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Recent Volcanic Eruptions and El Niño Southern Oscillations Affecting Climate

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Abstract

The Tonga submarine event refers to the volcanic eruption near the Tonga islands in the South Pacific Ocean, which produced a large plume possibly reaching the stratosphere and mesosphere. This interaction between volcanic activity and atmospheric layers can impact global climate. Identifying fundamental causes from atmospheric layers will help answer broader weather-related questions. El Niño Southern Oscillation (ENSO) is a natural climate pattern involving the warming and cooling of ocean waters in the equatorial Pacific, significantly affecting global weather patterns. Both events are compared with worldwide climate anomalies observed in the past three years. The results highlight that natural hazard anomalies cannot be solely explained by volcanic eruptions or ENSO variations.

Keywords

Tonga Eruption, Enso, Temperature Anomaly, Climate Changes

1. Introduction

The study of climate change involves multiple factors to understand why global temperatures decrease or increase. Globally speaking, we divide phenomena into two main factors, natural and anthropogenic ones. Natural has a massive impact on Earth, as the season's solar storms will create numerous hazardous events. The seasons attach Many natural changes to the Northern or Southern Hemisphere. However, some dangerous natural events occurring in isolated regions affecting the surroundings in the Hemisphere happened as the Tonga event caused unusual damage as far as observed. The Tonga eruption, February 2022, was a unique incident sending ashes, gases, and water to three atmospheric layers: the troposphere, stratosphere, and mesosphere; this extraordinary event (Hagen & Azevedo, 2024) affected Earth's global system. The Southern Hemisphere was affected by such eruptions regarding tsunamis, bolts of lightning, and rain. (Harvey et al., 2020)

The effects of Hawaii volcanoes were less and more local, disturbing most of the Northern Hemisphere. Manoa Loa is a shield volcano that erupted in November 2022, several months after Tonga. It emits SO_2 (sulfur dioxide), which reacts with Oxygen, water, and particles in the air to form sulfuric acid droplets and solid sulfate, known as volcanic smog and corrosive rain; when lava reaches the seawater, they form clouds of mist containing hydrochloric acid and airborne contaminants. Overall, the effects of Hawaii eruptions are more local. In some cases, it also profoundly affects the weather. Then, several eruptions occurred in 2022; the most harmful was in Tonga, which was supposed to disturb the global weather. Another factor affecting the climate is the seasons associated with the observed eruption. (Poli & Shapiro, 2022)

In Tonga, it happened in February 2022, in the end of summer, and affected the weather globally due to the intensity and the altitudes the explosion reached.

Notice the seasons, South and North, are opposite; therefore, when analysing a hazard event in a location is important to know what season was there.

Unfortunately, monitoring systems for the weather are precarious in many areas around the globe meaning there lack of comprehensive data, complicating the acquisition of reliable data predictions, for temperature enhancements taking place worldwide. When someone says global temperatures have risen, it's hard to understand because summer temperatures can be much higher than those in winter. Then, the average temperature does not accurately reflect what is really happening.

Each Hemisphere has its own set of seasons. The Southern Hemisphere is cold in winter, when the Northern Hemisphere enjoys Summer. These seasons have different maximum temperatures, with winter being negative and Summer being positive. The lack of comprehensive data and monitoring systems in remote areas further complicates in confirming if the temperature enhances or not globally.

Numerous regions, especially in developing countries, do not have sufficient weather stations or monitoring infrastructure to accurately measure temperatures. This data gap makes getting a complete picture of global temperature patterns challenging.

The complexity of Earth's climate system poses another hurdle. The interactions between different atmospheric layers and surface systems are intricate and poorly understood. Meteorologists primarily focus on studying and recording weather phenomena in the troposphere, the lowest layer of the atmosphere. However, phenomena occurring in the stratosphere, mesosphere, and ionosphere, such as the formation of auroras, remain poorly understood. Also, there are interconnections between those three low layers of the atmosphere and their influences on the Earth's weather.

The records of the El Niño-Southern Oscillation (ENSO) have been measured since 1950, allowing a better understanding of its effects on global weather patterns. This phenomenon occurs when the surface waters in the tropical Pacific Ocean become unusually warm (El Niño) or cool (La Niña), leading to changes in atmospheric circulation patterns. These changes can significantly impact weather worldwide, including shifts in precipitation patterns, temperature anomalies, and extreme weather events such as droughts and floods. Additionally, other oceanic events, such as the Indian Ocean Dipole (IOD) and the Atlantic Multi-decadal Oscillation (AMO), can also influence global weather patterns, although their individual contributions are not as well known. Understanding these oceanic events and their interactions with the atmosphere is crucial for accurately predicting and understanding global weather patterns. These events in the troposphere and above include atmospheric circulation patterns, jet streams, and weather systems. These processes are influenced by a multitude of factors, including temperature gradients, pressure systems, and the Earth's rotation. While evidence suggests that certain Earth's surface events and anthropogenic actions can indirectly affect these atmospheric events, their impact's exact extent and nature are not easily discernible. For example, land use and urbanization changes can alter surface temperatures, influencing atmospheric stability and weather systems' formation. However, understanding the intricate relationships and feedback mechanisms between Earth's surface events and their effects on the troposphere and above remains a complex scientific challenge.

Natural hazard events, such as hurricanes, earthquakes, volcanic eruptions, and wildfires, have the potential to interact with the troposphere and impact the global environment in various ways. Understanding these interactions is crucial to mitigate their potential negative effects on the planet. For instance, hurricanes can generate powerful winds that transport moisture and heat from the ocean surface to the atmosphere, influencing weather patterns and potentially leading to extreme precipitation events. Volcanic eruptions release large amounts of gases and particles into the atmosphere, including sulfur dioxide and ash. These emissions can have short-term and long-term impacts on climate patterns and atmospheric dynamics. By analyzing and modeling the interactions between volcanic eruptions and the troposphere, we can gain insights into how these events may contribute to global temperature fluctuations. Additionally, we will explore the relationship between the El Niño-Southern Oscillation (ENSO) events in the Southern Pacific and their potential influence on global temperature variations. ENSO events occur annually and involve complex interactions between the ocean and atmosphere, leading to significant climate anomalies worldwide. Understanding the connections between these natural hazard events and global temperature variations will provide valuable information for developing strategies to mitigate the impacts of climate change on a global scale. It is a gross mistake to associate climate change with the increase in average temperatures worldwide. The main error is the "average," which ignores the peaks that can be localized in a particular region or continent, an area on land or in the ocean. "Averages" only tell you that diverse values were taken as one during a period that covered the entire system. It is not physically accurate and hinders the possible discovery of the problem's origin. The increase in global temperatures may be happening, but this does not mean that it is associated with a particular event, such as the increase in CO_2 in the atmosphere, without knowing other factors that may be linked to the problem. Additionally, human activities must be considered when analyzing the factors associated with increased temperatures. Factors such as greenhouse gas emissions, deforestation, industrialization, and urbanization can affect climate warming locally. The anthropogenic influences are not included in this investigation since the authors understand that Northern overpopulation would be a determinant factor for any study on this matter. There are evidences that pollution and other warm gases coming from the Earth's surface and reaching the higher troposphere trapped into Hadley cells will suffer vertical winds and reaching the tropopause it becoming cooler and be back to the Earth's surface. It means the pollution and other particles will back to almost the same area they have been produced.

2. Volcanic Eruptions and Variations and Earth's Disturbances

Various studies emphasized that the Krakatoa volcanic eruption disturbed the weather, later known as the "year without summer" (Hagen & Azevedo, 2023a), and the conclusions were that eruptions cause global cooling. The Pacific "Ring of Fire" has shown that volcanic seasonality has the most active volcanoes (Mason et al., 2004), with some exceptions, including the Mediterranean, except for Etna and some oceanic islands. Those eruptions could be attached to the variation of gravitational forces influencing the crust. They also found that, on shorter time scales, seasonality in one eruption may interact with the temporal variability in the structure and circulation of the atmosphere. Material transport in the Northern Hemisphere is injected into the stratosphere during boreal winter, reducing insolation and additional surface cooling. Transport from the stratosphere to the troposphere is seasonal, reaching a maximum during local Spring. Comparing Northern (NH) and Southern Hemisphere (SH) temperature responses to volcanic forcing focused on mean annual or seasonal treads during post eruptions years in the SH. Significant SH temperature responses lag by 1 - 2 months compared to those in the NH following significant eruptions. Initial cooling starts earlier in the SH. Eruptions with an SO_2 mass between 10 - 20 Tg still need further consideration for the SH. (Harvey et al., 2020) Eruptions during SH autumn or winter induce a greater temperature response because more favorable circulations continue in winter. This SH response in autumn/winter coincides with the strongest NH cooling in summer/autumn. Understanding volcanic eruptions' impact on regional climates is essential for establishing early warning systems, mainly where climate-sensitive bio-systems and agriculture are influenced by such events.

3. The Tonga Eruptions Characteristics

On January 14, 2022, a submarine volcano happened on an uninhabited island in the Tonga archipelago. The eruption reached a powerful climax on January 15.

The blast caused tsunamis in Tonga, Fiji, American Samoa, and Vanuatu. Along the Pacific rim, damaging tsunamis in New Zealand, Japan, the United States, Russia, the Far East, Chile, and Peru. There was a combination of cyclones, such as Cyclone Cody, in New Zealand. Fiji floods occurred in Moce, Moala, Kadaire, and Taveuni islands. Tsunamis were recorded in Hawaii and Australia as well. In Asia, tsunami waves were observed in Japan (January 16), Taiwan Region, South Korea, and Russia's Kuril Islands. In South America, Peru reported tsunamis; in North America, they happened in Southern California and Northern California.

It also occurred in Alaska, the Mexican coast of Guerrero, Oaxaca, the Baja California Peninsula, Acapulco, Huatulco, and Salina Cruz. Minor tsunamis were measured in the Caribbean Sea, Texas, and Puerto Rico. Warnings in South America in Chile, Ecuador (Galapagos Islands). An earthquake magnitude above five around Tonga occurred on January 14 and subsequent days. Tsunamis happened around the Ring of Fire on the Pacific plate. On January 15, 2022, the Tonga eruption sent a shockwave worldwide (Smithsonian/USGS Weekly Volcanic Activity Report, n.d.). The waves spread in all directions, completing a circumnavigation of the globe and producing pressure peaks observed at weather stations in **Figure 1**.

Pyroclastic flows are a superheated mixture of hot rock fragments or tephra, ashes, and gases. Ash usually rises into the atmosphere as a cloud or plume, reaching up to 25 km in height. The ash may also be transported by wind, creating an ashfall covering hundreds of kilometers. Shock waves responsible for the cloud covers were reported in Japan, Utah, and Massachusetts. The pressure shock wave was observed in Chennai, India, as far as 1200 km from the eruption site. In addition, Nasa detected "gravity waves" in the atmosphere radiating outwards from the volcano in concentric circles. Atmospheric layers are full of waves that travel in all directions.

Phenomena, including geomagnetic storms, earthquakes, volcanoes, and thunderstorms, can generate atmospheric gravity to modify. Those waves propagate upward to the ionosphere. This region of the Earth's atmosphere extends from 65 km to 1000 km up. To this altitude, gases are partially ionized, forming plasmas or charged particles named ions and negative electrons. There is a continuous fluctuation in the ionosphere between plasma production and loss of ionized particles due to recombination. Volcanic eruptions can directly inject water vapor into the stratosphere. Some authors calculated that the Tonga volcanic eruption injected approximately 146 Tg water vapor into the stratosphere (Volcano Watch-Submarine Eruptions-Volcanoes on the Rise, 2005). It is four times the water vapor that the Pinatubo eruption (1992) in the Philippines lofted into the stratosphere. NASA affirms that volcanic eruptions seldom send water to a higher atmosphere; the excessive water that is injected into the Tonga volcano will remain in the stratosphere for several years. Scientists at NASA's Langley Research Center calculated that the plume from the January 15 volcanic eruption rose to 58 km at its highest point, reaching the mesosphere (Nasa Earth Observatory, 2022). Gas, steam, and ashes get into the mesosphere, the third layer of the atmosphere. "When volcanic material goes this high into the atmosphere, where the winds are weaker, the volcanic ash, sulfur dioxide, carbon dioxide, and water vapor can be transported all over Earth." Said Khlopenkov, a Nasa scientist. (Vincent, 2015)

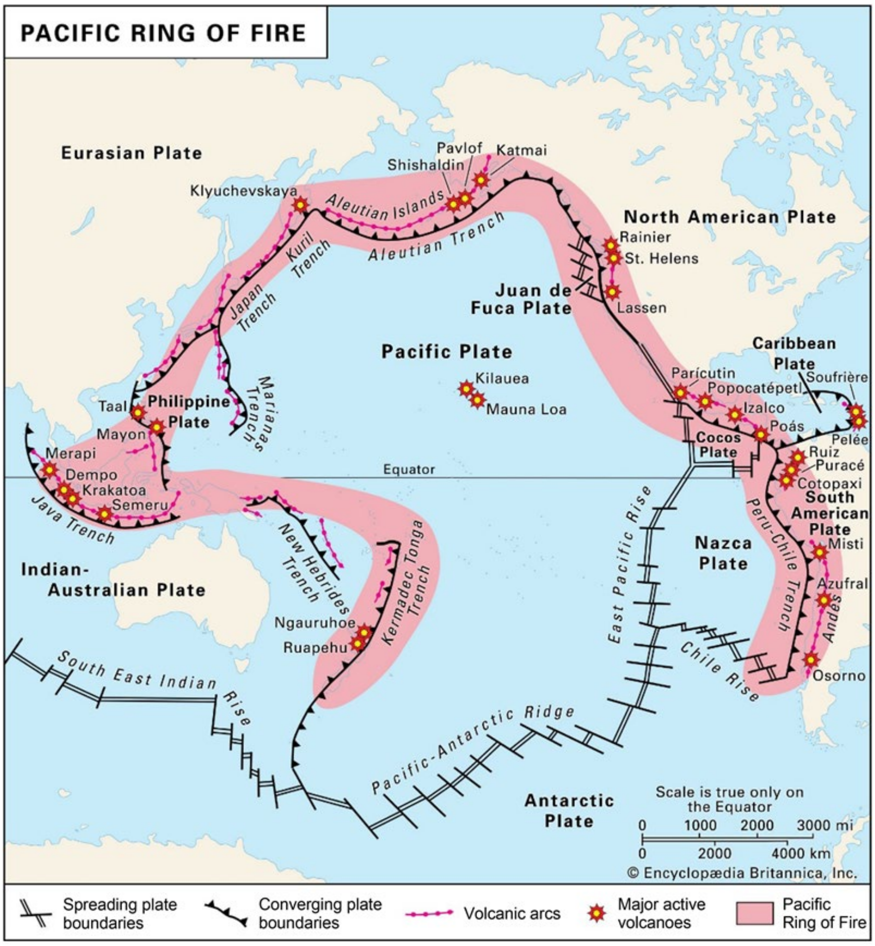

Figure 1. The Ring of Fire shows several volcanoes, including Tonga, Kilauea, and Manoa Loa. Observe the almost straight line connecting the events. (Northern and Southern Hemispheres)

It is possible that the plume has persisted into the stratosphere for nearly a month after the eruption and could stay for a year or more. The water emission from Tonga can be divided into two parts: one was kept in the troposphere, and the weather changed rapidly after the eruption. Therefore, it explains the intense storms on the Brazilian and South African coasts, with many Southern countries affected by storms even some days after the blasts. Satellite images of the January 15, 2022 eruption of the Hunga Tonga, Hunga Ha' apai volcano showed this volcano reached an altitude of 57 kilometers; this places the plume in the lower mesosphere and evidence of a volcanic eruption injecting material through the stratosphere and directly into the mesosphere (Hagen & Azevedo, 2022). The temperatures in the stratosphere and mesosphere are much lower than in the troposphere. So when the water vapor from the volcano comes back to the Earth's surface, the more significant temperature difference causes stormy weather in different locations. The temperature in those layers is around −50˚C in the stratosphere and −150˚C in the mesosphere. This means the water's vapor will condense and slowly start moving away from the volcano's location. Pinatubo expelled 37.5 megatons (Mt) of water and reached the stratosphere due to Pinatubo, with 10 Mt as vapor and the majority as ice. Based on measurements in the plume of the 2000 Hecla eruption, water is also known to reach the stratosphere in the form of ice coatings from volcanic ash. Water in the condensed phase quickly vaporizes in the dry, ambient air before the particles descend below the tropopause.

Tonga brought immediate changes in several locations around the Southern Hemisphere. Heavy rain in Pakistan storm Ana damaged Madagascar, Mozambique, Malawi, South Africa, and Zimbabwe. The report of cyclone Batsirai on January 24 affected Madagascar, Mauritius, and Reunion. Floods and landslides in Brazil are in locations with typically poor rainfall rates. The high rates of SO2 made the weather cooler. The massive amounts of water inserted into the three atmospheric layers were documented by scientists: the troposphere, stratosphere, and mesosphere. Tonga has changed the weather, including the released gases and water vapor. The year 2022 presented unusual amounts of rainfall in Brazil in the northeast, increasing the number of storms, cyclones, and Tropical storms. Also occurred sudden decreases and increases in the weather temperature were independent of the season.

The Hunga Tonga-Hunga Ha'apai volcano comprises Hunga Tonga and Hunga Ha'apai islands and shallow reefs surrounding a larger submerged structure in the western South Pacific Ocean. It belongs to twelve confirmed submarine volcanoes on the Tofua Arc, a segment of the Tonga-Kermadec volcanic arc subduction of the Indo-Australian Plate beneath the Pacific Plate led to the formation of the Tonga-Kermadec arc. Nuku'alofa, the capital city of Tonga, is situated 65 km south on the island of Tongatapu. New Zealand is 2,000 km South, and Australia is over 3,000 km to the southwest. (Loiacono, 2024)

The land area at Hunga Ha'apai grew after a short eruption in 2009. From December 2014 through January 2015, eruptive activity added land between the islands, creating the merged Hunga Tonga-Hunga Ha'apai island (BGVN 40:01). Explosions and eruption plumes, known as Major Surtseyan events, were recorded from late December 2021. These events caused significant changes to the central area of the combined island. On January 14, 2022, the activity intensified, removing most of the material from 2014-2015. On January 15, the following day, a larger eruption occurred. It created a plume that reached an altitude of at least 20 km, caused a tsunami across the Pacific Ocean, and sent shock waves through the atmosphere. Using information primarily from Tonga Geological Services (TGS), Tongan and New Zealand news outlets, Wellington and Darwin Volcanic Ash Advisory Centers (VAAC), and satellite data, this report will update the details of remarkable events that occurred on 14 - 15 January 2022.

Reports show ashfall on Ha'apai's Mango and Fonoi islands (75 km ENE). Based on satellite data, the eruption plume also contained an estimated sulfur dioxide mass of 0.05 Tg (50 kilotons). The sulfur odor was reported over Tongatapu, Ha'apai, and 'Eua. Fonoi and Mango were among the islands where ashfall was reported. By 22:30, the altitude of the plume had decreased to 18 km. The Global Lightning Detection Network (GLD360) ground-based network detected 191,309 lightning events from 03:34 on January 14 through 01:34 on January 15, or up to 30,000 events per hour.

The Tonga eruption sent ashes, gases, and water vapor to the mesosphere; it was an unusual eruption in many aspects; from a submarine volcano, those emissions reached the mesosphere. (Andrews, 2022) Other mighty volcanoes such as Pinatubo only reach the second atmospheric layer, the stratosphere, the second layer in the atmosphere above the troposphere. The characteristics of each atmospheric level make the edges for the next and have specific characteristics and names, such as tropopause, as the boundary troposphere to the stratosphere. Stratopause is the edge separating the stratosphere and mesosphere. (Gareth, 2022) The edges of each layer pursue distinctive characteristics from the layer below or above. The tropopause and abrupt change in the environmental lapse rate (ELR) of temperature from a positive rate from the troposphere to a negative rate in the stratosphere. In the stratopause, the region where a maximum temperature occurs if compared to the stratosphere is observed. On Earth, stratopause is 47 - 51 km above sea level. The atmospheric pressure is 10^{-3}compared with the sea level pressure and the temperature is −2.5˚C. Above these two layers, the mesosphere is the coldest region of Earth's atmosphere, close to −100. It extends from 50km to 85k above our planet's surface. (Xu et al., 2022) Within the mesosphere, temperatures decrease with increasing height. (Nasa Earth Observatory, 2022) The top mesosphere, mesopause, is the coldest part of Earth's atmosphere. The most crucial dynamic features in the region are strong zone (East-West) winds, atmospheric tides, internal atmospheric gravitational waves, and planetary waves.

The mesosphere lower thermosphere is the region of the atmosphere about 60-110km in altitude (Simpson et al., 2001) Atmospheric waves dominate the area, including planetary waves, tides, and gravity waves. The vapor that reached the mesosphere found the lowest temperature, becoming ice particles and leading to the noctilucent clouds. After the Tonga eruption, noctilucent clouds appear in unusual locations, as described in (Sioris et al., 2016). Noctilucent clouds appear in the mesosphere, meaning ice was formed in the layer for some source, such as Hunga Tonga ashes and emissions from the eruption. (Asher et al., 2023)

Let us briefly analyze the data obtained from NCEP CFSR climatology. Unfortunately, the data was interrupted in July when it started the El Niño in 2023. The vortex in the troposphere and stratosphere are different from each other; the tropospheric vortex affects our weather every winter. The sudden stratospheric warming is a significant disruption of the stratospheric polar vortex, beginning with large-scale atmospheric waves (Rossby waves) getting pushed higher into the atmosphere. If the waves are strong enough, the winds of the polar vortex weaken and can even reverse, becoming westerly to easterly.

Then, it would lead to displacement or splitting of the polar vortex, so cold air is locked in the polar region and will push further south into mid-latitudes. The troposphere, stratosphere, and mesosphere exhibit a rich and robust pattern of global currents. In the winter hemisphere, Rossby waves—generated when tropospheric winds interact with mountain ranges, weather systems, and temperature gradients at land-sea boundaries—drive a poleward flow known as the Brewer-Dobson circulation. The buoyancy waves, caused by smaller-scale disturbances like thunderstorms, in this specific case, the Tonga eruption injecting material directly into the mesosphere, can travel to the mesosphere. Once there, they induce a circulation pattern with poleward movement in the winter hemisphere and equatorward movement in the summer hemisphere.

Measurements in the fresh volcanic Hunga Tonga–Hunga Ha'apai plume in January 2022 revealed that stratospheric aerosol formation ended approximately three times faster than is typical in the presence of a large amount of water vapor, resulting in a high signal in aerosol extinction from an abundance of large particles. The amount of water vapor injected into the stratosphere by the eruption was estimated at 150 million tons. The number of aerosols formed in the stratosphere was faster than had ever been seen.

The quantities uncover an unexpected abundance of large particles, constraining the total sulfur injected as approximately 0.2 Tg. H_2O enhancement contributed 30% to ambient aerosol surface area and accelerated the plume's SO_2 oxidation and aerosol formation rates to approximately three times faster than under normal stratospheric conditions. The underwater volcano shot 146 metric megatons of water into the stratosphere, contributing to atmospheric warming. It was pointed out that it emitted relatively low sulfur dioxide concentrations. Volcanic sulfates commonly block sunlight from reaching Earth, and water vapor keeps it from leaving the surroundings. The large amounts of water in the stratosphere and above will persist for several years, affecting the chemistry, radiation balance, dynamic processes, and polar ozone depletion. The eruption impacts the atmosphere, creating fluctuations like surface-guided Lam, acoustic, and gravity waves. These disturbances mainly arise from Rayleigh and gravity waves, driving ionospheric disruptions. The Tonga eruption's atmospheric waves led to equatorial ionospheric plasma bubbles, observed by astronomers later.

4. Stratospheric Consequences of Tonga Eruption in 2022

Figure 2 displays the locations' latitudes that contributed to knowing the positions in **Figure 3**. **Table 1** shows the injected mass of water in the stratosphere, varying with time and time.

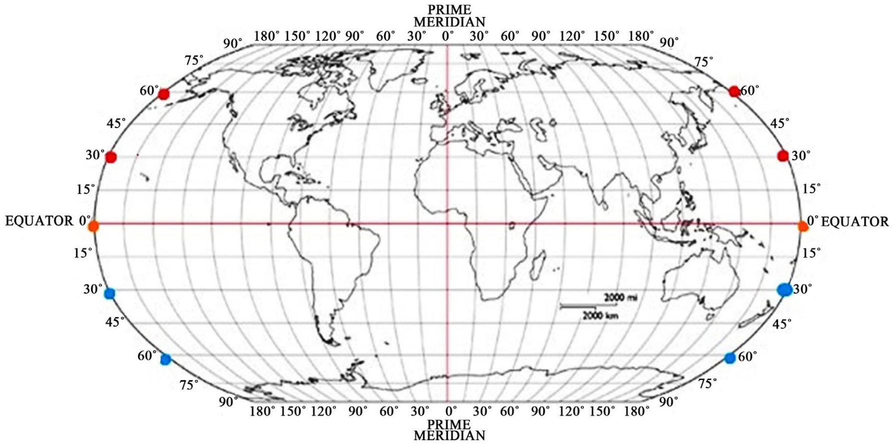

Figure 2. shows the latitudes and the locations worldwide. Compare this with Figure 3 to identify the locations of each stratospheric move. (wordatlas.com-modified)

Table 1. shows the calculation masses in Tg for both hemispheres divided by latitudes. The positive water vapor anomalies are determined using monthly means MLS vertical profiles according to the PNAS.ORG data.

LATITUDE	FEBRUARY	MARCH	APRIL	MAY	JUNE	LULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
60 - 82˚N											1
30 - 60˚N							3	3	4	7	10
0 - 30˚N	25	30	30	30	28	25	26	26	26	25	26
0 - 30˚S	116	108	95	83	72	63	57	52	52	48	43
30 - 60˚S	4	6	12	24	38	47	49	50	48	46	39
60 - 82˚S									6	9	16

Figure 3 shows the variation of water vapor in the stratosphere during 2022. The plot shows the highest amount of water vapor was 0 - 30˚S after the eruption and decreased during the year. The second highest was in 30 - 600˚S, increasing after April. This means the water vapor moves from the lower latitude south to the higher latitude. Surprisingly, the 0 - 30˚N has a maximum in March, keeping stable until the following year's summer. In the North, it is the opposite reaction; see the Table with the percentage of water vapor mass enhancement in the stratosphere by month in 2022 after the Tonga eruption for the latitude ranges 0 - 82˚N, 0 - 30˚S, and 30 - 82˚S all values extracted from the Table 1. Seasons for each Hemisphere gave the following results: in the North, the latitudes 0 - 30˚N enhanced in March-April-May, and 30 - 60˚N increased in October-December with a maximum in December. In the South Hemisphere, the maximum emissions occurred in February (after the eruption), decreasing slowly in March-May at 0 - 300˚S latitudes and the months corresponding to summer-fall.

To understand the evolution of the water vapor mass in the stratosphere and what those variations in latitudes mean, we show a map with the locations of latitude variations. Figure 2 shows how the location's latitudes contributed to knowing the positions. Tonga-Hunga Ha'apai is a submarine volcano in the South Pacific located about 30 km south of the submarine volcano of Fonuafo'ou and 65 km north of Tongatapu, Tonga's main island. It is part of the highly active Kermadec-Tonga subduction zone and has a volcanic arc. It extends from New Zealand north-northeast to Fiji and is formed by the subduction of the Pacific Plate under the Indo-Australian Plate. It lies about 100 km above an active seismic zone.

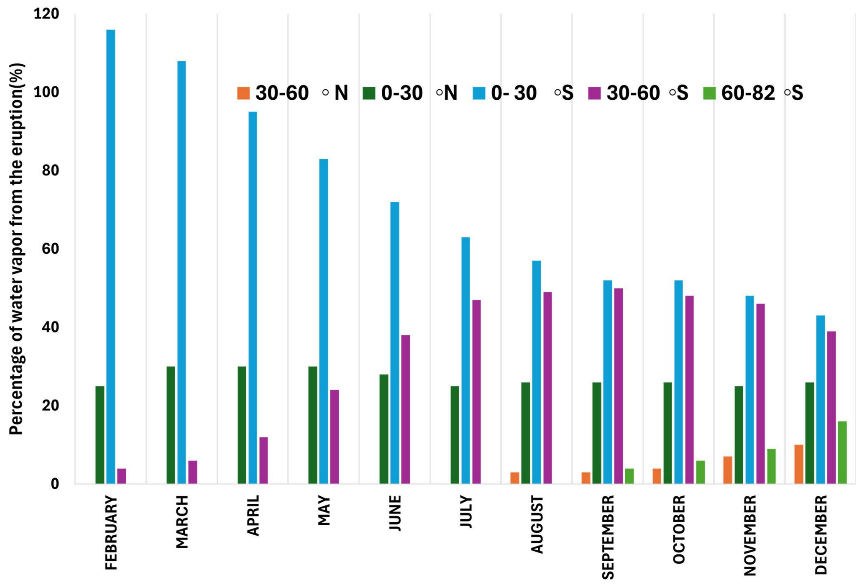

Figure 3. shows the water vapor mass anomaly in the stratosphere. Observe the increase of water vapor at higher latitudes, North and South. Observe the latitudes range,30 - 60˚S and 30 - 60˚N; they increased slowly for the higher latitudes decaying slowly.

The latitude 0 - 30˚N was practically stable all year, with a slight increase around August, the end of Summer for this latitude. The enhancement late in the year for higher latitudes, North or South, indicates water vapor transport into the stratosphere, most in the southern region, where the eruption occurred. Our observations indicated the eruption heavily affected 0 - 30˚S; however, it decreased faster in the following months following the event. The stratosphere-enhanced values were occurring all around the Southern Locations. In December, the Northern latitudes, 30 - 60˚N, reached the highest values compared with other latitude values. The seasons seem to play a role in this variation's evolution. In the Northern Hemisphere, the values at 30 - 60˚N started to show in late Summer and increased in the winter. In the South, however, the same perturbations at latitudes 60 - 82˚S began in Spring, rapidly decreasing in the Summer (December).

Now, we are comparing the worldwide maps with climate anomalies and the stratospheric variations. The aim is to find out how those variations in the stratosphere will affect the climate, creating anomalies as recorded by NOAA. Our data shows different enhancements for diverse latitudes, North and South. Starting analysis of the South Hemisphere where the Tonga eruption happened.

Next, we will examine the data collected for the climate anomalies and events during 2022 and find out if there is any coincidence between them.

The first observation concerning the event in Tonga heavily affected the latitudes 0 - 30˚S. Still, it decreased faster in the following months. However, the values remained high compared with other values in the Table. The stratosphere most enhanced water vapor around the Southern locations. In December, the latitude 30 - 60˚N had higher values than 60 - 80˚S. Seasons seem to play a role in the evolution of stratosphere latitudes. To the North Hemisphere, the values at latitudes 30 - 60˚N started to show in late Summer and increased to the winter. The South occurred the same to the 60 - 80˚S; however, it was the Springtime and rapidly rising in the summer (December).

Table 1 and Figure 2, allow examination of anomalies and events during the maximum occurrences from Tonga. As the latitudes were 0 - 30˚N, the water vapor remained constant from August to December, except in November. During this period, the North Hemisphere experienced unusual heat. Fewer and stronger hurricanes, such as Ian Fiona (USA), and powerful typhoons in the Western Pacific, such as Hinnamor and Noru (latitudes 30 - 60˚N), were recorded. Therefore, there is a possibility that the detection of increasing stratospheric water vapor in these latitudes disrupted the "normal" patterns that were in this period of 2022. In the analysis of the Southern Hemisphere between September and December, the climate anomalies between latitudes 30 - 60˚S and 60 - 82˚S were not remarkable. Still, the temperatures in November dropped to the coolest values in South America and Oceania. December to highest latitudes as 30 - 60˚N and 60 - 82˚S reached a maximum as Table 1 shows. The lowest temperature location were in the NA, Caribbean Islands, and England. Oceania's overall behavior was similar, and worldwide 2022 was warmer.

In 2023, it was impossible to find the exact data evolution in the stratosphere as in 2022. Another point is the formation of water vapor in the mesosphere, and how it could change during those years is unknown. The data is not available for analysis. Even though this inquiry found a connection between the Tonga eruption and some climate disturbances, it is limited to 2022. Posterior consequences as the debris reaching the mesosphere were detected as low latitude noctilucent clouds earlier in 2022.

Even though this inquiry found a connection between the Tonga event and some climate disturbances, it was limited for 2022. We also could determine the mesosphere was reached as the noctilucent clouds were observed in the same year. Without more satellite data, it was impossible to be sure that the discharges from the eruption had more consequences on the three atmospheric layers: mesosphere, stratosphere, and troposphere.

Using the climate maps available for the anomalies, show that at the beginning of 2023, the higher north latitudes, had heavy rain and floods, and around 45˚N and 45˚S showed the phenomena in January, February, and March, as in New Zealand and California.

In April, the north latitudes did not show perturbations, but we have Australia with heavy rain and floods to the South. The 2023 locations closer to the eruption continued to present anomalous behavior. Most of the West Pacific had heavy rain, floods, and cyclones. All the anomalies observed worldwide stopped around July, and the globe experienced the highest-ranked July temperature since 1850; in the following months, August, September, and November, the temperatures were higher with unusual storms in different locations, most at the Atlantic sides. 2024 starts the year with the highest temperatures, Jan-Mar warmest since the global records began in 1850, with a sudden decrease in April. Although 2022, 2023, and the beginning of 2024 had high-temperature anomalies, connecting the available data on atmospheric disturbances to the Tonga eruptions is impossible. Next, we are going to make a fast analysis on the Enso phenomenon before and after the volcano.

5. Enso Variations Last Three Years

The episodes with Enso by year have been recorded from 1950-2024; however, we will concentrate on the last three years, which are paramount in this analysis. The records pointed out that after 2019, La Niña has been occurring closed, and the neutral intervals became shorter. The Tonga eruption happened during a La Niña event in one of the longest periods, 2020-2023, with brief intervals and neutral episodes. (Wilmouth et al., 2023)

In 2023, El Niño occurred after a shorter occurrence of neutral water, and the warm event had a maximum lower than the one in 2015. Compared to December 2015, it was 2.6 Oceanic Nino Index (ONI), and in December 2023 was 2.0 ONI. In other years, El Niño's maximum occurrences are shown in **Table 2**.

Table 2. Shows the years when El Niño occurrences reached a maximum ONI value. It was 1972, 1982, 1998, 2015.

YEAR	SON	OND	NDJ
1972	1.8	2.1	2.1
1976	0.8	0.9	0.8
1977	0.7	0.8	0.8
1982	2	2.2	2.2
1986	0.9	1.1	1.2
1987	1.5	1.3	1.1
1991	0.8	1.2	1.5
1998	2.3	2.4	2.4
2014	0.5	0.6	0.7
2015	2.4	2.6	2.6
2023	1.8	1.9	2

Any of those years showed maximum values close to 2015 but 2023. Indeed, compared to 2023, it was one of the lowest maxima. Now, we did **Table 3** for La Niña events. Observe that La Niña episodes occur for two or more years, such as 1973-1976, 1998-1999, 2010-2011, and 2021-2023. The approximate interval for the La Niña event is 11 years, like the Solar cycles; however, it does not follow the same years between each other.

On the other hand, El Niño most happened in random years, and its maximum has been in 2015. Table 3 shows the maximum of La Niña episodes. Therefore, only La Niña presented periodical evolution. We considered all values for La Niña, as negative, suposing the water are cooling during those events.

Table 3. La Niña episodes are likely to occur in 11 years.

YEAR	SON	OND	NDJ
1973	−1.7	−1.9	−2
1974	−0.6	−0.8	−0.6
1975	−1.4	−1.6	−1.6
1998	−1.4	−1.5	−1.6
1999	−1.3	−1.5	−1.7
2010	−1.6	−1.6	−1.6
2011	−1	−1.1	−1
2012	−1.2	−1.3	−1.2
2022	−0.8	−1	−1
2023	−1	−0.9	−0.8

Table 3 shows the value variation for the La Niña event. La Niña episodes last two or three years, as in 1973-1976, 1998-1999, 2010-2011, and 2021-2023. The interval for the La Niña event is approximately 11 years, similar to the Solar Cycles. On the other hand, El Niño most occurred in random years, with a maximum value in 2014 (see Table 2). Therefore, only La Niña shows almost periodical behavior. In the following paragraphs, we will review how events such as the Tonga volcano or Enso could explain the catastrophic variation in the climate in the last years.

Discussion on atmospheric events last year.

Although both events discussed, the Tonga eruption and Enso variations were significant for the climate variations, and some natural hazard events seem closely connected with last year's climate change anomalies, the scientists cannot have a straight connection with all variations observed worldwide. (Hagen & Azevedo, 2023b) In April 2024, the global surface temperature consistently brought catastrophic consequences in South Brazil, East Africa, UAE and Oman, Southwest Russia. Heavy rain in Southern Brazil and Afghanistan in May and June and heavy rain in El Salvador, South Africa, Bangladesh, and Southeastern China persist. There is a possibility that the ashes expelled to the stratosphere and mesosphere are dissipated. Therefore, any effects of those particles and dust on the higher atmosphere levels vanish, and the system returns to normal conditions. So, we will observe normal climate variations in the following months after the turmoil caused by the disturbances on the higher levels of the magnetosphere.

Hence, it is paramount to discover the unknown connections to the climate, perhaps anthropogenic events enhancements. Although there is little evidence of human interference in the last three years, they are in some areas. 2020-2024 requires a new evaluation of those interferences from the ground to the atmosphere.

The authors are sure that more strategic measures must be added to understand what is happening with climate changes worldwide, proposing an intense data collection of natural events and the ones made by humans, such as wildfires and fracking. Events happening regularly in locations such as the Atlantic Ocean or the Indian Ocean lacked data. We can't affirm that only anthropogenic events are essential for those places.

This last part of our study will focus on climate variations in the previous decade or almost (2014-2024). The chart displayed in the **Table 4** compares the period 2019-2024 with the temperature records in the NOAA catalog.

Table 4. Temperatures Worldwide Enhancements 2019-2023 (//ncdc.noaa.gov/sotc) The data from 2019-2024 (April) compared the temperature with the worldwide records of global average temperature began in 1880.

YEARS	Temperatures
2019	2nd highest since 1880
2020	2nd highest since 1880
2021	6th highest since 1880
2022	6th highest since 1880
2023	highest since global records in 1880
2024	highest global temperatures January-April

Table 4 displays data from 2019 since NOAA could not analyze the years of climate anomalies before this year. The 2022 presented the Tonga eruption as we discussed the impact on the weather worldwide. (Robock, 2012)

In the subsequent years, an increase in the temperatures for each month is observed. Finally, from April 2024, the temperature began to decrease. Our investigation into climate events anomalies worldwide will offer more details about before, during, and after the eruption in 2022. Three central regions are analyzed in the Pacific plate, divided into Earth North Pacific (ENP), Western North Pacific (WNP), and South Tropical Pacific. The other regions are the Indian Oceans (North and South) and the Atlantic Hurricane Season. Observe the last one happens around or above the Equator. Our plots are constructed following the data records since 1850 (the first year in the records); the negative signs mean they were dated as below average. The plot will show the evolution of events in those locations since 2009. Starting with the Pacific Oceans, the variations are highly positive, showing an almost periodical behavior with positive events in Western North Pacific and East North Pacific and negative for Southern Tropical Pacific. [Worldwide Mapsbymonth] The highest positive occurred in 2015 for East North Pacific and East North Pacific in 2018. This region never reached negative numbers after 2012. See the **Figure 3**.

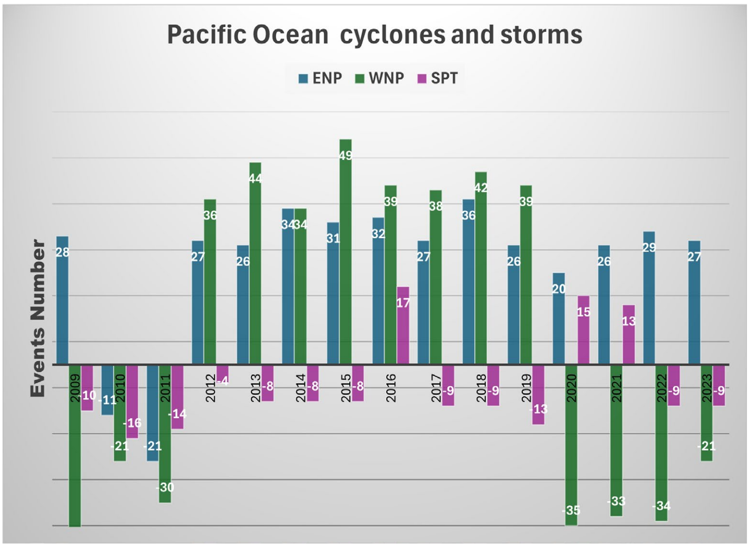

Figure 4. shows the evolution of events between 2019-2023. Negative numbers mean that the seasonal activity in each region, such as ENP, WNP, and SPT, they are positive for average or above activity and harmful for the ones considered below activity. (//noaa.gov)

The following investigation on the Atlantic and the hurricane season shows an intense depression between 2013-2016, which means the hurricane season was weaker than expected. In 2020, it reached double the number expected. Figure 5 displays that in the interval examined, there was a period from 2013 to 2016 in which a few hurricanes happened with weaker power compared with the following years. (Hagen & Azevedo, 2024) The most important was in 2020, when the hurricane season peaked at 43 intense events in the region studied. The Atlantic hurricane season does not seem to be attached to any of the main events studied here, such as Tonga eruptions, submarine events, the Kilauea or Manoa Loa events, and Earth's surface events in the Pacific.

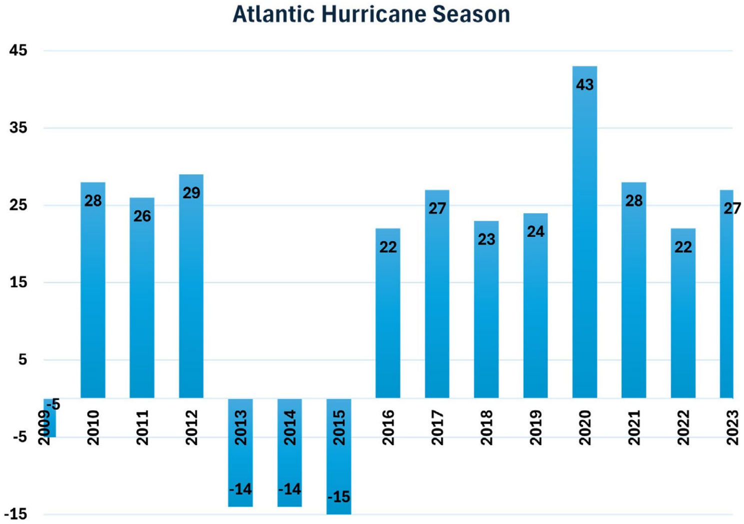

Figure 5. The hurricane season evolution, 2009-2023; the negative number means the hurricane season in those years was far below the other years; it is a comparative amount.

Enso variations seem unlikeable to affect the hurricane season; both La Niña and El Niño were not active in 2020 or at least not expected variation high as in 2023 (El Niño) or 2022 (La Niña). Both volcanoes and Enso were not directly connected with the hurricane's evolution in the Atlantic. (Storm Events, n.d.)

The last plot, Figure 6, shows the Indian Ocean's cyclone season and immediately observes that Southern India is more active; however, it is also less consistent in positive values. It means the Southern Indian is stormier than the North. The maximum occurrences in the South occurred in 2019, and a minimum in the same region ten years earlier in 2009. The minimum occurred in 2013, 2022.

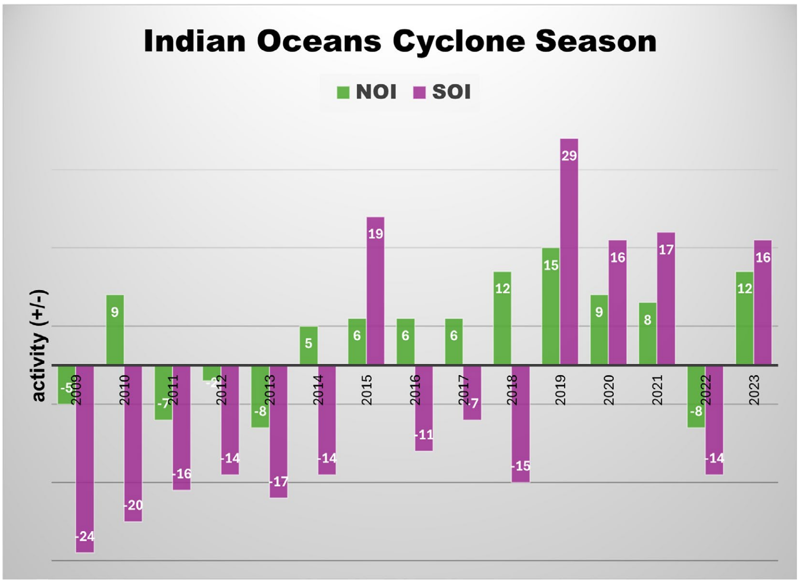

Figure 6. shows the evolution in the Indian Ocean cyclone season. The negative number means the activity in the year was below the average expected.

Next, a quick analysis of how the world temperatures varied from 2019 to 2024, meaning pre-volcano, during, and after the eruption. The analysis for 2024 is not complete since the year has not finished, see Table 3. The last five years have presented increased global temperatures, reaching a maximum in 2023 through 2024. The investigation shows that during 2024, the current year, between January and March, the global temperatures were at the highest record since 1850. April, the temperatures decreased as follows: the 11th consecutive record, May 12^{th} consecutive record, Jun 13^{th} consecutive record, and July 14^{th} consecutive record, all compared with 1850 when the records began. We conclude that several unknown factors are not attached to the Tonga event. Finally, 2023 had a high occurrence of unusually high temperatures associated with a small number of events. Although both events discussed, such as the Tonga eruption or ENSO variations, were highly important for climate variability and the surge of natural hazard events, they seem closely connected with the last years of climate change. This is primarily due to the uniqueness of the Tonga event 2022; however, scientists cannot find a straight connection between all variations observed worldwide and natural events only. This means there is not enough data in the stratosphere or mesosphere to show how the debris and ejections from the volcano moved into those layers over time.

The observations in April 2024 showed that the global surface temperature suddenly decreased worldwide. Since then, the global surface temperature has decreased in May and June. These sudden temperatures diminished and brought catastrophic consequences and conditions worldwide, such as floods in Southern Brazil, East Africa, UAE, Omana, and Southwest Russia in April 2024. There is persistent heavy rain in South Brazil and Afghanistan in May and June and heavy rain in El Salvador, South Africa, Bangladesh, and Southeastern China. It seems two effects after Tonga smoothly the effect over stratosphere the climate system was disturbed showing a different climate scenario than the usual expects for this time of the year.

We reviewed the influences of volcano eruptions in 2022 and the Enso variations on natural hazard events worldwide. It also investigates whether such events could influence the enhancement of temperatures that occurred in 2023. 2023 was an anomalous year with a sudden increase in the global temperature and few hazard events worldwide. The data shows several eruptions in Tonga in the Southern Pacific, Manoa Loa, and Kilauea in Hawaii in 2022; it seems to have a low impact on the climate anomalies observed in 2023. The Enso phenomenon showed a long period with La Niña followed by El Niño and a gap of neutral temperatures, and El Niño was not stronger than the one in 2015. Therefore, neither phenomenon correlated with the higher temperatures in 2023. The anthropogenic emissions most affect the Northern Hemisphere, as studied by the author; before, during this time, no particular gas or pollution increase or carbon monoxide was detected, and there is a real effort to decrease the emissions worldwide. All the evidence pointed out that there is a possibility that a third unknown factor, ignored by this author and other scientists, plays a role in the sudden increases in temperatures worldwide. Despite scientists denying this factor, we suggest further investigation into the Solar Cycles and how they could disturb the weather and climate, [https://www.ncei.noaa.gov/access/monitoring/monthly-report/]. We also noticed that the atmospheric layers seem to trap numerous gases at the two lower layers, the troposphere and stratosphere, and the connections with the mesosphere and how its gases and particles are displaced in those higher layers are primarily unknown. The particles moving from Earth's surface are trapped in Hadley cells, and once they reach cooler altitudes, they are back to the ground. Most pollution and gases are enclosed in such cells in quasi-elliptical movement from the ground and, once in higher altitudes, are forced to be back. The Northern Hemisphere has at least nine times more people creating dust and pollution; unbalanced temperatures and other phenomena occur due to those emissions. Understanding how a place such as China or the USA will be responsible for increasing crescent unbalanced temperatures and other catastrophes around their locations would be essential. The Southern Hemisphere has the most untouched forests and still clean waters, and there is much less evidence that the temperatures are increasing at the same pace as the Northern Hemisphere.

6. Conclusion

Our paper showed that partially, the disturbances in the weather that occurred in the last years after the volcanic eruptions in the Southern and Northern Hemispheres did not impact temperatures as expected. The Pacific events, such as Enso, were never corroborated, although it is challenging to prove directly that the Pacific events could relate to worldwide events.

Anthropogenic causes do not justify that natural hazard events are interconnected or dependent on eruptions or Enso.

Those active volcanoes are located around the Pacific Ocean. The same happens with ENSO variations, which have many connections with the seasons. Since it occurs around the Equator or in the Southern Hemisphere during the summer.

Some weather disturbances remain unexplained by known events. This paper does not focus on other regions like the South Atlantic or Indian Ocean due to a lack of data. Anthropogenic effects aren't examined here as no catalog currently addresses these actions. Human activities are linked to droughts, increased wildfire frequency and severity, greater desertification, and rising local temperatures. Despite the current inability to obtain comprehensive climate data globally, this paper concludes that natural causes primarily drive climate hazards, with anthropogenic impacts being more localized in densely populated areas.

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Conflicts of Interest

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

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