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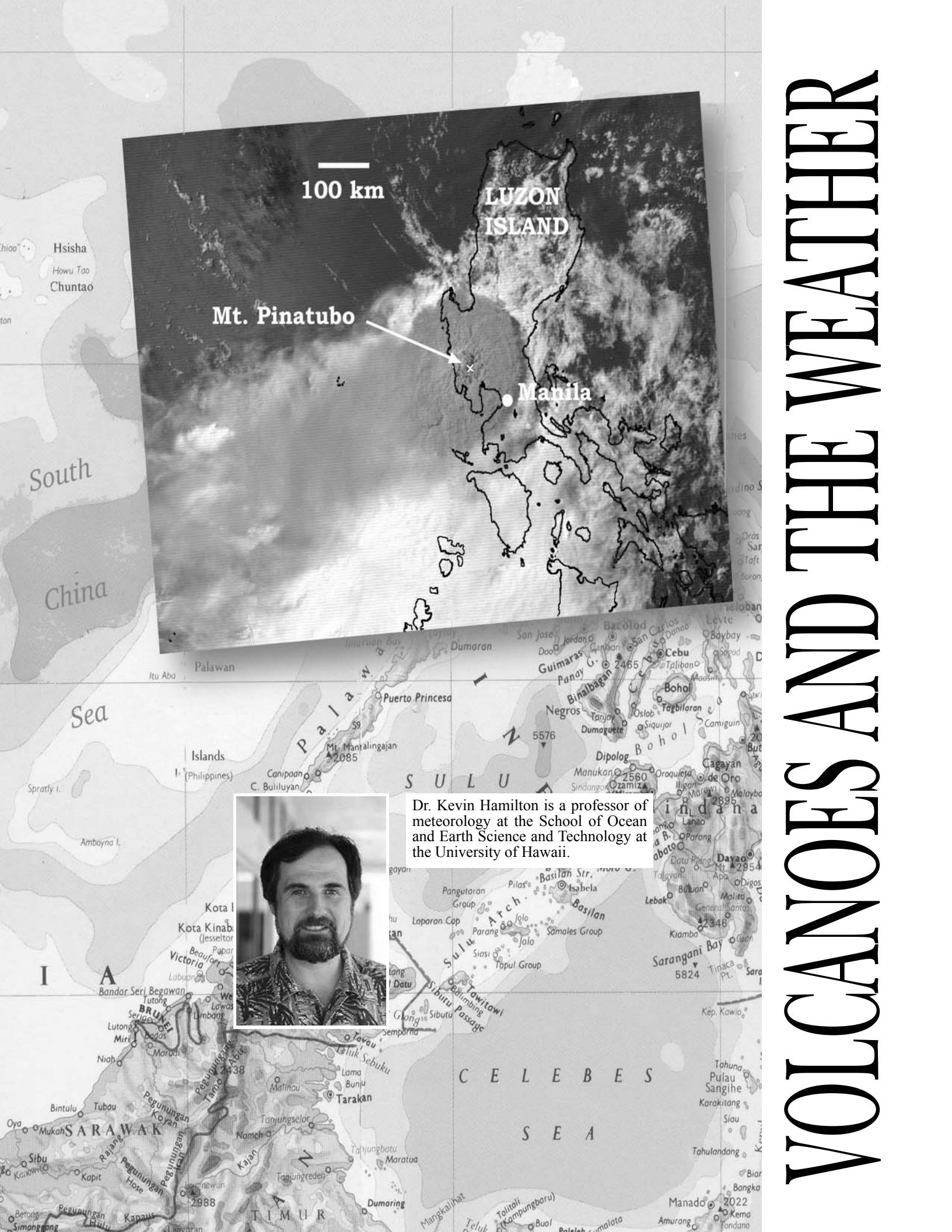
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Mt. Pinatubo in the Phillipines cools the world in 1991.

Fall/Winter 2003



100 km

LUZON ISLAND

Mt. Pinatubo

Manila

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VOLCANOES AND THE WEATHER

Volcanic eruptions are spectacular, catastrophic disturbances in the atmosphere. As deadly as they may be at the local level, their meteorological effects can be far-reaching and last for several years.

One of most unusual weather events in Canadian history occurred on June 7th, 1816, with heavy snow reported in eastern Ontario and much of Quebec (then the British colonies of Upper and Lower Canada, of course). Dr. Alexander Spark, a prominent Presbyterian pastor in Quebec City recorded in his diary entry for June 8th: "Bleak, cold, very uncommon weather for the season. On the 7th it snowed a little the whole day - at 10 at night the ground was completely covered." There are contemporary references to snow drifts up to the axles of carriages in Quebec City. The snowstorm extended at least from Kingston in the west, to Bangor, Maine, in the east, and Concord, New Hampshire, in the south. Nothing like this has been seen in more modern times. For example, the latest date for significant snowfall in post-1951 modern weather records at Quebec City is May 6.

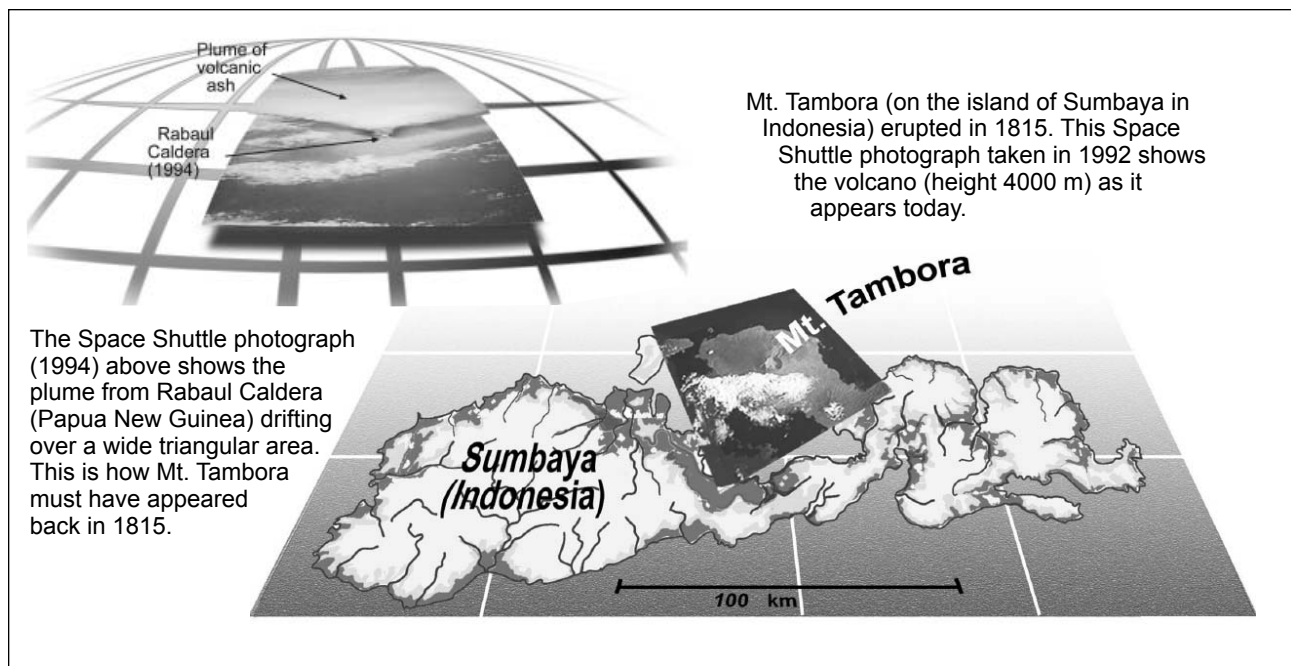
The late snowstorm occurred at the end of an unusually cold spring. Significant snowfalls at Quebec City were recorded on May 1 and 29, 1816, as well. Newspaper reports show that planting of crops had been delayed by the unusually cold weather. The summer was mostly cool with a cold wave around July 9 (including an extensive frost over much of New England). The delayed ripening of crops and early frosts in the autumn then led to significant crop losses and soaring food prices. A Quebec City news-

paper reported on October 8 that

"the failure of the harvest in certain parishes of the south shore of the St. Lawrence owing to the frosts, threatens the most serious consequences to the inhabitants. Several parishes are reported to have entirely lost their wheat harvest."

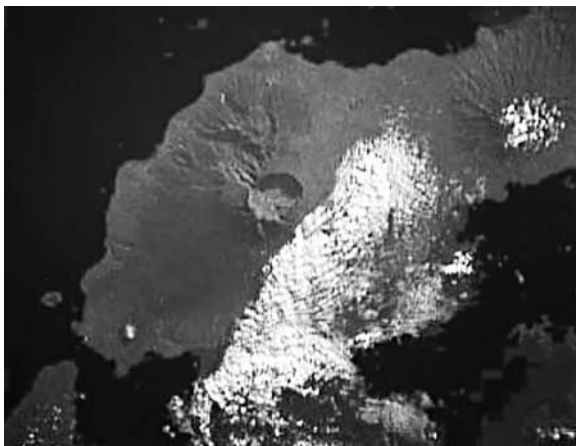
In eastern Canada and New England the year 1816 came to be remembered popularly as "the year without a summer" or "eighteen hundred and froze to death". The weather in Europe was also quite cold that summer and this affected food production and food prices there as well.

The people living in North America and Europe had no explanation for the devastating weather they experienced that summer, but we now realize that it was caused in large measure by a major geophysical event that occurred over a year earlier and halfway around the world. Beginning April 5, 1815, loud explosions were heard throughout the Indonesian archipelago (what we now know as the nation of Indonesia was then a Dutch colony which at this time was temporarily under the control of the British). By April 11 and 12 the sky over a huge area extending several hundred kilometers was darkened by a thick dust cloud that completely obscured the sun and made conditions during the day darker than on a moonless night. Dust fell so thickly in places that roofs col-



lapsed under its weight, and on the ocean surface the dust formed a thick scum layer that interfered with the movement of ships.

In September the British governor of the Indonesian colony sent out an expedition to determine exactly what had happened, and they quickly found that the cause of the events in April had been a massive eruption of Mt. Tambora on the island of Sumbawa. Of an estimated 12,000 residents of the island only 26 survived. The mountain itself was profoundly changed from its pre-eruption state, the sharp peak had been replaced by a deep crater - the total height of the mountain decreased by over 1000 metres, and



The peak of Mt. Tambora has been replaced by a caldera 1100 m deep and the mountain peak itself has been lowered by approximately 1000 m. Photo courtesy of NASA.

over 50 cubic kilometres of the mountain had apparently disappeared. In fact much of the missing material had been pulverized into dust and lofted into the atmosphere with the hot gasses emerging from the volcano. Much of this material fell out within several hundred kilometres of the volcano during the hours and days immediately after the eruption, but some stayed for years in the atmosphere as a global haze layer and helped produce the extremely cold summer experienced so dramatically in eastern Canada the next year.

1991 The Eruption of Mt. Pinatubo

The eruption of Mt. Tambora was a truly exceptional event – it is thought to have been largest in the last 10,000 years in terms of its explosive power. However in more recent times there have been a number of major explosive eruptions that are believed to have had significant impacts on global weather (for example those of Mt. Krakatoa in 1883 and Mt. Agung in 1963). The greatest explosive eruption since Mt. Tambora occurred in 1991 when Mt. Pinatubo in the Philippines erupted. In contrast to the situation back in 1815 (when it took months to get even the most basic understanding of what had occurred), the Mt.

Pinatubo eruption and its consequences could be studied in great detail in real time.

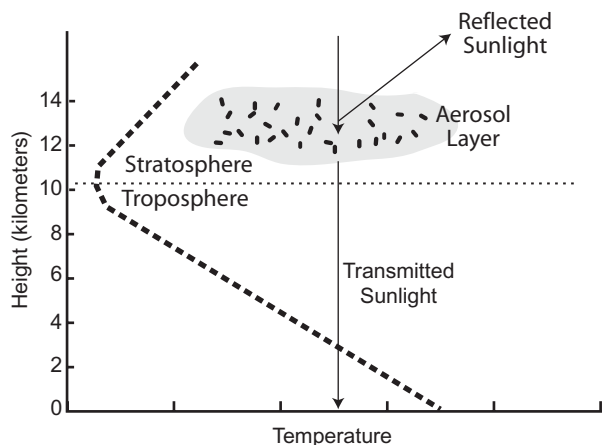
The cover picture shows a photograph (taken from a distance of 30 kilometres) of Mt. Pinatubo as it erupted on June 12, 1991. The plume of hot gas and volcanic dust seen in the picture is estimated to be reaching 18 kilometres altitude. While this is impressive, this photograph actually shows conditions three days before the main eruption on June 15. Even though it occurred during daytime, there are no ground-based photos of the main eruption because the volcanic dust cloud completely obscured the sun - no one on the ground could actually see the eruption!

The satellite picture at the beginning of this article shows the conditions a few hours into the main eruption. An enormous dark plume of volcanic dust is seen spreading out horizontally well above the clouds. In fact the dust was lofted as high as 40 kilometres above the Earth's surface.

The subsequent evolution of the volcanic material was tracked in detail by satellite measurements as well as ground-based observations. The volcanic dust and gasses that had been lofted high in the atmosphere were transported by the winds, and over a period of several months, spread fairly uniformly around the globe. The long-lasting component of the haze consisted of very small droplets of sulphuric acid, H_2SO_4 , that form from the reaction of sulphur-dioxide, SO_2 , with water vapour in the upper atmosphere. The droplets are so small that they stay suspended and simply move with the large-scale air currents. In the lower atmosphere the droplets are removed by absorption into falling raindrops and typically survive only a few days. The haze can exist much longer in the layer of the atmosphere known as the stratosphere, where there are almost no clouds and no precipitation. The sulphuric acid haze is slowly flushed out of the stratosphere into the troposphere by the large-scale winds in the stratosphere (rising at low latitudes and sinking at high latitudes). Some of the Pinatubo haze persisted for five or more years after the eruption, but most of the haze was flushed out of the stratosphere after about two years. This two year time period for the presence of the main haze layer corresponds to the observed period over which significant weather perturbations can be identified following major eruptions.

Global Cooling

A key effect of the volcanic haze is to reflect some of the sunlight that is incident on the atmosphere. This results in less direct solar heating of the lower atmosphere. This is a significant effect, and generally cooling of the earth's surface is observed in the global average following major eruptions. This is particularly the case in the summer season when

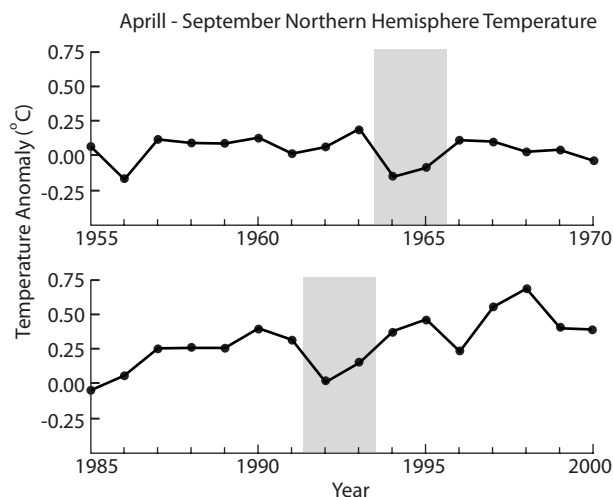


The amount of sunlight which reaches the Earth's surface is determined by the thickness of the aerosol layer and the size of the particles. The temperature decreases to a minimum at the boundary of the troposphere and stratosphere.

the daily-averaged sunlight reaching a square meter of surface is greatest, and hence the disruption of the normal sunlight by volcanic haze has potentially its largest effect.

The figure to the right shows the temperature at the surface determined as well as possible from standard daily meteorological measurements, and then averaged over the Northern Hemisphere during the spring-summer period (April-September) each year for two 16 year periods. There seems to be an overall trend to warmer temperatures, particularly since about 1980. This is the so-called "global warming" signal that has received a great deal of attention recently. In addition, however, there are year-to-year changes in temperature that seem less systematic. Some of these are connected with the "El Niño" phenomenon in the tropical Pacific Ocean, while others have no specific obvious explanation. However, it is noteworthy that

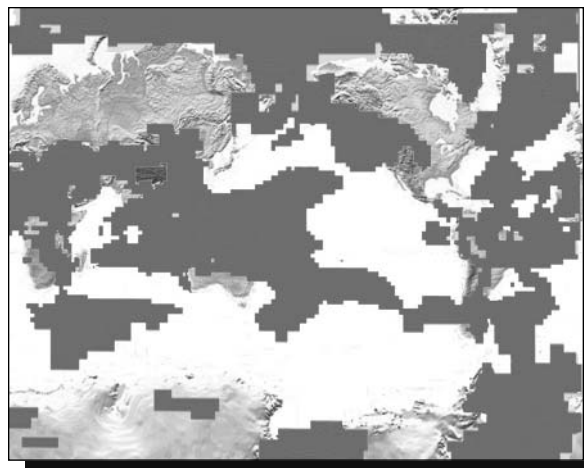
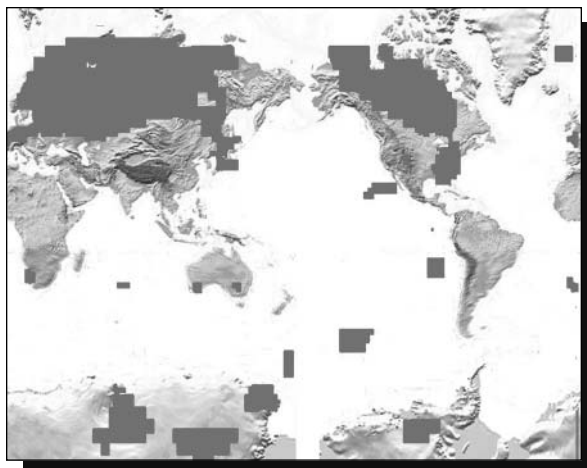
temperatures drop for the two summers following the largest volcanic eruptions during the period: those of Mt. Pinatubo (June 1991) and Mt. Agung (in Indonesia in March 1963). The effect in these cases are much less dramatic than those seen in 1816 following the much larger Mt. Tambora eruption, but the volcanic haze from these modern eruptions has had a major influence on weather.



The average spring-summer temperature anomalies (differences from the mean temperature in approximately 1960) of the Earth from 1955 to 1970 and 1985 to 2000. While a gradual increase of roughly 0.5 degree has occurred during this time, a drop in average surface temperature occurs for the years between 1991 and 1993, the two years after the Mt. Pinatubo eruption. A similar dip is seen in the years following the eruption of Mt. Agung (March 1963).

Winter High Latitude Warming

While an overall cooling of the global-average surface temperature is usually seen after each major volcanic eruption, in winter the high latitudes of the Northern Hemisphere usually show a more complicated pattern



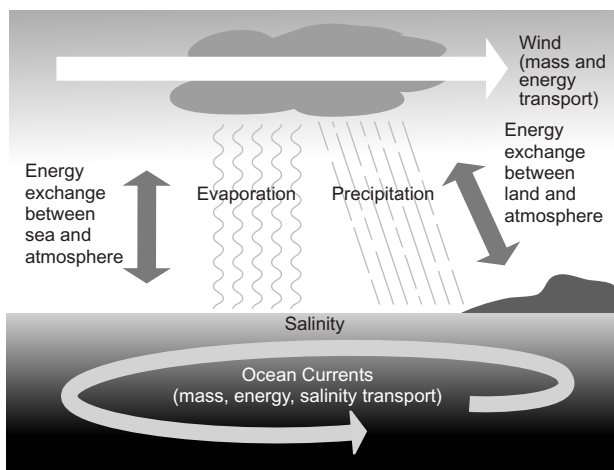
These maps provide an indication of how the temperature of the surface changed after the Pinatubo eruption. On the left, the shading shows areas in January, 1993, that were at least 0.5 degrees warmer than the long-term average for January. On the right, the shading shows areas that were at least 0.5 degrees colder than the long-term average.

with warmer than normal conditions in northern Europe, Siberia and northwestern North America, and colder than normal conditions in Labrador, Greenland and the North Atlantic. The detailed mechanism that causes the warming pattern is not completely clear, but it must ultimately be caused by the perturbation to the radiative fluxes in the atmosphere caused by the presence of the volcanic haze. One effect discussed above is the enhanced reflection of sunlight in the upper atmosphere, but the volcanic haze can also absorb the upward-directed infrared radiation emitted by the earth's surface and the lower atmosphere. This leads to a warming of the stratosphere which is observed to accompany the presence of volcanic haze. The interaction of this radiative warming of the stratosphere with the wind systems in the stratosphere and troposphere lead to the pattern of winter warming in high latitudes.

Computer Modelling of Weather Patterns

In recent years the detailed geographical patterns of warming and cooling observed following the Mt. Pinatubo eruption have been successfully simulated by sophisticated computer models of the earth's weather and climate. The models are the same as those applied to predict the response of the climate to long-term changes, notably the increasing levels of carbon dioxide caused by burning fossil fuels and are similar to those used for short range weather forecasting.

Such models represent the conditions (temperature, pressure, wind velocity, and humidity) on a grid of points around the globe and in the vertical. In a current climate model such a grid might have spacing of about 300 kilometres in the horizontal and 1 kilometre in the vertical. The equations governing the



A General Circulation Model creates a three-dimensional mathematical picture of the atmosphere, ocean and land surface. The equations are based on conservation of energy, momentum, moisture and mass and produce predictions of temperature, wind speed, humidity, etc.

motion of the atmosphere (conservation of mass, momentum and energy) are then solved approximately to produce an estimate for how the conditions at each point on the grid will change over a finite “time step” (typically about 30 minutes in current models). This then allows the computer model atmosphere to be “marched forward” in time. For short-term weather forecasts a model is started from the best estimate of observed present conditions and then marched forward for a few days.

For climate applications the goal is not a detailed day-by-day forecast of conditions, but rather a prediction of how the overall climate will change when the atmosphere is subject to a long-lasting perturbation such as increasing carbon dioxide. For this application a computer model may be marched for long periods (say several decades) in a “control” run with current carbon dioxide levels and then for another long period with increased carbon dioxide levels. The statistics of the simulations are then compared, e.g., for the long-term mean temperature at the surface. The results of such model comparisons are the basis for most current forecasts of global warming.

While the climate models start with sound scientific principles, there are significant uncertainties in their approximate representation of the atmospheric system on just a finite spatial grid and finite time steps. For example, some of the most important of these uncertainties concern the treatment of clouds in the model – most individual cloud features are actually much smaller than the horizontal grid spacing in the models.

Given these uncertainties it is very desirable to have “test cases” where the performance of climate models can be evaluated. The detailed observations of the haze layer and the climate response following the Mt. Pinatubo eruption provide such a “test case” for seeing how the computer model responds to a well-observed forcing. The fact that at least some current state-of-the-art climate models are successful in simulating the response to the Mt. Pinatubo eruption should provide a measure of confidence in their ability to accurately forecast long term climate changes.

Further Reading

The book by Henry Stommel and Elizabeth Stommel, “Volcano Weather” (Seven Seas Press, Newport Rhode Island) provides a nice review of the evidence for volcanic effects on weather with a focus on the 1815 eruption of Mt. Tambora and the “year without a summer”.

A recent discussion of the possibility of future eruptions even larger, and potentially more devastating, than the Mt. Tambora eruption is given at <http://news.bbc.co.uk/1/hi/sci/tech/628515.stm>. ◀