Volcanoes Rule Climate Change

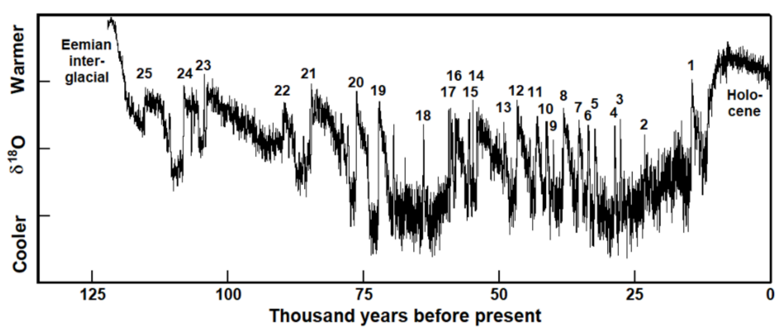
Peter L. Ward

Willi Dansgaard, a bright-eyed, 25-year-old Danish earth scientist, first travelled to Greenland to do research in 1947. He became so enamored with “its forces, its bounty, its cruelty and, above all, its beauty” that he spent the rest of his life studying the Greenland ice sheet. In the process, Willi developed what is probably the single most precise and, therefore, most important technique for observing and understanding paleoclimate. He discovered that the footprints of climate change in Greenland ice clearly record rapid warming within decades followed by slow, incremental cooling over millennia in sequences that average a few thousand years in length but are highly erratic in both onset and duration. These distinctive events during the past 120,000 years have now been named Dansgaard-Oeschger events in honor of Willie and his Swiss collaborator Hans Oeschger. There is considerable evidence that similar events have happened throughout Earth history. Climate, it seems, has been changing at much higher rates than most scientists have imagined. Such frequent rapid warming followed by slow incremental cooling is best explained by a very dynamic balance between two distinctly different types of volcanism—extensive basaltic lava flows and frequent major explosive volcanic eruptions.

Professor Willi Dansgaard examining an ice core in Greenland.

Air Bubbles in Ice

By 1954, Dansgaard demonstrated that the ratio of oxygen-18 isotopes compared to the more common oxygen-16 isotopes in atmospheric water vapor depends primarily on precipitation temperature. In 1964, he found, by measuring oxygen isotopes



Twenty-five Dansgaard-Oeschger events when air temperature in Greenland suddenly rose approximately 5 °C within decades. Temperatures are inferred by measuring ratios of oxygen-isotope concentrations ($\delta^{18}O$) in air bubbles in ice from three boreholes in Greenland.

in air bubbles contained in glacial ice, that he could estimate air temperature at the time the ice was formed. In 1969, he analyzed 1600 samples in the 1390-meter-deep borehole under Camp Century in Greenland, detailing numerous major oscillations in air temperatures over the past 100,000 years.

By 1995, many scientists had analyzed ice cores from Greenland clearly documenting 25 times in the past 120,000 years when air temperatures suddenly rose approximately 5 °C within years to decades, only to drift slowly over millennia back into the depths of the ice age. While some authors have argued that these events occur in 1470-year cycles, the data clearly show that the sequences are not cyclic—they are highly erratic in both time of onset and duration.

Isotopic analyses of air bubbles in ice, which Dansgaard initiated, provide the best time resolution of temperature change over tens of thousands of years because samples can be taken at as many depths as desirable, and each sample can be dated within years at the top of the core to decades at the bottom. Tree rings provide yearly resolution, but are not as sensitive to temperature changes and merging data from numerous trees to obtain a reliable record over thousands of years has proven problematic. Lake and ocean sediments can similarly be sampled at very fine resolution, but they measure the temperature of the water, which changes much more slowly and by much fewer degrees than air temperature because of the very large heat content of water.

There is ample evidence for similar rapid changes in climate occurring throughout the geologic record even though time resolution is typically more limited.

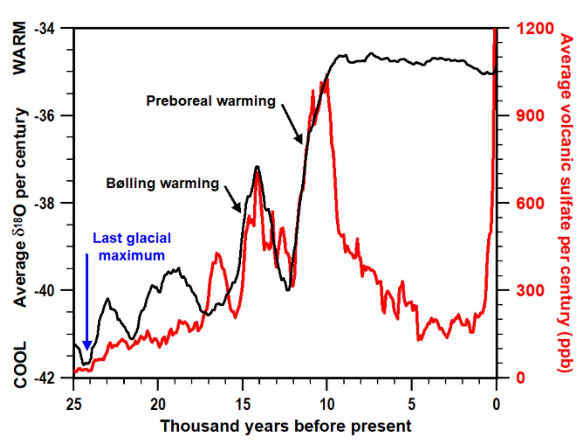
What Could Cause Such Rapid Changes?

Dansgaard-Oeschger warming events are contemporaneous with sudden influxes of fresh water into the North Atlantic Ocean. Many scientists have argued that these floods of non-saline water changed ocean currents, causing the warming events, but this begs the question of what caused the warming that melted ice to cause the floods. Similarly, it is very difficult to imagine how greenhouse gas concentrations could change fast enough to cause such rapid and frequent changes in climate. Some scientists have suggested volcanic eruptions through coal and peat layers might produce prodigious amounts of carbon dioxide, but this is grasping at straws and highly unlikely every few thousand years as observed in the data.

Much longer-term increases in concentrations of carbon dioxide do appear to track increases in ocean temperature over the past 800,000 years as seen in Antarctic ice cores, but such changes are easily explained. You know that as your beer or soda drink warms up, it loses fizz, exhaling carbon dioxide into the air. Similarly, the solubility of carbon dioxide in water is well observed to decrease with warming. When the ocean surface, covering 71% of Earth, warms ever so slightly, atmospheric concentrations of carbon dioxide are observed to increase. Ocean temperatures and concentrations of carbon dioxide have been increasing slowly since the last low in the Little Ice Age around 1850, and both ocean heat content and carbon dioxide concentrations have been increasing at escalating rates since 1970.

The opposite effect of ocean cooling leading to lower concentrations of carbon dioxide in the atmosphere was clearly observed following the eruption of Pinatubo volcano in the Philippines in 1991, the largest volcanic eruption since 1912. This eruption ejected as many as 234 megatons of carbon dioxide into the atmosphere, but the rate of increase in atmospheric concentration of carbon dioxide, measured at Mauna Loa, actually decreased for the next three years. The reason is, as will be discussed below, that the eruption of Pinatubo injected megatons of water vapor and sulfur dioxide into the lower stratosphere where they combined to form sulfuric acid aerosols that reflected and scattered sunlight, cooling the ocean surface nearly 0.5 °C for more than two years.

The greatest warming of air temperatures observed in Greenland, nearly 8 °C, occurred from 12,000 to 9,500 years ago at the end of the last ice age as shown by the black line in this figure. The red line shows the rate of volcanism calculated as the average concentration of volcanic sulfate per century measured in the same ice cores. These data strongly suggest that this major warming was caused by volcanism and that the high rate of volcanism for 2500 years was intense enough and lasted long enough to warm the ocean out of the last ice age. The oceans contain nearly all the heat in the ocean-atmosphere system. It takes centuries to millennia of warming to change ocean temperature significantly. During the 25 Dansgaard-Oeschger



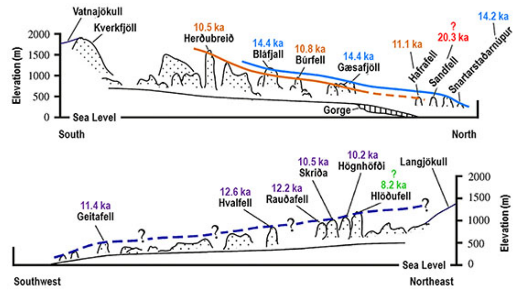
The highest rates of volcanism are generally contemporaneous with the highest rates of warming. Temperature (black line) and volcanic sulfate (red line) were measured in an ice core in Greenland.

events, volcanism does not appear to have lasted long enough, at a high-enough intensity, to warm the ocean completely out of ice-age conditions, although the Bølling warming 14,000 years ago came close. Thus, when basaltic volcanism wanes, the cold ocean appears to help cool air temperatures slowly back into ice-age conditions.

Volcanic activity was unusually high in Iceland during both the Bølling warming and the Preboreal warming. Basaltic lava flows under ice are chilled too quickly to flow horizontally. Instead they build vertically until they erupt out of the top of the ice sheet, forming broad-shouldered table mountains or tuyas. Twelve of the thirteen best dated tuyas experienced their final eruptive phase during the Bølling (blue) or Preboreal (orange) warmings as summarized in this figure.

Herðubreið tuya or table mountain in north-eastern Iceland formed by basaltic lava flows erupted under a glacier. The eruptions appear to have ended around 10,500 years ago. Herðubreið means broad shoulders.

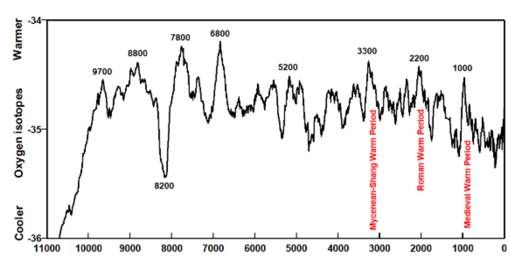
Voluminous basaltic lava flows in Iceland were formed during the major periods of warming out of the last ice age. Some scientists suggest a feedback loop where rapid melting of kilometer-thick glacial ice relieves pressure on shallow magma chambers, allowing increased volcanic activity causing increased melting of ice. Warming caused by basaltic volcanism in Iceland can explain the floods of fresh water into the North Atlantic Ocean observed during Dansgaard-Oeschger events.



Times of the final eruptive phase of tuyas in Iceland showing the thickness of the ice sheet around 14,000 and 10,000 years ago. Credit: http://dx.doi.org/10.1016/j.quascirev.2007.02.016.

More Recent Warming

During the past 10,000 years, there have been major peaks in temperatures measured in Greenland ice cores every thousand years or so as shown in this figure. The largest peaks in temperature occurred at the same time as the largest known basaltic lava flows. For example, the eruption of 800 km^2 of lava from Eldgjá in Iceland (934 to 940 A. D.) started the Medieval



Periods of warming during the last 10,000 years occurred at the same times as the largest basaltic lava flows.

Warm Period. The Roman Warm Period around 220 B.C. began with the eruption of the most recent lava flows in Craters of the Moon National Monument in south-central Idaho covering 700 km^2. It was 218 B.C. when climate was warm enough for Hannibal to lead his Carthaginian army and its many elephants over the Alps, surprising the Romans, one of the most celebrated achievements of any military force in ancient warfare.

The largest lava flows mapped in Iceland and in the Craters of the Moon National Monument are broadly contemporaneous with the warming peaks 6800, 7800, 8800, and 9700 years before present. The largest lava flow known in Iceland, the Great Þjórsá Lava, covering an area of 970 km^2 formed around 8600 years before present. As more large basalt flows become dated accurately, it will be interesting to see if any were <u>not</u> associated with major warming.

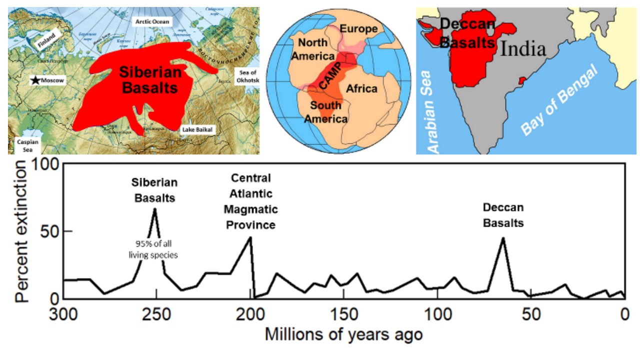
Note how short these periods of warming typically have been. It is entirely likely that more than one major lava flow occurred around the same time. While contemporaneity is not proof of cause, the fact that all known large lava flows during this period are associated with substantial warming, causes one to wonder.

Eruption of basaltic lava from Bárðarbunga volcano in central Iceland was never explosive enough to be of major concern to onlookers. Credit ©Arctic-Images/Corbis.

The most voluminous basaltic lava flow since 1783 was erupted from Bárðarbunga volcano in central Iceland from August 2014 to February 2015 covering an area of 85 km^2. Global temperatures had been relatively constant from 1998 through 2013. Since 2014, however, average temperatures have risen at nearly five times the rate of warming from 1970 through 1998 to be discussed below.

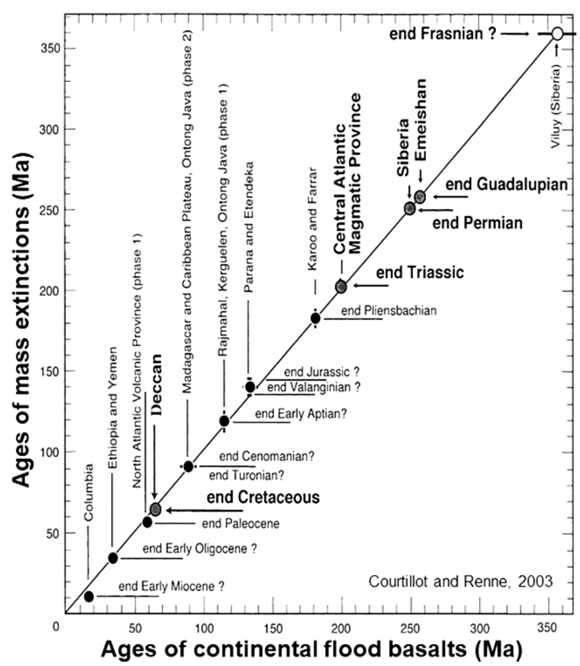
Warming Associated with Large Igneous Provinces

Richard Ernst has cataloged 211 Large Igneous Provinces (LIPs) in the past three billion years. Forty-three of these formed since the beginning of the Paleozoic some 540 million years ago. LIPs are gigantic flows of flood basalts. The smallest of these since the Precambrian, the Columbia River Basalt group, covers an area of 163,700 km^2 in eastern Washington and Oregon. There are more than 200 individual basalt flows in four major groups formed sometime between 17 and 14 million years ago.



Three Large Igneous Provinces with basaltic lava flows covering 7 million, 11 million, and 1.5 million square kilometers occurred at the same time as the three largest mass extinctions ending the Paleozoic, the Triassic, and the Mesozoic.

The largest known LIP is the Central Atlantic Magmatic Province (CAMP) covering more than 11,000,000 km^2 and formed 201 million years ago as North America rifted apart from Africa. The second largest is the Siberian Basalts formed 251 million years ago as a major rift tried to open through Siberia. These basalt flows covered an area of more than 7,000,000 km^2, equivalent to all the contiguous United States minus Montana and Texas! During these eruptions, equatorial ocean temperatures appear to have exceeded 40 °C (104 °F), the temperature of a very warm hot tub. Ocean acidity and lethally hot temperatures caused the "Great Dying" when about 95% of all living species went extinct. The Deccan basalts covered an area of 1,500,000 km^2 in India, 66 million



Major mass extinctions occurred at the same time as the most extensive Large Igneous Provinces throughout the past 400 million years.

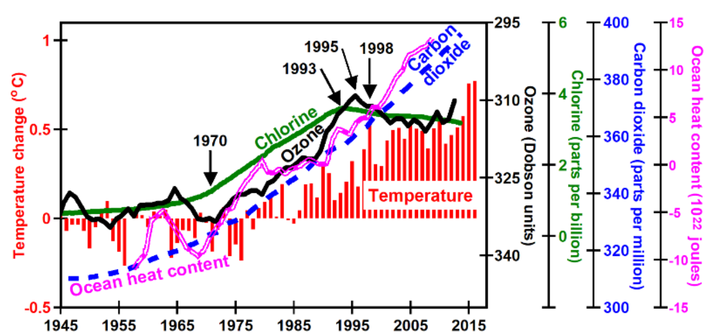
years ago, causing the third largest known mass extinction, made worse by a meteor impact on the northern end of the Yucatán Peninsula in Mexico.

The most extensive basaltic lava flows known on Earth occurred simultaneously with periods of major global warming, major ocean acidification, and major mass extinctions. In the last 400 million years, all known major mass extinctions occurred at the same time as all known LIPs that typically formed at the end of geologic eras, epochs and ages when there were major changes in climate mapped worldwide as sudden changes in sedimentation and fossils. LIPs punctuate the geologic time scale.

Warming Caused by CFCs

In the late 1920s, Thomas Midgley, Jr. led the effort to manufacture chlorofluorocarbon gases (CFCs), which were very inert—they did not react with most other substances. They could be used as refrigerants that were much safer than existing alternatives. In the 1960s, CFCs became very popular as refrigerants, spray-can propellants, solvents, and foam blowing agents. By 1970, depletion of the ozone layer circling Earth at altitudes of 20 to 30 km began to increase and average global average air temperatures began to rise. In 1974, scientists showed that CFCs, when high in the stratosphere, can be broken down by solar ultraviolet radiation to release atoms of chlorine and that one atom of chlorine can destroy 100,000 molecules of ozone, earning the Nobel Prize in Chemistry in 1995.

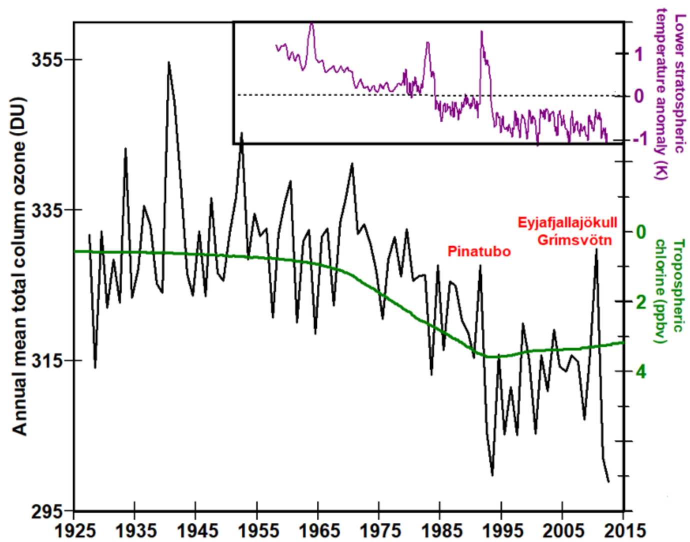
In 1985, scientists discovered the ozone hole over Antarctica where the ozone layer was depleted by as much as 50% during late winter and early spring. Ozone depletion was suddenly recognized as a major problem. Scientists and political leaders worked extremely well together to develop the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987, which took effect in early 1989. By 1993, increases in CFCs in the atmosphere stopped. By 1995, increases in ozone depletion stopped. By 1998, increases in global average temperatures stopped. Humans had caused the global warming from 1970 to 1998 and humans had stopped the increase in global warming by passing the Montreal Protocol. Ozone remains depleted to this



Tropospheric chlorine due to CFC gases increased beginning in the late 1960s (green line), ozone depletion began increasing around 1970 (black line), and then annual average near surface global temperatures began increasing (red bars).

day and is not expected to return to pre-1970 levels for many decades because CFCs are so inert.

This warming is the result of the ozone-oxygen cycle in the stratosphere, 15 to 50 km above Earth. The stratosphere is heated primarily when molecules of oxygen absorb ultraviolet-C solar radiation, causing the molecules to dissociate into two atoms of oxygen. These atoms of oxygen (O) can then join molecules of oxygen (O_2) to form molecules of ozone (O_3) which are then dissociated by solar ultraviolet-B radiation in an endless cycle. This is a very dynamic system so that a particular molecule of ozone only lasts, on average, about 8.2 days. When this cycle is interrupted by depletion of the ozone layer, more ultraviolet-B radiation than normal is observed to reach Earth. Ultraviolet-B is a very energetic radiation that causes sunburn, skin cancer, cataracts, and, when intense enough, mutations in DNA. When the ozone layer is depleted, less ultraviolet-B radiation is absorbed in the ozone layer, causing it to cool, and more ultraviolet-B is absorbed by ground-level ozone pollution causing dissociation and thus warming of air near Earth's surface. This is why global warming from 1970 through 1998 was greatest in the northern hemisphere containing 83% of world population and, therefore, the greatest amounts of ozone pollution. Ultraviolet-B is also absorbed very efficiently by oceans because it penetrates tens of meters and thus cannot be radiated back into space at night. Ocean heat content has been rising, especially since 1970 and continues to increase today because ozone depletion remains high.



The greatest ozone depletion observed since 1927 followed the eruption of Pinatubo in 1991 and Eyjafjallajökull and Grímsvötn in 2010. The black line shows annual average total column ozone observed above Arosa Switzerland. The green line shows tropospheric chlorine due to CFC gases. The purple line shows the decrease in temperature in the lower stratosphere as ozone depletion increases.

Ozone depletion is greatest in polar regions during late winter and early spring, explaining arctic amplification, the observation that warming is much greater in polar regions than in mid-latitudes.

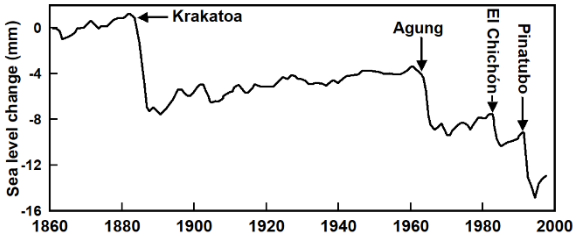
Warming Caused by Volcanism

The greatest ozone depletion observed since records began in 1927 was in 1992 and 1993, following the 1991 eruption of Pinatubo volcano. During the winter of 1991-1992, temperatures in major industrial areas in the northern hemisphere rose as much as 3.5 °C. The second greatest ozone depletion followed the much smaller 2010 basaltic eruptions of Eyjafjallajökull and Grímsvötn in Iceland. Most major volcanic eruptions since 1927 have been followed by significant ozone depletion apparently caused by megatons of chlorine and bromine gases rising into the lower stratosphere from volcanic eruptions. The concentrations of these gases in basaltic magma are typically at least an order of magnitude greater than concentrations in more evolved magma erupted by explosive volcanoes. The exact atmospheric chemistry involved is still not well understood because current thinking is that chlorine and bromine are water soluble and should be rained out of the atmosphere before they can reach the lower stratosphere. Ozone depletion following volcanic eruptions, however, is well observed. Mutations in fossil leaves during eruption of the Siberian basalts suggest ozone depletion was prevalent at that time.

What Causes the Cooling?

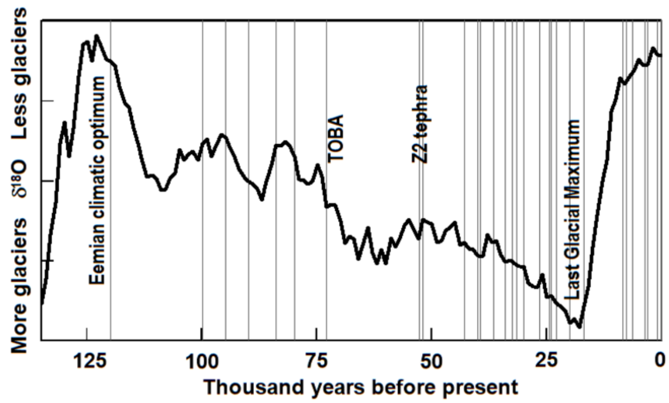
Major explosive volcanic eruptions, such as Mt. Pinatubo, have been observed throughout written history to be followed by 2 to 4 years of global cooling of typically 0.5 °C. The eruption of Tambora in 1815, the largest explosive eruption in 1800 years, was followed in 1816 by the "year without summer." This cooling is caused by aerosols in the lower stratosphere.

The eruption of Mt. Pinatubo in the Philippines in



Modelling of sea level change following four major explosive volcanic eruptions when aerosols in the lower stratosphere reflected and scattered solar radiation, causing observed cooling of near surface temperatures of 0.5 °C for 2 to 4 years.

Mt. Pinatubo in 1991 ejected hundreds of megatons of water vapor and 17 megatons of sulfur dioxide as high as the lower stratosphere where they combined to form sulfuric-acid aerosols that circled Earth within 21 days and spread from the tropics to both poles within a year. The aerosol particles grew large enough, within months, to reflect and scatter sunlight, cooling Earth. While the cooling of the whole ocean surface lasts for only 2 to 4 years, modelling shows that the effect of this cooling on ocean temperatures lasts up to a century. Modeling sea level as a function of ocean temperature, shows that the cooling due to the eruption of Krakatoa in 1883 had not recovered when Agung erupted in 1963. This modelling does not include the effects of the eruptions of Santa Maria in 1902 and Katmai in 1912. Thus, when there are several explosive eruptions per century for millennia, the ocean is cooled slowly and incrementally into ice-age conditions. This incremental cooling is shown quite clearly by oxygen isotope data from 57 deep-sea cores stacked together to improve the signal to noise ratio. This figure is for the same time period of the Dansgaard-Oeschger events shown above. Note the much higher resolution of climate change for the air temperature data from ice cores compared to water temperatures determined from ocean cores.



Ocean temperature in the last 130,000 years based on a stack of oxygen isotope measurements in 57 globally distributed deep-sea cores. Vertical black lines are times of known major explosive volcanic eruptions.

The June 1991 eruption of Pinatubo volcano did deplete the ozone layer causing short-term warming of as much as 3.5 °C from December 1991 through February 1992, especially in industrial areas in the northern hemisphere. Eventually cooling from the aerosols, however, became dominant, leading to net global cooling.

The Balance is Determined by Plate Tectonics

About 75% of all volcanism on Earth is in a submarine environment along mid-ocean ridges. Submarine volcanoes affect ocean acidity and ocean temperature, but do not have any direct effect on climate. Subaerial explosive volcanism, on the other hand, causes global cooling. Explosive volcanoes are most common above subduction zones where ocean plates are being subducted under continents. Extensive, effusive basaltic lava flows cause global warming and are most common in rift zones such as Iceland and the East African Rift where continents are being pulled apart. The ratio of explosive volcanism to effusive volcanism and, therefore, global temperatures, depends on the configuration of tectonic plates on the surface of Earth. For example, when subduction was very active around the Pacific Ocean from 37 to 27 million years ago, glaciers began to grow on Antarctica 34 million years ago. Rapid motion of the Pacific Plate over the past 3 million years appears to have caused the cooling into the last ice age.

Putting the Pieces Together

Periods of rapid global warming recently, throughout human history, and throughout Earth history are contemporaneous with extensive flows of basaltic lava covering areas of tens, to hundreds, to millions of square kilometers. The larger the flows, the greater the warming and the longer the warming lasts. Warming appears to be caused by ozone depletion resulting from high concentrations of chlorine and bromine gases emitted especially from basaltic lava flows. Warming from 1970 to 1998 also appears caused by ozone depletion, in this case resulting from manufactured CFC gases.

Major explosive volcanic eruptions, on the other hand, have been observed throughout written history to form aerosols in the lower stratosphere that reflect and scatter solar radiation, causing global cooling of about 0.5 °C for 2 to 4 years. This short-term cooling, however, affects ocean temperatures for as much as a century. When several major explosive eruptions occur each century for millennia, they are observed to cool global temperatures incrementally down into ice-age conditions. Warming and cooling are observed to occur in sequences that average a few thousand years in length but are highly erratic in both time of onset and duration.

A dynamic balance between extensive basaltic lava flows and frequent major explosive eruptions explains climate change observed throughout the geologic record in exquisite detail. Changes in atmospheric concentrations of carbon dioxide cannot explain the extensive observations. Volcanoes appear to rule climate change.

Peter L. Ward is a geophysicist who worked 27 years with the U.S. Geological Survey. More detail can be found at his website *WhyClimateChanges.com* and in his book *What Really Causes Global Warming? Greenhouse Gases or Ozone Depletion?*