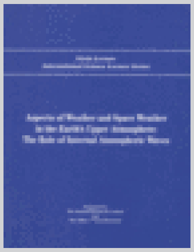

Aspects of Weather and Space Weather in the Earth's Upper Atmosphere: The Role of Internal Atmospheric Waves

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ASPECTS OF WEATHER AND SPACE WEATHER IN THE EARTH'S UPPER ATMOSPHERE: THE ROLE OF INTERNAL ATMOSPHERIC WAVES

by

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Preface

The International Science Lecture Series is a special project of the National Research Council's (NRC) Commission on Physical Sciences, Mathematics, and Applications. The series was established in 1990 at the request of the Office of Naval Research (ONR). The purpose of the series is to advance communication and cooperation within the international scientific community. A search committee established by the NRC selects prominent U.S. scientists to lecture in three areas of scientific inquiry: ocean and meteorological sciences, materials science, and information science. The countries in which the lectures are delivered are selected on the basis of consultations with the international scientific community, including the science attaché in U.S. embassies, senior representatives of ONR-Asia and ONR-Europe, and ONR representatives in Washington, D.C. Whenever appropriate, each lecture is followed by discussions with senior government, industrial, and academic representatives of the host country in order to identify opportunities for increased cooperation and collaboration.

Aspects of Weather and Space Weather in the Earth's Upper Atmosphere: The Role of Internal Atmospheric Waves by Michael C. Kelley, professor of electrical engineering at Cornell University, is the sixth lecture in the series. The first lecture, *The Heard Island Experiment*, was presented by Walter H. Munk, Secretary of the Navy Research Chair at the Scripps Institution of Oceanography, University of California at San Diego. The second lecture, *Fountainhead for New Technologies and New Science*, was presented by Rustum Roy, Evan Pugh Professor of Solid State Physics and professor of geochemistry at Pennsylvania State University. The third lecture, *Computing, Communication, and the Information Age*, was presented by John E. Hopcroft, Joseph C. Ford Professor of Computer Science at Cornell University. The fourth lecture, *Traffic Management for High-Speed Networks*, was presented by H.T. Kung, Gordon McKay Professor of Electrical Engineering and Computer Science at Harvard University. The fifth lecture, *Implementation Challenges for High-Temperature Composites*, was presented by Anthony G. Evans, Gordon McKay Professor of Materials Engineering at Harvard University.

Professor Kelley's lecture tour consisted of a trip to Australia and India during February of 1997. Professor Kelley's lecture was first presented on February 10, 1997, to the High Frequency Radar Division of the Australian Defence Science and Technology Organization (DSTO) in Salisbury, South Australia. Prior to the lecture, Professor Kelley's delegation met with scientists and engineers from DSTO and toured the facilities of the High Frequency Radar Division. The delegation also toured the facilities of Atmospheric Radar Systems Pty. Ltd., a science and technology consulting firm in Thebarton, South Australia, that designs and manufactures atmospheric radar systems. On the evening of February 10, Professor Kelley delivered his lecture to the quarterly meeting of the South Australian Branch of the Australian Institute of Physics at the University of Adelaide in Adelaide, South Australia. On February 11, he presented his lecture at the Physics Colloquium at the University of Adelaide, and later met with students and researchers to discuss their most recent research results.

Professor Kelley's delegation then traveled to India and on February 13, 1997, met with the chairman of the Indian Space Research Organization (ISRO), Dr. K. Kasturirangan, at the ISRO headquarters in Bangalore, India, to discuss possible collaboration between ISRO scientists and U.S. researchers. Dr. S. Rangarajan, director of the ISRO Telemetry, Tracking, and Command Network (ISTRAC), hosted a tour of the satellite test and integration facility at the ISRO Satellite Center (ISAC). On February 15, 1997, Professor Kelley presented his lecture at the National MST Radar Facility in Gadanki, India. In addition to the scientists and staff of the MST Facility, the audience included a number of scientists from the Physics Research Laboratory in Ahmadabad who had traveled to Gadanki to attend Dr. Kelley's lecture. The director of the National MST Facility, Dr. P.B. Rao, led a tour of the facility, after which Professor Kelley met with scientists from the facility and from the Physics Research Laboratory to discuss recent developments in space weather research.

The Naval Studies Board and the Office of Naval Research would like to thank their gracious hosts in Australia and India: Dr. Bruce Ward, research leader and senior scientist at the High Frequency Radar Division of the Australian Defence Science and Technology Organization; Dr. Ray Protheroe, professor of physics at the University of Adelaide and chair of the South Australian Branch of the Australian Institute of Physics; Dr. P.B. Rao, director of the Indian National MST Radar Facility; and Dr. D. Gupta, senior scientist at the Physics Research Laboratory in Ahmadabad, India.

Contents

Aspects of Weather and Space Weather in the Earth's Upper Atmosphere: The Role of Internal Atmospheric Waves

INTRODUCTION

Much of what we call the "weather" near the surface of the Earth involves patterns of winds that propagate like waves across the planet. In fact, the high- and low-pressure areas we see displayed in the newspapers or on television are the crests and troughs of what are called planetary waves by atmospheric scientists. Weather in the upper atmosphere and in space has many wavelike characteristics as well. These waves are of interest in their own right, and most of this lecture will revolve in one way or another around the topic of internal waves in the atmosphere and their effects on the near-space regions of the Earth and on space weather in the Earth's ionosphere.

Space weather is distinct from space science just as meteorology is distinct from atmospheric science. Weather deals more with the aspects of atmospheric phenomena that have a direct impact on humanity. Of course, detailed knowledge of the associated science is of great importance to understanding and predicting the behavior of these complex systems. In the field of space weather we are just beginning to see how our knowledge can be used in this manner.

There are two fundamental drivers in space weather, only one of which is treated here. One is the searingly hot, tenuous outer layer of the Sun's surface, which sweeps over and by the Earth's protective magnetic field. The second is the cool, dense, but extremely dynamic atmosphere of the Earth itself. The latter is of most interest here.

Wave phenomena play a very important role in human and animal behavior, chiefly through the sensory apparatus we use to sample our environment. Our eyes detect electromagnetic waves with a response more or less equivalent to the spectrum of light emitted from our Sun. Our ears detect sound waves propagating through our planet's atmosphere. As technology developed, we extended the reach of our perceptions using instruments capable of detecting signals our eyes and ears cannot perceive. As the phenomena we study range higher and higher in the atmosphere where the human eye is less useful, remote sensing using such tools is of greater importance. As a crucial tool for the study of space weather, remote sensing becomes the second topic of this treatise.

Humans are by and large oblivious to many other wave phenomena supported by the atmosphere or part of the electromagnetic spectrum. Other species, however, have specialized sensory organs with which they extract information from these waves. Bees use the ultraviolet (UV) portion of the electromagnetic spectrum. Large animals such as elephants and whales use infrasound (low-frequency sound waves) to communicate. Studying remarkable feats of animal navigation has revealed how little we actually know about sensory techniques in the animal kingdom. Clearly, migratory fish and birds see a world about which we have little awareness. Various species can detect and use electric and magnetic fields—both steady and wavelike—as well as chemical tracers, starlight, and many other natural phenomena.

South Sea Islanders have well-known navigational skills that are, in fact, attuned to just these sorts of wave phenomena, the eventual subject of this talk. They describe part of their technique as "feeling" the ocean; some navigators literally lie down in the bottom of a vessel and feel the pattern of currents and waves, which, it turns out, are not random, but reflect the pattern of islands and, quite possibly, other underwater features. This set of patterns forms a map that is passed on from generation to generation (but that may soon be lost to the human population). Another thread here is the extent to which increasing technology and remote sensing have allowed the human race to detect and study atmospheric waves, which are not obvious to the casual observer, and what this knowledge reveals about our environment.

My main interest here lies in atmospheric waves that are so low in frequency that their wavelengths range from the size of small countries to entire continents. The Earth's gravitational field plays such an important role in the propagation of these waves that they are usually referred to as gravity waves, although "buoyancy waves" may be a more appropriate term to avoid confusion with gravitational waves generated by black holes, and the like. An important distinction is that these waves carry energy and momentum upward, not just horizontally as exhibited in the normal weather. They travel up into space itself.

Wave activity in the Earth's oceans is a common sight. Ocean tides themselves are a wave phenomenon that propagates once around the Earth in a day's time and has a wavelength comparable in size to its circumference. Superposed on this slow waxing and waning of the tides are waves that break on the shoreline and come from distant storm systems. The misnamed tidal wave or tsunami is an extreme example of an ocean wave phenomenon that can carry energy from a massive earthquake or a volcanic eruption horizontally for vast distances, sometimes with devastating consequences. As we shall see, earthquakes and tornadoes also send enormous pulses of waves upward into space.

Surface ocean waves and tsunamis, which break on the shore, involve horizontal propagation. However, the ocean and the atmosphere can support *internal waves* as well, waves that were hardly noticed until recently. Mariners used to talk about slow water, a region of the ocean in which a ship traveled more slowly than normal. This phenomenon is now thought to be due to waves propagating in the water itself, not on its surface, internal waves invisible from above that oppose a ship's progress. The Earth's atmosphere has no palpable surface; hence, if it is to have waves of any importance to space weather, they must in some sense also be internal. In the next section we present some observations of internal waves in the Earth's atmosphere.

SOME OBSERVATIONS

Almost everyone has seen a visual manifestation of internal atmospheric buoyancy waves, most likely without recognizing them. They appear as parallel bands of clouds, each representing a certain phase of a wave as it travels through the atmosphere. As we shall see, these waves have intrinsic oscillations of virtually every parameter characterizing the atmosphere: fluctuating winds, pressure, density, and temperature all occur. It is the temperature variation that yields the cloud patterns as the air parcel periodically changes temperature from above to below the dew point. These patterns in the ice crystals can long outlive the wave packet that formed them and drift for long distances with the background wind.

The atmosphere has no surface, but if one remembers to look for these patterns in the clouds, either from the ground or from an airplane, it becomes very clear that there is as much wave activity in the air as there is in the oceans. An even better vantage point is the Space Shuttle (see Figure 1).

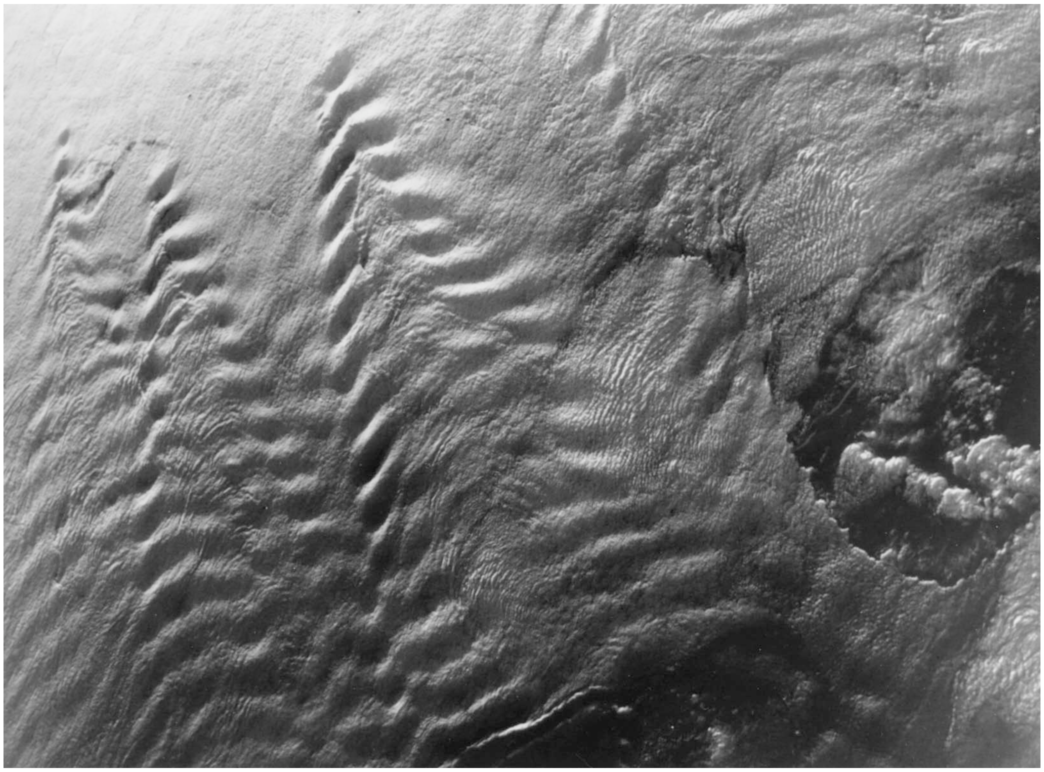

FIGURE 1 A view of cloud-covered mountainous terrain as captured by cameras on board the Space Shuttle. Image courtesy of NASA.

In mountainous regions, such as those viewed from the Shuttle, very interesting clouds often form upwind from the peaks, sometimes creating a string of clouds that do not move relative to the mountain. These orographic clouds (see Figure 2) form when the wind lifts up to go over the mountain. This launches a wave moving backward against the flow direction. A stationary wave pattern is created when the speed of the wave is equal to and opposite that of the wind and a fixed pattern of high and low temperatures arises. The result is a regular pattern of cloud puffs that may remain fixed for hours.

If an exact matching of wind speed and wave speed seems surprising or even unlikely, the next time you are on a boat stare at the water behind it without looking at the shoreline. The water exhibits a pattern of deep depression just behind the boat and a rise in the water level just aft. Then glance to the right and left, and imagine you are not moving at all; there are fixed patterns of high and low water levels radiating away from the boat. As far as you—the observer—are concerned, these patterns do not move; they simply are there! Yet we all know that an observer on shore sees a wave coming onto the beach with a definite frequency and wavelength. The water "cleverly" picks out exactly the right wave (e.g., the right wavelength and frequency match) moving with the boat. Standing on solid earth (as is the mountain) is just like a vantage point on the ship. The waves are simply there.

Other planetary atmospheres support waves as well. The Viking Probe camera has provided some spectacular examples when trained on Mars, where the winds are very fierce and any orography is bound to show wavelike behavior in its environs. Figure 3 shows a craterlike feature ringed by regular wave patterns, most likely mirrored in the dust kicked up by the wind.

Prior to this century the only way to detect upper atmospheric disturbances was through changes in the Earth's magnetic field. This method showed that tides existed in the air as well as in the ocean, but

FIGURE 2 Periodic lenticular (lens-shaped) clouds formed over mountains of the western states. Reproduced from National Audubon Society (1995) with permission of Grant W. Goodge, photographer.

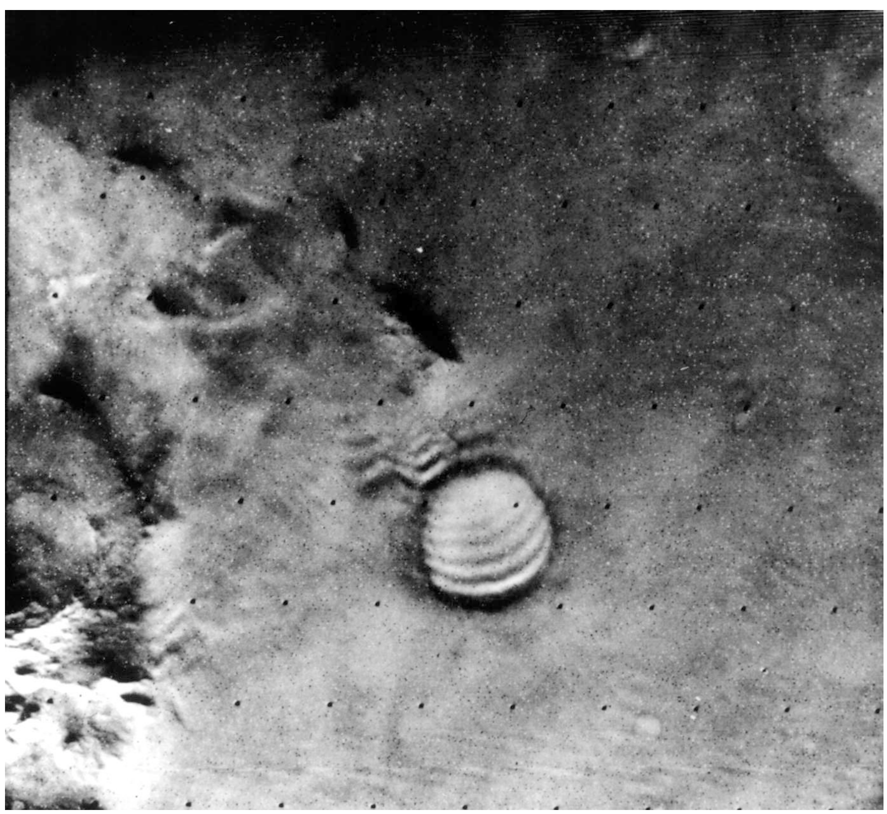

FIGURE 3 Patterns formed in the dusty Martian atmosphere by winds blowing over a crater. Image courtesy of NASA.

since the upper atmosphere was not even thought to exist, it was quite a problem to explain the observations. It was not until the Space Age allowed us to measure the thermal structure of the atmosphere that much progress was made in explaining tides in the atmosphere in any detail. The infamous V-2 rocket, taken as a spoil of World War II, was outfitted with a thermometer and launched over the New Mexico desert. Now we know that it gets cold on a mountaintop, and one might guess this trend would continue. But no, it turns out that the temperature begins to rise again due to absorption of UV light by the ozone layer. This discovery changed everything for theorists studying atmospheric tides. They were finally able to show that solar heating dominates atmospheric tides, as opposed to the well-established dominant role of the Moon and the Sun's gravitational pull on the oceans. A very interesting work by Sydney Chapman and R.S. Lindzen (see reading list) explains the history of tidal theory, including the dominant influence of Lord Kelvin, who espoused an incorrect theory with such authority that it was accepted for decades. The first hint about upward-traveling waves came out of tidal theory, and the regular pattern of magnetic fluctuations began to be understood. Electric currents must be flowing in space, driven by tidal surges. Space weather exists.

During the spectacular Leonids meteor shower of 1866, and possibly the equally bountiful one of 1833, strange distortions of meteor contrails were seen. The sketch in Figure 4 was drawn by an observer in Cardiff, England, for an event on November 14, 1866, an event that was visible for 10 minutes (Trowbridge, 1907). Illustrations were published and analyzed, but again, the explanations were not easy. At the time the atmosphere was not known to extend as high as the observations indicated, let alone thought to have internal wave activity. Such long-lived trails are very rare except during showers. Indeed, during the November 1996 Leonids shower the author observed five such displays, one lasting several minutes.

Buoyancy waves were first detected in the aftermath of the great volcanic explosion of Krakatau in 1885. This was indeed the first blast heard round the world, at least by instruments. Once the reports

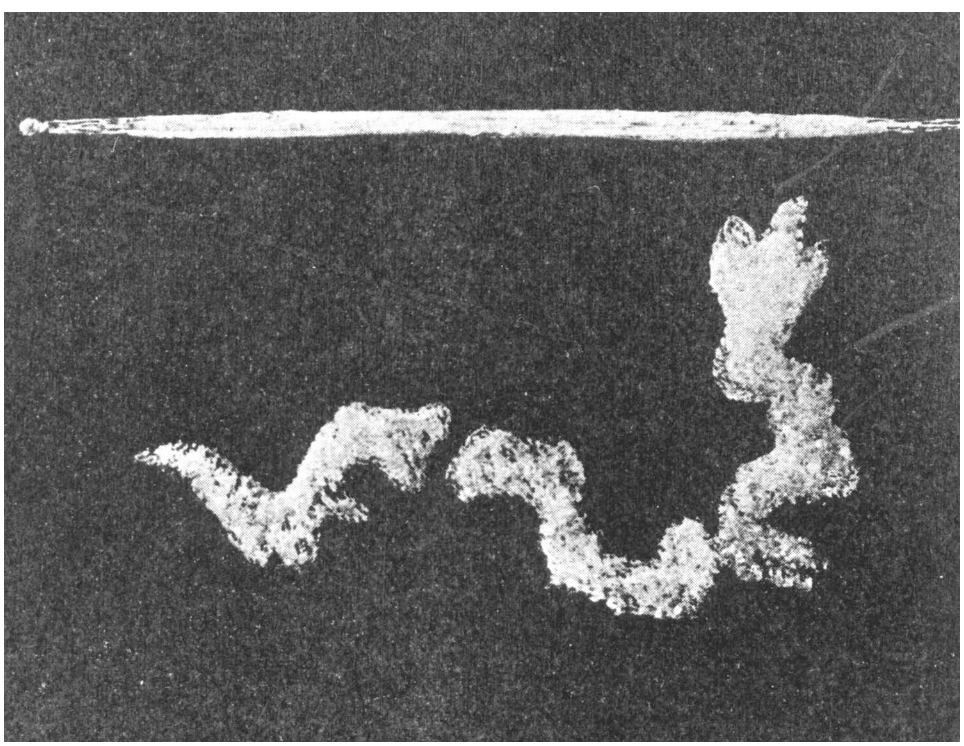

FIGURE 4 Meteor contrails distorted by atmospheric waves. Reproduced from Trowbridge (1907), p. 395, with permission of the American Meteorological Society.

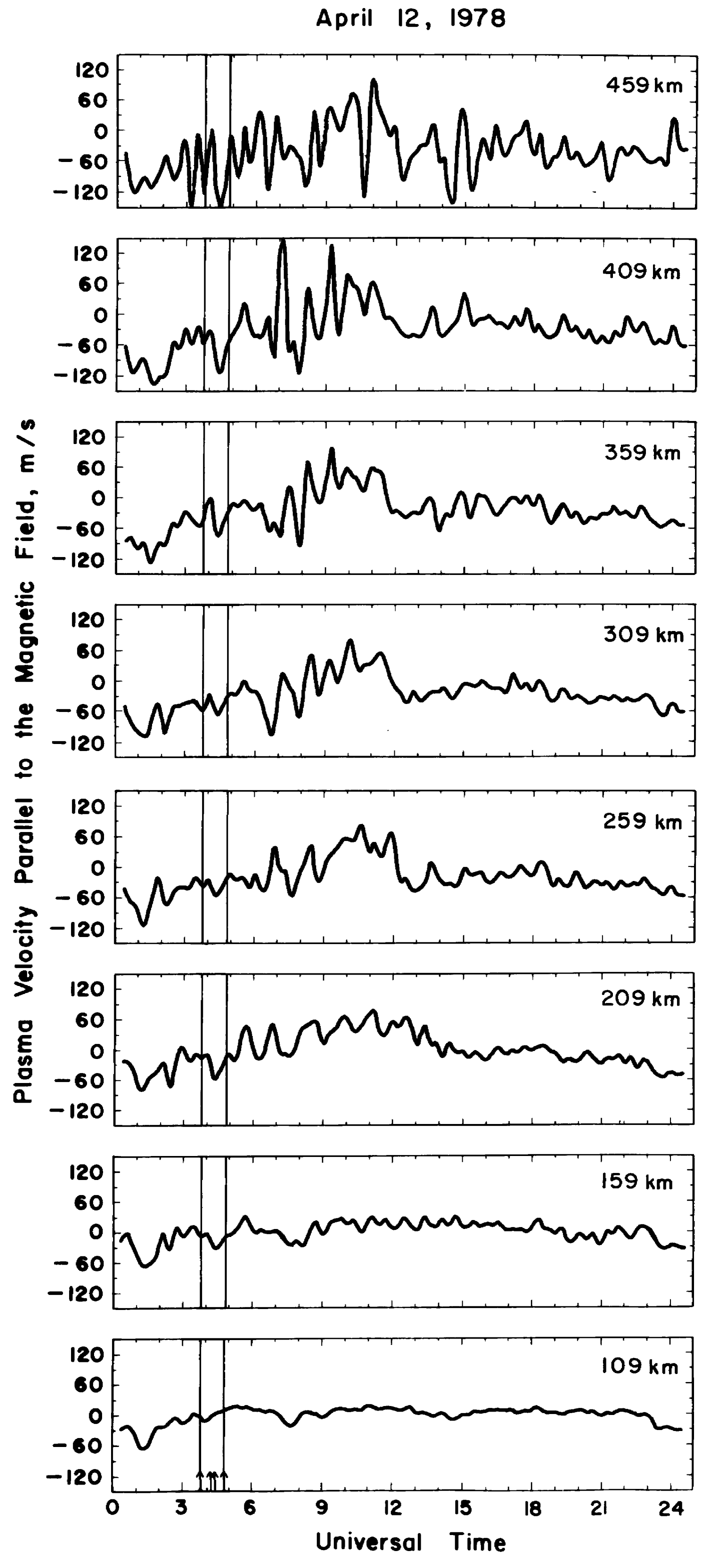

FIGURE 5 Huge vertical oscillations with winds up to 300 km per hour were induced in the Earth's ionosphere over Alaska by a 6.4 earthquake near Kodiak Island. Reproduced from Kelley (1985) by permission of the American Geophysical Union.

came in, it was clear that the atmosphere supported a wave mode with very low frequencies but quite high propagation speed. After the turn of the century, radio wave techniques showed that there was an ionized component of this upper atmosphere. When Marconi propagated a wireless signal across the ocean, it was clear that some sort of reflecting mirror existed for radio waves. In an ideal situation the waves bounce between the Earth and this mirror, following the curvature of the Earth. Now the Earth is pretty smooth compared to the radio wavelengths used, but the upper atmosphere turns out to be not so smooth. Listening at night to distant baseball games broadcast by AM radio, one finds that the signal waxes and wanes, sometimes disappearing entirely. This was my own introduction, a frustrating one, to space weather. The radio wave mirror, called the ionosphere, is not very smooth. One of the goals of space weather forecasting is to predict the effects of the dynamic ionosphere on radio wave communications of all sorts, whether passing through or bouncing off the ionosphere.

Much of this ionospheric roughness is caused by internal gravity waves. In the developing field of radio science hundreds of papers have been written on traveling ionospheric disturbances (or TIDs) by scientists who study the reflected or refracted signals from the disturbed ionosphere. Man-made "Krakatau's," called nuclear explosions, were found to create worldwide wave packets, as did large earthquakes.

Once, by pure chance, a wave launched by a major earthquake in the Kodiak Island region was captured by the current workhorse of upper atmospheric research, an incoherent scatter radar located in the Fairbanks area of Alaska (Kelley, 1985; see Figure 5). The disturbance lasted for nine hours as the atmosphere bobbed up and down with velocities exceeding 300 km per hour at heights of 400 km!

As we shall see later, Krakatau apparently also spawned the first observed clouds in the upper atmosphere. Within a few years after the volcano erupted, researchers began to report twilight clouds at the ridiculous height of 85 km where, it was thought, no atmosphere even existed. These are called noctilucent clouds since they can be seen by eye only when it is dark on the ground and the sun shines on them over the edge or limb of the Earth. Thus, the long summer twilights of Scandinavia are ideal conditions in which to see these clouds (Figure 6). These clouds have a lot of structure and it is clear that there is wave activity at this height, just as clear in retrospect as the waves indicated by meteor contrails, which form at about the same height.

SOME THEORY DEALING WITH INTERNAL WAVES

Traveling ionospheric disturbances show that even at the farthest reaches of the atmosphere, wavelike activity occurs. In fact, the largest-amplitude waves seem to occur at the highest altitudes. This curious feature was illuminated by rocket experiments that deliberately left a trail of visible material in their wake. Using tracers much like barnstorming skywriters, these trails made by rocket scientists told a story of ubiquitous wave activity at high altitudes.

The structure of this trail is very similar to the sketches of meteor contrails made in 1866 (see Figure 4). In the man-made case, trimethyl aluminum (TMA) burns in oxygen, yielding a visible trail as shown in Figure 7. Wave activity then distorts the trail with time. In the case of meteor contrails, some of the energy that ripped apart the meteor is stored and released over a long period, allowing the trail to be observed, if not fully understood, even today.

Colin Hines was among the first to recognize the implications of these observations and put together the first quantitative description of internal waves in a planetary atmosphere (Hines, 1960). The curious but undeniable result of his analysis is that wind and temperature fluctuations in any given wave packet should grow exponentially in strength as the wave propagates upward. No wonder such huge velocities are found in the highest reaches of the atmosphere above an earthquake, nuclear explosion, or thunderstorm.

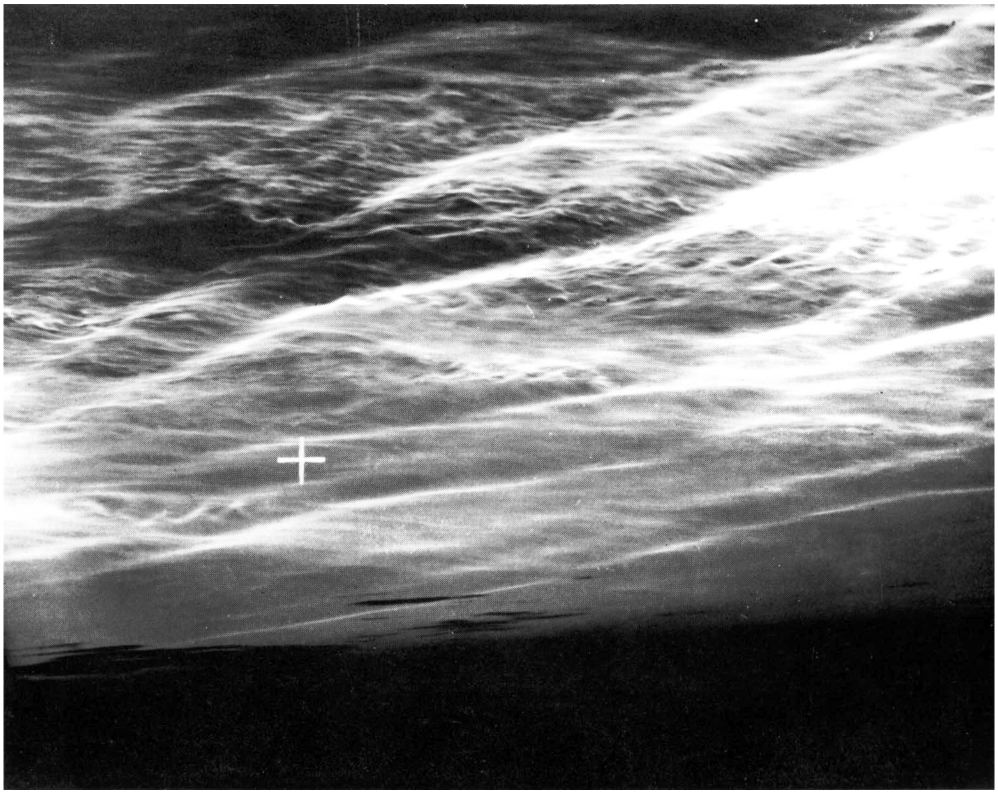

FIGURE 6 A noctilucent (night luminous) cloud photographed over Scandinavia. Reproduced from Witt (1957) with permission of Munksgaard International Publishers Ltd., Copenhagen, Denmark. Copyright 1957 by Munksgaard International Publishers Ltd.

Since all wave phenomena involve oscillatory behavior, it is illustrative to study a simple oscillation of the atmosphere before studying its wavelike behavior. Suppose we fill an imaginary, weightless balloon with air at a given height in the atmosphere. Since the balloon is weightless the parcel will stay where it is. Now suppose we gently displace it upward. Since atmospheric density decreases with height, the parcel will weigh more than the surrounding air and will sink back toward its original position. But it will overshoot the mark, only to be slowed down and eventually forced back up by buoyancy. The parcel will oscillate about its original spot with a frequency called the Brunt-Vaisalla frequency. In a more careful analysis, a real parcel of air will cool and expand as it goes upward and compress going downward, so this effect must be taken into account, but the result is changed only in detail. In the case of an atmosphere with a constant temperature, the oscillation period can be written in the form

$$P_{\text{air}} = (0.7\pi)\sqrt{\frac{H}{g}} \text{ seconds,}$$

where g is the gravitational constant for the Earth and H is the scale height of the atmosphere. In fact, H is the distance in which the air becomes thinner by about 30 percent, about 7 km near the surface. It is of some interest that the period of a pendulum is given by the expression

FIGURE 7 Highly distorted TMA trail released over Virginia from a sounding rocket. Reproduced from Kelley (1989) with permission of Academic Press, Inc.

$$P_p = 2\pi \sqrt{\frac{L}{g}} \text{ seconds,}$$

where L is the length of the pendulum. Since H depends on the temperature, the period of (atmospheric) oscillation also depends on the temperature and on the rate at which it changes with height. The Brunt-Vaisalla period for the Earth's atmosphere varies as a function of height and solar cycle conditions, ranging from a few minutes to about 15 minutes (see Figure 8).

Such a purely vertical oscillation does not propagate and corresponds to what would happen directly above a volcanic eruption as hot gases push upward on the ambient atmosphere. Far away, however, like the effect of a pebble thrown into a pond, a set of waves is observed to propagate outward from the disturbance with frequencies less than the buoyancy frequency and longer periods. For example, the disturbances from an earthquake shown earlier had periods of the order of about an hour. In general, buoyancy waves have periods longer than the Brunt-Vaisalla period and sound waves have periods shorter than those of buoyancy waves.

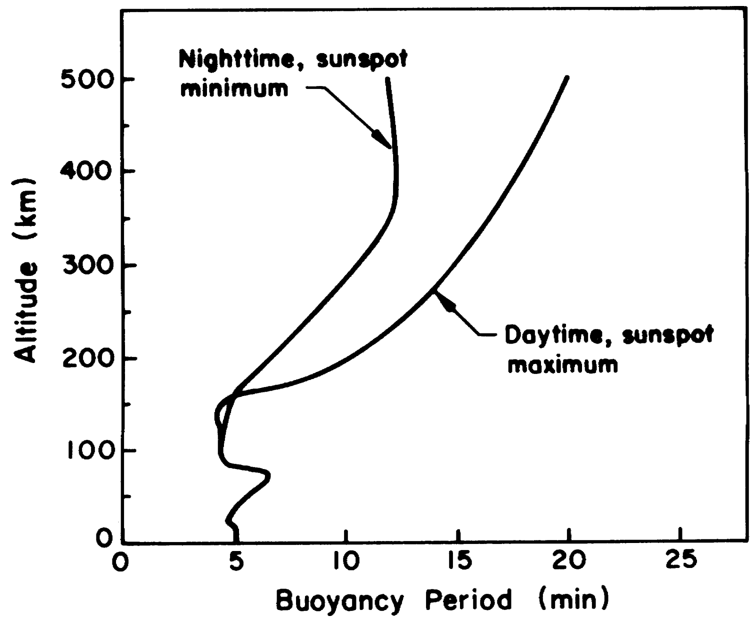

FIGURE 8 The free oscillation period of an atmospheric parcel as a function of height. Reproduced from Yeh and Liu (1974) with permission of the American Geophysical Union.

Hines provided a mathematical framework for the study of these waves by considering small changes in five quantities: pressure (p), temperature (T), density (ρ), horizontal velocity (v), and vertical velocity (w). Solving this problem thus requires five equations, which he accomplished by using two components of the momentum equation, the energy equation, the continuity equation, and the equation of state for the gas. The first four equations correspond, respectively, to the principles of momentum, energy, and mass conservation. Hines searched for solutions corresponding to a young physicist's best friend: a plane wave solution. In this formalism, $k_x = 2\pi/\lambda_x$, $k_z = 2\pi/\lambda_z$, and $\omega = 2\pi/P$, where λ_x is the horizontal wavelength, λ_z is the vertical wavelength, and P is the period of the wave. In the small-amplitude approximation, all products of small quantities are ignored (small times small is really small) and a set of linearized equations results. By using the perfect gas law, one of the variables is quickly eliminated, leaving four equations with four unknowns:

$$\frac{\partial\,(\delta\rho)}{\partial t} + \mathrm{U}\cdot\nabla\rho_0 + \rho_0\,\mathrm{U}\cdot\nabla = 0$$

$$\rho_0\,\frac{\partial v}{\partial t} + \frac{\partial\,(\delta p)}{\partial y} = 0$$

$$\rho_0\,\frac{\partial w}{\partial t} + \frac{\partial\,(\delta p)}{\partial z} + \delta\rho \mathrm{g} = 0$$

$$\frac{\partial\,(\delta p)}{\partial t} + \mathrm{U}\cdot\nabla p_0 - C_0^2\frac{\partial\,(\delta\rho)}{\partial t} - C_0^2\mathrm{U}\cdot\nabla\rho_0 = 0$$

where v and w are the components of the two-dimensional wind perturbation due to the wave; C_0 is the speed of sound; and, p_0 and ρ_0 are the atmospheric pressure and density, respectively, at the height of interest; the temperature variable has been eliminated by using the ideal gas law. The four-dimensional solution vector for the small perturbations is given by

$$\Phi = \begin{bmatrix} \delta\rho / \rho_0 \\ \delta p / p_0 \\ v \\ w \end{bmatrix}$$

A tricky way to find the solution of four equations with four unknowns is to use matrix notation. Then either the vector **F** is zero (there is no wave at all) or the determinant of the matrix is zero. For the equation set above, the matrix equation is

$$\begin{bmatrix} i\omega & 0 & -ik_y & -1/H - ik_z \\ 0 & -ik_y C_0^2 / \gamma & i\omega & 0 \\ g & -C_0^2 (1/H + ik_z)/\gamma & 0 & i\omega \\ -i\omega C_0^2 & -i\omega C_0^2 / \gamma & 0 & (\gamma - 1) g \end{bmatrix} \cdot \mathbf{F} = 0.$$

The solution after setting the determinant of the matrix equal to zero and after some algebra relates ω and k. For this set of equations, the result is

$$\omega^4 - \omega^2 C_0^2 (k_y^2 + k_z^2) + (\gamma - 1) g^2 k_y^2 + i\gamma g \omega^2 k_z = 0.$$

In these equations, i is the imaginary number, $\sqrt{-1}$ one of the more valuable contributions of mathematics to science. Among the many interesting properties of the solution of these equations, two stand out:

1. The amplitudes of the pressure, density, temperature, and velocity all increase with altitude (just as the observational evidence suggested). But since the kinetic energy per unit volume is $(1/2)\rho_0(v^2 + w^2)$, how can the solution satisfy conservation of energy if v and w are increasing drastically with height? The answer to this riddle is that the kinetic energy of the wave is more precisely $(1/2)\ \rho_0(z)[v^2(z) + w^2(z)]$; that is, both quantities change with height. Since ρ_0 decreases exponentially with height in a planetary atmosphere, $(v^2 + w^2)$ must *increase* in order to conserve energy. So rather than defying this law, the increasing wave amplitude is necessary to satisfy it. In fact, all the perturbation quantities vary as

$$\sim e^{+z/2H},$$

where $e = 2.71...$ and H is the scale height of the atmosphere ($H \sim 7$ to 15 km below about 200 km and grows to 50 km at the top of the thermosphere). Thus, as the background density decreases by a factor of about 3, every scale height $(v^2 + w^2)$ must increase by a factor of 3 just to compensate.

2. Another curious property of these waves is that as the energy propagates upward, the crests and troughs of the waves move downward (see Figure 9). Again, this was observed in the data and provided clear support of Hines' theory. To illustrate this feature provides a chance to once again showcase an important remote sensing tool—the incoherent scatter radar.

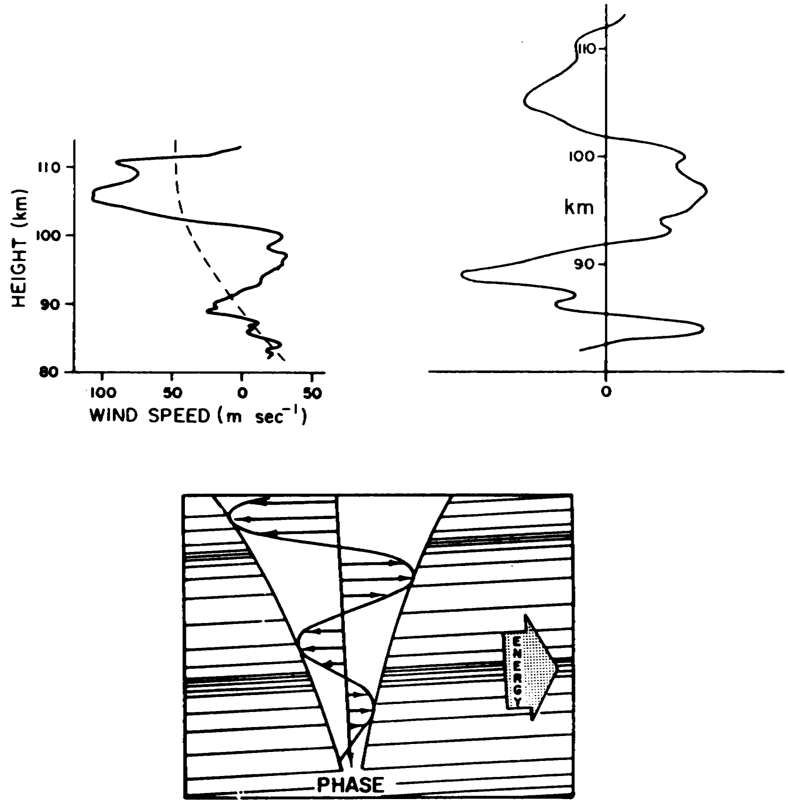

FIGURE 9 Real data and a cartoon showing the growth of atmospheric waves as they propagate upward (after Hines, 1974, as reprinted in Kelley, 1989, p. 228). Reproduced with permission of the American Geophysical Union.

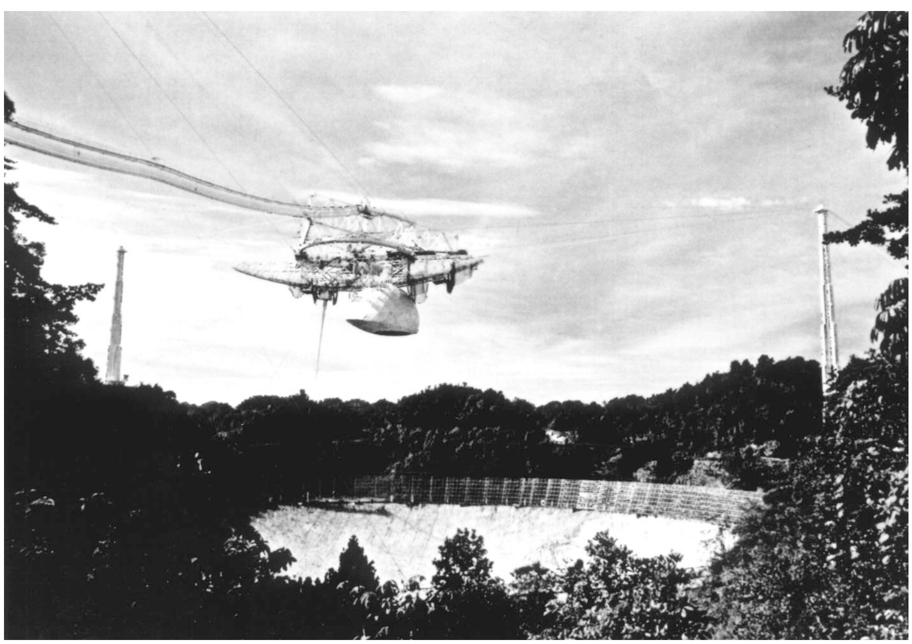

FIGURE 10 The Arecibo Observatory dish, the largest contiguous radio wave collection surface ever built. Image reproduced courtesy of Charles Harrington/Cornell University Photography from the NAIC 1997 Summer Student Program Announcement. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.

In the late 1950s, Bill Gordon, a professor at Cornell University, realized that a large enough radar could bounce a small signal from the ionosphere, even if the radio frequency was high enough to penetrate into space: that is, even though 99.99 percent of the radio wave signal would leave the Earth forever, some energy would "scatter back" incoherently. Each little electron—and I do mean little—would capture some of the energy and then radiate it back like a tiny antenna. Each electron's collection area is only 10^{-28} m^2, so not much energy was going to be captured. Why not make up for this problem by building a huge collecting surface back on the Earth? The numbers looked good, and a few years later the Arecibo Observatory of the National Astronomy and Ionosphere Center (NAIC) was completed in Arecibo, Puerto Rico (Figure 10). Thus, just about the time satellites were getting into space, so was remote sensing. With Arecibo, we could look through the ionospheric looking glass deep into space itself.

Being so tiny, electrons in the ionosphere can be pushed around easily by the wind. The ions are not so small, but electrical forces keep positive and negative charges together, and they all slosh back and forth like sand and small organisms in the surge of an ocean wave along the seafloor. This organization of the electrons makes the waves observable by radar as shown in the Arecibo data in Figure 11. The downward slant of the oscillations is unmistakable (Djuth et al., 1997). The waves only seem to be coming down, since the energy is going upward just as Hines predicted.

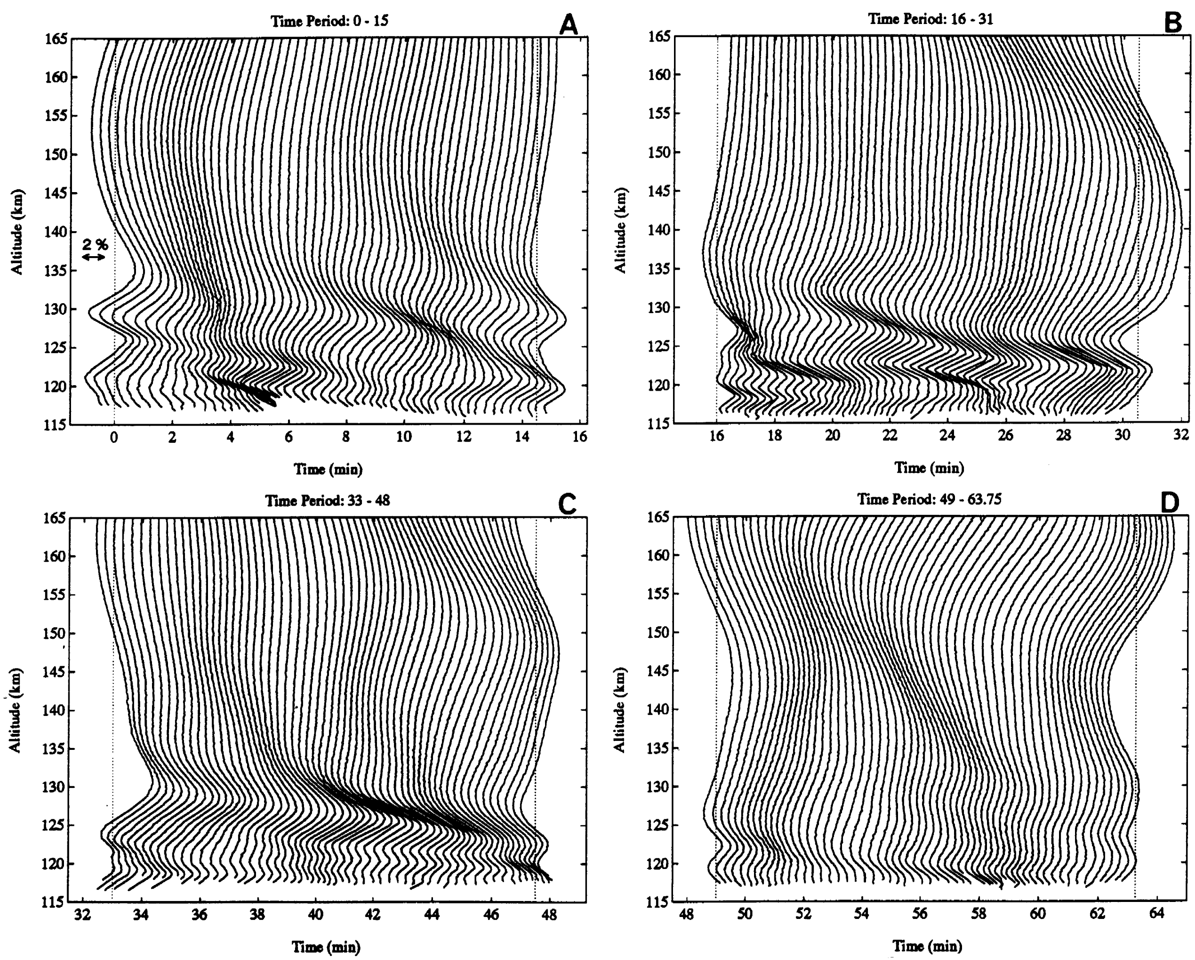

FIGURE 11 High-resolution profiles of ionospheric content versus time. Reproduced from Djuth et al. (1997) with permission of the American Geophysical Union.

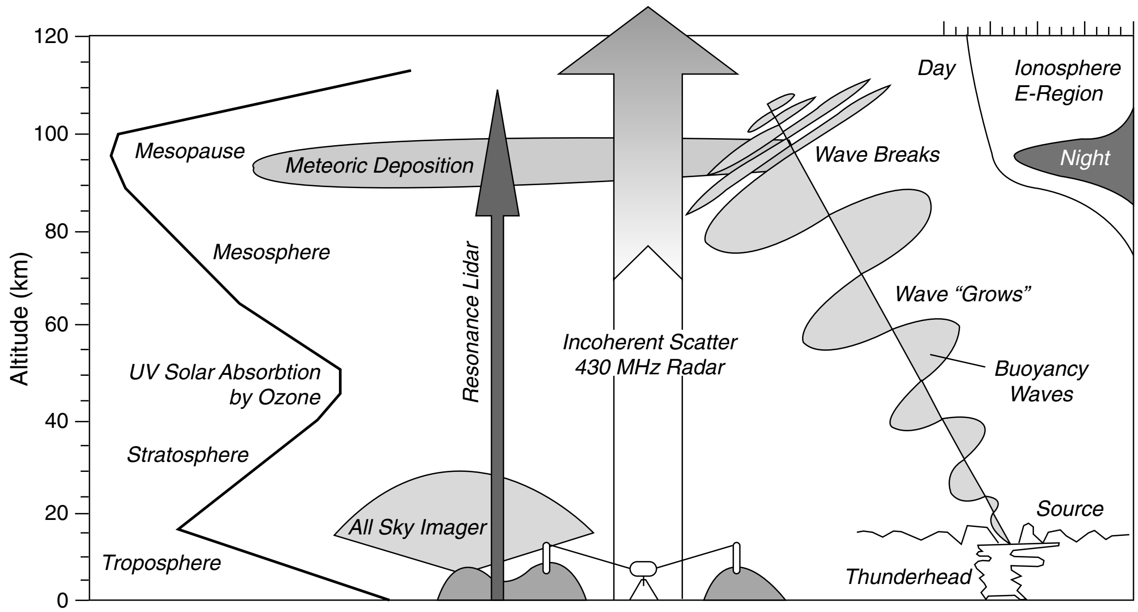

FIGURE 12 A cartoon showing some of the methods used to study the upper atmosphere over Arecibo, Puerto Rico. Courtesy of Paul Castleberg, Toyon Research Corporation, Goleta, California.

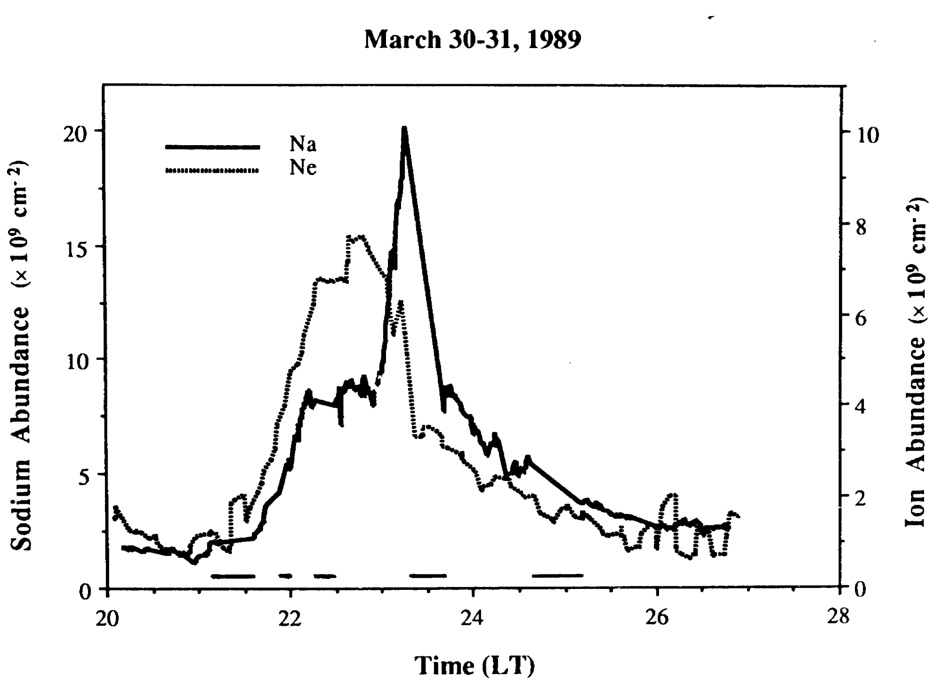

FIGURE 13 Sudden intense layers of meteoric atoms sometimes appear out of "nowhere" and can be illuminated by lasers from the ground. Here, the electron density of neon (Ne) was detected by the Arecibo radar and the sodium atoms (Na) by lidar. Reproduced from Mathews et al. (1993) with permission of the American Geophysical Union.

A wave cannot grow forever, and Hines' small-amplitude approximation must break down. In the case of a surface water wave, it breaks when the velocity of the water "inside the wave" is faster than the speed of the wave itself. As the wave approaches the beach and necessarily slows down to zero, this condition must occur, and the wave steepens, overturns, and breaks on the shore. In the case of an internal wave, it does not have to slow down to break since the velocity of the air "inside the wave" is getting higher and higher as the amplitude increases with altitude. Eventually, the internal oscillating wave velocity exceeds the wave speed and it must break. Most of the energy and momentum of the wave, in both cases, is then deposited in the background medium. This has important implications for the atmosphere since the turbulence generated by breaking waves contributes to complete mixing of the air up to the very base of space.

NEW REMOTE SENSING SCHEMES

Making these wave phenomena manifest by using incoherent scatter radar techniques or using TMA and meteor trails is not the only way to detect upper atmospheric waves (Figure 12). Modern technology has made the study of these waves possible in many ways. The vapor debris from burned-out meteors allows these waves to be detected not only visually, but also as a target for powerful lasers on the Earth's surface. Such lasers can be tuned to the resonant frequency of, say, sodium or iron from meteors, and when reradiated, the metal atom layers can become visible to photomultipliers. The strength of the returned signal is proportional to the density of the atoms in the region and can be used to track their response to passing waves.

The atom layers display complicated height changes in response to passing waves. Some very sophisticated systems can also measure the Doppler spread of the returning signal, yielding the temperature fluctuations in the wave, a more meaningful and direct measure of the wave amplitude than the height change. Remarkably, even the wind can be determined by the Doppler shift effect, a change in frequency of one part in 10^8 or better.

Sometimes the layers appear to grow out of the background with remarkable speed and strength. First dubbed Sudden Sodium Layers (Figure 13), these rapid changes in space and/or time are quite remarkable and not yet well understood. They are found in iron and potassium (K) as well as sodium (Na) and are now called Sudden Atom Layers (SAL). There seems to be some relationship between atoms and electrons in the ionosphere, but as yet we do not know what it is.

The properties of these metal atom layers have become of sufficient interest to warrant National Aeronautics and Space Administration (NASA) rocket flights through them. One of the planned payloads is shown schematically in Figure 14. The plan is to use ground-based lidars at the Arecibo Observatory in Puerto Rico to detect the SAL and then to fly payload instruments through them.

Instruments on board will provide vertical profiles of the atom layers using their natural optical emissions as well as resonant scatter from an Na-K lamp on board; will measure the plasma density and electric field profiles as well as the density of positive and negative ions; and will measure the small dust particles thought to exist in the upper atmosphere. We hope that these flights will yield more information on the source of atom layers.

Although very powerful, these methods result only in vertical cuts through the region. With modern cameras, however, it has also become possible to take two-dimensional pictures of the region using photons emitted in the chemical reactions that occur in thin layers of the atmosphere. For example, sequences of images such as the ones shown in Figure 15 can be used to trace the motion of waves across the sky. Here, a wall of light is seen to propagate across the night sky with ripples trailing behind, just like waves behind a boat; they move at the same speed as the disturbance.

The direction from which the waves arrive can yield some information on their sources, which by and large remain a mystery. Are the waves caused by weather fronts? Are their sources isotropic, and

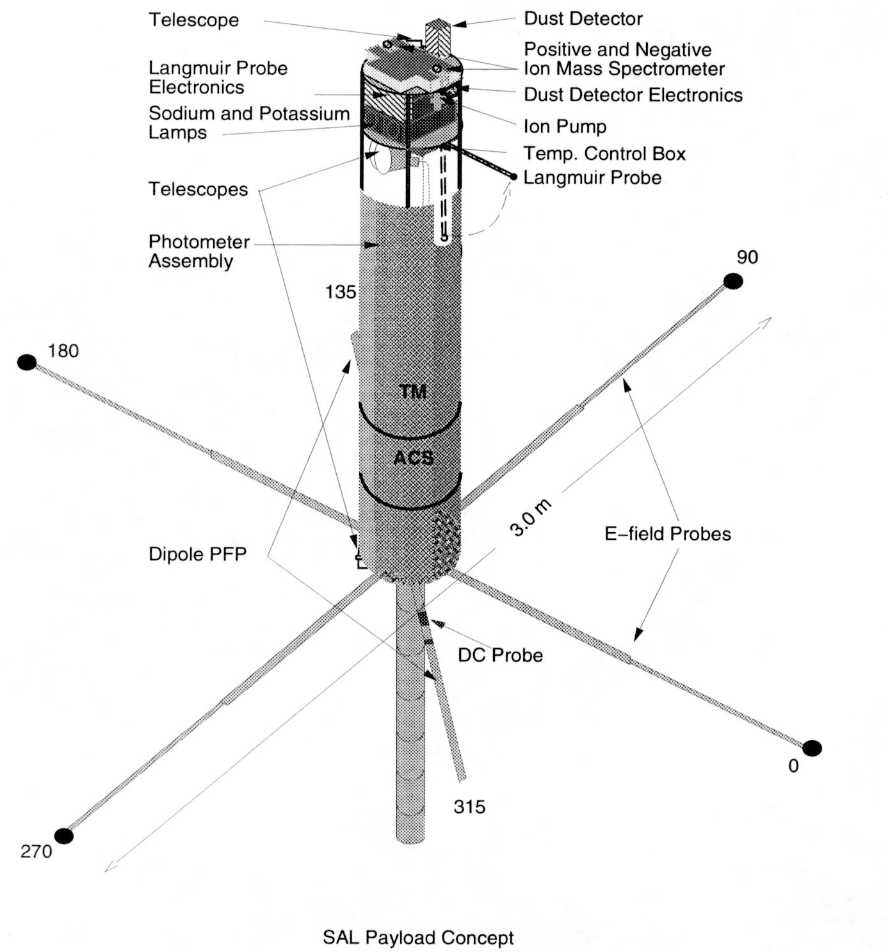

FIGURE 14 A schematic diagram of Cornell University's Sudden Atom Layer rocket. Coinvestigators from the University of New Hampshire, Utah State University, Goddard Space Flight Center, Aerospace Corporation, and the Naval Research Laboratory have contributed instruments.

do only some get through to the upper atmosphere? Or do they have a preferred direction from the beginning? We simply do not know.

We also do not fully understand how the waves break and return their energy and momentum to the atmosphere, although this is perhaps the most important question of all. Since waves grow exponentially with height, even the most insignificant wave must break eventually or be absorbed back into the flow when its phase velocity matches the wind, but in either case the wave energy and momentum become part of the local budget of these important parameters. A number of analysis schemes are being applied to this problem, many of which involve spectral analysis of data sets. One interesting approach has been to make two-dimensional spectra of the waves detected in the airglow images. An example in which two monochromatic waves cross is given in Figure 16. The analysis clearly shows two separate peaks corresponding to two different directions and wavelengths (Taylor and Garcia, 1995). Once the peaks are identified they can be emphasized by digital filters centered on the peaks and the crossing pattern reconstructed, as shown at the bottom right. Sometimes such an analysis reveals more complicated patterns involving what seem to be nonlinear wave behavior that may shed light on wave-breaking processes.

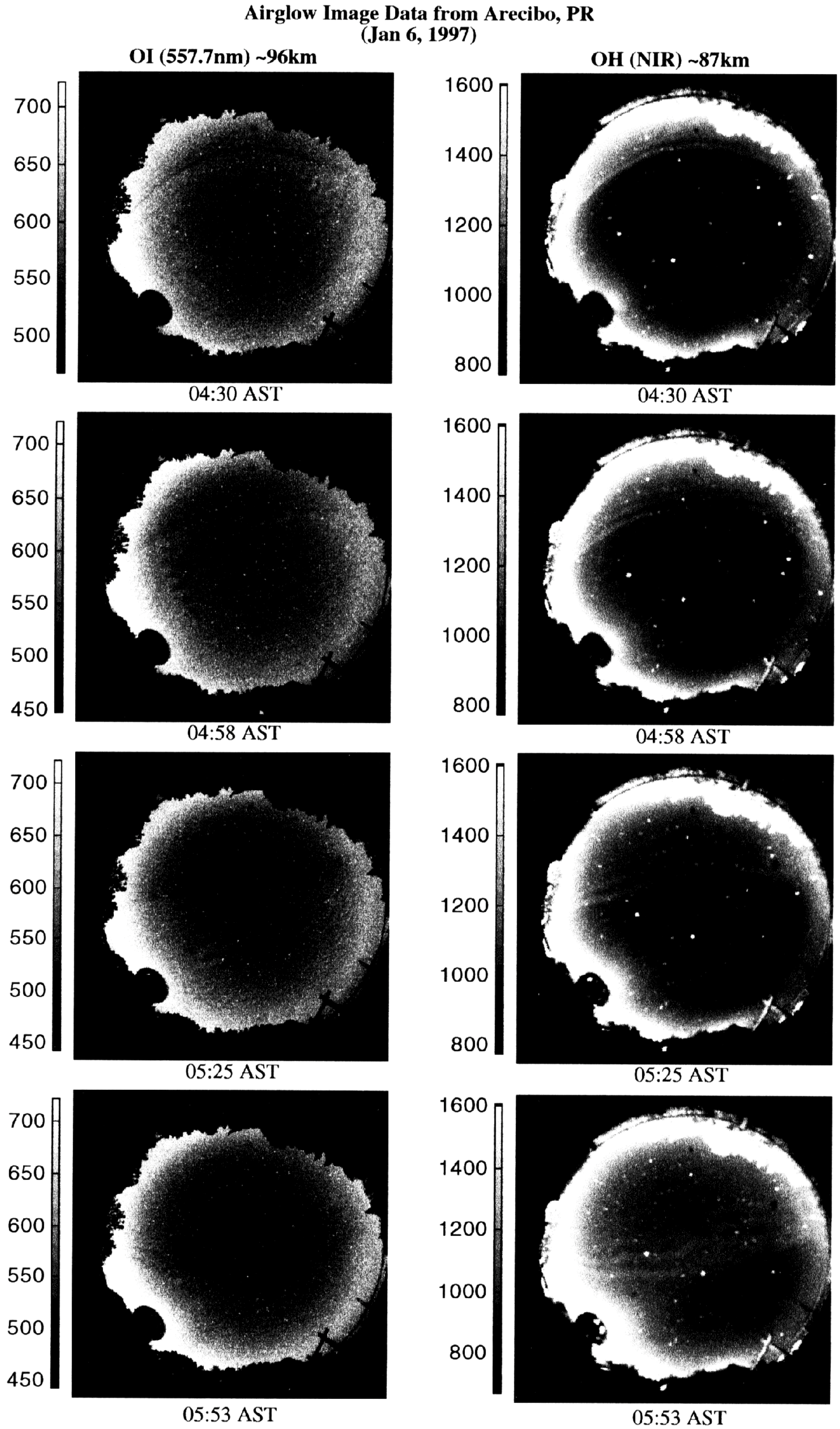

FIGURE 15 Sequential photos of emission from chemical reactions in the mesosphere make waves visible. Courtesy of Francisco J. Garcia, graduate student, School of Electrical Engineering, Cornell University.

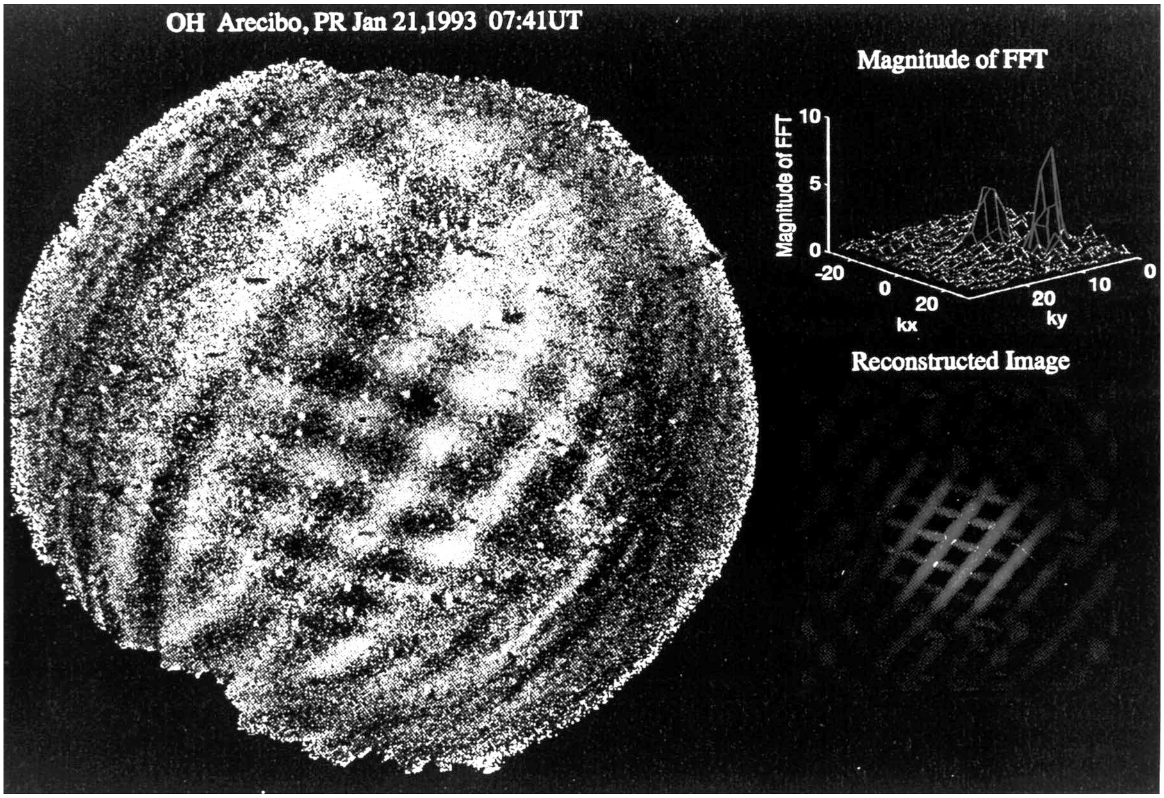

FIGURE 16 Crossing waves revealed by light emissions from the mesosphere. Reproduced from Taylor and Garcia (1995) with permission of the American Geophysical Union.

A sequence of photos thus allows not only the horizontal wavelength to be found but also the horizontal phase velocity and, of course, the period. This leaves only the vertical wavelength as an unknown. Since airglow emissions come from a layer where conditions are just right for the chemistry, the only information we obtain is that the wavelength cannot be much smaller than the layer thickness or the image would be smeared out. So, there is still plenty of experimental work to be done, but some progress has been made. Most advances are likely to involve measurements from more than one instrument at a time since each has its own limitations.

In the next decade, enormous progress will occur in remote sensing of the atmosphere. NASA plans a Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) mission, which will look down on the Earth's atmosphere from above, in addition to several Department of Defense (DOD) satellites such as the Advanced Resolution and Global Observation Satellite (ARGOS) and those in the Defense Meteorological Satellite Program (DMSP). Already, signals from the global positioning satellites, which must traverse the ionosphere on their way to the Earth, are being used for space weather observations as part of the National Space Weather Program. More observation points are being built on the Earth. The National Science Foundation and Canada are jointly building an observatory in the Canadian Arctic, the Japanese and Indonesians are planning an equatorial station, the Indians have a world-class facility, and the Europeans have extended their high-latitude Scandinavian observatory system as far north as Spitzbergen. This will increase the number of major Earth-bound space weather observatories to 10, giving Spaceship Earth a reasonable number of portholes through which to view its surrounding environment.

Two important specific consequences of internal waves are treated next, one dealing with global change and the upper atmosphere, and one with space weather.

A WAVE-DRIVEN REFRIGERATOR

The very existence of the noctilucent clouds described earlier reveals a fascinating aspect of the Earth's upper atmosphere, which can be understood only by including the effects of internal waves. First, we reiterate the surprising fact that the summer polar atmosphere is truly the coldest place on Earth, with reported temperatures sometimes less than 100 K (-173 degrees Celsius). A scatter plot illustrating this compares rocket-borne temperature measurements in winter and summer over Norway in Figure 17.

The summer mesosphere is really cold. Most of the air we breathe is nitrogen, which turns to liquid at 77 K. The stark difference between north and south is evident. The summer atmosphere is 100 K colder than in the winter, even though the sun shines on this region of the sky virtually continuously in summer and hardly at all in winter! How does this happen?

This refrigeration process is now thought to be driven by the transport of momentum from the lower atmosphere to the upper atmosphere by exactly those waves of interest here, waves that propagate upward from the dense lower atmosphere, grow in amplitude, and eventually break in the mesosphere much like a water wave on a beach. This analogy with a water wave is actually quite illuminating.

Swimmers are often warned about rapid longshore currents, which can sweep them parallel to the shore very rapidly. The direction of the current is the same as the projected direction of incoming waves parallel to the shore (Figure 18). Most of the momentum and energy of the waves is dissipated in the turbulence and froth of the breaking waves, but a fraction is converted into an average velocity of the water along the shore. The swimmer is carried along with it, as is some of the sand. This river

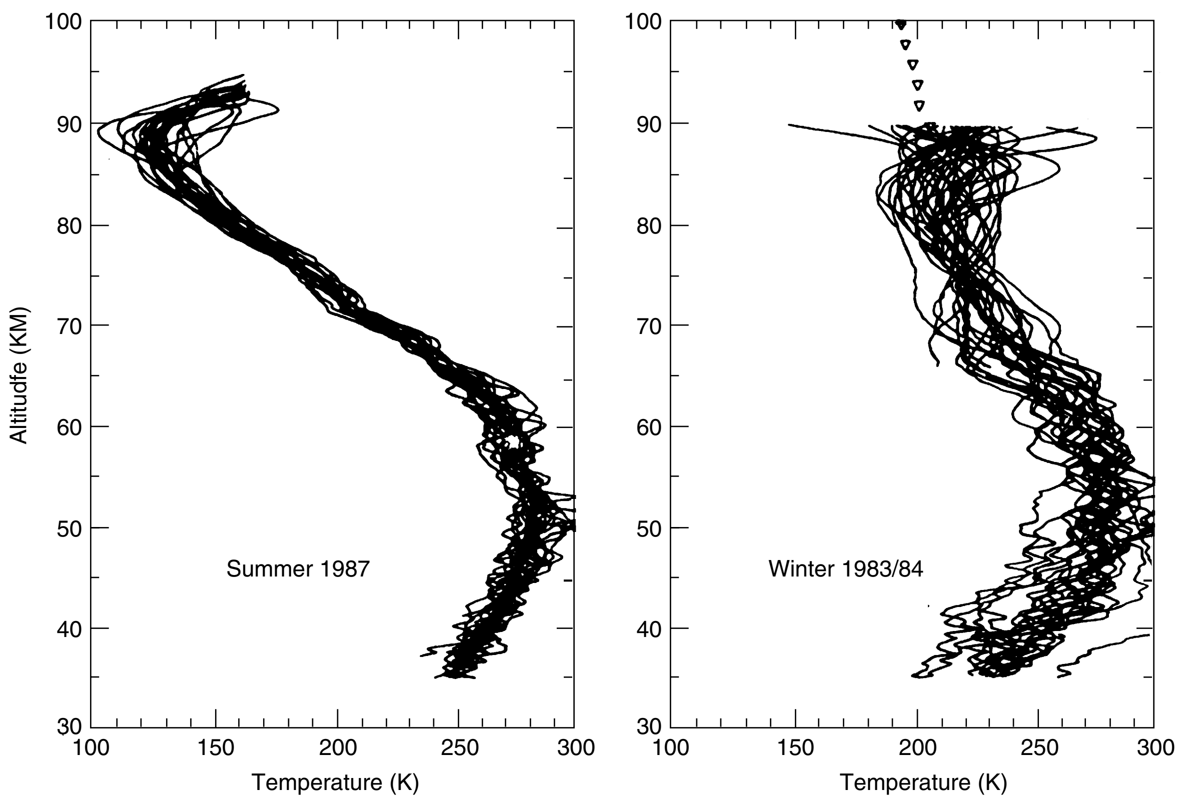

FIGURE 17 Profiles of atmospheric temperature measured by using small rockets launched over Norway. Reproduced from von Zahn and Meyer (1989) with permission of the American Geophysical Union.

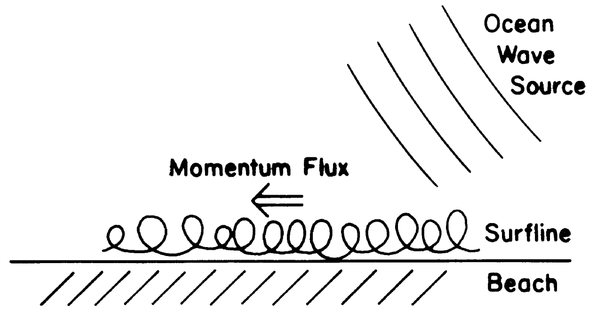

FIGURE 18 Ocean waves breaking in the surf line can deposit momentum in the region and drive a net current down the beach.

of sand shapes the beaches and sand spits all over the world. It is remarkable that distant storms can shape the beaches and move objects in the surf line hundreds of miles away simply through the waves they generate.

However, this is the same type of process that drives the circulation pattern of the Earth's mesosphere, a transport of momentum by waves generated in one portion of the atmosphere and absorbed in another. On average, however, one would expect that these waves would have no preferred direction; hence, it is not obvious that any net momentum would be transferred to the upper atmosphere. This objection is resolved by noting that atmospheric wave dynamics have yet another curious aspect that requires a brief explanation of the Doppler shift phenomenon. Most people have experienced the change in tone of an ambulance siren as it first approaches, then recedes from, the observer, the high pitch gradually descending to a low one. This phenomenon is due to the Doppler effect, a shift in frequency due to relative motion. Recall now the earlier discussion concerning waves observed from a moving boat. On the boat, the waves stand still; they are Doppler shifted to zero frequency, moving with the source. Now suppose an internal wave is launched from a thunderstorm or a cold front. It will have some velocity with respect to the Earth, but if the wind speed at the same higher altitude is in the same direction as the wave, as far as air parcels are concerned, the wave will be Doppler shifted to lower frequency. If at some height the wind speed exactly equals the wave speed, the wave is Doppler shifted to zero and it simply vanishes like the smile on the Cheshire cat.

When a gravity wave propagates upward into the jet stream, the local fluid perceives it at a Doppler-shifted frequency, lower if the wave travels in the same direction and higher if the two velocities are opposite. If the Doppler shift is so severe that the wave becomes stationary in the wind frame, the wave merely becomes part of the flow and is absorbed in it. The oppositely directed waves simply go through into the mesosphere. The result is a directional filter that, when the waves break as they must, results in a net momentum source in the upper atmosphere (Figure 19). Just like the sand in the surf line, the mesosphere is pushed around by distant storms.

Because of the dominant east-west (zonal) character of the jet stream in the Earth's stratosphere, this momentum source operates in the zonal (east-west) direction and causes the summer upper stratosphere and mesosphere to spin up relative to the rotating planet and the winter region to spin down. This additional angular momentum source is compensated by an equatorward shift of the fluid in the summer and a poleward shift in the winter. Such a shift is in turn accompanied by an upwelling in the center of the summer vortex and a downward motion in the winter. The upwelling is a source of adiabatic cooling, whereas the downward flow heats the mesosphere, thus creating a 100 K temperature difference and incredibly cold temperatures in the summer, a wave-driven refrigerator.

This process leads to the production of the noctilucent clouds illustrated earlier. Remarkably, no such clouds were reported before 1885 and they seem to be forming much more often throughout this

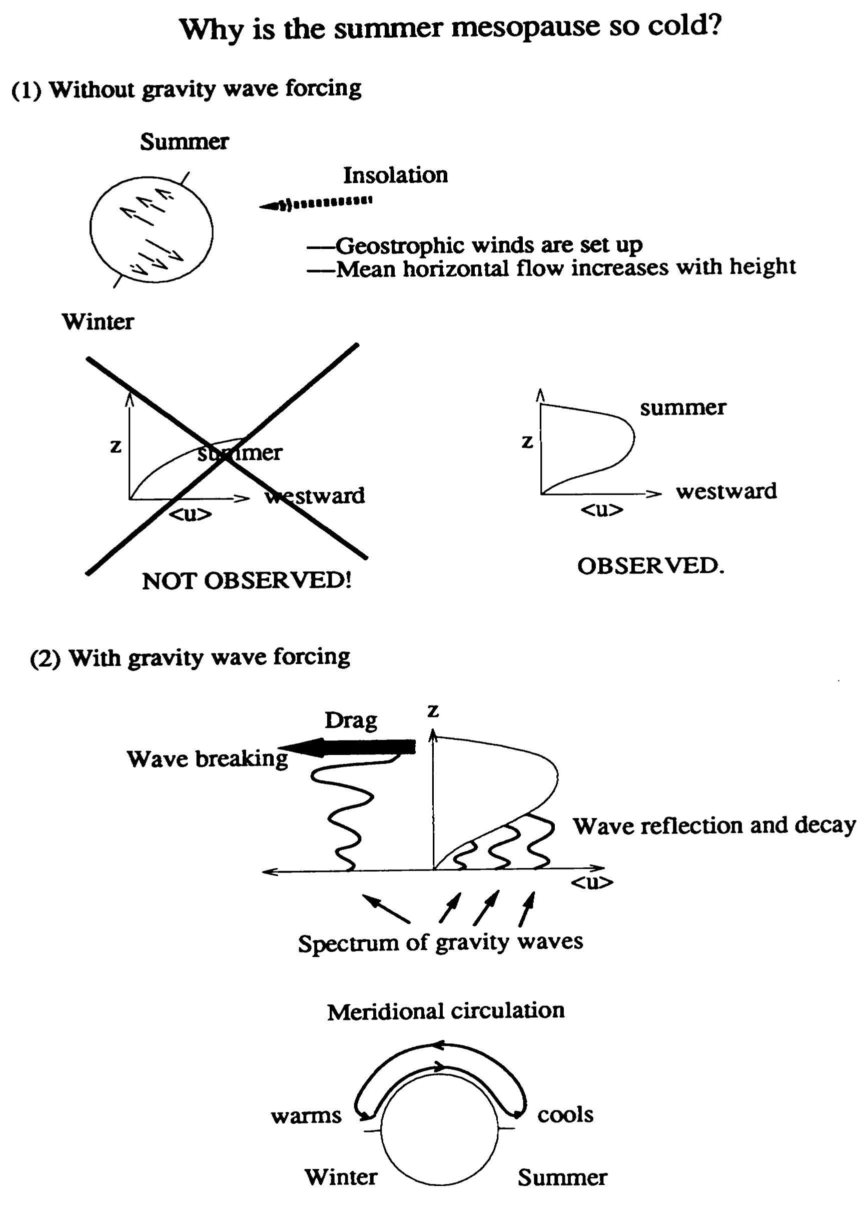

FIGURE 19 The jet stream absorbs waves in one direction but allows them to pass in the opposite. This creates a net momentum source for atmospheric layers above it. Reproduced courtesy of John Cho, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology.

century. Two theories have been proffered for this increasing cloudiness, both involving global atmospheric change. One is that methane (CH_4) is increasing the amount of hydrogen available to form water vapor and, eventually, ice for the ice clouds. The primary human source of methane is agriculture. The second idea is that as the lower thermosphere warms up (global warming), the upper atmosphere cools. Both processes may be contributing to the increasing cloudiness (Thomas, 1996), and a lively debate is under way concerning these two possibilities. In either case, the whole topic is likely to remain an interesting one for years to come.

RELATIONSHIP OF INTERNAL WAVES TO SPACE WEATHER

Since internal waves find their way into the near space region of the Earth, they are a potential contributor to space weather. This emerging field is still defining itself, but from a practical viewpoint it can be described as those aspects of upper atmospheric and space plasma processes that affect human endeavors. This is, of course, only a subset of the phenomenon that attracts the interest of space scientists, but it includes those processes having some relevance to technological systems as we enter the new millennium.

The two main sources of space weather are the Earth's cool, but dense, lower atmosphere and the Sun's million-degree but tenuous upper atmosphere (Kelley, 1989). It is a tribute to the vast power of the solar atmosphere that even in the near vacuum of its solar wind extension to the Earth's orbit, with a shrug of its mighty shoulders it can turn out the lights in, say, the entire Canadian province of Quebec. To paraphrase some lines from Star Trek: "Spock, if this magnetic storm keeps up much longer I don't think the [magnetic] shields will hold. We're likely to have a power surge at any time . . . !" This exact scenario happened in 1989 when ground-induced currents (GICs) created havoc in Quebec and very nearly throughout the entire eastern seaboard of North America. Solar wind-magnetospheric interactions are also responsible for the "killer electrons" that have wiped out numerous expensive communication satellites at geosynchronous orbit, and solar protons will make Mars missions and life aboard the space station dangerous indeed.

Another important space weather problem involves the effect of the Earth's ionosphere on radio waves traversing it. In this arena, gravity waves radiated by the dense lower atmosphere play a key role. The aurora, another solar wind-magnetospheric interaction effect, certainly creates its own exceedingly disturbed ionosphere, but its location at high latitudes much reduces its impact on humanity. However, severe space weather occurs in the equatorial and low-latitude zones as well, and much of it is initiated by gravity waves.

Two factors dominating the technological effects of low- and temperate-latitude space weather are navigational or positional errors and communication disruptions. In the former case we refer to the Global Positioning System (GPS), which is becoming ever more important in the commercial arena. At present, simple ionospheric models allow climatological corrections to be made for the phase delay associated with the ionospheric plasma content. More sophisticated models are in the offing, and there is some hope that GPS data can eventually mimic the vast array of weather stations on the Earth. If so, both nowcasts and, eventually, forecasts will make coping with global-scale space weather more tractable and perhaps even more predictable. Mesoscale conditions are another matter, however, and it is in this arena that gravity waves play a role.

A night in the life of the ionosphere over the Caribbean is illustrated in Figure 20 by using contour plots of the ionospheric content. The profiles show that the ionosphere over Puerto Rico sometimes bobs up and down in a distinctive wavelike manner.

It has been known for decades that such waves exist, and in fact, these "traveling ionospheric disturbances" provided the first evidence for internal wave interactions with the ionospheric plasma. As these waves buffet our plasma blanket, they easily push it up and down along the direction of the magnetic field lines since there is essentially no resistance in that direction. Winds upward of 100 km per hour blowing in the same direction for an hour or more have a huge impact. Vast rolls of plasma surge in a slow-motion dance across the sky, raising the plasma content in some directions and lowering it in others. The presence or absence of plasma alternately slows down or speeds up the velocity of radio waves from their usual average. Since the GPS depends upon knowing the speed of the radio waves, space weather becomes a vital issue.

As these waves propagate across the sky, regions of differing total electron content crossing the field of view of a geostationary satellite exhibit the same periodicity as waves do in an Earth-fixed reference frame. From a moving platform such as the GPS, however, the frequency is Doppler shifted, sometimes to higher values. In the example in Figure 21, waves crossing over the Caribbean created variations in the signal delay from a GPS satellite with about a 20-minute period (Beach et al., 1997). If the relative motion is the opposite, however, the Doppler shift can bring the frequency to zero and the ionospheric effect could exist for a long time. As discussed below, sometimes ionospheric weather causes satellite signals to twinkle just like stars, and space weather can become a problem.

During the day these ionospheric waves usually roll in from the poleward direction in either hemisphere, moving at speeds ranging from several tens to several hundreds of meters per second. Their source is thought to be the auroral zone, where intense heating of the upper atmosphere can occur due to the aurora. This direction is the "path of least resistance" for internal waves since equatorward propagation also means that the bulk of the wave-induced plasma motion is parallel to the magnetic field lines, the near-frictionless direction. This can be understood as follows. When a neutral atom strikes an ion in the direction parallel to the magnetic field, the ion just tags along for the ride. But when a neutral atom strikes an ion in any other direction, it can only circle around the magnetic field. In effect, the magnetic force "stops" the ion, which then must wait for a neutral collision to get another tiny nudge across the magnetic field. The plasma essentially never accelerates to the wind speed and always acts as a break on it, the so-called ion drag effect. The upshot is that during the day, even without a poleward source, the equatorward direction is preferred for two reasons: (1) the aurora is near the poles and is a major source of waves, and (2) this is the path along which there is a minimum in wave damping.

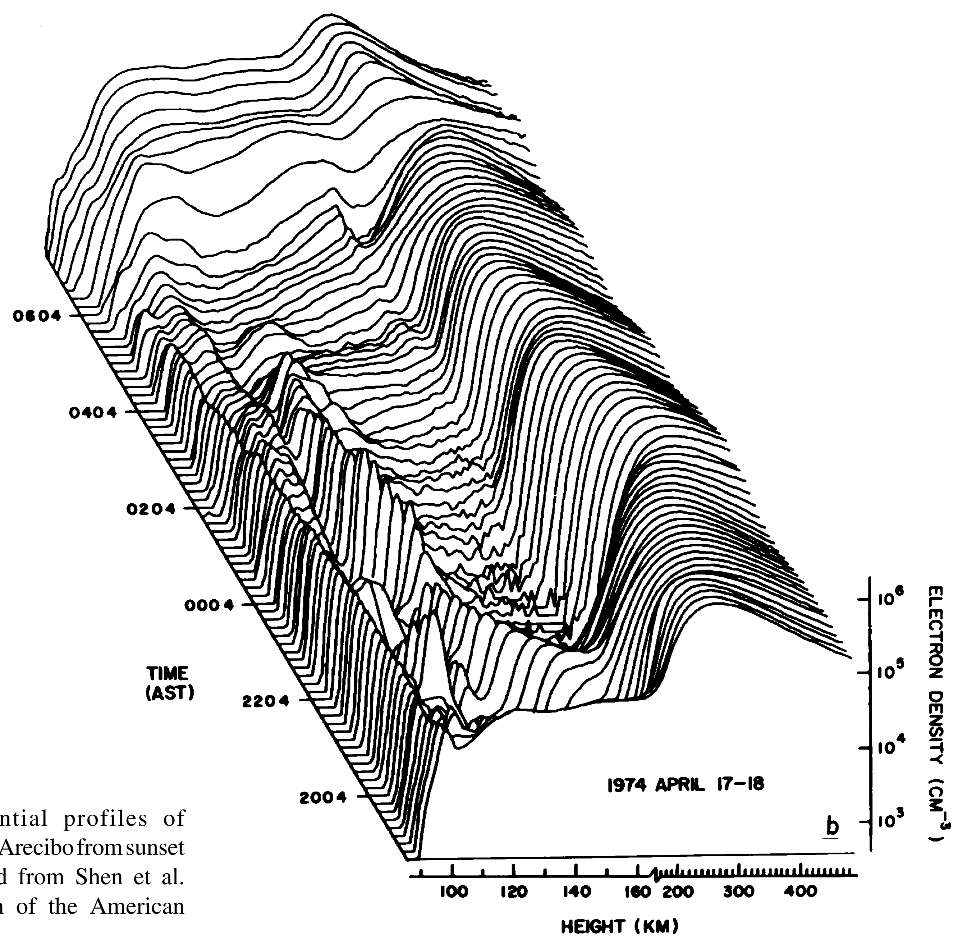

FIGURE 20 Sequential profiles of ionospheric content over Arecibo from sunset to sunrise. Reproduced from Shen et al. (1976) with permission of the American Geophysical Union.

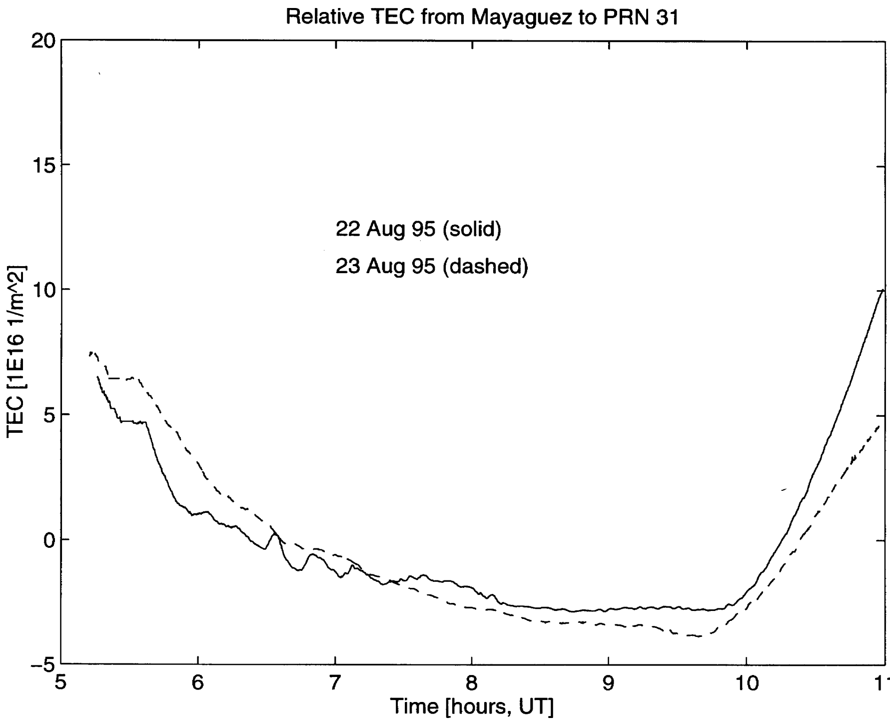

FIGURE 21 Total electron content (TEC) between the Earth and the GPS satellite for a night with and without internal wave activity. Reproduced from Beach et al. (1997) with permission of the American Geophysical Union.

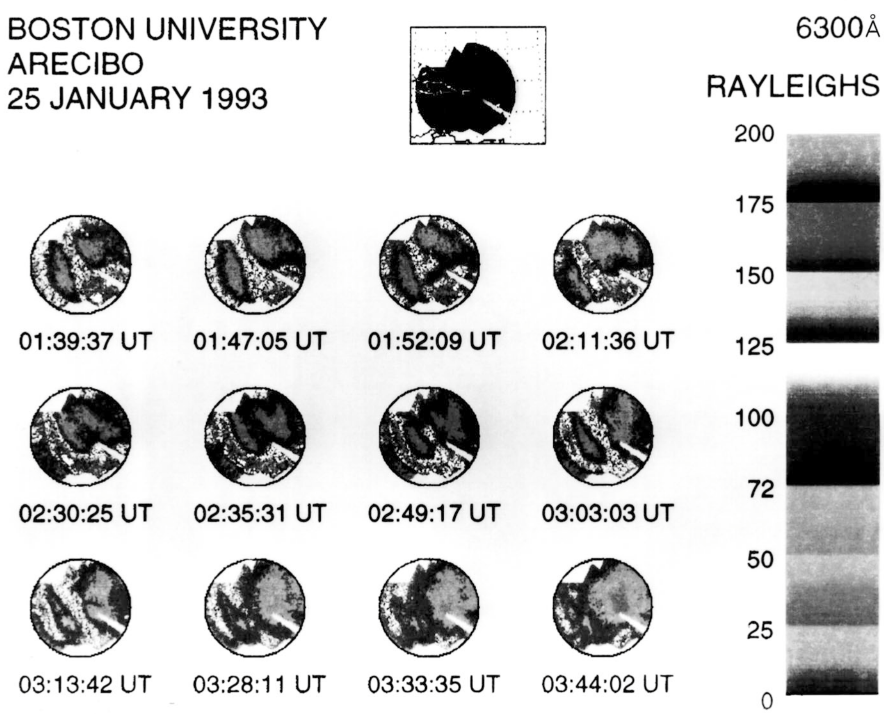

FIGURE 22 Airglow emissions from the ionosphere make huge wavelike oscillations visible from the ground by using sensitive cameras. Reproduced from Mendillo et al. (1997) with permission of the American Geophysical Union.

At night, the physics is more interesting. In azimuthal-of-arrival plots for TIDs, another arrival maximum pops up in the east-west direction. For this case, neither the auroral zone source nor the minimum ion drag seems to be relevant, at least at first glance. However, at night these waves may be photographed by using the modern all-sky imaging methods discussed above, and remote sensing has offered some chance to understand this unusual disturbance (see Figure 22). In this case the photons come from an ion chemistry reaction in which an ionospheric electron recombines with an ion-releasing red light. Unfortunately (or perhaps, fortunately), the red light is too faint for human perception or the night sky would look like a continuous sunset. Indeed, in 1993, horizon-to-horizon bands of increased and decreased red emissions were recorded on several nights in January of that year (Mendillo et al., 1997).

These waves were found not only to have the usual properties of gravity waves but to exhibit an electrical component as well (Kelley and Miller, 1997). One wave packet studied simultaneously with the imager and the Arecibo radar had a nearly 1,000-volt potential across the wave fronts, giving rise to the term "electrobuoyancy wave." We know that steady winds and tides can create electrical potentials in the ionosphere by the dynamo effect, but the electric field measured in this particular wave was larger than this limit, and some examples have been reported that are an order of magnitude larger. What is going on? Plasma physics!

The term "plasma" refers to the fourth state of matter (solid, liquid, gas, plasma) corresponding to the ionized state (see the *Encyclopedia Britannica* article in the reading list). Most of the universe is plasma, in fact, and for about the last 50 years, physicists and engineers have been learning quite a lot about such media. Space plasma physics applies this discipline to the study of plasmas such as those in the Earth's ionosphere.

Before taking on a plasma physical description of the mid-latitude zone, we move first to a more spectacular space weather system that has inspired much more study and is better understood: the equatorial zone, called by the generic term "equatorial spread F." Here, towering ionospheric convection storms very similar to thunderstorms erupt after sunset and create palpable havoc with communication systems. In the last, and presumably every, solar cycle, even at the relatively safe frequencies used by the GPS signals traversing the ionosphere will wax and wane by a factor of 100 during many of these storms. In such storms, not only is the plasma moved around but it also becomes highly turbulent in the process. This turbulence creates the degradation of transionospheric satellite signals and extends in scale size from hundreds of kilometers down to 10 cm or smaller, more than 6 orders of magnitude (Figure 23).

The weather first deteriorates on the bottomside of the ionosphere and is often confined there, where it has little effect on satellite systems. But even in this relatively benign form, severe effects occur on high-frequency (HF) systems using the ionosphere as a mirror. During so-called bottomside equatorial spread F conditions, this mirror becomes very distorted and is in motion as well. Over-the-horizon (OTH) radars, for example, can see the equatorial ionosphere from halfway around the world. If any space weather event occurs in the field of view, the resulting radar clutter effectively wipes out any signal source.

Such paths can be affected in two ways. The most severe effects occur when some path intersects the turbulent plasma in such a way that the ray path is perpendicular to the magnetic field. Then the irregularities, which are highly magnetic and field aligned, act like efficient secondary antennas, radiating the signal back at the radar. A huge backscatter cross section results, and even though only a small fraction of the ionosphere has the necessary geometrical relationship, severe clutter arises. On other paths, the plasma builds up phase variations due to the irregular plasma medium along its propagation path. By the time the waves reflect one or two times off the ionosphere and the sea or land surface, amplitude variations build up, creating clutter. The effect is similar to the twinkling of stars in

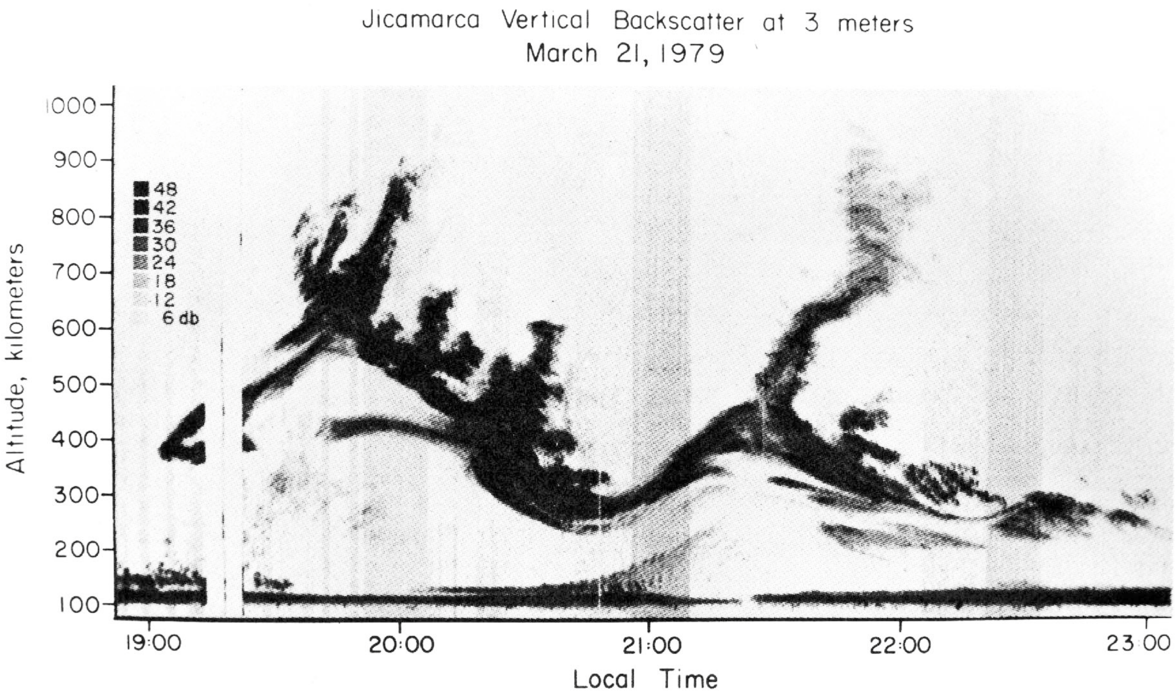

FIGURE 23 A space weather radar map provided by the Jicamarca Radio Observatory near Lima, Peru, shows that turbulence can be generated for hours over height ranges of hundreds of kilometers (Kelley et al., 1981). Reproduced from Kelley (1989) with permission of Academic Press, Inc.

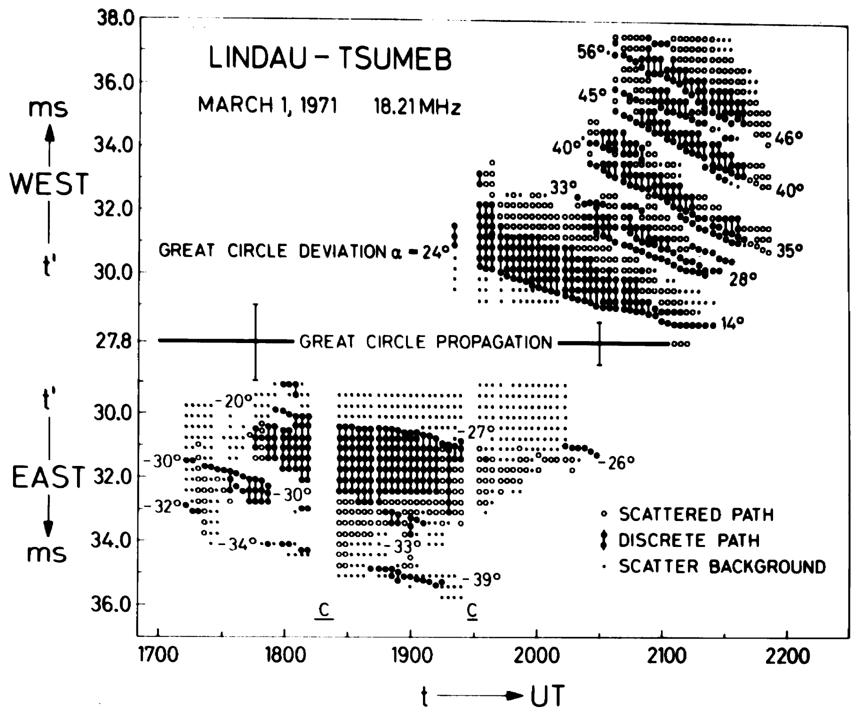

FIGURE 24 Signals sent from Europe to Africa by bouncing off the ionosphere often exhibit long delays due to regular wavelike distortions of the bottom of the ionosphere (Röttger, 1981). Reproduced from Kelley (1989) with permission of Academic Press, Inc.

the Earth's turbulent atmosphere. This space weather effect on OTH systems is essentially identical to the effect of ionospheric turbulence on transionospheric radio wave signals from satellites to the Earth.

To understand the origins of this intense space weather, a classic experiment was performed in the early 1970s using an HF transmitter in Europe and a receiving system in Africa (Röttger, 1981; Figure 24). Signals were found not only along the expected great circle path due to a simple mirror reflection, but from numerous large angles east and west of that path as well. Furthermore, these "off great circle paths" were located at periodic spatial separations a few hundred kilometers apart, exactly the separation that would occur if gravity waves created undulations in the bottom of the ionosphere that could bend radio waves back toward the receiver from the side.

This type of lazy undulation of the ionosphere creates the sort of smooth variations in total electron content discussed above in the GPS context and shown earlier in the Arecibo data and the all-sky images. Furthermore, they are now thought by many to provide the conditions needed to create the most severe weather in the Earth's near-space environment: the towering plume structures characterizing equatorial spread F.

A set of images can be used to show how the process works (Figure 25). After sunset, the dense lower ionosphere disappears and an internal wave begins to make its presence known on the bottom of the ionosphere where some wiggles arise in the east-west direction. With the passage of several tens of minutes these wiggles grow, extracting energy from the gravitational potential of the ionospheric slab, exactly (well, almost exactly) as a child's toy extracts energy from a heavy fluid supported by a light one (Figure 26).

In the ionospheric case, the heavy fluid is the ionospheric plasma and the light "fluid" is the magnetic field, which at the magnetic equator is exactly horizontal. The wiggles get larger and larger due to the fact that they are electrified. Charge builds up on each wall of the growing structure. Eventually, the uplift accelerates, and huge towering ionospheric convective storms evolve, complete with highly turbulent plasma. The regions growing upward consist of turbulent low-density regions, which originally were located well below the peak in density, the so-called bottomside of the ionospheric layer. This process is very nearly identical to that which transports water vapor from the troposphere up to stratospheric heights where tropical cirrus clouds occur: that is, "deep atmospheric convection" brings up high-humidity air just as deep plasma convection brings up low-altitude plasma (Kelley, 1989).

The analogy with tropical convection can be extended even further since the plasma analogue is also electrical in nature. As far as we know, there is no lightning involved, but the towering plumes are definitely electrified. A typical voltage across a developing plume is the order of 2 to 3 keV, which is well below any breakdown condition but still results in huge ionospheric winds with velocities often exceeding 1 km/s. This value is comparable to the highest speeds reported in and around the aurora so

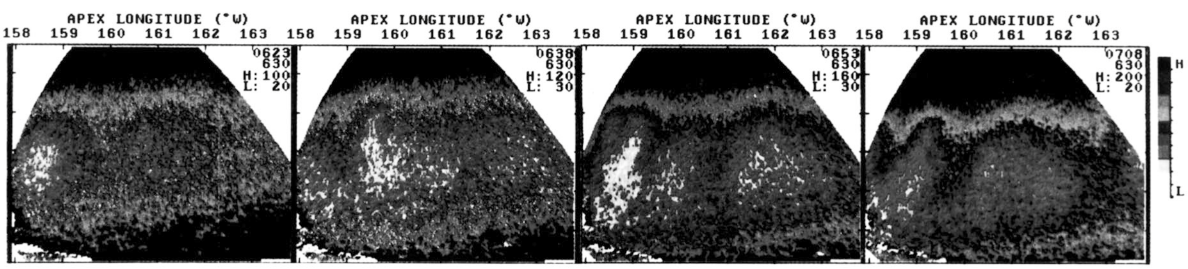

FIGURE 25 Sequence of airglow images looking south from the Haleakala Volcano on Maui shows the increasing influence of growing disturbances on the bottom of the tropical F layer. Reproduced from Tinsely et al. (1997) with permission of the American Geophysical Union.

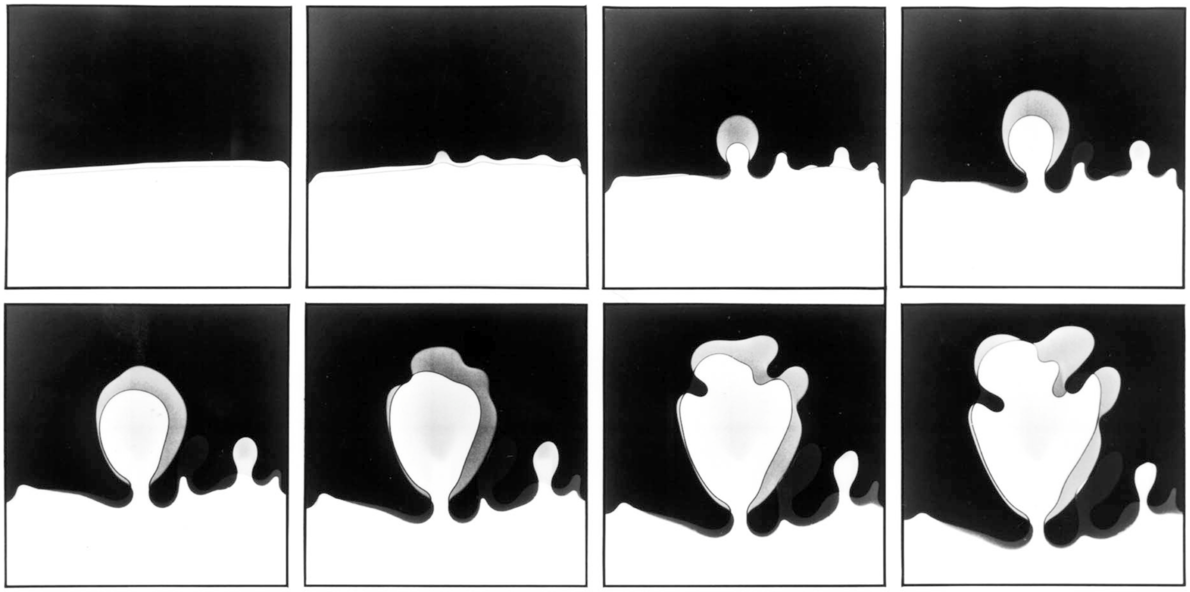

FIGURE 26 Photo sequence of a child's toy showing the growth of disturbances at the interface of a heavy fluid and a light one after the device is flipped over. There are actually two heavy fluids separated by a thin membrane, which accounts for the "shadow" trace.

there is good reason to consider weather in the equatorial zone to be as severe as that in the high-latitude sector.

How does this charging occur? In response to the gravitational force, ions slowly drift eastward in the presence of a northward magnetic field while electrons drift even more slowly to the west. This constitutes a net current. Now suppose there is a weak undulation in the plasma caused by a gravity wave. For the current to be continuous, as it must be according to the conservation of charge principle, an electric field builds up in the eastward direction where the plasma density is low and in the westward direction where the plasma is more dense. The electrical currents driven by these two fields add to the gravitational current where the latter is low and subtract from it where the gravitational current is high due to the undulation. But according to the principle of unintended consequences, these electric fields push the plasma upward in the low-density portion of the undulation and downward in the high-density region. Thus, the initial undulation is made deeper by the electric field, and the low-density region grows upward, with the high density region pushed downward just like the hydrodynamic analogy. The gravity wave has stimulated an instability in the plasma, which quickly takes on a life of its own as if the initial wave did not even exist.

The typical scale for periodic undulations that erupt into high-altitude convective storms is 100 to 400 km, as found by Röttger (1981) in his transequatorial experiments. But one side of the structure often breaks into smaller fingerlike upwellings separated by 50 km. Computer simulations of the physical equations have reproduced many features of these processes over the years, beginning with the pioneering work by the Naval Research Laboratory in the late 1970s (Scannapieco and Ossakow, 1976) and continuing now in India (Huang and Kelley, 1996), Canada, Australia, and several groups in the United States.

In Figure 27, we see the development of a multiple plume event much like the one illustrated in the radar data. It was initiated by a gravity wave traveling to the west. The plumes erupt after a few tens of minutes and become entrained in the plasma flow, which is usually eastward at the peak of the ionospheric layer.

There are still a few details to clear up in this physics, but the field has entered a serious stage of nowcasting and forecasting development, which should make future effects on communication

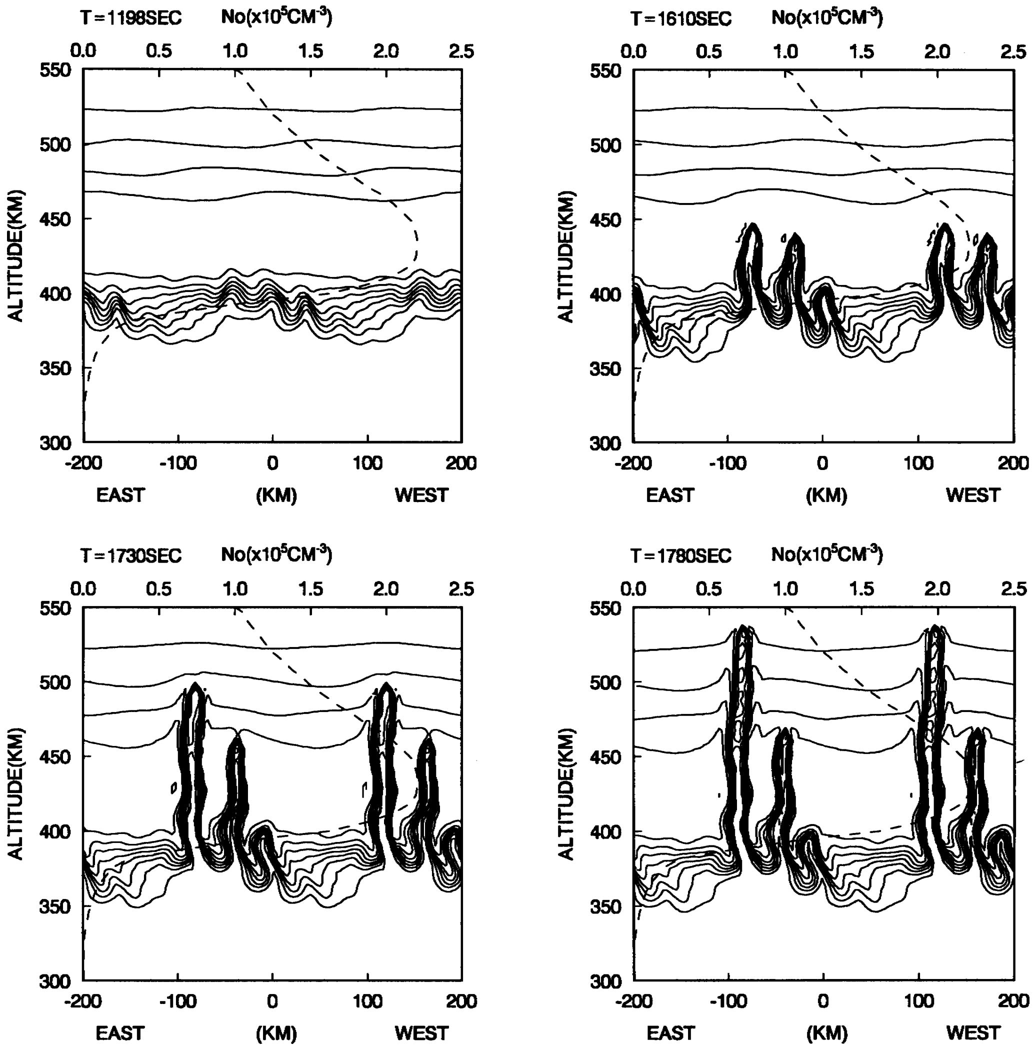

FIGURE 27 Computer simulations of gravity wave seeding of the ionosphere. Reproduced from Huang and Kelley (1996) with permission of the American Geophysical Union.

systems much more predictable. The hope is that by the next solar cycle maximum when GPS and other space-based systems are truly a part of everyday life, military and commercial users will have access to severe space weather information. For example, if the postsunset ionosphere is very high and has detectable wiggles on the bottom edge to the west of your location, you are pretty certain that severe communication disruptions are on the way.

At mid-latitudes our knowledge of the underlying physics is much less but so is the severity of the weather. The gravity wave effects are known to be present and some severe weather has been reported, particularly over Japan (Figure 28) where the powerful middle upper atmospheric (MU) radar system has been trained in the most sensitive orientation (perpendicular to the magnetic field). Some turbulent upwellings of ionospheric plasma have been seen, especially in summer and at solar minimum, which are too far off-equator to be the same Rayleigh-Taylor process discussed above.

These violent ionospheric storms have also been attributed to gravity wave seeding of the so-called Perkins instability in which energy is drawn from the background current system in the ionosphere. Much more work is needed to justify this claim, but the National Science Foundation program called CEDAR (Coupling Energetics and Dynamics of Atmospheric Response) is a beginning.

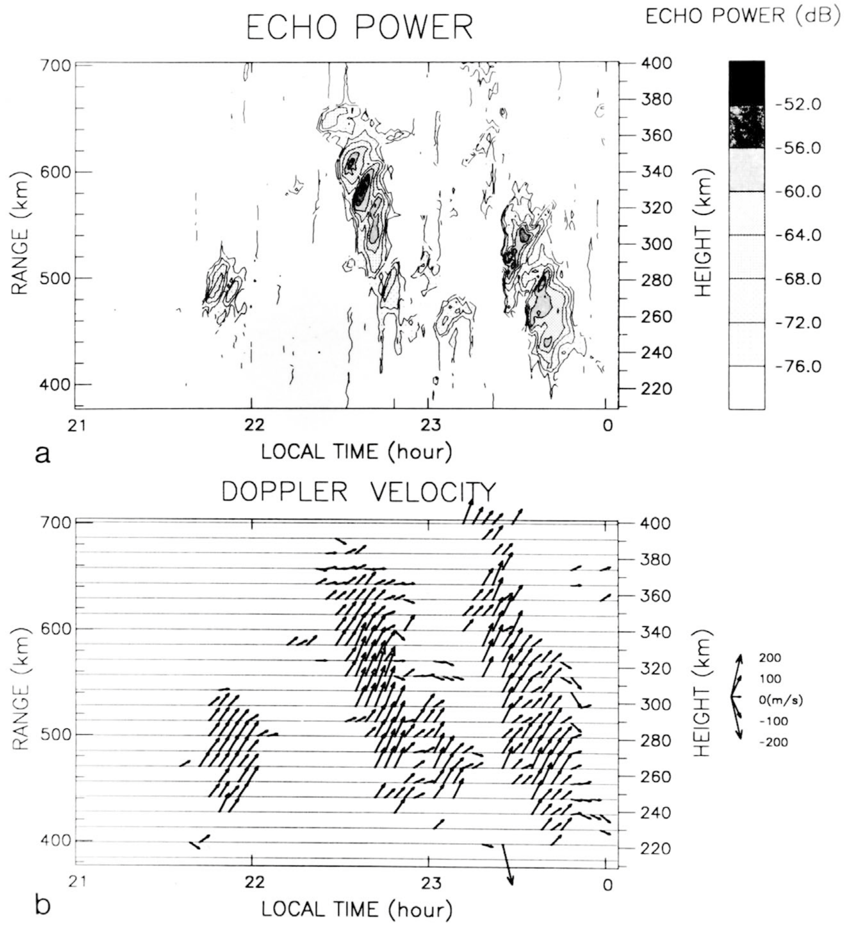

FIGURE 28 Periodic turbulent updrafts in the ionosphere over Japan may be seeded by internal waves and grow via the instability first described by Rip Perkins. Reproduced from Fukao et al. (1991) with permission of the American Geophysical Union.

In short, the ionosphere is a battleground affected by the lower atmosphere from below and by the solar wind, energetic solar photons, and particles from above. The latter need an entire treatise in their own right. Here we have tried to show some effects that come up from below. As we have seen, internal waves carry much of the atmospheric energy upward from below and, in tandem with electromagnetic effects, make the plasma blanket covering the Earth highly structured, sometimes turbulent, and always interesting in its scientific richness.

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