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# BERNHARD HAURWITZ

*1905—1986*

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*A Biographical Memoir by*
JULIUS LONDON

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*Biographical Memoir*

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# BERNHARD HAURWITZ

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BY JULIUS LONDON

BERNHARD HAURWITZ WAS AN unusually productive physical scientist and educator throughout his adult life. His principal scientific interests and accomplishments were in the area of dynamic meteorology, that is, the application of mathematics and fluid dynamics to all scales of atmospheric motions. In addition to his many basic contributions to the study of short-period atmospheric wave motions, planetary waves, including atmospheric tides, and vortex motions in tropical cyclones, he wrote important papers on such subjects as atmospheric radiation, wave structure of noctilucent clouds, and attempts to document internal tides in the oceans. The main directions of his work were in both analytic and diagnostic investigations of the structure and motions of the atmosphere.

Although primarily a theoretician, Haurwitz enjoyed working with observed atmospheric and oceanic data. His analyses were always directed toward gaining insight into the physical structure and important physical processes in the atmosphere. This was already evident in his Ph.D. thesis on the relations between changes of atmospheric pressure and temperature and continued throughout his research career. In general, he preferred writing short papers, with the idea that they would be more apt to be read than long ones. At the memorial for Haurwitz at the National Center for Atmospheric Research (NCAR), Philip Thompson, who had an almost continuous association with him for about forty years, commented, "I gradually came to realize that the range of Bernhard's interests and contributions spanned virtually the whole range of atmospheric science."

His role as an educator went beyond the more than fifty years he spent in active involvement at different academic institutions. Two of his textbooks were still listed in the *Science Citation Index* covering the five-year period of 1988-92.

## EARLY YEARS

Bernhard Haurwitz was born in Glogau, Germany, in 1905, to upper-middle-class parents. His father, Paul Haurwitz, was a reasonably successful merchant in the city. He had a younger sister, Ilse, who was born in 1907. While still a teenager, he developed an interest in astronomy and, together with his friend Wolfgang Gleissberg, became a cooperative solar observer, sending sunspot information to the central solar observatory in Zürich, Switzerland. This interest in solar phenomena stayed with him through his entire professional life.

Haurwitz completed his Gymnasium (high school) studies, specializing in classical languages (Latin and Greek) and in mathematics and physics. In 1923, at the age of eighteen, he enrolled at the University of Breslau, where he spent one and a half years before going on to the University of Göttingen where he studied mathematics, physics, and geophysics. In Göttingen he took courses from Richard Courant, Richard Frank, Emil Wiechert, and others. It was during that time that he developed an interest in meteorology as a result of preparing to present a seminar in his course in geophysics. The paper he reviewed was on the subject of atmospheric waves written by Ludwig Weickmann, then professor of geophysics at the University of Leipzig. He decided to apply to Professor Weickmann to write his Ph.D. thesis at the Geophysical Institute in Leipzig and was soon accepted.

Haurwitz arrived at the University of Leipzig in 1925 and began work on his thesis under Weickmann's direction. The thesis made use of then-available data from self-registering atmospheric sounding balloons. (Radiosonde observations became available only after their development in the late 1920s.) His thesis was motivated by observations that weather systems tended to move along with patterns of large surface-pressure changes. Haurwitz's results indicated that an atmospheric pressure decrease at the surface, accompanied by a surface-temperature increase, is associated with a pressure increase at levels near the tropopause, a relation to be anticipated if hydrostatic conditions obtain. This effect would suggest the existence of a layer in midtroposphere where the wind field was geostrophic and thus nondivergent, an important assumption made in the late 1940s at the time of early numerical weather prediction efforts as applied to two-dimensional flow at 500 mb.

After completing his dissertation (1927) and his second (habilitation) thesis (1931), Haurwitz became a lecturer at the University of Leipzig. It was there that he first heard guest lectures from the early British and Scandinavian pioneers in atmospheric and ocean dynamics—namely, Lewis F. Richardson, Vilhelm Bjerknes, and Harald U. Sverdrup. Haurwitz was impressed with the lectures and subject matter presented and arranged for a three-month visit to Oslo and Bergen in early 1929. Thus, he could interact with meteorologists who were in the forefront of research in geophysical fluid dynamics (Oslo) and synoptic meteorology

(Bergen). This research was of particular interest to him since his own studies at that time involved methods of solving the highly nonlinear problems of wave motions in the atmosphere and oceans by a simplification process based on perturbation approximations to the nonlinear equations. This technique continued to be used extensively before numerical methods of solution were practical as a result of the development of high-speed computers. Indeed, up to that time, applied mathematicians would quip that there were two types of differential equations—linear and nonsolvable! In an article written for the *Compendium of Meteorology* in 1951, Haurwitz reviewed the rationale for the use of the perturbation equations as a method of getting closed-form solutions to problems in atmospheric dynamics.

During his stay in Norway, Haurwitz spent most of his time working on problems of fluid dynamics with Scandinavian colleagues Halvor Solberg and H. U. Sverdrup and with a young student at that time, Jörgen Holmboe, with whom he frequently went skiing. As a matter of fact, one of the attractions for his Norwegian visit was the increased opportunity for cross-country skiing and mountain hiking, which were his favorite sports. These interests certainly played a nontrivial role some thirty years later in his decision to move to Boulder, Colorado.

While in Oslo he also occasionally visited with Carl Störmer, who was involved in a program of observations of the height of occurrence and main features of the polar aurora. This experience clearly contributed to his later interests and research applied to upper-atmosphere phenomena.

Upon his return from Norway, Haurwitz continued to work on the problem of wave motions in a compressible fluid, the general area of his main interest when he came to the Geophysical Institute in Leipzig. He used this subject for his "Habilitationsschrift." His research quickly became focused on the problem of short-wave "billow" clouds that appear at the interface of a two-layer model in the atmosphere (or oceans). By introducing assumptions of inhomogeneity, stratification, compressibility, and wind shear across the interface, Haurwitz was able to get good agreement between theory and observations of the billow cloud wavelengths and periods. He returned to this problem off and on over the next forty years and extended his model applications in an attempt to explain waves associated with noctilucent clouds.

After completion of his thesis and professional examination, Haurwitz became a lecturer at the University of Leipzig. During the next two years he gave a set of three courses in atmospheric physics: atmospheric acoustics, meteorological optics, and atmospheric radiation. Haurwitz then felt that it would be interesting to spend some time abroad, and at the invitation of Carl-Gustaf Rossby, who was then associate professor at the Massachusetts Institute of Technology, he came to the United States in 1932 for what was supposed to be a relatively brief seven-month visit.

## PROFESSIONAL ACTIVITIES IN THE UNITED STATES AND CANADA (1932-41)

Bernhard Haurwitz arrived in the United States in October 1932 to share a temporary appointment at MIT and the Blue Hill Observatory of Harvard. He divided his time between giving a series of lectures at MIT on problems related to the integration of the atmospheric perturbation equations and a research program at the Blue Hill Observatory involving, among other things, analysis of solar radiation data and their use in determination of atmospheric turbidity. Among the graduate students at MIT who attended his lectures and who later made significant contributions in meteorology and oceanography were Harry Wexler, Jerome Namias, Athelstan Spilhaus, and Raymond Montgomery.

During his stay in the Boston-Cambridge area, he also worked on a problem that had intrigued him for some time. In the absence of high-flying aircraft or other practical methods of measuring the midtropospheric pressure in and around hurricanes, it had commonly been assumed that tropical cyclones extended only to heights of about 2 to 3 km above the ocean surface. No one up to that time had attempted to determine the vertical extent of these storms, that is, the height at which the pressure would be horizontally uniform. Haurwitz assumed that atmospheric columns near the center and the outer part of the storm are each in approximate hydrostatic equilibrium and that the vertically averaged mean temperature near the center of the storm is warmer than that at the outer part. He was then able to show that the level of the pressure equalization—the height of uniform pressure around the storm—was approximately 10 km. This height range was, of course, substantially verified as both direct and indirect measurements became available. Moreover, he was also able to show that the shape of the eye of the storm approximated that of a funnel, as verified by later observations.

In early 1933 Haurwitz accepted an invitation from the seismologist Beno Gutenberg, a former colleague in Germany, to visit the California Institute of Technology in Pasadena where he gave lectures on atmospheric dynamics. Among the attendees at these lectures was Albert Einstein, who had just come from Berlin to spend the winter at CalTech. A short time after Haurwitz's arrival at Pasadena, Adolf Hitler was appointed chancellor of the German Reich. Both Haurwitz and Einstein independently chose not to return to Germany. Haurwitz decided that when his visitor's visa expired he would apply for a visa extension and investigate the possibility of a position in Canada. He was able to get a research appointment in the physics department at the University of Toronto through a Carnegie Institution grant. However, it took two years, until the summer of 1935, before the clerical red tape was straightened out. Meanwhile, he spent those two years continuing his lectures and research at MIT and the Blue Hill Observatory.

In 1934 he married Eva Schick, who had done her academic studies in Germany in physics before immigrating to the United States. They went to Toronto in 1935 where he worked at the University of Toronto and the Canadian Meteorological Service for the next six years before they returned to the United States in 1941.

Haurwitz came to Toronto as a Carnegie Institution fellow (1935-37) in the physics department at the University of Toronto and continued as a visiting lecturer in the department until 1941. When the Carnegie fellowship ended, he took a position as meteorologist with the Canadian Meteorological Service (1937-41). The Canadian Service had set up a cooperative meteorological training program with the physics department at the University of Toronto, and each year he gave a regular graduate course in dynamic meteorology. In addition, he presented a series of eight lectures at the university on the subject of "The Physical State of the Upper Atmosphere." The lectures were based, in part, on the course he gave while he was at the University of Leipzig. They were published as a series in the *Journal of the Royal Astronomical Society* (Canada) and as a special short book in 1937. Although the material in that book is now almost completely out of date, it was the first book of its kind and summarized what was then known about the "upper atmosphere." A second edition was published in 1941, when a large-scale meteorological training program was started during the early period of World War II.

By 1940 there was also increased need for a new English-language textbook on dynamic meteorology. This gave Haurwitz the opportunity to refine and edit his lecture notes. His book, *Dynamic Meteorology,* was also published in 1941, at the time of the rapid increase in the training of meteorologists in the United States during World War II. The book was widely used as a standard textbook on dynamic meteorology for the next twenty years.

The meteorology program at the University of Toronto was also used to train people newly hired by the Canadian Meteorological Service. As a result, Haurwitz spent considerable time in Toronto preparing educational programs for weather forecasters and instructional booklets for the British Commonwealth Air Training Plan. In 1938 Eva gave birth to their son, Frank. (At the time Bernhard was giving a lecture at the university.)

When World War II started in 1939, Haurwitz, who still held a German passport, was classified as an "enemy alien" and had to report to the Royal Canadian Mounted Police once a month. But after a brief background check, that requirement was lifted. Being an enemy alien, however, did not interfere with his having access to the "secret" weather codes developed for use at that time or his being involved with coordinating the joint use of these codes by the meteorological services of the United States and Canada.

Despite all of these academic and semiadministrative duties, he still made time to work on a number of research problems, including fundamental studies of the motions of large-scale atmospheric disturbances. The latter resulted in three publications during the period 1937-40 that are still considered classic in the field of planetary waves in the atmosphere.

Haurwitz's study of planetary waves stemmed from his early interest as a graduate student in the theory of solarinduced atmospheric tides. The original motive for the 1937 paper, "The Oscillations of the Atmosphere," was to find an explanation for resonance of the solar semidiurnal pressure tide. However, the emphasis on that paper was on the class of planetary waves whose periods are long compared to a sidereal day and move westward relative to the mean zonal flow in which they are embedded. It was in that paper that Haurwitz derived the speed of low-frequency nondivergent planetary waves on a spherical earth that are typical of large-scale meteorological systems. An analogous result was derived by Rossby and collaborators in 1939 for the speed of long waves in midlatitudes based on the assumptions that the air motion was horizontal and nondivergent on a plane earth with no lateral shear in the basic westerly current. Only the latitudinal variation of the Coriolis parameter was considered, and the wave motion was assumed to be purely zonal. These waves are known as Rossby waves. In the two papers Haurwitz published in 1940, "The Motion of Atmospheric Disturbances" and "The Motion of Atmospheric Disturbances on a Spherical Earth," he extended the work of Rossby et al. and also rederived the formal results of the paper he published in 1937 to show direct application of the results to the observed "centers of action" of the northern hemisphere mean circulation system.

Haurwitz modified Rossby's assumptions to include the meridional extent of the wave, the effects of friction and of baroclinic forcing as, for instance, with zonal flow across a north-south coastline. His results indicated that the importance of the latitude variation of the Coriolis force ($\beta$ effect) on the wave speed decreased as the lateral extent of the disturbance became smaller. He also found that, when the effect of friction is applied to the perturbed flow, the amplitude of the disturbance decreases exponentially with time.

In addition, he showed that the effect of imposing a longitudinally fixed external force on the flow pattern, such as a land-ocean interface, generates stationary waves of approximately the same wavelength as the free oscillation of the system. This latter result was subsequently shown in the literature to apply as well to imposed fixed external forcing on planetary waves associated with north-south orographic surface features. The treatment of these horizontal planetary waves on a rotating spherical earth as developed in the two papers by Haurwitz in 1940 has given rise to the identification of this general class of waves as Rossby-Haurwitz waves, and they are so referred to in the literature.

In 1940 Sverre Pettersson, then chair of the Department of Meteorology at MIT, visited the Meteorological Service in Canada. He had known Haurwitz from the time when they were both in Norway. He invited Haurwitz to come back to the department at MIT, and in July 1941 Bernhard returned to Cambridge, this time as associate professor of meteorology. At the same time, Bernhard received an appointment as Abbott Lawrence Rotch Research Fellow at Harvard's Blue Hill Observatory.

When Haurwitz arrived at MIT in mid-1941, the department was already involved in the Army Air Corps/Navy advanced training program in meteorology. (MIT was then one of five universities participating in the national program that eventually trained over 10,000 weather officers.) While at MIT, Bernhard's principal academic responsibilities were to teach a course on dynamic meteorology and a course dealing with the physical principles of climate. The latter course led to the publication of a textbook, *Climatology*, coauthored with his colleague James Austin.

At the time of his return to Cambridge, the United States was not yet at war and Bernhard's official immigration status was as a "neutral alien." However, when the United States entered the war on December 7, 1941, he again became an "enemy alien." Early in 1942 a representative of the Army Air Force (formerly Army Air Corps) asked him to conduct a research program on long-range weather forecasting that was based on statistical techniques tried a decade earlier in Germany. The project was labeled as secret, and since Bernard was classified as an enemy alien, he was only able to supervise the program as the unofficial director. As he had anticipated, the results of the suggested technique showed no particular forecasting skill, but it did give him the opportunity to work with two very bright, young weather officers who had just completed the meteorology course—Richard Craig and Edward Lorenz—who remained colleagues and friends of his for a long time afterward.

During this time his research dealt with problems of atmospheric fluid dynamics, atmospheric radiation, and possible solar-weather relations. One of the more notable of the fluid dynamic studies involved a continuation of some of the problems dealt with in his habilitation thesis on the theory of wave motion in a stratified fluid. Waves in the atmosphere that give rise to cloud bands or billow clouds may occur as a result of convective patterns where the instability due to atmospheric stratification is an important factor in their development, or they may be a manifestation of internal waves that result from vertical wind shear across a surface of density discontinuity or within a shallow transition region. In a paper he published in 1947, he concluded that convection patterns and internal wave patterns are "largely one and the same phenomenon."

Haurwitz's return to the Cambridge-Boston area also provided him with the opportunity to resume his past association with Hurd Willett and other colleagues and friends at MIT and the Blue Hill Observatory. At Blue Hill he extended some of his earlier studies of observed solar irradiance to develop empirical relations between solar irradiance measurements at the earth's surface and synoptic reports of total cloudiness and cloud type. He reasoned that, if such relations were found to be statistically reliable, they could be used to derive information on the solar irradiance at the surface in the absence of such measurements because total cloudiness and cloud type information was normally available from routine weather reports. The results of these studies have been used as historic references in recent years as more direct information on the dependence of cloud transmittance as a function of cloud type has been derived from satellite and surface observations.

Haurwitz's renewed association with the Blue Hill Observatory and its director, Charles F. Brooks, also revived an earlier interest of his on solar variability and its possible effect on the lower atmosphere. Most published studies on this subject were confined to statistical analyses of such possible solar relations. He felt that this approach was inadequate and stated that "when looking for empirical proofs of the connection between solar activity and weather, it is imperative to have a clear picture of the physical cause of the relation to be established." Although it was well known from both observations and theory that solar perturbations resulted in disturbances in the high atmosphere, he thought it important to provide a plausible physical mechanism by which anomalous solar behavior could either directly or indirectly affect the lower atmosphere in an observable fashion.

In 1948 Haurwitz qualitatively outlined such a proposed mechanism based on a physical-dynamic model of how a solar eruption could influence the pressure distribution in the troposphere. He postulated that the initial disturbance could come from increased ultraviolet radiation associated with a short-lived solar flare. This energy would be absorbed by ozone in midstratosphere over subsolar (equatorial) latitudes. Then in a simplified model he showed that the resultant heating would produce a net poleward air flow in the stratosphere that would result in a temporary reduction in the surface pressure at low latitudes and thus affect the low-tropospheric winds in the tropics. He later abandoned this model when observations indicated that his initial assumed solar energy perturbation was much too high, by orders of magnitude, and it was not possible to detect any of the predicted changes. Nevertheless, the concept proposed by Haurwitz of latitudinal differential heating of the ozone layer during times of high solar activity, as has been postulated over solar-rotation or solar-cycle periods, continues to be one of the main directions of study in the search for solar-weather relations.

Difficulties had been developing in his marriage, and in early 1946 Bernhard and Eva were divorced. Shortly afterward he accepted an invitation from Herbert Riehl to visit the Institute of Tropical Meteorology in Puerto Rico, which at that time was administered by the University of Chicago. The visit was planned for midsummer and early fall but was somewhat delayed until shortly before he received his naturalization papers. When he finally arrived in October, Haurwitz was able to take advantage of the results of a special program of three hourly radiosonde observations over the Eastern Caribbean to carry through a preliminary analysis of the diurnal and semidiurnal pressure and temperature oscillations at various levels in the troposphere. Determination of the characteristics of solar and lunar tidal oscillations in the oceans, at the earth's surface, and in the free air up to heights of 100 km continued to occupy him through the rest of his research career.

The following summer (1947), while he was a research associate at the Woods Hole Oceanographic Institution

(WHOI), Haurwitz was asked by Athelstan Spilhaus, then head of the Meteorology Department at New York University, to be the new chair of the department. Haurwitz accepted and in September 1947 moved to New York as professor and chair of the Department of Meteorology at NYU, where he built a strong and interactive department. He broadened its academic scope and soon changed its name to the Department of Meteorology and Oceanography. He also arranged to increase the size of the faculty to accommodate the growing number of graduate students in the department. He brought to the department an informal and collegial mode, particularly among graduate students and academic staff, that was characteristic of his own interpersonal and professional style.

While at NYU, Bernhard actively worked with other professional groups on problems of mutual interest. For instance, he developed a program of occasional joint seminars with the graduate mathematics department at NYU, which was then directed by Richard Courant, from whom he had taken a course when he was a student at the University of Göttingen. Participants in those seminars included faculty and graduate students of both the Department of Meteorology and Oceanography and the Courant Institute. The seminars gave both groups a chance to interact on applied mathematical problems of atmospheric interest, such as atmospheric tides and the stability of atmospheric waves.

Bernhard spent at least part of each summer (1947-55) as a research associate at WHOI, where he worked closely with many institution colleagues, namely, Andrew Bunker and Henry Stommel, and visiting associates, namely, Richard Craig, Hans Panofsky, and others. Although he couldn't swim, he did enjoy spending time on the beach near Falmouth relaxing with his son, Frank. They both enjoyed New England seafood and frequently walked on the beach hunting crabs. They both enjoyed, and often attended, the summer Gilbert and Sullivan operetta program in the area. Being at Woods Hole also gave Haurwitz the chance to be away from New York City during the summer months.

During his time at Woods Hole, Bernhard's research efforts were largely devoted to investigations of internal waves in the oceans and analysis of the observations and theoretical basis for the existence of tidal oscillations, particularly of the semidiurnal lunar period, associated with these waves. In 1950 he was able to show that, if the earth's rotation was included in the theoretical analysis, the periods of long internal waves would be reduced and their speeds increased so that internal waves in the oceans could contain motions that were characteristic of tidal oscillations. After careful statistical analysis of temperature and density data taken from ship observations at different depths and from remote recording thermometers, it was found that such periodic oscillations may indeed exist. But the data were rather noisy. In discussions about twenty-five years later of tidal influences within the oceans, Bernhard agreed that there was still a lack of substantial observational evidence of a lunar period at levels below the ocean surface.

Bernhard returned to the study of tidal oscillations in the atmosphere in the early 1950s. At that time he was interested in further development of resonance theory as an adequate explanation of the solar semidiurnal pressure oscillation and to document the global distribution of the amplitude and phase of these tides. These studies continued as a major part of his research activities during the remaining part of his active professional career at NYU and subsequently when he moved to Colorado. During these times he worked closely with a number of colleagues, namely, Sydney Chapman, Walter Kertz, Fritz Möller, Manfred Siebert, Gloria Sepulveda, and Ann Cowley (one-third of his papers on atmospheric tides were coauthored with Ann Cowley). The areas covered in his tidal studies involved analyses of (a) the diurnal and semidiurnal surface-pressure oscillation, (b) the lunar semidiurnal surface-pressure oscillation, and (c) the diurnal and semidiurnal wind oscillation in the mesosphere.

In 1956 Haurwitz published an analysis of the mean annual global distribution of the solar semidiurnal surface-pressure oscillation, $S_2(p_0)$. This was an extension and systematic improvement of the representation presented by George Simpson about forty years earlier based on a limited data set. His principal motivation for the study was to provide improved empirically derived descriptions of the two components of the $S_2(p_0)$ oscillation: (a) the east-to-west-traveling wave and (b) the stationary zonal wave.

He analyzed the geographic distribution of the mean annual observed amplitude and phase of $S_2(p_0)$ and computed spherical harmonic representations of the improved set of observed values. The computed maximum amplitude at the equator (1.2 mb) decreased to near zero at polar latitudes. The computed local phase was approximately 9.7 hours up to about ±50° but varied locally at higher latitudes, where the stationary wave was dominant. The results of this important paper were documented the following year in two studies with Gloria Sepulveda in which they verified that in the Northern Hemisphere poleward of about 70° the amplitude and phase of the semidiurnal pressure oscillations are mainly controlled by the standing wave.

In the winter semester of 1955-56 Bernhard spent a sabbatical leave visiting with Fritz Möller in Mainz, Germany, motivated, in part, by the wish to continue an earlier study done with Möller at NYU on the analysis of the global distributions of the semidiurnal temperature variation [$S_2(T_0)$] and its effect on the semidiurnal pressure variation [$S_2(p_0)$].

During that time, he had the chance to revisit Göttingen and meet with two of Bartels's students, Manfred Siebert and Walter Kertz, who were then working on the problem of direct thermal input as an alternative to resonance theory for the main forcing of the semidiurnal atmospheric tidal oscillation.

## MIGRATION TO THE WEST

Bernhard had his first onsite experiences with the Rocky Mountain region in 1954 when he began his summer visits to the western states. He spent part of that summer at the Sacramento Peak Observatory (Sac Peak) at Sun Spot, New Mexico, at the invitation of Jack Evans, then director of the observatory. There he interacted with solar physicists who were involved in, among other things, studies of the effect of solar disturbances on radio propagation in the upper atmosphere. Discussions with colleagues at Sac Peak brought to mind his earlier attempts at finding a possible physical mechanism for solar influences on atmospheric variability. The gradual shift of his summer workplace locale from WHOI on the east coast to Sac Peak in New Mexico and later to the High Altitude Observatory (HAO) in Boulder, Colorado, represented a transition toward increased research application to problems of upper-atmosphere dynamics.

When Walter Orr Roberts, knowing of Bernhard's desire to spend some time away from New York, asked him to participate in the HAO summer program dealing with solar-terrestrial relations, Bernhard agreed and consequently spent the summers of 1957 and 1958 as a visiting research associate with the High Altitude Observatory. In 1959 he accepted Walt's offer of a joint, full-time appointment as professor of geophysics at the University of Colorado and research associate at HAO.

The attractions in Boulder, both intellectual and environmental, were many. Bernhard was able to work in more relaxed surroundings than before, especially with a minimum of administrative responsibilities. After 1959, when he became a permanent resident in Boulder, he would go to the mountains almost every weekend—hiking during summer and fall and ski touring or snowshoeing during the winter and spring. Frequently he would go hiking with his son when Frank visited Boulder during the summer or with local or visiting colleagues. One of those colleagues was Sydney Chapman, who was a member of the research staff of HAO and with whom Bernhard maintained a close association. They had strong overlapping scientific interests and a shared appreciation of Boulder because of, among other things, its proximity to the many nearby mountain trails.

One of Bernhard's hiking companions was Marion Wood, a scientist working at the National Bureau of Standards in Boulder and a native of Colorado who shared his appreciation of the mountains and associated outdoor activities. Bernhard and Marion were married in January 1961 and were together until his death twenty-five years later.

Bernhard and Marion went to Europe during the summer of 1961 for an extended visit to Switzerland, Austria, and Germany. This was their first trip abroad together, and it represented a somewhat delayed honeymoon. They participated in scientific symposia in Arosa and Vienna and went to Munich for three months at the invitation of Fritz Möller, who was then professor of meteorology at the Meteorological Institute in Munich. Bernhard held a professorial chair at the university for the summer and gave a course on atmospheric dynamics. During his stay in Munich, he worked principally on a representation of the global distribution of the daily variations of surface temperature through the use of Legendre functions. Some of the results of that study were used in his later discussion of the possible thermal excitation of the observed diurnal surface pressure oscillation.

After five years at the University of Colorado, Haurwitz decided in 1964 to move to a full-time position at NCAR as a senior scientist with the Advanced Study Program, which he directed for a three-year period (1967-69). He continued his appointment at NCAR until his retirement in 1976, when he became a senior research associate. In 1964 he also started his affiliation with the Geophysical Institute of the University of Alaska, first as a research associate and then as a visiting professor. He and Marion went to Fairbanks for three months in what was to become an almost annual visit until the winter of 1985.

Soon after he arrived at the Geophysical Institute in Fairbanks, Bernhard had the opportunity to continue to work on a problem that had intrigued him since his visit with Carl Störmer in Oslo some thirty-five years before. Störmer had been an early and diligent observer of noctilucent clouds (NLC). In 1930 Haurwitz was involved in a theoretical analysis of the dynamics of billow clouds in the lower troposphere, and Störmer thought that he, Haurwitz, might find applications of the theory to the observed waveforms in noctilucent clouds. In 1961 Bernhard published a paper that attempted to draw an analogy between billow clouds that form at an interface between two layers in the troposphere and billow clouds observed at the top of the mesosphere. As a result of preliminary analysis, however, he concluded that "it appears likely that the billow clouds observed in noctilucent clouds are manifestations of internal waves" rather than windshear.

At the Geophysical Institute, Bernhard met Benson Fogle, who was then a graduate student working with Sydney Chapman. Fogle had been collecting data on NLC observations made in polar regions, and in 1966 they wrote a review paper describing what was then known of the observed characteristics of these clouds. Then in 1969, after Fogle joined NCAR, they published a theoretical analysis of the origin of the wave forms of noctilucent clouds. Observations indicated that the clouds generally took on two different forms: high-frequency, short-wavelength billow clouds and lower-frequency, longer-wavelength bands. They proposed that the shorter lifetimes for billow clouds were probably due to viscous damping, which is more effective for shorter than longer wavelengths. On the basis of their analysis they concluded that the wind shear in the layer of the NLC bands was certainly smaller than that required if these bands appeared as an interface wave near the mesopause, and they suggested that both bands and billow clouds are caused by internal gravity waves. Bernhard became convinced that the problem of the origin and energy source, particularly for the high-frequency component of the NLC, could not be definitively resolved without a carefully designed observational program to measure NLC heights, wavelengths, and amplitudes of the different waveforms.

During this time, Bernhard continued with his studies of atmospheric tides. It had long been known that the solar atmospheric surface pressure tide is thermally rather than gravitationally produced. However, the observed amplitude of the diurnal tide is smaller than that of the semidiurnal tide, which is apparently inconsistent with the relative amplitudes of the diurnal and semidiurnal temperature oscillations. In a paper published in 1965 Bernhard pointed out that "one of the main problems of atmospheric tidal theory is to explain the small size of $S_1(p_0)$ as compared to $S_2(p_0)$." It was by then generally agreed that resonance could not be the major cause for the large amplifications of $S_2(p_0)$. Resonance theory, normally accepted up to ten years earlier to explain the dominance of $S_2(p_0)$, required that the atmosphere have a free period very close to twelve hours. This would call for an upper-stratospheric temperature of about 350 K, 75 K higher than observed. By the early 1960s, however, it had been shown by Siebert, Butler, Small, and others, that direct heating by absorption of solar radiation by water vapor and ozone in the troposphere and stratosphere could largely account for the observed amplitude of $S_2(p_0)$.

In the 1965 paper Haurwitz presented for the first time a spherical harmonic analysis of the worldwide geographic distribution of $S_1(p_0)$, similar to that done earlier for $S_2(p_0)$, to document the observed relative amplitudes of the two principal components of the surface pressure solar tide and to explain the apparent suppression of $S_1(p_0)$. He showed that the main part of $S_1(p_0)$ was a westward-traveling wave with an equatorial amplitude of ~0.6 mb, one-half that of $S_2(p_0)$. Also, the average amplitude of the diurnal oscillation decreased strongly with latitude, and the diurnal wave, unlike the semidiurnal wave, was strongly modified by properties of the lower boundary such as orography and the distribution of land and water surfaces. Bernhard, however, erroneously attributed the excitation of $S_1(p_0)$ to the daily surface temperature oscillation, $S_1(T_0)$. At the time of the analysis, he did not realize that the representation of $S_1(p_0)$ by Hough functions should contain negative equivalent depths, as later pointed out by Richard Lindzen and others. The excitation of such Hough modes would result from absorption of solar radiation principally from water vapor and ozone in the lower and upper stratosphere, respectively. For a number of reasons, the propagation of this energy from the source regions to the surface is not very effective, thus producing a diminished $S_1(p_0)$.

In his last major study of atmospheric tides (completed in 1973), Bernhard, together with Ann Cowley, presented an analysis of the quasi-global distribution and seasonal variation of the diurnal and semidiurnal pressure oscillations. Again, they performed spherical harmonic analyses of the station data, and the wave characteristics were expressed by associated Legendre functions and Hough functions. They extended their earlier studies to higher-order wave numbers and confirmed that the dominant component of the diurnal wave was zonal wave number 1 and that for the semidiurnal wave was zonal wave number 2. The more complete study again showed that at the equator the ratio of the relative amplitudes of $S_1(p_0)$ to $S_2(p_0)$ was approximately 1:2. $S_2(p_0)$ was found to be much more regular than $S_1(p_0)$, a result that is consistent with the nature of the forcing of the two waves. The results of this study are cited in the literature as one of the standard references on atmospheric tides.

While at NCAR, Bernhard would frequently give courses at Colorado State University and in 1973 he and Marion moved to Fort Collins. For the next three years he divided his time among CSU, NCAR, and the Geophysical Institute at Fairbanks. In 1976 he resigned his formal NCAR position but kept his ties to NCAR as a senior research associate.

Bernhard was elected to the National Academy of Sciences in 1960, and in 1964 he was elected to the Deutsche Akadamie der Naturforscher Leopoldina (the German Academy of Sciences, founded in 1562). He was awarded the Order of Merit First Class by the Federal Republic of Germany in 1976 for his efforts in helping German meteorologists return to the mainstream of the international scientific community in the years following World War II. Bernhard received the prestigious Carl Gustaf-Rossby Award for Extraordinary Scientific Achievement from the American Meteorological Society in 1962, and in 1972 he received the Bowie Medal of the American Geophysical Union.

In December 1985 while he was in Fairbanks, Bernhard developed a chest infection that was diagnosed as pneumonia, and he returned with Marion to Fort Collins. He was hospitalized in January, and on February 27, 1986, he died of renal failure.

Bernhard represented a prime example of a person who successfully combined superior teaching with excellence in research by removing the unnatural barrier that often separates the two. He was unpretentious, and although he did not suffer fools, his interchanges with students and colleagues were never marked with derogation. It is clear that he left a strong imprint on his colleagues and students through his writings and lectures. Both were outstanding examples of tidiness and clarity with a studied avoidance of jargon, particularly when dealing with complex and difficult subjects.

IN PREPARING THIS MEMOIR, considerable use was made of the material contained in a series of papers, "Meteorology in the 20th Century—A Participant's View," by Bernhard Haurwitz, published in 1985 in the *Bulletin of the American Meteorological Society* (vol. 66, pp. 281-91, 424-31, 498-504, 628-33), and *Conversations with Bernhard Haurwitz*, by George W. Platzman (NCAR/TN-257, 1985). I am indebted to George Platzman for many discussions about Bernhard and for his comments on an early draft of this memoir.

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