Volcanic Emissions: Causes, Impacts, and Its Extremities

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Rahul Kant Yadav, Debasish Mahapatra, and Chinmay Mallik

Abstract

Volcanoes are an extreme expression of the mostly invisible movements of the fragments of the earth's crust connecting the interior of the earth to its exterior. Since eons, they have had a major impact on the exterior surface of the earth and its gaseous envelope modulating the earth's surface and its atmosphere. Depending on the type, intensity, and location of an eruption, the impacts can be both short term and long term, mild to extreme. The intensity of a volcanic eruption represents its explosivity in terms of volume of material ejected, ejection height, and distance the volcanic cloud travels away from its origin, which can span a wide range of scales. The requirement of a logarithmic scale to classify an eruption itself indicates how extreme one volcano can be compared to another. Volcanic emissions encompass all the three states of matter with tephra in solid form, lava in liquid form, and several acidic gases. The volume of ejected material for a very large eruption can amount to several cubic miles as in case of Krakatau (1883). Strong eruption can be related to silica-rich magma leading to large viscosity enabling trapping of gases until pressure builds up high enough to cause explosive eruption. The atmospheric impacts of volcanic eruptions range from small particles and ash playing havoc with aviation to ozone-depleting gases to global cooling as a result of emitted sulfur gases. The most explosive volcanoes can easily reach over 20 km and can lead to several feet of ash even 150 km away from the eruption site. Relationships between volcanic events and ENSO are an active field of research. Severe volcanic eruptions like Mt. Pinatubo have had an impact in all the five major spheres of the earth including the lithosphere,

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R. K. Yadav · D. Mahapatra · C. Mallik (✉)
Department of Atmospheric Science, School of Earth Sciences, Central University of Rajasthan, Kishangarh, Rajasthan, India
e-mail: chinmay.mallik@curaj.ac.in

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hydrosphere, atmosphere, biosphere, and the anthroposphere. The potential severe consequences of volcanic eruptions demand greater awareness and investigation of these extreme events with extreme consequences.

Keywords

Volcano · Eruption causes · Extreme events · Atmospheric impacts · Tephra · Volcanic gases

10.1 Introduction

The earth as a planet is dynamic. There are forces on and inside the planet that bring about drastic changes to the planet's interior, surface, and its gaseous envelope, the atmosphere. While the surface forces change the surface of the planet gradually in hundred thousand and millions of years through various exogenic processes like weathering and erosion, there are other changes that may be brought about by endogenic processes. Endogenic processes include diastrophic processes (orogenic or mountain-building processes and epeirogenic processes or continent-building processes) and sudden movements like earthquakes and volcanism.

A volcano is a rupture on the earth's crust through which hot lava, volcanic ash, and gases are spewed out during the course of the eruption from a magma chamber underneath the surface. Most of them are found near the tectonic plate boundaries, where they converge and subduct or diverge. Volcanism can be caused by diapirs 3000 km deep within the earth forcing their way from the core–mantle boundary, with impacts far away from plate boundaries. As a result of this hotspot, volcanism occurs, for example, the Hawaiian hotspot and the Reunion hotspot. As the planet's 71% of total surface area is covered by water, it is only logical that most of these volcanoes are found underwater. Depending upon the type and region of eruption, a volcanic eruption may have a very profound effect on the atmosphere and the environment. They have the potential to change the global climate. As a matter of fact, this has occurred in the past geological age. The evidence of these ancient catastrophic eruptions can be found in the stratigraphic column in many places in the world. Other proxies include evidence of tephra deposits from ice cores and from tree rings, which make valuable paleoclimatic proxies to effectively describe the impacts of volcanic gases and tephra on the atmosphere. While the impacts of volcanic eruptions can be alarming and devastating, their scale and magnanimity provide fascinating and awesome insights. The Vesuvius eruption in 79 AD, despite the damage caused, preserved for us Pompeii and insight into that civilization (Capellas 2007). The Toba eruption in Indonesia was suspected to spew almost 230 cubic miles of erupted material on the planet's surface 75,000 years ago. Indonesia is a region of large eruptions with Mt. Tambora being one of the most explosive ones, killing thousands of people and eclipsing the sun in 1815. The Mt. Pelee eruption notoriously subdued a whole city in its lava killing thirty thousand people in the Caribic in 1932. The Pinatubo eruption of 1991 is known all across the globe for its explosivity and atmospheric impacts including plummeting temperatures and large-scale ozone depletion. The most famous observatory for climate research is located in the cradles of one of largest volcanoes of the world, the Mauna Loa. While eruptions like Krakatoa (1927) have left us with fear due to the devastating effects, eruptions like that of the Etna are impacting the earth and its atmosphere for millions of years now. Though India is a region to many extinct volcanoes, there are also active ones as in Barren and Baratang Islands. However, volcanic eruptions do not recognize any borders and plumes can span transoceanic and transcontinental domains. The Dalaffila eruption in Ethiopia caused SO_2 enhancement as far as Delhi in India (Mallik et al. 2013).

As volcanoes can connect the whole world in terms of their impacts, it is necessary to understand the science of volcanoes in reach of common people. The rationale of this book chapter is to provide a holistic walk pertaining to volcanoes and their atmospheric impacts. It aims to simplify and summarize the information available regarding volcanic eruptions from an atmospheric science perspective. First, we introduce the different types of volcanoes and then discuss the causes of volcanic emissions. This discussion is followed by the impacts of volcanic emissions mainly from an atmospheric and climate perspective and ends with the case study of the most famous volcano the Mt. Pinatubo of 1991.

10.1.1 Types of Volcanoes

To understand the magnanimity of volcanic eruptions, it is essential to understand the type of volcanoes and how they erupt. Depending upon the basis of classification of structure or activity, volcanoes can be grouped into several types as mentioned below.

10.1.1.1 On the Basis of Activity

(a) **Active volcanoes:** According to the Smithsonian global volcanism program, a volcano is considered active if it has erupted in the Holocene within the last ten thousand years. Most active volcanoes can be traced to the Pacific ring of fire. According to the Smithsonian global volcanism program, a volcano is considered active if it has erupted in the Holocene, i.e., in the last 10,000 years, while the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) considers historical times to define active volcanoes. So, there is actually no consensus among volcanologists on the definition of an active volcano. Most active volcanoes are situated on the Pacific Ring of Fire. A map of active volcanoes is shown in Fig. 10.1. The Smithsonian Global Volcanism Program (SGVP) has documented till date about 560 volcanoes whose historical eruptions have been confirmed (Global Volcanism Program 2013). Despite the fact that the SGVP has documented over 10,000 Holocene eruptions, only six eruptions account for more than half of the total quantified fatalities (Cottrell 2015).

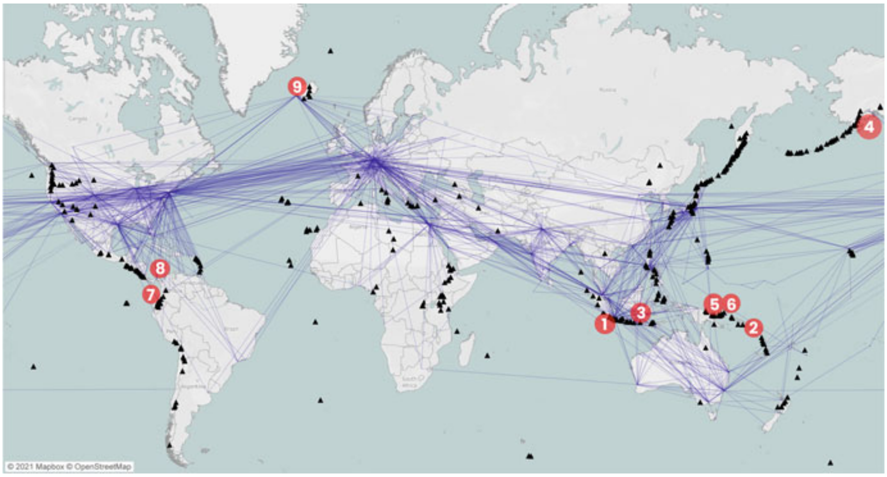

Fig. 10.1 Active volcanoes around the world and the top nine most explosive volcanoes of the past 2000 years superimposed on global aviation route map. (1) Samalas, in 1257. (2) Kuwae of 1452. (3) Tambora in 1815. (4) Mount Churchill in 700 CE. (5) Rabaul Caldera between 531 to 566 CE. (6) The Rabaul caldera in Papua New Guinea is the fifth and sixth from 531 to 566 CE. (7) Quilotoa in 1280. (8) Ilopango in 450 CE. (9) Grimsvotn and Laki eruptions around 1785. The active volcano locations are based on https://volcano.si.edu/list_volcano_holocene.cfm#. The route data are taken from https://openflights.org/data.html and filtered on Codeshare and Airline. The Codeshare filter keeps null. The Airline filter keeps 13 members. The view is filtered on exclusions (Destination airport, Path ID, Source airport), which keeps 75,174 members (*illustration*: Debasish Mahapatra & Madhumay Mallik)

(b) **Dormant volcanoes:** Dormant volcanoes are the ones that have not been associated with any eruption in the last ten thousand years but may erupt in the near future. Such volcanoes can erupt suddenly after remaining dormant for a fairly long time and then. The Geological Survey of India has classified the Narcondam Island in the Andaman and Nicobar archipelago as a dormant volcano. Other examples are Mount Kilimanjaro in Tanzania and Mount Fuji in Japan.

(c) **Extinct volcanoes:** They are the ones that are thought unlikely to erupt again most likely because it does not have a magma supply. Some examples of extinct volcanoes are Hohentwiel of Germany and Zuidwal in the Netherlands. It is difficult to determine whether the volcano is fully extinct. There are also many active volcanoes in India dating about 750 million years before present.

10.1.1.2 On the Basis of Structure

On the basis of structure, volcanoes may be identified as fissure volcano, shield volcano, composite volcano, supervolcano, submarine volcano, and subglacial volcano. The internal structure of a volcano is shown in Fig. 10.2 along with the eruption cloud.

(a) **Fissure volcano:** Fissure volcanoes are fractures on the earth's crust through which lava flows. Large fissure eruptions are considered as one of the hazardous

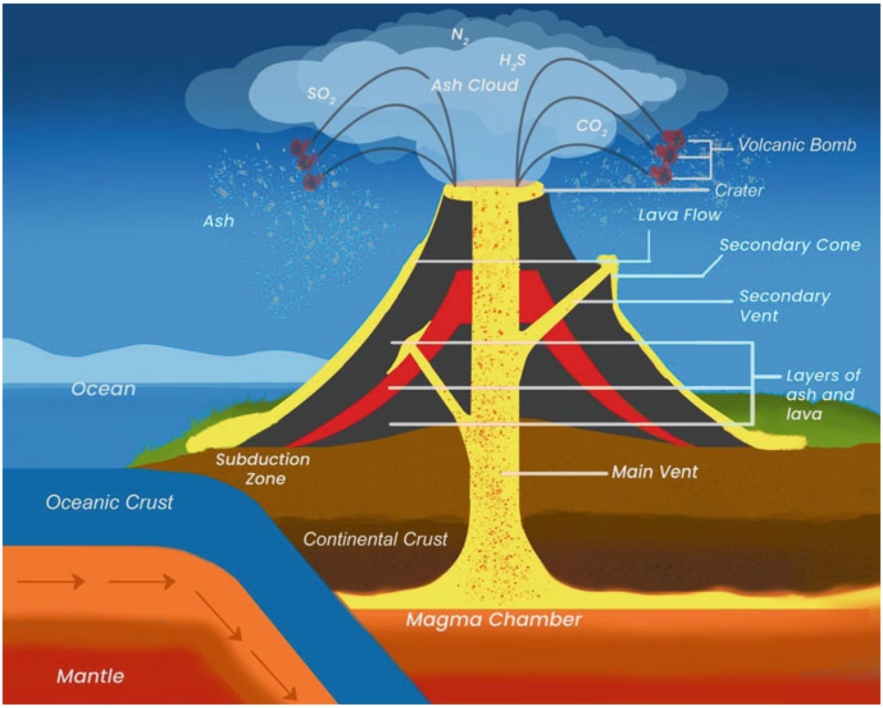

Fig. 10.2 Structure of a volcano (adapted from abc.net.au and modified)

volcanic situations because of their huge arrival of gases and aerosols into the troposphere and lower stratosphere (Ilyinskaya et al. 2017). The Holuhraun eruption in Iceland in 2014–2015 is one of the biggest such occasions.

(b) **Shield volcano:** It is a large volcano with a very large diameter and very gentle slopes. The name suggests the similarity of its structure to that of a warrior's shield. It is a low-angle volcano formed by the piling up of low-viscosity lava flow, mainly basaltic lava (Paris 2013) Most of these volcanoes are in the mantle plume region and a result of hotspot volcanism. The magma is almost always mafic, basaltic, and basic, and the eruption is generally effusive. They include the largest volcano on earth like Mauna Loa in Hawaii. Giant shield volcanoes are also discovered in Mars and Venus. The largest volcano in the solar system is found on Mars, known as Olympus Mons, and is interestingly a shield volcano. Sapas Mons of Venus is another example of giant shield volcanoes in the inner planets of the solar system.

(c) **Composite Volcano:** They are the most common types of volcanoes. Almost all of these volcanoes are found near subduction zones, i.e., destructive plate boundaries. The lava is acidic, felsic, and ranges from rhyolitic and dacitic to andesitic. Because the lava is highly viscous and has relatively lower temperature than basic lava, it solidifies rapidly. The rapid solidification of lava in the vents sometimes clogs it and thereby increasing the pressure in the vent. This results in a loud explosion, and the volcano throws a large amount of volcanic bombs and other pyroclastic material. These volcanoes can also be commonly known as stratovolcanoes as they are built by many layers of solidified felsic lava and tephra. These volcanoes have steeper sides and a summit crater that erupts periodically. Some of them have collapsed summit craters called Calderas. Owing to its high viscosity, the lava does not flow extensively. Examples of stratovolcanoes include the Krakatoa in Indonesia, which had a catastrophic eruption in 1883 and the recent Mount Pinatubo eruption. Simkin and Siebert (1994) said that at least 700 stratovolcanoes are active. Pyroclastic density currents, also called pyroclastic flows, which are sort of an avalanche of volcanic tephra, are possibly the most catastrophic among all impacts of volcanic hazards. The density of the current, the gradient of the slope, and the volcanic output rate are deciding factors of its speed. Its kinetic energy is enough to vanquish building, trees, crops, and almost everything in its path. They can incinerate any living organism and that is what makes it particularly so lethal. Example of such an event was the devastation of Pompeii when it was, along with some of its inhabitants, buried by the pyroclastic flows from the eruption of **Mount Vesuvius in 79 CE**. Stratovolcanoes are on the eighth out of top ten killer volcanoes over twentieth century (Witham 2005), and it has killed more than 0.2 million people since 1783 AD (Tanguy et al. 1998). Mount St. Helens, a stratovolcano in Washington state that erupted on May 18, 1980, caused devastation of 200 sq. miles of forest winds that carried the volcanic ash eastward over the USA during the day, causing total darkness in Spokane, Washington, 236 miles from the volcano (Nania and Bruya 1982). Stratovolcanoes have the most considerable effect on local weather and can also considerably affect the climate of one or both hemispheres and significantly modulate the atmospheric chemistry and the earth's energy balance.

(d) **Supervolcano:** According to the USGS, these eruptions can exhibit of Volcanic Explosivity Index (VEI) of 8 and have ejected more than 1000 km^3 of materials. VEI is used to measure the explosiveness of an eruption. Supervolcanic eruptions are extremely rare and the most dangerous types. Supervolcanoes can also be associated with formation of widespread lava flows and basaltic traps, and Deccan traps in India and Siberian traps in Russia are such examples of such large igneous provinces (LIPs). These are very large eruptions and can usually be related to hotspot (Yellowstone) and destructive plate boundaries (Toba) (Wotzlaw et al. 2015; Budd et al. 2016). These can cause lasting changes to the climate and can cause extinction events. The Siberian Traps coinciding with the Permian–Triassic extinction event are the largest flood basalt event and were formed around two hundred fifty million years ago and. The Deccan Traps are produced by the Réunion hotspot, currently lying in the Indian Ocean under the Réunion Island, some 66 Mya, and are coincident with the Cretaceous–Paleogene extinction event (Keller 2014).

(e) **Submarine volcano:** More than 70% of all volcanic eruptions occur underwater. Submarine volcanoes are the volcanoes that are formed underwater. Most submarine volcanoes are found near divergent plate boundaries in the mid-oceanic ridge. The total number of submarine volcanoes is indeed very high and easily reaches a million, although most of these types of volcanoes are now extinct (Speight and Henderson 2013). Most submarine volcanoes are found in deep waters, but some are present in shallow waters and reveal their presence when they erupt with steam and eject rock high above the surface of the sea. Hydrothermal vents found near submarine volcanoes are rich sites of biological activity. The unlimited supply of water changes the characteristics of these eruptions. The weight of the copious amount of water prevents explosive eruption of the volcano, and when magma comes in contact with the water, it cools rapidly and turns into Obsidian, which is a volcanic glass and advancing lava flows from pillow lava. **Seamounts** are submarine volcanoes that are extinct and rise abruptly from the seafloor. Despite the fact that no big explosive undersea eruption is yet documented, prevalence of such eruptions is evident from ancient seafloor deposits. Large-scale, caldera-forming explosive submarine eruptions of silicic magmas have occurred on the modern seafloor south of Japan in the geological past, and in 2012, the sea surface expression of such a large-scale explosive eruption was identified for the first time ever (White et al. 2015).

(f) **Subglacial Volcano:** These types of volcanoes are also known by the name of Glaciovolcano, which represents a volcano that is formed beneath the surface of a glacier or ice sheet. Most of these volcanoes are found in Iceland and Antarctica. During the eruption of the Subglacial Volcano, the ice over it melts forming a lake, and the water cools the lava rapidly and thus forming pillow lava shapes similar to underwater eruptions. On a later stage, however the pillow will break off and fall down and form hyaloclastite, tuff breccia, and pillow breccia. If a large amount of meltwater is formed, these volcanoes can produce dangerous floods called a **Jökulhlaup**. A Jökulhlaup is an Icelandic term and refers to a flood that is produced due to a subglacial volcano melting the surrounding glacier. These volcanoes are generally flat in the early stages due to the weight and pressure of the overlying layer of ice and water. But in later stages, they can erupt subaerially and form the more conventional conical shape. In late evening of September 30, 1996, a Jökulhlaup occurred following the subglacial eruption on the Vatnajökull ice sheet, Iceland. On November 7, the Jökulhlaup came to an end. A new subglacial ridge 6–7 km long was produced by volcanic materials with a volume of 0.7–0.75 km^3 and floods affected an area of 750 km^2, stretching the shoreline by 800 m. The eruption and flood were Iceland's fourth largest natural disasters in the twentieth century (Smellie 1999).

10.2 Causes of Volcanic Emissions

Most of the volcanoes are not continuously in a vigorous state of activity. They spend a lot of their life span at rest, typically for thousands of years before eruption. The landforms and eruptive nature of volcanoes are diversified, reflecting numerous complex interactions, which determine how magma is generated, stored, rises up along dykes, and conduits and finally erupts. Eruptions are **inveigled** by the tectonic setting. Additionally, the different properties of earth's crust can impact the final eruption, and hence, the history of the volcano can also play a major role as past eruptions can also modify these governing properties. However, despite the great uncertainty about how and where different volcanoes can erupt, the causes can be mostly grouped into a set of common chemical and physical processes. Understanding the formation and eruption of volcanoes and the consequences of these eruptions can be obtained from an understanding of geographic and geologic processes, which can cause melting of rocks to melt and alter its composition, leading to the storage of molten magma in the earth's crust and eventually causing into rising to the surface, and interact as well as impact the surroundings.

10.2.1 Plate Tectonics

We have already discussed how dynamic our planet is. Events like earthquake and volcanic eruptions have occurred throughout the history and are constantly changing and reshaping our planet. Yet, it is only a few decades ago that we got a glimpse into why these events occurred that could explain almost every important question in the field of geology. It is like the grand unified theory of earth science. This fascinating new theory is called plate tectonics. According to plate tectonics, the crust is broken into many rigid plates and they move horizontally with respect to each other, which means the crust is not stationary, it is mobile, and the continents move around on earth's surface. As these plates move, they interact with each other and these interactions build the most amazing features like mountain belts and volcanoes and deep ocean trenches. The theory was built on the concept of continental drift and seafloor spreading. In the year 1912, a meteorologist by the name of Alfred Wegener described the idea of continental drift and gave the theory in his book "The Origin of Continents and Oceans." This theory was endorsed by the scientific community after the idea of seafloor spreading was validated by the works of W.J. Morgan and J.T. Wilson in the 1960s and 1970s (Bangar 2008).

10.2.1.1 Crustal Plates

The earth's crust is composed of several rigid but relatively thin plates. The earth's outer layers are categorized into lithosphere and asthenosphere. The lithosphere is not only cooler but also more rigid compared to the asthenosphere, which is much more hotter and plastic. On an average, these plates are 125 km thick. Continental plates (200 km) are thicker than oceanic plates (50–100 km). The plates slide over the partially molten and plastic asthenosphere. The asthenosphere occurs below the lithosphere in the upper mantle at depths of 100–200 km. This zone is highly viscous, ductile, and mechanically weak. In this zone, the velocity of seismic waves decreases, and thus, it has been called the low-velocity zone (Forsyth 1975). The LVZ's lower boundary is located at a depth of 180–220 km (Condie 1997). Due to the high temperature and pressure conditions in the asthenosphere, the rocks become ductile and plastic, deforming and moving slowly at speeds of cm/y, and eventually moving thousands of kilometers in millions of years. The rigid lithosphere is thought to float on the slowly flowing asthenosphere (Garrison and Ellis 2016). The plates can move with respect to one another format an annual rate of 0–100 mm (Read and Watson 1975). The earth's lithosphere is divided into 20 crustal plates, of which 7 are large and are called major plates, while the rest are called minor plates. The large plates are as follows: (1) the North American plate, (2) the South American plate, (3) the Eurasian plate, (4) the African plate, (5) the Indo-Australian plate, (6) the Pacific Plate, and (7) the Antarctic plate. Some plates are so large that they are constituted from both continental and oceanic crustal portions like the African plate and the South America plate and North American Plate, while the Pacific plate is almost entirely ocean.

10.2.1.2 Plate Boundaries

Plate margins are regions of meeting of two plates. Almost all seismicity volcanicity and tectonic activity happen around plate margins. The majority of the world's active volcanoes occur along these plate boundaries (Fig. 10.1). Depending open the relative motions of the adjoining plates, the ***plate boundaries can be classified into three types***.

(a) **Divergent plate boundaries**

Divergent plate boundaries additionally known as constructive plate boundaries are places where plates move away from each other. This process happens along spreading center where the plates are moving apart and the magma that rises up from the asthenosphere to fill the newly created gap forming the new lithosphere. This phenomenon is called seafloor spreading. Perhaps the best known example of a divergent boundary is the mid-Atlantic ridge. Such boundaries are characterized by high volcanic activity and shallow focus earthquakes. Most of earth's volcanism occurs on the seafloor along spreading zones. These volcanoes are mostly submarine. Iceland being the most famous exception is on the mid-oceanic ridge and has high volcanic activity. The diverging and thinning lithosphere plates allow hot mantle rock to rise and thus causing decompression melting. Ultramafic mantle rock mostly consisting of peridotite partially melts to produce basaltic magma. This is why almost all volcanoes on the ocean floor are basaltic in nature. This basaltic lava erupts underwater and forms pillow-shaped pillow basalt. Deep-sea hydrothermal vents or black smokers are vents that are tall and emit black hot mineral-rich water near mid-oceanic ridges enable entire ecosystems to thrive underwater. Thus, the oceanic ridges are the newest part of earth's lithosphere. The rates of seafloor spreading at ridges vary from 1 cm to 6 cm per year. Some volcanoes also erupt at continental rifts where crustal thinning is caused by diverging continental plates. One such example is the East African Rift Valley.

(b) **Convergent Plate Boundaries**

A convergent plate boundary, additionally referred to as destructive plate boundary, is the type of plate margin where two or more plates move toward each other. Eventually depending upon the densities, one plate slides beneath the other by a process called subduction. Convergent boundaries occur between oceanic–oceanic plate, oceanic–continental plate, and continental–continental plate. These collisions between the plates have occurred over millions of years and can lead to volcanic activity and sometimes even earthquakes and orogenesis.

Oceanic–continental plate Continental lithosphere is of lower density and thus more buoyant than oceanic lithosphere. By the process of subduction, the denser oceanic plate is pushed beneath the less-dense continental plate when continental and oceanic plates converge. As the subducting plate is forced deeper into the mantle, the temperature reaches the melting point and the plate starts to melt. This partial melting produces magma chambers under the overriding continental plates. And these magma chambers are more buoyant and thus begin its slow ascent often melting and fracturing the overlying layers of rock. If and when a magma chamber rises to the surface, the magma will cause a fissure on the ground and will break through the crust in the form of a volcanic eruption. When multiple eruptions occur in a chain on the overriding plate, it is called a volcanic arc. Some of the well-known examples of continental volcanic are the Cascade Mountains in the western North America and the Andes Mountains in South America. Here, the dense Juan de Fuca oceanic plate dives beneath the North American Plate and the Nazca Plate is subducting under the South American plate, respectively.

Oceanic–oceanic plate The characteristics of a subduction zone in which an oceanic plate is forced to sink under another oceanic plate are the same as a continent–ocean subduction zone. The older, denser plate as mentioned before subducts underneath the less-dense plate. The region where the plate is pushed down into the mantle is marked as an ocean trench. In such a region, there can exist a line of volcanoes that thrives on the upper oceanic plate and is popularly known as an island arc.

Continent–continent plate When two continental plates collide, they can form another type of convergent plate boundary known as continent–continent plate. The continental lithosphere although very think cannot subduct as it is low in density. Thus, during the collision of two continental plates, as subduction of one of the plates is not a possibility, the plates just smash together, which forces the material to up as it cannot go down. The result of the tremendous forces of the collision is the genesis of earthquakes and metamorphic rocks. These continent–continent collision zones are not conducive for volcanoes as the crust is too thick for magma to get through.

(c) **Transform Fault Boundaries**

These are boundaries along which plates slide past one another. Hence, at transform fault boundaries, there is no production or destruction of lithosphere. The transform faults are characterized by shallow focus earthquakes with horizontal slips.

Hotspot Volcanism Hotspot volcanism is different as it does not occur at the zones of convergence and divergence, rather this type of volcanism occurs at the interior parts of the lithospheric plates. The cause of hotspot volcanism can be traced to abnormally hot centers in the mantle, which are commonly also known as mantle plumes.

10.3 Emissions from Volcanoes

The volcanic eruption can be violently explosive to gently effusive and can persist for few hours to several decades (Siebert et al. 2015). The volcanic eruption may get triggered due to internal magmatic system of the volcano or due to external processes like precipitation, landslides, or earthquakes. The magnitude and intensity of the volcanic eruption are usually described by its total erupted mass and the mass eruption rate and were quantified by Pyle (2015):

$$\text{Magnitude} = \log_{10}(\text{mass, in kg}) - 7, \text{and}$$

$$\text{Intensity} = \log_{10}(\text{mass eruption rate, in kg/s}) + 3$$

Newhall and Self (1982) introduced “The Volcano Explosivity Index” (VEI). VEI scale is logarithmic with indices ranging from 0 to 8. The 0 value is given to nonexplosive eruptions, and the largest volcanic eruptions in history are given the value of 8. Events with smaller VEI are usually common, whereas larger VEI events are dramatically less continuous (Siebert et al. 2015).

The style of volcanic eruption includes factors like emission span and relentlessness, extent, gas transition, column height, and association of magma or potentially external source of water. Grouping of eruption style is often qualitative and dependent on historical records of trademark emissions from type volcanoes. Notwithstanding, many sort volcanoes show a scope of emission styles over the long haul, which has led to terms, for example, subplinian or violent Strombolian.

On the basis of the nature of volcanic eruptions, volcanoes can be classified as Plinian, Vulcanian, and Strombolian.

(a) **Plinian eruptions** are highly explosive continuously sending out a variety of ejecta with a wide range of sizes. Pyroclastic flows result from gravitational collapse of Plinian eruption columns or lateral explosions and from gravitational collapse of lava domes (Nakada 2000). The explosive eruption generates an enormous amount of tephra, and belches ash, which can exceed 11 km in height into the atmosphere (Auger et al. 2001). These are accompanied by excessive degassing.

(b) **Strombolian eruptions** are also violent in nature sending out ejecta tens of meters into the atmosphere. Low-viscosity, silica-poor magmas characterize Strombolian eruptions and include the complex bursting of gas pockets around the volcanic vent (Taddeucci et al. 2015).

(c) **Vulcanian eruptions** are short-lived, ash-rich, and generate bombs and blocks. In an early earth, gas from volcanic eruptions resulted in the formation of our atmosphere and produced our oceans, without which life would never have existed on this planet. The volcanic emissions majorly contain water vapor (H_2O), carbon dioxide (CO_2), sulfur gases (SO_2, COS, H_2S, CS_2), and hydrogen halides (HCl, HBr, and HF) (Textor et al. 2004). More than 95% by volume of volcanic gases is comprised of H_2O, CO_2, and SO_2 (Symonds et al. 1994). The abundance of these gases differs considerably from volcanoes to volcanoes. The volcanic emissions reveal the composition of their source magma. The characteristics of volcanic emissions depend on the geological setting of the region where it is located; e.g., eruptions near subduction zones are associated with more water vapor and chlorine (Sigurdsson 2000).

Volcanic emissions include violent eruptions and noneruptive degassing. The degassing process occurs continuously during eruptions and through vents and fumaroles. The degassing determines the type of eruption that will take place. Volcanoes are responsible for about 14% to the global sulfur emissions (Graf et al. 1997). It is a no-brainer that gases emitted from subduction zone volcanoes should be commonly very rich in water vapor (95%). However, in hotspot regions the compositions are different and here volcanic gases are much more CO_2-rich and H_2O-poor (Giggenbach 1996; Wallace 2005). These gas emissions occur not only from the craters, but also from faults, vents, or even through soils or even dissolve in groundwater and springwater.

Although the composition of magmas can be widely variable, in general they are constituted mainly from only eight elements: oxygen, aluminum, silicon, calcium, iron, magnesium, sodium, and potassium. Among these eight elements, oxygen is the most abundant followed by silicon. The magma is formed by melting of rocks, and the magmatic composition depends on the rock it was formed from and the conditions of that melting. Melting induces generation of magma as temperatures rise, pressure is released, and influx of volatiles occurs (Peterfreund 1981).

Most of the magma erupted from volcanoes is of basaltic nature mostly occurring in deep ocean water at the mid-oceanic ridges and forms pillow lava basalt and in hotspot volcanism. When the eruption rate is large, the eruption reaches the atmosphere. The basaltic magma is poor in silicate and rich in magnesium and iron, hence characterized by low viscosity and low gas content. Basaltic magma contributes very less portion of sulfur emissions into the atmosphere and it reaches the stratosphere rarely.

Another kind of magma is called Felsic magma, which is rich in silicate and has high viscosity and is associated with explosive eruptions. Normally, felsic magmas tend to have higher levels of volatile compounds, which are emitted as gases during eruptions. The most abundant volatile in magma is H_2O, followed typically by CO_2, and then by SO_2. Compared to basaltic volcanoes, felsic magma erupts less frequently. Sometimes, they release large amounts of ashes and gases directly into the atmosphere.

10.3.1 Volcanic Material

A volcanic eruption can spew material in form of gases, lava, and tephra as mentioned below:

(a) **Volcanic gases:** In an early earth, gases from volcanic eruption gave us not only our atmosphere but also our oceans without which there would be no life on planet earth. The most common gases from volcanoes are water vapor, carbon dioxide, and sulfur dioxide. Other gases that are also emitted during volcanic eruptions are carbon monoxide, H_2S, HCl, CH_4, HF, etc. The abundance of these gases differs considerably from volcanoes to volcanoes. Due to the addition of seawater in the magmas at convergent plate boundaries, volcanoes near subduction zones erupt with more water vapor and chlorine. Similarly, volcanoes at divergent plate boundaries and at hotspots produce significantly less water vapor and chlorine (Sigurdsson 2000).

(b) **Lava:** Lava is nothing, but magma erupted to the surface due to volcanic eruption. The temperature of lava usually ranges from 800 to 1200 °C. As we know, the eruption can be either effusive or explosive. Effusive eruption causes lava flow by outpouring of lava. Explosive eruptions on the other hand produce volcanic ashes and tephra. There are two basic types of lava flow ***'A'ā and pahoehoe***. While *'A'ā* flow is rough and rubble-like and composed of broken cinder blokes, the *pahoehoe* type is smooth and ropy. The surface is formed due to very fluid lava under a solidified crust.

(c) **Tephra:** Explosive volcanism sometimes ejects materials like rock fragments into the atmosphere. These rock fragments are called tephra regardless of composition or size (Amaral and Rodrigues 2019). Tephra represents airborne pyroclastic material that is ejected during the course of an eruption (Durand and Thorarinsson 1981). Tephra is classified into three size groups: (1) ash, when particles are minuscule to the tune of less than 2 mm in diameter; (2) moderate size particles are called lapilli or volcanic cinders, with diameter between 2 and 64 mm; and (3) large size ejected materials with diameter greater than 64 mm constitute volcanic bombs or blocks. Bombs and blocks are shot from the volcano ballistically. Because these fragments are large, they generally fall near the source. Most particles greater than 1 mm will fall out within hours of eruption. Being smaller in diameter, ash can travel thousands of kilometers from its originating volcano. The wind speed and direction, the air temperature, and the height of the eruption column are the variables that decide the distance that tephra will be transported away from the volcano. Larger particles, lapilli, and volcanic bombs fallout within an hour they are ejected from the volcano. The smallest particles can remain even for a couple of years after the eruption in the atmosphere. Sometimes, they produce amazing sunsets like seen after the 1991 Pinatubo eruption.

10.4 Impacts of Volcanic Emissions

10.4.1 Radiative Forcing

Radiative forcing is a concept to understand change in energy fluxes in the earth atmosphere system. The particles and the gases present in the atmosphere change the balance between incoming solar radiation and outgoing IR radiation (Pulselli and Marchi 2015). The term forcing explains the earth's radiative balance being pushed away from the normal state. The particles present in the atmosphere absorb or scatter solar and terrestrial radiation. Positive forcing is exerted when particles absorb the radiation and it contributes to warming of the earth's surface, whereas negative forcing is exerted when the particles present in the atmosphere scatter the incoming solar radiation and it causes the cooling of the earth's surface (Fig. 10.3).

Volcanism induces short-term climatic variations. The secondary sulfate aerosols (SO_4^{2-}) emitted from volcanoes can change the energy balance of that area (Franklin 1784; Charlson et al. 1991, 1992; Stenchikov et al. 1998). Sulfate aerosols scatter the incoming solar radiation due to their high single scattering albedo. In troposphere, SO_2 gets converted to H_2SO_4 and it increases the aerosol optical depth and the albedo. It causes cooling at the surface (Robock 2000). In the biologically important UV-B region, the average cross section for SO_2 is double of ozone (O_3); thus, for regions of high SO_2, if the changes in UV-B need to be predicted, we must consider the changes in both SO_2 and O_3 columns. Shindell et al. (2003) simulated the volcanic forcing and found that the mean annual cooling for the periodic Pinatubo eruption, Tambora 2P eruption, and Tambora 3P eruption and for the observed 1959–1999 volcanoes were −0.35 °C, −0.77 °C, −1.99 °C, and −0.44 °C, respectively, and the average instantaneous forcing was −0.47, −0.91, −1.39, and −0.44 W/m^2, respectively.

Crop failure and famine have been found to be associated with large eruptions as an aftermath as a result of the cooling produced, the ashes, and gases emitted. Large historic eruptions are aptly documented in archives such as that of 1815 Tambora eruption, which was associated with large-scale global cooling, which had eventually led not only to famine, but also social unrest, and as if this was not enough, this was followed by epidemic typhus, leading to as described beautifully in Oppenheimer (2003) was what came to be known as the "Year Without a Summer". The Laki eruption of 1783 caused several years of crop failure and cold winters leading to death of ~20% of the Iceland population (Grattan et al. 2003; Thordarson and Self 2003).

Without mention of the little ice age, the discussion would remain incomplete. Regional cooling was very intense during this period roughly between 1300 and 1850 AD with temperature in Europe and North America plummeting by as much as 2 °C. This intense drop in average temperatures can be attributed to several large sulfur-rich explosive eruptions, and may be possibly triggered or enhanced by the massive Samalas volcanic eruption in 1257 (Amos 2013). Geological records suggest that throughout the little ice age there was heightened volcanic activity (Robock 1979). Historical evidence suggests that many rivers and lake in Europe

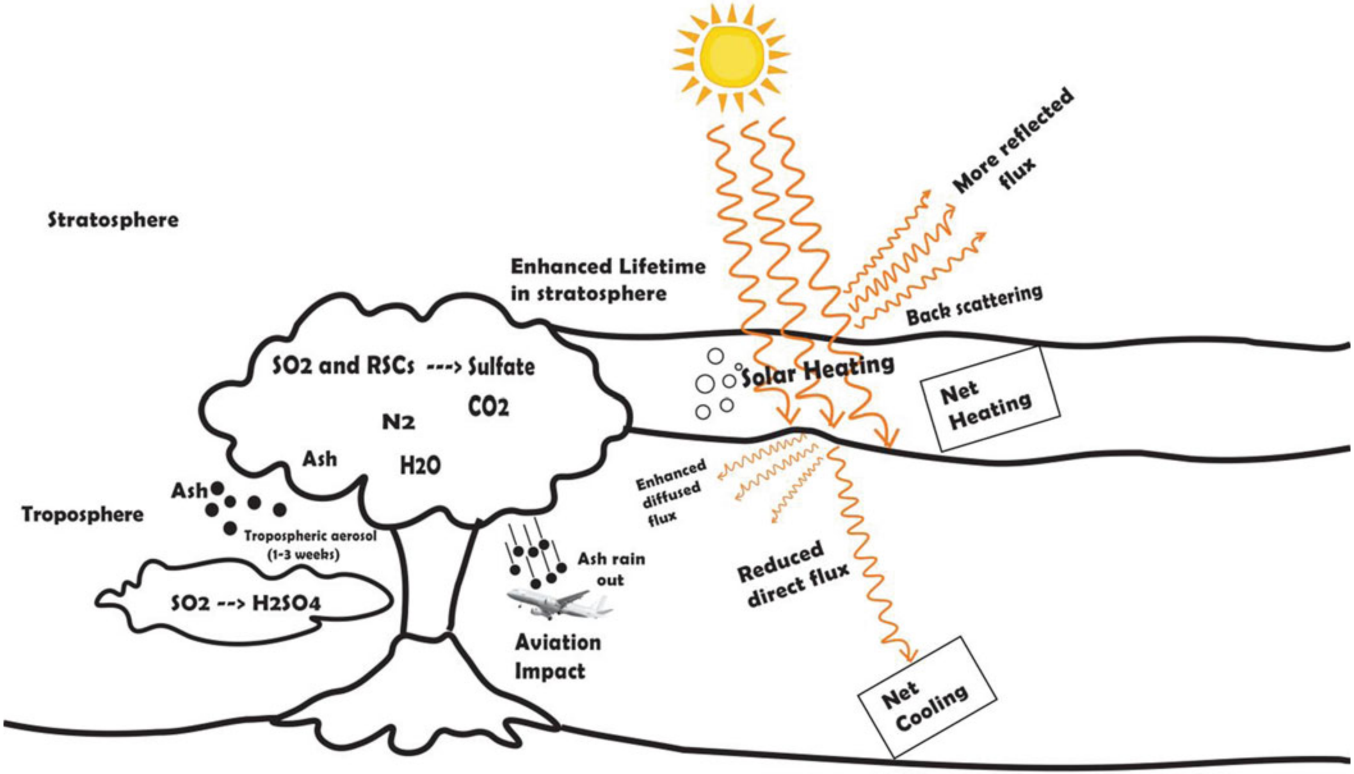

Fig. 10.3 Impacts of volcanic emissions. The impacts range from radiative effects of ash and sulfate leading to regional cooling, O_3 depletion by acidic gases, damages to aircraft engines, acid rain, and direct demolition of buildings and burying of crops by ejected material (*illustration*: Debasish Mahapatra & Souveek Roy)

froze over. Some records even suggest the Baltic Sea freezing (Meacham 2020). The period was marked with advancing glaciers in Scandinavia, with tree line and snowline dropping. Crops failed, and there were widespread droughts across Europe due to the prolonged cold and dry climate. Unemployment and malnutrition and poor living standards resulted in many vector diseases and epidemics (Post 1984). As a result, there was increase in crime rate and caused massive social unrests. The whole period was marked with unpleasant weather, crop failure, large-scale unemployment, increase in intergroup violence, economic hardship, and high mortality rate due to malnutrition and several epidemics. It did not only cause socioeconomic problems but also cause political unrest throughout Europe. Historians also suggest this period of high social unrest may have led to the 30 years of war (1617–1648) (Zhang et al. 2011).

10.4.2 Impact on Ozone

The ozone layer protects the living beings on the planet surface by absorbing 93–99% of the sun's high-frequency ultraviolet light. Oxidation of molecular oxygen leads to O_3 formation, but the mechanisms exist in the troposphere and stratosphere. Stratospheric O_3 is considered beneficial because it prevents the harmful UV from reaching the earth's surface, while tropospheric O_3 has several ramifications to air quality, atmospheric chemistry, crop yield, environment, and human health (Saxena et al. 2019; Saxena and Sonwani 2020). Though most of these ramifications are a problem for the humanity, O_3 being an oxidant may also help to remove pollutants from the atmosphere (Mallik et al. 2018).

Up in the troposphere, radiation is intense enough to destroy O_3 either by itself or through a chain of free radical reactions involving the nitric oxide radical (NO), atomic chlorine (Cl), and atomic bromine (Br). Bromine released during volcanic eruption has the potential to damage the ozone even more compared to chlorine, Br being 40 times more effective than Cl w.r.t. O_3 depletion (Daniel et al. 1999). All of the mentioned radicals can have both natural and anthropogenic origins. Of particular concern is the dramatic increase in the levels of chlorine and bromine attributed to anthropogenic activities, mostly traced to halocarbons, e.g., chlorofluorocarbons (CFCs) (Mohanakumar 2008). The CFCs are stable organic compounds and find their way to the upper atmosphere due to their substantial lifetime. As CFCs reach the stratosphere, UV radiation splits them releasing the Cl and Br atoms from the parent, which were acting as effective reservoirs for these radicals. The below equation shows this mechanism. Here, "h" is Planck's constant and "ν" is frequency of electromagnetic radiation.

$$\mathrm{CFCl_3} + \mathrm{h}\nu \rightarrow \mathrm{CFCl_2} + \mathrm{Cl}^{\circ} \qquad (10.1)$$

The free halide easily decomposes O_3 into its the more stable form of O_2. The halogen oxide can react with another ozone molecule and will give another halogen radical and two oxygen molecules.

$$Cl^{\circ} + O_3 \rightarrow ClO + O_2 \tag{10.2}$$

$$ClO + O_3 \rightarrow Cl^{\circ} + 2O_2 \tag{10.3}$$

Similar reactions can occur for most halides. As the concern of depletion of O_3 in the stratosphere grew, the scientists started examining the role of volcanoes in ozone depletion. It was observed that the gases emitted by the volcanoes during eruption can quickly reach the upper troposphere and lower stratosphere (UTLS); hence, their lifetime increases as they are saved from the high concentration of oxidants in the lower troposphere/boundary layer. The hydrogen halides particularly HCl emitted during eruption, when it reaches the stratosphere, they lead to destruction of ozone (Solomon et al. 1996; Hofmann and Solomon 1989). In addition, aerosols produced by volcanoes can increase the effectiveness of halides in depletion of O_3 in the stratosphere. While most sulfur eruptions reach the stratosphere, halogens are susceptible to being washed away by water and ice in the rapidly ascending column. The increased lifetime of particles and gases from volcanic emissions in the UTLS region makes them more impactful in their radiative and chemical effects.

Zuev et al. (2015) studied the O_3 depletion caused by Erebus volcanic eruption during which the emitted HCl and SO_2 reached the UTLS (upper troposphere and lower stratosphere) with the aid of high latitude cyclones and polar vortex. The polar stratospheric clouds also significantly assist O_3 depletion by converting chlorine compounds into more destructive forms.

Ozonesonde experiments traced a significant decrease in the total ozone column in lower stratosphere after the eruption of Mt. Pinatubo (Grant et al. 1994; Schoeberl et al. 1993; Tang et al. 2013). The decrease in tropospheric and stratospheric ozone was also noted by Fusco and Logan (2003) and Oltmans et al. (1998). Tang et al. (2013) found that the maximum decrease was 2 ppb on interannual time scale, whereas 5 ppb decrease was observed in monthly averages. Robock (2000) estimated the column depletion, and it ranged from 2% in the tropics to about 7% in the midlatitudes.

10.4.3 Acid Rain

The term acid rain entered the scientific domain in 1872 when Robert Angus Smith used it for the first time to describe the acidic nature of rain around the industrial town of Manchester, UK. Bouwman et al. (2002) identified atmospheric acid deposition in the form of rain, fog, or snow to be a major problem for the environment.

SO_2 and oxides of nitrogen are the primary cause of acid rain (Singh and Agrawal 2008). Acid rain can occur in the form of H_2SO_4 and HNO_3, so the emission sources for SO_2 and NO_2 including motor vehicles, power plants, refineries, and industries are precursors for acid rain. These precursor gases are converted into sulfuric acid and nitric acid in wet atmospheric conditions.

Acid rain adversely affects biogeochemical cycles and soil quality, and it also harms flora and fauna. It also causes degradation of buildings and yellowing and weakening of fabrics. Human health is affected by acid rain as it can cause itching, skin burn, respiratory problems, headache, etc.

The sulfur dioxide gas emitted from volcanoes when reacts with oxygen and moisture present in the atmosphere produces acid rain and can also lead to volcanic smog (vog). VOG can not only corrode metals and impact plants but also lead to respiratory and cardiovascular problems in humans. The main vent of Kilauea Volcano on the Hawaii islands emits 63,000–95,000 metric tons of SO_2 every year due to ordinary fuming leading to acid rain, but discrepancies exist if SO_2 is the sole cause of reduced pH (Siegel and Siegel 1984; Gerlach and Graeber 1985; Casadevall et al. 1987; Siegel et al. 1987; Nachbar-Hapai et al. 1989).

10.4.4 Impact on Aviation

Since the beginning of the aviation age in 1960s, with the advancement in technology there have been rapid advances in the sector of air travel. Correspondingly, there has been an increase in probability of an aircraft encountering the volcanic clouds. The ash particles ejected by volcano in the atmosphere impact the fuselage, windscreens, and compressor fan blades and can essentially chafe these forward-facing surfaces. The navigational and operational instruments might fail critically when contaminated with the ash. Ash particles consist of the glassy silicate material, which can melt at combustion temperatures inside modern jet engines (Chen and Zhao 2015). The melted ash particles rack up as re-solidified deposits in cooler parts of the aircraft leading to deterioration of engine performance even to the point of in-flight compressor stall and loss of thrust power.

Volcanic ash poses a major threat to the aviation sector with immediate and long-term consequences (Casadevall 1993). Over 129 incidents have been reported of aircrafts encountering volcanic ash from 1953 to 2009 (Guffanti et al. 2010). Of all these reported incidents, 79 are related to inflicting some physical damage to the aircraft, and 26 led to severe ramifications among which nine led to in-flight power loss in one or more engines. Miller and Casadevall (2000) documented incident of “all engines out” encountered by a Boeing B747 in 1982 with volcanic ash from Galunggung volcano over Indonesia and Boeing B747 in 1989 from Redoubt volcano over Alaska.

10.4.5 Environment and Health

Of an approximately 500 active volcanoes, 10–40 eruptions occur on an annual basis (Zuskin et al. 2007). Volcanic eruptions not only affect climate, but also affect terrestrial ecosystem and human and animal health (Mather et al. 2003). Volcanic eruptions can pose a threat on the environment even from a distance of thousand kilometers from the eruptive center (Galas 2016). Due to rapid accumulation of the ashes and the high density of individual volcanic ash particles during ash fallout, the buildings may collapse (Spence et al. 2005). The volcanic ash fall can also contaminate the water supplies (Stewart et al. 2006).

SO_2 emitted during volcanic eruption can change the precipitation rate (Twomey 1974; Nober et al. 2002). SO_2 acts as cloud condensation nuclei, and it increases the number of cloud droplets resulting in decrease in rain. It increases the albedo of the cloud, which causes cooling at the surface. As discussed above, the sulfate aerosols emitted during a volcanic eruption can react with the oxygen in the troposphere and cause acid rain.

The sulfate aerosols are generally injected in the upper troposphere above the boundary layer. At this height, mixing is weaker and the removal process is slower and the sulfate aerosols remain there for considerable time compared to the anthropogenic sulfur (Graf et al. 1998). Compared to the heating effect of each CO_2 molecule in the atmosphere, a molecule of SO_2 can overcompensate in cooling by at least a factor of 50 (Kaufman et al. 1991). The volcanic aerosols in the stratosphere can lead to a rise in stratospheric temperatures. It also increases the pole to equator temperature gradient (Quiroz 1984; Parker and Brownscombe 1983).

The impact on health can be traced to the type and style of volcanic eruptions, e.g., the effusive emissions, which mainly emit gases, and aerosols may cause disorders of the respiratory system (Horwell et al. 2015; Saxena and Srivastava 2020). We know volcanoes emit hazardous gases. The SO_2 emitted by the volcanoes can be transported globally and potentially trigger acute respiratory diseases like asthma in the exposed people (Hansell and Oppenheimer 2004; Horwell and Baxter 2006).

10.4.6 Volcano and ENSO Relation

El Nino and the Southern Oscillation, also known as ENSO, are a large-scale oceanic warming and the variation in the air pressure of the overlying atmosphere in the tropical Pacific Ocean that occurs every few years. Though ENSO originates and develops in equatorial Pacific region, it affects the climate, ecosystem, and economies around the world (Fang and Xie 2020; Ropelewski and Halpert 1987). ENSO is receptive to external forcing on different time scales, and solar forcing is the cause for millennial ENSO variability due to orbitally induced changes in insolation (Predybaylo et al. 2020; Moy et al. 2002). According to Timmreck (2012), strong volcanic eruptions can rattle ENSO on a short time scale (2–5 years).

As discussed in the previous section, the presence of sulfate aerosols in the atmosphere causes cooling at the surface that can persist for years in the stratosphere with potential to impact the ocean temperature and circulation (Church et al. 2005; Gleckler et al. 2006). Handler and Andsager (1993) proposed that the reduction in incoming shortwave radiation due to the emissions from volcanoes has increased the number of ENSO in the last 150 years. Also, the strong tropical volcanic eruptions may change the atmospheric and oceanic circulation (Mann et al. 2005; McGregor et al. 2010; Shiogama et al. 2010; Zanchettin et al. 2012). At the end of the twentieth century, the relation between ENSO and strong tropical volcanic eruptions is an active field of research. The three largest eruptions in last 50 years (Agung in 1963, El Chichon in 1982 and Pinatubo in 1991) took place in conjunction with the warm phase of ENSO; therefore, there are possibilities that the strong tropical volcanic eruptions do have a role to play in ENSO system (Ohba et al. 2013). Adams et al. (2003) also found that the ENSO system may become more active due to volcanic eruptions. In contrast, Self et al. (1997) found that the volcano–ENSO relationship does not exhibit a statistically significant value over the last 150 years. Further millennium-long climate and volcanic records analysis points to the fact that even most explosive eruptions are too small to affect ENSO (Emile-Geay et al. 2008).

10.5 Impacts and Extremities

Depending on the type and region of eruption, volcanic events can range from mild to severe resulting in mild to extreme impacts on the different spheres of the Earth. The impacts of volcanoes are already discussed in the above paragraphs. However, depending on the circumstances, the net result is different. The tropospheric aerosols resulting from a quiescent volcano will have a lifetime of weeks, but an explosive eruption injecting the aerosols in the stratosphere can scale up the lifetime from weeks to years. The resulting impact on radiative forcing will hence be much more significant. The extremity of an eruption impact is not only visible in the amount of material that is ejected but also by the distance the impact propagates. Even smaller eruptions can have a long-range impact under favorable meteorological conditions. The Dalaffila eruption of November 2008 in the Afar region of Ethiopia, despite generating only about 0.1–0.2 Tg SO_2 in the eruption cloud, was one of the few recent volcanoes whose effect was observed as far as India (Mallik et al. 2013). SO_2 plume from this small eruption in Ethiopia traversed over 5000 km under favorable winds causing 10–20 times enhancement in background SO_2 columnar levels over the Indo-Gangetic plains of India and injected 1.4 Tg SO_2 over the Delhi region, equivalent to 25% of annual anthropogenic emissions over Delhi (Mallik et al. 2013). Recently in 2018, Manaro Voui Volcano on Ambae Island of South Pacific injected a record amount of 400,000 tons of SO_2 in the UTLS region, which was thrice the amount of SO_2 released from all volcanoes in the previous year (NASA report 2018). The impacts ranged from destruction of homes, burying of crops, blackening of the sky by volcanic ash, acidifying the drinking water, and forcing the entire population of the island to evacuate. No discussion of severity of volcanic impacts is complete without describing the Mount Pinatubo eruption.

10.5.1 Mount Pinatubo: A Case Study

The Mount Pinatubo eruption on June 15, 1991, was a landmark event not only for the Philippines but also for the entire planet as this was the world's largest volcanic eruption to happen in the past 100 years. Mount Pinatubo is an active volcano amid a chain of volcanoes located on the western fringe of the island of Luzon. They are subduction volcanoes, formed by the Eurasian Plate drifting below the Philippine Plate along the Manila Trench to the west. Smith (1909) provided the first geologic narration about Mount Pinatubo, describing it as destitute of "volcanic ash (and) any of the usual indications of volcanic activity." He surmised that "Mount Pinatubo is not a volcano and we saw no signs of it ever having been one, although the rock constituting it is porphyritic.... The region is quite unique and I have seen nothing in the Philippines quite like it."

Ash production was documented for Mount Pinatubo eruption for the first time at 0851 local time on June 12, 1991, where a series of explosive eruptions with an eruption cloud crossing 19 altitudes (Koyaguchi and Tokuno 1993). Satellite image analysis indicated that the high-level winds (~15–20 m/s) carried the ash clouds from the eruption of June 12 into the airspace west of Manila along the heading of 215° from the volcano (Potts 1993). Pinatubo Volcano Observatory Team also reported the intermittent lapilli fall and fine ash fall mainly in the region of the southwest of Pinatubo. Pinatubo exploded most violently releasing the largest ash cloud on June 15. (Koyaguchi and Tokuno 1993). Because of the passage of Typhoon Yunya, the pattern of dispersion of these ash clouds was complicated (Oswalt et al. 1991). The ash would have moved to west–southwest under normal weather conditions, but the Typhoon Yunya forced the ash clouds to the south (Paladio-Melosantos et al. 1991). The eruption of Mount Pinatubo caused the evacuation of more than 0.2 million people with more than 300 deaths mainly due to heavy ashfall and rain leading to collapsing of buildings. The amount of 6000–10,000 Mt of dacite magma in a Plinian eruption was ejected during the 9-h eruption of Mount Pinatubo volcano on June 15, 1991 (Pallister et al. 1996).

Aerosols from the eruption of Mount Pinatubo caused solar dimming in turn led to a lower troposphere cooling across the globe. This cooling was so strong that it led to a decrease in water vapor concentrations globally. The eruption cloud spanned 1100 km wide and 35 km high ejecting volcanic gases and ash leading to 17 megatons of SO_2 injected into the stratosphere, as documented in "Fire and Mud" by Self et al. (1997). The cooling continued over 2 years up to 1993, leading to 0.4 °C temperature drop over several regions. Bluth et al. (1992) and Hansen et al. (1992, 1996) also reported that around 20 MT of SO_2 was ejected in that eruption. SO_2 from Pinatubo was detected in the stratosphere as late as June 1994, 3 years after the eruption. Parker et al. (1996) observed a global cooling of about 0.5 °C at the surface and 0.6 °C in the troposphere between the eruption of Mount Pinatubo and the northern summer of 1992, interrupted, however, by relative warmth between January and March 1992.

Research on tree rings shows that after the eruptions of large volcanoes including Pinatubo and Tambora, Mongolia, and most parts of southern China continued to receive less rainfall, while an increase in rainfall was observed over mainland Southeast Asia in the reduced precipitation due to Pinatubo led to a record decrease in runoff and river discharge into the ocean from October 1991–September 1992. In April 1993, that is around 2 years after eruption, the ozone column showed a deficit of around 6% compared to the annual mean from 1979 to 1990 (Gleason et al. 1993;

Herman and Larko 1994). The cloud spread covered most of the area of the equatorial band from about 10° S to 20° N on June 15.

The eruption had great effect on the aviation sector contaminating some of the world's busiest air traffic corridors. Eruptions between June 12 and 15, 1991, led to as many as 16 damaging encounters between drifting ash clouds from the eruption and jet aircrafts. Out of these 16, three encounters occurred within a 200 km of eruption site with fresh ash clouds less than 3 h old. Further away between 720 and 1740 km west from the volcano, 12 encounters occurred over Southeast Asian region with 0.5- to 1-day-old ash clouds. A total of ten engines were damaged by the ash cloud, with additional two instances of in-flight loss of power. Long-term damage to aircrafts and engines attributed to Pinatubo SO_2 led to resulted in crazing of acrylic airplane windows, premature fading of polyurethane paint on jetliners, and accumulation of sulfate deposits in engines (Pallister et al. 1996).

10.6 Summary

Volcanism is an endogenic process that has the potential to change the earth's surface fairly quickly in contrast to exogenic processes through surface forces whose effects become perceptible in millions of years. A volcano is a rupture on the earth's crust through which hot lava, volcanic ash, and gases are spewed out during the course of the eruption from a magma chamber underneath the surface. Most of the volcanoes on earth are found near the tectonic plate boundaries, where they converge and subduct or diverge. Active volcanoes are those that have erupted in the Holocene, i.e., within the last 10,000 years and mostly concentrated along the Pacific Ring of Fire. Also of concern are dormant volcanoes, which are likely to erupt in near future. Identifying volcanoes on the basis of their structure gives a better insight into the type and intensity of eruption. Plate Tectonics, which is like the grand unified theory of Earth Science, is generally invoked to explain the causes behind volcanic eruptions. Depending on the volume of products and height of eruption, the explosiveness of a volcano is estimated on the basis of VEI scale of 1–8 representing the smallest, nonexplosive to mega-colossal explosions. On the basis of the nature of volcanic eruptions, volcanoes can be classified as Plinian, Vulcanian, and Strombolian. Volcanic emissions include violent eruptions and noneruptive degassing, which occurs continuously during eruptions and through vents and fumaroles. The degassing determines the type of eruption that will take place. The characteristics of volcanic emissions depend on the geological setting of the region where it is located; e.g., eruptions near subduction zones are associated with more water vapor and chlorine.

Eruptions spew out gases, lava, and tephra. Most of the magma erupted from volcanoes is of basaltic nature. The solid tephra includes ash, lapilli, and bombs/blocks. Most particles greater than 1 mm will fall out within hours of eruption. Ash can travel thousands of kilometers from its originating volcano due to its tiny size of less than 2 mm. The most common gases from volcanoes are water vapor, carbon dioxide, and sulfur dioxide but additionally include carbon monoxide, hydrogen sulfide, chlorides, and fluorides of hydrogen and methane. Most often, volcanism induces short-term climatic variations. The secondary sulfate aerosols emitted from volcanoes can change the regional energy balance and lead to cooling at the surface. Volcanic cooling can cause crop failure and famine for many years after large eruptions as was observed for Tambora eruption of 1815. The halogen-containing gases from a volcano impact the stratospheric ozone layer. Significant decrease in the total ozone column in lower stratosphere was observed by ozonesondes after the eruption of Mt. Pinatubo. Volcanic material can lead to increased pH of rainwater and can even contaminate drinking water sources of a region as was observed during the recent Manaro Voui eruption of 2018. The severest impacts of volcanoes are borne by the aviation sector leading to engine damage and aviation hazards. Apart from modulating climate due to perturbed radiative balance, volcanic eruptions have also been associated with ENSO, changed rainfall patterns, and modified circulation patterns. The Mt. Pinatubo eruption has acquired a special place in volcanology due to its gigantic scale and extreme impacts. However, on VEI scale, Tambora eruption of 1815 is higher than Pinatubo, while the highest is Yellowstone Caldera, which erupted 0.5 million years ago. But the Pinatubo has given us a lot more information due to the presence of modern technology and satellites.

The effects of volcanic eruptions are already incorporated in global climate models and earth system science models. While on one hand, specialist scientific agencies and vulcanologists are always on lookout for possible new eruptions, a synergistic approach additionally involving other branches of science where eruption effects are anticipated can be an important step to face the challenges posed by volcanic emissions. Scientists working with emission inventories can incorporate the effects of transcontinental and transoceanic plumes in regional inventories for relevant eruptions; e.g., SO_2 enhancement observed over Delhi was traced to an eruption in Afar region of Ethiopia (Mallik et al. 2013). Policymakers will also be benefitted from such inclusions, specifically in regions and localities prone to impacts of volcanic emissions. Such holistic approach will also lead to greater awareness and understanding among nonexpert stakeholders who knowing/unknowingly suffer from these extreme expressions of nature.

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