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The impacts of long-term changes in weather on small-scale fishers' available fishing hours in Nosy Barren, Madagascar

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Small-scale fisheries (SSF) are highly susceptible to changes in weather patterns. For example, in Nosy Barren, Madagascar, SSF use traditional pirogues with handcrafted sails that rely on seasonal wind and sea conditions. As climate change is expected to increase the intensity and frequency of severe weather, it is important to understand how changes in weather affect SSFfishing efforts. Yet, a gap exists in the understanding of how changes in meteorological conditions affect small scale fishers. This study combines fishers' meteorologicalknowledge of weather conditions that allow for small-scale fishing with long-term remotely sensed meteorological data to quantify how fishing effort, defined as available fishing hours, of SSFin coastal Madagascar has changed between 1979-2020 in response to long-term weather trends. Results show a significant decrease in available fishing hours over the examined time period. Particularly, we found that a decrease in available fishing hours between 1979-2020 with a loss of 21.7 available fishing hours per year. Increased adverse weather conditions, likely associated with climate change, could decrease fishers access to crucial resources needed for the food and livelihood security. Climate change adaptation strategies will need to account for changing weather impacts on fishing availability.

KEYWORDS

small-scale fisheries, weather, climate change, non-motorized, Madagasacar, fishing effort, traditional knowledge (TK)

Introduction

Climate change, such as changes in ocean temperatures and ocean acidification can affect marine fisheries in multiple ways including changes in fish species distribution, fish reproduction, fish-species composition (Lam et al, 2020), distribution (Perry et al, 2005; Munday et al, 2008; Daw et al., 2009), increased mortality of larval fish or alteration in the composition and productivity of fish habitats (Blanchard et al., 2012; Barange et al., 2014). Yet, knowledge about impacts of climate change on the fishers themselves are less understood compared to ecological impacts, in particular for more long-term meteorological changes. An increase in extreme weather events or bad weather days, for example, has the potential to affect fishers' infrastructure, including boats and gear, disrupt fishing effort, and cause physical harm to the fishers themselves (Daw et al., 2009; Sumaila and Cheung, 2010; Sainsbury et al, 2018; Heck et al., 2021). Small-scale fishers (SSF) in particular, are highly susceptible to changes in weather and climate conditions, due to their high dependency on resources, exposure to the elements, and sensitivity to impacts (Huber and Gulledge, 2011; Onyango et al, 2012; Limuwa et al., 2018; Freduah et al., 2019; Thoya and Daw, 2019; Karlsson and Mclean, 2020; Ramenzoni et al., 2020; Turner et al, 2020). This is concerning given that over half of allfish caught in developing countries is produced by SSF and up to 95 percent of these landings are for local consumption (The World Bank, 2012). Thus, SFF play an important role in many societies and any threats to this role could have severe consequences for the food and livelihood security of millions of people.

SSF can be defined in multiple ways (Smith and Basurto, 2019). 1n this paper, we adopt the FAO definition that defines SSF as traditional fisheries that involve fishing households, use relatively small amount of capital and energy, relatively small fishing vessels (if any), make short fishing trips close to shore, and mainly fish for local consumption (PAO, 1994). SSF are embedded in complex, dynamic social-ecological systems (Chuenpagdee, 2011) that are highly nested in the local context. Climate change impacts on SSF thus might not only affect the sustainability of SSF but also havelarger social impacts such as change in food availability and security in coastal areas (Allison et al, 2009).

This studyexplores changes in SPF fishing effort due to long-term changes in weather conditions. Previous work has already highlighted how climate change can reduce the efficiency of SSF fishing and consequently reduce food production (Tidd et al., 2022). Yet, given the lack of data on many SSF activities and SSF are diverse in nature, there is a need to investigate weather impacts on SSF effort in more local, placed-based approaches. We investigate this question in Madagascar, a small island state on the East coast of Africa that has an estimated 1.5 million people dependent on fisheries (Obura et al., 2017). At the same time, the country is highly vulnerable to climate change impacts on its fisheries (Heck et al., 2021). Some coastal communities in southwest Madagascar have already perceived an increased in bad weather in recent decades and report that it has reduced their ability to fish (Farquhar, personal communication). In Southwest and West Madagascar, fishing is mainly done by the *Vezo* people who use a traditional canoe, a "laka", carved out of a single tree (Astuti, 1995; Gough et al., 2009). A mast, sail, and seat are attached to the!aka then, using seasonal winds and celestial navigation, these vessels allow them to reach the fishing grounds (Astuti, 1995). Given that these SSF are using non-motorized fishing vessels, they are likely to be more highly affected by changes in adverse weather conditions. Yet, knowledge about impacts on weather conditions on such SSF is hardly understood, partly because both historical weather and fishing effort data for SSF are limited. This study thus combines fishers' knowledge of ideal weather conditions with long-term remotely sensed meteorological data to quantify how fishing effort, defined as available fishing hours, of SSF in coastal Madagascar has changed over time in response to long-term weather trends.

Methods

Study site

This study focused on the fishing activity occurring in the Barren Isles or Nosy Barren archipelago that is located in the Mozambique Channel off the city of Maintirano, in the Melaky region of Madagascar (Figure 1). This 4632.0 km^2 area includes large coral reef and mangrove habitats which supportsover 4000 traditional fishers for livelihood (Cripps, 2010). The region has a tropical savannah climate with distinct wet and dry seasons (Peel et al., 2007). The majority offishers are Vezo people who reside in nearby villages on the coast of Madagascar or come from the southwest. Both travel to the islands to fish. While the majority typically fish seasonally between April and December during the dry season, others frequent the islands year-round for fishing activities (Cripps and Gardner, 2016). Fishing trips usually last 1-2 days, occurring during the day or at night in near shore areas. Fishers usea variety of gears including gill nets,handlines, or spearguns. (Cripps and Gardner, 2016).

Data collection

Interviews

Fishers' meteorological knowledge (FMK) of weather conditions and associated impacts on fishing was assessed using semi-structured interviews. Similarly to fishers ecological knowledge (FEK), which has been used to reduce uncertainties and increase salience and credibility of models in data poor situations (Lavides et al., 2016; Lopes et al., 2019; Leduc et al,

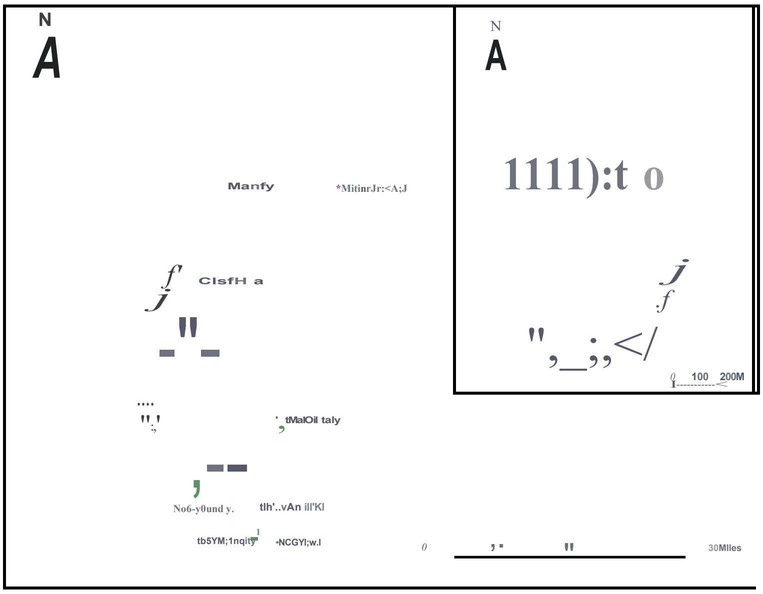

FIGURE 1
Map of Nosy Barren. also known as the Barren lies or Barren Islands. of Madagascar.

2021), we assessed FMK to identify which weather conditions allow or prohibit SSF fishing activities at sea. We interviewed fishers that live in the neighborhood of Ampasimandroro of the nearby city of Maintirano where fishers who frequent the Barren Isles as their primary fishing area live. Interview participants were sampled using a snowball sampling method in which known contacts to author A.N. introduced him to more fishers who then agreed to be interviewed as key-informants. Fishers were determined to be informants if they have fished in the Nosy Barren for more than 15 years. A total of 23 key-informant interviews were completed between October 2021 and December 2021. Given that over 1000 fishers are thought to live in Maintirano, this sample represents a small proportion of the fishing community. All interviews were conducted in Sakalava Malagasy language.

To identify how weather affects the ability of fishers to go fishing, we asked fishers to identify {1) What wind speed is too strong to go to sea?; {2) What wind speed is too weak to go to sea?;{3) What wave height is too high to go to sea?; and (4) Is there a certain wind direction that prevents you from going to sea? Questions were asked in semi-structured interview format so we could gain both specific numerical estimates, but also understand in-depth information on local descriptions and terminologies for specific weather conditions that allow or hinder fishing at sea.

Remote sensing data

As Madagascar does not have observed historical maritime weather data records (i.e. marine meteorological buoys), we used modeled remote sensing data to assess historical marine weather conditions. We used modeled, 10m u-component of wind, 10m v-component of wind, and significant height of combined wind waves and swell available from the fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERAS) single hourly dataset (Hersbach et al., 2018) (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-eraS-single-levels?tab=form) for years 1979-2020. The reanalysis improves the accuracy from previous modeled historical weather datasets (Hersbach et al., 2020). The 10m u-component of wind is the horiwntal speed of air moving towards the east, at a height of ten meters above the surface of the Earth. Similarly, 10m v-component of wind is the horizontal speed of air moving towards the north at ten meters above the surface. Significant height of combined wind waves and swell is the average height of the highest third of surface ocean/sea waves generated by wind and swell. It accounts for both surface waves and wind-sea waves. For windcomponents, data wasavailable at a 0.25 degrees horizontal resolution. For significant height of combined wind waves and swell, data was available at a 0.50 degrees horizontal resolution. The uncertainty estimate for the ERAS data is 0.5 degrees for wind data and 1 degrees for ocean wave data (Hersbach et al., 2018). Given the relatively small area of the Barren Iles, only six locations of data were available within the study site for wind data whereas three locations were available for wave data.

The data was imported into MATLAB for analysis. In order to obtain long-term data for wind speed and direction, the u-component andv-component of wind were calculated using two formulas following Guillory and Giusti (2020):

$$\text{Windspeed} = \text{sqrt}(\text{ul0.}^2 + \text{vl0.2})$$

$$\text{Winddirection} = \text{mod}(180 + 180*\text{atan2}(\text{ul0}, \text{vl0})/\text{t.}, 360)$$

We then calculated the mean wind speed, wind direction, and significant height of combined wind waves and swell across all locations within the Barren Iles to get hourly datasets of the three weather parameters between 1979-2020. The mean was taken to help standardii.e the data across all locations within study area. However, due to the spatial uncertainty, it is likely that weather conditions outside of our defined study area are incorporated into our data The estimated the spatial uncertainty is approximately 111km for wave data and 55km for wind data Our study area is about 4632.0 km^2. We assume that the weather conditions are relatively similar between the study area and outside the study area.

Data Analysis

Calculating available fishing hours

Based on the interview data, we developed thresholds for wind speed, wind direction, and wave height that prevent fishers of going out to sea.These thresholds were used to determine the range of weather conditions that allow fishers to go out to sea. When weather conditions met these thresholds for the hour, it wasconsidered an 'available fishing hour'. Allowable ranges were determined by using the mean values for minimum wind speed, maximum wind speed, and wave height reported from interviews and fishers' insights on wind directions that prohibit fishing in this calculation. Based on these data, the following parameters were used to calculate available fishing hours: wind speeds between 5.4-30.8 km/h; wave heights between 0- l.3m; and wind direction that was blowing from any direction except the south at 20km/h or greater. Given the technology the fishers are using, the traditional pirogues and sails,has not changed, it is assumed that these thresholds remain constant throughout time. Similarly, while there is some seasonality and cultural components that govern the individual preference of fishers' decision to go to sea, our analysis does not attempt to incorporate these because some fishers also choose to fish day or night and year-round. Thus, for simplicity we consider all months and times in our analysis. Available fishing hours were calculated based on the sum of all hours that fell within the weather conditions derived from the FMK Available fishing hours wereaggregated by eachyear and byeach month between 1979-2020.

Calculating annual change in available fishing hours

Yearly available fishing hours between 1979-2020 were used to calculate annual change over time. To calculate the annual change in available fishing hours, we used a linear regression where the dependent variable was the total available fishing hours per year and the independent variable is time. Regression was appropriate because all the test regarding normality, stationarity, and linear assumptions were met: 1) there is no seasonal pattern in the yearly data; 2) the results of the augmented Dickey-Fuller test indicated that the data series is stationary and 3) any autocorrelation in the series could be attributed to weather changes driven by broader weather phenomenon whose affect lasts longer than one year (i.e., Indian Ocean Dipole). Furthermore, the residual plots showed that the fishing hours can be expressed as a linear function of time. Further information on the linear regression analysis can be seen in the Supplementary Information file.

Calculating decadal change in available fishing hours

Monthly available fishing hours between 1979-2020 were used to calculated decadal change over time. For each decadal period, 1979-1989, 1990-1999, 2000-2009, and 2010-2020, the monthly available fishing hours was averaged. Next, a T-test was used to understand if there was a significant difference in available fishing hours between the most recent decade (2010-2020) and the oldest (1979-1989). Further information for the T-test analysis can be found in the Supplementary Information file.

Results

Interview findings indicate a range in wind speed and wave height conditions that fishers identify as safe for operating their boats (Table 1). Mean wind conditions that were mentioned as good conditions for SSF were between 5.4 to 30.8 km/h and a maximum mean wave height of 1.30m. Standard deviations shows that fishers' perceptions of safe fishing conditions varied in particular for maximum wind speed (Std. = 7.23) and less for maximum wave height (Std = 0.58).

Fishers described the dynamics of weather as "masay" when the ocean is very calm and "molenge" when the wind conditions are so calm that fishers cannot operate. Fishers' report that molenge conditions happen at all times of the year but usually are most common around noon when winds are shifting from the morning winds to the afternoon winds. The majority of interviewees (96%) further emphasized that the condition that prevents them the most from going to sea is "valaza", when winds become too strong-sometimes for weeks at a time. Valaza conditions are associated with strong winds coming from the south typically during May, June, July, and August.

While available fishing hours showed some cyclic behavior of years with high available fishing hours followed by and low available fishing hours, we found an overall decline in available fishing hours. Linear regression showed a significant decrease in

TABLE 1 Weather thresholds for wind speed and wave height given by fishers' meteorological knowledge (N=23).

	Wind Speed Min (km/h)	Wind Speed Max (km/h)	Wave Height (m)
Mean	5.40	30.80	1.30
Srandard Error	0.33	1.50	0.12
Mode	5	30	
Srandard Deviation	1.62	7.23	0.58
Sample Variance	2.62	52.30	0.34
Kurtosis	4.26	2.88	0.70
Skewness	2.00	1.54	1.03
Range	7	30	2.30
Minimwn	3	20	0.70
Maximum	10	50	3

available fishing hours between 1979-2020 at the 99% confidence interval (R^2 = 0.39, p<.005, t (41) = -5.13) (Figure 2) with a loss of 21.7 available fishing hours per year (See supplement for additional statistical information).

Mean fishing hours by month for each decade showed that more available fishing hours occurred during the rainy season (November-April) than the dry season (May to October). Mean values for fishing hours showed a decline in available fishing hours between decades (Figure 3) with a significant difference in mean values of available fishing hours between decadal periods 1979-1989 and 2010-2020 (t (11) = 6.17, p<.005) (See supplement for additional statistical information).

Discussion

Changes in weather can have significant impacts on fisheries, in particular SSF. Based on the combination of historical remotely sensed weather data and weather parameters defined by fishers, we found that available fishing hours have declined over the past four decades due to worsening weather conditions. Changing weather patterns thus can also significantly affect SSF as fishers may need to choose between reduced access to the resource or an increase in physical risks (Sainsbury et al., 2021).

As fishers are usually averse to higher wind and waves (Sainsbury et al., 2021), changing weather conditions may reduce access to the resource, which could have implications for food production, food access, and food stability in coastal areas. Because many small-scale fishers in Nosy Barren also sell fish for income to exporters, lack of fishing could reduce income for households and economic livelihood assets. Yet, perceptions of what was deemed as safe to operate varied among fishers-in particular for maximum wind speed. Variations could be driven by individual risk perceptions based on social and cultural factors (Salas et al., 2004; Thoya and Daw, 2019; Pfeiffer, 2020).

Adaptation strategies will be needed that help fishers cope with disruption of fishing activities to prevent an increase in physical risks that fishers take to sustain their livelihoods. However, traditional fishers might not be able to easily switch to less sensitive gear types or vessel sizes which requires substantial financial means.

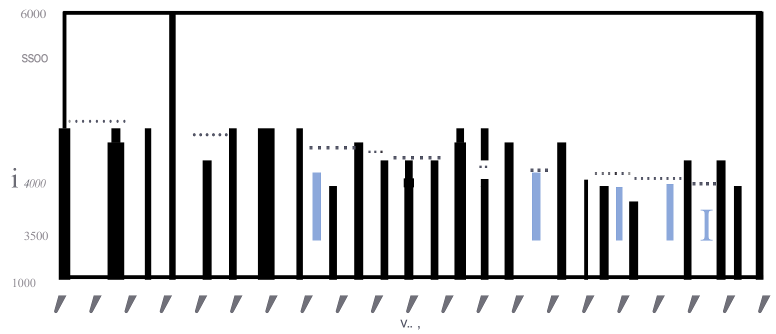

FIGURE 2
Total available ftshing hours by year for the Nosy Barren area between years 1979-2020. The trendline represents the linear regression (y = -21.71+ 47787) showing an overall signiftcant decrease in available fishing hours over time.

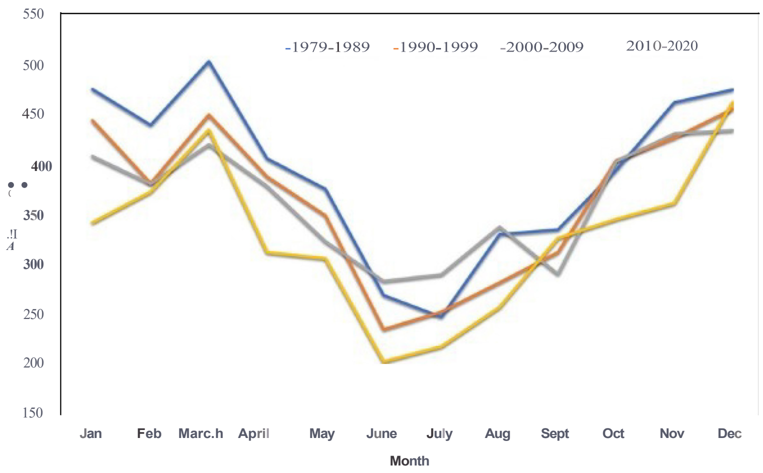

FIGURE 3
Decadal averages of available fishing hours by month for theNosy Barren area.

In Madagascar, there has been efforts to use marine protected areas to help SSF adapt to climate change by promoting sustainable fisheries management, ecological restoration, adaptive management governing bodies, and livelihood diversification. Some initiatives have aimed to help SSF diversify their income specifically through seaweed and sea cucumber aquaculture ventures (Ri:innback et al., 2002; Rasolofonirina et al., 2004; Robinson and Pascal, 2009; Ateweberhan et al., 2015). Yet, developing alternative livelihoods can be challenging depending on the social-ecological context of the fisheries. For example, the water quality near Maintirano is not conducive to sea cucumber aquaculture due the high sediment load from the nearby rivers that empty into the ocean ("Maintirano" literally translates to "black water"). Another challenge are financial issues. For example, aquaculture on the Barren Iles themselves may be possible, but would require significant infrastructure investment. Environmental or economic conditions thus can limit the use of aquaculture as an alternative livelihood strategy to marine fishing and might not be a suitable livelihood alternative in some coastal areas.

Methodologically, this study illustrates how FMK may be combined with remote sensing data to understand changes in fishing trends in data-poor regions. Given that SSF often exist in data-poor contexts, this methodology could be applied in other coastal communities. Future research could build on this study by including more details of fishing behavior and other weather conditions to calculate available fishing hours (e.g., temperature, precipitation, lunar cycles, culturally significant holidays, etc.). For example, our study found that more available fishing hours were available in the rainy season than the dry season. This is likely because our model did not include fisher's preferences and FMK for fishing during rain events.

Given that this study was intended to be a proof-of-concept, it would also be beneficial to further test and validate the data and the methodology in the future.This study used weather data that was remote sensing data and at a coarse resolution. As mentioned earlier, the uncertainty estimate for the ERAS data is 0.5 degrees for wind data and 1 degrees for ocean wave data (Hersbach et al, 2018). This does not account for how local features, such as the islands, may affect the weather patterns. Additionally, due to the spatial uncertainty, weather data from outside of our defined study area may have been included in our analysis. However, given that it is known that SSFin this area are highly migratory and operate in other places outside the Nosy Barren, these results are still meaningful. Yet, future work thus could include observed, *in-situ* weather data where available to ground truth and reduce uncertainty of remote sensing data.

Similarly, the model used the average weather parameters based on 23 interviews. Within each of these parameters was some variability which affected the calculation of available fishing hours. For example, while there was little standard deviation on minimum windspeed needed to go to sea (1.62 km/h), a larger standard deviation was found in regards to the maximum windspeed that prevented fishers from going to sea (7.23 km/h). Such deviation increases the uncertainty of these results. A larger interview sample size across multiple fishing communities could provide more empirical insights into fishers' definition of weather condition thresholds. Also, the study only investigated changes in available fishing hours, not actual fisheries production. Future research could explore whether fisheries production have changed due to changes in available fishing hours and assess the indirect and direct social, economic, ecological, cultural consequences of weather impacts on SSF to better understand how SSF are affected not just by extreme events but also changes in long-term weather patterns.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SF designed the study and calculated available fishing hours. AN collected the interview data, completed all translations, and organized data for processing. SF and NH wrote the manuscript. MS conducted statistical analysis. YX created cartographic figure. All authors read and approved the final version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that *could* be construed as a potential conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.841048/full#supplementary-material

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