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Development Trend of Tropical Cyclones under Climate Change

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Abstract:

Climate change presents a significant global challenge, with one of its effects being the alteration in the frequency and intensity of tropical cyclones. These shifts in cyclone patterns threaten both human societies and economic progress directly. This paper aims to study the effects of climate change on the development trend of tropical cyclones. As the planet continues to warm, there is a growing emphasis on how such intense natural phenomena will change in terms of frequency, intensity, and trajectory. This study examines the impact of climate change on warmer sea surface temperatures, atmospheric conditions, and tropical cyclone distribution. It employs historical data, future projections, and recent case studies to investigate these phenomena. The findings suggest that while the overall frequency of tropical cyclones is anticipated to remain relatively consistent in a warmer climate, with a slight decline, the intensity of these storms is likely to increase significantly, resulting in considerably larger impacts on coastal populations. The study also highlights the pressing need for disaster preparedness and mitigation strategies, particularly in highly vulnerable areas, to reduce the socio-economic losses from more frequent, intense tropical cyclones in the future.

Keywords: Tropical cyclones; climate change; distribution.

1. Introduction

Climate change in the 21st century is one of the most serious problems facing the world, with impacts on far-reaching aspects of the Earth system. Tropical cyclones are among the most destructive natural disasters on Earth. Changes in their frequency, intensity, and track directly affect the lives and property of millions of people worldwide. In recent years, as global temperatures have risen, so have sea surface temperatures, and much attention has been paid to changes in tropical cyclone activity. This problem is not only a frontier of scientific research but also closely related to the sustainability of socio-economic development. Thus, such research on the development of tropical cyclones under climate change conditions has both theoretical significance and an important practical role.

Although progress has been made in understanding the effects of climate change on tropical cyclones, empirical records, and numerical models indicate that rising global temperatures are likely to lead to increases in tropical cyclone intensity, changes in track, and changes in landfall frequency. Analysis of past records has helped many experts identify the increasing trend in the frequency of intense tropical cyclones, especially over the North Atlantic and Northwest Pacific. Moreover, landfalls from tropical cyclones are expected to be more devastating due to the heating up of the ocean. It has to be realized that results obtained from different models and methodologies are inconsistent with each other on the issue of changes in frequency and variability with regard to regional aspects. More elaborative research and improvement in the simulation techniques will have to be done in order to gain a more substantial understanding of the potential change patterns of the tropical cyclones due to climate change.

The principal objective of this paper is to examine the impact of climate change on tropical cyclones, including their geographic distribution and the implications for future storms. The initial section will examine the conditions that precipitate the formation and intensification of tropical cyclones. These include sea surface temperatures, the Coriolis effect, nonlocal conditional instability, humidity, wind shear, and synoptic-scale vorticity. Furthermore, this dissertation will examine the historical distribution and intensity of cyclones. The following section will illustrate the impact of global warming on tropical cyclones, presenting relevant empirical evidence on frequency and intensity. The final section will examine potential future changes in tropical cyclones and explore strategies for mitigating the risks they pose to society and the economy. This will facilitate an understanding of the ways in which tropical cyclones are changing due to climate change and inform policy decisions.

2. Formation of Tropical Cyclones

Tropical cyclones go by various names depending on their location: they are referred to as hurricanes in the North Atlantic and North Central Pacific, cyclones in the South Pacific and Indian Ocean, and typhoons in the Northwest Pacific.

These storms form from tropical disturbances in warm ocean waters, specifically where surface temperatures exceed 26.5 degrees Celsius (80 degrees Fahrenheit). These low-pressure systems harness energy from the surrounding warm waters. A tropical depression is characterized by wind speeds of up to 61 kilometers (38 miles) per hour. When wind speeds rise above 63 kilometers per hour (39 miles per hour), these storms are classified as tropical storms and are named according to guidelines established by the World Meteorological Organization. Hurricanes function as massive thermal engines that expel significant amounts of energy. They absorb heat from the warm, humid marine air and release it when water vapor condenses in thunderstorms. The storm is centered around a low-pressure core known as the eye of the hurricane, an area usually 32 to 64 kilometers (20 to 40 miles) in diameter that is often calm, surrounded by the “eye wall,” where the most severe winds and precipitation occur [1]. The development of tropical cyclones depends on seven critical conditions: the availability of a warm sea surface, a non-zero Coriolis force, nonlocal conditional instability, elevated humidity in the mid-troposphere, minimal wind shear, enhanced synoptic-scale vorticity, and a triggering mechanism [2].

2.1 Warm Sea Surface

Sea surface temperatures need to be about 26.5°C or higher, and the warm surface water must extend to a depth of at least 50 meters. This temperature is critical for promoting intense evaporation from the sea surface and heat transfer to the boundary layer. Warmer, wetter boundary layer air is the source of energy for thunderstorms in tropical cyclones. The strong winds associated with tropical cyclones produce large waves that disturb the upper waters of the ocean. When the warm water is shallower, this violent agitation causes the deeper, cooler water to rise to the surface. This phenomenon causes sea surface temperatures to drop below 26.5°C, which ultimately kills tropical cyclones [3].

2.2 Non-zero Coriolis Force

Tropical cyclones are unable to form within approximately 500 km of the equator (i.e., $\leq 5°$ latitude) due to the near-zero Coriolis force present in this region (exactly zero at the equator). It is rare for tropical cyclones with very small diameters to be observed at latitudes closer to the equator; however, none have been observed at the equator itself. It is not possible for tropical cyclones to form at the equator, and existing cyclones are unable to cross the equator.

In the absence of Coriolis force, boundary-layer air would be drawn into the eye by the low-pressure gradient. This would result in an accumulation of air molecules within the eye, leading to an increase in pressure towards ambient values. As a result, the low will dissipate, the winds will weaken, and the tropical cyclone will disappear within a day. This is the fate of tropical cyclones close to the equator. The Coriolis force exerts a significant influence on the winds in the lower troposphere, directing them

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around the eye at speeds that can be described as gradient- or cyclostrophic-wind speeds. In most cases, the majority of the airflow is tangential to the eye, rather than radial, as one might expect. However, at lower elevations, drag plays a more prominent role, transforming the winds into boundary-layer gradient winds. This results in a slight convergence towards the eye, which contributes to the longevity of tropical cyclones [4].

2.3 Nonlocal conditional instability

Given that tropical cyclones are composed of thunderstorms, it is clear that the tropical environment must have sufficient instability of non-local conditions to sustain deep thunderstorm convection. This implies the existence of a stable layer (i.e., the cap) above the warm, wet boundary layer, and a relatively cool middle troposphere compared to the boundary layer. The warm-wet boundary layer is formed by the transfer of heat and moisture from the warm sea surface to the air. These conditions, combined with cold air in the mid-troposphere, result in a high convective available Potential energy (CAPE) value, which is detailed in the chapter on Thunderstorms [5]. Therefore, a high CAPE value indicates that tropical cyclones have sufficient non-local conditional instability.

2.4 High humidity in the mid-troposphere

In the mid-troposphere, at an altitude of approximately 5 km, the humidity is likely to be relatively high. In the absence of sufficient moisture, nascent thunderstorms are unable to continue developing and organizing into tropical cyclones. It is noteworthy that this is in contrast to mid-latitude thunderstorms, where the mid-troposphere is drier, resulting in more intense thunderstorms. The influx of dry ambient air into the sides of mid-latitude thunderstorms results in the evaporation of a portion of the storm's water medium, leading to the formation of strong downdrafts [6]. These downdrafts are a defining characteristic of super-large storms and are responsible for the generation of gust fronts and tornadoes. In tropical environments, the occurrence of downdrafts from individual thunderstorms has the potential to disrupt the development of neighboring thunderstorms, thereby reducing the likelihood of their coordinated formation within the nascent eyewall. Furthermore, the influx of cold downdrafts at the bottom of the troposphere has the capacity to enhance static stability and impede deep convection.

2.5 Weak ambient wind shear

In order for thunderstorm clusters to form, wind shear within four degrees of the incipient storm's latitude must be weak ($\Delta M < 10$ m s^{-1} between pressure levels 80 and 25 kPa). For a cluster of thunderstorms to form, wind shear within four degrees latitude of the initial storm must be weak. These thunderstorms are indicative of the imminent formation of tropical cyclones. In the event of excessive wind shear, the updraft within the thunderstorm will undergo a tilting motion, thereby distributing the latent heat generated by water vapor condensation over a more expansive area [7]. This phenomenon results in a reduction in concentrated warming and a diminished capacity for the formation of low-pressure centers at sea level, which are necessary for the development of tropical cyclones. This requirement is different from that of mid-latitude thunderstorms. At mid-latitudes, strong shear in the environment is conducive to the formation of mesocyclones and very large thunderstorms. In the tropics, by contrast, this rotation of a single thunderstorm is harmful because it prevents many thunderstorms from working together to form the eyewall.

2.6 Enhanced synoptic-scale vorticity

A relative maximum of relative vorticity in the lower troposphere can facilitate the organization of thunderstorms into an incipient tropical cyclone. In the absence of this maximum, thunderstorms would likely form independently of one another (Fig.1).

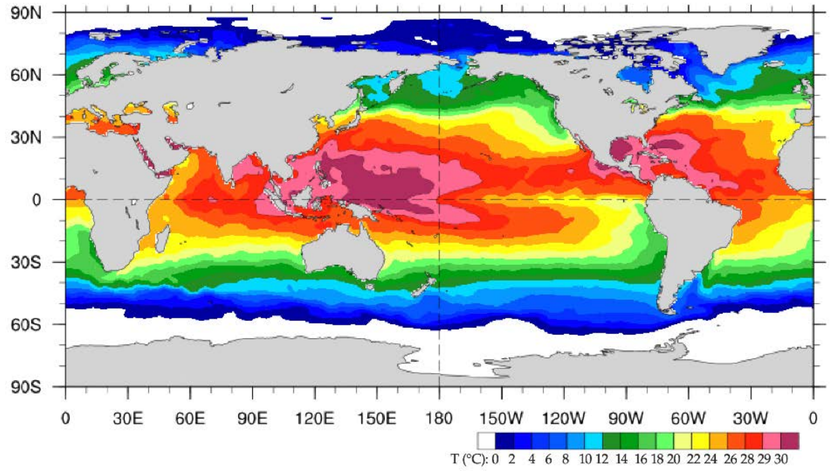

Fig.1 Sea surface temperatures (°C) as the one-week average during 4 - 10 Sep 2016 [1].

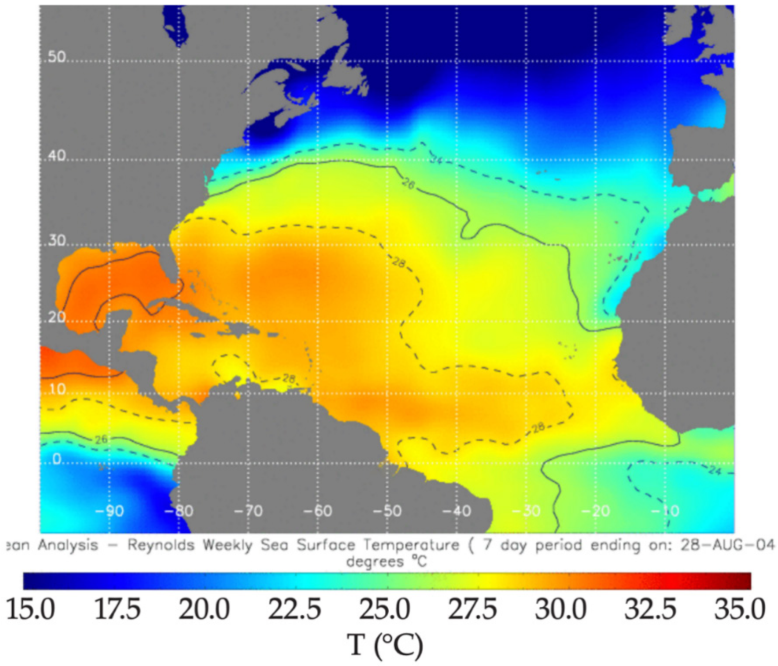

Fig. 2 The analysis of Atlantic Ocean sea surface temperatures (in degrees Celsius) averaged over a seven-day period concluding on August 28, 2004, encompasses the timeframe during which Hurricane Francis occurred [1].

The data utilized in this analysis were adapted from a United States National Hurricane Center image, which was created using data from the National Centers for Environmental Prediction (NCEP) and the National Oceanic and Atmospheric Administration (NOAA) (Fig.2).

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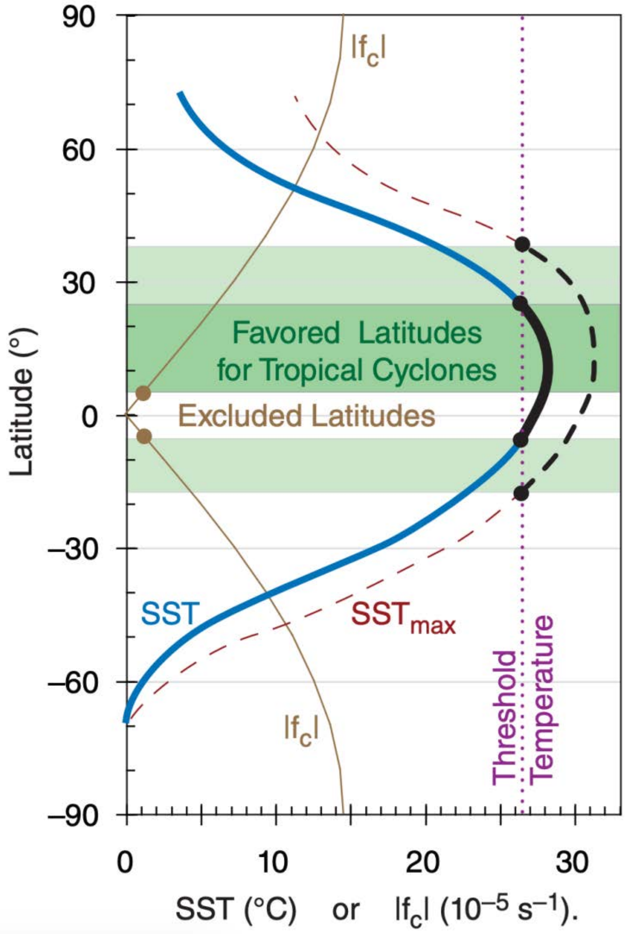

Fig. 3 The approximate zonal average sea-surface temperature [1]

Fig.3 depicts the approximate zonal average sea-surface temperature (SST) on August 3, 2009, with a global overview. As the seasons progress, the location of peak SST shifts, resulting in a change in the favored latitudes compared to this particular August example.

3. Distribution of Tropical Cyclones

Fig. 4 shows the regions where tropical cyclones occur most frequently and illustrates typical storm paths. Most tropical cyclones are guided by the large global circulation, and most of these storms form between 10° and 30° latitude. Prevailing trade winds in this region cause most tropical cyclones to initially move from east to west. Subsequently, under the influence of the monsoon circulation, these storms tend to move poleward. For example, the Bermuda High Pressure (also known as the Azores High Pressure) in the North Atlantic has a clockwise circulation that deflects tropical cyclones northward in the northern Western Atlantic. As tropical cyclones and weakened tropical cyclones penetrate deeper into the mid-latitudes and encounter westerly winds in the global circulation, their tracks will continue to be deflected to the northeast.

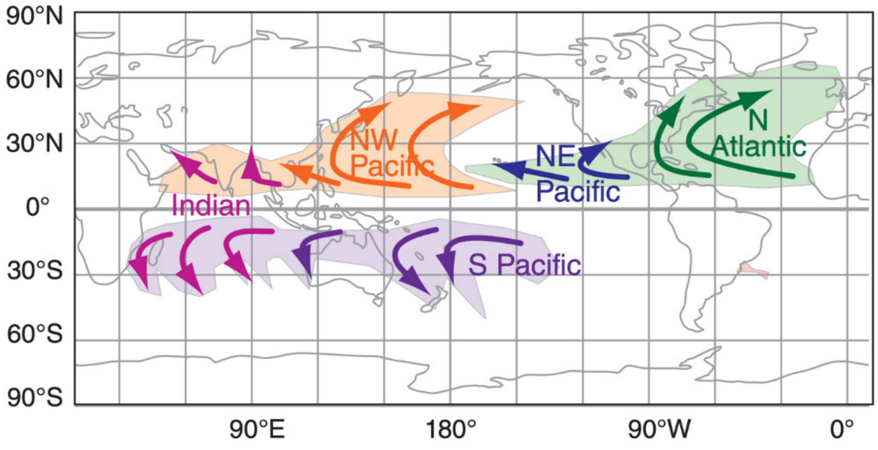

Fig. 4 Map of tropical-cyclone locations (shading), with a general sense of the cyclone tracks (arrows) [2].

4. Tropical Cyclones and Global Warming

It seems probable that climate change will affect the behavior of tropical cyclones in two aspects. First, tropical cyclones are most likely to form when the ocean surface temperature is too high and the vertical temperature gradient in the atmosphere is obvious. As the climate continues to warm, the temperature difference between the Earth's surface and the upper atmosphere is likely to shrink because the atmosphere is warming. This anticipated weakening of the vertical temperature gradient is expected to result in a reduction in the formation of tropical cyclones.

Secondly, the increase in sea surface temperature has an effect on the intensity of the cyclone, including the maximum wind speed and the intensity of precipitation associated with the cyclone. That's because storms draw energy from the surface waters of the ocean. Since these upper waters store more heat (energy), the cyclone has a larger source to draw energy from. In conclusion, it is probable that there will be a reduction in the number of tropical cyclones as the climate warms. However, it is possible that a larger number of them will form that are stronger and more destructive.

Based on this fundamental physical understanding, strong cyclonic activity has been observed to increase statistically in the North Atlantic region since the 1970s. However, due to the lack of long-term, consistent observation data, it is challenging to identify trends in the frequency and intensity of tropical cyclones in most parts of the world. Australia is one such example, where there has been no significant trend in the number or intensity of cyclones from 1981 to 2007. However, a comparison of the number of cyclones from the 1981-82 to 2012-13 period indicates a downward trend.

5. Empirical Evidence

5.1 Frequency of Tropical Cyclones

Over the 32-year period from 1990 to 2021, the global frequency of tropical cyclones (TCs) exhibited a slight decreasing trend, although this trend was not statistically significant. This finding suggests that, although there are annual fluctuations, the total number of tropical cyclones worldwide does not show significant variations. Notably, there was an increase in the number of short-lived named storms (lasting two days or less) in both the North Atlantic and Eastern North Pacific basins. This increase can be attributed to advancements in observational technology, such as enhanced microwave sensors and scatterometers. Microwave sensors are better able to penetrate clouds, allowing detection of weaker storms, while scatterometers improve wind field observations. With regard to regional frequency differences, the North Atlantic basin exhibited a significant upward trend in the number of named storms, which is likely driven by more favorable conditions, including warmer sea surface temperatures (SSTs) and reduced wind shear. The North Atlantic basin has exhibited a notable increase in hurricane activity since the mid-1990s. In contrast, the Western North Pacific has demonstrated a significant decline in tropical cyclone activity, particularly in the number of named storms and hurricanes. This reduction in frequency may be associated with the transition toward a more La Niña-like base state during the period.

5.2 Intensity of Tropical Cyclones

Even though the total number of tropical cyclones as a whole doesn't show a considerable change, there has been a marked shift in the direction of stronger storms on a global scale. The proportion of Category 4–5 hurricanes (the most intense storms, with wind speeds exceeding 130 mph or 113 knots) has gone up, yet this trend is not statistically significant globally. This rise shows that although the total number of hurricanes has reduced, those that form are more intense.

The Accumulated Cyclone Energy (ACE) index, which includes both the strength and time duration of tropical cyclones, has shown a distinctively global decline since 1990. The drop in ACE is largely due to the decrease in cyclone activity in the Western North Pacific and South Indian Ocean. Even with this global downturn, the North Atlantic basin has proved to have an increasing ACE pattern, while this trend is not statistically significant, the continued upward shift of Category 4-5 hurricanes suggests that there may be a longer-term shift in storm intensity. The increasing trend in the North Atlantic infers that storms in this area are growing in both strength and length.

Rapid intensification (RI) refers to the meteorological event where storms rapidly develop strong winds, for instance, the wind speed increases by at least 50 knots during a 24-hour time. There has been a noticeable increase in the number of RI events worldwide, especially in the Western North Pacific, North Indian Ocean, and South Indian Ocean. The elevation in RI is propelled by higher sea surface temperatures (SSTs) and increased potential intensity (PI), these factors allow storms to gain energy fast so they tend to intensify rapidly. The climb in SSTs because of climate change is generating better conditions for these speedily intensifying events

5.3 Future Projections

As a result of greenhouse warming, it is likely that the frequency of tropical cyclones will either decline globally or stay largely unchanged. Nonetheless, there is little faith in the anticipated alterations in certain basins. By the late 21st century, the present models predict changes ranging from a 6% to 34% global decline and up to ±50% increase in certain basins.

Additionally, there is a good chance that the mean maximum wind speed of tropical cyclones will increase; increases are predicted to range from +2 to +11% worldwide.

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Although it is not a given, it is expected that in some basins, the warming of the twenty-first century will lead to an increase in the frequency of the strongest (rare/high-impact) storms.

Also, there is a considerable probability that precipitation levels will rise. The estimated magnitude within a 100 km radius of the tropical storm's core is approximately +20%. Furthermore, the projected alterations to the genesis, location, trajectory, duration, and impact zones of tropical cyclones are not well-established. The prevailing model projections do not suggest any significant shifts in these characteristics. However, future sea-level rise and coastal development are anticipated to enhance the vulnerability of coastal regions to storm-surge flooding. Nevertheless, future storm characteristics are also expected to influence this susceptibility.

6. Adaptation and Strategies

Countries need to pay attention to or actively respond to tropical cyclones. A case on Zimbabwe will be used here: A review of cyclones in Zimbabwe over the past two decades reveals an increase in the number of deaths, individuals reported missing, and economic damage. This is the wrong direction for achieving the global targets set by the SFDRR. Zimbabwe needs to be more prepared for disasters. Evacuation is an effective way to reduce deaths and injuries from tropical cyclones. For example, two million people were evacuated from Florida before Hurricane Matthew in 2016. The GoZ seems reluctant to issue evacuation orders. This is because there are not enough prepared resources, evacuation routes or centers, and an ineffective early warning system for cyclones. The government and communities in the affected areas believed that the cyclone was not that bad. This has resulted in loss of life and economic losses. In New Orleans, some people didn't evacuate before Hurricane Katrina because they didn't think it was that bad.

Firstly, Zimbabwe should review its disaster legal framework to bring it more in line with global standards, including the Strategy for Disaster Risk Reduction for Sustainable Development. The current framework was outdated and did not reflect significant developments in disaster risk reduction. Zimbabwe needed a new disaster framework that moved away from the "relief-recovery-reconstruction" cycle to "planning-prevention-preparation". The law should encourage people to work together to reduce disaster risk. This is everyone's responsibility, including government, business, and citizens. The private sector can help with disaster preparedness by sharing early warning information and providing technical help when needed. Similarly, academic institutions can help governments develop monitoring and early warning services, map and analyze natural hazards, and make scientific or technical information easier to understand. This will help Governments prepare for disasters.

Secondly, local authorities need legal support to evacuate people. This means that the government must work with other groups to take responsibility. Local authorities can run programs to help people make a living, earn more money, and learn to cope with disasters. They can also share knowledge about floods in their communities and create flood risk measures and early warning systems.

Thirdly, local authorities can also help people stay safe and informed about risks, preparedness, and EWS. In the Netherlands, local authorities evacuate communities when there is a flood threat. We need to improve how well institutions can evacuate people in an emergency. The Civil Protection Act does not say which institution orders evacuations in emergencies. Evacuation is a way to avoid death. A trusted institution should order the evacuation. Evacuation is more than just leaving unsafe places. It also includes alerting, warning, deciding, and preparing people before they leave. There are two ways to evacuate. There are two types of evacuation: the first one is moving to a safe place outside the area at risk, and the second one is moving to a safe place within the area at risk. Safe routes and centers must be set up at the community level to make evacuation effective. Evacuations can cost a lot of time, money, and credibility. It can even expose people to more dangerous places. The challenge is how to balance the benefits of saving lives against the costs.

Fourthly, the central government should assess the risk of various disasters across the country. The risk of flooding should be assessed across the country because climate change is changing the way of getting flooded. Three cyclone case studies reveal new flood-prone areas. These areas are different from traditional hotspots such as Muzarabani, Mbire, Malipati, and Chikwalakwala. Community involvement is useful for such assessments, as participants learn about disaster preparedness. They can also help set up and operate community warning systems. There are also opportunities to work with non-governmental organizations to educate communities on disaster reduction and preparedness.

Finally, The central government ought to allocate investments for constructing a system that forecasts and issues warnings for cyclones, incorporating a system for real-time monitoring. They should also share more information about cyclone warnings. Because better forecasting and warning systems can help save lives in the face of atmospheric disasters. Civil protection agencies should have all kinds of communication technologies, not just telephones. Zimbabwe needs to improve its common alert protocol and impact-based forecasting. Space-based technologies such as radar and the Internet can help monitor cyclones, while radios with shortwave signals can improve early warning systems in mountainous areas.

7. Conclusion

This paper mainly discusses the significant impact of climate change on the dynamics of tropical cyclones. Although the overall frequency of storms is not expected to increase significantly, the intensity of these storms is anticipated to rise, leading to an increased likelihood of more catastrophic hurricanes, typhoons, and cyclones in the coming years. This underscores the necessity of global and local initiatives that prioritize disaster readiness and adaptation strategies. It is imperative for governments, regional authorities, and communities to collaborate in developing enhanced early warning systems, evacuation protocols, and sustainable infrastructure to address these evolving hazards. The future resilience of coastal communities hinges on prompt and effective policy actions designed to mitigate the heightened risks posed by climate change to tropical cyclones.

References

[1] Geosciences LibreTexts. Intensity and Geographic Distribution. 2020, https://geo.libretexts.org/Bookshelves/Meteorology_and_Climate_Science/Practical_Meteorology_(Stull)/16%3A_Tropical_Cyclones/16.01%3A_Section_2

[2] Geosciences LibreTexts. Evolution, 2020. https://geo.libretexts.org/@go/page/9633

[3] Climate Council. Fact Sheet: Tropical Cyclones and Climate Change. 2024.

[4] Klotzbach, P. J., Wood, K. M., Schreck, C. J., Bowen, S. G., Patricola, C. M., & Bell, M. M. Trends in Global Tropical Cyclone Activity: 1990–2021. Geophysical Research Letters, 2022, 49(6).

[5] Mathura, E. Learning from the tropical cyclones that ravaged Zimbabwe: policy implications for effective disaster preparedness. Nat Hazards,2020, 104, 2261–2275.

[6] Nunez, C. Hurricanes, Cyclones, and Typhoons Explained. National Geographic Society.2023. https://education.nationalgeographic.org/resource/hurricanes-cyclones-and-typhoons-explained/

[7] Knutson, T., McBride, J., Chan, J. et al. Tropical cyclones and climate change. Nature Geosci, 2010, 3, 157–163.