Policy Implications of Escalating Tropical Cyclone Threats to Malawi Amidst Rising Indian Ocean Temperatures

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Executive Summary

The threat of extreme tropical weather impacting Malawi is rising. In over 130 years of recorded history up to 1980, only a single storm made landfall on the coast of Mozambique with winds high enough to be categorized as a cyclone. From 1980 to 2001 there were seven, one of which was stronger than a category 1. From 2002 to 2023 there were nine, including six that were stronger than category 1. Stronger storms have begun surviving long enough to impact Malawi. We use United States National Oceanic and Atmospheric Administration data to investigate whether recent extreme weather events is an unfortunate coincidence or part of a trend that can be expected to continue. We see water surface temperatures rising in the parts of the Indian Ocean where storms that threaten the southeastern coast of Africa are formed. Warmer water causes stronger storms, as evidenced by rising average sustained wind speeds. Stronger storms, in turn, are more likely to survive over land long enough to threaten Malawi, implying more extreme tropical weather can be expected in the future. In the near-term policymakers and donors could respond by supporting disaster preparedness for effective response, developing comprehensive multi-sectoral and multi-hazard risk maps and investment plans. In the longer-term, Malawi could invest in disaster risk reduction and resilience building through a range of investments that include establishing water drainage, high-efficiency irrigation systems, catchment and road infrastructure, and promoting soil health to improve retention.

1. Introduction

Malawi has been heavily impacted by multiple major tropical storm events in recent years. The storm named Idai formed off the coast of Africa in early March of 2019, eventually reaching Malawi, displacing millions of people and ending thousands of lives along the way through Mozambique, Zimbabwe and Malawi.[1] In January of 2022 Tropical Storm Ana wreaked havoc in Malawi's Southern Region, negatively affecting over 84,000 Malawian households by destroying crops, homes and property, and taking lives (Nyirenda et al., 2022). After making landfall in March 2023, cyclone Freddy made its way to Malawi where over 1,000 people died or went missing and half a million people were displaced (Khunga, 2023).

Tropical cyclones have coincided with significant declines in the Gross Domestic Product growth rate, which has declined from 5.4 percent in 2019 to 1.5 percent in 2023 (Figure 1). Partly, this reflects the impact storms can have on the Malawian economy. For example, the tropical Cyclone Freddy is estimated to have caused USD 36.4 million in production losses (representing a 0.5 percent loss in real GDP loss and slowing its growth by 2.2 percent), with about 47 percent of these production losses recorded in the agriculture, forestry, and fishing sectors (Government of Malawi, 2023). The tropical storms and cyclones Ana, Gombe and Freddy affected approximately 130,000 hectares of crops (Government of Malawi, 2023; International Federation of Red Cross, 2023). The correlation with GDP growth decline also coincides with major global events like Covid-19 and the Russian war in Ukraine, highlighting the fact that these detrimental storms impacted Malawi at particularly vulnerable times. This had serious implications on household agricultural diversification and commercialization efforts, as the infrastructure and crop production underpinning multiple different agricultural value chains suffered substantial damage (Nyirenda et al., 2022).

As devastating as these storms were, they were exceedingly rare by historical standards; in roughly 175 years of recorded data, only 5 storms categorized as Tropical Depressions or stronger have ever crossed Malawi's border. The surge might partly be attributable to the recent occurrence of an El Niño Southern Oscillation (ENSO) event (Gondwe et al., 2024).

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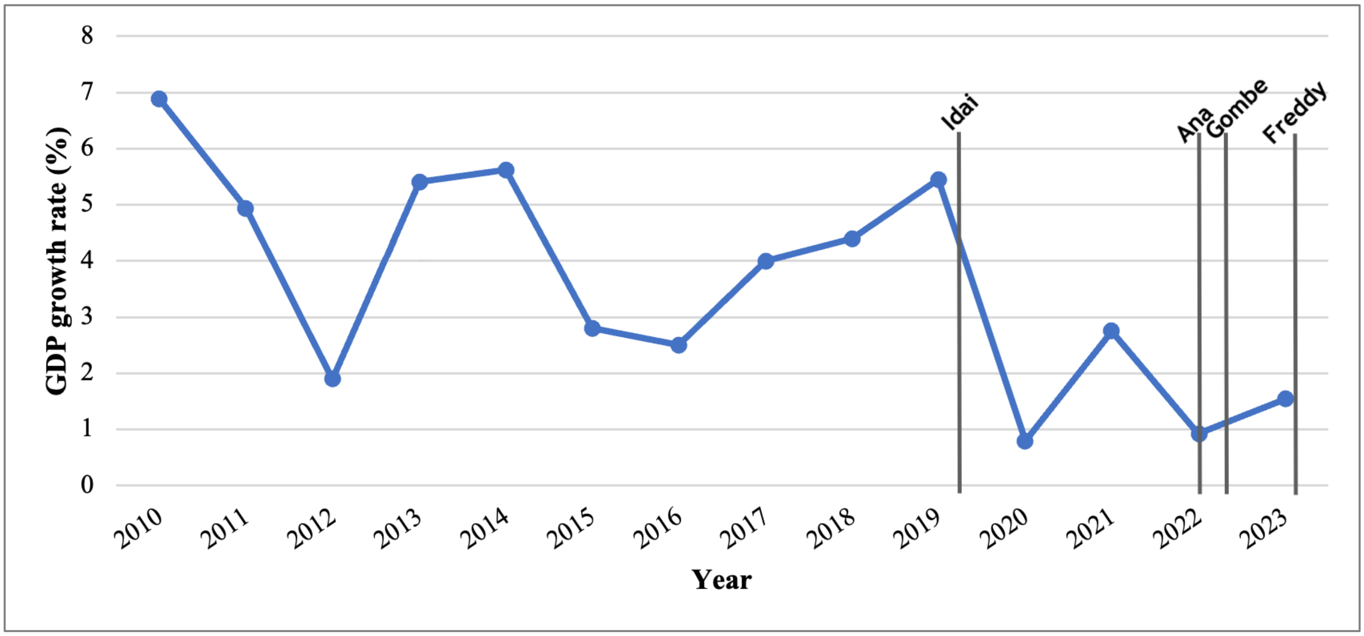
[1] https://www.worldvision.org/disaster-relief-news-stories/2019-cyclone-idai-facts

Figure 1: Malawian GDP Over Time and Cyclone Occurrences



Source: https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?end=2022&locations=MW

But dozens of ENSO events have occurred over the past 175 years[2] without an associated spike in major storms reaching Malawi. Alternatively, the recent increase in Malawian storm events could be associated with broader climate trends. The consensus among scientists studying climate change is that, globally, we can expect to see fewer, but more intense storms (Walsh et al., 2016). For Malawi, this could suggest a rising threat as there will be an increasing number of storms strong enough to reach farther inland.

The objective of this analysis is to examine whether the succession of extreme weather over the past few years is an unfortunate coincidence, or a continuation of a trend that should be expected to continue. If larger storms reaching Malawi will continue to be more likely in the future than in the past, there are important implications for policy makers.

Climate change will affect Malawi in complex and interacting ways, and specific predictions are the subject of rigorous and continuing analyses (Chinsinga et al., 2012; Chinowsky et al., 2015; Warnatzsch and Reay, 2019; Mataya et al., 2020; and more). World Bank analyses have described Malawi as one of the most vulnerable countries to the effects of climate change (Mearns and Norton, 2009). Most of the academic literature, however,

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[2] https://psl.noaa.gov/enso/past_events.html

focuses on policy implications, taking the evidence of the importance of policy change somewhat for granted. Perhaps reflecting a lack of urgency, Malawian policies to address to the threats of climate change have been underwhelming, focusing more on emergency responses, which remain nonetheless underfunded, and relatively little on proactive preparedness or incentivizing adaptation (Gondwe et al., 2024).

This study will therefore focus on highlighting a general and simple, but important prediction around one aspect of the threat to Malawi, cyclones, and one of its major proximal causes, rising sea surface temperatures. This leads to a conclusion that major storms like those which dramatically affected Malawi in the past few years are not outliers. They are rather points around a trend line that Malawians can expect to continue for the foreseeable future, and which policy makers and farmers can more readily address. Rather than counting on a run of bad luck to end, Malawians (and others in the region) would be well-advised to plan on responding to intense weather-driven emergencies more frequently and adapting to their increased likelihood. The results of this study provide Malawian policymakers with critical evidence emphasizing the importance of moving away from the pattern of yearly humanitarian appeals for food and other emergencies and instead focus on building resilience and implementing early warning initiatives, such as those outlined in the Malawi National Resilience Strategy from 2018 to 2030

The storms that threaten Malawi originate in the Indian Ocean, to the east of Madagascar, so the paper will begin by examining pertinent changes to sea surface temperatures and storm intensities in that region of the world. We then view the recent Malawian storm events as situated in the larger global and historical context and discuss the implications of these data for Malawians.

2. Data

The study uses storm location and wind speed data provided by the United States National Oceanic and Atmospheric Administration (NOAA) International Best Track Archive for Climate Stewardship (IBTrACS) project.[3] IBTrACS combines numerous sources of data and, for our purposes, provides some information as far back as the 1842 cyclone season and as

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[3] Available at https://www.ncei.noaa.gov/products/international-best-track-archive

recent as 2023. The analysis for wind speeds will focus on the period beginning in 1981, though, because this is when the data collection shifted to include more technologically modern methods. This period also roughly coincides with the available relevant sea surface temperature data.

Indian Ocean surface temperature (IOST) data comes from the NOAA Advanced Very High-Resolution Radiometer (AVHRR) Pathfinder Collated Global 4km Sea Surface Temperature dataset, accessed using Google Earth Engine.[4] We use data from August 1981 (the earliest available) up through December 2022. AVHRR provides fairly high-resolution pixel-level measurements of IOST nearly every day and usually multiple times per day. For our purpose, it is sufficient to reduce these data to an average over a swath of the Indian Ocean between, for reasons described below, 7.25 and 25.25 degrees south, latitude, and 32.5 and 65.5 degrees east, longitude.

All data presentation and analysis are done using with QGIS or Stata. Codes and layer data are available.

3. A primer on tropical storms

It is widely accepted that global climate change is leading to more extreme weather and higher-intensity weather events (Walsh et al., 2016). Globally, this means more hot spells, more dry spells, more wet spells and more intense high strength storms that originate near the equator. Since these storms tend to form between the tropics of Cancer and Capricorn (roughly 23.4 degrees north and south of the equator, respectively), where the planet is marginally closer to the sun and thus warmer, they are referred to as "tropical". Specifically, they are tropical depressions at lower intensities (sustained winds lower than 38 mph), tropical storms if they become stronger (39-73 mph sustained winds), and when they become stronger still, they are called cyclones in the southern hemisphere and hurricanes or typhoons in the north. There are 5 categories of cyclone, again defined in ascending order according to wind speeds: 1 (74 – 95 mph), 2 (96 – 110 mph), 3 (111 – 129 mph) 4 (130 – 156 mph), and

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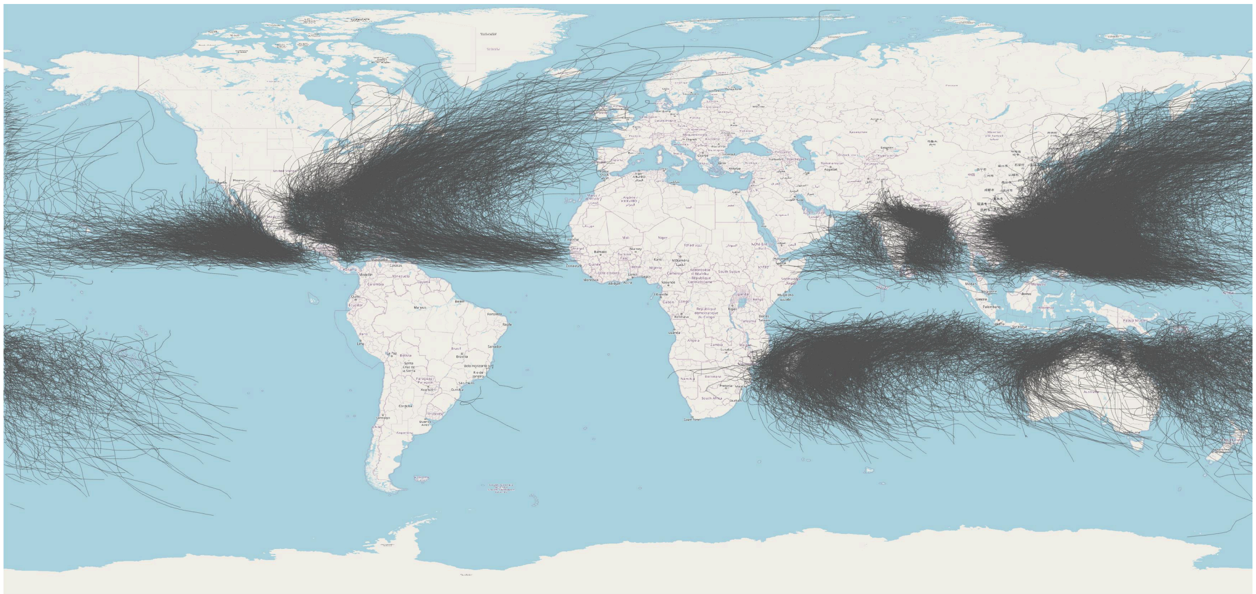
[4] The code used to extract these data were written and shared by Brad Peter, Assistant Professor of Geosciences at The University of Arkansas. An example is appended. A description of the dataset is at https://developers.google.com/earth-engine/datasets/catalog/NOAA_CDR_SST_PATHFINDER_V53

Figure 2. Pathways of Every Major Storm Recorded from 1911 to 2023



Source: NOAA IBTrACS

5 (157 mph and higher).

Because of the direction of the Earth's rotation, storms tend to move east-to-west before spinning away from the equator and weakening as they travel to cooler areas farther north and south (Figure 2). This is due to something called the Coriolis effect, which also explains why storm systems rotate in opposite directions in the northern and southern hemispheres, and why they almost never cross the equator.[5] Importantly for the present subject, it also explains why the birthplace of storms that threaten Malawi originate to its east, in the Indian Ocean.

Bodies of water provide fuel for storms, and warmer water provides more fuel (Bengtsson et al., 2009). There are many other factors at play that determine the ultimate strength of a storm, but a major component is that warmer water surface temperatures lead to more evaporated water particles in the atmosphere. These particles can then be collected by passing storm systems, leading to bulkier clouds and higher wind speeds. Differences in daily

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[5] https://oceanservice.noaa.gov/education/tutorial_currents/04currents1.html

surface temperatures that lead to even seemingly small movements in the average over time can have a significant effect.

Finally, while storms tend to gain strength as they pass over warmer water, they tend to start dying when they hit land masses and become deprived of their fuel. A fuel tank is a reductive but useful analogy for the strength of a storm. One can think of a storm making landfall (passing the last bit of sea surface) as similar to a vehicle passing a final filling station. The fuller the tank of the vehicle when it leaves the last station, the farther it will be able to continue travelling before running to empty. Similarly, the stronger a storm is when it leaves the ocean, the longer it will survive on land. Each storm making landfall with a “fuller tank” will have a higher probability of affecting inland areas, including Malawi.

To claim the recent increase in Malawian storm events is associated with broader climate trends there are three things that must be established: 1) IOST in the area that gives birth to storms that approach Malawi is rising, 2) there is a corresponding increase in the strength of these storms, and 3) this rise in strength of storms poses an increased threat to Malawi and other inland areas.

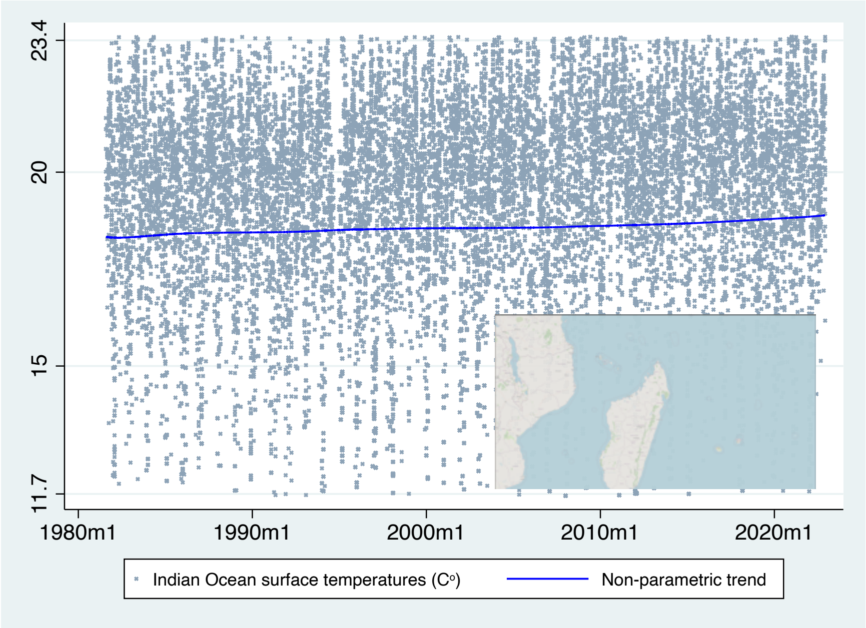
4. The formation, strength and pathways of storms over time

The factors determining the formation, strength, pathway and outcomes of any given storm are many and their interactions are complex. However, understanding these complexities is not necessary to accomplish the present objective of determining whether the probability of Malawi being affected by any given storm season is rising. We rather adopt a fairly straightforward approach of observing trends in data relating to the formation, strength and pathways of extreme weather events.

4.1. Indian Ocean Surface Temperatures

Once again, the storms that threaten the eastern coast of southern Africa are born in the nursery that lies to its east, in the Indian Ocean. Meticulous analysis of multiple historical data sources shows the IOST have been warming (Wenegrat et al., 2022). To highlight this change in a broad sense, consider how NOAA-AVHRR data from the region relevant to Malawi has changed over time. Specifically, we aggregate all the IOST data between 7.25 and 25.25 degrees south, latitude, and 32.5 and 65.5 degrees east, longitude to a single mean value for

Figure 3. Indian Ocean Surface Temperatures Over Time Around Madagascar (Map Inset)



Source: NOAA AVHRR.

Notes: N=35,289 (light navy dots) used to predict the LOWESS moving average (blue line). The top and bottom 5% of temperatures were included in LOWESS regression but are not shown.

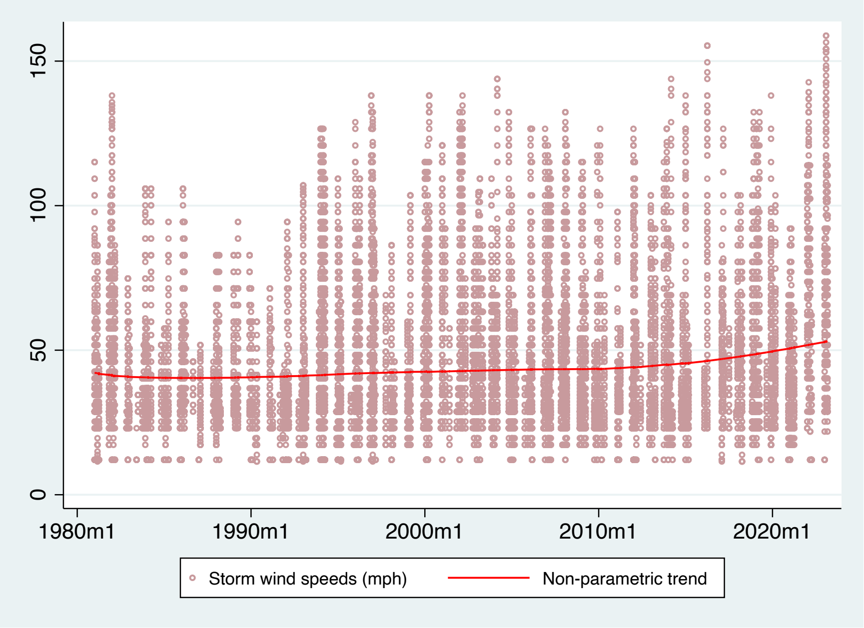
every observation period (usually twice daily) between 1981 and 2022. Geographically, this is the area shown on the map that is inset in Figure 3. The same Figure plots these data (over 35,000 observations) over time, behind a non-parametric LOWESS trend line.

While substantial variation is evident, the simple, important takeaway is that the surface temperature of the Indian Ocean's storm nursery is rising. Specifically, the LOWESS prediction for average temperature in this zone has increased by 0.6 Celsius (from 18.3 to 18.9) over the 44 years shown. Notably, a simple linear regression (not shown) finds a similar positive trend that is statistically significantly different from zero ($p<0.000$).

4.2. Intensity of major storms

Changes in storm strength as measured by wind speeds over time are examined using NOAA IBTrACS data from 1981 to 2023. Specifically, these data provide a record of the sustained wind speed of every major storm occurring in the area over this period up to four times per day. Given the frequency of storms, this results in just under 24,000 observations of storm wind speeds, which are plotted in Figure 4. These data are also overlaid by a non-parametric

Figure 4. Wind Speeds Over Time for Storms in the Area Approaching and Around Malawi



Source: NOAA IBTrACS.

Notes: N=23,988 (light maroon dots) used to predict the LOWESS moving average (red line). Storms with sustained wind speeds below 10.5 mph are not strong enough to be considered tropical depressions and are not included in this analysis.

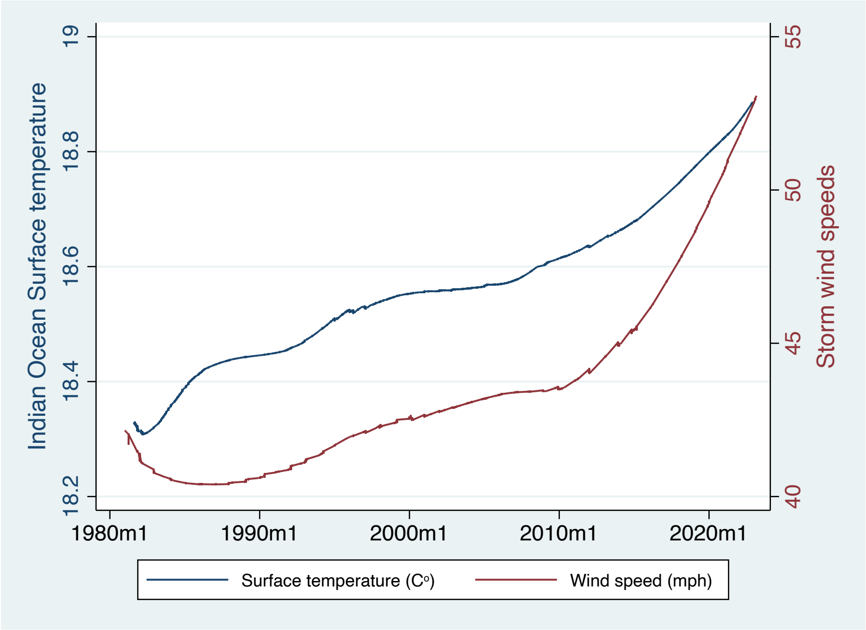
LOWESS trend line to indicate the changes in average speeds, again showing a generally upward trend.

Initially with a LOWESS mean prediction around 42mph, this reached a nadir of 40 mph in the early 1990s before climbing more than 25% to 53 mph more recently. As with IOST, a simple linear regression also finds a positive trend in sustained storm wind speeds that is statistically significantly different from zero ($p<0.000$).

One thing these trends mask is the rising extremeness of storms. For example, out of over 25,000 observations, only 25 recorded a storm with sustained winds over 150 mph. Five of these were in 2016 and 20 were in 2023.

The fact that there is wide variation in IOST and wind speed data somewhat diminishes the visual evidence of the trends in Figures 2 and 3, and the relationship between the two is not obvious. In Figure 5 we remove the individual points of data and rescale each vertical axis to focus on the changes in LOWESS predicted values over time. From this vantage point, the

Figure 5. Rescaled and Overlapping LOWESS Trends from Figures 2 and 3



Source: NOAA IBTrACS and AVHRR.

Notes: Combines and rescales LOWESS regression lines shown in Figures 3 and 4.

direction of and relationship between IOST and wind speed trends is obvious.

4.3. Mainland encroachment

The data presented so far highlights two uncontroversial points: 1) IOST has been increasing over time, and 2) this has spawned higher intensity tropical weather events. The importance of these points to Malawi hinges on whether higher intensity storms are consequently more likely to encroach farther into the African mainland after landfall. If we follow the "full tank" analogy, it is intuitively sensible that they would be, but this question can be examined empirically.

Figure 6 presents all the historical data on storm paths and strengths in the vicinity of Malawi dating back to 1911. The top panel combines all the years up to 1979, all of which are storm records that predate the data shown in Figures 2-4.[6] The middle and bottom panels

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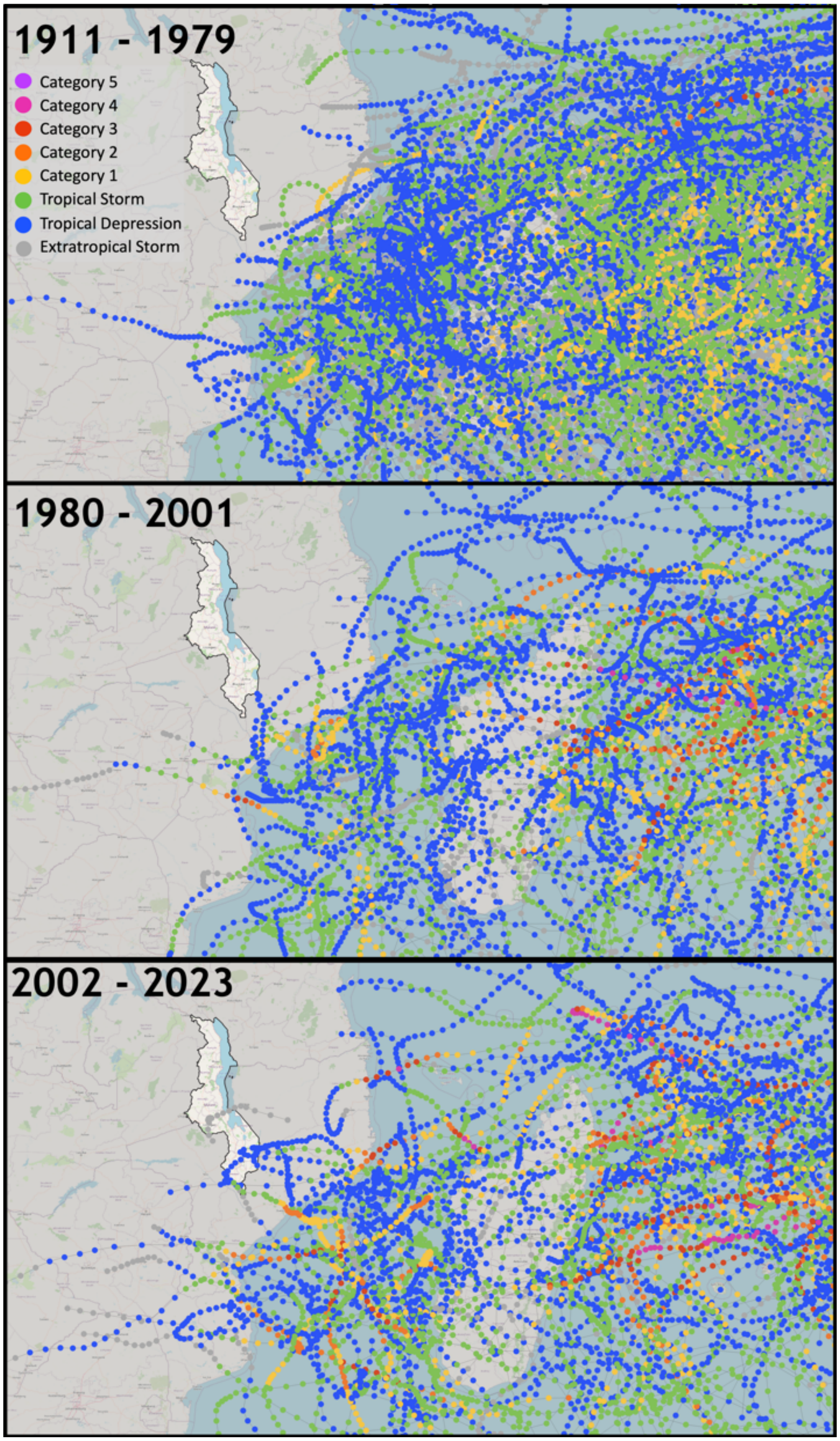
[6] This figure shows data dating to 1911. The NOAA data actually go back as far as 1842, but all storms before 1911 have a recorded wind speed of exactly "10.5", meaning simply that they were categorized as Depressions.

Figure 6. Increasing Storm Intensity and Threat to Malawi



Source: NOAA IBTrACS

Notes: Pathways and intensity of all major storms in the shown area for three periods between 1911 and 2023.

evenly divide the remaining data into two sequential blocks (1980–2001 and 2002–2023).[7] The top panel shows that for the first nearly 70 years of data, storms seldom graduated from "storm" to "cyclone" status, and when they did it was almost exclusively as a Category 1. As such, the island of Madagascar acted as a significant buffer, often breaking up storms entirely before they reached mainland Africa. Occasionally a storm would gain (or re-gain) momentum in the Mozambique Channel and impact the African coast. In all of that time, however, only a single cyclone-strength storm hit the mainland. This was an unnamed category 1 storm that made landfall just north of Nampula in 1934.[8,9]

The middle panel shows storm data from the 22-year period from 1980 through 2001. Evidence that the threat to Malawi had increased can be seen to the east of Madagascar, where more high-intensity storms were forming than previously recorded. With their "fuller tanks", more of these storms are able to traverse the island, "refuel" in the Mozambique Channel and impact the mainland coast. Whereas only a single cyclone in all of previously recorded history had made landfall on the region's eastern coast, seven cyclones made landfall between 1980 and 2001.[10] Although weakened to tropical depressions along the way, two of these seven (Benedicte in 1982 and Nadia in 1994) came within 100 km of directly hitting Malawi, as did Electre in 1982, which made landfall as a depression.

The bottom panel of Figure 6 shows storms from the remaining 22-years of data up through 2023. During this time the total number cyclones that made mainland landfall increased from seven to nine.[11] Notably, of the seven that made landfall in the previous

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[7] A video produced by the MwAPATA Institute further disaggregates these data in 5-year increments.

[8] We acknowledge that some historical records refer to other "cyclones" hitting Malawi during this time. In the past, "cyclone" has been used as a catchall phrase for destructive storms, especially if they included heavy rainfall. For example, Vol. 1, No. 2 of the Nyasaland Journal refers to a cyclone hitting Zomba in 1946 (Edwards, 1948). However, according to wind speeds and internationally recognized definitions, these storms would not be called cyclones. The aforementioned storm that hit Zomba would have been downgraded to an extratropical depression before it made landfall. For consistency and to track trends over time, NOAA applies (and we refer to) the same modern definitions for all storms in the dataset.

[9] Ignoring wind speed, we could plot tracks as far back as 1848, but doing so would reveal only one more storm making landfall on mainland Africa, and it was categorized as a depression.

[10] These were Benedicte (1982), Filao (1988), Nadia (1994), Bonita (1996), Lisette (1997), Eline (2000), and Hudah (2000).

[11] These were Japhet (2003), Favio (2007), Jokwe (2008), Dineo (2017), Kenneth (2019), Idai (2019), Eliose (2021), Gombe (2022), and Freddy (2023).

period, only Eline (in 2000) was stronger than a Category 1; amongst the nine that occurred more recently, there were six (Favio, Jokwe, Kenneth, Idai, Gombe and Freddy). Not coincidentally, this is also the first period shown in which storms survived long enough to directly hit Malawi. The first was Delfina in 2003. Three of the six that made landfall as Category 2 cyclones or stronger (Gombe, Idai and Freddy) also hit eventually hit Malawi, as did tropical storm Ana.

5. Conclusion and implications

The evidence strongly suggests the recent spike in extreme storm events in Malawi is not an unfortunate coincidence, but the continuation of a trend that will continue for the foreseeable future. IOST is rising, leading to stronger storms forming in the area that gives birth to threats to southern Africa's east coast, and these are surviving longer after landfall, increasing their probability of striking Malawi and other inland areas. Another factor not addressed with the data used for this study is the impact of deforestation. To continue the previously used analogy, just as a "full tank" allows storms to travel farther, so do smoother roads. In addition to acting as a physical barrier to storm winds, forested land keeps ground surfaces cooler and increases the land's ability to hold water. These factors combine to limit the duration of post-landfall survival duration and flooding impact of cyclones (Polcher and Laval, 1994; Bradshaw et al., 2007). The areas that would serve as a buffer to Malawi, particularly eastern Mozambique and Madagascar, represent some of the most deforested areas over the past two decades.[12]

In light of this information, a number of actions could be taken to reduce harm in the nearer- and longer-terms. In the nearer-term, policy makers and donors could plan to support disaster preparedness for effective response, develop comprehensive multi-sectoral and multi-hazard risk maps and investment plans, as well as establish area-specific preparedness awareness and emergency plans. Increasing any budget allocation would be useful, but some specific improvements to Malawi's preparedness could also be pursued. For example, maintaining up-to-date population databases to expedite response planning could

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[12] https://www.globalforestwatch.org/dashboards/country/MOZ/; https://www.globalforestwatch.org/dashboards/country/MDG/

prevent life-threatening delays. Also, early warning systems, which often rely on word-of-mouth to convey incoming threats, have proven woefully inadequate (Gondwe et al., 2024). Finally, households themselves could be aided in improving preparedness by conducting public awareness campaigns to explain the importance of being ready for these increasingly likely events, and what "being ready" means (e.g., having an evacuation plan).

These proposed actions would also be part of Malawi's responsibilities under the Southern Africa Development Community Disaster Preparedness and Response Strategy and Fund (SADC, 2017). Honoring these and other responsibilities could increase Malawi's ability to respond to emergency situations through shared knowledge and improved coordination.

In the longer-term, Malawi can become more resilient to these events through a range of investments. Improving road infrastructure, for example, would facilitate both evacuating areas facing an incoming threat and the provision of aid in its aftermath. Action could also be taken to mitigate the actual damage caused by these events. For example, most damage from major storms is caused by flooding, which could be reduced through flood-resilient investments in water drainage and catchment infrastructure. Flooding could also be reduced by promoting better agricultural soil health interventions. Much of Malawi's soils is declining in organic and carbon content, which reduces the water carrying capacity of land (Jones et al., 2013; Burke et al., 2022). This is a reversable trend. Rotating cereal crop production with legumes that produce more biomass and incorporating residues can make a significant difference, for example.

These are just some recommendations. Appropriate and thorough planning for improving preparedness and adaptation at different national, sub-national and household scales will require in-depth attention to needs and priorities that are beyond the scope and capacity of this study and these data. Rather, the information presented here underscores the urgent importance of filling these knowledge gaps where they exist and taking action to employ available means to protect and aid at-risk populations for the foreseeable future.

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Appendix A. Example of Google Earth Engine code for extracting IOST data:

```
var start_year = 2020
var end_year = 2020
var start_month = 1
var end_month = 12

var geometry =
  ee.Geometry.Polygon(
    [[[32.5, -7.25],
      [65.5, -7.25],
      [65.5, -25.25],
      [32.5, -25.25]
    ]], null, false
  )

var imageCollection = ee.ImageCollection("NOAA/CDR/SST_PATHFINDER/V53")

var date_filter = imageCollection
  .filter(ee.Filter.calendarRange(start_year, end_year, 'year'))
  .filter(ee.Filter.calendarRange(start_month, end_month, 'month'))
  .select('sea_surface_temperature')

var proj = imageCollection.first()
  .projection().nominalScale()

var convert = date_filter.map(function(i) {
  var props = i.propertyNames()
  return i.multiply(0.01)
    .rename('SST')
    .copyProperties(i, props)
})

var chart_options = {
  title: 'Mean Sea Surface Temperature',
  hAxis: {
    title: 'Date',
    titleTextStyle: {italic: false, bold: true}
  },
  vAxis: {
    title: 'Temperature (°C)',
    titleTextStyle: {italic: false, bold: true}
  }
}

var chart = ui.Chart.image.series({
  imageCollection: convert,
  region: geometry,
  reducer: ee.Reducer.mean(),
  scale: proj,
  xProperty: 'system:time_start'
}).setOptions(chart_options)

print(chart)
Map.centerObject(geometry)
Map.addLayer(geometry, {}, 'bounds')
```