



THE YEAR
WITHOUT SUMMER:

1816

AND THE VOLCANO
THAT DARKENED THE WORLD
AND CHANGED HISTORY

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AND NICHOLAS P. KLINGAMAN

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ST. MARTIN'S PRESS  NEW YORK

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To Janet and Emma

CONTENTS

Title Page

Copyright Notice

Dedication

1. The Volcano

2. Portents

3. Cold Fronts

4. The Handwriting of God

5. Day After Day

6. The Lost Summer

7. Poverty and Misery

8. The Price of Bread

9. Harvest

10. Emigration

11. Relief

Epilogue

Acknowledgments

Notes

Bibliography

Index

Also by William K. Klingaman

About the Authors

Copyright

1.

THE VOLCANO

JUST BEFORE SUNSET on April 5, 1815, a massive explosion shook the volcanic island of Sumbawa in the Indonesian archipelago. For two hours, a stream of lava erupted from Mount Tambora, the highest peak in the region, sending a plume of ash eighteen miles into the sky.

More than eight hundred miles away, Thomas Stamford Raffles, the lieutenant-governor of Java, heard the blast at his residence and assumed it came from cannon firing in the distance. Other British authorities on the island made the same mistake. Fearing a neighboring village was under attack, the commander of the city of Djogjokarta, in central Java, dispatched troops to repel the invaders. Officials along the coast interpreted the sounds as signals from a ship in distress, and launched rescue boats to look for survivors.

At Makassar on the southwestern tip of Sulawesi, 240 miles northeast of Tambora, the commander of the *Benares*, a cruiser of the British East India Company, reported “a firing of cannon” on April 5. The explosions appeared to come from the south; as they continued, “the reports seemed to approach much nearer, and sounded like heavy guns occasionally, with slighter reports between.” Assuming the pirates were in the area, the *Benares* put to sea and spent the next three days scouring nearby islands for any signs of trouble, but found nothing. Nearly five hundred miles farther to the east, the British resident on the island of Ternate heard “several very distinct reports like heavy cannon,” and sent another cruiser, the *Teignmouth*, to investigate. It, too, returned empty-handed.

British authorities might have been excused for assuming that the threatening sounds came from potential enemies rather than the earth itself. They were not yet accustomed to the frequent volcanic eruptions that plagued the Indonesian islands. Britain had gained control of Java and the surrounding islands less than four years earlier, when British troops overwhelmed a vastly outnumbered band of French defenders who themselves had held Java for only a short time, having taken it from the Dutch when France conquered the Netherlands in 1794. By the spring of 1815, neither the government in London nor the British East India Company was entirely certain that they wanted to keep the island, since the expense of administering and defending it had outweighed the commercial benefits thus far.

Responsibility for British policy on the scene lay squarely with Raffles himself. The son of a ship captain, Raffles—who actually was born at sea, off the coast of Jamaica—dreamt of a British maritime empire throughout South Asia, an “Eastern insular Empire” that would provide new markets for English cotton and woolen textiles, and a profitable supply of coffee and sugar for Europe. It was

Raffles who had persuaded the governor general of India, Lord Minto, to seize Java in the first place. Raffles also hoped to use Java as an avenue to improve relations with Japan, which he viewed as a rising Asiatic power. Meanwhile, heeding Minto's advice to "do as much good as we can" while governing Java, Raffles reformed the colonial administration of the island, limiting the powers of the great landowners over their tenants and ameliorating the worst abuses of slavery while banning the importation of slaves under fourteen years of age.

But Raffles' interests in the region extended beyond politics and commerce. After years of study, he was sufficiently fluent in the Malay language to conduct discussions directly with local chieftains. He regularly employed botanists and zoologists to obtain—at his own expense—specimens of local flora and wildlife, some of which he had preserved in spirit and shipped back to Britain. In his capacity as president of the Batavian Society, dedicated to the study of Java's natural history, Raffles frequently toured the island and recorded his observations of geological phenomena. Several weeks before Mount Tambora erupted, Raffles became the first European to ascend a nearby mountain known as Gunong Gede; by using thermometers to measure the difference in temperature between the base and the peak, Raffles and his companions determined that they had climbed at least seven thousand feet. "We had a most extensive prospect from the summit," he subsequently wrote to a friend. "The islands all round were quite distinct and we traced the sea beyond the southernmost point of Sumatra; the surf on the south coast was visible to the naked eye."

So Raffles' scientific curiosity was piqued when the cannonlike explosions from the southeast continued throughout the night of April 5 and into the morning hours. Shortly after dawn, a light rain of ash provided evidence that a volcano somewhere in the region had erupted. Few suspected Mount Tambora. It was generally believed that Tambora was extinct, although natives living in the nearest village had reported rumblings from deep inside the mountain during the past year. Besides, few on Java believed that such powerful sounds could have come from a volcano several hundred miles away. As Raffles subsequently noted, "the sound appeared to be so close, that in each district it seemed near at hand, and was generally attributed to an eruption either from the mountains Merapi, Klut, Bromo."

As a fog of ash drifted across Java, the sun faded; the warm, humid air grew stifling, and everything seemed unnaturally still. The oppressive pressure, Raffles noted, "seemed to forbode an earthquake." Over the next several days, however, the explosions gradually subsided. Volcanic ash continued to fall, but in diminishing quantities. Relieved, Raffles returned to his routine administrative duties.

* * *

FAR from Tambora and the island of Java, a different sort of shock greeted the rulers and citizens of Europe in April 1815: Napoléon had returned to Paris.

The Emperor had spent the past year ruling the island of Elba, a rocky, desolate piece of real estate

of no discernible strategic importance off the coast of Italy. Sixteen miles long and only seven miles across at its widest point, Elba in the early nineteenth century was home mainly to goats, deserted ruins, a variety of vines and scraggly shrubs on arid hillsides, and approximately twelve thousand impoverished peasants with a well-deserved reputation for being “extremely irritable” and “almost universally ignorant.” Its primary natural resource was rocks. One French observer who visited Elba shortly before Napoléon’s arrival warned that the island’s unremittingly inhospitable topography was likely to “fatigue the senses and impart sensations of sorrow to the soul.”

Napoléon had been consigned to Elba by the victorious allied coalition of Britain, Prussia, Austria, and Russia shortly after abdicating the French throne on April 6, 1814. (Perhaps as an ironic jest, the Allies allowed him to retain the title of “Emperor.”) But the Allied statesmen who gathered at Vienna to sort out the consequences of nearly two decades of war neglected to provide a jailer, or even an effective network of informants to keep them apprised of Napoléon’s movements. Encouraged by press reports of widespread popular disaffection with the restored Bourbon monarchy in Paris, Napoléon decided that his former subjects would welcome him back. And so on February 25, 1815, accompanied by slightly more than a thousand troops, forty horses, and four cannon, Napoléon sailed away from Elba unopposed.

Six days later he landed at Golfe Juan, about a mile west of Cannes. “Frenchmen! In my exile I have heard your complaints and your wishes,” he exclaimed. “I have arrived in spite of every obstacle and every danger.” Napoléon marched north rapidly, opposition crumbling as his entourage expanded at every town. “Taking towns at his liking and crowns at his leisure / From Elba to Lyons and Paris he goes,” crowed Lord Byron, who admired Napoléon and fancied himself an English counterpart of the Eagle. Although many of Napoléon’s former subjects—particularly his troops—greeted him enthusiastically, others responded more warily. Their caution reflected the heavy costs of Napoléon’s previous quest for glory: more than 900,000 French soldiers dead, and a depleted national treasury now saddled with millions of francs of reparations due the Allies. Napoléon attempted to allay the anxieties by publicly disavowing any new imperial ambitions. “I want less to be sovereign of France,” he told the people of Grenoble, “than the first of her citizens.”

News of Napoléon’s flight reached Vienna on March 7. Stunned, the Allied representatives decided within hours to send troops to oppose Napoléon, but they also embargoed the news from France for several days until they were prepared to make a public statement. Several days later, they jointly declared that by reappearing in France, Napoléon had proved himself “an enemy and disturber of the peace of the world,” and that together, “the sovereigns of Europe would be ready to give the King of France and the French nation the assistance necessary to restore peace.”

King Louis XVIII would need all the help he could get. Twenty-two years after the execution of his brother, Louis XVI, few Frenchmen outside of a die-hard circle of royalists desired to return to the days of a pre-Revolutionary monarchy. Too much land belonging to the king, the aristocracy, and the church had been dispensed to too many members of the Third Estate to turn back the clock. Nor had

year of life under the restored Bourbon dynasty endeared King Louis to his subjects. Facing an immense national debt which he inherited from Napoléon, Louis' ministers found it necessary to slash the army budget, cancelling contracts for military supplies and throwing nearly three hundred thousand soldiers out of work. The government also reduced spending on public construction projects while maintaining an oppressive array of taxes. As unemployment rose along with the price of bread, hungry citizens in Channel ports rioted against the shipment of grain to Britain. "We are really going on very badly," wrote one government official, "and we must do better if we do not wish to perish completely."

Louis himself engendered little personal loyalty, or even respect; a British bishop once said that the French king was "a man fit only to cook his own capons." Fifty-eight years old and so grossly overweight that he could not sit on a horse, Louis abhorred hard work and delegated authority with little alacrity. Despite a modest measure of charm in private conversations, Louis never developed a compelling public presence. Certainly he paled in comparison with the charismatic former emperor. As Napoléon hastened towards the capital in March, covering two hundred miles in six days, Louis grew increasingly anxious. Ominous strains of the incendiary *Marseillaise* rang through Paris streets as royal troops deserted en masse and went over to Napoléon; and newspaper editorials likened the situation to the eve of the Terror, when nobles and monarchists were slaughtered. Recognizing that, as one writer put it, "the Parisians love for their King has so died down that barely a spark remains," Louis decided on the evening of March 18 to flee Paris.

Three days later, Napoléon entered the city without a shot being fired. By the first week of April, however, it was clear that the weary and impoverished French public lacked any appetite for ambitious schemes to restore the glory of the empire. Napoléon's proposals for new taxes to fund a revitalized army met with widespread opposition. Visible signs of disaffection appeared; rallies in support of the emperor's return clashed with demonstrations demanding his ouster. To bolster his defenses against the Allied assault he knew was coming, Napoléon issued orders on April 8 for a general mobilization of the French nation. Meanwhile, he assured the sovereigns of Europe (whom he formally referred to as "my brothers") that he wanted nothing more than "the maintenance of an honourable peace."

But more than anything else, France—and the rest of Europe—desperately needed a breathing space. A year earlier, the Marquis de Caulaincourt had written that "the need for rest was universally felt through every class of society, and in the army, that peace at any price had become the ruling passion of the day." Napoléon's return from Elba only deepened the prevailing exhaustion. "Our objective is to make sure that our children have years of peace," noted the Austrian general Karl Schwarzenberg, "and that the world has some repose. The Emperor Napoléon had shown all too plainly of late that he desires neither of these things."

* * *

AROUND seven o'clock on the evening of April 10, Mount Tambora erupted once again, this time for

more violently. Three columns of flaming lava shot into the air, meeting briefly at their peak in what one eyewitness termed “a troubled confused manner.” Almost immediately the entire mountain appeared to be consumed by liquid fire, a fountain of ash, water, and molten rock shooting in every direction. Pumice stones—some walnut-sized but others twice the size of a man’s fist—rained down upon the village of Sanggar, nineteen miles away. After an hour, so much ash and dust had been hurled into the atmosphere that darkness hid the fiery mountaintop from view.

As the ash clouds thickened, hot lava racing down the mountain slope heated the air above it to thousands of degrees. The air quickly rose, leaving behind a vacuum into which cooler air rushed from all directions. The resulting whirlwind tore up trees by the roots and swept up men, cattle, and horses. Virtually every house in Sanggar was flattened. The village of Tambora, closer to the volcano, vanished under a flood of pumice. Cascading lava slammed into the ocean, destroying all aquatic life in its path, and creating tsunamis nearly fifteen feet high which swept away everything within their reach. Violent explosions from the reaction of lava with cold seawater threw even greater quantities of ash into the atmosphere, and created vast fields of pumice stones along the shoreline. These fields, some of which were three miles wide, were light enough to float; they drifted out to sea where they were driven west by the prevailing winds and ocean currents. Like giant icebergs, the pumice fields remained a hazard to ships for years after the eruption. The British ship *Fairlie* encountered one in the South Indian Ocean in October 1815, more than 2,000 miles west-southwest of Tambora. The crew initially mistook the ash for seaweed, but when they approached they were shocked “to find [composed of] burnt cinders, evidently volcanic. The sea was covered with it during the next two days.” As there was no land for hundreds of miles (and evidently being unable to believe that the pumice could have traveled that far) the crew attributed the field to an underwater eruption of an unknown location.

At ten o’clock the magma columns—which now consisted almost entirely of molten rock and steam, with most of the water having boiled away and evaporated—collapsed under their own weight. The eruption destroyed the top three thousand feet of the volcano, blasting it into the air in pieces, leaving behind only a large crater three miles wide and half a mile deep, as though the mountain had been struck by a meteor. Propelled by the force of the eruption, gray and black particles of ash, dust, and soot rose high into the atmosphere, some as high as twenty-five miles above the crumbling peak of the mountain, where the winds began to spread them in all directions. As they moved away from the eruption, the largest, heaviest particles lost their momentum first and began to fall back towards the ground. This gave the ash cloud the shape of a mushroom or an umbrella, with the still-erupting Tambora as the fiery shaft. The lightest particles in the cloud, however, retained their momentum and remained high in the air; some even continued to rise.

By eleven o’clock, the whirlwind had subsided. Only then did the explosions commence. At Bimadon on the northeast coast of Sumbawa about forty miles east of Tambora, the British resident reported that the blasts sounded like “a heavy mortar fired close to his ear.” A rain of ash poured down upon

the villages, heavy enough to crush the roofs of houses, including the resident's, rendering the uninhabitable. Waves surged in from the sea, flooding houses a foot deep and ripping fishing boats from their moorings in the harbor, tossing them high up onto the shore. In place of dawn, there was only darkness.

On board the *Benares*, still moored at Makassar, sailors heard the explosions—far louder than those of the previous eruption—throughout the night. “Towards morning the reports were in quick succession,” noted the ship’s commander, “and sometimes like three or four guns fired together, and so heavy, that they shook the ship, as they did the houses in the fort.” As soon as a semblance of dawn broke, the cruiser again set sail southward, to determine the cause of the blasts.

But the sky troubled the *Benares*’s captain. “By this time,” he noted, “which was about eight A.M., it was very apparent that some extraordinary occurrence had taken place. The face of the heavens to the southward and westward had assumed the most dismal and lowering aspect, and it was much darker than when the sun rose.” What appeared to be a heavy squall on the horizon quickly took on a dark red glow, spreading across the sky. “By ten it was so dark that I could scarcely discern the ship from the shore, though not a mile distant.” Ash began to fall on the decks of the *Benares*. An hour later, nearly the entire sky was blotted out.

By this time, Tambora’s umbrella ash cloud extended for more than three hundred miles at its widest point. As the cloud spread, the heavier clumps of ash within it drifted to the ground, but the remainder remained aloft. “The ashes now began to fall in showers,” the ship’s captain wrote, “and the appearance altogether was truly awful and alarming.” By noon, the darkness was complete, and the rain of ash—which one sailor described as a tasteless “perfect impalpable powder or dust” that gave off a vaguely burnt odor—covered every surface on the ship. “The darkness was so profound throughout the remainder of the day,” continued the commander, “that I never saw any thing equal to it in the darkest night; it was impossible to see your hand when held up close to the eye.” Ash continued to fall throughout the evening; despite the captain’s efforts to cover the deck with awnings, the particles piled as much as a foot high on many surfaces. At six o’clock the following morning there was still no sign of the sun, but the accumulated weight of the ash—which one officer estimated at several tons—forced the crew to begin tossing the powder overboard. Finally by noon on April 12, a faint light broke through, and the captain was struck by the thought that the *Benares* resembled nothing more than a giant calcified pumice stone. For the next three days, however, he noted that “the atmosphere still continued very thick and dusky from the ashes that remained suspended, the rays of the sun scarce able to penetrate through it, with little or no wind the whole time.”

A Malaysian ship from Timor sailing through the region also found itself in “utter darkness” on April 11. As it passed by Tambora, the commander saw that the lower part of the mountain was still in flames. Landing farther down the coast to search for fresh water, he found the ground “covered with ashes to the depth of three feet,” and many of the inhabitants dead. When the ship departed on a strong westward current, it had to zigzag through a mass of cinders floating on the sea, more than a foot thick

and several miles across.

On the island of Sumatra, over a thousand miles west of Tambora, local chieftains heard the explosions on the morning of April 11. Fearing a conflict had broken out between rival villages, they hurried down to Fort Marlborough, the British encampment in Bengkulu. Other tribal chieftains of Sumatra and the neighboring islands also assumed the sounds presaged some sort of invasion, but once they received reassurance on that score, they ascribed the explosions to supernatural causes. "Our chiefs here," reported an official at Fort Marlborough, "decided that it was only a contest between J (the very devil), with some of his awkward squad, and the manes of their departed ancestors, who had passed their period of probation in the mountains, and were in progress towards paradise."

At Gresik on eastern Java, natives decided that the blasts were the "supernatural artillery" of the venerated South Java Sea spirit queen Nyai Loroh Kidul, fired to celebrate the marriage of one of her children; the ash was "the dregs of her ammunition." If so, her ammunition made most of April 11 utterly dark in the village. When the British resident in Gresik awoke that morning, he had the impression that he had slept through a very long night. Reading his watch by lamplight, he discovered that it was 8:30 A.M., and pitch-black outside from the cloud of ashes descending. He breakfasted by candlelight at 11:00 and thought he could see a faint glimmering of light, but at 5 P.M. he still could "neither read nor write without candle." In the nearby village of Sumenep, ash fell about two inches thick, and "the trees also were loaded with it."

A tsunami reached eastern Java around midnight on April 10–11, and tremors struck the central region of the island eighteen hours after the eruption. Between two and three in the afternoon of April 11, a European observer in the village of Surakarta (Solo) noticed "a tremulous motion of the earth distinctly indicated by the tremor of large window frames; another comparatively violent explosion occurred late in the afternoon.... The atmosphere appeared to be loaded with a thick vapour: the Sun was rarely visible, and only at short intervals appearing very obscurely behind a semitransparent substance." Surakarta remained in darkness for much of the following day, as well. Raffles, too, reported that even at a distance of eight hundred miles, "showers of ashes covered the houses, the streets, and the fields, to the depth of several inches; and amid this darkness explosions were heard at intervals, like the report of artillery or the noise of distant thunder."

Twenty-four hours after Tambora erupted, the ash cloud had expanded to cover an area approximately the size of Australia. Air temperatures in the region plunged dramatically, perhaps as much as twenty degrees Fahrenheit. Then a light southeasterly breeze sprang up, and over the next several days most of the ash cloud drifted over the islands west and northwest of Tambora. By the time the cloud finally departed, villages within twenty miles of the volcano were covered with ash nearly forty inches thick; those a hundred miles away found eight to ten inches of ash on the ground.

Even a small quantity of ash could devastate plants and wildlife. One district that received about one-and-a-quarter inch of ash discovered that its crops were "completely beaten down and covered by it." Dead fish floated on the surfaces of ponds, and scores of small birds lay dead on the ground.

By the time the volcano finally subsided, Tambora had released an estimated one hundred cubic kilometers of molten rock as ash and pumice—enough to cover a square area one hundred miles on each side to a depth of almost twelve feet—making it the largest known volcanic eruption in the past 2,000 years. Geologists measure eruptions by the Volcanic Explosivity Index, which uses whole numbers from 0 to 8 to rate the relative amount of ash, dust, and sulphur a volcano throws into the atmosphere. Like the Richter Scale for earthquakes, each step along the Explosivity Index is equal to a tenfold increase in the magnitude of the eruption. Tambora merits an Index score of 7, making the eruption approximately one thousand times more powerful than the Icelandic volcano Eyjafjallajökull, which disrupted trans-Atlantic air travel in 2010 but rated only a 4; one hundred times stronger than Mount St. Helens (a 5); and ten times more powerful than Krakatoa (a 6). Only four other eruptions in the last hundred centuries have reached a score of 7. Modern scientists identify and measure past eruptions using layers of volcanic debris found in ice cores, lake sediments, and other undisturbed soils. Each eruption has a distinct chemical signature that, along with conventional methods of carbon dating, can be used to associate each layer of volcanic material with a particular eruption.

VOLCANO	LOCATION	YEAR OF ERUPTION	VOLCANIC EXPLOSIVITY INDEX
VESUVIUS	ITALY	79	5
HUAYNAPUTINA	PERU	1600	6
TAMBORA	INDONESIA	1815	7
KRAKATOA	INDONESIA	1883	6
SANTA MARIA	GUATEMALA	1902	6
MOUNT ST. HELENS	WASHINGTON, USA	1980	5
PINATUBO	PHILIPPINES	1991	6
EYJAFJALLAJÖKULL	ICELAND	2010	4

(SOURCE FOR TABLE: SMITHSONIAN MUSEUM OF NATURAL HISTORY; [HTTP://WWW.VOLCANO.SI.EDU/WORLD/LARGEERUPTIONS.CFM](http://www.volcano.si.edu/world/largeeruptions.cfm))

It was also by far the deadliest eruption in recorded history. As soon as the volcano quieted, Raffles ordered the British residents to make a survey of their districts to ascertain the extent of the damage. The reports that reached him detailed a horrific picture.

Before the eruption, more than twelve thousand natives lived in the immediate vicinity of Tambora. They never had a chance to escape. Nearly all of them died within the first twenty-four hours, most from ash falls and pyroclastic flows—rapidly moving streams of partially liquefied rock and superheated gas at temperatures up to 1,000 degrees, hot enough to melt glass. Carbonized remains of villagers caught unaware were buried beneath the lava; fewer than one hundred people survived. “The trees and herbage of every description, along the whole of the north and west sides of the peninsula,” reported one British official, “have been completely destroyed.” Another found that in the area surrounding Mount Tambora, “the cattle and inhabitants were nearly all of them destroyed ... and

those who survived were in such a state of deplorable starvation, that they would unavoidably share the same fate.” One village had sunk entirely, its former site now covered by more than three fathoms (eighteen feet) of water. And the Raja of Sanggar confirmed that “the whole of his country was entirely desolate, and the crops destroyed.” The survivors of his village were living on coconuts, but even the supply of that food was nearly exhausted.

On April 19, the *Benares* reached Bima. The coastline was barely recognizable; what had been one of the most beautiful and regular harbors in Asia now was an obstacle course, littered with masses of black pumice stone, tree trunks burnt and splintered as if by lightning, and the prows of previous sunken ships which the ocean had thrown onto land. The village had only a small supply of rice to stave off starvation. When the *Benares* departed several days later, it sailed past Mount Tambora which had been one of the highest peaks in the archipelago, often used by sailors as a landmark. Clouds of smoke and ash still obscured the volcano’s peak. Even at a distance of six miles, sailors could see patches of lava steaming along the mountainside.

A heavy rainstorm on April 17 had left the air cleaner and cooler, and probably saved a substantial number of lives on the more distant islands as the rain washed the ash off crops and provided fresh drinking water to help stem an incipient epidemic of fever. But nothing could save those closer to Tambora. Over the following month, thousands more perished—some from severe respiratory infections from the ash that remained in the atmosphere in the aftermath of the eruption, others from violent diarrhoeal disease, the result of drinking water contaminated with acidic ash. The same deadly ash poisoned crops, especially the vital rice fields, raising the death toll higher. Horses and cattle perished by the hundreds, mainly from a lack of forage. Lieutenant Owen Phillips, dispatched by Raffles to investigate conditions and provide an emergency supply of rice to the inhabitants, arrived at Bima several weeks after the eruption and reported that “the extreme misery to which the inhabitants have been reduced is shocking to behold. There were still on the road side the remains of several corpses, and the marks of where many others had been interred: the villages almost entirely deserted and the houses fallen down, the surviving inhabitants having dispersed in search of food.” In the nearby village of Dampo, residents were reduced to eating stalks of papaya and plantain, and the heads of palm. Even the Raja of Sanggar lost a daughter to hunger.

In the end, perhaps another seventy to eighty thousand people died from starvation or disease caused by the eruption, bringing the death toll to nearly ninety thousand in Indonesia alone. No other volcanic explosion in history has come close to wreaking disaster of that magnitude.

And yet there would be more casualties from Tambora. In addition to millions of tons of ash, the force of the eruption threw 55 million tons of sulfur-dioxide gas more than twenty miles into the air into the stratosphere. There, the sulfur dioxide rapidly combined with readily available hydroxide gas—which, in liquid form, is commonly known as hydrogen peroxide—to form more than 100 million tons of sulfuric acid. The sulfuric acid condensed into minute droplets—each two hundred times finer than the width of a human hair—that could easily remain suspended in the air as an aerosol cloud. The

strong stratospheric jet streams quickly accelerated the particles to a velocity of about sixty miles per hour, blowing primarily in an east-to-west direction. The sheer power of the jet stream allowed the aerosol cloud to circumnavigate Earth in two weeks; but the cloud did not remain coherent.

Variations in the wind speed and the weight of the particles caused some parts of the cloud to travel faster or slower than others, and so the cloud spread as it moved around Earth, until it covered the equator with an almost imperceptible veil of dust and sulfurous particles. It also began to spread north and south, albeit far more slowly. While it took only two weeks for the aerosol cloud to cover the globe at the equator, it was likely more than two months before it reached the North and South Poles.

Rather than a slow, steady broadening of the equatorial cloud into the Northern and Southern Hemispheres, the cloud expanded in fits and starts. As some pieces of the cloud were blown away from the equator, they were quickly caught up in the dominant stratospheric jet streams—which may blow east to west in the Northern Hemisphere, and west to east in the Southern Hemisphere. The cloud soon began to resemble streamers or filaments, with small portions regularly pushed off the equator and into the middle latitudes in each hemisphere. Eventually, these filaments coalesced into a single, coherent cloud that covered Earth.

And there they remained. Had the aerosol cloud ascended only into the lowest part of the atmosphere, the troposphere, where clouds form, rain would soon have cleansed the ash from the air. But in the more stable stratosphere, conditions mitigate against the formation of clouds of water droplets. The coldest air already is at the bottom of the stratosphere, with warmer air above it, so air rarely rises from the troposphere into the stratosphere. With no rising plumes of warm air to carry moisture into the stratosphere, clouds almost never form; the stratosphere is drier than most deserts. With no clouds, there could be no rain to wash away the stratospheric aerosol veil. Only the slow action of gravity and the occasional circulation of air between the stratosphere and the troposphere could drag the droplets back to the earth. And so the extraordinarily fine sulfur particles from Tambora that reached the stratosphere remained suspended in the air for years, freely transported around the globe by the winds. By the winter of 1815–16, the nearly invisible veil of ash covered the globe, reflecting sunlight, cooling temperatures, and wreaking havoc on weather patterns.

2.

PORTENTS

“The country has all the appearance of the middle of winter...”

FROM TERAMO IN central Italy, near the Adriatic coast, came reports in late December 1815 of “the heaviest snow ever known in that country.” According to one account, over a six-hour period “a greater quantity of snow [fell] than has been known in the memory of man.” More astonishing was the nature of the precipitation. The snow “was of a red and yellow color ... [which] excited great fear and apprehension in the people.” Believing that “something extraordinary has taken place in the air,” the local residents organized religious processions to placate God; in the meantime, provincial authorities summoned a professor of physical science from Parma (who was also a Jesuit priest) to study the phenomenon. For the rest of the winter, the Abruzzo region remained cold, with significantly more snow and freezing rain than usual.

Several weeks later, an intense blizzard raged across northeastern Hungary for two days. The snow reportedly covered houses to the rooftops, and killed more than ten thousand sheep and hundreds of oxen. Despite the magnitude of the storm, news accounts focused primarily on the fact that “the snow was not white, but brown or flesh colored.” April brought reports of another colored snowfall in Italy, this time around the Tonale Pass, in the Italian Alps: “It was brick red and left an earthy powder, very light and impalpable, unctuous to the touch ... [with an] astringent taste.” The colored snow almost certainly was the result of ice droplets forming with ash particles from Tambora as their nuclei. The deepest clouds associated with severe storms occasionally are able to reach into the stratosphere, which is consistent with the colored snow falling in particularly extreme weather events. Over the course of months—and, in this case, years—gravity also slowly dragged the stratospheric sulfur particles into the upper reaches of the troposphere, where the particles could more easily form the centers of ice crystals.

No contemporary accounts appear to have made the connection between the phenomenon of colored snow in Italy and Hungary and the eruption of Mount Tambora nearly halfway around the world, although reports of Tambora had reached London by the end of 1815, and a few amateur scientists—most famously Benjamin Franklin—had previously essayed a connection between volcanic eruptions and unusual atmospheric conditions. Following the eight-month-long eruption of Laki in southern Iceland in June 1783, Europe and North America experienced highly unusu

weather, including a persistent dry haze during the summer and an extremely cold and snowy winter that killed thousands of people across Europe. Although Franklin, who was living in Europe at the time, acknowledged in a 1784 lecture to the Manchester Literary and Philosophical Association that “the cause of this universal fog is not yet ascertained,” he suggested that it may have been “the vast quantity of smoke, long continuing, to issue during the summer [from Laki] ... which smoke might be spread by various winds, over the northern part of the world.” And the frigid temperatures, he proposed, probably resulted from this fog blocking the rays of the sun, thereby reducing the amount of solar energy that reached Earth.

Throughout the winter of 1815–16, the spreading aerosol cloud from Mount Tambora had been doing precisely that: cooling global temperatures by reflecting and scattering sunlight. Although the cloud reflected only one half to one percent of the incoming energy, it reduced the Northern Hemisphere average temperature in 1816 by about three degrees Fahrenheit. This seemingly small cooling had a considerable impact on global weather patterns, with devastating consequences for agriculture on both sides of the Atlantic. Ironically, however, the effects of Tambora’s aerosol cloud could have been far worse if the eruption had been slightly weaker. While immense in size and scope, Tambora’s aerosol cloud was not particularly efficient at reflecting sunlight. Stronger volcanic eruptions tend to eject more sulfur dioxide into the stratosphere than weaker eruptions, which leads to more sulfuric acid droplets within the same volume of atmospheric gases. A greater number of droplets increases the chance that droplets will meet and collide, forming larger droplets that will be removed more quickly from the stratosphere by gravity. A single, larger droplet also has less total surface area than two smaller droplets, and so is less effective at scattering sunlight. There is therefore a balance to be struck between eruptions that are too weak to penetrate into the stratosphere—and produce small, short-lived cooling—and eruptions that produce large, less effective sulfuric acid droplets. By measuring the remnants of Tambora’s aerosol cloud in ice cores and lake sediments, modern scientists have determined that the climatic consequences—while undoubtedly devastating—could have been far worse if the particles had been roughly half their size.

Unlike the sudden drop in temperatures in the Indonesian archipelago that occurred immediately after the eruption of Mount Tambora, the planet-wide cooling was a gradual process that took up to a year to be fully realized. While air temperatures can, and frequently do, change rapidly in response to variations in solar energy, soil and ocean temperatures adjust much more slowly. The land and sea possess considerable capacity to store heat, while the atmosphere has practically no storage. When the atmosphere is cooler than the land and sea, heat will flow from these reservoirs back into the air; but since the air cannot store heat for long, much of this is soon lost to space. If, on the other hand, the atmosphere is warmer, some of that excess heat will be stored in soil and water until a balance is reached. This process may be seen clearly in summer: The warmest weather often occurs not in June, when the sun is strongest, but in August, when the ocean and land have warmed.

As Tambora’s stratospheric aerosol cloud began to cool temperatures by subtly reducing the

amount of solar energy reaching the earth, the land and oceans would have resisted this cooling by transferring stored heat into the atmosphere, and cooling themselves as a result. By early 1816, the land, ocean, and atmosphere were shifting toward a new balance of energies, largely as a result of the solar-dimming effect of the aerosol cloud. The adjustment cooled first air, then land, and finally ocean temperatures across the globe. Using information from tree rings—the width of each ring is related to the growing conditions (mostly temperature and precipitation) that year—climatologists have determined that 1816 was the second-coldest year in the Northern Hemisphere since 1400, surpassed only by 1601, following the eruption of Huaynaputina in Peru. Even as the aerosol began to settle out of the atmosphere through gravity, it would take years for land and ocean temperatures to return to normal. And so 1817 was the fifth coldest, 1818 the twenty-second coldest, and 1819 the twenty-ninth coldest year in the Northern Hemisphere since 1400.

In the meantime, the aerosol cloud had produced other noticeable optical phenomena, most notably a series of spectacular red, purple, and orange sunsets in London in the summer and autumn of 1816. Observers noted repeatedly that “the sky exhibited in places a fire,” with “crimson cirri” [high altitude cirrus clouds, composed of fine ice particles] and “much redness in the twilight.” “The evening twilight has been generally coloured of late,” wrote one contemporary, “and at times streaked with converging shadows, the origin of which could not be traced to clouds intercepting the light.” On several particularly unsettled September nights, the storm clouds continued to glow various shades of red for half an hour after sunset.

Sunsets typically appear yellow, orange, or red because atmospheric gases scatter blue light more effectively than other colors, skewing the visible-light spectrum toward red. The effect is even more pronounced when the sun is low on the horizon, since its light must pass through a thicker layer of the atmosphere to reach the ground, resulting in less blue and more red light.

Stratospheric ash, dust, and soot particles from volcanic eruptions—or from pollution or fires—enhance this atmospheric scattering effect, leading to brilliant red sunsets. After the sun passes below the horizon and light no longer reaches the surface, some sunlight still passes through the upper portions of the atmosphere. Aerosol veils reflect this sunlight toward Earth, giving the colorful postsunset glows reported in London. So exceptional were these sunsets that Londoners commented on them repeatedly in letters, journals, and newspaper articles, which suggests that they likely were caused by the Tambora aerosol cloud rather than the heavy industrial pollution that habitually afflicted the city during that era. In fact, scientists have taken advantage of this effect by using the amount of red in contemporary paintings of sunsets to estimate the intensity of volcanic eruptions. Several Greek scientists, led by C. S. Zerefos, digitally measured the amount of red—relative to other primary colors—in more than 550 samples of landscape art by 181 artists from the sixteenth through the nineteenth centuries to produce estimates of the amount of volcanic ash in the air at various times. Paintings from the years following the Tambora eruption used the most red paint; those after Krakatoa came a close second.

AMERICANS greeted the year 1816 with confidence and optimism. They had recently concluded two and a half years of war with Great Britain, arguably the strongest and certainly the wealthiest nation in the world, and the conflict had ended essentially in a draw. Admittedly the British had captured and partially burned the nation's capital, forcing President Madison and his wife, Dolley, to flee for their lives, accompanied by several wagons full of White House valuables and Cabinet papers stuffed in trunks. But American troops led by General Andrew Jackson had ended the fighting on such a positive note with their overwhelming victory over a numerically superior force of British regulars at New Orleans in January 1815, that many Americans believed they had actually won the War of 1812.

European events since that time offered hope that the United States could look forward to a long period of peace, undisturbed by events abroad. On June 18, 1815, British and Prussian troops commanded by the Duke of Wellington and Marshal Blucher dealt a crushing defeat to Napoléon's army outside the Belgian town of Waterloo. The outcome had hung in the balance for most of the day. Wellington later acknowledged that the battle had been "the nearest run thing you ever saw in your life." It had been exactly a hundred days since Napoléon had entered Paris in triumph. This time, the Allied statesmen at Vienna gave the British government sole authority to choose the site of the Eagle's exile—it selected the remote island of Saint Helena, in the South Atlantic—and so assumed responsibility for keeping him there. With Napoléon removed from the scene, it seemed unlikely that the United States would be drawn into European affairs anytime in the near future. "We are, happily, at peace with all the world," exulted one Massachusetts congressman, "and there are no indications which threaten soon to disturb this tranquility."

Everything in the United States appeared to be expanding. Since 1789, the nation had added fifteen new states and five territories. By European standards, the United States's population was growing at an astonishing rate. In 1815, there were nearly 8.5 million Americans, twice as many as there had been only twenty-five years earlier. Immigration—primarily from northern and western Europe—contributed to this prolific growth, but most of the increase came from Americans who married young and had large families; on average, American women in the early nineteenth century had between seven and eight live births. It was also a very young population: 85 percent of the population was under the age of forty, including nearly all of the leaders of Congress.

Slightly more than 80 percent of Americans were white, and in a nation where land was cheap but labor scarce, the vast majority of white adults—more than 80 percent—made their living as subsistence farmers. Most American farmers spent only a portion of their working hours tending the crops, however, doubling as coopers, or tanners, or blacksmiths, or shoemakers. Wives and children frequently carded wool or spun linen in the evenings after spending their days in the fields. Farm families produced enough goods for their own needs, and sold the rest. "Go into the interior of the country," wrote Albert Gallatin, former secretary of the treasury, "and you will scarcely find a farmer who is not, in some degree, a trader. In a grazing part of the country, you will find them buying and

selling cattle; in other parts you will find them distillers, tanners, or brick-makers.”

Fewer than seven percent of Americans lived in cities, the largest of which were New York and Philadelphia, but neither even remotely approached the size of London or Manchester. Nearly all of the nation's towns were located on the East Coast, relying on commerce for their prosperity. Most municipalities lacked any public sewer or water system, which meant that garbage, dead animals, and human waste routinely accumulated in the streets.

Manufacturing remained relatively primitive. Beyond the products of farm families, most of the goods offered for sale were fashioned by mechanics working by hand, either in a small shop or at home. Transportation was even less advanced. Goods and passengers rarely traveled very far over land; American roads were notoriously poor, many no more than narrow, bumpy, overgrown trails that turned into quagmires when it rained. (Travelers told stories of horses actually drowning in the pits and wagons sinking slowly out of sight.) It cost as much to send a ton of goods thirty miles from an ocean port inland as it did to ship it three thousand miles across the Atlantic. And progress was slow; a traveler who set out by carriage from Boston in April would not arrive in Charleston, South Carolina until July. In 1802, Congress had authorized the construction of the National Road across the Appalachians, but fourteen years later the road had not yet crossed the Ohio River. Hence merchants and farmers continued to rely on river systems to move goods in the interior.

Yet significant improvements lay close at hand. Steamboats, dismissed as “floating smokestacks” by skeptical observers when Samuel Fulton's prototype made its debut on the Hudson River in 1807, were slowly gaining popularity, especially on the Western rivers. And Governor DeWitt Clinton of New York had begun to elicit legislative support for the construction of a canal (derided by his critics as “Clinton's Big Ditch” or “the Governor's Gutter”) that would stretch across the state for 340 miles from Albany to Buffalo, through thick forests and disease-ridden swamps, connecting the Hudson River with the Great Lakes.

Manufacturing was poised to expand as well. When the recent war temporarily deprived American consumers of British goods, New England merchants and entrepreneurs provided financial backing for scores of small-scale domestic textile “manufactories” that produced a total of \$24 million worth of cotton goods and provided employment to nearly a hundred thousand men, women, and children. Americans produced an additional \$19 million worth of woolen goods in 1815, and the Boston Manufacturing Company, headed by Frances Cabot Lowell, had recently completed the nation's first integrated textile factory along the Charles River in Waltham, Massachusetts.

In the aftermath of war, a new spirit of nationalism swept over the United States. For the past twenty-five years, the nation had been riven by deep divisions over domestic issues—primarily Alexander Hamilton's economic proposals—and the war in Europe. The disagreements produced the first two political parties in the United States: the Federalists, led by Hamilton and John Adams, who were horrified at the disorder and excesses of the French Revolution; and the Democratic-Republicans, who shared Thomas Jefferson's dislike of a strong central government, and Madison

distrust of Great Britain.

Lately, however, many Republicans had come to accept much of the Federalist domestic agenda; powerful central government seemed less threatening if they controlled it, as they had since 1800. (Madison, however, had grown no more fond of Britain since the king's troops burned the President's Mansion in Washington; in early 1816 Madison was living in a private dwelling on the corner of New York Avenue and 18th Street known as the "Octagon House," while workmen repaired and repainted the mansion, this time with white rather than gray paint.) Moderate Federalists who could recognize a lost cause were deserting to the opposition in increasing numbers. And a series of costly missteps by the dwindling band of hard-core Federalist stalwarts—including vocal opposition to the war effort and a thinly veiled threat by New England political leaders in December 1814 to secede—destroyed any hopes the Federalists may have entertained to regain power on the national level.

Partisan rancor thus subsided, although it did not entirely disappear when the Fourteenth Congress concluded its regular session in the spring of 1816. Legislators spent much of their time debating economic issues. In early April, Congress approved the first protective tariff in the nation's history. Several weeks later, legislators voted to establish a second Bank of the United States, to provide uniform, stable currency and a source of credit for business ventures.

Yet there remained many congressmen and voters, especially from rural areas, who distrusted the power of a central bank independent of popular control. These same critics demanded that the federal government cut taxes now that the war had ended. Since military expenditures during the war had sent the federal debt soaring to nearly \$124 million, Congress hesitated to slash taxes and decrease revenues too rapidly. It did repeal all duties on domestic manufactures, but it retained several other minor taxes, including those on carriages and postage. Administration officials estimated that the new higher tariff rates would bring in at least \$25 million per year, which they claimed would be sufficient to pay the government's routine civil and military expenses, fund annual increases in the size of the navy (which had proven woefully inadequate during the recent hostilities), and pay off the remaining debt in about twelve years.

Before Congress adjourned, it also voted itself a pay raise. Since the first Congress convened in 1790, legislators had received six dollars per diem in lieu of a regular salary. Although the cost of living had increased by at least 75 percent over the past twenty-six years, their remuneration had not changed. Hence congressmen felt justified in approving the Compensation Act, which granted them an annual salary of \$1,500. Few realized at that time that this measure would destroy many members' political careers.

As lawmakers departed Washington at the end of April, they congratulated themselves on accomplishing their tasks in an unusual display of good feelings. "Among the most auspicious appearances of the times, is the obliteration of party spirit," declared a Southern representative. "No question at the present session of congress has been discussed or determined on the ground of party. Let us then cherish these feelings; let us emulate each other only in serving our country with the mo-

zeal, and the more fidelity.”

* * *

ON April 29, Americans noticed a large, irregular spot on the surface of the sun when they glanced skyward. One observer compared it to “a spider, having parts extending from the main body,” while another claimed that “its general appearance is not unlike that of a cluster of islands ... surrounded by a belt of rocks.” A representative of the National Mathematical Academy in Philadelphia estimated the length of the spot at just under 40,000 miles, with a breadth of nearly 3,000 miles. It lay just north of the center of the sun’s surface, and its stationary nature over the course of a week led a group of American astronomers to dismiss their initial hypothesis that it might simply have been the planet Mercury moving across the face of the sun. Instead, they decided it was probably a wandering comet pulled in by the sun’s gravitational force.

In its May 1816 issue, the *North American Review* cited the theories of Sir Frederick William Herschel, a British astronomer, who argued that the spots were “chasms in the [sun’s] atmosphere occasioned by ascending currents of gaseous fuel.” Since there appeared to be “a variable emission of light and heat, intimately connected with the appearance and disappearance of spots,” Herschel theorized that “seasons of uncommon heat and cold, of fertility and barrenness, so far as they depend upon the supply of heat, are to be traced not so much to accidental causes near at hand, as to the inconstancy of the fountain.” (Herschel, a legendary figure in the history of astronomy, made numerous important discoveries, including Uranus and its two moons, but also believed the sun was inhabited, along with all the other planets and stars. He speculated that the sun’s surface was actually cool enough to support life; only the outer solar atmosphere was hot.)

Others suggested that the sunspots were volcanoes on the surface of the sun, or “burning mountains of immense size; so that when the eruption is nearly ended and the smoke dissipated, the fierce flames are exposed, and appear as luminous spots.” Yet another explanation proposed the spots to be “a kind of excavation of the luminous fluid supposed to envelope [sic] the opaque [sic] and solid body of the sun.” Even those who supported this concept found it difficult to imagine how any gap within a liquid could remain unfilled; one contributor to the *Gentleman’s Magazine* in Britain likened it to “no less a miracle than the passage of the Israelites through the Red Sea.” Perhaps, suggested a writer in the *Baltimore American*, “the Sun has cast forth several immense bodies, and ... there is a danger of one of them coming in contact with our little tiney [sic] globe, when, in the horrible crash, we may experience another deluge, or suffer a terrible conflagration!”

No one in 1816 understood that sunspots are formed by variations in the strength of the magnetic field that surrounds the sun. Occasionally, a portion of the magnetic field grows strong enough that the field coils back on itself and punctures the surface of the sun, a process which inhibits the fusion reactions that produce solar energy. This in turn reduces the temperature of the sun’s surface at the point of the puncture. Since the brightness of the sun’s surface is proportional to its temperature, the

sunspots appear darker than the rest of the sun.

Scientists in Europe and the United States had regularly recorded sunspot activity with telescopes since the early seventeenth century, when several astronomers, including Galileo, first observed them. Most of the earliest sunspot observations were taken during the period now known as the Maunder Minimum—named for the English scientist Edward Maunder—that extended from 1645–1717, when sunspot activity was at an unusually low level. The near disappearance of sunspots in the 1650s puzzled astronomers, as did their sudden reemergence in the second decade of the eighteenth century.

While individual sunspots occur almost randomly, the total number of spots follows a fairly predictable eleven-year cycle (a cycle that was discovered in 1844). But sunspot activity also varies over much longer periods of time which are less predictable and less regular than the short-term cycles. The eruption of Tambora coincided with another minimum in sunspot activity—the Dalton Minimum of 1790–1830. The Dalton Minimum was shorter and less intense than the Maunder Minimum, but still resulted in a notable decrease in sunspot activity; hence the surprise exhibited by the appearance of a large sunspot in April 1816.

According to one contemporary account, no sunspots of this magnitude had been witnessed in the United States since 1779. Moreover, observers could stare at the spot without the usual protection of shaded glasses, because the atmosphere lately had been filled with a curious thick haze—“a fine dust,” reported a Virginia newspaper, “very injurious to respiration.” “It had nothing of the nature of a human fog,” noted an American physician. “It was like that smoking vapour which overspread Europe about thirty years ago.” And while sunspots typically are visible to the naked eye only when the sun is barely above the horizon, when the atmosphere has scattered much of the sunlight, this spot could be seen throughout much of the day. In fact, the aerosol haze from Tambora may have lengthened by as much as five times the usual window for viewing sunspots after sunrise and before sunset.

Since most Americans had never witnessed the sunspots that routinely move across the face of the sun, this highly visible spot—much larger than usual—generated more apprehension than the haze. Some feared it was an omen of impending apocalypse, a “calamitous sign in heaven,” or a warning that “the sun may, in time ... become wholly incrustated” with spots, “so as to plunge us at once into the unutterable darkness that characterized the primitive chaos.” Others predicted the huge spot would weaken the sun’s rays and permanently cool Earth’s atmosphere. While the editors of the *Norfolk American Review* dismissed such speculation, they did admit that “the observation ... that the light of the sun is less brilliant and dazzling than usual, is unquestionably well founded. We have remarked on different times during the present season, on days when the sky was perfectly clear, that there was a degree of feebleness and dimness in the Sun’s rays, not unlike the effect produced by a partial eclipse.”

Yet the first four months of 1816 were not noticeably colder than normal in the Eastern United States. In New England, the winter had been one of the mildest in a decade, with significantly less snow than usual. “The winter was open,” noted Noah Webster in his diary at Amherst, Massachusetts.

“A snow in January, which was sufficient for sledding, was swept away in a few days. The ground was uncovered most of the winter.” Judging by the measurements of several amateur meteorologists at Northeastern colleges, January’s temperatures appeared to have been slightly above normal, with a warming trend at the end of the month. In Maine, the days were so pleasant “that most persons allowed their fires to go out and did not burn wood except for cooking.” Similarly, the *Connecticut Courant* reported that “January was mild—so much so as to render fires almost needless in sitting rooms.” (Thomas Jefferson, on the other hand, wrote to a friend from his retreat at Monticello, just west of Charlottesville, Virginia, shortly after New Year’s Day that he was “shivering and shrinking my body from the cold we now experience.”)

February brought generally mild temperatures with only a few snowstorms. “The first of March was very warm,” noted Adino Brackett, a farmer and schoolteacher in Lancaster, New Hampshire, “and almost all the snow went off.” The weather then turned clear and cold for several weeks, but the month ended with another warm spell and a rare appearance of early spring thunderstorms in the Northeast. There had been sharp cold snaps along the East Coast in mid-March, however, including a bout of sleet in Richmond, Virginia, that left fruit trees covered in icicles. As winter departed, the first week of April was slightly warmer than usual in New England, with very little precipitation.

Although it appears counterintuitive, the stratospheric aerosol cloud from Tambora was partly responsible for both the mild winter of 1815–16 in North America and the stormy conditions across central Europe. The aerosol cloud not only scattered sunlight, preventing it from reaching Earth’s surface, it also absorbed some of the incoming energy, reradiating it as heat. This warmed the stratosphere immediately above the cloud. If the aerosol cloud had warmed the stratosphere evenly around the globe, its effect would have been minimal. In the depths of winter, however, the high northern latitudes are plunged into continual darkness for several months. Without sunlight to absorb, the aerosol cloud could not heat the Arctic stratosphere; yet it continued to heat the stratosphere in the sunlit middle and lower latitudes.

A strong, cyclonic vortex forms near the North and South poles each winter. Strong west-to-east winds surround the vortex and expand to cover much of the high latitudes. These winds are created by the difference in winter temperatures between the sunlit middle and perpetually dark high latitudes. Air always flows from warmer temperatures toward colder ones, but Earth’s rotation turns the air off its path, towards the right in the Northern Hemisphere and the left in the Southern, to produce westerly winds. These westerly winds prevent cold, polar air from moving into the middle latitudes. When the vortex is particularly strong, lower atmospheric pressures exist near the pole; higher pressures are found in the middle latitudes; and the westerly winds provide an effective barrier. Should the vortex weaken, the pressure rises near the poles and falls in the middle latitudes, leading to frequent outbreaks of polar air. In the Northern Hemisphere, scientists have defined the North Atlantic Oscillation index to describe this seesaw of pressures between the poles and the middle latitudes, with a high index associated with a strong vortex.

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