CHAPTER ONE

Earth's Biggest Mountain

An arc of some 132 islands and reefs sweeps 1,500 miles (2,400 km) across the Pacific Ocean (Plate 1). The chain is the Hawaiian Archipelago, and its major islands are among the most scenic and remote on Earth. As Mark Twain reminisced more than four decades after his 1866 visit, they are "The loveliest fleet of islands that lies anchored in any ocean" (Twain 1908).

The largest island in the fleet is Hawai'i, which is anchored twenty degrees north of the equator, more than 2,000 miles (3,200 km) from the nearest continental landmass. Known to its residents as the Big Island, Hawai'i has a provisional area of 4,028 square miles (10,433 square km). The area is provisional because the island is slowly growing as molten volcanic lava pours into the sea off the southeastern coast.

All the islands of Hawai'i are the summits of volcanic peaks that emerged from the sea floor over geologic time. The Big Island is formed from a cluster of five volcanoes, two of which exceed the elevation of Mount Everest when their height is measured from the ocean floor.

The highest of these volcanoes is Mauna Kea, which is usually translated from the Hawaiian as "White Mountain," but which some attribute to a Hawaiian deity. Mauna Kea, which is considered dormant, rises 13,796 feet (4,205 meters) over the sea. Its summit, which is home to some of the world's most important astronomical observatories, has become a popular sunset destination for tourists who rent four-wheel drive vehicles or who join professionally conducted tours.

The summit of Mauna Loa, the second highest mountain, is 13,679 feet (4,169 meters) above the Pacific. Perched high on its north slope is a cluster of buildings and domed structures known as the Mauna Loa Observatory. Very few tourists visit or even know about MLO. Maps and brochures label it a weather station, but MLO does much more than measure wind, temperature, and humidity. For more than half a century, scientists at MLO have carefully measured the respiration of Earth, the status of the ozone layer, the intensity of sunlight, and the clarity and composition of the free atmosphere over Hawai'i.

Today the Mauna Loa Observatory is widely regarded as one of the world's leading atmospheric monitoring observatories. A key factor behind its fame is its almost continuous record of measuring the increasing concentration of carbon dioxide in the atmosphere since 1958. This single measurement series has led to many international research programs about the role of carbon dioxide and other gases in warming the planet. The major reason for this success and that of many other measurement programs at MLO is the placement of the observatory on the upper slope of Mauna Loa in the middle of the Pacific, and an introduction to the great mountain, its vegetation, and its climate will explain why.

Mauna Loa

While Mauna Kea is slightly higher, Mauna Loa is far greater in volume and area. Indeed, Mauna Loa is believed to be the world's largest mountain. Its name means "Long Mountain," which well describes this huge pile of lava that forms the southern half of Hawaiʻi and extends 56 miles (90 km) from the base of its north slope to the southernmost point of the island.

On January 14, 2005, the snowcapped summits of Hawaiʻi's Mauna Kea and Mauna Loa (Plate 2) were captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite (Earth Observatory 2005). The snow blocked access to the Mauna Loa Observatory on January 10–11. On January 12, physical scientist Steve Ryan and engineer Bob Uchida hiked through the snow to service the observatory (Barnes 2005).

The grand dimensions of Mauna Loa are belied by its gentle profile, which lacks a prominent peak and resembles a giant warrior's shield lying atop the island. The famous botanist and explorer David Douglas, who climbed Mauna Loa in 1834, perfectly described the mountain in his memoir:

> Mauna Loa appears, indeed, more like an elevated tableland than a mountain. It is a high, broad dome, formed by infinitude of layers of volcanic matter, thrown out from the many mouths of its craters. Vegetation does not exist higher than eleven thousand feet; there is no soil whatever, and no water. The lava is so porous that when the snow melts it disappears a few feet from the verge, the ground drinking it up like a sponge. . . .
>
> The summit of this extraordinary mountain is so flat, that from this point no part of the island can be seen, not even the high peaks of Mauna Kea, nor the distant horizon of the sea, though the sky was remarkably clear. It is a horizon of itself, and about seven miles in diameter. (Jarves 1843)

The north slope of Mauna Loa is usually in plain sight from the Saddle Road, which crosses the island between Hilo and Waimea. From Hilo the view of the mountain is often obscured by clouds, and the Hualālai volcano blocks the view from Kailua-Kona, the popular tourist destination on Hawaiʻi's west coast. When clouds do not block the view, Mauna Loa's shield can be seen in the distance over the coconut palms and canoes at Kawaihae Bay north of Kona.

Mauna Loa has erupted thirty-three times since 1843 (Lockwood and Lipman 1987), and it shows no sign of stopping anytime soon. During eruptions, the mountain can emit vast volumes of liquid rock and produce explosive eruptions that throw boulders of lava far out of its summit crater, the giant Mokuʻāweoweo. But these eruptions are gentle when compared to the explosive eruptions of volcanoes such as Mount Pinatubo in the Philippines, which in 1991 propelled vast columns of ash, steam, and gas high into the stratosphere. Instead, Mauna Loa's eruptions are characterized by flowing streams of molten lava, often punctuated by spectacular curtains of orange fire jetting up from one of the mountain's three rift zones. The last eruption occurred in 1984, when a river of lava advanced to within about 4 miles (6 km) of the outskirts of Hilo. On the way, it sliced through the power line that provides electricity to the Mauna Loa Observatory.

The Lava

Mauna Loa is principally composed of just two forms of lava that are chemically identical and differ only in their appearance and structure. One kind of lava is known as *pāhoehoe* (pronounced pah-hoy-hoy). It forms when a shallow flow of molten rock having little gaseous content stops moving downhill and cools in place. Thus, *pāhoehoe* lava can be likened to a homogenous sheet of black or dark gray rock poured across the landscape like honey on a pancake. Its relatively smooth surface preserves the surges, swirls, ripples, folds, eddies, and coils that once characterized the viscous lava as it oozed its way down the slope of the mountain. *Pāhoehoe* lava flows, which are easily walked upon, are laced with cracks that provide shelter for ferns and mosses. The cracks reveal layers of color that indicate the presence of minerals that solidify at different temperatures.

The second kind of lava is called *ʻaʻā* (pronounced ah-ah), which arises when a gas-rich *pāhoehoe* flow slows to a crawl and becomes fragmented into clinkers. While *pāhoehoe* lava covers the landscape like the frosting on a cake, *ʻaʻā* resembles the cake. The 1984 *ʻaʻā* flows from Mauna Loa were from 6 to 23 feet (2 to 7 meters) thick (Volcano World 2005). According to the Hawaiian Volcano Observatory (HVO),

> Often what starts out as a pahoehoe flow may go through the transition to ʻaʻa when there is a change in conditions, such as a sudden steepening in slope, or just by the continuous loss of heat and gas as distance from the vent increases. (HVO 1999)

Both *pāhoehoe* and, especially, *ʻaʻā* lava are packed with vesicles formed when sulfur dioxide and other gases emerged from the lava, much like carbon dioxide forms a foam when it emerges from a carbonated beverage. *ʻAʻā* lava contains much more gas than the *pāhoehoe* form (Simkin 2000), and open bubbles in *ʻaʻā* form very sharp edges when they solidify at the surface of clinkers, where they quickly grind away the soles of shoes and boots and the tread of tires. *ʻAʻā* fields are very difficult to traverse and painfully unforgiving to those who fall onto the lava without the protection afforded by thick gloves and trousers. MLO is constructed over a field of *ʻaʻā* clinkers, which is why boardwalks are provided for the staff and visitors.

The Life Zones

The staff of the Mauna Loa Observatory travels through a sequence of climate zones as they drive between their office near sea level in Hilo to the mountain station 11,140 feet (3,400 meters) above the Pacific. The climate zones were succinctly described more than 140 years ago by Samuel Clemens, who toured Hawaiʻi in 1866 while serving as a correspondent for the *Sacramento Union.* Clemens had a fine view of Mauna Loa from the interisland schooner *Boomerang* as it approached Kailua-Kona on the western side of the Big Island. Writing under the name Mark Twain, he described several of the climate zones between the blue Pacific and the top of the great mountain:

> The rays of glittering snow and ice that clasped its summit like a claw looked refreshing when viewed from the blistering climate we were in. One could stand on that mountain (wrapped up in blankets and furs to keep warm), and while he nibbled a snowball or an icicle to quench his thirst he could look down the long sweep of its sides and see spots where plants are growing that grow only where the bitter cold of winter prevails; lower down he could see sections devoted to productions that thrive in the temperate zone alone; and at the bottom of the mountain he could see the home of the tufted coco palms and other species of vegetation that grow only in the sultry atmosphere of eternal summer. He could see all the climes of the world at a single glance of the eye, and that glance would only pass over a distance of four or five miles as the bird flies! (Twain 1866)

Twain was short on the distance, for the nearest beaches are 20 miles (32 km) as the bird flies from the summit of Mauna Loa. But he captured the essence of the dramatic changes between the stately coconut palms and the leafy banyans and bananas of Hilo to the vast wasteland of crunchy, boot-chewing lava at the Mauna Loa Observatory. Perhaps no place better illustrates the contrast between sea level and the desolation of the Mauna Loa Observatory than the small sandy beach decorated with tropical flowers and coconut palms on the west coast of Hilo's Waiākea Peninsula, where the US Exploring Expedition landed on the Big Island in December 1841 (Plate 3) prior to its three-week stay at the summit.

For more than half a century, the observatory staff has driven through the climate zones described by Twain. For the first dozen or so miles past Hilo, the way is lined with exotic trees and shrubs and luxurious display of tropical flowers. In the 1950s, the staff drove through the Kulani Prison to reach the rough road to MLO. Since 1963 they have left Hilo on Saddle Road, a curvy, scenic highway that links the east and west sides of the Big Island. The road follows the traditional Ala Mauna route, which in 1943 was developed into a cross-island gravel road by the Civilian Conservation Corps and the US Army Corps of Engineers in preparation for a possible Japanese invasion of the Big Island (Saddle Road 2005). Then as now, the road was known more for its many traffic accidents than the exotic scenery, a reputation that will likely change as major improvements are completed to the road.

Saddle Road climbs up from Hilo through what seems like a lush botanical garden. At an elevation of several thousand feet (around a kilometer), the large trees that shade the pavement give way to *ʻōhiʻa* trees that sometimes form a canopy over giant tree ferns as high as a house. The tall grass along both sides of the road is festooned with nonnative bamboo orchids bearing white blossoms tinged in lavender. Often this stretch of road is cloaked by orographic clouds that form as warm, moist trade winds rise into the cooler air of the saddle between Mauna Kea and Mauna Loa. This is rain forest country, where the annual rainfall is measured not in inches or centimeters but in feet. When the clouds are at the elevation of the road, visibility can fall to a few car lengths in the thick fog.

As the ferns are left behind, *ʻōhiʻa* trees continue to dominate the lavascape. They grow from near sea level and are the most common tree on the Big Island. Their flame-red lehua blossoms, each resembling a miniature lava fountain, announce their presence and more than make up for their dull green foliage.

Saddle Road is constructed over an old *pāhoehoe* lava flow from Mauna Loa. As the road climbs through about 4,800 feet (1,460 meters) and enters a broad expanse of bare lava, patches of shrubs and trees are scattered about. These are *kīpuka*s—islands of vegetation growing from old lava flows that are surrounded by younger flows (Saddle Road 2005).

At an elevation of 6,560 feet (2,000 meters), the roads to the observatories on Mauna Loa and Mauna Kea branch, respectively, south and north from Saddle Road at Puʻu Huluhulu, an ancient cinder cone that long ago erupted from Mauna Loa's flank and was later surrounded by lava flows (Plate 4). This *puʻu* (lava hill) is an especially accessible and scenic example of a *kīpuka* that preserves a remnant of the dry koa forest that once covered much of the slopes of Mauna Kea at this elevation prior to its conversion to ranch land. Puʻu Huluhulu is surrounded by a fence to keep out feral sheep, goats, and pigs, and it features a network of trails leading to large koa trees at the summit. Also found on Puʻu Huluhulu are *māmane, ʻiliahi* (sandalwood), and *ʻōhiʻa* trees and a wide variety of plants and shrubs, all of which provide a rare habitat for equally rare birds, including the endangered nēnē goose, Hawaiʻi's State Bird.

On a hot afternoon, the trees and plants growing from the bone-dry *ʻaʻā* lava of Puʻu Huluhulu seem to defy natural laws. How can any plant, much less large koa trees, survive in such a forboding place? The answer arrives with the trade wind orographic clouds that pour through the saddle and water the lava with cool showers or with mist and fog that paint plants and lava alike with a film of nourishing moisture.

On a clear day, when the clouds are below the elevation of the intersection of Saddle Road with the Mauna Loa road, the Mauna Loa Observatory is visible as a thin white rectangle high on the north slope of the big mountain (Plate 5). The observatory appears deceptively near, but it is another forty-five minutes or so away by car along a single-lane road (Plate 6). The first several miles of the road were repaved in 2007 and are a dream to drive compared to the previous condition of this section of the road.

From Puʻu Huluhulu to MLO, the vegetation becomes increasingly scarce. *ʻŌhiʻa* remains the dominant tree until the elevation reaches about 9,000 feet (2,740 meters), where they are reduced to miniature trees no larger than potted plants. Small ferns can be seen scattered about *pāhoehoe* lava flows, where they grow from cracks in the rock. In this region some portions of the road are in poor condition and must be driven with great care (Plate 7). Visible vegetation disappears long before the Mauna Loa Observatory is reached at 11,140 feet (3,400 meters) (Plate 8). Yet gray moss and a few small tufts of grass and fern were once found hiding in cracks in old *pāhoehoe* lava (Fosberg 1959).

The Climate

"The island of Hawaii, with a surface area of only 10,455 km^2, exhibits a spectacular range of climatic diversity comparable with that found on large continents." So began James Juvik, D. C. Singleton, and G. G. Clarke in their concise report on the climate of Hawaiʻi in *Mauna Loa Observatory: A 20th Anniversary Report* (1978). While the range of climate on the Big Island is indeed remarkable, the moderating influence of the Pacific Ocean and its tropical location combine to give much of Hawaiʻi a mild climate in which extremes of temperature, humidity, and wind are unusual. Drought, dust devils, thunderstorms, localized floods, and even hurricanes and tornadoes sometimes occur, but these weather extremes are unusual.

While the overall climate of Hawaiʻi is mild, the mountainous terrain of the major islands provides a wide variety of microclimates. The wet and dry extremes are especially evident along Saddle Road, for the windward, eastern side of Hawaiʻi is known for its abundant rainfall, while the leeward or *kona* side of the island is much drier and somewhat warmer. Saul Price, formerly Hawaiʻi's state climatologist and a US Weather Bureau scientist who worked closely with the original staff at the Mauna Loa Observatory, explained the difference in rainfall in an essay in the second edition of the *Atlas of Hawaii:*

> Over the open sea near Hawaii, rainfall averages between 25 to 30 inches a year. The islands themselves receive as much as 15 times this amount in some places and less than one-third of it in others. The cause of this remarkable variability, and of yearly totals that rival the greatest on earth, is principally the "orographic" (mountain-caused) rains which form within the moist trade-wind air as it moves in from the sea and overrides the steep and high terrain of the islands. . . . On the higher mountains the belt of maximum rainfall lies at only 2,000 to 3,000 feet, and amounts drop off rapidly with further elevation, so that the highest slopes are relatively dry. (Price 1983)

The transition between the rainy and dry microclimates of Hawaiʻi is a fact of life for the residents of the town of Waimea (or Kamuela) on the southeastern flank of the Kohala Mountains on the northwest portion of the Big Island. The east side of Waimea town is often sprinkled by cool showers that fall from a misty, cloud-filled sky. The west side is usually dry, warm, and sunny. The transition zone between the two weather patterns passes through the center of the town and can quickly flip between a cool, gentle shower and bright sunshine. The presence of both rain and sun often frames the town and nearby Mauna Kea within a brilliant rainbow.

A drive to the Mauna Loa Observatory may provide a similar weather experience, for the road often leads through heavy rain and thick fog before emerging into dry, clear air halfway or more up the mountain. The best description of the climate of Mauna Loa remains that provided by two meteorologists closely linked with the early history of the Mauna Loa Observatory, Saul Price and Jack Pales, the first director of MLO. They introduced a detailed account of the mountain's climate with a paragraph that perfectly summarizes its rather mellow nature:

> In keeping with its tropical maritime locale, the Observatory has a mild climate for the altitude. Severe weather is infrequent and the rigors of Alpine life virtually unknown. On the contrary, the brilliant skies, intense insolation, moderate temperature, and low humidity, encountered in so unusual and remote a setting, induce in most visitors a feeling of exhilaration and well being. (Price and Pales 1963)

While conditions on the mountain vary with the seasons, the changes are modest for an alpine site. For example, Price and Pales also reported that the mean maximum temperatures in February and June are, respectively, 46.6 and 58.8 degrees Fahrenheit. The mean minimums for the same months are, respectively, 28.9 and 37.1 F. During summer it is often possible to wear a short-sleeved shirt at the observatory, but this can be risky, for the sun's ultraviolet radiation is typically 20 percent more intense than at sea level.

Many of the scientific measurements made at MLO are much more influenced by the daily cycle of weather on the mountain than by annual variations in the climate. This is a result of a phenomenon called the *trade wind inversion layer* or simply the *trade inversion.* This is a layer of air typically 6,500 feet (2,000 meters) over the ocean that is warmer than the air below. Because the cool air below the inversion layer is denser than the warm air above, it is unable to rise through the inversion layer. In effect, the inversion layer serves as a cap that traps the cool air below, including its burden of moisture and any air pollution that might be present. The free atmosphere above the inversion layer is much drier and usually much cleaner than the air trapped below. Exceptions may occur where there is considerable airplane traffic, volcanic eruptions, or dust or smoke from distant sources.

Hilo is located on the northeast flank of Mauna Loa, where the giant volcano emerges from the Pacific Ocean. Trade winds from the east-northeast and the trade inversion prevail at Hilo during most of the year, and the inversion layer often plays the dominant role in Mauna Loa's daily weather pattern. As cool, moist Pacific air passes up and over the saddle that crosses the Big Island between Mauna Loa and Mauna Kea, orographic clouds are formed that, as noted earlier, often shroud the vegetation and the lower half of the road to the Mauna Loa Observatory in dense, wet fog. The eastern slopes of the lower half of the two mountains receive abundant rain from these clouds and are thick with vegetation. As noted by Price (1983), maximum rainfall occurs between about two to three thousand feet and decreases rapidly at higher elevations.

Conditions for monitoring the atmosphere at the Mauna Loa Observatory are best when the inversion layer is far down the slope of the mountain and the air at the observatory is extraordinarily dry and pristine. For weeks at a time the inversion layer will behave and remain tethered far below, in keeping with its altitude over the adjacent ocean. More commonly, between midmorning and early afternoon the inversion layer adjacent to the mountain will rise well above its usual height. No sensors are needed to notice the arrival of the layer, for one's face will feel the sudden chill that signifies the presence of cool, moist air from below even before the clouds arrive. Sometimes the cloud layer will cease rising just below the observatory and remain parked in place during the afternoon. When this occurs, the upper portion of Mauna Loa is invisible from below, while from an aircraft it resembles an island floating on a sea of clouds. More often, the rising clouds sweep by and then rise above the observatory, often preceded by cumulus clouds from the southwest that play overhead as their gossamer fragments and streamers engage in a complex ballet that is a delight to watch.

The observatory is immersed in cool, damp fog when the orographic layer arrives. Measurements of the ozone layer, solar ultraviolet, the atmosphere's optical depth (haze), and any other parameter involving sunlight are impossible when clouds block the sun. Instruments that sniff the air to measure its burden of particles, carbon dioxide, ambient (ground level) ozone, and a dozen other gases are unaffected by the clouds and moisture, and their pumps continue sucking in air to be measured.

Light rain often accompanies the clouds. Occasionally a thunderstorm arrives and throws lightning bolts at the power line poles and even the observatory's cluster of buildings and structures. Instruments and computers are sometimes damaged by lightning strikes. Small hail often accompanies these storms, and a strong storm can create quite a racket as the hail pounds on the metal roofs of the buildings. Some hailstorms can drop an inch or more of ice onto the observatory and transform its desolate environs into a chilly, wintry wonderland.

After a hailstorm, large expanses of black lava may remain cloaked in white ice until the next day. The hail around the observatory itself melts much faster, for the metal roofs and the asphalt of the parking area and road form a heat island that is warmer than the porous lava. This phenomenon helps explains the MLO garden, a random assortment of small plants scattered about the lava near the buildings and pavement. Some of the plants bear clusters of flowers that attract a few insects. Both the plants and the insects are ordinarily found far down the slope of the mountain.

The catchment systems on the roofs of several buildings at MLO capture water from the storms. When there is hail, the corrugated metal roof of the original building from 1956 serves as a mold for the sheet of ice that forms.

After the storm, the ice slides down toward the rain gutter and decorates it with an undulating, translucent border that eventually drips away.

By late afternoon, the cloudy flags of the inversion layer return to their normal elevation far down the slopes of the mountain. The sky quickly becomes as clear and dry as it was prior to the passage of the inversion layer.

The upper regions of Mauna Loa cool rapidly after sunset, and the freezing point can be reached even on spring and summer nights. A distinct change in wind direction is observed after sunset, as the breeze switches from the north or northeast to the south. Or at least that is its apparent direction, for this is a mountain, and one cannot be sure. Down in Hilo, the trade winds are still arriving from the Pacific. But Mauna Loa is so large that it creates its own weather. Dense, cool air from the free atmosphere above the island sinks over the mountain's summit and flows gently downward toward the observatory. So while the air appears to be arriving from the south at MLO, it is actually arriving from far above the mountain.

This is the downslope breeze favored by atmospheric chemists, who measure with precision almost unimaginably minuscule traces of gases in the air at MLO. They are especially interested in gases that are by-products of human activity, including carbon dioxide and methane, which have the ability to warm the earth, and the chlorofluorocarbons, which can cause both warming and destruction of the ozone layer that shields the earth from the sun's most dangerous ultraviolet rays. The clean air usually remains at MLO through midmorning, which is the best time to make measurements that require an ultraclear view of the sun. What happens thereafter is up to the inversion layer.

The Air Quality

On an especially clear day, a liter of air at the Mauna Loa Observatory may contain fewer than a dozen particles of matter larger than a micrometer across. Far below MLO, the situation is very different, for there both the chemistry of the sky and its burden of particles are dominated by an active volcanic vent on the slopes of Kīlauea that has been pouring molten rock into the Pacific off the southeast side of the island since 1982. When the lava plunges into the water, a huge plume of acidic steam erupts from the ocean and rises high in the sky to become a stream of cumulus clouds. A mist laden with bits of volcanic glass and hydrochloric acid falls from the steam cloud, and signs warn against staying in the area when the steam cloud is overhead. Those who stay might find that the mist falling from the cloud tastes a bit like lemonade.

The steam cloud causes far less air pollution than the lava itself, which emits vast quantities of sulfur dioxide gas. The gas reduces visibility only after it becomes tiny particles of sulfate upon which water vapor readily condenses. As the particles become coated with a film of liquid water, they gradually grow in size until they scatter light very efficiently. Eventually the sky is covered by a thick veil of gray. Residents of Hawai'i call this end product "vog" (from volcanic fog). On especially voggy days, the stuff looks much like smoke drifting across the lava and through the palm trees (Mims 2006). Vog increased significantly after March 12, 2008, when a new vent opened in the wall of Halema'uma'u, a large crater embedded in the summit crater of Kīlauea.

Why Place a World-Class Observatory on a Hawaiian Volcano?

The purpose of the Mauna Loa Observatory is to conduct long-term monitoring of sunlight and to probe, sample, count, and measure stuff in the air. The ozone layer high above the observatory is measured. Particles in the ambient air are collected and counted, and the concentration of a few dozen gases is measured with extraordinarily high accuracy. All this is done high in the free atmosphere over Hawai'i with minimal interference from vegetation and nearby human activity. Measurements made at MLO from as far back as 1956 provide a baseline against which subsequent measurements can be compared to look for hard evidence of changes in climate and the composition of the atmosphere. No better example of this is the observatory's measurements of the concentration of carbon dioxide, which began in March 1958 and have continued virtually uninterrupted for more than half a century.

Because carbon dioxide is an essential nutrient for plants, its concentration fluctuates around seven or eight parts per million (ppm) with the seasons. Thus, the measurements at MLO record the respiration of the earth. This oscillating seasonal signal is superimposed over the natural background level of carbon dioxide and its annual increase caused by the combustion of wood, coal, natural gas, and oil products. When the measurement of carbon dioxide was begun by Dr. Charles David Keeling in the spring of 1958, the concentration of carbon dioxide in the air at MLO was 316 ppm. By the summer of 2011, the concentration had reached 393.7 ppm (Scripps 2011), an increase of 24.6 percent.

Ordinarily an active volcano in Hawai‘i would seem a completely unsuitable home for a baseline atmospheric and meteorological observatory. Indeed, as noted earlier, a lava flow from the 1984 eruption severed the power line to MLO for a few months. The observatory itself was undamaged and back in operation after a borrowed diesel generator was temporarily connected to the undamaged power line at the 8,300-foot (2,530-meter) level. Yet despite the presence of a lava diversion dike, the possibility remains that some or even all of the ongoing experiments and long-term observations conducted at the observatory might be damaged or destroyed by a future lava flow. This raises the obvious question about the wisdom of placing a world-class atmospheric and meteorological observatory on a mountain in Hawai‘i when higher mountains with road access are available in the continental United States.

Consider that the summits of Colorado’s Mount Evans and Pikes Peak are accessible by good roads, and neither mountain is an active volcano. Both mountains are higher than any of Hawai‘i’s peaks, with Mount Evans being 14,264 feet (4,348 meters) and Pikes Peak 14,110 feet (4,301 meters) (Forest Service 2006). Moreover, both of these mountains are convenient to the nerve centers for climate and atmospheric research in the United States, including MLO’s parent organization, the Global Monitoring Division of the National Oceanic and Atmospheric Administration and the National Center for Atmospheric Research in Boulder.

A summer drive to the summits of Pikes Peak and Mount Evans will quickly demonstrate why these mountains are unsuited for the kind of baseline measurements made at the Mauna Loa Observatory. The most obvious reason is that the significant volume of automobile traffic on both mountains would contaminate delicate measurements of carbon dioxide, particulate matter, and sunlight. Pikes Peak is much worse in this regard, for, according to the City of Colorado Springs, in 2007 some 300,000 visitors made the drive to the summit along an unpaved, dusty road. The summit parking area can be filled by many scores of vehicles and hundreds of tourists enjoying the view. The road to Mount Evans is paved, and, according to the City of Denver, an average of 13,338 cars drive to Mount Evans each day it is open.

The proximity of vegetation is another issue. While the summits of both Pikes Peak and Mount Evans are above the timberline, upslope winds carry to the summits of both mountains the by-products of the forests far below. During July 1995, the summits of these mountains were evaluated by the author while making alpine measurements of solar ultraviolet and the clarity of the sky. The updraft at Pikes Peak was so strong that hang gliders rose above the summit as their pilots leapt from their takeoff points. The same updraft propelled across the summit a substantial assortment of dust particles, pine needles, detritus from the forest floor, and many insects. The breezy conditions also caused plumes of dust behind arriving and departing vehicles. The lesson is clearer than the air at the summit: Pikes Peak provides a superb view of the mountains and plains of Colorado, but it lacks the pristine conditions required for precise baseline measurements of the sun, sky, and atmosphere.

Regional air quality is an important consideration, even atop mountains like Pikes Peak and Mount Evans. Pollution from cities can reach the summits of both mountains, as can dust storms and smoke from forest fires.

Still another issue is security, for the delicate instruments of an atmospheric observatory are best placed in an isolated location secured against vandalism and theft. Even a well-meaning, curious tourist might inadvertently cause problems simply by leaving a fingerprint on the quartz dome of an ultraviolet monitor or by touching the moving shadowband of a sunlight radiometer.

Finally, winter snow accumulation makes access to the summits of mountains like Mount Evans and Pikes Peak unpredictable at best. The Pikes Peak road is open all year when snow has been cleared. The Mount Evans road is open from July 4 to Labor Day.

Mauna Loa bests Pikes Peak and Mount Evans in all these considerations. Snow only rarely blocks the road, and the giant mountain's vast fields of virtually lifeless lava isolate the observatory from the influences of dust, vegetation, and human activity. On a typical day, only several vehicles drive the observatory road. And thanks to the elevation of the observatory and the thousands of miles of open ocean that surround Hawai'i, the air over Mauna Loa is probably as clean as air can be in the Northern Hemisphere.

Yet even Mauna Loa is not the perfect site for an atmospheric observatory, for maintaining the road has long been a major problem, and there remains the threat of a future volcanic eruption. Moreover, the giant volcano leaks carbon dioxide and sulfur dioxide, both of which sometimes drift up to MLO and cause spikes and bumps over the normal background levels of these gases. Because the wind direction is carefully measured, eliminating interference caused by the volcano has long been a routine step in evaluating background measurements of these gases. As for the physical threat to the observatory posed by the volcano, according to the Hawaiian Volcano Observatory, 98 percent of the volcano's surface is covered with lava less than 10,000 years old (Lockwood 1995). Placing the observatory on an active volcano was a calculated risk made under the assumption that the site would provide many years of uninterrupted baseline measurements of the pristine sky over Hawai'i. It's a gamble that has paid off for more than half a century.

A Spring Day on the Mountain

First light on a typical spring day at the Mauna Loa Observatory begins when a thin orange glow emerges over the clouds overlying the Pacific east of Hilo while stars are still sprinkled across the black sky above. The air is cold, and sometimes there are traces of ice on the boardwalks between the buildings. The breeze from the south means clean air from the free troposphere is flowing down the slope of the big mountain.

The twilight glow gradually spreads along the horizon as it bulges upward into the darkness. Eventually an orange arch pushes high into the purplish sky, its base growing brighter by the minute as the eastern sky transitions from violet to blue. Thin, dark layers over the horizon are sometimes visible, especially during spring. They suggest the presence of Asian dust or air pollution, a phenomenon that was not reported during the early days at the observatory. While the twilight glow is rising in the eastern sky, the antitwilight glow is setting over the summit of Hualālai in the west. It forms a pink arc in the sky, and the crisp, clear air over Mauna Loa assigns it much more prominence than when it is observed from sea level. Looking back to the east, suddenly there is a brightening at the base of the arch in the sky, and within half a minute the upper edge of the solar disk bursts into view over the cloud deck cloaking the Pacific. It's sunrise at the Mauna Loa Observatory.

Arrival of the MLO Team

While the instruments that measure sunlight are awakening, many other instruments at the observatory have been working all night. These include an impressive array of meteorological instruments that continuously measure temperature, dew point, relative humidity, pressure, and wind speed and direction. More specialized are instruments that continuously count particles in the air and gas analyzers that measure carbon dioxide, ozone, sulfur dioxide, methane, and the CFCs and other halocarbons. All these instruments rely on noisy pumps that force air collected from the forty-meter tower or the Keeling Building mast through their sampling filters or chambers.

The window of time for the calibration of some of the instruments that stare directly at the sun begins around half an hour after sunrise. These are the instruments that track the sun and measure aerosols, the ozone layer, and water vapor in the atmosphere over MLO. Most are perched on a large deck over the NDACC (Network for the Detection of Atmospheric Composition Change) Building, the largest structure at MLO. Others are installed in telescope domes or on a concrete pad resting on the lava. They are best calibrated during the early morning during clean downslope conditions and when the position of the sun ranges from about 10 to 30 degrees over the horizon.

About an hour after sunrise, one of the MLO Solar Observatory staff arrives to begin a long day of work imaging the solar disk with specialized telescopes installed in a pair of domes south of the central buildings at MLO. Around 9:30, two or three staff members from the Mauna Loa Observatory arrive from Hilo. They bring supplies, replacement parts, empty air sampling flasks, and lunch. After unloading their vehicle and unlocking the original Mauna Loa building, now named the Keeling Building, the staff retrieve their clipboards and check sheets and quickly begins their rounds, checking dozens of instruments scattered around the site. Each staff member has specific responsibilities, and work on the mountain is generally limited to no more than three days a week. Therefore, while some instruments are checked every workday, others are checked two or three times a week. The schedule changes over time, so in the account that follows, all the tasks have been merged together for a hypothetical day.

More than a dozen solar instruments mounted on the solar deck over the NDACC Building must be checked and their optical surfaces cleaned. Special attention is given to the two Canadian Brewer spectrophotometers that measure the ozone layer and solar ultraviolet. While the data are sent directly to Canada's Atmospheric Environment Service via the Internet, a pair of computers in the NDACC Building below the deck permits the operation of the Brewers to be checked so that adjustments can be made when necessary.

Also in the NDACC Building are some of the ultrasensitive gas analyzers that sniff the atmosphere for carbon dioxide, methane, and a variety of other greenhouse gases that have the ability to trap infrared emitted by the earth and cause warming of the planet. Tall, heavy cylinders of calibration gas must be checked to be sure they contain an ample supply of gas. The freeze trap that removes water vapor from the air being sampled for carbon dioxide must be checked, for water vapor—by far the most potent of all the greenhouse gases—must be entirely removed to avoid artificially inflating the measurements.

In the Keeling Building are found instruments that capture or count particles in the air and measure the ambient ozone. There is also the Scripps Institution of Oceanography carbon dioxide analyzer. The original Model 70 Applied Physics Corporation Infrared Analyzer installed in the building in March of 1958 was retired a few years ago, much to the relief of a staff weary of the temperamental nature of the ancient—but accurate—vacuum tube instrument. Today Scripps is beginning its second half century of precisely measuring carbon dioxide with an analyzer as modern as the one used by NOAA in the NDACC Building. All these instruments are carefully inspected by the staff, and their operational status is checked off on the clipboard forms.

Varieties of instruments are mounted outside on the lava, and they too must be checked. This includes NASA's array of solar-powered, robotic sun photometers perched on a concrete pad west of the NDACC Building. Immediately south of the building is NOAA's GPS receiver system that measures the water vapor in a column through the atmosphere and automatically sends its data to Boulder via the Internet. While the GPS system needs no attention, the staff checks to make sure that current meteorological data are also being sent to Boulder, for when the temperature and wind data stop flowing, the GPS data are not plotted on the Web site.

In the midst of the checking and inspecting, one of the staff unlocks the tiny door of the Dobson dome and begins to make precise measurements of the ozone layer using an old Dobson spectrometer almost identical to the one that has been in the same location since 1957.

In the days before computers, the output of most instruments was automatically inscribed on rolls of chart paper. Today most data is sent directly to Boulder and various universities over the Internet. NASA's array of robotic sun photometers sends data directly to the Goddard Space Flight Center in Maryland via a satellite link. While the staff does not see much of the data unless they look for it on the Web, the recipients on the mainland are quick to inform them when there is a problem, which explains why the phone sometimes rings even before the staff arrives.

While the MLO mountain crew is at work, once a week a staff member in Hilo drives to the Coast Guard lighthouse at Cape Kumukahi to collect samples of air to be sent to the Global Monitoring Division in Boulder and the Scripps Institution of Oceanography in San Diego. Also once each week, an ozonesonde suspended from a weather balloon is launched from the National Weather Service office in Hilo to sample the ozone between sea level and the upper stratosphere.

Back on the mountain, as the morning progresses the cloud deck far below the observatory might remain locked in place, or it might begin rising upward. When the latter occurs, staff on the mountain will periodically glance down to the northeast to keep track of the rising clouds. Experienced MLO hands will also keep an eye on the sky to the southwest. The slope of the mountain blocks the view of any clouds in that direction until they suddenly spring into the sky and quickly swirl overhead. What happens next is unpredictable. The observatory may simply be covered by clouds. Or the cloud deck below may rise up and suddenly envelop the station in thick fog.

By noon, all the instruments have been inspected and the ozone layer has been measured two or more times. It's time for a lunch break and a chance to discuss any problems that might have been noted during the morning routine. Thereafter, the team works on troubled instruments, updates check sheets, replaces empty gas cylinders with full ones, and performs routine maintenance on everything from sophisticated analytical instruments and computer networks to vacuum pumps, air lines, and water pipes. When there is spare time, a timeworn shed or building might receive a fresh coat of paint.

Around 2:30, the MLO team packs shipping boxes with their cargo of fragile air-sampling flasks and a few bags of trash into their van and heads back to the Hilo office. When an occasional thunderstorm approaches the observatory, the staff pays special attention to the sound of thunder and may leave the station early to avoid the hazard posed by lightning (Plate 49).

The departure time is occasionally altered. Once every week or two the MLO mountain team stays past 4:00 to await the arrival of replacement gas cylinders and a large liquid nitrogen tank carried by a truck that also services the observatories atop Mauna Kea. The MLO staff assists the driver with unloading the heavy tanks and then helps him load the empty cylinders onto the truck.

Sunset

Even on days when the inversion layer rises near or above the observatory, the clouds have usually thinned significantly by sunset. As the sun descends toward the western horizon, the antitwilight glow begins to rise from the eastern horizon. Once a month, the simultaneous rising of the full moon and the deep pink antitwilight glow provides a spectacular sight in the eastern sky. During winter months, the shadow of Mauna Loa is visible over the north slope of the huge mountain, where it forms a purplish, triangular shadow in the antitwilight glow.

Turning back toward the west, occasionally the proverbial green flash can be seen just as the uppermost edge of the sun slips behind the cloud deck. The phenomenon is usually a brief green glow rather than the much rarer green flash.

If clouds are still present at or above the altitude of the observatory, they provide the backdrop for a strikingly beautiful display. Sometimes a series of sunsets occurs as the solar disk descends in sequence behind cloud layers stacked over the western horizon.

The colors in the twilight display provide clues about the clarity of the sky, for when the sun nears the horizon, its rays traverse a much longer path through the atmosphere than when it is high in the sky. The result is that the violet, blue, and green wavelengths are scattered away, leaving behind yellow, orange, and red (Minnaert 1940, 1993). Thus the sun reddens as it sets and illuminates clouds with increasingly orange and red wavelengths as it approaches the horizon. If there is dust in the sky, it too is reddened by the setting sun and may provide especially brilliant sunsets, unless there is so much of it that it absorbs more light than it scatters toward the observer. After the sun falls below the cloud deck, the twilight arch becomes increasingly red as it descends and forms a vivid crimson cap over the horizon.

If a lidar session has been scheduled to probe the stratosphere with a laser beam, after dark a thin green beam will be seen emerging from the roof of the NDACC Building. In his combined office and lab inside, MLO Station Chief Dr. John Barnes checks the power of the laser beam and slides a mouse across his desk to activate the program he developed to visualize the scattering of the beam by any aerosols that might be floating in the stratosphere high over MLO. Meanwhile, a scientist from the Jet Propulsion Laboratory (JPL) arrives to activate NASA's ultraviolet lidar, whose invisible beam measures the ozone layer while NOAA's lidar probes for aerosols and water vapor.

The lidar sessions end before midnight, the lights in the NDACC Building are switched off, and Dr. Barnes and the occasional visiting scientist retire to the two tiny bedrooms. By now sleep is very much on the mind of those who have been at the observatory since before sunrise. Sometimes the sleepy scientists are treated to a surprise light show while sliding into their sleeping bags, for, when the air is especially dry, streamers of crackling sparkles light up the interior of their bags.

Some visitors experience difficulty sleeping, especially during their first night or if they have a hint of a cold. The problem may be due as much to the dryness of the air as to the lack of oxygen, and a few spurts of saline solution in one's nostrils can make breathing much easier for the visitor in good health. Those with a cold or who experience altitude sickness should avoid staying overnight.

Having company while overnighting is helpful, for, after the lights are out, inexperienced visitors are sometimes startled when one of the resident Mauna Loa wolf spiders pays a visit or by the cacophony of sounds produced by the shutters, fan motors, air sampling pumps, and ventilators that drone away in the background or switch on and off at intervals. As Station Chief Barnes (2006) has observed, "Yes, at night if you are up there alone, it gets a little spooky."

Spooky indeed: Lonely scientists who realize they are the only human being spending the night on the world's largest mountain can turn their thoughts to other topics, like the huge crater looming a few thousand feet up the slope of the mountain. Will tonight be the night it erupts? Will there be any warning? Was former MLO director Russell Schnell serious when he said to grab the heavy Dobson spectrophotometer and run downhill should there be an eruption? Will molten lava melt the base of the forty-meter tower and vaporize the hapless scientist who flees to its top for safety? After the lonely scientist finally falls fitfully to sleep, the mountain might provide a reminder of who's really in charge in the form of a small earthquake that pushes the scientist's feet soundly against the wall to awaken him and initiate an even more animated cycle of spooky thoughts.

During its first decade, the observatory was manned around the clock, but today overnight stays are usually unnecessary, for, with the exception of the lidars, nearly all the instruments at the observatory are fully automated. Today staying overnight is beneficial for those who conduct occasional audits of the observatory's instruments and for those who must arise early to begin manual calibrations of sun photometers that are pointed toward the sun as it rises in the sky. The calibration session lasts only a few hours, but it's best performed when rested, not immediately after the tedious, bouncy drive from Hilo, often through thick fog. Staying overnight also provides the opportunity to experience the life of old-timers on the mountain back in the 1950s and 1960s, who observed and photographed the sunrises and sunsets, no two of which are alike. Sunsets watched through the crisp, cool air at MLO are visual treats that provide the perfect ending to a long day at the observatory. And there's no better way to begin the next day than walking carefully up the ice-coated steps of the solar radiation deck to watch the twilight glow slowly rising in the east while inhaling the pure downslope air flowing down from the summit.

The Old-Timers

The occasional scientist who stays at MLO for a week or ten days at a time will experience only some of what the old-timers did, for the routine on the mountain today is far less rigorous than when the observatory was manned twenty-four hours a day from 1957 through the mid-1960s. Back then it was essential to keep someone on the mountain to maintain the noisy diesel generators that provided electrical power and to fix the carbon dioxide analyzer when it ceased operating properly. Overnighting on the mountain became unnecessary only after the power line was installed in 1966. For decades the observatory has worked so well on its own that it is unmanned on weekends and holidays, and modern computer data acquisition systems long ago replaced nearly all the finicky pen-and-ink chart recorders.

The old-timers who used to stay on the mountain for four or more days at a time still recall the difficulties they faced. But they also remember how their well-being and work output improved after the first day on the mountain allowed them to become acclimated to the reduced oxygen at the observatory. The day crews that followed them don't have that advantage, and some report mild discomfort from the altitude change.

But even the old-timers at the observatory forty to fifty years ago faced few of the risks and challenges encountered by the ultimate old-timers who more than two centuries ago first ascended Mauna Loa for the purpose of making scientific observations and measurements. They had no roads, vehicles, or modern hiking boots. They had no electricity, and battery-powered flashlights had not been invented. Their only maps were the ones they drew, and GPS receivers were beyond imagination. Navigation was accomplished by dead reckoning, compass, and sextant. A barometer was considered portable when its delicate glass tube could be carried inside a padded leather case slung across the back along with a flask of mercury required for its operation. Back then there were no structures on the mountain, water holes were scarce, and food sources were nonexistent. Yet early scientific explorers managed to conduct pioneering research at the summit of the great mountain. They pioneered the science that has been performed every day at the Mauna Loa Observatory since June of 1956. Thus it is fitting that this history of today's Mauna Loa Observatory begins with the story of the scientific pioneers who led the way. We begin by traveling back to the year 1794, to join the first scientific expedition to the summit of the world's largest mountain.

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