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Influence of Volcanic Activity on Weather and Climate Changes

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Abstract

This paper examines possible connections between volcanic eruptions and their consequences on the weather. Gas emissions, such as CO_2 and SO_2, are vital in the troposphere and change temperatures on Earth's surface. The water vapor discharges can be moved for three atmospheric layers creating extra atmospheric rivers and disrupting the Polar vortex. All those deviations will bring consequences to the weather. It depends on the intensity, the emission type, the kind of volcano, and the location. Then, eruptions can change the atmospheric layers with sudden fluctuations unexpected for the season.

Keywords

Volcanoes, Tonga, Manua Loa, Kilauea, Climate Changes

1. Introduction

As mentioned before, the Northern Hemisphere has most of the land on Earth and 68% of the total mass. Five of the planet's continents (they are seven) are in the Northern. They are Asia, the world's largest continent, with Russia's largest country by area. Resuming a small portion of South America is also located in the Northern. Therefore, most of the severe climate changes on land are occurring in the Northern.

The study of volcanic eruptions and the weather consequences is paramount for understanding climate change better.

The authors formally worked on the connections between Solar events and climate change [1] [2] [3]. Now, the aim is to ally this knowledge to the volcanic eruptions and consequences for the climate.

This paper focuses on volcanic eruptions and how they change the weather. Several factors from eruptions allow disturbances in the atmospheric layers—

mainly the troposphere, stratosphere, and mesosphere. Volcanic eruptions inject sulfur gases into the stratosphere, which convert to sulfate aerosols with an e-folding residence time of about one year.

Large ash particles fall out much more quickly. This aerosol cloud's radioactive and chemical effects produce responses in the climate system. For the tropical eruption, the aerosol layers heat the stratosphere; this heating is more significant in the tropics than in the high latitudes producing an enhanced pole-to-equator temperature gradient, especially in winter in some cases and circumstances. According to meridional aerosol distribution, there are three types of volcanoes: North Hemisphere (N.H.), South Hemisphere (S.H.), and equatorial. Fei Liu and others [4] found that global monsoon (G.M.) precipitation in one Hemisphere is significantly enhanced by the remote volcanic forcing occurring in the other Hemisphere. N.H. volcanic eruptions are more efficient in reducing the N.H. monsoon precipitation than the equatorial ones, and so do the S.H. eruptions in weakening the S.H. monsoon. Volcanic activity changes the atmospheric circulation, stratospheric chemistry, the hydrological cycle, and ocean heat content in a complex way for months to years, to even decades after the eruption.

The mechanism by which a volcano disturbs climate is the injection of large amounts of SO_2 gas into the stratosphere. SO_2 reacts with O.H. and H_2O to form H_2SO_4 + H_2O aerosols. Large volcanoes can provoke global cooling for 2 or 3 years. According to the authors, the global monsoon (G.M.) is enhanced in the Southern Hemisphere, and volcanic eruptions reduce the N.H. monsoon. They concluded that explosive volcanoes reduce G.M. precipitation a few years after the eruptions. The NH and S.H. monsoon have different responses to extratropical explosive volcanoes because of the asymmetric aerosol distributions.

In this paper, we are analyzing the factors that will cause disturbances in the climate due to the volcanoes and their connections with Earth's weather. Most of the particles spewed from volcanoes cool the planet by shading incoming solar radiation. Because of atmospheric circulation patterns, eruptions in the tropics can affect climate in both hemispheres, while eruptions at the mid or high latitudes only impact the Hemisphere they are within. As an exception, if the discharges reach the mesosphere, which causes the volcano emissions affect the weather worldwide.

Sulfur dioxide emitted by volcanoes cools the climate. The sulfur dioxide moves into the stratosphere and combines with water to form sulfuric acid aerosols. The sulfuric acid makes a haze of tiny droplets in the stratosphere that reflects in incoming solar radiation causing the Earth's surface to cool. Factors in the eruptions will determine the volcano's potential to cool or warm the weather. If the volcano expelled more sulfur dioxide, the temperature in other locations became chillier. If it is CO_2, the temperature will increase [5].

2. Volcanic Eruption Mechanisms on Climate Changes

The first effect of volcanic impact on the global climate is to reduce the amount of solar radiation reaching the Earth's surface, lowering temperatures into the troposphere and changing atmospheric circulation patterns.

Large-scale volcanic activity may last only a few days. However, the massive outpouring of gases and ashes can influence climate patterns for years. Suppose the eruption cloud is rich in SO_2. In that case, the eruption will produce a long-lived aerosol cloud in response to the sulfate aerosols that form over the region over the next few years. Following events, those aerosol particles can linger for as long as three to four years in the stratosphere. Significant eruptions alter the Earth's radiative balance. The volcanic aerosol clouds launch a substantial amount of the incoming solar radiation, an effect known as "radioactive" forcing, which may last for two or three years after a volcano eruption. A volcano eruption spews out some main products. The ashes are produced during an explosive phase. The effusive phase produces lava. It is supposed to create a limited climatic impact. Another component of emission during the eruption is volcanic gas. They are sulfur, carbon, chloride, and fluoride. Water vapor also is abundant gas released during combustion. Once these gases are injected into the atmosphere, they react with other compounds forming acid particles or aerosols like hydrochloric acid (HCl). Aerosols, that form in the stratosphere remain there, impacting the climate for 3 - 4 years following the eruption. The aerosols in the troposphere will be washed out by precipitation in a short period, around one or two weeks [6].

To understand how volcanoes influence the weather, it is necessary to know what material was released into the atmosphere and which layers it reached.

The SO_2 and CO_2 impact on Earth; however, seldom times is it discussed how water vapor in the atmosphere impacts the weather. Zielinski pointed out that an equatorial eruption needs to reach about 15 km to penetrate the tropopause regardless of the season. These more minor eruptions will impact climate if it is located in the mid to high latitudes. He also explained that outbreaks occurring in mid-or-high latitudes would affect the hemisphere where the eruption originates, not the global climate. The reason is the low mixing of air masses across the equator, thereby limiting the gathering of aerosols that could migrate into the opposite hemisphere. Recently it happened in Manoa Loa, Hawaii. We observed this considerable impact from the recent Manoa Loa eruption in the Northern Hemisphere. Volcanic aerosols also serve as surfaces for heterogeneous chemical reactions that destroy the stratosphere ozone, lower ultraviolet absorption, and reduce the radiative heating in the lower stratosphere, but the net effect is still heating. Tropical eruptions produce asymmetric stratospheric heating creating a stronger polar vortex and associated positive mode of Arctic Oscillation in tropospheric circulation. Volcanic eruptions emit gases, H_2O, N_2, and CO_2 (plus abundant). The atmosphere is mainly composed of N_2 (78%) and O_2 (21%), both had sources of volcanic emissions. The volcano emissions have explosive eruptions emitting sulfur species to the stratosphere, mainly in the form of SO_2, sometimes as H_2S. The sulfur species react with H_2O and resulting H_2

SO_4 aerosols, which produce the dominant radiative effect from volcanic eruptions. The threshold amount from volcanic SO_2 emissions required to make some climate impacts have yet to be discovered. Nasa guesses from prior eruptions that an injection of roughly five teragrams (5 million metric tons) of SO_2 or more into the stratosphere has sufficient potential for climate forcing of −1 W (watt) per square meter and warrants the application of substantial observational assets [7].

Clorofluor carbons (CFCs) in the atmosphere start a chain of chemical reactions on aerosol surfaces, destroying ozone molecules in the mid-latitude stratosphere and intensifying observed stratospheric ozone depletion.

Kilauea and Etna produced significant quiescent tropospheric emissions of sulfate precursors. However, it is necessary for a dramatic change in these emissions to observe disturbances in the weather. The volcanic eruption affects the stratospheric cloud on solar radiation. Some radiation is scattered back to space, increasing the planetary albedo that cools the Earth-atmosphere system. Explosive eruptions, such as the 1980 May 18 (Spring) Mount of St Helen's eruption, produce significant local weather perturbation but short-term climate effects. The several submarine eruptions influence most of the rainfall occurrences. After several submarine events were investigated, there is also an indication that rainfall increased five months later. Those results differ from those found for eruptions on land, such as Pinatubo (1992, Summer) and Krakatoa (1883, Fall, Winter), which relate to draughts instead [8].

3. Some Cases Studied

1) Krakatoa effects

Krakatoa is a caldera in the Sunda Strait located between the islands of Java and Sumatra, Indonesia. The last famous eruption was in 1883; a fourth island, Anak Krakatau, emerged from the caldera formed by the outbreak. Krakatoa is a Strato volcano, and this type of volcano is often found above subduction zones; it is located on the Eurasian and Indo-Australian plates. The August 27, 1883 explosion of Krakatau Volcano in Indonesia is one example of an eruption-caused tsunami. The eruption generated a 30 meters tsunami in the Sunda Strait, which killed about 36,000 people and washed away 165 coastal villages on Java and Sumatra.

The explosions sent an estimated 45 km^3 of volcanic ash and debris into the atmosphere, darkening skies up to 442 km from the volcano. Near Krakatoa, the Sun did not be seen for about three days [9].

The explosion sent so much volcanic ash into the atmosphere that it filtered the amount of sunlight reaching Earth's surface. As a result, temperatures went back to normal again in 1888. For months after the Krakatoa eruption, the world experienced unseasonably cool weather, brilliant sunsets, and prolonged twilights due to the spread of aerosols throughout the stratosphere. The year after the Krakatoa eruption, the average global temperature fell by as much as 1.2˚C.

Weather patterns became chaotic for years, and it took five years for the temperature to return to normal (1888). It was caused by an unusual amount of sulfur dioxide (SO_2) sent to the stratosphere. Subsequently, it is located near the Equator. Both ejected similar amounts of ashes and gases into the atmosphere. The explosion of Krakatoa may have helped to volcanic winter-like conditions; the four years following the explosion were icy, and the Winter of 1887-1888 included intense blizzards. Record snowfalls were documented worldwide.

2) Pinatubo eruption effects

On June 1991, Mount Pinatubo in the Philippines erupted, ejecting vast amounts of ash and gas into the atmosphere so high that the volcano's plume penetrated the stratosphere. In addition, Pinatubo injected about 15 million tons of sulfur dioxide into the stratosphere. It reacted with water to form a hazy layer of aerosol particles composed primarily of sulfuric acid droplets. Over the next two years, stratospheric solid winds spread these aerosol particles around the globe.

Since the stratosphere has no rain clouds to wash out pollutants, the heavy influx of aerosol pollutants, like the plume from Mount Pinatubo, remained in the stratosphere for years until the processes of chemical reactions and atmospheric circulation could filter them out [10].

In the case of Mount Pinatubo, the result was a measurable cooling of the Earth's surface for almost two years [8]. The Pinatubo contributions were: Cooler air temperatures over Northern Hemisphere by up to 2˚C during the 1992 Summer, Warmer air temperatures in the NH by up to 3˚C in the winters of 1991-92. The annual temperature in the boreal zone increased by 9.7 mm. Global warming was slowed after the Pinatubo eruption because of the cooling effects of volcanic aerosols.

The following two sections are about the volcanoes which happened in 2022 and suddenly changed the weather in several locations. The first one is Tonga, whose eruption was on January 15, middle of Summer in the Southern Hemisphere [11]. The main difference between Tonga and Krakatoa was the location. There are similarities to the atmospheric layers reached; however, Tonga went through three atmospheric layers, and Krakatoa did not have instruments to detect that time. The second, in 2022, was in Hawaii, Manoa Loa, on November 27 in the late fall of the Northern Hemisphere.

4. The Tonga Eruption

On January 14, 2022, a submarine volcano happened on an uninhabited island in the Tonga archipelago. Only 119 submarine volcanoes in Earth's oceans and seas have erupted during the last 11,700 years. There are estimated to be 40,000 to 55,000 seamounts in the global oceans.

Most are not well-mapped, and many may have yet to be identified. Most are unnamed and unexplored. The additional water discharge to very high altitudes increased the importance of the Tonga volcano in worldwide weather.

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 cycles 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, 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 [12].

Minor tsunamis were measured in the Caribbean Sea, Texas, and Puerto Rico. Warnings in South America in Chile, Ecuador (Galapagos Islands). It occurred earthquakes magnitude above five around Tonga 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 [13]. The waves spread in all directions completing a circumnavigation of the globe and producing pressure peaks observed at weather stations. 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. On the ground level, the ionosphere is subject to weather. When atmospheric gravity waves generated by a volcanic eruption (or other sources) reach the ionosphere, they trigger traveling convection vortices [14]. These compression waves quickly enhance plasma density fluctuations and travel thousands of miles around the globe.

Volcanic eruptions can directly inject water vapor into the stratosphere. Some authors calculated that Tonga volcanic eruption injected approximately 146 T_g water vapor into the stratosphere [15]. It is four times the water vapor that the Pinatubo eruption (1992) in the Philippines lofted into the stratosphere. Nasa affirms that seldom times volcanic eruptions send water to a higher atmosphere;

the excessive water Tonga volcano injected will remain in the stratosphere for several years (**Figure 1**).

Scientists at Nasa's Langley Research Center calculated that the plume from January 15 volcanic eruption rose to 58 km at its highest point, reaching the mesosphere [16]. Gas, steam, and ashes get into the mesosphere, the third layer of the atmosphere. "When volcanic material goes this high into the atmosphere,

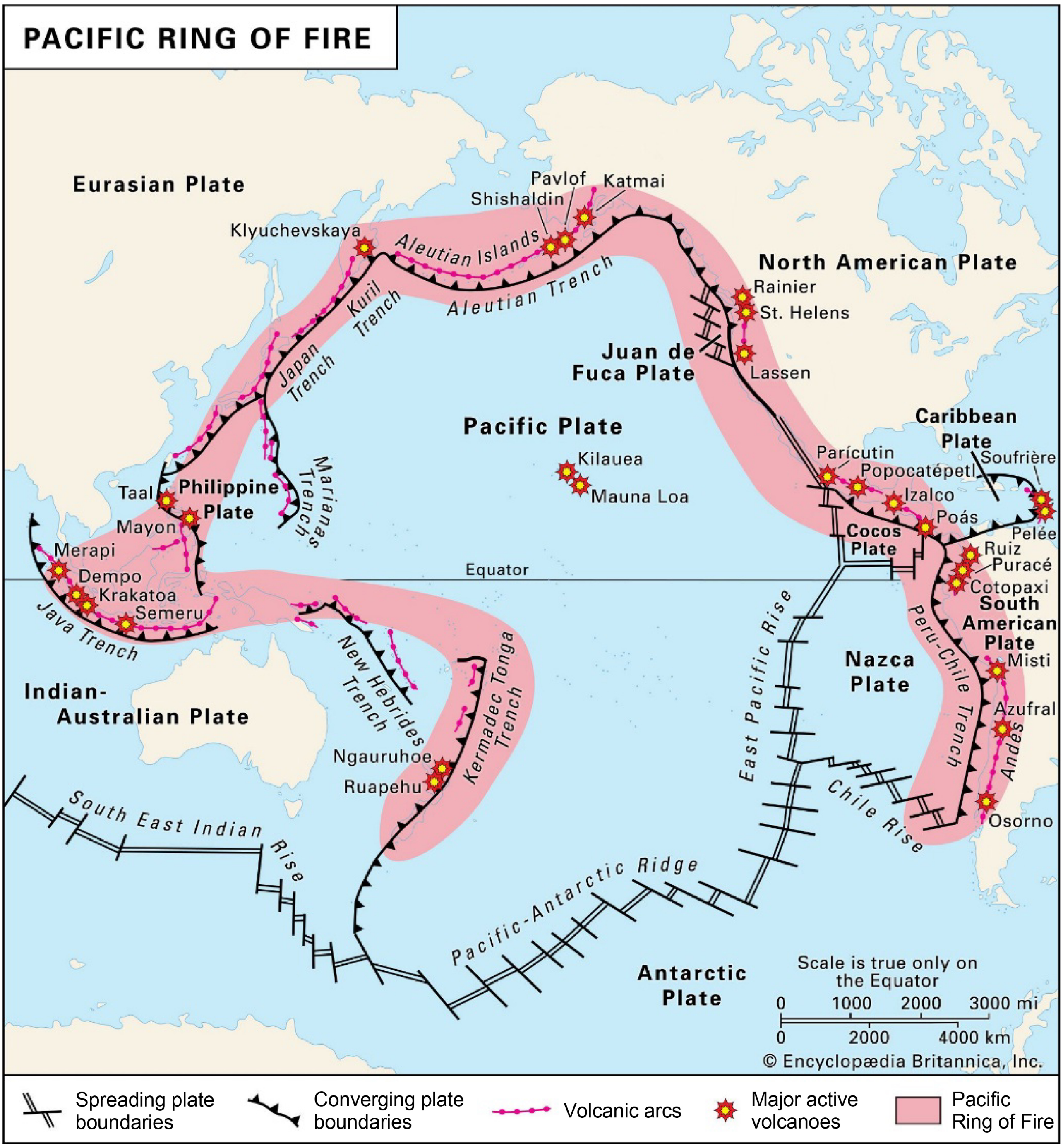

Figure 1. The ring of fire shows the Krakatoa near the Equator, and the Manoa Loa and Tonga are almost in the same straight line (Northern and Southern Hemisphere).

where the winds are weaker, the volcanic ash, sulfur dioxide, carbon dioxide, and water vapor can be transported all over Earth." Said Khlopenkov. 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 [17].

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 [18].

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 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. It was reported reddish atmosphere in southern Brazil for three or four days due to the sulfur dioxide. Aerosols were transported by winds and illuminated the skies close with volcano ashes. All the east Brazilian coast from Paraiba (northeast) to Rio Grande do Sul (far south).

But what about the red sky? Why did that happen? It is because of the way smoke particles scatter sunlight. The dominant form of light scattering in the atmosphere usually is Rayleigh scattering. Light rays hit particles, such as nitrogen and oxygen molecules, and bounce off in all directions. The short wavelengths of blue light are scattered more efficiently by elements than other colors, which is why we see the sky as blue in the daytime.

Figure 2 and **Figure 3** indicate that the emissions from Tonga reached higher levels than the Manoa Loa. Tonga eruptions caused red skies for several days after the explosions in Australia, Brazil, New Zealand, and South Africa. After some days were reported during all of January, dangerous weather in several locations which experienced red skies after the eruptions were floods in Madagascar and heavy rain in Pakistan storm Ana damaged Madagascar, Mozambique, Malawi, South Africa, and Zimbabwe. The report of cyclone Batsirai on January

Figure 2. Vava'u and Ha'apai islands evening of January 14 orange skies could be seen in the Australian sky. Photo/Gladys Guttenbeil.

Figure 3. Tonga's eruptions sent ashes for 13 thousand kilometers to R. J. (Brazil). This picture was taken on January 22 (local press).

24 affected Madagascar, Mauritius, and Reunion. Floods and landslides in Brazil are in locations with typically poor rainfall rates. The high rates of SO_2 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. However, sudden decreases and increases in the weather temperature were independent of the season.

5. The Manoa Loa Eruption

Mauna Loa in Hawaii erupted on November 28, 2022, after a 38-year-long gap.

Likewise, Mount Semeru exploded on December 4, 2022, after a year.

In 2022, the world recorded 25 new volcanic eruptions, according to the Global Volcanism Program, a database distributed by Smithsonian Institution. In 2021, 33 recent outbreaks occurred. In addition, two explosions in 2022 were significant, the first in Tonga on January 15 and the second in Mauna Loa, Hawaii. **Figure 3** shows the location of three significant eruptions, Krakatoa, Tonga, and Manoa Loa.

The USGS said the eruption of Mauna Loa migrated from the volcano's summit to the Northeast Rift Zone, where fissures are feeding several lava flows. In addition, staff from the USGS' Hawaiian Volcano Observatory (HVO) confirmed that the cracks at higher elevations within Hawaii Volcanoes National Park have been feeding lava flows up the Mauna Loa Weather Observatory.

According to USGS, lava flows are not threatening any downslope communities. All indications are that Mauna Loa's eruption will remain in the Northeast Rift Zone. However, winds in the area may carry volcanic Gas, ash, and "Pele's Hair" downwind. Pele's Hair is made of thin glass fibers formed during a volcanic eruption. It is named after the Hawaiian volcano deity Pele. The emissions were not reported, nor how many days they were being thrown in the atmosphere.

The emissions were lower than the ones from Tonga since there was no red sunset observed after the eruption as from Tonga. The emissions of water are also less than their cousin in Southern Hemisphere.

6. Kilauea Eruption

Kīlauea volcano began erupting within Halema'uma'u crater at HST on January 5, 2023, following a couple of weeks of intermittently elevated summit earthquake activity and gradual inflationary summit ground tilt. On January 6, very few fountains remained active in the central-eastern portion of the Halema'uma'u crater floor. The high initial effusion rates are declining rapidly as lava stored within the magma system over the past month erupts.

Lava flows have inundated much of the crater floor (nearly 300 acres or 120 hectares). The higher-elevation island formed during the initial phase of the December 2020 eruption remains exposed, as well as a ring of older lava around the lava lake that was active before December 2022. There were elevated volcanic gas emissions during the period.

Sulfur dioxide gas, continuously emitted during Kilauea's current long-lived eruption, has resulted in persistent volcanic smog ("vog") in downwind areas. Vog, as well as acid rain, forms when sulfur dioxide gas reacts with atmospheric moisture. Vog aggravates respiratory problems, and acid rain damages crops and corrodes metal.

Before and during an eruption, many small earthquakes occur as molten rock (magma) forces its way through the upper parts of a volcano's interior. Such quakes often provide early warnings of changes in eruptive activity.

7. Tonga Eruptions and Worldwide Weather 2022

January—The global average temperatures before the Tonga eruption were the sixth-highest for the month since 1880. The Arctic sea extent was the most significant January sea ice extent since 2009. The Antarctic sea extension was the second most minor January ice extent in a forty-four-year record.

The Tonga volcano is different from others since it releases lots of water to the three lower layers of the atmosphere.

The following months were closely connected with the eruption in the Southern Hemisphere.

February—Brought much rainfall to the Southern Hemisphere. From West to East in approximately the same latitudes, heavy rains and floods occur in Brazil, Australia, and Puerto Rico. Cyclones happened in Madagascar, with three storms landing in a single month.

March—An increase in above-average cyclone activity was reported around the globe, with a total of nine named storms. Mozambique on March 11 had cyclone Gombe, category 3, bringing devastating winds and heavy rain to the region. In Antarctica, temperature records and the ice extent were below average, which occurred since February.

In **April**, heavy rainfall was reported nearer the equator as in Colombia, South Africa, and the Philippines; the cyclone activity had an above-average performance as a total of five named storms.

May—The rainfall and hurricane disasters in different latitudes and approximately the same longitudes; we had a hurricane on the Pacific Coast of Mexico, and a subtropical storm in Yakecan, South Africa, and Australia faced heavy rainfalls. The wet effects from Tonga eruptions and subsequent anomalies in bolts of lightning occurrences last until May in the Southern Hemisphere.

There were also consequences in the Northern Hemisphere after Tonga's volcano. Agaieeeee started in February, considering the volcano would only impact Tonga in February.

February—North America, Europe, and Asia presented drier conditions than the Southern Hemisphere in the same period.

March—North America, North Africa, Asia, and Europe (but the Iberian peninsula) show drier conditions than average.

April—North Hemisphere indicated drier, warmer conditions but North America with the coldest April since 2019.

May—display the ninth highest temperature since global records began (1880).

June—Northern Hemisphere presented anomaly rains in Yellowstone National Park and surrounding towers. Nevertheless, overall Northern Hemisphere had temperature records, but China in June presented severe flooding.

Nevertheless, overall Northern Hemisphere had temperature records, and China in June had severe flooding.

July—worldwide showed the sixth warmer July since global records started.

The global behavior of warmer temperatures and dry weather remained in August, with a strong monsoon fall in Pakistan.

September had warmer global temperatures and two locations with strong rainfalls. Italy, Portugal (Europe), and Nigeria reported a rain belt.

October pointed out anomalies in temperature in Northern South America and Oceania. Stormy rainfalls in Australia, warmer in North America, Europe, and Asia, with record low water levels in parts of the Mississippi river.

November—Most of NH's warmest temperatures on records and South America and Oceania.

December—the conditions of climate anomalies returned to normal levels. However, the Manoa Loa eruptions on November 27 caused other disruptions in the system. Although the volcanoes most disturb the weather in the same hemisphere after their occurrence in a short period. Submarine volcanoes must be studied carefully, as in Tonga. Tonga emissions were different since they reached the mesosphere. Once the eruption reaches such altitude, the weather system will be disrupted worldwide. Tonga event and their consequences on the weather were abrangent in several regions and different locations from the Northern Hemisphere, affecting any season the planet is going through. In the Southern Hemisphere, it happened several times after the eruption, with intense rainfalls in southern locations, floods, and other natural disasters. Months later and a year later, weather disturbances still happen in the Southern. The water released to the Mesosphere will come lower only when the weather is warming from the season. The Southern Hemisphere during the Summer will be warmer, and the Sun will melt the ice drops to the lower layers even some eruptions discharges in the stratosphere will melt once the Earth is warmer in such regions.

The phenomena will turn into heavy rainfalls following the jet streams, mainly during warmer seasons. At the end of 2022 and the beginning of 2023, it affected Brazil and Argentina with heavy rains and floods during December and March.

8. Manoa Loa, Kilauea on the Northern Hemisphere Weather

The eruption of the Hunga Tonga volcano injects large amounts of water vapor into the stratosphere and mesosphere. Horizontal winds dragged water vapor over Manoa Loa in April 2022 [19]. With the low temperature in the stratosphere, the water was frozen and relatively held in the mesosphere. The eruption of Manoa Loa allowed warmer emissions into the atmosphere. It made water liquid, helping to form atmospheric rivers over the Northern Pacific Ocean during the winter. These elements slowly moved to California's coast, eventually encountering the Polar Vortex pushed down to the USA; the shock between the two fronts caused the blizzard name Elliot storm in December (**Figure 4**).

The combination of those two events disrupts the entire weather system and changes the winter system.

After this event, another one happened, the Kilauea eruption. The same

Figure 4. The Hawaiian Islands are at the southeast end of a chain of volcanoes that began to form more than 70 million years ago. Each island is made of one or more volcanoes, which first erupted on the sea floor and emerged above the ocean's surface.

weather pattern happened now with lower intensity since it is the middle of the winter and the polar vortex is weaker. However, it precipitates the late snowstorm in the country's Northeast. The weather environment from these two volcanic events moved from west to east and eventually will affect North Europe and Asia [20].

9. Volcano's Interactions with Atmospheric Layers

Earth's atmospheric layers are five: troposphere, stratosphere, mesosphere, thermosphere, and exosphere. The troposphere is the lowest, extending about 12 km in height. The height is lower at the poles and highest at the Equator. Most of the Earth's weather happens here, and almost all clouds are found in this layer except for cumulus nimbus thunderclouds, whose tops can rise into the lowest part of the stratosphere.

The troposphere is the lowest layer in the atmosphere; all the weather changes are here. The troposphere depth varies from 8 km to nearly 20 km. It is the deepest above the equator and gets thicker above both poles. Above this layer is the stratosphere, 11 - 20 km thick and very dry. The Polar vortex is responsible for all the dynamics in the stratosphere. The Polar vortex is a tri-dimensional ring with stout winds. Earth has two, one surrounds the North, and another is above the South pole; during the winter, they become stronger (**Figure 5**). It gets more robust with the proximity of the winter season. When poles are getting cooler, the atmosphere further south remains quite warm. The southern layers receive more sunlight and energy from the Sun than the polar regions. The temperature difference North pole and to equatorial region increases. A significant low-pressure (cyclonic) circulation develops across the polar stratosphere. Therefore, Polar Vortex is a large cyclone covering the whole North Pole. Occasionally, its lobes turn South towards mid-latitudes since the polar front is a

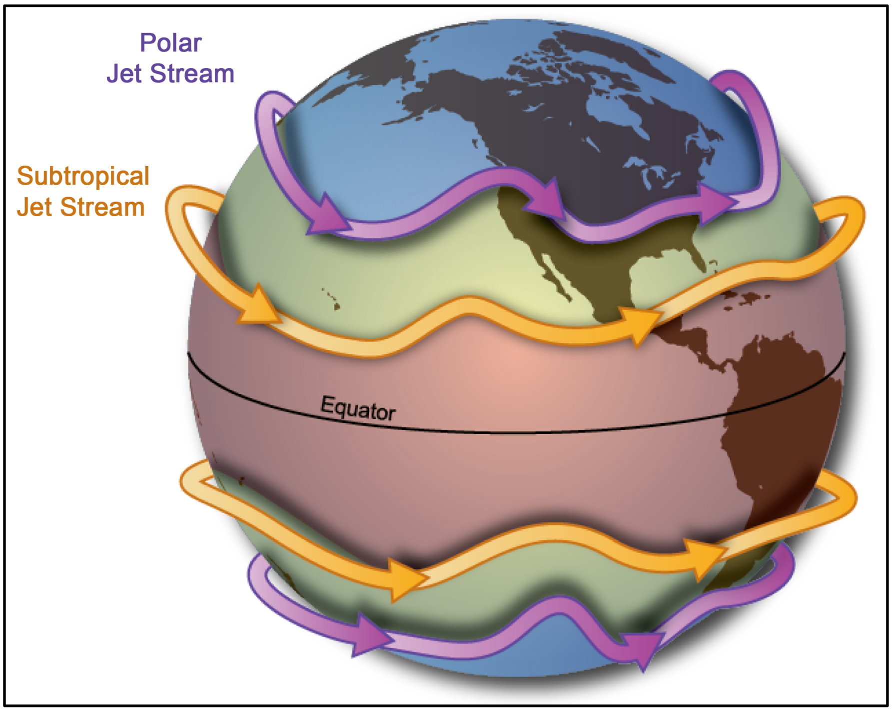

Figure 5. Transport of winds in the Polar and Subtropical Jet streams (NOAA-Jet stream).

dynamic feature. Extra-tropical cyclone's latitudes when the polar vortex is weaker create smaller vortices that can persist for more than a month.

Volcanic eruptions can lead to a stronger polar vortex during winter. It is also possible that due to the amount of water released by volcano emissions, the polar vortex will interact with atmospheric rivers formed in the Pacific traveling to the USA.

The stratosphere locates approximately between 12 and 50 km above Earth's surface, and the Ozone layer is placed there. The higher stratosphere is warmer due to U.V. radiation (**Figure 6**).

Therefore, there is sometimes a presence of stratospheric clouds in their lowest altitudes. Mesosphere is between 50 - 80 km above Earth's surface. The average temperature in this layer is −85 degrees Celsius, and there is also a presence of noctilucent clouds. In 2022, there were several right noctilucent clouds (NLC) in Europe ten days after the Tonga eruption (**Figure 6**).

Tonga's eruption provided a plume of ash, sulfur dioxide, and water vapor; after some days, the steam and water became ice in the mesosphere. Therefore, those three atmospheric layers were significantly affected by Tonga in 2022. Since the volcano emissions reached the mesosphere, the consequence is an evident perturbation at high altitudes, as observed by several scientists. NLC was recorded in London, Germany, in June and in July in Finland and Denmark. They described the lights from the NLC as more bright than years before (**Figure 7**).

Planetary waves naturally occur in rotating fluids within the Earth's ocean and

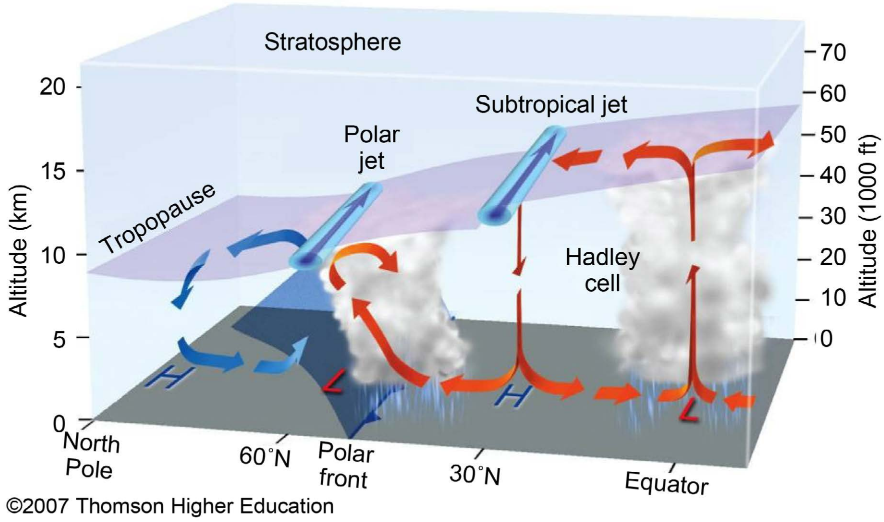

Figure 6. Shows the two lowest levels of the atmosphere troposphere and stratosphere. The weather most happens in the troposphere; however, climate changes are managed into three layers, troposphere, stratosphere, and mesosphere (not in the picture).

Figure 7. In June, 2022 the national weather service office in seattle captured this image of noctilucent clouds, which they described as one of the most vivid displays in years. (NWS Seattle).

atmosphere; these waves form as a result of the rotation of the planet. Rossby waves transfer heat from the tropics toward the poles and cold air toward the tropics to return the atmosphere to balance. Rossby waves need specific criteria and are natural by-products of the Coriolis effect. Atmospheric Rossby waves are excited by the instabilities of the latitude temperature gradient and vertical wind gradient. Jet streams are strong winds that generally blow from west to east all across the globe. Jet stream form when air masses meet cold air masses in the atmosphere. From a volcano eruption such as Manoa Loa, the hot emissions will meet cold air masses in the higher atmosphere. The effects will be more important during the Winter and Spring. On Earth are four main streams two polar jet streams and two subtropical jet streams. On average, jet streams move about 177 km per hour. However, dramatic temperature differences between the warm and cooler air masses can cause the jet stream to move to higher speeds at 450 km/h.

These fast rates usually happen in the polar jet stream during the winter. Jet streams are located 8 to 15 km above Earth's mid to upper troposphere surface.

The mid to upper troposphere surface Polar vortex is a low-pressure area during Winter; the polar vortex at the North Pole expands, sending cold air southward. It surrounds the North Pole 16 - 48 km above the Earth's surface.

Jet streams form when warm air masses meet cold air masses in the atmosphere. The Sun doesn't heat the whole Earth evenly due to its position facing Sun. That's why areas near the equator are hot and near the poles are cold [21].

Subtropical Jets—subtropical jet stream, a belt of solid upper-level winds lying above regions of subtropical high pressure. Unlike the polar front jet stream, it travels in lower latitudes and at slightly higher elevations, owing to the increase in tropopause height at lower latitudes. This jet stream's associated horizontal temperature gradients do not extend to the surface, so a surface front is not evident. In the tropics, an easterly jet is sometimes found at upper levels, mainly when a landmass is located poleward of an ocean, so the temperature increases with latitude.

Since subtropical jets are warmer than polar, they would affect the different weather causing more rain and floods in the area below it as Southern USA. Volcanoes emissions easily reach this region and enhance rainfall to subtropical jets and feed the polar stream with water which is becoming frozen (**Figure 8**).

The Polar Vortex is heavily affected during the winter season, with catastrophic consequences to the weather according to the Hemisphere when a volcanic eruption happens as in 2022. The winter season makes a stronger contrast between the temperatures at the poles vs. the Equator.

Variations in the circulation of the polar—front and jet stream (Rossby waves)

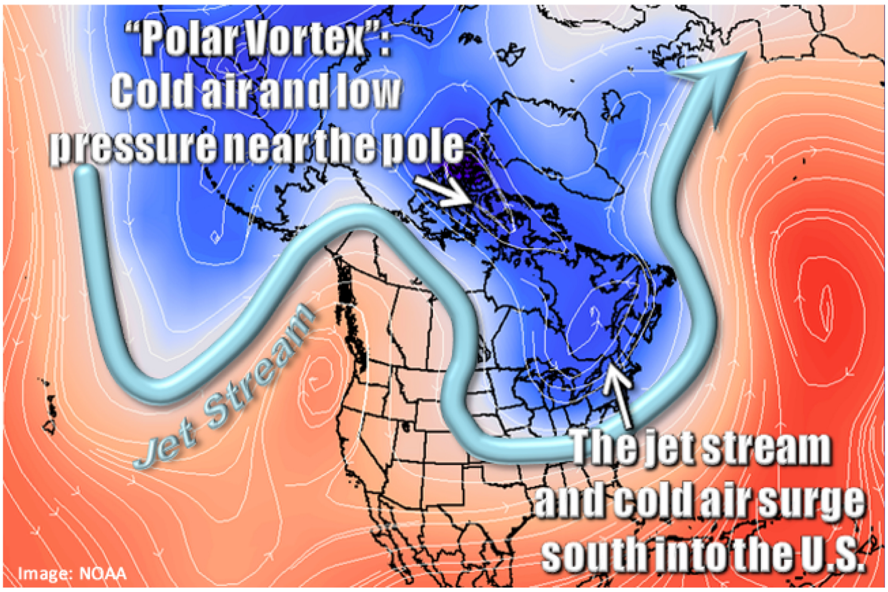

Figure 8. Extreme weather, as the blizzard in the USA in 2022 Winter, are the consequence of the connections between the Polar Vortex and atmospheric rivers.

result from incursions of energy generated by land, oceans, and air deflected by large mountain ranges into the path of the Jet stream in the stratosphere (**Figure 8**). Disruptions in the polar vortex push part of the central region of frigid Arctic air southward a thousand kilometers, producing wide-ranging "cold-air outbreaks" or "cold waves", decreasing air temperatures to dangerous levels in locations overpopulated as Eurasia and North America [22].

There are other factors connecting the emissions and the weather. It depends on where the ashes send the emissions into the atmosphere. Emissions can reach the Polar vortex, and the disturbance in the weather will follow all the same latitudes and different longitudes where the vortex went [23].

The Effects of Volcanoes on Atmospheric Rivers

Atmospheric rivers are relatively long, narrow regions in the atmosphere, like rivers in the sky, that transport most of the water vapor outside of the tropics. These columns of vapor move with the weather, carrying an amount of water vapor roughly equivalent to the average flow of water at the mouth of the Mississippi River. When the atmospheric rivers make landfall, they often release this water vapor in the form of rain or snow. After the eruption in Manoa Loa, the volcano emissions enhanced the moisture in the atmospheric rivers formed above Hawaii [24].

Those rivers met the Polar Vortex maximum during the Winter season. As a result, they caused the blizzard observed in the USA from December 21 to 26, 2022. A historical extratropical cyclone created winter storm conditions, including blizzards, high winds, snowfall, and record-cold temperatures across most of the United States and parts of Canada. Areas that experienced blizzard conditions included parts of Minnesota, Iowa, Wisconsin, Michigan, Ohio, New York, and Ontario. The Buffalo area of New York and the Fort Erie and Kingston areas of Ontario experienced almost two full days of blizzard/zero-visibility conditions on December 23 and 24. The cold wave affected all U.S. states from Colorado to the eastern seaboard and as far south as Miami, Florida.

Scientific research yields essential data that helps NOAA's National Weather Service forecasters issue warnings for potential heavy rain and flooding in areas prone to the impacts of atmospheric rivers as many as five to seven days in advance. Atmospheric rivers are large, narrow sections of the Earth's atmosphere that carry moisture from the Earth's tropics near the Equator to the poles. On average, the Earth has four to five active atmospheric rivers at any time. They carry massive amounts of moisture. Each moves the equivalent of the liquid water that flows through the mouth of the Amazon River. When they reach land, atmospheric rivers release this moisture, producing heavy snow and rain.

Atmospheric rivers usually begin over tropical regions. Warm temperatures there cause ocean water to evaporate and rise into the atmosphere. Strong winds help to carry the water vapor through the atmosphere. As atmospheric rivers move over land, the water vapor increases farther into the atmosphere. It then cools into water droplets, which fall as precipitation. In 2022, after the Manoa Loa eruption, lots of water and gases were released immediately into the atmosphere, enhancing the atmospheric rivers above the west coast of the USA. It joined with the Polar Vortex and made a catastrophic change in the winter storms on the continent, creating bomb cyclones and blizzards. As occurred in 2022, the polar vortex breakdown is an extreme event known as sudden stratospheric warming; here, the vortex completely breaks down, and a blizzard was observed.

Atmospheric rivers and polar vortexes are both low-pressure systems. The eruption of Manoa Loa on November 27 released a lot of water vapor that rose into the atmosphere. It enhanced the atmospheric rivers; the meteorologist reported an extra number of atmospheric rivers in 2023. It meant that the Tonga eruption could send HO_2 in large amounts to the North Hemisphere to Manoa Loa during 2022. It probably also increased the water vapor even though the stratosphere's temperatures were lower than in the troposphere. Therefore the eruption of Manoa Loa increased the Polar Vortex, and the cyclone bomb Eliot was observed. Also, it increases the rainfall in the Southern states of the USA. Although Manoa Loa enhances the weather system with snow and rainfalls, it is mainly kept in the Northern Hemisphere with much connection with the Southern Hemisphere systems.

10. Discussion of Results

In this research, we are showing the importance of volcanic eruptions on the weather. Volcano emissions caused seasonal disruptions, enhancing the power of the hazard events that occurred in 2022-2023. The Tonga eruption increased hazardous natural events such as rainfalls, floods, and the appearance of brighter noctilucent clouds in the Northern Hemisphere since the water's vapor, ashes releases, and gases reach the highest altitudes in the atmospheric layers as the mesosphere. Shockwaves from the propagating volcano create several natural phenomena, such as thunderstorms and lightning. The most important was the amount of water from Tonga, which immediately influenced the troposphere, causing floods and heavy rainfalls during some months in the Southern. In the stratosphere, the emissions became ice or ice drops, and the release of it was slower, depending much more on the amount of sunlight. The heavier precipitation happened later in Spring and early Summer in the Southern Hemisphere. Some emissions went higher to the mesosphere than possible; the transportation of those ice droplets created the noctilucent clouds in the European summer. It also enhances the atmospheric rivers in the Northern. Manoa Loa eruption on November 27 also emitted water vapor to the troposphere; therefore, it was the source of other atmospheric rivers, as reported by some observations. Although the Manoa Loa had much lower emissions than the Tonga eruption in the atmospheric layers then, the snowfalls, blizzards, and other catastrophes happened earlier. The bad weather in the Northern was an unhappy combination of several different events simultaneously in the wrong season (Winter). Volcano eruptions modify the temperature according to location (on land or submarine), intensity, and altitude the emissions reach. The height of the emission target is one of the most critical parameters. Suppose the emission is in the system troposphere/stratosphere. In that case, the effects are likely to keep in the Hemisphere the event happened. The entire environment will suffer disturbances if the emissions reach higher altitudes than the mesosphere. Submarine volcanos are rare and heavily impact the weather, increasing rainfalls, floods, and droughts regardless of the season.

11. Conclusion

This paper worked with one of the submarine eruptions in Tonga; the powerful emissions reached the mesosphere, a rare occurrence in volcanoes. The opportunity to work with the ashes, pollutants, also water in the three lower layers of the atmosphere shows the influence on the weather five days after the eruption. As described, the explosion has perturbed the entire world. In addition, the Manoa Loa eruption during the winter in the Northern Hemisphere also causes catastrophic perturbations in the weather and most of the highly populated areas around the Polar Vortex influence. More research is needed to understand all processes involving volcanic eruptions and climate change.

Data Catalogs in This Research

This research used data catalogs and statistics to analyze the possible impacts of volcanic activity on the weather. Those catalogs are separated by the category searched [24]-[29].

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Conflicts of Interest

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

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