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FIRST REPORT OF FISHKILL INCIDENCE IN BONNY-ANDONI COASTAL AREA, NIGERIA: INFERENCES OF PROBABLE CAUSES FROM REMOTELY SENSED DATA

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ABSTRACT

A fish kill is characterised by the mortalities of a large number of fish in a given area within a short period of time. This is an indicator that water quality and ecosystem health in general have deteriorated. Remote sensing data from the MODIS instrument on the Aqua and Merra-2 satellites were accessed from 18 to 22 March 2020, a period spanning before and after a fishkill event was reported. Analysis of the remote sensing data shows that the fish kill was preceded by strong winds, i.e. major and sustained wind events. The maps of sea surface temperatures prior to the fish kill show that high-temperature water masses flowed from the equator toward the Bonny-Andoni coast. The dates of occurrence of the high-temperature surface water masses and high wind events around the Bonny-Andoni coastal area were consistent with the location and timing of the fish kill, as indicated by community reports. We hypothesize that the low-oxygen, high-temperature surface water masses passing from the equator on the windward side of the coast may have encountered migrating croakers and trapped an entire school of this benthopelagic fish species, causing acute respiratory distress. The results and hypothesis confirm local reports of gasping fish about 2 nautical miles off the Bonny-Andoni coast. This study confirms the relationship between wind patterns, temperature, and fish kills, providing the first empirical account of probable causes. Because fish kills occur episodically and often leave no trace, this report and future analyses of remote sensing data may be the best way to elucidate this event.

Keywords:
Wind speed
Coriolis effect
Respiratory distress
High-temperature surface water mass
Croaker

How to Cite

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INTRODUCTION

Public concern about ecosystem health and fisheries in the Bonny-Andoni coastal area was heightened by the recent fish kill of hundreds to thousands of croaker fish (personal communication) between 19 March and 22 March 2020. Cassava croaker *Pseudotolithus sengalensis* were found dead along the shoreline and in surface waters of the area in such large numbers that they may have accounted for several months' catch. According to community reports, the sight was disturbing to local residents and attracted considerable media and stakeholder attention.

The term fish kill, also known as fish mortality, describes localized die-offs of fish populations and can also be extended to include general die-offs of aquatic life (USEPA, 2000; Hoyer et al., 2009). Although human alteration and pollution of aquatic and terrestrial systems are increasing the frequency and magnitude of fish kills worldwide, fish kills resulting from natural phenomena can lead to greater magnitudes (La and Cooke, 2011). The most common cause of fish kills due to natural phenomena is reduced oxygen levels in the water, which in turn can be due to factors such as drought, algal blooms, overpopulation, or a sudden change in water temperature (Meyer and Barclay, 1990). Infectious diseases and parasites are usually considered secondary factors in the occurrence of fish kills (Al-Ghabshi, 2015).

Many fish species have a relatively low tolerance to fluctuations in environmental conditions (Wannamaker and Rice, 2000), and their deaths are often strong indicators of problems in their environment that may affect other animals and plants. In the case of pollution, fish kills often affect many species, and may also affect amphibians and shellfish.

Fish kills are usually of limited duration, they occur over a short period of time, possibly hours to a few days, and are usually highly geographically restricted (Marti-Cardona et al., 2008). The occurrence of fish kills has been attributed to both natural phenomena, i.e. physical factors, particularly wind-driven upwelling events, and anthropogenic, i.e. chemical or biological factors (Marti-Cardona et al., 2008). Natural phenomena are often described as wind-induced disturbance of the density stratification (temperature) of water bodies, leading to the upwelling of denser water to the surface (Stevens and Imberger, 1996; Farrow and Stevens, 2003). While upwelling events are associated with nutrient mobilization and increased phytoplankton growth that supports local fisheries (MacIntyre and Romero, 2000; MacIntyre and Jellison, 2001), they can also lead to an anoxic situation in which fish are trapped and suffocate en masse if the upwelling water is significantly oxygen-deficient or contains high concentrations of known biotoxins (Roman et al., 2019).

Despite the worldwide occurrence of fish kills, regional or national summaries of the frequency and magnitude of fish kills and their possible causes exist for only a few countries (La and Cooke, 2011). Many studies point to hypoxia as a major cause of fish kills in coastal waters (Thronson and Quigg, 2008; Quigg et al., 2009). Although the combination of oxygen-depleted bottom waters and unique wind conditions is a widely accepted theory for the occurrence of fish kills (Paerl et al., 1999), fish kills due to natural events have never been documented on the coast of Nigeria. Even more remarkable is the fact that while fish kills of multiple species have been documented in dozens and hundreds of cases attributed to oil spills in the Niger Delta (Osuagwu and Olaifa, 2018), fish kills of individual species have not been documented anywhere in the coastal waters of Nigeria.

Research interests in the causes and events surrounding fish kills are imperative, as fish kills are often the first visible signs of environmental stress. Given the occurrence of individual fish kills in the Bonny-Andoni region and the documented expert opinions on the causes of fish kills, we hypothesize natural causes. To test our hypothesis of possible natural causes, we examined remote sensing data (local wind speed, sea surface temperature) within the same time window associated with fish kills in the Bonny-Andoni coastal area. We hypothesize that natural causes are plausible when there is clear evidence of fish kills on the windward side of the sea following periods of strong, sustained winds and altered surface water temperature. The Moderate Resolution Imaging Spectroradiometer (MODIS) satellites acquire 36 spectral bands daily with high temporal resolution, and can thus reveal spatial variations in water quality and provide verification of episodic environmental events even when physical and chemical evidence is no longer detectable.

MATERIALS AND METHODS

Nigeria has a coastline of approximately 853 km, facing the Atlantic Ocean. This coastline lies between latitude 4° 10′ to 6° 20′ N and longitude 2° 45′ to 8° 35′ E (Fig. 1). The Nigerian coast consists of four distinct geomorphology units, namely the Barrier-Lagoon Complex, the Mud Coast, the Arcuate Niger Delta and the Strand Coast (Nwilo and Badejo, 2006). The Bonny-Andoni coastal area is one of the intersection inlets within the Arcuate coastal stretch of the Niger Delta Area (Sexton and Murday, 1994) (Fig 1, 2).

To ascertain the causal relationship between the single species fish die-off and wind patterns in the Bonny Andoni area, monthly and hourly records of wind speed within the area were accessed and downloaded from the NASA database https://giovanni.gsfc.nasa.gov/giovanni/. A detailed time analysis of wind patterns around the dates of the fish die-off was captured using Merris MODIS data. To highlight outlier or abnormal incidence of wind speed within the area of die-off incidence, a histogram of hourly wind speed over a year interval (18 March 2019 – 20 March 2020) was generated from the NASA database.

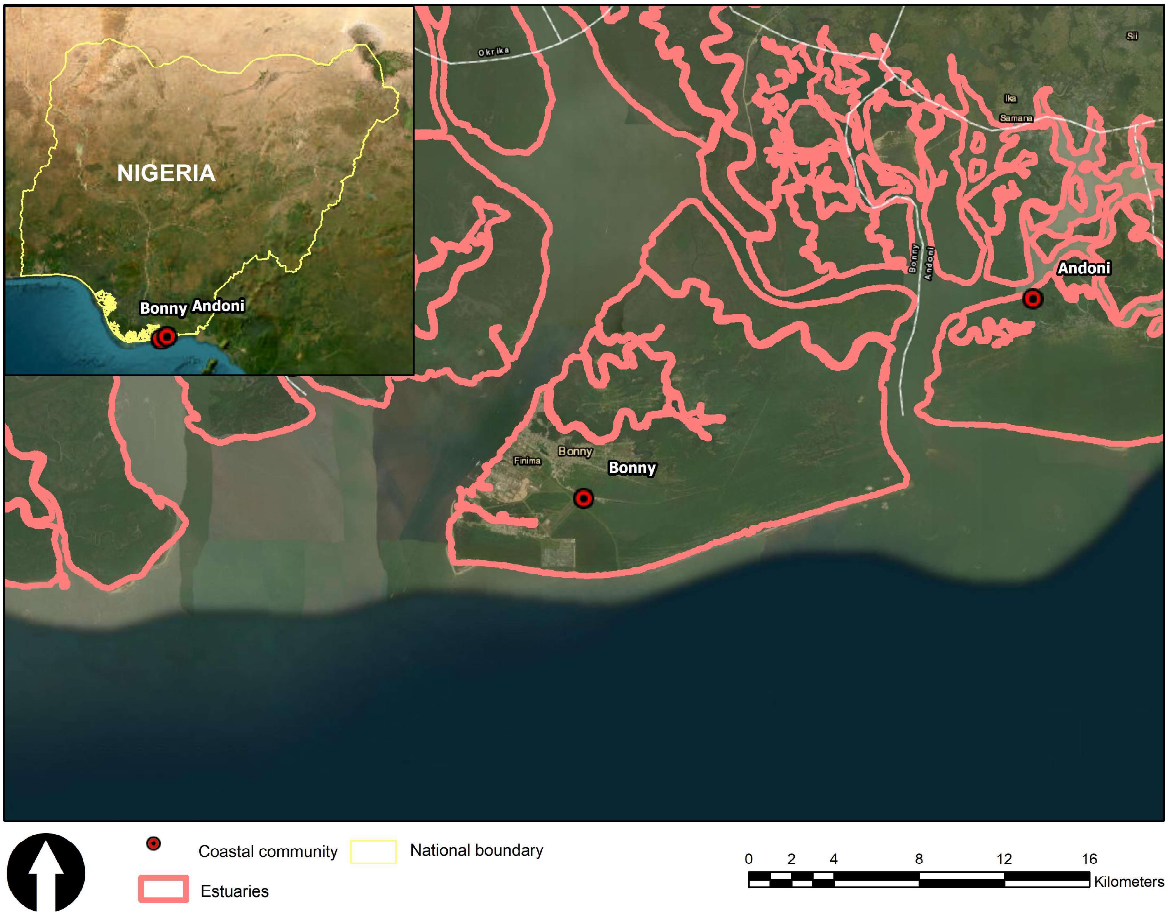

Fig 1. Map of the Bonny-Andoni coastal area

Where an outlier (s) value is identified in the wind speed frequency histogram, a time-series frequency line plot was generated to highlight the month and the year of the outlier wind speed event. The Hovmoller diagram of the longitude-averaged maximum hourly surface wind speed 0.5 x 0.625 deg. [MERRA-2 model M2T1NXFLX v5.12.4] m s^{-1} was used. Where the spike or outlier wind speed event coincides with the month of the fish kill, smaller time intervals, e.g. 5-day intervals, were plotted to narrow down the day of the event.

Spatial thermal patterns are difficult to capture by using on-site measurements because of their discrete character (Handcock et al., 2012). Observation data of instantaneous spatially distributed temperatures were taken at a regional scale over the Bonny-Andoni coastal area using TIR radiance emitted from Earth's surface, measured by MODIS (Salomonson et al., 2006). To highlight temperature gradients across days preceding and succeeding the die-off incidence within the Bonny-Andoni area, Time Series, Area-Averaged Sea Surface Temperature at 11 microns (night) 8-daily 4 km [MODIS-Aqua MODISA_L3m_NSST_8d_4km vR2019.0] C was generated for the period of 2017-09-29 12:10:01Z - 2020-03-28 15:00:00Z. Aqua MODIS-derived sea surface temperature (SST) L2 GeoTIFF data were processed/re-projected in ocean colour remote sensing processing software SeaDAS® 7.5.1 and visualized in ArcMap® 10.4 to highlight incidences of high-temperature pixels off the Bonny-Andoni coast before, during and after the fish die-off occurrence.

Fig 2. Fish die-off strewn along a portion of the Bonny coast

RESULTS AND DISCUSSION

Histogram analysis of wind speed within the fish kill area revealed a mean speed of 4.33±1.56 ms^{-1} since March 2019. Outlier values of approximately 12 ms^{-1} were determined from the histogram plot (Fig. 3a). Time-frequency plot from March 2019-March 2020 showed outliers in wind events around March 2020; a coincidence of outliers with the month in which the fish kill occurred (Fig. 3b).

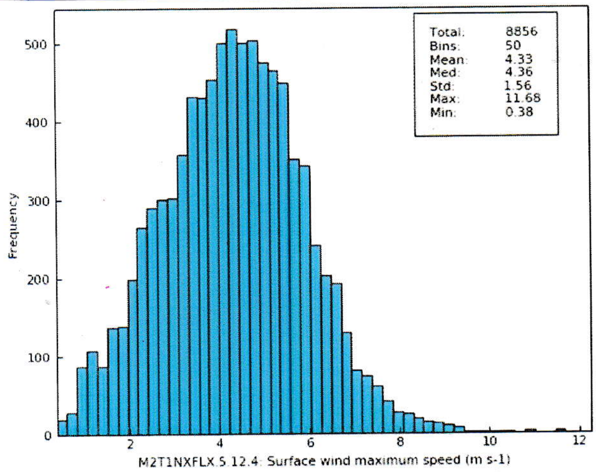

Fig 3a. Histogram of the maximum hourly surface wind speed 0.5 x 0.625 deg. [MERRA-2 Model M2T1NXFLX v5.12.4] m s^{-1} over 2019-03-18 00Z - 2020-03-20 23Z, Region 8.5982E, 4.2737N, 8.9525E, 4.7269N

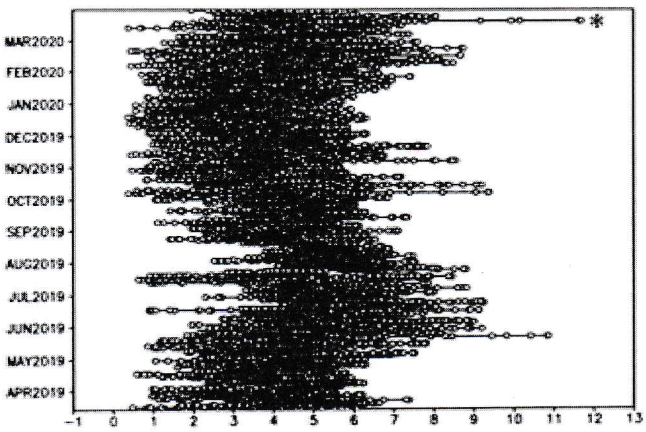

Fig 3b. The Hovmoller diagram of the longitude-averaged maximum hourly surface wind speed 0.5 x 0.625 deg. [MERRA-2 model M2T1NXFLX v5.12.4] m s^{-1} over 2019-03-14 00Z - 2020-03-30 23Z, Region 8.5982E, 4.2737N, 8.9525E, 4.7269N (asterix= outlier value)

Plots of smaller time intervals, e.g. 14 days, showed outliers around 20th March, coinciding with the week of the fish kill (Fig. 3c). Accumulated 24-hour wind strength was calculated for the days preceding the fish kill, which was reported by the community to have occurred during the last week of March 2020. Accumulated wind results on 20th March 2020 showed outliers or spikes in surface wind speed with a strength of 11.9 ms^{-1} (Fig. 3d), which is approximately three times the average speed since 18 March 2019. Previous reports have described that surface winds on the Nigerian coast are characterised by southwesterly winds with speeds of 2-5 ms^{-1}, which can double to about 10 ms^{-1} during the rainy and thunderstorm season (Dublin-Green et al., 1999). Therefore, this outlier effect in the dry to wet season transition window is an anomaly. The fact that fish kills were reported on days within this peak in surface wind speed suggests oceanographic events. In studies of fish kills outside the Atlantic, cases of fish kills following accumulated wind speeds have been noted (Marti-Cardona et al., 2008).

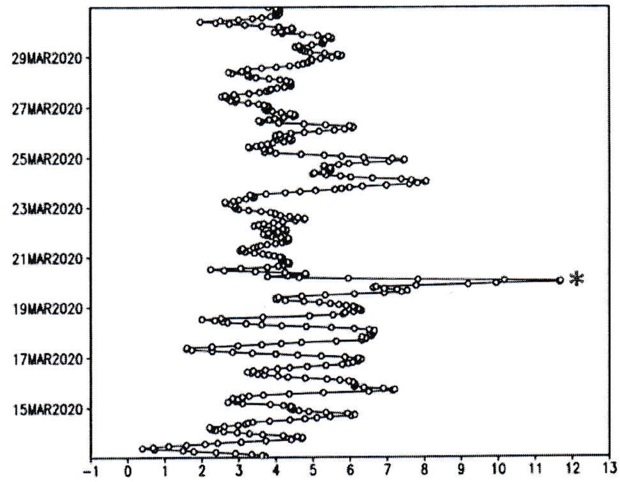

Fig 3c. The Hovmoller diagram of the longitude-averaged maximum hourly surface wind speed 0.5 x 0.625 deg. [MERRA-2 model M2T1NXFLX v5.12.4] m s^{-1} over 2020-03-13 00Z - 2020-03-30 23Z, Region 8.5982E, 4.2737N, 8.9525E, 4.7269N (asterix= outlier value)

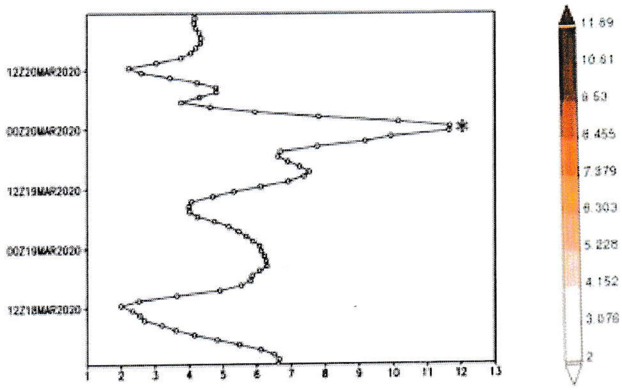

Fig 3d. The Hovmoller diagram of the longitude-averaged maximum hourly surface wind speed 0.5 x 0.625 deg. [MERRA-2 model M2T1NXFLX v5.12.4] m s^{-1} over 2020-03-18 00Z - 2020-03-20 23Z, Region 8.5982E, 4.2737N, 8.9525E, 4.7269N (asterix= outlier value)

Time series, area-averaged sea surface temperature at 11 microns (night) 8-day 4 km [MODIS-Aqua MODISA_L3m_NSST_8d_4km vR2019.0] line plot from 12:10 pm on 29 September 2017 to 3:00 pm on 28 March 2020 showed a strong temperature gradient of 2.5 °C in March 2020, just before April 2020 (Fig. 4a). NAASA Geotiff imagery processed with SeaDAS® and visualised in ArcGIS showed two separate masses of brighter pixels on 19 March. The orientation of the water temperature masses at the surface indicates the movement of water masses at an angle of about 35° from the equator toward the coastal area of Bonny-Andoni (Fig. 4b).

The nearest high-temperature mass is about 32 nautical miles offshore, while the second major temperature mass is about 200 nautical miles away. Prior to this date, i.e. 18 March 2020, low surface water temperatures prevailed several nautical miles offshore of Bonny-Andoni. On 21 March, the initial masses were no longer visible and reached the coast. Interestingly, another high-temperature mass appeared about 300 nautical miles offshore, moving at a slightly higher angle, about 43°, from the equator. On 21 March 2020, the higher-temperature surface water mass reached nearshore waters east of the Andoni coast. In the Northern Hemisphere, surface water flows at an angle of 20-45° to the right of the wind, a deflection of water motion attributed to the Coriolis effect due to Earth's rotation (Karleskint et al., 2012). The formation of the surface water masses is plausible due to the fact that the wind transfers heat energy from the air to the water through friction, causing a mass of water to flow under the moving air and form a surface current that accumulates downwind (Beer, 1996; Karleskint et al., 2012).

Like the outlier pattern in winds, the occurrence of these two distinct groups of higher surface temperature masses within a two-day interval and days before the fish kill suggests oceanographic factors. Typical coastal areas that are in a calm and stratified state are characterized by nearly homogeneous temperatures over the entire area, whereas in the case of a wind-driven disturbance, a horizontal temperature gradient should be evident across the surface water around the coastal area in question (Watts et al., 2001). In this study, sea surface temperature observations between 18 and 21 March 2020 showed a separate group of brighter pixels indicating the presence of high-temperature surface water masses. The orientation of the high-temperature masses relative to the equator suggests that they are moving toward the Bonny-Andoni coast under the likely influence of accumulated wind strength. A large accumulated wind strength is often indicated by winds that blow strongly and persistently within narrow angles of the wind rose (Wedepohl et al., 2000; Odekunle and Eludoyin, 2008).

The emergence of high-temperature surface water masses moving away from the equator at an angle of < 45° suggests ocean currents originating from and around the equator. The equatorial ocean is known to remotely influence the African coast through the propagation of equatorial Kelvin waves that generate waves trapped on the coast (Servain et al., 1982; Picaut, 1983). Elsewhere, Kelvin waves have been hypothesised to disturb the thermal structure at the equator and in the Gulf of Guinea, resulting in thermocline spreading and coastal upwelling from west to east (Moore et al., 1978). Although this theory has been given credence, additional measurements and modelling of the thermal structure have been recommended before confirming it (Picaut, 1983).

Although fish kills are a widespread phenomenon and are generally defined as localized mass mortalities of fish that may occur in seas and estuaries (Meyer and Barclay, 1990), the occurrence of a single species kill in the Bonny-Andoni coastal area of the Niger Delta is the first ever on the Nigerian coast.

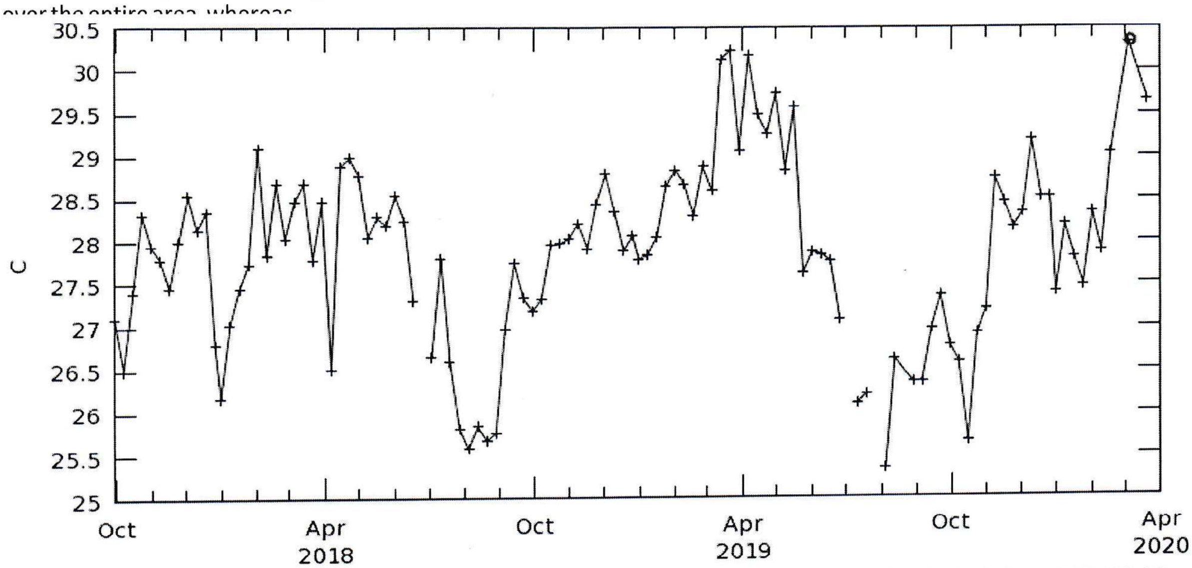

Fig 4a. Time Series, Area-Averaged Sea Surface Temperature at 11 microns (Night) 8-daily 4 km [MODIS-Aqua MODISA_L3m_NSST_8d_4km vR2019.0] C over 2017-09-29 12:10:01Z - 2020-03-28 15:00:00Z, Shape Nigeria, Region 8.5982E, 4.2737N, 8.9525E, 4.7269N. The red circle indicates the time window in which the fish kill was reported.

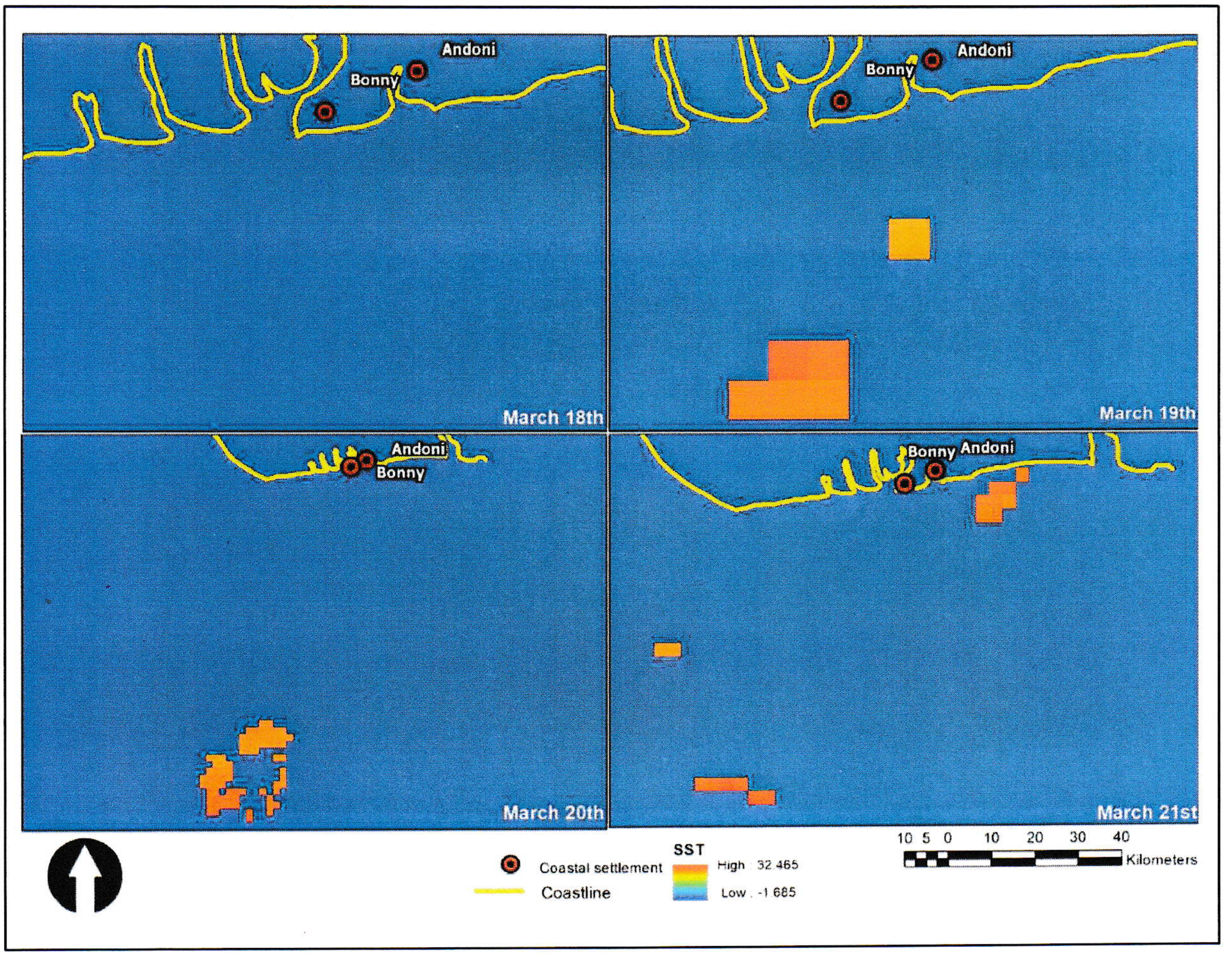

Fig 4b. Time Series Sea Surface Temperature (SST) at daily 9 km (Aqua MODIS) within the time window of single species fish kill (2020-03-18 to 2020-03-21)

The results of remote sensing of the meteorological situation, i.e. wind speed and sea surface temperatures on the Bonny-Andoni coast a few days before the fish kill was reported, debunks the view that pollution was a cause of the fish kill. The fact that the fish kill involved only one species, cassava croaker *Pseudotolithus senegalensis* (personal communication), suggests several possible scenarios and causative factors for the fish kill. From a public perspective, fish kills are readily indicative of pollution and habitat degradation. However, documented guides for evaluating fish kills indicate that natural causes are much more common than pollution causes (Meyer and Barclay, 1990). In addition, fish kills that affect a particular fish species and involve both small and large fish are attributed to acute stress caused by sudden changes in water temperature and, consequently, dissolved oxygen levels in surface waters. Tolerance to hypoxia varies among species (Wannamaker and Rice, 2000). For example, the Atlantic menhaden (*Brevoortia tyrannus*) has low sensitivity to hypoxia, having adapted over time to naturally recurring episodes (McNatt and Rice, 2004).

Temperature maps covering days before the fish kill indicate a possible sudden rise in temperature attributable to the windward movement of high-temperature surface water masses originating from or around the equator (Fig. 4b). Although the exact details of the nomenclature and wind interplay behind the movement and arrival of high-temperature surface water masses at the Bonny-Andoni coast are not covered by this preliminary report, the tropical maritime (Tm) air mass, one of the three major airstreams acting on the Nigerian coast (Adejuwon and Odekunle, 2006), has a trajectory path from the south Atlantic Ocean, across the equator to the southern coastline of Nigeria (Peters and Tetzlaff, 1988).

Since the affected species is a shoaling fish that undertakes its reproductive migration between the warm months of March and June, these likely low-oxygen, high-temperature masses may have encountered and captured a school of croakers resulting in mass mortality. Local estimates by fishermen indicate that more than 300,000 croakers of a single species died (personal communication). This suggests that the sudden arrival of the high-temperature surface water mass, travelling at increased wind speeds, may have encountered a large shoal that had no way to swim away (McNinch and Luettich Jr, 2000). This is plausible because many studies have shown that most finfish can detect and avoid hypoxic conditions (Breitburg, 1994; Wannamaker and Rice, 2000; Eby et al., 2002) unless the event was sudden. Wind-driven lateral ascending and descending as a possible mechanism for pelagic fish mortality due to hypoxic water has been documented (Reynolds-Fleming and Luettich Jr, 2004). Hypoxia is a critical parameter to consider when determining the cause of a fish kill because water temperature and DO are the most important parameters affecting fish survival, movement, and growth (Coutant, 1987; Christie and Regier, 1988).

The fact that two different sets of high-temperature surface water masses arrived in the Bonny-Andoni coastal area within 72 hours (Fig. 3b) suggests that two sudden events of temperature rise may have occurred, placing the school of fish in a dire situation of severe hypoxia with lowered chances of survival. This is consistent with reports from local fishermen and offshore workers that fish were seen gasping for air about 3 nautical miles offshore, while dead fish washed ashore hours later. In studies of fish kills around the world, the sluggish movement and gasping of fish at the surface have been attributed to a lack of oxygen or low oxygen levels in the water due to weather-related thermocline disturbances, low water levels, high temperatures, etc. (Kibria, 2014). Whether this event is related to climate change or not is not yet certain. However, one of the impacts of global climate change is that ocean currents may change in both temperature and strength, for example, due to changing wind patterns and heat balance, with an increased likelihood of altering entire communities and impacting the connectivity of ocean migrant populations (Hays, 2017).

CONCLUSIONS

For fish kills caused by dissolved oxygen or DO to occur, a combination of environmental conditions must occur simultaneously. Weather patterns, water temperature, water depth and quality, amount and type of plant growth, fish community structure, and the presence of viruses and bacteria are all factors necessary to trigger a fish kill. Remotely sensed wind speed data and thermal infrared imagery from the Bonny-Andoni area at the time of the fish kill illustrate the likelihood of high-temperature gradients and oxygen depletion off the Bonny-Andoni coast exactly where the fish kill is observed. Based on the findings of this report on the single species fish kill, the question is whether this is the beginning of a chain of climate change-related events that could upt u r n local fisheries along the Nigerian coast. It also raises the question of what other changes have occurred in the poorly mapped Nigerian coastal area that could manifest in a depletion or complete loss of certain fish stocks. While these questions remain unanswered, the fact remains that the magnitude of single species extinctions detected in this first-ever fish kill could result in significant economic losses.

Although the natural origin demonstrated in this report is plausible, frequent fish kills can have ecological and economic consequences (e.g. reducing populations of fish valuable for recreation and commerce, and limiting fish protein available to humans), so the use of remote sensing data for environmental monitoring should be explored to prevent future events.

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PRVO IZVJEŠĆE O POMORU RIBA U OBALNOM PODRUČJU BONNY-ANDONI, NIGERIJA

SAŽETAK

Pomor ribe karakterizira uginuće velikog broja riba u određenom području u kratkom vremenskom razdoblju. To je pokazatelj pogoršanja kvalitete vode i općenito stanja ekosustava. Podacima daljinske detekcije s instrumenta MODIS na satelitima Aqua i Merra-2 pristupljeno je od 18. do 22. ožujka 2020., razdoblje koje se proteže prije i nakon prijavljenog pomora ribe. Analiza podataka daljinskog istraživanja pokazuje da je pomoru ribe prethodio jak i dugotrajan vjetar. Karte površinskih temperatura mora prije pomora ribe pokazuju da su vodene mase visoke temperature tekle od ekvatora prema obali Bonny-Andoni. Datumi pojave visokotemperaturnih površinskih vodenih masa i jakih vjetrova oko obalnog područja Bonny-Andoni bili su u skladu s lokacijom i vremenom uginuća ribe, kako je naznačeno u lokalnim izvješćima. Pretpostavljamo da su površinske vodene mase s niskim sadržajem kisika i visokim temperaturama koje prolaze od ekvatora na privjetrinoj strani obale možda naišle na krokodile selice i zarobile cijelo jato ove bentopelagičke vrste riba, uzrokujući akutni respiratorni distres. Rezultati i hipoteza potvrđuju lokalna izvješća o ribama na izdisaju oko 2 nautičke milje od obale Bonny-Andoni. Ovo izvješće potvrđuje odnos između uzoraka vjetra, temperature i uginuća ribe, pružajući prvi empirijski prikaz vjerojatnih uzroka. Budući da se uginuća riba događaju povremeno i često ne ostavljaju traga, ovo izvješće i buduće analize podataka daljinskog istraživanja mogu biti najbolji način za rasvjetljavanje ovog događaja.

Ključne riječi: brzina vjetra, Coriolisov efekt, dišne poteškoće, površinska vodena masa visoke temperature, kreketuša

REFERENCES

Adejuwon, J. O., Odekunle, T. O. (2006): Variability and the Severity of the “little Dry Season” in southwestern Nigeria. Journal of Climate, 19(3), 483-493.

Al-Ghabshi, A. S. (2015): Bacteria Recovered from Aquaculture in Oman, with emphasis on *Aeromonas* spp.

Beer, T. (1996): Environmental oceanography. CRC Press.

Breitburg, D. (1994): Behavioral response of fish larvae to low dissolved oxygen concentrations in a stratified water column. Marine Biology, 120(4), 615-625.

Christie, G. C., Regier, H. A. (1988): Measures of optimal thermal habitat and their relationship to yields for four commercial fish species. Canadian Journal of Fisheries Aquatic Sciences, 45(2), 301-314.

Coutant, C. C. (1987): Thermal preference: when does an asset become a liability? Environmental biology of fishes, 18(3), 161-172.

Dublin-Green, C., L. Awosika, Folorunsho, R. (1999): Climate variability research activities in Nigeria. Nigerian Institute for Oceanography Marine Research, Technical Paper Marine Research, Victoria Island, Lagos, Nigeria

Eby, L. A., L. B. J. C. J. o. F. Crowder, Sciences, A. (2002): Hypoxia-based habitat compression in the Neuse River Estuary: context-dependent shifts in behavioral avoidance thresholds, 59(6), 952-965.

Farrow, D. E., Stevens, C. L. (2003): Numerical modelling of a surface-stress driven density-stratified fluid. Journal of engineering mathematics, 47(1), 1-16.

Handcock, R. N., C. E. Torgersen, K. A. Cherkauer, A. R. Gillespie, K. Tockner, R. N. Faux, J. Tan, Carbonneau, P. (2012): Thermal infrared remote sensing of water temperature in riverine landscapes. Fluvial remote sensing for science management 1(2012), 85-113.

Hays, G. C. (2017): Ocean currents and marine life. Current Biology, 27(11), R470-R473.

Hoyer, M. V., D. Watson, D. Willis, Canfield, D. (2009): Fish kills in Florida’s canals, creeks/rivers, and ponds/lakes. Journal of Aquatic Plant Management 47(1):53-56.

Karleskint, G., R. Turner, Small, J. (2012): Introduction to marine biology. Cengage Learning.

Kibria, G. (2014): Global fish kills: Causes and consequences.

La, V. T., Cooke, S. (2011): Advancing the science and practice of fish kill investigations. Reviews in Fisheries Science, 19(1), 21-33.

MacIntyre, S., Jellison, R. (2001): Nutrient fluxes from upwelling and enhanced turbulence at the top of the pycnocline in Mono Lake, California, Saline Lakes. Springer. p. 13-29.

MacIntyre, S., Romero, J. R. (2000): Predicting upwelling, boundary mixing, and nutrient fluxes in lakes. nternationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 27(1), 246-250.

Marti-Cardona, B., T. Steissberg, S. Schladow, Hook, S. (2008): Relating fish kills to upwellings and wind patterns in the Salton Sea. In: The Salton Sea Centennial Symposium, p 85-95.

McNatt, R. A., Rice, J. A. (2004): Hypoxia-induced growth rate reduction in two juvenile estuary-dependent fishes. Journal of Experimental Marine Biology Ecology, 311(1), 147-156.

McNinch, J. E., Luettich Jr., R. A. (2000): Physical processes around a cuspate foreland:: implications to the evolution and long-term maintenance of a cape-associated shoal. Continental Shelf Research, 20(17), 2367-2389.

Meyer, F. P., Barclay, L. A. (1990): Field manual for the investigation of fish kills. US Department of the Interior, Fish and Wildlife Service.

Moore, D., P. Hisard, J. McCreary, J. Merle, J. O'Brien, J. Picaut, J. M. Verstraete, C. Wunsch. (1978): Equatorial adjustment in the eastern Atlantic. Geophysical Research Letters, 5(8), 637-640.

Nwilo, P. C., Badejo, O. T. (2006): Impacts and management of oil spill pollution along the Nigerian coastal areas.

Odekunle, T. O., Eludoyin, A. (2008): Sea surface temperature patterns in the Gulf of Guinea: their implications for the spatio-temporal variability of precipitation in West Africa. International Journal of Climatology: A Journal of the Royal Meteorological Society, 28(11), 1507-1517.

Osuagwu, E. S., Olaifa, E. (2018): Effects of oil spills on fish production in the Niger Delta. PloS one, 13(10).

Paerl, H. W., J. D. Willey, M. Go, B. L. Peierls, J. L. Pinckney, Fogel, M. L. J. M. E. P. S. (1999): Rainfall stimulation of primary production in western Atlantic Ocean waters: roles of different nitrogen sources and co-limiting nutrients. Marine Ecology Progress Series, 176, 205-214.

Peters, M., Tetzlaff, G. (1988): The structure of West African squall lines and their environmental moisture budget. Meteorology Atmospheric Physics, 39(2), 74-84.

Picaut, J. (1983): Propagation of the seasonal upwelling in the eastern equatorial Atlantic. Journal of Physical Oceanography, 13(1), 18-37.

Quigg, A., L. Broach, W. Denton, Miranda, R. (2009): Water quality in the Dickinson Bayou watershed (Texas, Gulf of Mexico) and health issues. Marine Pollution Bulletin, 58(6), 896-904.

Reynolds-Fleming, J. V., Luettich Jr., R. A. (2004): Wind-driven lateral variability in a partially mixed estuary. Estuarine, Coastal Shelf Science, 60(3), 395-407.

Roman, M. R., S. B. Brandt, E. D. Houde, Pierson, J. J. (2019): Interactive effects of hypoxia and temperature on coastal pelagic zooplankton and fish. Frontiers in Marine Science, 6, 139.

Salomonson, V. V., W. Barnes, Masuoka, E. J. (2006): Introduction to MODIS and an overview of associated activities, Earth science satellite remote sensing. Springer. p. 12-32.

Servain, J., J. Picaut, Merle, J. (1982): Evidence of remote forcing in the equatorial Atlantic Ocean. Journal of Physical Oceanography, 12(5), 457-463.

Sexton, W. J., Murday, M. (1994): The morphology and sediment character of the coastline of nigeria: The niger delta. Journal of coastal research, 959-977.

Stevens, C., Imberger, J. (1996): The initial response of a stratified lake to a surface shear stress. Journal of Fluid Mechanics, 312, 39-66.

Thronson, A., Quigg, A. (2008): Fifty-five years of fish kills in coastal Texas. Estuaries Coasts 31(4), 802-813.

USEPA, U. E. P. A. (2000): The Quality of Our Nation's Waters, A Summary of the National Water Quality Inventory: 1998 Report to Congress.

Wannamaker, C. M., Rice, J. A. (2000): Effects of hypoxia on movements and behavior of selected estuarine organisms from the southeastern United States. Journal of Experimental Marine Biology Ecology 249(2), 145-163.

Wedepohl, P., J. Lutjeharms, Meeuwis, M. J. S. A. J. o. M. S. (2000): Surface drift in the south-east Atlantic Ocean. South African Journal of Marine Science 22(1), 71-79.