destroyed, for the quantity of rain which fell was very great. The type scattered. All in all it is one of the saddest calamities that could possibly befall us. (USPG D38, Rev. A. Chiswell, Antananarivo, 21 March 1872)

The track of the storm as shown in the IBTrACS dataset is likely to be correct, as observers at the coast and as far inland as Mahasoa use terms indicative of TC-strength winds (see Table 2), whereas only storm-force winds and limited damage were reported at Antananarivo (LMS MAD Incoming Correspondence 10A-1-C, Rev. W. Pool, Antananarivo, 21 March 1872) and Fianarantsoa (USPG D38, Rev. G. Percival, Tamatave, 31 July 1872).

The TC of 28 January–1 February 1893 (Figure 4) was a Type III storm and caused extensive damage across the island. The geographical distribution of, and details contained within, damage reports allow the storm track to be determined with accuracy. Reports suggest that the TC crossed the east coast near to Vatomandry on 28 January. The quarterly report for the SPG mission at Ambatomasino indicates that nine churches in and around the town were destroyed and at least a further nine damaged, along with the destruction of European and indigenous dwellings (USPG E48b, unknown author, Ambatomasina, 15 March 1893). Similar levels of wind damage were reported from Mahonoro to the south, where there was also coastal flooding and the '… Mangoro River rose about 30 feet above its usual level … ' (LMS MAD Personal Box 6, Rev. J. Sibree scrapbook Vol. 2). The severity of the storm over Antananarivo was such that, according to Sibree (1893) '… no one we believe, even the oldest inhabitants, can remember anything approaching it.' Heavy rainfall caused the Ikopa River to burst its banks, creating a 50 ft (16 m) wide breach in its containing embankments (LMS MAD Personal Box 6, Rev. J. Sibree scrapbook Vol. 2) and flooding the extensive rice fields around the city (LMS MAD Incoming Correspondence 24A-3-B, E. Craven, Antananarivo, 20 February 1893).

Wind strengths appear to have been slightly lower over the centre of the island but class F3 wind damage to major buildings and dwellings is reported by NMS missionaries based at Betel Mission (Morondava) on the west coast. The arrival of the storm at the Mozambique Channel coincided with high tide, leading to coastal flooding (MHS A1045-141-12, Pastor R.L. Aas, Morondava, 22 February 1900). At least 3 days of extremely strong winds were followed by 3–4 days of freshwater flooding, presumably caused by heavy rains, which led to the course of the Morondava River being diverted. Hundreds of deaths (500 in the district of Menabe alone) were reported, with sharks and crocodiles feasting on corpses for several months after the event (MHS A1045-140A-14, Pastor R.L. Aas, Morondava, 30 December 1893). The storm then turned and exited the island in the southeast. The TC track reconstructed from historical evidence matches well the track mapped by Colin (1913) and Poisson (1930) using early meteorological data (Figure 4).

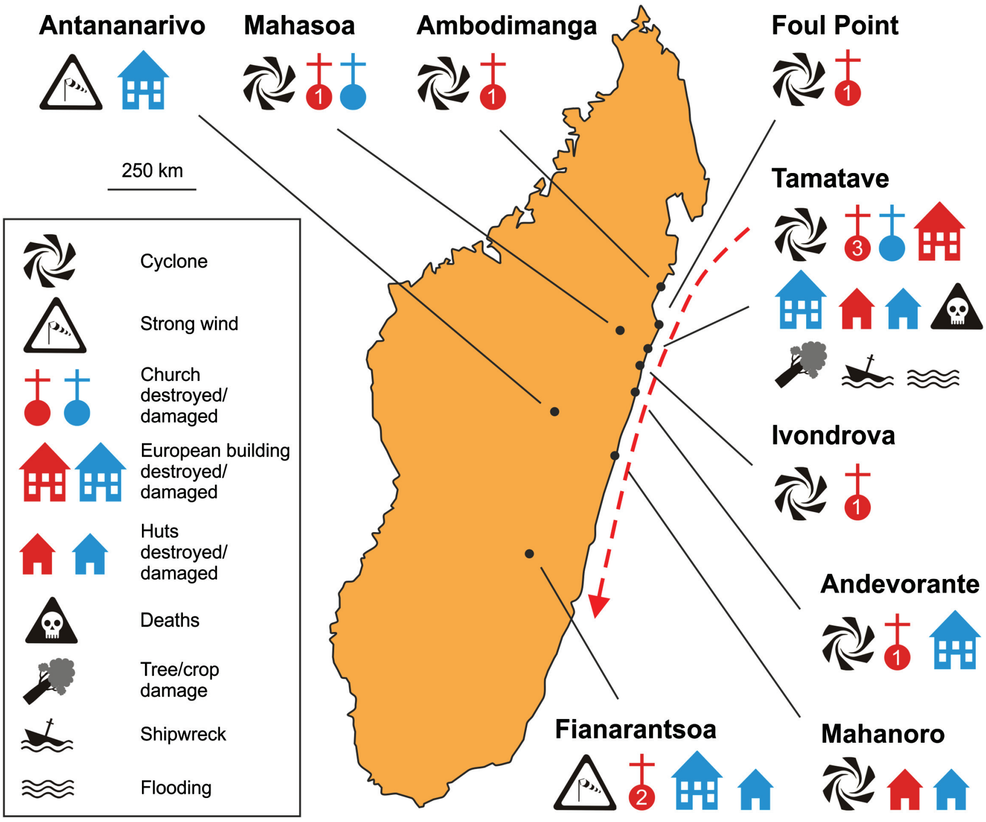

Figure 3. Map of damage caused by the F3+ tropical cyclone that passed along the east coast of Madagascar on 13–14 March 1872. Numbers within symbols indicate the number of buildings destroyed. Dashed line indicates the track of the storm as mapped in the IBTrACS dataset.

5. Comparisons with IBTrACS data for the late 19th century

The chronology of TCs in Table 4 agrees well with the record of major 19th century tropical storms making landfall on Madagascar within the IBTrACS dataset. Indeed, all of the TCs between 1862 and 1900 that made landfall on Madagascar mapped within IBTrACS are identified in this study. Our results, therefore, provide semi-independent verification of this portion of the IBTrACS dataset – we stress the term semi-independent as it is possible that some of the same sources may have been used for the development of both the IBTrACS storm record and this study. There are, however, two areas of discrepancy. First, IBTrACS shows the path of the 24–25 February 1885 TC as making landfall along the east coast of Madagascar, whereas historical documents suggest that the impacts were felt mainly in the north. This storm precedes the cyclone record presented by Poisson (1930), so it is not possible to cross-check using this source. Second, three TCs – those of 23–27 January 1868, 29–30 January 1884 and 20–23 February 1893 – are identified from historical sources but are not included in IBTrACS records. The first of these is documented mainly by missionaries in the region around Antananarivo, including the LMS missionary Rev. W. Pool, who states:

> … we have been visited by a hurricane which played its gambols among the thatch, and the mountain torrents have so swollen the river that its banks have burst and serious fears are entertained for the safety of the young rice; at the Friday market, a proclamation ordered all both men and women to repair the breach, on pain of death, today there are no services owing to a fresh bursting of the dam they had erected. (LMS MAD Personal Box 4 Folder 2, Rev. W. Pool, Antananarivo, 26 January 1868)

From the dates noted in this and other sources, the storm must have passed near to Antananarivo one or two days prior to Friday 24 January. It is not possible to determine the precise track of this TC, although the SPG missionary Rev. A. Chiswell describes in his daily journal: '… 27th and 28th [January]: It was so wet, and such rough weather, I could not go out … ' (USPG E23A, Rev. A. Chiswell, Tamatave, 1868), so the storm may have exited over the central eastern coast of Madagascar.

Evidence for the 1884 TC is available mainly from accounts by NMS missionaries stationed in the Morondova district on the west coast. Pastor R.L. Aas, for example, reports in May 1884:

> January started with a big flood, which left almost the whole Morondava district under water until the end of the month, when the flood was followed by a hurricane-like storm, which uprooted and blew down huge trees and two of the houses at the station. Down by the sea the storm surge left the sandbank upon

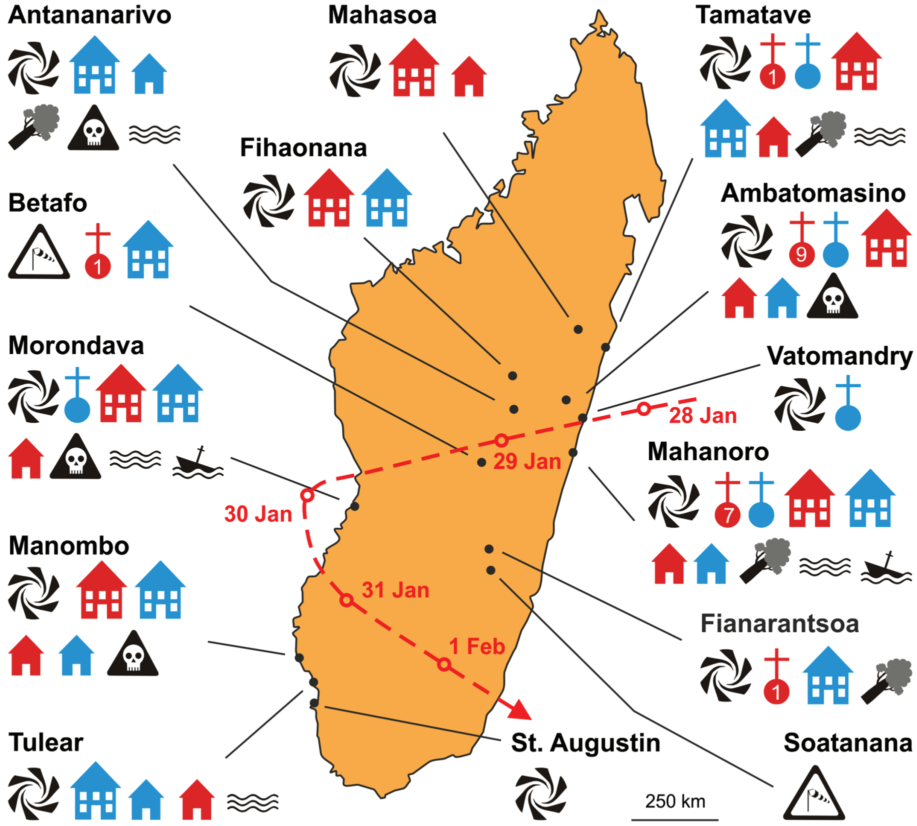

Figure 4. Map of damage caused by the F2-F3+ tropical cyclone that crossed Madagascar on 28 January–1 February 1893. See Figure 3 for key to symbols. Dashed line indicates the track of the storm as mapped by Colin (1913) and Poisson (1930).

> which Morondava is built under water and washed away so much of the town that it does not deserve the name town anymore. (MHS A1045-136-8, Pastor R.L. Aas, Morondava, 15 May 1884, translated from the original Norwegian)

From this description we can tell that wind damage associated with the TC was class F1-F2. It is not possible to ascertain the precise track, although the fact that the TC is neither noted in the *Antananarivo Annual and Madagascar Magazine* nor by Blosset (1924) suggests that it did not cross the central plateau and was probably a Type I storm.

The TC of 20–23 February 1893 (Figure 5) occurred less than three weeks after the F3+ storm shown in Figure 4. We can be confident that it is a separate event from descriptions and maps within Colin (1913), Blosset (1924), and Poisson (1930) and from historical accounts. The first Anglican Bishop of Madagascar, Robert Kestell-Cornish, for example, records in a letter from March 1893:

> What is to be done? We have had two hurricanes this year, already, the first January 28th, the second February 20th-21st. By the first some £150 damage was done at Mahanoro (£100 is my own estimate for Mahanoro itself, but there are besides 23 stations each with its tale of woe). This last hurricane has hit Tamatave again very hard. (USPG D106a, Bishop R. Kestell-Cornish, Ambatobe, 2 March 1893)

The second TC of 1893 followed a similar track to the end-January storm, crossing the coast of Madagascar to the north of Tamatave and passing over the central plateau before exiting the island in the southeast. There are extensive reports of damage, including to buildings which had only just been repaired following the end-January storm. The occurrence of two TCs in such close succession makes it more difficult to classify the severity of the second event using wind damage reports, because so many buildings were damaged or destroyed by the first storm. We have categorised the storm as F2-F3, but wind speeds may have been stronger in places. Winds at Tamatave, for example, were almost certainly greater than described for the first cyclone of 1893, with SPG missionary Rev. G. Smith reporting:

> This cyclone is certainly the most destructive since the terrible one in '88 and I have never seen so much damage done to trees; every leaf is stripped off. (USPG E48b, Rev. G.H. Smith, Tamatave, 24 February 1893)

6. Discussion

The number of TC strikes on Madagascar identified in this study is shown chronologically in Figure 6.

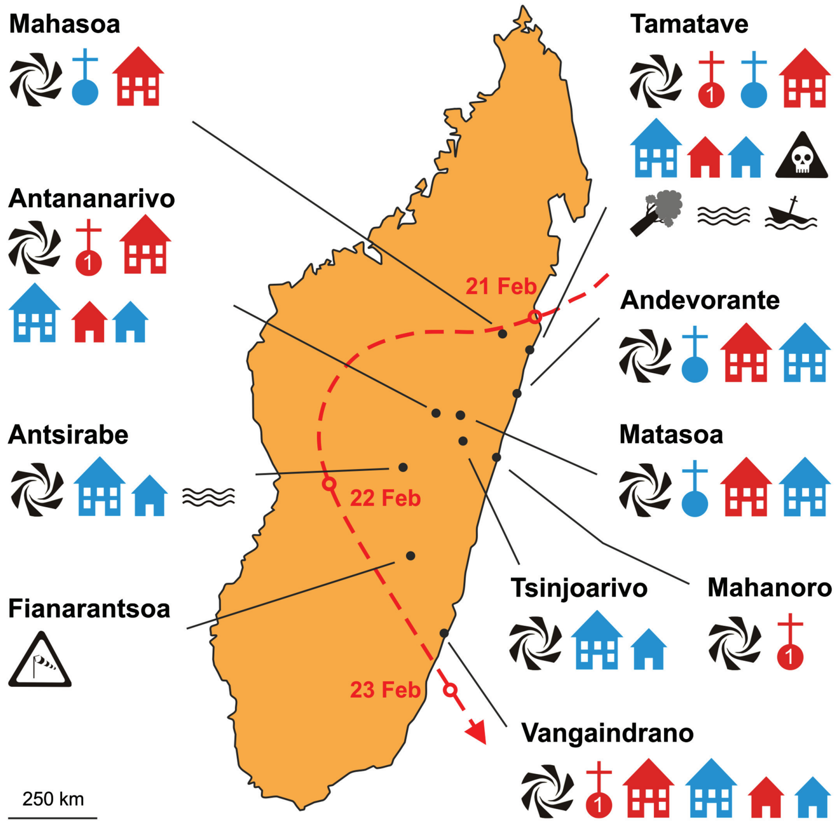

Figure 5. Map of damage caused by the F2-F3 tropical cyclone that crossed Madagascar on 20–23 February 1893. See Figure 3 for key to symbols. Dashed line indicates the track of the storm as mapped by Colin (1913) and Poisson (1930).

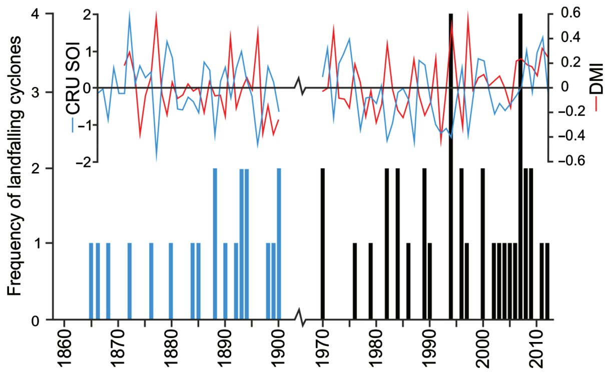

Figure 6. Frequency of tropical cyclones making landfall on Madagascar from 1862 to 1900 (blue) and during the post-satellite portion of the IBTrACS database (1970–2012; black). Also shown are mean annual SOI (blue) and DMI (red) values for the same periods; see text for details of data sources.

Also shown are counts of all TCs in the IBTrACS dataset that made landfall on the island during the post-satellite era (1970–2012), the portion of the dataset for the SWIO that is most complete and reliable (see ftp://eclipse.ncdc.noaa.gov/pub/ibtracs/original-bt-data-files/reunion/). To derive the data for 1970–2012, only storms in the IBTrACS dataset that reached 10-minute sustained wind speeds of ≥ 55 kt at some point in their track across the island were counted. Those that grazed the coastline (i.e. were within 0.1° of the coast – the finest resolution of IBTrACS location data) and may have caused TC-strength winds on land, were also included. TCs that made multiple landfalls were counted only once.

Given the temporal and spatial density of historical observations, and the importance of cyclones to missionary and other livelihoods, we are confident that we have identified the majority of TCs that made landfall on Madagascar during the period 1862–1900. As such, it would appear that the frequency of TCs making landfall on Madagascar in the latter half of the 19th century (20 TCs in 38 years, or 1 TC per 1.95 years) was considerably lower than during the post-satellite period (36 storms in 43 years, or 1 TC per 1.19 years). The peak number of TC strikes in any 3-year period during the latter 19th century was also lower, with five strikes between 1892 and 1894 compared with eight between 2007 and 2009. These results do, however, require some qualification, since better TC observations are available for the post-satellite period.

Mean annual values of the Southern Oscillation Index (as calculated by the Climate Research Unit; hereafter CRU SOI) from 1866 onwards, and the Dipole Mean Index (Japan Agency for Marine-Earth Science and Technology; DMI) from 1871 onwards, are also shown on Figure 6. Calculation of the CRU SOI series follows Ropelewski and Jones (1987), with details of early pressure sources and methods given in Allan *et al.* (1991) and Können *et al.* (1998). DMI data are derived from the HadISST dataset, using detrended data (without time filter) for 1871–1900; see Saji *et al.* (1999) for details.

Table 5. Frequency and percentage (*italics*) of different cyclone types making landfall on Madagascar from 1862 to 1900 (this study) and during the post-satellite era (1970–2012; data derived from IBTrACS).

Year		Cyclone type			
		I	II	III	IV
1862–1900	*n*	2	9	4	3
	%	*11*	*50*	*22*	*17*
1970–2012	*n*	6	13	9	8
	%	*17*	*36*	*25*	*22*

See Figure 2 for depiction of cyclone types, as defined by Colin (1913) and Poisson (1930).

As noted in Section 2, recent studies have suggested that minima in TC numbers in the SWIO commonly coincide with strong La Niña events, whilst maxima are often concurrent with strong El Niño events (Ho *et al.*, 2006; Kuleshov *et al.*, 2008; Fitchett and Grab, 2014). A Kendall's Tau test of correlation between landfalling TC frequency and mean annual CRU SOI suggests that this pattern does not hold for landfalling TCs on Madagascar, either for the study period ($\tau = 0.075$, $p = 0.583$) or post-satellite era ($\tau = 0.041$, $p = 0.733$). Performing the same test with TC frequency lagging CRU SOI by 1 year produces equivalent results ($\tau = -0.077$, $p = 0.585$ for the study period; $\tau = -0.060$, $p = 0.620$ for the post-satellite period). Similarly, there is no significant correlation between the frequency of landfalling TCs and mean annual DMI during the study period ($\tau = -0.093$, $p = 0.531$). There is, however, a weak correlation between landfalling TC frequency and mean annual DMI from 1970 to 2012 ($\tau = 0.207$, $p = 0.084$). Interactions between ENSO and the IOD appear to have a varying impact upon the frequency of landfalling cyclones (Figure 6). Periods of cool/neutral ENSO and positive DMI (e.g. 1893–1894, 2000, and 2007–2009) were associated with higher numbers of landfalling cyclones; this supports recent observations by Ash and Matyas (2012). There were, however, some ENSO cool phases with concurrent positive mean annual DMI (e.g. 1872, 1976) where only one TC made landfall.

Additional insights may be obtained by looking at variations in TC tracks over time. Table 5 shows the number and percentage of TCs that made landfall during the study period according to Colin/Poisson 'type' (Figure 2; Table 3). Where the track could not be identified with confidence from the historical record, the trajectory shown in IBTrACS was used to aid classification (although we note the uncertainty involved in adopting such an approach). Data for 18 of the 20 TCs identified in this study are included. The storms in 1868 and 1884 are left unclassified as their type could not be determined with any certainty from historical materials and they are not in the IBTrACS dataset. Table 5 also indicates the Colin/Poisson 'type' for each of the TCs that made landfall from 1970 to 2012. TC type was determined visually from maps accompanying the IBTrACS dataset. For the purposes of this analysis, the TCs Leon-Eline and Jaya which crossed Madagascar in 2000 and 2007, respectively, and do not fit readily into a Colin/Poisson TC type, were both classified as Type II.

The data in Table 5 suggest that a greater proportion of Type II TCs (i.e. those that cross the northeast coast) made landfall on Madagascar during the late 19th century compared to the 20th and 21st centuries. Conversely, the relative proportions of Type I, III, and IV cyclones were all lower than the 1970–2012 average. This provides support for observations made by Fitchett and Grab (2014), who identified that the tracks of landfalling TCs in the SWIO have shifted southwards during the last few decades. With the exploration of further historical sources, it will be possible to refine our TC track data and determine whether the variations shown in Table 5 are a product of data quality or are linked to the documented impacts of global climate modes upon SWIO TC trajectories.

7. Conclusions

This study has used descriptions of storm damage contained within historical documents to construct the first chronology of TCs that made landfall on Madagascar during the second half of the 19th century. A total of 20 landfalling TCs are identified between 1862 and 1900. The TCs of 13–14 March 1872 and 28 January–1 February 1893 were the most destructive of the 19th century, with F3+ levels of wind damage identified from historical accounts.

Our chronology provides a semi-independent check of IBTrACS records for the SWIO. Of the 20 identified TCs, only 17 are included within IBTrACS. The storms of 22–27 January 1868, 29–30 January 1884 and 20–23 February 1893 should be added to the dataset, with the track for the 20–23 February 1893 TC shown within Poisson (1930) used for mapping purposes (see Figure 2). With the exception of the TC of 24–25 February 1885, which appears from historical records to have tracked further north than shown in IBTrACS, the trajectories of 19th century storms within the dataset are reliable.

Comparing our results against IBTrACS data for 1970–2012 suggests that relatively fewer TCs made landfall on Madagascar during the latter 19th century, although the improved quality of TC observations during the post-satellite era must be noted. A greater proportion of TCs appear to have crossed the northeast of the island from 1862 to 1900, with fewer storms passing down the Mozambique Channel or crossing the central east coast.

As with any historical climate reconstruction, the record presented here should only be regarded as a starting point. Whilst we are confident that we have identified the majority of TCs that made landfall on Madagascar during the late 19th century, it must be noted that missionaries were present mainly in the central plateau and east-central districts during the 1860s and 1870s; the analysis of additional sources is needed to enhance the spatial coverage of observations for these periods. In addition to the Lutheran and French missionary materials noted in Section 3, we are aware of a number of collections which may house potentially useful information. These include the military archives at the Château de Vincennes and the Archives d'Outre Mer, Aix-en-Provence, which contain French naval records and other pre-colonial materials for the late 19th century. The investigation of these collections is essential if the initial framework presented in this study is to be expanded.

Acknowledgements

This research was funded by Leverhulme Trust Research Project Grant number F/00 504/D. We extend our thanks to the archivists for permission to access collections of 19th century materials and to Stan Stanier for designing the database used for the storage and analysis of documentary evidence.

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