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Analysis of the impact of volcanic eruptions on fishery resources using Earth Observation data

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Abstract

In recent years several volcanic eruptions have made headlines for their significant economic and humanitarian costs. Notably these include the eruptions of Cumbre Vieja (La Palma, Spain) and Hunga Tonga-Hunga Ha'apai (Fonuafo'ou, Tonga). Both eruptions disturbed not only the human population living around them but also the natural ecosystem, leading to health consequences for marine life due to the change in habitat conditions. In cases such as Tonga, where an estimated 82% of families survive on subsistence fishing, it is necessary to investigate not only damage to property caused by the eruptions but also the impact of the eruptions on marine conditions and consequently the impact on local livelihoods.

The aim of this paper is to analyze and perform a comparative study of the effect of several volcanic eruptions on aquatic ecosystems using available Earth Observation data. The methodology of this research considers the study of four eruptions of different volcanoes from which lava flowed to the sea. The four eruptions are: Kīlauea in 2018, Stromboli in 2019, Cumbre Vieja in 2021, and Hunga Tonga-Hunga Ha'apai 2021/22. Marine parameters derived from Earth Observation data used in this analysis include sea surface temperature (SST), sea surface height (SSH) turbidity (NDTI), iron concentration (FE) and chlorophyll (NDCI). The research involves the evaluation of the evolution and correlations between these parameters.

The results of this study allow for a modelled characterization of volcanic eruptions through prediction of their socio-economic impact in communities dependent on fishing, while improving the understanding of the impact of these events on marine ecosystems. The findings from this research prove that Earth Observation satellite data parameters are essential for an in-depth analysis of the repercussions of volcanic eruptions.
Keywords: volcanic eruptions, earth observation satellite data, ocean fisheries, volcanoes socio-economic impact, remote sensing

Acronyms/Abbreviations

GDP	Gross Domestic Product
SST	Sea Surface Temperature
NDCI	Normalized Difference Chlorophyll Index
NDTI	Normalized Difference Turbidity Index
GEE	Google Earth Engine
SSH	Sea Surface Height
FE	Iron concentration
GFW	Global Fishing Watch
AIS	Automatic Identification System
EEZ	Exclusive Economic Zone

1. Introduction

Volcanic eruptions can produce hazardous effects for the environment, climate, and the health of the exposed persons, and are associated with the deterioration of social and economic conditions. The eruptions can last from several minutes to decades, and can produce sequential, concurrent, and/or recurrent hazards [1]. These hazards include tsunamis, blasts of air, pyroclastic flows, earthquakes, flows of mud, gases and steam, release of dangerous gases and toxic volcanic ashes into the atmosphere, physical and psychological injuries to humans, transport and communication problems, disruption of water supplies, power outages and collapse of buildings, deterioration of water quality, crop damages, and the destruction of vegetation [2]. Generally, the more severe impacts occur close to the vent, but in some cases the destructive hazards can travel several kilometers from the vent (e.g. [1, 3, 4]).

The eruptions can also cause severe damage to aquatic environments and habitats [5] and could cause extensive damage to coral reefs, erosion of coastlines and disruption of fisheries [6]. Several researchers have documented the physical, chemical and biological impacts of volcanic eruptions on the environment. For example, in [7] the physical impacts and social and economic consequences of volcanic activity on vegetation are discussed. Some of the research has focused on the marine and aquatic environment. The authors in [8] adopted a multi-proxy palaeoecological approach for assessing the response of aquatic ecosystems to volcanic ash deposition in two Neotropical lakes on the eastern Andean flank of Ecuador. In each lake, they examined the effect of thick (> 5 cm) volcanic deposits on chironomids and other aquatic organisms. Their data suggested that volcanic ash deposited within a system is the most important factor determining the lasting impact of volcanic eruptions on the chironomid community. In another study [9], the authors reviewed the effects of volcanic eruptions in freshwater environments and on freshwater organisms. The most commonly reported physical and chemical effects were increases in water turbidity and increases in concentrations of inorganic elements respectively.

In the present study, we carry out a comparative evaluation of the effect of four volcanic eruptions on the aquatic environment. The four eruptions are: Kīlauea (Hawaii) in 2018, Stromboli (Italy) in 2019, Cumbre Vieja (Spain) in 2021, and Hunga Tonga-Hunga Ha'apai (Tonga) in 2021/22 (all shown in Fig. 1). These four eruptions, which differ in magnitude and occur at different geographic locations, are presented to illustrate the range of effects of volcanic eruptions on the aquatic ecosystem. The following research questions are investigated: (i) what are the interrelationships between physical and chemical marine parameters (sea surface temperature, turbidity, chlorophyll, sea surface height and iron concentration) in waters perturbed by volcanic eruptions, and (ii) how do the changes in these parameters affect the local marine ecosystem and socio-economic livelihoods.

This research is significant for the United Nations Sustainable Development Goals (UN SDGs), specifically SDG 14 which is targeted towards the conservation and sustainable use of the oceans, seas and marine resources for sustainable development. It also contributes to the body of knowledge on the environmental impact of volcanic activity in different regions of the world.

Fig. 1. Map showing the locations of the volcanoes under study in this paper

2. Context and description of volcanic eruptions

Both the socio-economic drivers in the area around the volcanoes and the volcanic eruption characteristics are briefly described in this section. Table 1 introduces a summary of the location and start and end dates of interest for each eruption.

Table 1. Dates and coordinates of the volcanic eruptions under study

Location	Start date	End date	Lon*	Lat**
Kīlauea	2018/04/30	2018/08/04	155.29ºW	19.42º N
Stromboli	2019/07/03	2019/08/28	15.21 ºE	38.79º N
Cumbre Vieja	2021/09/19	2021/12/13	17.83 ºW	28.57º N
Hunga Tonga	2021/12/20	2022/01/15	175.38ºW	20.54º S

* Lon = Longitude
** Lat = Latitude

2.1. Kīlauea volcano, Hawaii island, 2018

Kīlauea is the youngest and most active volcano on the island of Hawaii. This island is the largest in terms of area and second largest in terms of population of the Hawaiian archipelago, with a population of 202,906 people in July 2021 and an area of 4,028.45 km^2 [10]. The two largest economic sectors in Hawaii are tourism and military defense. However, agriculture is still an important driver with Hawaii being a major agricultural exporter [11].

Eruptive activities were recorded in a span of 4 months in Kīlauea's Lower East Rift Zone (LERZ) from April 30th to August 4th. An estimated 1.4 km^3 of lava has been produced [12]; covering 35.5 km^2 of land, creating 3.5 km^2 of new land when it reaches the ocean, destroying 716 homes in its path [13] and displacing more than 2,000 people [14]. The 60,000 earthquakes created were of magnitudes ranging from 3 to 6.9 [13]. It caused the largest earthquake in Hawaii in nearly 40 years [15] and the eruption deepened the Halema'uma'u crater to 488 m, doubling its perimeter [14]. Other impacts including ash plumes, fog, flames, ballistic particles, and toxic steam (hydrochloric acid and sulfur dioxide) carried by air currents are not only harmful to forests and other vegetation, but also to humans.

2.2. Stromboli volcano, Stromboli island, 2019

Stromboli, in the north of Sicily, is one of the eight volcanic Aeolian Islands, with a population of fewer than 500 people and an area of 12.6 km^2 [16]. The island contains Mount Stromboli, one of the three active volcanoes in Italy, which has been almost constantly active for nearly 2,500 years [17]. The few residents in Stromboli island live in two villages: Stromboli and the former fishing town of Ginostra.

Fishing and agriculture were the most important activities during the last century. However, nowadays the continuous volcanic activity attracts people from all over the world, making tourism the main source of income for the island.

The eruptions on Stromboli and their effects were recorded between July 3rd and August 28th, 2019. The first sudden sign of the eruption was a magma bubble explosion, also known as paroxysm, generating a 5 km tall ash column [18]. The explosions affected the southwestern village Ginostra on July 3rd, and the northeastern village Stromboli on August 28th [19]. Though mild to moderate Strombolian explosions have been frequent on this island since the 8th century, two consecutive paroxysm such as these are rare [20]. This can be very destructive, releasing blazing projectiles and dense ash clouds, as well as sending strong shock waves to the villages. The incandescent rocks (tephra) sparked bush fires as far as 500 m away [19]. Moreover, the resultant pyroclastic density currents set off a tsunami detectable hundreds of km away. The explosion damaged nearby GNSS, seismic, and SO_2 monitoring stations. One hiker was found dead from inhaling fire smoke and hundreds of tourists were evacuated [21].

2.3. Cumbre vieja volcano, La Palma island, 2021

La Palma is a volcanic island in the Canarian archipelago, and it was born through the volcanic activity of more than 100 volcanoes that lie at the bottom of the ocean. Along with Tenerife, they are currently the most volcanically active of the Canary Islands. La Palma's population is around 85,000 inhabitants [22], and it is the fifth largest of the eight Canary Islands, with an area of 708 km^2 [23].

One of the main economic drivers of La Palma is tourism which represents more than 20% of the island's GDP, according to recent data [24]. Besides this, a significant portion of La Palma's income results from irrigation-based farming where bananas, avocados and grapes used for winemaking are mainly cultivated. Banana cultivation alone represents over 50% of the island's economic output [25], and it is estimated that half of palmeros (people from La Palma) economically depend on banana production. Thus, the importance of tourism and farming activities in this region (which suffers from high levels of unemployment) are high.

On the other hand, fishing activity constitutes a very small percentage of the Canaries' GDP, partly due to lack of infrastructure (such as harbours and cold chain infrastructure). It is estimated that over 150 families depend directly on the fishing industry in La Palma [26].

The eruption in La Palma in 2021 was the most damaging eruption in Europe since the 1944 Vesuvius eruption. It started on September 19th and ended on December 13th, lasting for 85 days - the longest in La Palma eruption history. The early warning signs of the eruption were a series of earthquakes starting on September 11th, allowing La Palma inhabitants to evacuate in time. The eruption started from the southwest flank, opening fissures and vents that produced lava as far as 800 m from the vent and ash flumes as high as 7.5 km [27]. Many crater walls collapsed, even forming lava deltas as the flow reached the sea [28]. Throughout October and November, more than 3,000 earthquakes were detected. By December, the weakened lava flows continued feeding the lava delta while ash plumes reduced. In the aftermath, six craters were formed. 200 million km^3 of lava erupted, covering 12.19 km^2 [27], including 0.69 km^2 of lava deltas.

2.4. Hunga Tonga-Hunga Ha'apai, Tonga, 2021

The Kingdom of Tonga comprises an archipelago of 179 islands, 36 of which are inhabited, with a total population of approximately 106,000 [29]. The total surface area is 729 km^2, scattered over 700,000 km^2 of the southern Pacific ocean [30].

Tonga is heavily dependent on agriculture, fisheries and tourism, with agricultural and fish exports making up two-thirds of total exports [31]. The economy includes a large non-monetary sector, while the monetary sector is heavily dependent on remittances from the Tongan diaspora. In fact, remittances are the largest source of hard currency earnings, followed by tourism.

Tonga is among the places most vulnerable to natural disasters globally, as it is frequently hit by tropical cyclones, earthquakes, tsunamis and droughts, while the submarine volcano Hunga Tonga-Hunga Ha'apai has been sporadically erupting during the last two centuries. Natural disasters cause losses of US$15 million on average per year (3% of GDP) [32] in Tonga, which intensifies the needs of the 25% of households that live under the poverty line and are in general reliant on subsistence fishing and farming. The country faces high unemployment among the young, in addition to moderate inflation.

Surtseyan explosions, that occur when water heated by magma becomes explosive, started in Tonga on December 20th morning local time, releasing an ash plume radiating 30 km [33] and drifting northward, covering Tonga entirely by the afternoon. Intermittent eruption plumes and bursts of lightning were reported several days after that, until the last submarine eruption on January 15th covered all the Tongan islands within 8 minutes. Ashfall from the 300-km-radius plume was several centimeters thick, leading to breathing troubles among residents and an internet disconnection.

The resulting sonic boom from the shock waves was heard in New Zealand, Samoa, Fiji, Vanuatu, the Cook Islands and Alaska. The volcanic eruption produced tsunami waves that impacted several inhabited islands of the Tonga archipelago, as well as a Pacific-wide tsunami that reached coasts across the Pacific regions and as far as South and North America and Northeast Asia [34].

3. Material and methods

3.1. Data acquisition

3.1.1 Water quality parameters

Water quality data used in this study was retrieved or derived from several different collections of satellite data. The advantage of using satellite remote sensing for water quality analysis is the near continuous spatial coverage of satellite imagery, allowing for synoptic estimates over large areas, as well as the long record of archived imagery from satellite series such as Landsat that allows for estimation of historical water quality when no ground measurements can or could be performed. This is particularly salient during eruptions when it may be too dangerous to perform in-situ analysis in many areas of interest.

Sea surface temperature (SST), Normalized Difference Chlorophyll Index (NDCI) and Normalized Difference Turbidity Index (NDTI) data was compiled using scripts in the Google Earth Engine (GEE) platform. GEE is a cloud-based platform developed by Google that facilitates geospatial analysis and data access [35].

SST data was collected from the Ocean Color SMI: Standard Mapped Image level 3 dataset from NASA MODIS Aqua [36]. The data is relatively low resolution (when compared with e.g. Copernicus or Landsat satellites) at 4616 m, but the corollary of this is that such a large viewing swath allows for a fast revisit period of about 1 to 2 days [37]. The SST band of the dataset ranges from -2 to 40 °C in temperature.

NDCI and NDTI data were both derived from NASA Landsat 8 level 2, collection 2 tier 1 data [38]. The resolution of Landsat is slightly lower than Sentinel-2 for the bands used (30 m vs 10-20 m), but data from Sentinel-2 was unavailable for at least Kīlauea in GEE during the period of study, so Landsat was used for consistency across sites. Landsat 9 data is also not used for a similar reason (being unavailable prior to October 2021). The revisit period of Landsat 8 is 16 days.

Cloud masking was used on the Landsat 8 data to prevent interference. This was done using the QA_PIXEL band cloud masking bits (3 for cloud shadows, 5 for clouds). Land was similarly masked from the data using SR_QA_AEROSOL bit 2. This was not necessary for SST as the data was pre-processed in the image collection.

NDCI is widely used to predict chlorophyll-a (chl-a) concentration from remote sensing data in estuarine and coastal turbid productive waters [39]. NDCI is calculated as the normalized difference between band 4 (red) and band 5 (red edge, or near infrared for Landsat), formulated as follows [40].

$$NDCI = \frac{(band\ 5) - (band\ 4)}{(band\ 5) + (band\ 4)} \quad (1)$$

NDTI was developed to estimate the turbidity of water [41]. Turbidity is a measure of water clarity derived from how much light is scattered by material in a body of water, and is a commonly assessed water quality parameter due to its optically active properties. The red (band 4) and green (band 3) reflectance bands are computationally combined to derive the NDTI as follows.

$$NDTI = \frac{(band\ 4) - (band\ 3)}{(band\ 4) + (band\ 3)} \quad (2)$$

Sea surface height (SSH) data was retrieved from two different sources covering different dates:

1. From 16/01/1993 - 16/05/2020: data was used from Global Ocean Physics Reanalysis (GLOBAL_MULTIYEAR_PHY_001_030) SSH above geoid [42]. Geoid refers to the mean sea level when the ocean is at rest and so the modelled SSH is the difference between the SSH above the reference ellipsoid and the geoid. Level 4 data was used from the model version LIM2 EVP NEMO 3.1. The spatial resolution of the data is 0.083°.
2. From 01/12/2019 - present: data was used from Global Ocean Gridded L4 Sea Surface Height (SEALEVEL_GLO_PHY_L4_NRT_OBSERVATIONS_008_046) [43], which provides SSH above geoid with respect to a 20-year 2012 mean. The spatial resolution of the data is 0.25°.

Molar concentration of dissolved iron in seawater (FE) in $mmolm^{-3}$ data was also retrieved from two sources:

1. From 16/01/1993 - 16/12/2020: data was used from Global Ocean Biogeochemistry Hindcast (GLOBAL_MULTIYEAR_BGC_001_029) [44]. Level 4 data was used from numerical model PISCES. The spatial resolution of the model is 0.25° and the depth is 0.5058 m.
2. From 16/01/2020 - present: data was used from Global Ocean Biogeochemistry Analysis and Forecast (GLOBAL_ANALYSIS_FORECAST_BIO_001_028). Level 4 data from PISCES was also used for this data source [45]. The spatial resolution of the model is 0.25° and the depth is 0.494 m.

Both sets of SSH and FE data were taken from EU Copernicus Marine Service Information.

3.1.2. Socio-economic parameters

Qualitative and reported socio-economic information was collected through a literature review of reports and government databases that included the main figures for derivation of the economic impact of the eruptions (see subsection 4.2).

In addition to qualitative and reported information gathered as part of this study, the socio-economic impact of the Kīlauea and Stromboli eruptions was assessed using data from Global Fishing Watch (GFW). GFW track and record vessel presence using positioning data from Automatic Identification System (AIS) devices on over 114,000 fishing vessels. This data is measured in units of hours per vessel and classified as fishing activity via a neural network classifier, vessel registry databases, and manual review by GFW and regional experts [46].

GFW fishing effort data was, at the time of the study, only available from 2012 - 2020. Therefore this particular analysis was only conducted for the Kīlauea and Stromboli eruptions (occuring in 2018 and 2019 respectively).

An important limitation of this dataset is that it only tracks vessels with AIS devices onboard. As of 31 December 2004, the International Maritime Organisation (IMO) requires AIS to be fitted aboard all ships of 300 gross tonnage and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size [47]. This means that small fishing vessels with below 500 gross tonnage operating locally may not carry AIS, which means a significant part of the fishing economy may be excluded from this analysis. However, eruption impacts on the fishing activity of larger vessels could similarly be reflected for smaller vessels.

The data may also exclude illegal fishing activity by vessels not permitted to fish within the Exclusive Economic Zone (EEZ) of the nation under study, as these vessels may disable their AIS devices to avoid detection during these activities [48]. However, as this study concerns the impact on the local economy, illegal fishing by foreign vessels is not considered an important variable.

3.2. Quantitative analysis

The areas of interest for this study were decided by defining a polygon of 5 degrees in each cardinal direction from the coordinates of each volcano, in order to capture a sufficiently large area to measure the impact of the eruptions (particularly considering volcanic ash deposition and shipping/fishing activity, which may affect and be effected many km from the eruption site). These polygons were further subdivided into grid cells, creating grids of two different resolutions: of 5x5 cells (with each cell measuring 2 degrees on each side), and 11x11 cells (with each cell measuring 0.91 degrees on each side). If it was not possible to subdivide into these scales, extra columns or rows of cells were added to the edge (see Fig. 2). These grids were then restricted by discarding any grid cells which did not at least partially intersect with the borders of the Exclusive Economic Zone (EEZ) of the country in which the volcano resides (using data from [49]), to limit the scope of the study to consider primarily the impact on the local shipping/fishing economy and marine environment, as each nation has jurisdiction to govern the use of its marine resources in accordance with the United Nations Convention on the Law of the Sea (UNCLOS) [50]. EEZ extends 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, except when this would lead to an overlap with the EEZ of another nation.

Numbering of the cells for identification in analysis starts from the south west corner of the grid, increasing northward until the north edge, after which they increase from the south again, moving east. This can be seen for Kīlauea in Fig. 2, but the same scheme was followed for all grids used.

Each of the data discussed in section 3.1 was analyzed in section 4.1 on a monthly basis, either by taking the mean average of all satellite data points within the cell, or by summing the total vessel fishing or non-fishing hours in the case of the GFW fishing data. This data was recorded for the year in which the eruption took place, as well as the years directly before and after to control for typical seasonal variations in each parameter.

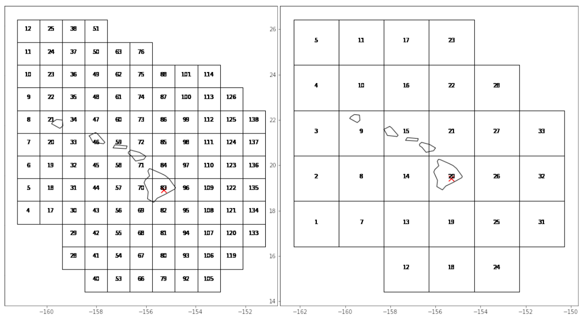


Fig. 2. Chart of grid cells generated around Kīlauea within the USA's Hawaiian EEZ (left: 11x11 grid, right: 5x5 grid)

4. Results and discussion

4.1. Water quality parameter and fishing effort analysis

As described in section 3.2, fishing effort socio-economic data was analyzed together with water quality parameter data for the Kīlauea and Stromboli eruptions. Some noteworthy results from the present study are included in the following section.

4.1.1. Overall correlation analysis of water quality parameters

Some significant correlations were observed between the physico-chemical water quality parameters at the four eruptions.

For example, In Cumbre Vieja (5x5 and 11x11 sample grids), there was a weak positive association between mean NDCI and mean NDTI (Pearson correlations of 0.303 and 0.388 for each grid size respectively), and a strong positive association between mean SSH and mean SST (0.683 and 0.627 respectively).

In Hunga Tonga (5x5 sample grids), there was a strong positive association between mean SSH and mean SST (0.605), but this was more moderate for the 11x11 grid (0.572).

In Hunga Tonga (11x11 sample grids), there was a moderate positive association between the mean NDCI and mean NDTI (0.430) and between the mean SSH and mean SST (0.572). In the 5x5 sample grid the correlation between NDCI and NDTI was not significant (-0.058), but there was a stronger correlation than the 11x11 grid for SSH and SST (0.605).

In Kīlauea (5x5 and 11x11 sample grids), there was a weak positive association between the mean SSH and mean SST (0.367 and 0.306 respectively for each grid size).

In Stromboli (5x5 and 11x11 sample grids), there was a weak positive association between the mean dissolved iron and mean SST (0.306 and 0.324 respectively), between mean SSH and mean SST (0.353 and 0.348), and a moderate negative correlation between mean dissolved iron and mean NDTI (-0.494 and -0.478).

4.1.2. NDTI anomalies detected during eruptions

Using the 5x5 grid cells centered on and directly adjacent to the island of each of the eruptions (cell 20 and surrounding, see Fig. 2 for the example of Kīlauea), all the parameters were analyzed for any unseasonal effects during and after the eruptions. Using this approach most parameters followed seasonal patterns also reflected in the year preceding and following the eruptions, however there was a significant drop in mean NDTI for all volcanoes except Cumbre Vieja (however for Stromboli this could also be due to a mostly seasonal fluctuation or noise). There were increases in NDTI for Kīlauea in cells 25 and 27 however.

Ash deposits are known to increase turbidity in the waters surrounding a volcano [51, 52], so this result is particularly unusual as a higher NDTI should reflect increased turbidity in the water. A number of explanations could be hypothesized: errors in the data or calculations, interference from the ash clouds of the eruptions that may not have been masked correctly, or a smaller number of data points available in those months (possibly due to heavy cloud masking) leading to skewed data.

The last two explanations can be discounted for Kīlauea at least, as it can be seen in Fig. 4 that during the eruption there was a large number of data points available for calculating the mean average (despite cloud masking removing many), and that the clouds were correctly masked as can be seen by their absence in the RGB imagery (where only the dark ocean surface is visible).

Therefore it seems likely that, if the cause is ash deposits, they are having an unexpected effect on the NDTI that requires additional analysis. It can also be seen in the imagery in Fig. 4 that the NDTI and NDCI are both affected to the south west of the island, which suggests that this may be the direction of the wind blowing ash over the ocean. The NDCI may have been reduced as chlorophyll was prevented from photosynthesising by ash deposits on the surface, or by thick ash clouds created by the eruption blocking sunlight.

The following cells showed anomalous decreases in mean NDTI during the months of the eruption for each volcano (see section 3.2 for an explanation of the cell numbering scheme).

1. Kīlauea: 13, 14, 15, 20, 21 (25, 27 increased)
2. Stromboli: 14, 20
3. Hunga Tonga: 13, 14, 15, 19, 20, 21, 26
4. Cumbre Vieja: None

As an illustrative example, mean monthly NDTI for cell 20 (the cell directly centered on each volcano in the 5x5 grids) is shown in Fig. 3 below for each of the volcanoes.

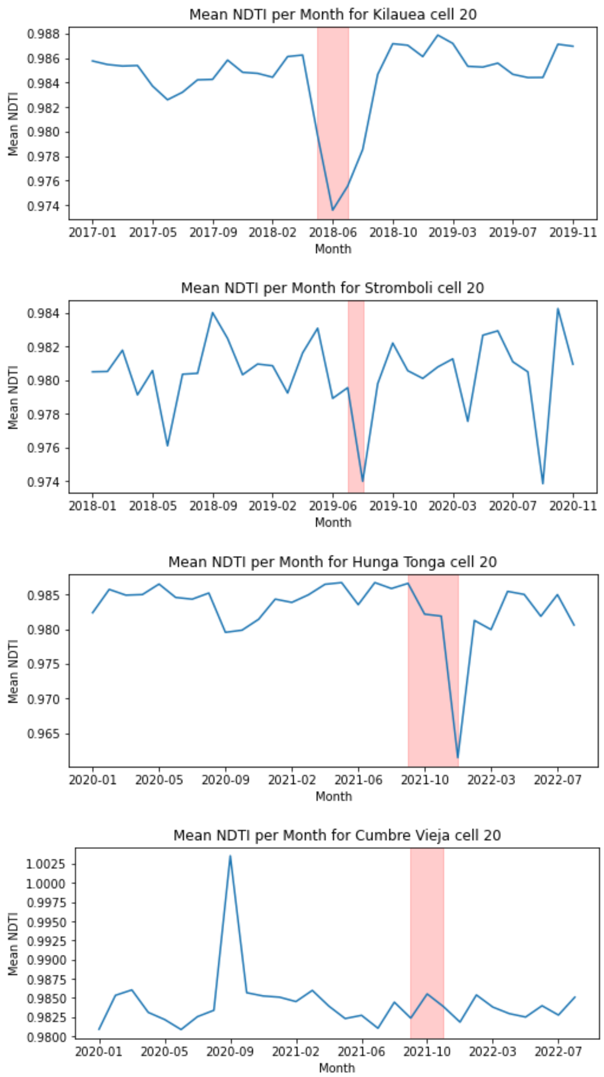


Fig. 3. Mean NDTI per month for the 5x5 cell surrounding each volcano (cell 20), with the main months of the eruptions highlighted, showing anomalous decreases in NDTI for at least Kīlauea and Hunga Tonga

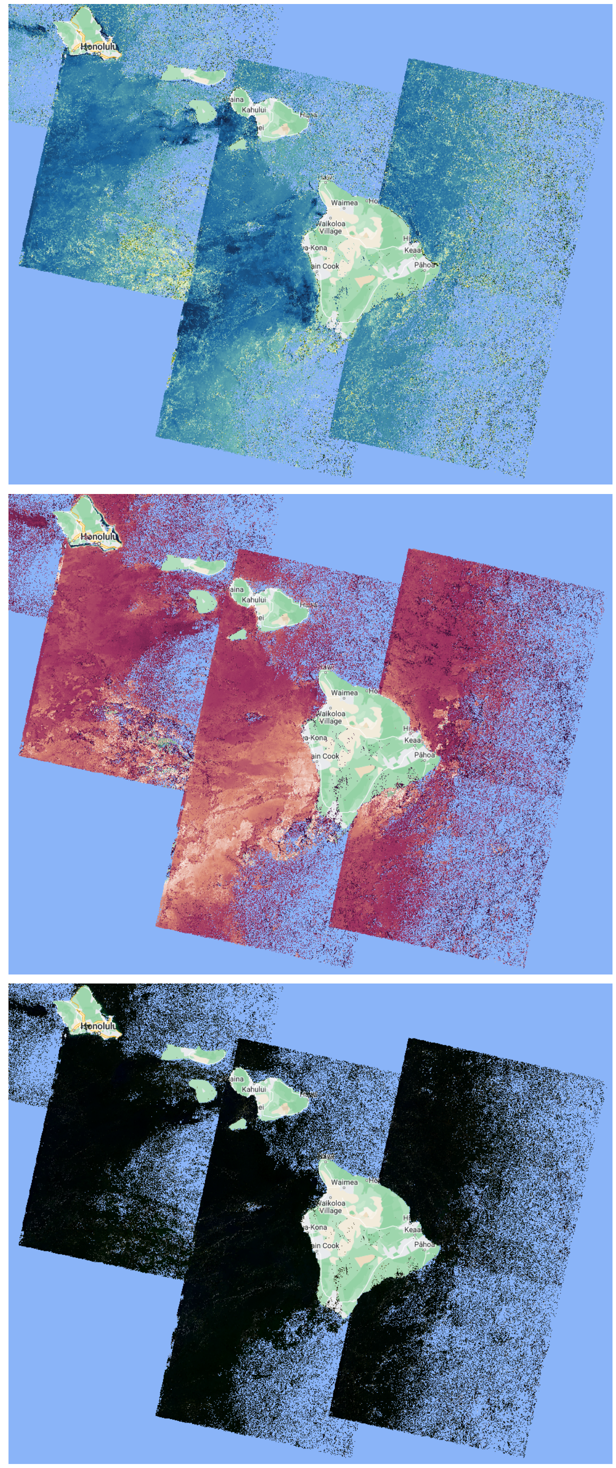


Fig. 4. NDCI, NDTI and Landsat 8 RGB data shown in GEE, mean averaged over the period 2018/04/30 - 2018/08/04 with cloud masking applied on all images prior to mean reduction

4.1.3. Impact on total AIS and fishing hours in Kīlauea and Stromboli

The sum of total AIS hours and sum of fishing hours from the GFW dataset were similarly analyzed per month in the central cells for each eruption. In Fig. 5 the sum of hours per month for both parameters can be seen for cell 19 (directly south of each of the islands), showing a peak around the time of the eruption and then a sharp decrease. This may be explained by seasonal trends (in the case of Stromboli) or noise in the case of Kīlauea (where AIS activity was much lower in the cell).

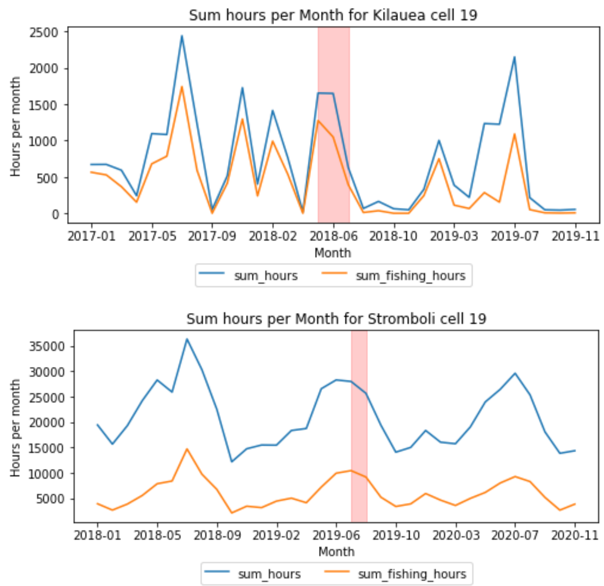
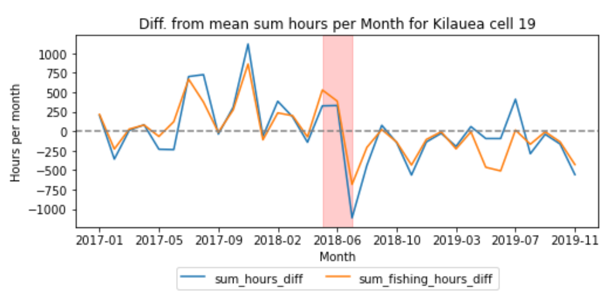


Fig. 5. Sum of total AIS hours (sum_hours) and total fishing hours (sum_fishing_hours) for Kīlauea and Stromboli, with the main months of the eruptions highlighted

To account for the possibility of seasonal trends, the difference from the mean monthly value over all three years analyzed is used in Fig. 6. This suggests the possibility of some effect of the eruption on the sharp decrease in AIS activity during and immediately after each eruption.



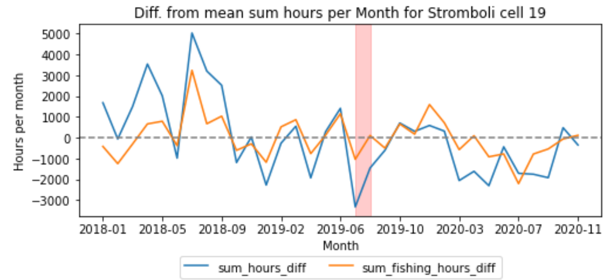


Fig. 6. Difference from mean sum of hours for total AIS and fishing over the same month in all 3 years for Kīlauea and Stromboli, with the main months of the eruptions highlighted

This analysis was similarly performed for cell 20 and adjacent cells. Of these cells, the following demonstrated anomalous changes in total AIS and fishing hours:

5. Kīlauea: 13 (increase), 14 (inc.) 19 (decrease), 20 (dec.), 25 (dec.), 26 (dec.)
6. Stromboli: 19 (dec.), 26 (dec. after eruption)

4.1.4. Anomaly detection using Isolation Forest algorithm

The parameters were also analyzed in cell 20 for each eruption using the Isolation Forest algorithm from the Scikit-learn Python library [53]. Isolation Forest 'isolates' observations by randomly selecting a feature and then randomly selecting a split value between the maximum and minimum values of the selected feature. The implementation in this paper follows the one described in [54].

Using this approach, the anomalies in NDTI described in section 4.1.2 were again detected for Kīlauea, Stromboli and Hunga Tonga. An anomalous increase in iron concentration was detected in Kīlauea following the eruption (Fig. 7), which preceded a large drop-off in concentration after. A small anomaly (that could also be explained by seasonal variations) was detected for SST in Cumbre Vieja. Finally, an NDCI anomaly was detected for Stromboli following the eruption, although this could be explained as noise.

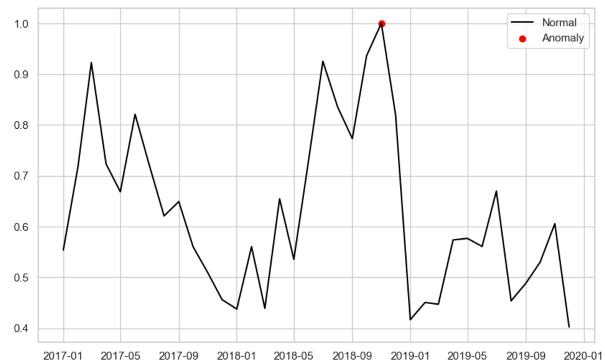


Fig. 7. Kīlauea min-max normalized iron concentration over time in cell 20, with anomaly detected by Isolation Forest highlighted in red

4.2. Socio-economic parameter analysis

4.2.1. Kīlauea volcano, Hawaii island, 2018

To understand the effect of the Kīlauea eruption in 2018, data was analyzed for the Hawaii county (which covers the Island of Hawaii, commonly referred to as "Big Island"). The data collected from [55] includes time series socio-economic parameter data related to the labor market, economic activities and services, taxes and travel performance indicators.

Fig. 8 visualises monthly data for the number of employed civilians in 2018 in comparison with monthly data collected for other years from 2015-2021 (excluding 2020, due to the anomalous effects of the COVID-19 pandemic). This comparison allows for the detection of seasonal trends in the data. In the figure, it is possible to detect a reduction in employment between the months of May and June 2018. However, it is not clear whether this effect was caused by the eruption or not as a similar effect can be observed in the corresponding months in 2021 and 2019. Therefore this may be a seasonal variation.

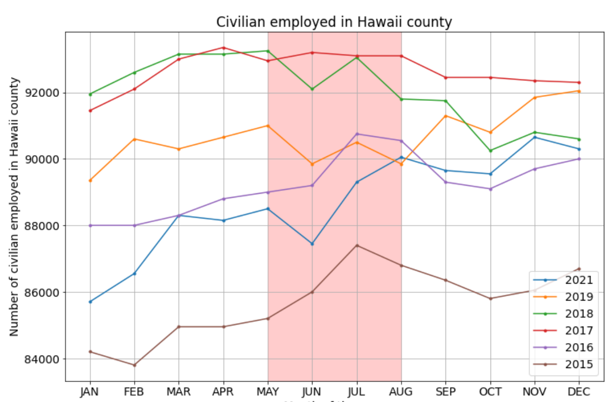


Fig. 8. Hawaii county total civilian employment per month per year from 2015 to 2021 (omitting 2020 due to peculiarities associated with the COVID-19 pandemic)

In Fig. 9, the data suggests that educational services suffered some impact from the eruption. The authors of this paper were unable to theorise a reason for the drop in educational service jobs relating to the eruption, aside from general population displacement and disruption of normal activities.

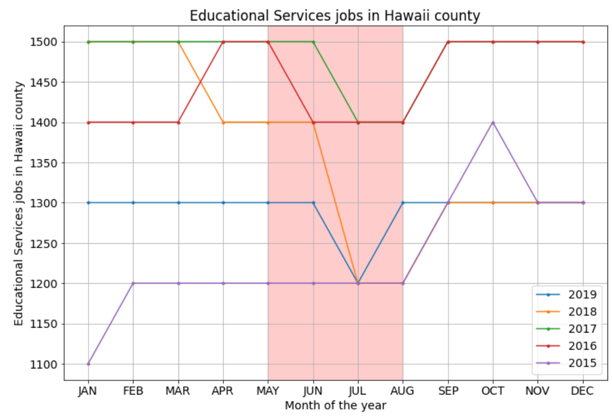


Fig. 9. Hawaii county educational services jobs per month per year from 2015 to 2019

Food services and drinking places job statistics (Fig. 10) present a drop in April 2018. If this decline occurred in May it could have been explained through a loss in tourism impacting employment in the hospitality sector. However, as the change is reflected in April, it is not clear whether the statistics given for this month have some misalignment or there is some causality other than the eruption that could have affected the sector.

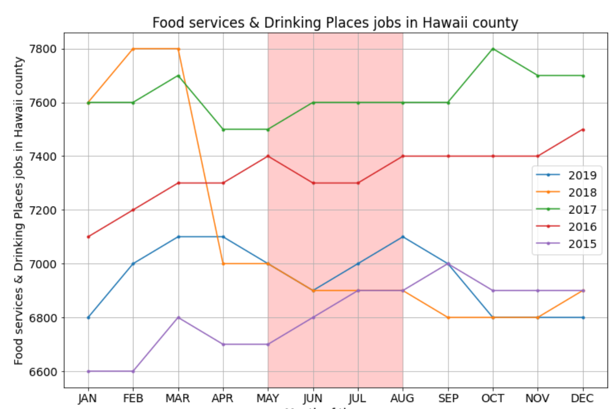


Fig. 10. Hawaii county food services and drinking places jobs per month per year from 2015 to 2019

Fig. 11 shows monthly data for the number of visitors arriving on international flights in 2018 in comparison to the monthly data collected for other years. An abrupt reduction in the number of visitors can be detected between April and May 2018. While this drop in the number of international visitors is also seen in other years, the effect is significantly greater in 2018. The number of visitors also fails to rebound as much as in 2017 and 2019 after the eruption is over. This reduction in the number of visitors may have had a causational effect on the food services and drinking places employment (Fig. 10) failing to rebound after the eruption.

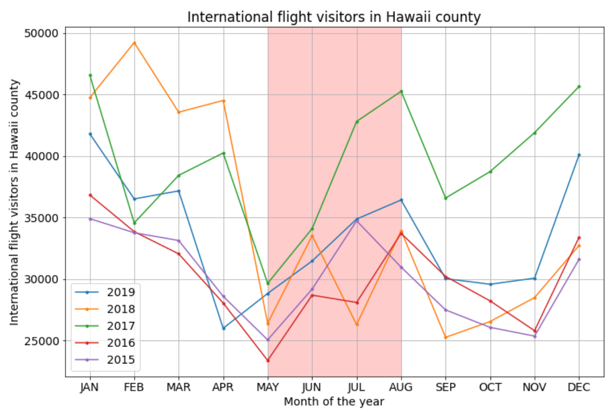


Fig. 11. Hawaii county international flight visitors per month per year from 2015 to 2019

4.2.2. Stromboli volcano, Stromboli island, 2019

The eruption of Stromboli sparked widespread wildfires, causing serious damage to agricultural heritage and vegetation loss. The agricultural areas most affected by wildfires are those in the south western part of the island, which are characterized by wild terraced olive groves and Mediterranean shrubberies and bushes. Agricultural and semi-natural vegetation areas decreased in 2018 and 2019 by 34.2% and 81.1%, respectively. Artificial areas were not significantly impacted, with the exception of industrial areas, public services and power stations, which were reduced by 14.1% [56].

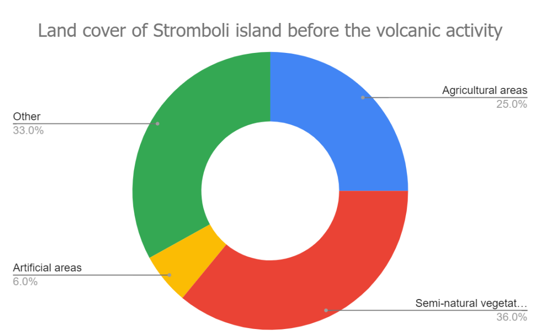


Fig. 12. Land cover percentages of Stromboli island prior to the volcanic activity

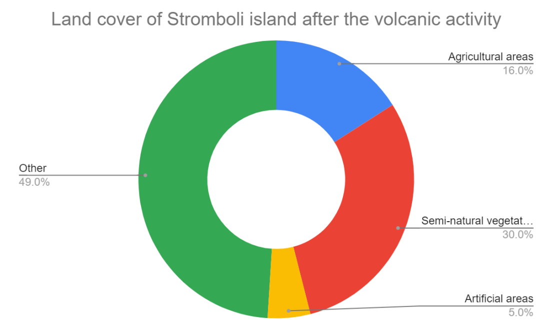


Fig. 13. Land cover percentages of Stromboli island following the volcanic activity

4.2.3. Cumbre Vieja volcano, La Palma island, 2021

The lava flow affected less than 8% of La Palma and devastated around 1,200 hectares. Lava damage destroyed 3,000 buildings; as well as roads, farmland and related networks. The Spanish authorities estimated a total direct financial impact due to damage of €862.7 million [57].

The economy of La Palma revolves around the cultivation and sale of bananas. Banana plantation was significantly impacted by the eruption in several ways. Greenhouses of bananas were destroyed by the lava flow and ash fall, while those that survived dealt with other problems: due to damage to the main water supply network the cultivations remained without irrigation and greenhouses were covered by toxic ash, blocking the sunlight and consequently affecting fruit growth. Additionally, the scorching heat and volcanic dust from the eruption destroyed banana crops, making them unsuitable for sale [58].

According to the banana growers association for the Canary Islands, ASPROCAN, La Palma produces 145,000 tons of bananas per year, and 80 million of these are produced by the western part of the island, where the volcano is located [59]. It is estimated that 1,500 of the 5,000 local owners of banana crops have been impacted by the volcanic eruption [60], as 500 hectares of banana plantations have been affected.

The volcanic activity also worsened an already severe situation for vineyards. Vineyards were suffering from water stress due to heatwaves, which had led to a reduction in production. Following the eruption, at least 7% of vineyards have been affected by lava flows and ash, resulting in significant production damage [61]. Despite the damage caused, the periodic volcanic activity may positively affect wine production in the long term, as the volcanic ash is an ideal subsoil which is fertile for the vine plants. Additionally, rocks thrown up during the eruption help retain water. This is important in an area like Cumbre Vieja which suffers from water shortages due to heat waves. These rocks are an ideal material to maintain and grow varieties of plants that do not need much water [62].

The tourism sector was also affected. It is estimated that 690 out of 16,400 tourist beds in La Palma were destroyed by the eruption [63]. According to data gathered from the Tourist Accommodation Survey of the Canary Institute of Statistics (ISTAC), the tourism industry of La Palma experienced losses of 66% in terms of overnight stays in 2021 compared to 2019 [64].

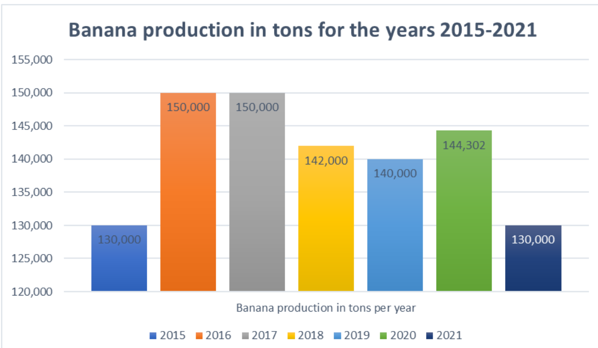


Fig. 14. Banana production in La Palma for the years 2015 - 2021

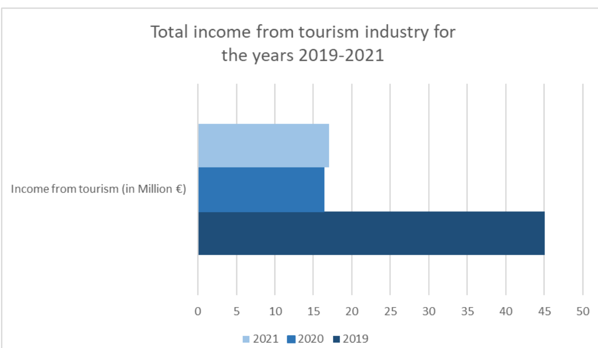


Fig. 15. Total revenue in the tourism sector for the period 2019 - 2021

4.2.4. Hunga Tonga-Hunga Ha'apai, Tonga, 2021

As per the Global Rapid Post-Disaster Damage Estimation report of the World Bank [34], the latest eruption of Hunga-Tonga-Hunga-Ha'apai affected 85,000 people (85% of the population) and caused approximately US$90.4M in damages, equivalent to approximately 18.5% of Tonga's GDP. More than 600 buildings were destroyed or damaged and crops, livestock and fisheries have been significantly impacted.

The damage is distributed unevenly across Tonga's islands with Tongatapu, the main island of Tonga, suffering the greatest losses and accounting for around 76% of the total damage costs (Fig. 16). The worst tsunami was experienced in the densely populated islands (Tongatapu, 'Eau and the Ha'apai group). The populations of the islands of Atatā, Fonoifua, and Mango were evacuated to Tongatapu, as these islands suffered complete destruction, making life there unsustainable until their reconstruction.

	Residential Buildings ($m)	Non-Residential Buildings ($m)	Infrastructure ($m)	Agriculture, Forestry, Fishing ($m)	Total ($m)
Tongatapu	9.3	27.0	14.7	18.0	68.9
Ha'apai	3.8	1.1	1.7	1.1	7.7
'Eua	1.9	0.8	1.1	1.8	5.5
Cable	*0.0*	*0.0*	*3.4*	*0.0*	*3.4*
Subtotal	**14.9**	**28.8**	**20.9**	**20.9**	**85.5**
Ash Cleanup Costs	*4.9*				*4.9*
Total					**90.4**

Fig. 16. Best estimate of direct damage (values in US$ million) for the islands of Tongatapu, Ha'apai and 'Eua according to [34]. Cable represents the damage to the undersea telecommunications cable.

	Direct Damage (as percentage of country GDP)					
	Buildings		Infrastructure	Agriculture	Ash cleanup	Total
	Residential	Non-Residential				
Tonga	3.0%	5.9%	4.3%	4.3%	1.0%	18.5%

Fig. 17. Best estimate of direct damage (as a percentage of GDP based on World Bank estimates) according to [34]

The agriculture sector is one of those most impacted by the eruption, with damages of US$20.9M accounted for. The 85% of Tongan households (approximately 60,000 people) that depend on agriculture were affected to some extent from the eruption. The damage caused to agriculture and livestock endangers both the food security and the livelihoods of the affected households.

Regarding infrastructure, approximately US$20.9M of damage has been accounted for. A combination of tsunami and volcanic ashfall damage was seen in the road, power and water sectors, with ports and wharves mostly damaged by the tsunamis.

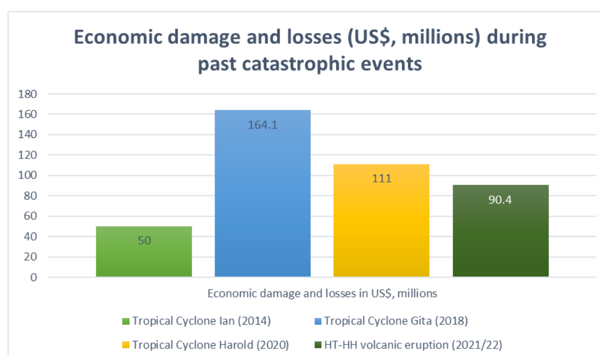


Fig. 18. Comparison of economic damage and losses (in US$ million) during Cyclone Ian, 2014, Cyclone Gita, 2018, Cyclone Harold, 2020, and the Hunga-Tonga-Hunga-Ha'apai volcanic eruption, 2021/22

5. Conclusions

This study assesses four volcanic eruptions in different locations that occurred during different dates that share the common characteristic of the lava from the eruption reaching the ocean.

The eruptions are analyzed from two main perspectives: water quality parameters (mostly derived from satellite data) and socio-economic factors.

Water quality data (SST, NDCI, NDTI, FE and SSH) was analyzed to assess correlations between the different parameters. These parameters were then analyzed individually for grid cells at 5x5 and 11x11 resolutions surrounding the volcanoes under study (but within the EEZ of the country). This revealed a likely impact on NDTI (in most cases leading to a seemingly counter-intuitive decrease, possibly driven by ash deposition from the volcano). AIS data from GFW was also analyzed to measure the impact on fishing activity around Kīlauea and Stromboli, suggesting a more significant relative decrease around Kīlauea than Stromboli. Noteworthy correlations were also observed between several water quality parameters.

The main challenge when studying the socio-economic results was the heterogeneity of data sources for the different areas. In the case of Hawaii county, there is an abundance of data accessible online and different parameters have been assessed. On the other hand, Stromboli island suffers from a scarcity of socio-economic information publicly available, likely due to the low population of the area.

The communities and industries of each island suffered negative socio-economic outcomes due to their respective eruptions.

The data studied showed losses in employment and tourist flights around the time of the Kīlauea eruption in Hawaii county. In La Palma there were also losses in terms of tourist beds and overnight stays relating to the eruption of Cumbre Vieja.

Agricultural losses were recorded in Stromboli where there was a severe reduction in agricultural areas following the eruption. Land and infrastructure damage was also reported in La Palma and Tonga. In La Palma, banana plantations and vineyards suffered economic losses, while in Tonga agricultural losses have endangered food security in the Kingdom.

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