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Local Impacts and Surface Characteristics of Cold Pools Wind Gust Observed from Thunderstorm

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Abstract

Cold pools and associated wind storms are frequent occurrences in Southwestern Nigeria, especially during the early monsoon phase. The associated surface wind gust frequently destroys properties resulting in economic losses. Two case events were investigated in this study; one event occurred in May 2019 and the other occurred in March 2020, both in southwestern Nigeria. The National Oceanic and Atmospheric Administration (NOAA) National Center for Environmental Prediction (NCEP)/Climate Prediction Center (CPC) Infrared brightness temperatures and CPC Morphing technique (CMORPH) rainfall products were analysed alongside *in-situ* observations from the Nigerian Meteorological Agency (NiMET). Other data sources analysed are the National Aeronautics and Space Administration (NASA) Prediction Of Worldwide Energy Resources (POWER) and the World Wide Lightning Location Network (WWLLN). Cold pools were identified in the impacted communities as indicated by surface characteristics investigated from the *in-situ* observations. There was a sudden change in wind direction, with a simultaneous drop in temperature accompanied by increasing wind speed. Pressure and humidity were observed to change in the same period. Thunderstorms were also present in the impacted communities, as observed by the *in-situ* observations, in both case events. The presence of lightning as observed by WWLLN agrees with the *in-situ* thunderstorms. The cloud characteristics showed the presence of cloud shields, by their brightness temperature, over the impacted communities during the period of the cold pools in both case events. The systems were raining at the time of the observations in both cases, consistent with the *in-situ* thunderstorm observations. The communities were heavily impacted with several properties destroyed in the events. These early monsoon seasonal windstorms require a forecasting tool for their prediction and this study presents an eye-opener for further investigation and innovative research to address the menace.

Keywords

Impacts, Cold Pools, Windstorms, Thunderstorms, Rainfall, Disasters

1. Introduction

A convective cold pool is a region of evaporatively cooled air that has been transported to the surface through convective downdrafts and has then, upon reaching the surface, spread out as a density current [1] [2]. As cold pools expand, they displace warmer ambient air [3]. This more buoyant environmental air is then uplifted, and new clouds can form as a result [3] [4]. Colliding cold pools can be a particularly effective trigger for new convection [5]. Furthermore, cold pools bring gusty winds that enhance sensible and latent heat fluxes, which in turn modify the thermodynamic properties and moisture structure of the sub-cloud layer [6] [7].

Cold pools are known for the development or initiation of secondary storms, which are dependent on factors such as the speed and depth of the cold pool, among other environmental factors [8]. The development or initiation of convective cells in the boundary between the environment and the cold pool constitutes the major mechanism that sustains multicell thunderstorms [9] [10]. For stronger cold pools, the supply of warm air to the updraft is rapidly cut off due to the speed of the cold pool, thus resulting in the decay of the thunderstorm.

[11] showed a significant increase in maximum wind gusts in Ibadan during the period 1989-2008 in which most of the second half (1998-2008) of the period experienced more windstorm events than the first half (1989-1997). [12] investigated the relationship between average wind speed and maximum wind speed (wind gust) for a single year (2020), which showed stronger seasonal correlations during the dry season than the wet season. Devastating rainstorms are seasonal recurring disasters during the rainy season in West Africa, particularly Nigeria, which often affect lives and properties negatively and frequently occur as flash floods and heavy downpours, lightning and thunderstorms, or commonly in form of very strong windstorms [13] [14]. Strong winds also affect agricultural crops, and expose airplanes to a high risk of crashing during take-off and landing [15] [16]. In 2014, [17] reported that 980 natural disasters (associated with losses) occurred globally; 42% were floods-related (hydrological), 41% were storms-related (Meteorological), 8% were geophysical-related phenomena (earthquakes and volcanic eruptions), 9% were climatological-related phenomena (heatwaves, cold waves, droughts, wildfires).

The devastating effects of annual rainstorm/windstorm disasters are usually caused by uncontrolled and indiscriminate anthropogenic activities over time and space, which directly impacts communities, lives, and properties [18]. The vulnerability of any society or individual to disaster can be cushioned by short-term coping approaches and long-term adaptation practices that change anthropogenic activities in other to minimize impacts. This can be achieved by effective disaster relief agencies and institutions in Nigeria and through the involvement of potential victims of climate hazards in the planning and operations of such institutions [19].

Nigeria is situated between latitudes 4˚N and 14˚N above the equator. The longitude is between 3˚E and reaches nearly 15˚E. It is surrounded by Niger to the north, Cameroon to the east, Benin to the west, Chad to the northeast, and the Atlantic Ocean to the south. Nigeria is divided into 36 states and a Federal Capital Territory (FCT). Her population is over 200 million and spread over an area of 923,768 sq km. it has a width of about 1,200 km from west to east and about 1050 km from south to north. Nigeria's topography ranges from lowland along the coastal areas and in the lower Niger Valley to high plateaus in the north and mountains along the eastern or Cameroonian border. The northward/southward migration of the Inter-Tropical Convergence Zone (ITCZ) is the fundamental factor controlling the Nigerian climate [20].

The two stations are located in southwestern Nigeria, as shown in **Figure 1**, with similar climate characteristics. Southwestern Nigeria has a tropical climate with two distinct seasons. The wet season is from April to October and the dry season is from November to March [21] [22]. The temperature values ranged between 21˚C and 34˚C whereas the annual rainfall amount ranged between 150 and 3000 mm. The rainy season is linked with the Southwest monsoon trade

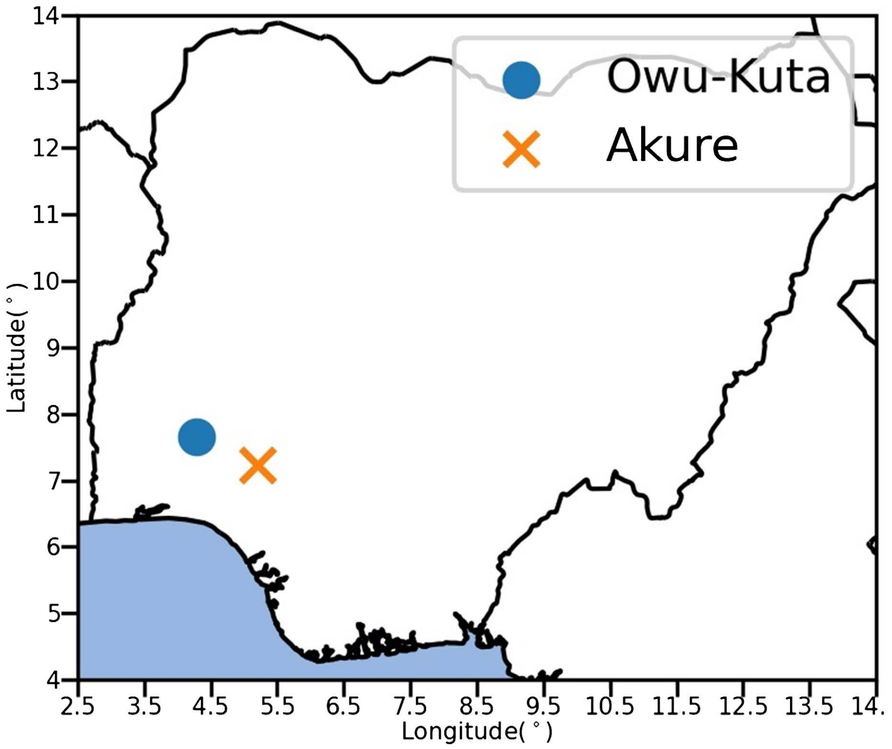

Figure 1. Map of Nigeria showing the two locations of the case studies (impacted communities).

wind from the Atlantic Ocean whereas the dry season is linked with the northeast trade wind from the Sahara desert. Vegetation in Southwestern Nigeria comprises freshwater swamps and mangrove forests at the belt. The lowland in the forest stretches inland to Ogun and part of Ondo State, while the secondary forest is towards the northern boundary where the derived southern Savannah exists [21].

This study was born out of the need to investigate the gusty winds that resulted in the severe destruction of properties from two different/selected storm events associated with cold pools over two different locations in Nigeria in 2019 and 2020. Very little research had been conducted to investigate the weather (e.g. cold pool) associated with disasters and addressed the impacts of climate hazards over West Africa and Nigeria in particular. These hazards are persistent during the early phase of the monsoon season e.g. [11] assessed a major windstorm event that occurred in Ibadan in March 2008), and there are no decision support systems on ground to monitor and predict the events before they occur. For example, the first rain in Akure (one of the communities currently investigated in this study), which occurred on 18th February 2022, had a devastating impact on the city with some communities left without electricity for some weeks, roofs of houses were blown away, among others. So it is a common and frequent occurrence during the early phase of the monsoon. The result section, in this paper, is divided into observed surface characteristics, observed cloud characteristics, and observed impacts for each of the impacted communities.

2. Data and Methodology

Data from the Nigerian Meteorological Agency (NiMET) and National Aeronautics and Space Administration (NASA) Prediction Of Worldwide Energy Resources (POWER) were used to identify the cold pools and to describe the surface characteristics of the cold pools in each of the two case events. The NiMET data served as *in-situ* observation to complement/validate the POWER data for each case event. *In-situ* data consist of wind speed and direction, temperature, surface pressure, and humidity. The data were available in hourly intervals for one week but analysis was performed only during a-day period since visual inspection/observation indicated that there are no specific phenomena preceding the cold pool event.

The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) created the CPC Morphing technique (CMORPH) from level-2 rainrate retrievals of the Passive Microwave (PMW) observations from multiple Low-Earth Orbit (LEO) satellites (DMSP 13, 14 & 15 (SSM/I), the NOAA-15, 16, 17 & 18 (AMSU-B), and AMSR-E and TMI aboard NASA's Aqua and TRMM spacecraft). It also housed Infrared (IR) Brightness Temperature (TB) data merged from different geostationary satellites. The IR data is a globally-merged (60˚S - 60˚N) 4-km pixel-resolution, from the Japanese, European, and U.S. geostationary satellites (GMS-5/MTSat-1R/2/Himawari-8, METEOSAT-5/7/8/9/10, and

GOES-8/9/10/11/12/13/14/15/16). It can be downloaded from https://disc2.gesdisc.eosdis.nasa.gov/data/MERGED_IR/GPM_MERGIR.1/. The CMORPH is bias-corrected and produced on a resolution of 8km by 8km (0.07277 degrees Lat./Lon.) in 30 min intervals since December 3, 2002 till date (http://www.cpc.ncep.noaa.gov/products/janowiak/cmorph_description.html). It is based on this fine spatio-temporal resolution that the NOAA NCEP/CPC Infrared brightness temperatures and CMORPH rainfall products were used to show the presence of storms over the locations of the cold pool events.

The WWLLN (https://wwlln.net/) is a global lightning detection network around the Earth. A project Team, led by Prof Robert Holzworth of the University of Washington, collects these data remotely with the cooperation of the universities and institutes which host the stations of detection. The electromagnetic radiations emitted by lightning strokes at Very Low Frequency (VLF) and called Sferics are detected by the WWLLN sensors. The Detection Efficiency (DE) of WWLLN has significantly improved between 2005 and 2015 [23], reaching up to 80% when compared to New Zealand Lightning Detection Network [24]. This detection efficiency is close to TRMM'S LIS detection efficiency of 90% [25] [26]. These strokes are then localized by using the Time of Group Arrival technique (TOGA: [27]). The stations can be separated by thousands of kilometers because the VLF frequencies can propagate within the Earth-Ionosphere wave guide with very little attenuation. The stations are targeted at 3000 km apart on the average to cover the globe and to localize at least 50% of the Cloud-to-Ground (CG) strokes with an average accuracy better than 10 km [28]. Since its inception in March 2003, and global observations in August 2004 [24] [29], the WWLLN has been improved in terms of number of stations and development of the processing algorithm [30]. This provides a robust climatological database of lightning, which are applicable for seasonal and diurnal analysis of the earth's climate [29]. In 2014, it had more than 60 sensors spread over the planet, and the Federal University of Technology Akure became part of the partner/host universities in May 2021. This work used actual total stroke counts, on the assumption that the WWLLN Detection Efficiency (DE) variation is fairly uniform across Nigeria.

Provod *et al.* [31] stated that 30-min time period previously used to identify pre-storm minima and maxima surface variables [32] was limited for the case study of Niamey used in their study, particularly for surface pressure, hence justifying the need to use hourly intervals for this study. Similar to [31], cold pool identification in this study was based on a sudden change in wind speed and direction, consistent with decreasing temperature and rising surface pressure. The two case events, for this study, were subjectively identified as in [31].

3. Results and Discussion

3.1. Observed Surface Characteristics and Cold Pool Identification

There are two sources of surface data used to describe surface characteristics and for comparison. The NASA POWER data shown in Figure 2(a) and the *in-situ* NiMET data (Figure 2(b)). Both Figures represent plots of wind speed and direction (top), relative and specific humidity (middle), and temperature and surface pressure (bottom). On 26th May 2019, Owu-Kuta in Osun State Nigeria experienced a cold pool wind gust. As indicated by the continuous vertical red line, there is a sharp drop in the wind direction for more than 1-hr as reflected in both Figure 2(a) and Figure 2(b). The temperature, at this time, was already decreasing and the pressure was rising (increasing) with corresponding increasing wind speed. The relative humidity was increasing until close to saturation (100%) during the same period. The above environment established the presence of cold pools based on [31]. The maximum wind gust was around 2 m/s on the average from the two different sources (NASA POWER and NiMET) during the period of the cold pool.

On 19th March 2020, the city of Akure Ondo State Nigeria experienced cold pool wind gust during the evening hours, which lead to destruction of properties. Figure 3(a) and Figure 3(b) showed a sudden drop in the wind direction (top), which lasted more than 1-hr. the temperature was decreasing also during this period, whereas, the surface pressure was increasing, based on the NASA POWER observation, but surface pressure was constant as observed by the *in-situ* NiMET observation. The relative humidity was increasing and reached near saturation (100%) during the same period. The wind speed was fluctuating and exceeds 3 m/s on the average from the two different sources. As in the first case event, parameters that described the Akure cold pool wind gust showed

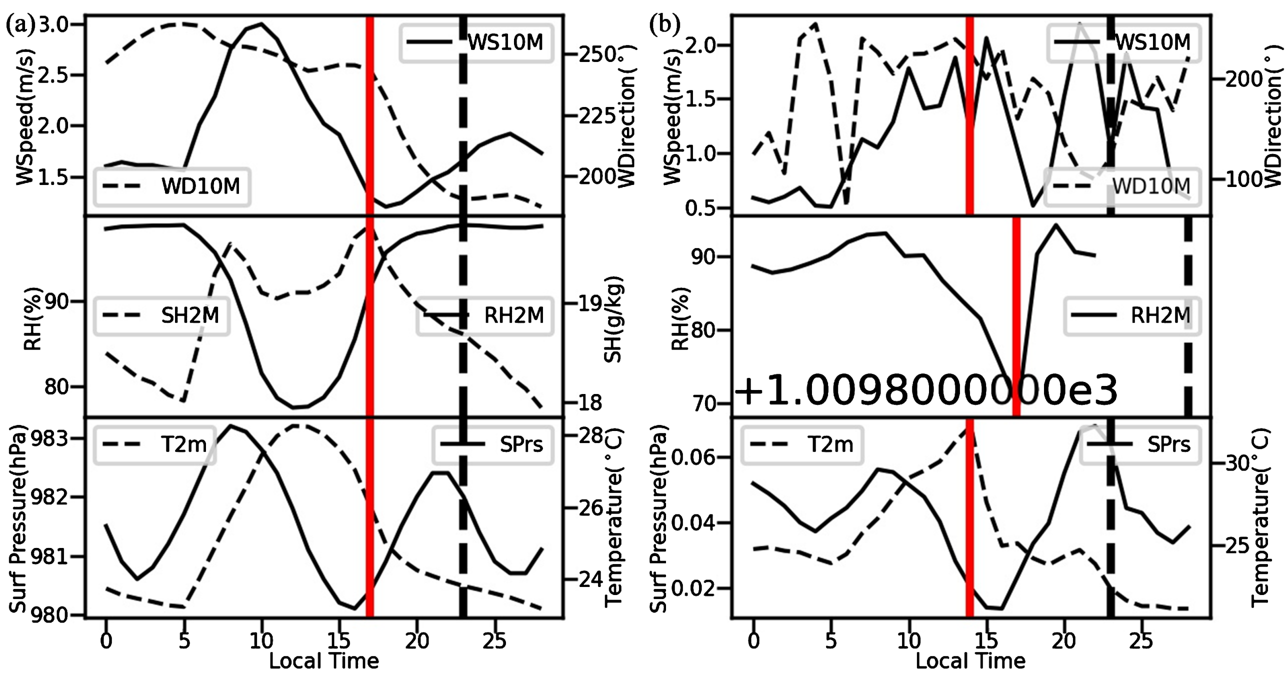

Figure 2. Daily time series for Owu-Kuta as observed by the NiMet surface station some kilometers from the impacted community. This time series is for 26 May 2019, when a cold pool crossing was identified at around 1400 - 1600 Local Time (LT) (denoted by the vertical red line). Black dashed lines denote the transition into another day.

conformity with [31]. In each case event, the black dashed lines indicated the boundary/transition into another day.

3.2. Observed Cloud Characteristics

The cloud parameters analysed are the Brightness Temperature (Tb), Rainfall amount, Lightning and thunderstorm amount. The May 26th 2019 cold pool event was observed to have great impact in a community in Osun State of Nigeria. Owu-Kuta is situated at Latitude 7.65˚ and Longitude 4.28˚ Osun State Southwestern Nigeria. The NOAA brightness temperature (Figure 4) clearly indicated the presence of cold cloud (core < 200 K) in the vicinity where the cold pool was observed. The core of the cloud shield was not centered over the impacted

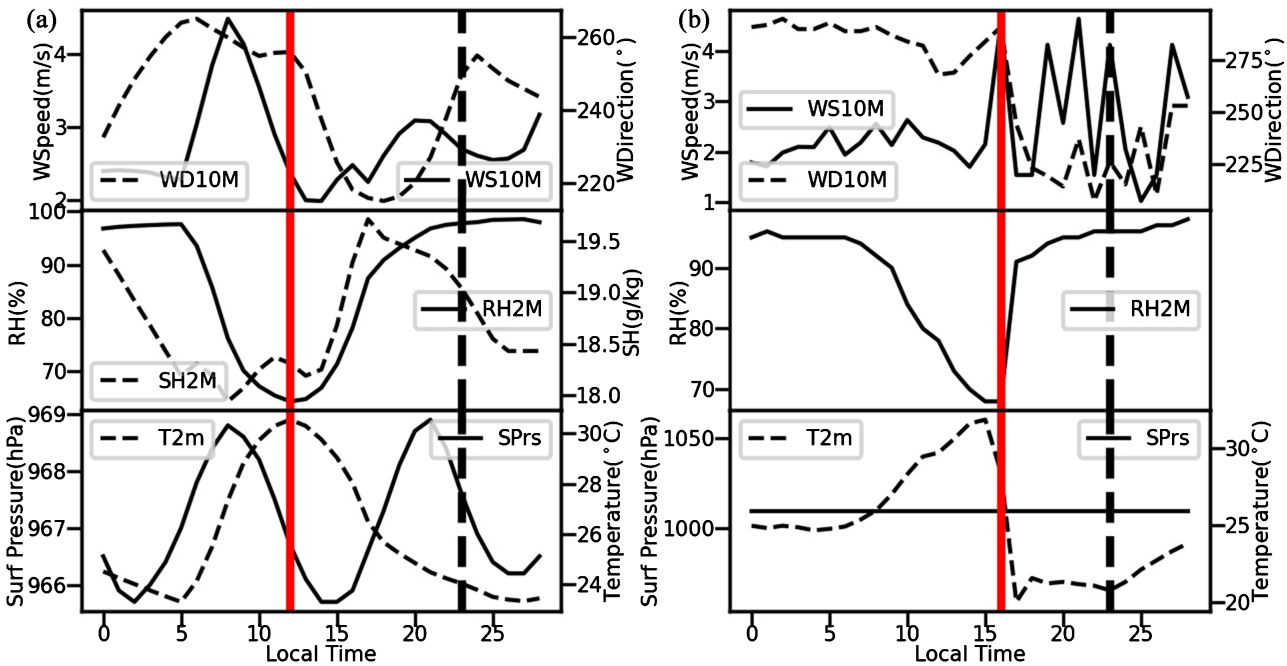

Figure 3. As in Figure 2 but for Akure metropolis.

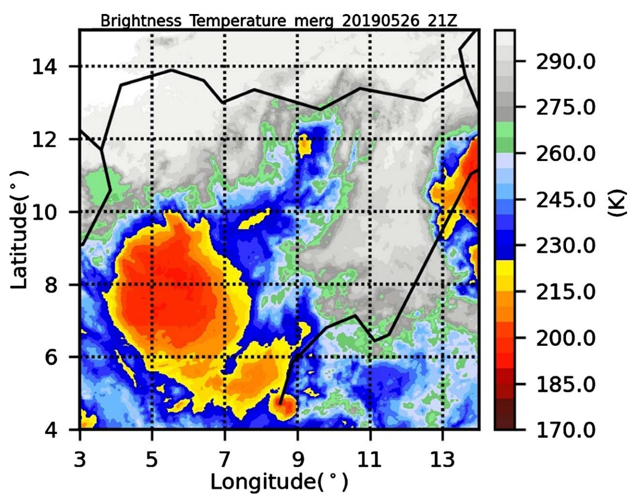

Figure 4. Cloud shield over the impacted community on 26th May 2019 at 21 UTC.

community at the time of the satellite snapshot (21Z) on 26th May 2019, however, clouds over West Africa are known to migrate westward [33] [34] [35], therefore it is expected that the cloud would have migrated over the impacted community few minutes/hours later.

The cloud shield spread over several kilometers across some states in southwestern Nigeria of which the peak 3-hr accumulated rainfall amount (~60 mm), as shown in **Figure 5(a)**, was observed over Akure (Latitude 7.23, Longitude 5.21) and environs in Ondo State. The system, which is already dissipating at the time it was capture, indicate that it had initiated in the mid-afternoon [36]. The satellite imagery (**Figure 5(b)**) of the CMORPH rainfall indicated that the system had migrated slightly westward 3-hr later and accumulated rainfall amount peaked at 60 mm·3hr^{-1} during 21:00 - 00:00 UTC, except for a location north of 8˚ Latitude.

In **Figure 6(a)** and **Figure 6(c)**, representing the case event of 26th May 2019, the *in-situ* NIMET observed (locally observed) rainfall amount and number of thunderstorms present indicated that the hourly rainfall peaks at 15 Local Time (LT), that is, 16 UTC in **Figure 6(a)**, and three thunderstorms were observed to be present at exactly the same time in the impacted community, as shown in **Figure 6(c)**. The WWLLN stroke density discussed in the next paragraph, and shown in **Figure 7(a)**, does not depict actual number of thunderstorms, but presents patterns and possible location/presence of thunderstorms. Separate thunderstorms can be determined using clustering algorithm to cluster strokes in time and space [37], which is beyond the scope of this work. Thus, this work has not compared the number of locally (NIMET) observed thunderstorms with the WWLLN observations of stroke density but presented the results separately. Although, **Figure 7(a)** indicated relatively few possible presences (about two or three) of thunderstorms, similar to the locally (NIMET) observed number of thunderstorms, this cannot be ascertained since clustering algorithm was not

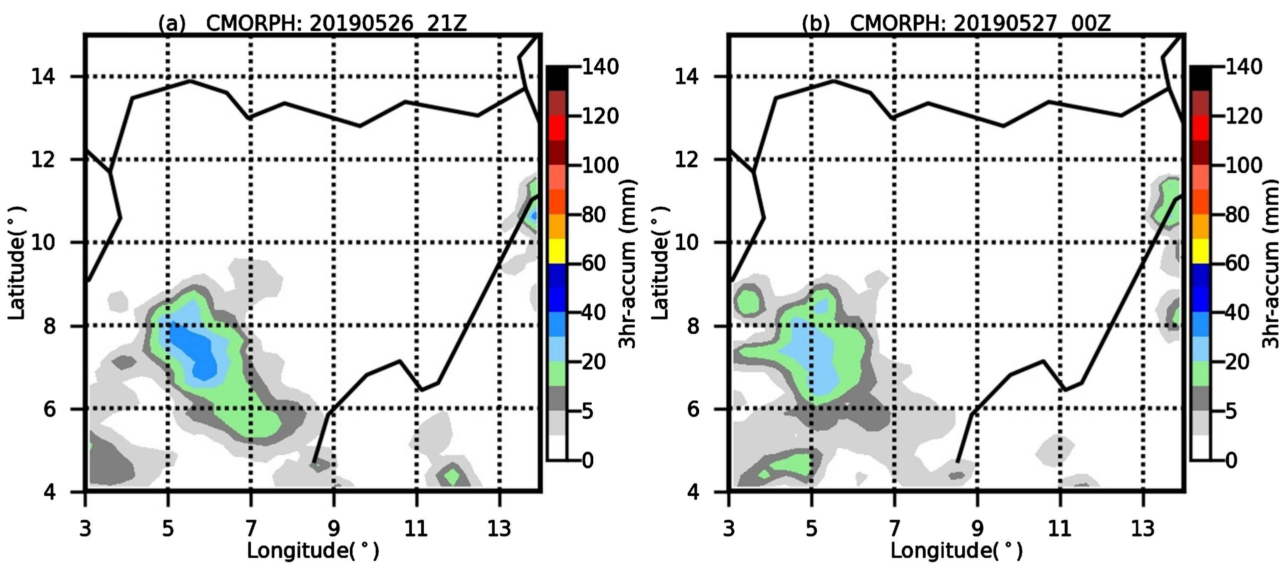

Figure 5. 3-hr accumulated rainfall amount on 26th May 2019 during (a) 19 UTC - 21 UTC, and (b) 22 UTC - 00 UTC.

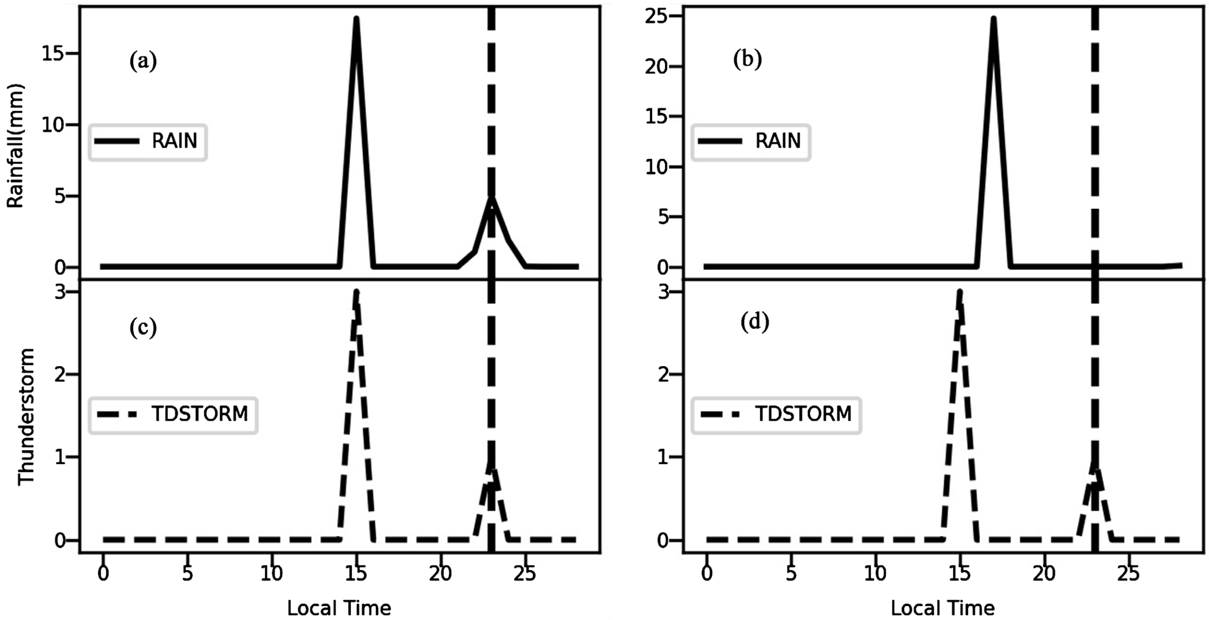

Figure 6. *In-situ* rainfall amount and number of thunderstorms on 26th May 2019 for (a) and (c) and 19th March 2020 for (b) and (d). The black dashed vertical lines are the transition into another day.

performed on the strokes. The rainfall amount had dropped from its peak value of 17.5 mm to about 5 mm at mid-night indicated by the dashed black vertical line. The thunderstorms present had also reduced to only one, meaning that two thunderstorms had decayed during the pass hours. In Figure 6(b) and Figure 6(d), representing the case event of 19th March 2020, the *in-situ* NIMET observed (locally observed) rainfall amount and number of thunderstorms present indicated that the hourly rainfall has it highest value at 17 Local Time (LT), that is 18 UTC in Figure 6(b), whereas there are three thunderstorms present at 15 (LT, synoptic hour) as shown in Figure 6(d). It was observed that two thunderstorms had decayed as at mid-night, the remaining one was not producing rainfall at mid-night. Although there were clusters of thunderstorms, as shown by the WWLLN observation (around ten localized and separated stroke density maxima, which could mean possible isolated and separated thunderstorms) in Figure 9(a), again this number could not be ascertained since clustering algorithm was not performed on the strokes to determine the actual number of separate thunderstorms from WWLLN observation. The local (NIMET) observations were recorded on synoptic hours whereas the WWLLN observations represents the whole day for both case events.

Lightning observations from WWLLN showed distributions, with 0.5˚ × 0.5˚ resolution, of stroke density (strokes·km^{-2}·day^{-1}: since the plot is observation for one day) in locations where lightning were observed. Figure 7(a) showed stroke density of about 400 stroke·km^{-2}·day^{-1} around or in close proximity to Owu-Kuta as indicated by the arrow. This also justified the presence of thunderstorm around or in close proximity to the impacted area (Owu-Kuta). There were observed higher stroke densities over the Land-Ocean boundaries (Figure 7(a)). The diurnal

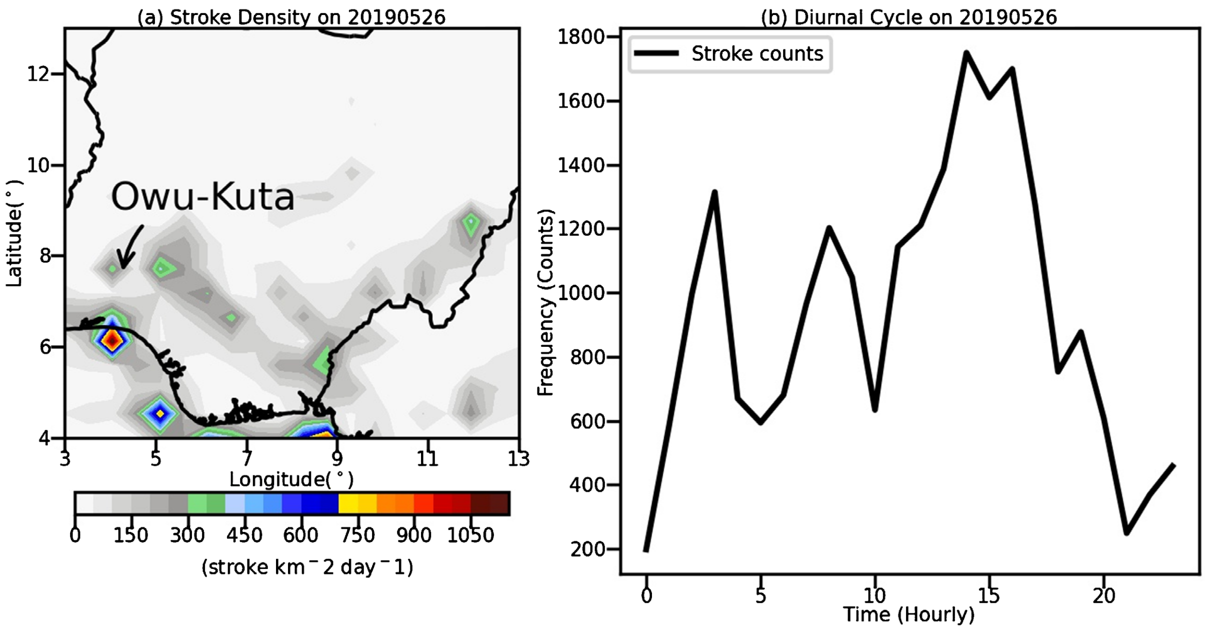

Figure 7. Showing (a) lightning/stroke density distributed over Nigeria on 26th May 2019 and (b) diurnal cycle of stroke counts over Nigeria [Lat.: 4˚ - 13˚; Lon.: 3˚ - 13˚] on 26th May 2019.

cycle, in **Figure 7(b)**, showed peak activities and hence highest stroke counts at around 14 - 16 UTC (daytime), whereas the minimum lightning activities were observed at night and morning hours. This is consistent with [23], based on TRMM and WWLLN data, that maximum diurnal lightning activities over Benin peaks around 18:00 UTC and minimum frequencies are observed during morning hours (10:00 - 11:00 UTC). Balogun *et al.* [38] justified more stratiform precipitation (precipitation with little or no flashes) during night and morning hours and more convective storms (thunderstorms and deep convective systems) during afternoon and evening hours over West African sub-regions. The highest observed occurrence of lightning was about 1750 stroke counts during the 14:00 UTC. About 1600 and 1700 stroke counts were observed during the 15:00 and 16:00 UTCs, which represented the highest during that particular day.

Results for the case event on 19th March 2020, which occurred in Akure the Ondo State capital, indicated the presence of cloud (Tb < 200 K and substantial rainfall amount observed) over Akure (Latitude 7.23, Longitude 5.21). Satellite observations, using geostationary weather images, are known to be appropriate for identifying thunderstorms and hence MCSs [39] [40]. The core of the cloud shield, indicated by the brightness temperature in **Figure 8(a)**, is centered over Akure with value as low as 170 K at 18 UTC on 19th March 2020. The system was also producing rainfall, as shown in **Figure 8(b)**, with 3-hr accumulated rainfall amount of 20 mm between 15 - 18 UTC on same day over the impacted location (Akure).

The WWLLN lightning observations showed distributions over Akure, with 0.1˚ × 0.1˚ resolution, of stroke density (strokes km^{-2} day^{-1}: since the plot is observation for one day) in locations where lightning were observed. In **Figure 9(a)**,

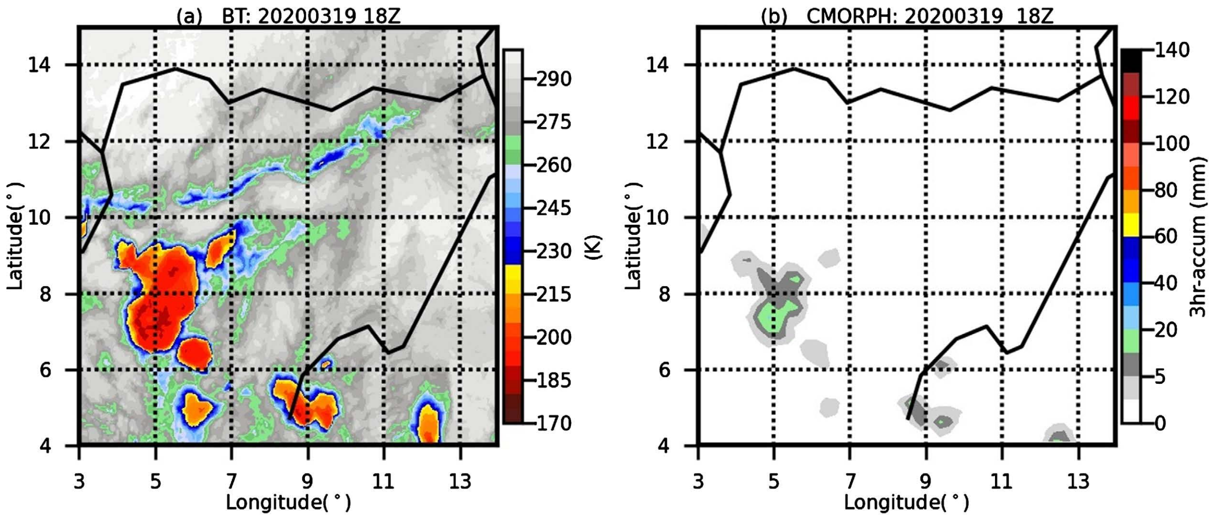

Figure 8. (a) Cloud shield over the impacted community on 19th March 2020 at 18 UTC, and (b) 3-hr accumulated rainfall amount on 19th March 2020 during 16 UTC - 18 UTC.

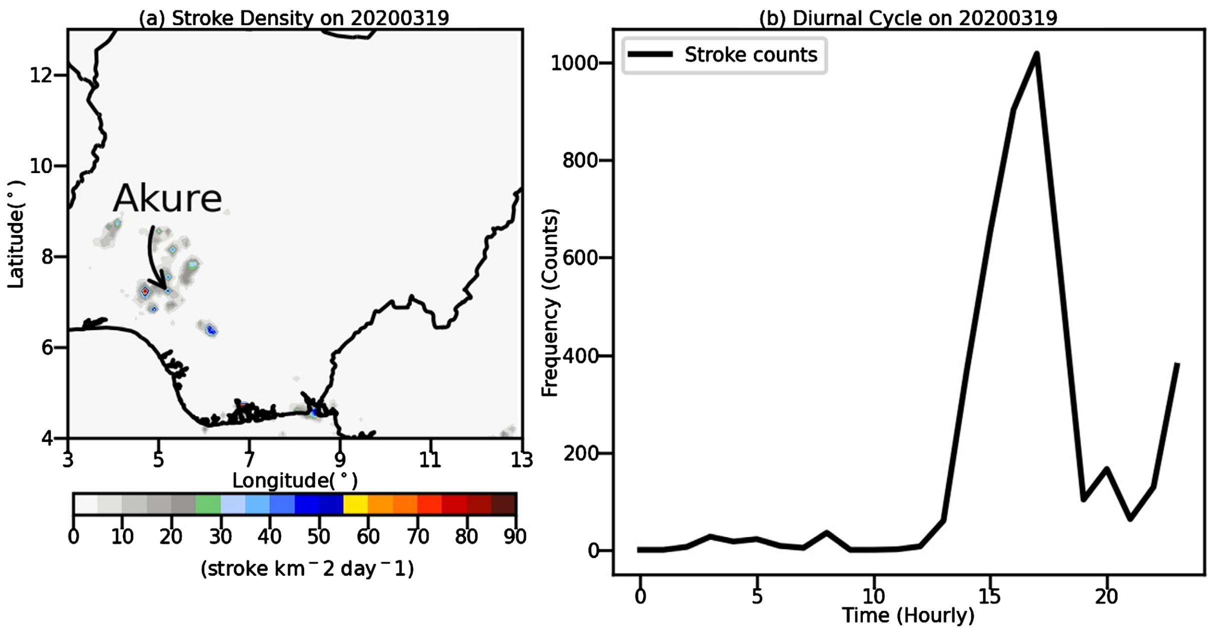

Figure 9. Showing (a) lightning/strokes density distributed over Nigeria on 19th March 2020 and (b) diurnal cycle of stroke counts over Nigeria [Lat.: 4˚ - 13˚; Lon.: 3˚ - 13˚] on 19th March 2020.

the stroke density is above 50 strokes·km^{-2}·day^{-1} in the vicinity of the impacted area (Akure) indicated by the arrow. The stroke density resolution used for Akure (0.1˚ × 0.1˚) is different from the case event over Owu-Kuta (0.5˚ × 0.5˚). Another location, left of Akure city, within or outskirt of Akure indicated stronger stroke density, which could also have strong influence over major Akure communities. These are scattered thunderstorms in and around the impacted area (Akure). During this particular day, there were no observed stroke densities over the Land-Ocean boundaries (**Figure 9(a)**), unlike in May 26th 2019. In **Figure 9(b)**, the diurnal cycle showed peak activities and hence highest stroke counts at around 17 UTC (evening time), whereas the minimum lightning activities were observed at night and morning hours, as was observed for the Owu-Kuta case event. This result is also consistent with [23] and [38] as discussed for the Owu-Kuta case event. The highest observed occurrence of lightning was about 1000 stroke counts during the 17:00 UTC, whereas, the morning hours recorded little or no stroke counts up until about 13:00 UTC, after which the strokes begin to increase.

3.3. Observed Local Impacts

Local communities experience disasters most acutely [41]. The local impacts of the cold pool wind gust are presented in **Figure 10** for the case event of 26th May 2019, which occurred in Owu-Kuta Osun State Nigeria. The wind gust broke down mounted structures, which fell on parked vehicles (**Figure 10**: left wing), and it also opened the roof of the Oba's palace in Owu-Kuta (**Figure 10**: right wing). The Hope newspaper [42] gathered that about sixteen buildings, besides the palace of Oba Adekunle Oyelude Makama, the Olowu (king/paramount ruler) of Owu Kuta, had their roofs fully blown off by the windstorm. The windstorm blew off a part of the roof of the Oba's palace and some other properties, such as furniture, where damaged inside the palace. The blown-off roof fell on the traditional ruler's car, which resulted in some damages on the car. These observed and usually high impacts on communities, particularly in this part of the world, are caused by poor (little or zero) mitigation approach or complete absence of disaster risk reduction strategy [43].

Another source, Nigerian Tribune [44] gathered that antecedent of the destructive rainfall occurred in the atmosphere over the impacted community few minutes earlier when an unusually dark cloud, presumably a Nimbostratus cloud, suddenly occupy the sky at about 3:30 pm, which caused anxiety among dwellers. While the residents were hoping for a moderate rain that would suppress the hot temperature on their bodies, what they experienced was a destructive windstorm, violently blowing-off roofs of buildings. Other infrastructure affected was electricity poles, and the windstorm uprooted trees, of which some explained the event as spiritual.

Figure 10. The damage on a parked vehicle on the left side, and blown off roof of the Oba's palace on the right side.

However, the traditional ruler dismissed the argument that the windstorm was caused by spiritual factor or by certain forces. He stated that it was a natural disaster, on the ground that the storm affected two nearby communities like Ikoyi and Iwo. According to him, a public school's roof was blown off in Ikoyi and in Iwo, a well-known place known as Odori was strongly hit by the windstorm. He further said, "Just take a look at this place well and tell me the number of trees standing here. This is an open place which needs trees to shield the buildings from heavy winds as we just experienced. The world has developed beyond attributing every bad occurrence to the gods or anger by the ancestors. If the ancestors have the opportunity of returning to the world, they would not want to do things the way they did it in their first coming. What I am saying is that an incident like this is simply a wake-up call and a reminder that we should endeavor to plant trees. This deforestation is counter-productive despite the fact that it is evidence of development. But when we cut trees in the forest we should always endeavor to plant more".

Gencer [45] wrote that increasing density of human population, deforestation, expansion of slums, blocking of natural derange, soil erosion, among others frequently increased the risk of disasters. Others responsible factors include inadequate governance, inappropriate use of resources, and poor preparedness. According to [46], increasing environmental degradation, risk of geological events and extreme weather as a result of growing population encourage vulnerability and reduced resilience to risk disasters.

The traditional ruler used the opportunity to call on the Nigerian Meteorological Agency (NIMET) to learn from developed nations where natural disasters are forecasted before they occur, and precautionary measures taken to prevent it. "NIMET is saddled with that responsibility to guide us on the behaviour of the weather. We all know that the entire world is experiencing climatic change. That is more reason the agency should always update us so that we prepare before calamity comes", he said.

The second event investigated occurred in Akure City and impacts are presented in **Figure 11**. The windstorm rendered some residents homeless, some injured, and some dead. The Hope Newspaper [47] recounted some of the damages as follows; an eye witness explained that the windstorm carried a container and the owner inside, which resulted in several injuries on the fellow inside the container. Also, the wind lifted a car slightly above the ground from the road, which made the passengers alighted and took to their heels in the heavy downpour. Dwellers in Abusoro/OluFoam, Onigari area of Shagari village, and Igoba communities in Akure had their electricity poles broken and pulled down. A forty year old electrician whose building almost collapsed to the unfortunate incidence, informed The Hope Newspaper in Olufoam community that the wind removed the roof of his building and destroyed the roof of another house in the impacted community, and the storm later pulled down almost all his entire building. An inhabitant in the impacted community narrated that his three children left the house to stay with a neighbor as a result of fear due to the intensity

Figure 11. Damage on different locations of windstorm in Akure metropolis on 19th March 2020.

of the wind, which later wreak havoc on his building. As suggested by [48] and [49], most climate disasters can be mitigated (reduced) by community-based collective response and building resistance in other to cope with the event at the time and location it occurred.

Kayode Jide, a bricklayer with four children, whose house was pulled down to its foundation. In his words; "I was in town on that day but the rain which fell in town was not destructive. I was surprised when I received a call that my house had been pulled down by the wind and my children were inside the house. I thank God because He used my neighbours to rescue the children from the scene. The wind was just too much. I have never seen that kind of wind before in my entire life".

According to [50], the people most affected by windstorms/rainstorms are the poor (low-income earners). For example, a 63-year-old widow recounted her losses while speaking with The Hope Newspaper. In her words; "I trade in garri (cassava flour) at Odokoyi market and I built this 10 bedroom face me I face you apartment after the demise of my husband some five years ago. I was in the house with six other people including my daughter-in-law who had a six-month-old baby with her. It was raining and suddenly, the wind began to operate. We started praying to God for mercy and the next thing we saw was a block that fell right in our midst in the room before the whole ceiling fell on us. Nobody was injured and we all escaped through the window before most parts of the house were pulled down. All our roofs which were removed during the rain spread across the road preventing vehicular movement". The finding by [51] indicated that natural disasters often increase poverty due to human and material losses.

4. Conclusions

Two case-study events have been analysed in this study, at different locations and times (year) but in the same climate region. The two events were associated with cold pools locally and did not result in secondary storm development. The first event occurred in Owu-Kuta, a small community in Osun State Southwest Nigeria and the second event occurred in the Akure metropolis and suburbs in Ondo State also in southwest Nigeria.

Wind gusts, resulting from cold pools, are known to be a seasonal phenomenon, particularly during the early phase of the West African monsoon. All parameters used for the analysis clearly supported the presence of cold pools, cloud shields, thunderstorms, and hence precipitation in the impacted communities. Sudden changes in wind direction and drop/decrease in temperature are particular evidence of identified cold pools for the two case events. Identified cloud shields and thunderstorms which spread over the impacted community, during the period of the events, also supported the *in-situ* results. Results from this work proved the relevance of combining *in-situ* observations (such as temperature, wind speed/direction, surface pressure, number of thunderstorms, and humidity) together with remote sensing observations (such as brightness temperature, CMORPH rainfall, and WWLLN lightning) for investigating locally-based phenomena. The results are also consistent with newspaper reports from the impacted communities based on interviews with affected inhabitants.

Following discussions from literature, as highlighted in previous sections, there is a need for government enlightenment, community awareness, and preparedness, reducing deforestation or increasing forestation, community-based collective response, adaptation practices that change anthropogenic activities, involvement of relevant institutions and agencies, among others, to mitigate climate risk hazards. Impacted communities should also not attribute natural hazards as being spiritual. They have roles to play in other to avert or mitigate the occurrence of such events. Decision support systems and forecast systems, as suggested by a monarch, should be operational to help communities take precautionary measures to prevent or reduce severe damage and/or losses as a result of natural disasters.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Simpson, J.E. (1969) A Comparison between Laboratory and Atmospheric Density

Currents. *Quarterly Journal of the Royal Meteorological Society*, **95**, 758-765. https://doi.org/10.1002/qj.49709540609

[2] Charba, J. (1974) Application of Gravity Current Model to Analysis of Squall-Line Gust Front. *Monthly Weather Review*, **102**, 140-156. https://doi.org/10.1175/1520-0493(1974)102<0140:AOGCMT>2.0.CO;2

[3] Goff, R.C. (1976) Vertical Structure of Thunderstorm Outflows. *Monthly Weather Review*, **104**, 1429-1440. https://doi.org/10.1175/1520-0493(1976)104<1429:VSOTO>2.0.CO;2

[4] Warner, C., Simpson, J., Helvoirt, G., Martin, D.W., Suchman, D. and Austin, G.L. (1980) Deep Convection on Day 261 of GATE. *Monthly Weather Review*, **108**, 169-194. https://doi.org/10.1175/1520-0493(1980)108<0169:DCODOG>2.0.CO;2

[5] Droegemeier, K.K. and Wilhelmson, R.B. (1985) Three-Dimensional Numerical Modeling of Convection Produced by Interacting Thunderstorm Outflows. Part I: Control Simulation and Low-Level Moisture Variations. *Journal of the Atmospheric Sciences*, **42**, 2381-2403. https://doi.org/10.1175/1520-0469(1985)042<2381:TDNMOC>2.0.CO;2

[6] Tompkins, A.M. (2001) Organization of Tropical Convection in Low Vertical Wind Shears: The Role of Cold Pools. *Journal of the Atmospheric Sciences*, **58**, 1650-1672. https://doi.org/10.1175/1520-0469(2001)058<1650:OOTCIL>2.0.CO;2

[7] Langhans, W. and Romps, D.M. (2015) The Origin of Water Vapor Rings in Tropical Oceanic Cold Pools. *Geophysical Research Letters*, **42**, 7825-7834. https://doi.org/10.1002/2015GL065623

[8] Marion, G.R. and Trapp, R.J. (2019) The Dynamical Coupling of Convective Updrafts, Downdrafts, and Cold Pools in Simulated Supercell Thunderstorms. *Journal of Geophysical Research*: *Atmospheres*, **124**, 664-683. https://doi.org/10.1029/2018JD029055

[9] Weisman, M.L. and Klemp, J.B. (1982) Characteristics of Isolated Convective Storms. In: Ray, P., Ed., *Mesoscale Meteorology and Forecasting*, American Meteorological Society, Boston, 331-358. https://doi.org/10.1007/978-1-935704-20-1_15

[10] Weisman, M.L., Klemp, J.B. and Rotunno, R. (1988) Structure and Evolution of Numerically Simulated Squall Lines. *Journal of the Atmospheric Sciences*, **45**, 1990-2013. https://doi.org/10.1175/1520-0469(1988)045<1990:SAEONS>2.0.CO;2

[11] Adelekan, I.O. (2012) Vulnerability to Wind Hazards in the Traditional City of Ibadan, Nigeria. *Environment and Urbanization*, **24**, 597-617. https://doi.org/10.1177/0956247812454247

[12] Elemo, E.O., Ogobor, E.A., Alagbe, G.A., Ayantunji, B.G., Mangete, O.E., Tomori, O.S., Doherty, K.B. and Onuh, B.O. (2021) Statistical Analysis of the Average Wind Speeds and Maximum Wind Speed (Gust Winds) at a Location in Abuja, Nigeria. Open Access Library Journal, **8**, e7935. https://doi.org/10.4236/oalib.1107935

[13] Ayoade, J.O. (2004) Introduction to Climatology for the Tropics. 2nd Edition, Spectrum Books Limited, Ibadan.

[14] McGuire, T. (2004) Weather Hazards and the Changing Atmosphere. *Earth Science*: *The Physical Setting*. Amsco School Publications, Inc., New York.

[15] Mogil, M.H. (2007) Extreme Weather. Black Dog and Leventhal Publishers, New York.

[16] NWSFO (2009) National Weather Service Forecast Office Morristown Tennessee Definitions of Flood and Flash Flood. National Weather Service Southern Region Headquarters.

[17] Munich, R. (2015) Review of Natural Catastrophes in 2014: Relatively Low Losses

from Weather Extremes and Earthquakes, Globally and in U.S.
https://www.munichre.com/us-non-life/en/company/media-relations/press-releases/2015/2015-01-07-natcatstats2014.html

[18] Odjugo, P.A.O. (2010) Regional Evidence of Climate Change in Nigeria. *Journal of Geography and Regional Planning*, **3**, 142-150.
http://www.academicjournals.org/JGRP

[19] Birkmann, J. (2011) First- and Second-Order Adaptation to Natural Hazards and Extreme Events in the Context of Climate Change. *Natural Hazards*, **58**, 811-840.
https://doi.org/10.1007/s11069-011-9806-8

[20] Ojo, O. (2007) The Climates of West Africa. Heinemann Educational Books Ltd., London.

[21] Faleyimu O.I., Agbeja, B.O. and Akinyemi, O. (2013) State of Forest Regeneration in Southwest Nigeria. *African Journal of Agricultural Research*, **8**, 3381-3383.
https://doi.org/10.5897/AJAR09.035

[22] Akinloye, L., Joseph, A. and Makinde, A. (2017) Analysis of Climate of Southwestern Nigeria for Building Design. *International Journal of Constructive Research in Civil Engineering*, **3**, 38-45.

[23] Onah, M.W., Adéchinan, J.A., Guédjé, F.K., Kougbéagbédé, H. and Houngninou, E.B. (2020) Climatology of the Lightning in the Northern of Benin Republic. *Journal of Materials and Environmental Science*, **11**, 1987-2006.

[24] Holzworth, R.H., McCarthy, M.P., Brundell, J.B., Jacobson, A.R. and Rodger, C.J. (2019) Global Distribution of Superbolts. *Journal of Geophysical Research*: *Atmospheres*, **124**, 9996-10,005. https://doi.org/10.1029/2019JD030975

[25] Bovalo, C., Barthe, C. and Bègue, N. (2012) A Lightning Climatology of the South-West Indian Ocean. *Natural Hazards and Earth System Sciences*, *European Geosciences Union*, **12**, 2659-2670. https://doi.org/10.5194/nhess-12-2659-2012

[26] Rudlosky, S.D. and Shea, D.T. (2013) Evaluating WWLLN Performance Relative to TRMM/LIS: Evaluating WWLLN Relative to TRMM/LIS. *Geophysical Research Letters*, **40**, 2344-2348. https://doi.org/10.1002/grl.50428

[27] Dowden, R.L., Brundell, J.B. and Rodger, C.J. (2002) VLF Lightning Location by Time of Group Arrival (TOGA) at Multiple Sites. *Journal of Atmospheric and Solar-Terrestrial Physics*, **64**, 817-830. https://doi.org/10.1016/S1364-6826(02)00085-8

[28] Rodger, C.J., Brundell, J.B. and Dowden, R.L. (2005) Location Accuracy of Long Distance VLF Lightning Location Network: Post Algorithm Upgrade. *Annals of Geophysics*, **23**, 277-290. https://doi.org/10.5194/angeo-23-277-2005

[29] Virts, K.S., Wallace, J.M., Hutchins, M.L. and Holzworth, R.H. (2013) A New Ground-Based, Hourly Global Lightning Climatology. *Bulletin of the American Meteorological Society* (*AMS*), **94**, 1381-1391.
https://doi.org/10.1175/BAMS-D-12-00082.1

[30] Rodger, C.J., Brundell, J.B., Holzworth, R.H. and Lay, E.H. (2008) Growing Detection Efficiency of the World Wide Lightning Location Network. *Coupling of Thunderstorms and Lightning Discharges to Near-Earth Space*: *Proceedings of the Workshop*, Corte, 23-27 June 2008, 15-20.

[31] Provod, M., Marsham, J.H., Parker, D.J. and Birch, C.E. (2016) A Characterization of Cold Pools in the West African Sahel. *Monthly Weather Review*, **144**, 1923-1934.
https://doi.org/10.1175/MWR-D-15-0023.1

[32] Engerer, N.A., Stensrud, D.J. and Coniglio, M.C. (2008) Surface Characteristics of Observed Cold Pools. *Monthly Weather Review*, **136**, 4839-4849.

https://doi.org/10.1175/2008MWR2528.1

[33] Mathon, V. and Laurent, H. (2001) Life Cycle of Sahelianmesoscale Convective Cloud Systems. *Quarterly Journal of the Royal Meteorological Society*, **127**, 377-406. https://doi.org/10.1002/qj.49712757208

[34] Laing, A.G., Carbone, R.E. and Levizzani, V. (2011) Cycles and Propagation of Deep Convection over Equatorial Africa. *Monthly Weather Review*, **139**, 2832-2853. https://doi.org/10.1175/2011MWR3500.1

[35] Vemado, F. and Pereira Filho, A. (2021) Convective Rainfall in Lake Victoria Watershed and Adjacent Equatorial Africa. *Atmospheric and Climate Sciences*, **11**, 373-397. https://doi.org/10.4236/acs.2021.113022

[36] Laing, A.G. and Fritsch, J.M. (1993) Mesoscale Convective Complexes in Africa. *Monthly Weather Review*, **121**, 2254-2263. https://doi.org/10.1175/1520-0493(1993)121<2254:MCCIA>2.0.CO;2

[37] Hutchins, M.L., Holzworth, R.H. and Brundell, J.B. (2014) Diurnal Variation of the Global Electric Circuit from Clustered Thunderstorms. *Journal of Geophysical Research: Space Physics*, **119**, 620-629. https://doi.org/10.1002/2013JA019593

[38] Balogun R.A., Adefisan E.A., Adeyewa Z.D., Okogbue E.C. and Akinbobola A. (2022) Diurnal Cycle of Rainfall and Convective Properties over West and Central Africa. *Atmospheric and Climate Sciences*, **12**, 74-85. https://doi.org/10.4236/acs.2022.121006

[39] Laing, A.G., Carbone, R., Levizzani, V. and Tuttle, J. (2008) The Propagation and Diurnal Cycles of Deep Convection in Northern Tropical Africa. *Quarterly Journal of the Royal Meteorological Society*, **134**, 93-109. https://doi.org/10.1002/qj.194

[40] Goyens, C., Lauwaet, D., Schröder, M., Demuzere, M. and Van Lipzig, N.P. (2011) Tracking Mesoscale Convective Systems in the Sahel: Relation between Cloud Parameters and Precipitation. *International Journal of Climatology*, **32**, 1921-1934. https://doi.org/10.1002/joc.2407

[41] Cutter, S., Osman-Elasha, B., Campbell, J., Cheong, S.M., McCormick, S., Pulwarty, R., Supratid, S. and Ziervogel, G. (2012) Managing the Risks from Climate Extremes at the Local Level. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. and Midgley, P.M., Eds., *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, New York, 291-338. https://doi.org/10.1017/CBO9781139177245.008

[42] Rainstorm Wreaks Havoc in Osun. https://www.thehopenewspaper.com/rainstorm-wreaks-havoc-in-osun

[43] Mohammed, M. and Kawu, A. (2014) Disaster Vulnerability and Resilience of Urban Residents: A Case of Rainstorm Disaster Risk Management in Bida, Nigeria. *Journal of Environment and Earth Science*, **4**, 52-62.

[44] Owu-Kuta: Downpour Brings Ruin to Osun Community. https://tribuneonlineng.com/owu-kuta-downpour-brings-ruin-to-osun-community

[45] Gencer, E. (2013) The Interplay between Urban Development, Vulnerability, and Risk Management: A Case Study of the Istanbul Metropolitan Area. Springer, Berlin. https://doi.org/10.1007/978-3-642-29470-9

[46] Lankao, P.R. and Qin, H. (2011) Conceptualizing Urban Vulnerability to Global Climate and Environmental Change. *Current Opinion in Environmental Sustainability*, **3**, 142-149. https://doi.org/10.1016/j.cosust.2010.12.016

[47] Rain Wreck Havoc in Akure Communities. https://www.thehopenewspaper.com/rain-wreck-havoc-in-akure-communities

[48] Pearce, G. and Ayres, S. (2012) Regional & Federal Studies Back to the Local? Recalibrating the Regional Tier of Governance in England. *Regional & Federal Studies*, **22**, 1-24. https://doi.org/10.1080/13597566.2012.652418

[49] Kovats, S. and Akhtar, R. (2013) Climate, Climate Change and Human Health in Asian Cities. *Environment and Urbanization*, **20**, 165-175.

[50] Akintunde, T.B. and Sanmi, A. (2019) Analysis of Rainstorm Disasters and Management in Ado Ekiti, Nigeria. *International Journal of Research and Development*, **4**, 89-95.

[51] Sanmi, A. and Akintunde, T.B. (2004) Poverty Implications on Natural Disasters Occurrence in Nigeria. *The International Journal of Engineering and Science*, **3**, 8-14. https://www.theijes.com