NATIONAL ACADEMY OF SCIENCES

CARL-GUSTAF ARVID ROSSBY

1898—1957

A Biographical Memoir by
HORACE B. BYERS

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C. G. Rossby

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December 28, 1898–August 19, 1957

BY HORACE R. BYERS

WHEN METEOROLOGY is referred to as a young science, one has in mind the new life given to it in the early 1920s by Scandinavian mathematical physicists and meteorologists. As one surveys the development of American meteorology from its static condition in the late 1920s to its position of world leadership today, one finds the name of Carl Rossby appearing so prominently that it would seem that this one man was responsible for the entire movement. This Scandinavian-American, early missionary of the Bjerknes school and later creator of the equally famous Rossby school of atmospheric science, organized, led, and, through his own outstanding research, spearheaded the thinking in meteorology in this country for twenty-five years. Then, during the last ten years of his life, having returned to his native Sweden, he came close to performing an equally leading role on a world-wide basis.

Rossby was really two men. On the one hand he was the organizer, director, and promoter and on the other the scholarly research scientist. Perhaps that is why he died while relatively young; no man could play this double game at his pace and last very long. Only the mentally and physically stronger of his associates tried to keep up with him, but his dual make-up and unbounded energy account for his great impact on the field.

Carl-Gustaf Rossby was born December 28, 1898, in Stockholm, the first of five children of Arvid and Alma Charlotta (Marelius) Rossby. His father, a construction engineer, had just sufficient means to insure that the children received an adequate basic education. As a boy, Carl-Gustaf, although spirited and excitable, conformed to the traditional formal Swedish training in the home and at school. His teachers' reports, which have been saved by the family, show that he was an excellent and conscientious scholar. Only later did his restless spirit begin to affect and even to dominate his actions.

It was at the University of Stockholm (Stockholms Högskola) that the young Carl Rossby developed his consuming interest in mathematical physics. In 1918, at the age of nineteen, he received the degree of Filosofie Kandidat, with specialization in mathematics, mechanics, and astronomy. Then, after making a start on further studies there, he allowed his restlessness to lead him into an action that started his career in meteorology. He suddenly left Stockholm to engage in meteorological work at the Geophysical Institute in Bergen, Norway. This act was partially stimulated by a lecture he heard on moving discontinuities in the atmosphere given by Professor Vilhelm Bjerknes of the Bergen Institute, but from comments he made in later years, one would judge that he was also bored with Stockholm.

In Bergen, Rossby's interest in meteorology was thoroughly and permanently aroused. He was there at the time the results of the discovery of the polar-front theory of cyclones had just been published, and the activity to apply these new methods to current synoptic charts was at an exciting pace. New characteristics of the atmosphere were revealed nearly every day. V. Bjerknes and his son, J. Bjerknes, H. Solberg, and Tor Bergeron, the last-named also from Sweden, were among the meteorologists working on the development of the system. Also in Norway Rossby met the oceanographer B. Helland-Hansen, the oceanographer-meteorologist H. U. Sverdrup, and other renowned geophysicists whose activities brought them to Bergen in those days. Rossby was supported at Bergen by an assistantship and later received the title of meteorologist. He learned and applied the techniques of synoptic analysis and listened to the lectures of V. Bjerknes on physical hydrodynamics. His name did not appear on any of the published reports of the Bergen school during the two years he was present. Those who were there say that he contributed some good ideas, but his interests leaned toward theory and he did not yet have the mathematical and physical equipment for good work in dynamic meteorology.

Staff members of the Geophysical Institute of the University of Leipzig meanwhile had become interested in the meteorology of the Bergen school; in fact, V. Bjerknes had developed some of his ideas while lecturing there during the latter part of the First World War. The liaison between the two institutes had continued and there was some exchange and visiting of personnel between them. So, in 1921, Rossby also went on to Leipzig. There he began to look at the interesting features revealed by upper-air soundings, an area that had been glossed over by the "indirect aerology" approach at Bergen. So interested did Rossby become in upper-air data that he spent a large part of the year 1921 at the Aeronautisches Observatorium at Lindenberg, near Berlin, which was an active center for kite and balloon soundings.

The young Rossby must have realized that he lacked the tools for the theoretical approach which he felt must be taken to solve problems of the atmosphere, so he returned to the University of Stockholm in 1921–1922 to learn more mathematical physics. He remained there until 1925, with interruptions. To finance these studies he took a year off to work as a meteorologist for the Swedish Meteorologic-Hydrologic Service. He also kept his hand in meteorology by writing in 1923 an article "On the Origin of Traveling Discontinuities in the Atmosphere," which was published in 1924 in *Geografiska Annaler,* Vol. 2, No. 2. This was his first scientific publication, of which later he was not very proud, but it showed discernment of some of the real problems of meteorology and a desire to reach precise solutions. In the summer of 1923 he accompanied the *S.S. Conrad Holmboe* expedition to Jan Mayen and eastern Greenland, assisting in the meteorological and oceanographic work. During the next summer, 1924, he served as meteorologist on the sailing vessel *H.M.S. af*

Chapman on a cruise around the British Isles. The meteorological results of this cruise were published in Swedish under his name a few months later as an issue of the series of contributions produced by the Swedish Meteorologic-Hydrologic Service.

No meteorological studies were offered anywhere in Sweden at that time, so Rossby devoted his time and effort to studying mathematical physics at the University and reading meteorological literature on the side. He kept up his contacts with meteorologists in Bergen and in Germany.

In 1925 he received his Filosofie Licentiat in mathematical physics. That summer he made another trip on the *af Chapman,* this time to Portugal and Madeira. There is no published record of his meteorological work on this cruise.

With his 1925 degree from Stockholm, Rossby ended his formal education. It is probable that he never intended to go back for a doctor's degree. He might have had in the back of his head some vague ideas about it, but he was impatient to get on with meteorology.

Meanwhile he had applied for a fellowship of the American-Scandinavian Foundation to go to the U.S. Weather Bureau in Washington "to study the application of the polar front theory to American weather." He was granted a fellowship, and early in 1926 arrived in Washington.

His first undertaking was to collaborate with Richard H. Weightman, Washington Weather Bureau forecaster, in a study of the polar-front theory as applied to American weather maps. Before the year was out their joint paper was published in the *Monthly Weather Review.*

The Central Office of the Weather Bureau was not a pleasant place for the twenty-seven-year-old Swede. He encountered unexpected hostility to the polar-front theory and to air-mass analysis and other approaches derived from it. On the Weather Bureau staff there was strength in the area of atmospheric physics in the person of W. J. Humphreys, but there was no one to talk to about hydrodynamics, atmospheric flow, and mathematical physics. Only the forecasters had an appreciation of the large-scale atmospheric motions which form the main flow patterns of the atmosphere, and these men were half-educated practitioners who had risen through the ranks because of some practical knowledge and ability to outguess the weather. This period was before the reforms introduced by the later Bureau chiefs. The Bureau was headed by unimaginative administrators who had no interest in Rossby's scientific brilliance but rather found the young Swede, with his schemes for revitalizing meteorology in the United States, a great nuisance.

In this uninspiring atmosphere Rossby turned his attention to a careful study of atmospheric turbulence, preparing three manuscripts which were published in the *Monthly Weather Review* in 1926 and 1927. These papers summarized the subject and showed a remarkably clear insight into the great problems besetting studies of flow in the friction layer near the surface of the earth.

Upon the recommendation of W. J. Humphreys, W. R. Gregg, R. H. Weightman, and others, Rossby was given a temporary appointment as junior meteorologist in the Weather Bureau in 1926.

While at the Weather Bureau Rossby made some attempts to construct and operate, with the aid of technicians, a rotating tank experiment to study atmospheric circulations. These efforts did not prove fruitful and it was not until twenty-five years later that he could achieve success in hydrodynamic models through a young associate at the University of Chicago.

In 1926 there was developing in the United States an interest in aviation accomplishments. Representatives of the Daniel Guggenheim Fund for the Promotion of Aeronautics, planning flights such as those of Richard E. Byrd, came to the Weather Bureau seeking a young man to work on the meteorological aspects of their plans. The air-minded young Swede with his knowledge of modern meteorology was chosen for this work, which he carried on beginning in October of 1926, although still attached to the Weather Bureau. A series of minor incidents and irritations in connection with this work resulted in an open clash between Rossby and the Weather Bureau administration. By the time he left the Bureau in 1927 to work full time for the Guggenheim Fund as Chairman of its Committee on Aeronautical Meteorology, Rossby was literally *persona non grata* to the Weather Bureau.

In the midst of this turmoil, Rossby dug deeper than ever into his scientific work. Three of his best-known papers were completed at that time, finally appearing in *Beiträge zur Physik der freien Atmosphäre*. They had to do with changes of pressure in an air column and the dynamics of the stratosphere. They corrected a number of misconceptions which had pervaded the literature at that time concerning the effects of the stratosphere on the low-level systems.

The year 1927 saw the great stimulus to aeronautics provided by the first solo flight across the Atlantic, accomplished by Charles A. Lindbergh. The Daniel Guggenheim Fund was in the forefront developing plans for aeronautical technology, including the establishment of aeronautical engineering laboratories and promoting the growth of commercial aviation. Early in 1928 the Fund established a model airway on the route between San Francisco and Los Angeles, and Rossby was given the job of organizing a model airway weather service there. This was Rossby's first significant organizing job, and the successful way in which he handled it foretold the later organizing and promoting successes of his career. The service which he developed became the model from which present-day airways weather systems have been designed. Through this activity, the Weather Bureau found it wise to accept Rossby as a force for good in American meteorology. Shortly after the experimental service was put in operation in the summer of 1928, it was handed over to the Weather Bureau to operate, and Rossby went on to bigger things.

In connection with a department of aeronautical engineering established by the Guggenheim Fund at the Massachusetts Institute of Technology, Rossby in that year of 1928 was made associate professor and head of a new course in meteorology, the first such complete program of its kind in the United States. With the help of

Hurd C. Willett, whom he had enticed away from the Weather Bureau, Rossby struggled through the first year at M.I.T. teaching a handful of Navy officers. The following year civilian graduate students began to appear on the scene. As part of his program while chairman of the Guggenheim Fund Committee on Aeronautical Meteorology, Rossby had sent Willett to Bergen, Norway, for a year's study. Thus it came about that the team of Rossby and Willett at M.I.T. were the great American proponents of the polar front and air-mass analysis practices which had been developed by the Norwegians.

In proper chronology, it should be stated here that after a year at M.I.T. Rossby married Harriet Alexander of Boston and was settling into academic life. However, he did not receive his full professorship until 1931, when he was approaching the age of thirty-three. This was a long wait for the impatient Swede.

At M.I.T. Rossby exhibited that leadership for which he became famous. Those who studied under him practically worshiped him. They were participating in his great crusade—to bring modern meteorology to the United States, where the science had been existing in a stifling atmosphere for years. The experience of studying under him was most exhilarating. His lectures were carefully prepared and given with enthusiasm, and his informal discussions over luncheon or a cup of coffee in the neighborhood lunchroom across the street on Massachusetts Avenue were nothing less than an inspiration. No matter how bizarre or incorrect the ideas of a student or associate might be, Rossby always listened respectfully and in his discussion led the way for the individual to find the truth himself. He was never impatient with anyone with a wrong idea and almost without fail he was quick to show enthusiasm for those proposals that had merit. He always bent over backward in giving credit to the younger men for their contributions.

The application of thermodynamics to air-mass analysis attracted his attention for the first two or three years at M.I.T. Through the theoretical part of a paper published under the authorship of a graduate student, he demonstrated how the work done on a parcel of air undergoing a finite upward displacement by buoyancy forces can be computed numerically and graphically from certain types of thermodynamic diagrams. In a large paper (1932) he shed light on the importance of instability and overturning in a saturated atmosphere and provided a graphical means of identifying air masses and studying the processes which created or modified them. His recognition of the lifting condensation level as the "characteristic point" at each level of an air mass to be derived from a sounding started the investigation of the upper structure of air masses and fronts on the right track.

While awaiting the proofs on his thermodynamic paper, Rossby began to delve again into the subject he had studied seven or eight years earlier when he first came to the United States—the subject of turbulence in the friction layer. This renewed interest was in part stimulated by a visit to Göttingen, Germany, where he became acquainted with new parameters from experimental aerodynamics, and in part by his association, as a research associate, with the newly formed Woods Hole Oceanographic Institution, where ocean-air boundary problems caught his fancy. At great speed and with tireless effort he put out his paper on the "mixing length" (1932). In this paper he brought into meteorology for the first time the results of aerodynamics—the concepts of the mixing length, the roughness parameter, von Kármán's constant.

Then he settled down to a more deliberate study of turbulence and the air-ocean boundary, assisted by his student Raymond B. Montgomery. Together they published the second big M.I.T. paper on turbulence (1935). The roughness parameter and the logarithmic law of vertical wind profile were introduced and, through theory and crude observational data, the physical (as contrasted with the later statistical) approach to turbulence was carried toward perfection, although it remained a subject which could be treated only imperfectly.

Through his work in oceanography, Rossby was attracted to the problem of ocean currents and the role of friction, turbulence, and mixing in their generation and maintenance. A large paper on this subject was published (1936). While this paper might appear to have missed its mark, it was useful in pointing out that the then almost religious belief in the Bjerknes circulation theorem was leading to the neglect of other factors, and this paper seems to have had an influence on the thinking of oceanographers in their reexamination of ocean currents.

These studies led him to realize that lateral mixing was an important process to consider in explaining the adjustment of current systems. Following an earlier suggestion of Sir Napier Shaw, he reasoned that lateral mixing would occur on isentropic surfaces. With the aid of colleagues, he began the routine construction of isentropic charts, using natural water vapor as a tracer. What he saw on these charts opened his eyes as well as those of his co-workers. They not only saw evidences of large-scale mixing in the atmosphere but saw how these charts could trace the moisture of the atmosphere from its source to the areas of condensation and precipitation. The charts were a valuable synoptic meteorological tool. They also revealed a great deal of information about the general circulation of the atmosphere. This "isentropic" period of Rossby's resulted in the publication of several papers in 1937 and 1938, by himself and with co-authors, and much new understanding about the atmosphere and its behavior resulted.

At the end of his M.I.T. period, in 1938 and 1939, Rossby was studying the large-scale circulations of the atmosphere. This work led to what may be considered his two most important papers (1939, 1940). The concept of the conservation of the vertical component of the absolute vorticity (relative plus terrestrial) in currents going from one latitude to another was invoked. He showed that in a simple linear system this effect could account for the perturbations in the upper westerlies. From these results the famous Rossby equation for the long waves in the upper westerlies was developed. This equation became so much a part of meteorology that it is worth repeating here:

$$U - c = \frac{\beta L^2}{4\pi^2}$$

where *U* and *c* are the west-to-east current and perturbation speeds, respectively, β is the northward rate of increase of the earth's vertical component of vorticity, and *L* is the perturbation wave length. Rossby also took into consideration the compensating effects of shrinking and stretching of atmospheric layers (the horizontal divergence).

Now enjoying world-wide recognition as a great scientist, Rossby meanwhile left the academic halls to take a position in 1939 as assistant chief of the Weather Bureau in charge of research and education. This position afforded him an opportunity to exercise his great organizing ability, which had not been altogether dormant at M.I.T. In the Bureau he helped the new chief, F. W. Reichelderfer, to place the organization on a more scientific footing and to strengthen its mission in meteorology. He did not remain in this position long, however. In 1941 he went to the University of Chicago to take over the chairmanship of the Department of Meteorology which had been created the preceding year.

At Chicago he continued his work on the long waves in the upper westerlies and led a research team of younger men with even more miraculous results than at M.I.T. The war and his many activities in connection with it did not deter him from his quest for knowledge about the atmosphere. His participation in the war effort was wholehearted and complete. With the aid of colleagues at other universities he organized what was considered by many as the finest military scientific educational program in the country, to turn out the thousands of meteorologists needed in the Army Air Forces, the Navy, and the Weather Bureau. He traveled to distant parts of the globe to help solve operational weather problems and sent out consulting teams of his associates and others to follow up on the application of the principles learned in school or to try out new concepts. He negotiated for the establishment of an institute of tropical meteorology to study the neglected tropics where many of the battles had to be fought. All of these things he enjoyed doing with a Hollywoodian flair for dramatic executive actions.

This writer recalls an inability to convince nonmeteorologist colleagues and administrators at the University of Chicago that Rossby's research during these hectic days was really of high caliber. They could not understand how a man they saw only as a promoter could go to the other extreme so readily and become a serious scientific worker. They did not understand his dual personality, how he could be two men. In addition to his own work, he fostered research by his associates and graduate students, whose published work shows unmistakable evidence of Rossby's hand.

Two papers published in 1942 had an important influence in the field of meteorology. One, written with two graduate assistants, developed the theory and practice of what subsequently became known as "single-station analysis." The other was a continuation of his studies of the long waves in the westerlies, showing interesting relationships of the combined fields of temperature and pressure in determining the displacement of the waves. Through 1943 he continued to work on this and related problems. Two papers in 1944 and 1945 in the new *Journal of Meteorology,* which periodical he was instrumental in founding, developed the idea of the group velocity of the upper waves, showing influences of the waves on developments at great distances. The theory also was applied to ocean "tidal waves."

After the war, Rossby gathered around him an outstanding group of graduate students and a few of Europe's leading meteorologists, the most famous being Erik Palmén of Finland. In their fertile minds, under the intense prodding and flow of ideas from Rossby, most of the basic concepts of the jet stream and its perturbations were developed. His explanation of the concentration of velocity as being a result of vorticity conservation did not prove entirely successful, but his ideas fed the wellspring from which improved concepts were drawn. The jet stream ideas were published under the authorship of "Staff Members" in 1947 in the *Bulletin of the American Meteorological Society,* and Rossby's theories appeared in the same volume under his own name.

In the early postwar years he was the major force in the reorganization of the American Meteorological Society. He started climatic and meteorological investigations in Hawaii in cooperation with the Pineapple Research Institute and, in the field of pure science, launched Dave Fultz on his well-known hydrodynamic model experiments at Chicago. With John von Neumann and Jule Charney he actively participated in the development of machine computation of the prognosis.

In 1948 to 1950 Rossby's Chicago period gradually came to an end. Although he had been naturalized as an American citizen in 1939, his eyes again turned to his native Sweden. The Swedish government wanted his advice concerning the future of meteorological education, research, and services. With continuing research commitments to the U.S. Department of Defense, Rossby became almost a commuter between Chicago and Stockholm. Later he transferred his American affiliation to the Woods Hole Oceanographic Institution, an arrangement which still existed at the time of his death.

In Stockholm, an institute of meteorology was established around Rossby at the University. To match the scope of his interest and to satisfy Sweden's desire to be an international cultural force, he made great efforts to have the institute recognized as an international institute. Some important international bodies gave it such endorsement not only in words but in token financial support. With scholars gathered from many lands, there never was any question about its international character.

In his Chicago-to-Stockholm transition period in 1948 and 1949, Rossby developed further his ideas on vorticity and stable and unstable vortices. He showed that a cyclonic vortex around the pole is stable, while an anticyclonic one is unstable. Thus the cold anticyclones of the polar regions represent potential energy which is released in cold waves spreading equatorward.

In addition to general leadership, Rossby's last Stockholm period was marked by three principal achievements: (1) the establishment of the geophysical journal *Tellus,* (2) the inauguration of the first European machine forecasting center, which had great success in using a barotropic model, and (3) the fostering of a rebirth in interest in atmospheric chemistry. A broad look was taken at atmospheric and ocean currents. He co-authored a paper (1949) which represents an excellent example of the application of Rossby ideas to a study of large-scale atmospheric phenomena. His 1951 papers on the concentration of momentum in air and ocean currents perhaps represent the culmination of his thinking on these subjects. Having turned now to machine computations (Staff, 1952), Rossby left the field of dynamic meteorology, to which he had devoted his entire career up to that time.

Rossby's excursion into atmospheric chemistry, or, more specifically, precipitation chemistry, was regarded by many of his friends and colleagues as a most singular thing for him to do. His background in chemistry was meager. He explained that meteorology needed to expand its horizons into a wider geophysical view, and when chemistry seemed to offer, in Sweden, a good opportunity for such broadening, he seized upon it and enjoyed the challenge of it and his own initial ignorance of the subject. His institute, with the journal *Tellus,* became the world center for symposia on many aspects of atmospheric chemistry. At the time of his death he was just completing a major manuscript on this subject, published in translation posthumously. In it he sees the atmosphere as a carrier of particles and related chemical constituents, continually interacting with the earth, particularly the oceans, in a chemical sense and playing its part in a great geochemical balance. Even the giant circulations of the atmosphere are related to the minutest processes of the biosphere.

In evaluating the contributions of this man it must be recognized that they did not result alone from his great energy and enthusiasm.

His accomplishments, which were mostly in the field of theoretical meteorology, were in part made possible by what he liked to call the heuristic approach, that approach which is concerned with finding a useful answer without the impediments of all of the small-scale effects. As practice has shown, especially in such efforts as machine forecasting, the neglect of certain factors has led to greater accuracy than is attainable when these factors are taken into consideration. It was interesting to hear Rossby argue this point with outstanding scientists who did not understand this peculiarity of open, thermo-convective hydrodynamic systems such as the atmosphere and ocean.

Rossby's personal life was supercharged with excitement, but his wife and three children stood the strain well. On the practical side, his principal weakness was an inability to save money. He spent freely for the education of his children and for family travel, and loved to spend lavishly on his favorite pastime—discussion with as many friends and colleagues as he could gather about him over a dinner in an expensive restaurant.

A peculiarity of his make-up was his complete inability to master anything mechanical. His own deficiency in this connection gave him an almost childlike respect for his colleagues and associates who were clever with instruments and apparatus. At one time while at M.I.T. he managed to pass a test for an automobile driver's license, but after a few experiences, the nature of which he did not disclose to his friends, he never again sat behind the wheel, but delegated the driving chore to his wife. His lack of mechanical aptitude extended to many aspects of his personal life, leaving his friends and associates with a host of "Rossby" stories about the comical situations in which he found himself because of his inability to cope with material details.

Above all, he had a charming personality. To be with him not only was exciting but also made one feel important and enthusiastic. His best personal qualities seemed to be reflected automatically in those about him.

HONORS

DEGREES

Hon. Sc.D., Kenyon College, Ohio, 1939
Hon. Ph.D., University of Stockholm, 1951

AWARDS

Albert Sylvanus Reed Award of the Institute of the Aeronautical Sciences (jointly with H. C. Willett), 1933
Robert M. Losey Award of the Institute of the Aeronautical Sciences, 1946
Symons Medal of the Royal Meteorological Society, 1953
American Meteorological Society Service Award, 1956
World Meteorological Organization Prize, 1957 (Posthumous)
American Meteorological Society Award in Applied Meteorology, 1959 (Posthumous)

TITLE

Andrew MacLeish Distinguished Service Professor, University of Chicago, 1943

MEMBERSHIP HONORS

National Academy of Sciences
American Philosophical Society
Austrian Academy
Finnish Academy
German Academy
Norwegian Academy of Science
Swedish Academy
Academy of Engineering Sciences, Stockholm
Honorary Member, Royal Meteorological Society

KEY TO ABBREVIATIONS

Ann. N.Y. Acad. Sci. = Annals of the New York Academy of Sciences
Arch. f. Met. Geophys. u. Bioklim. = Archiv für Meteorologie, Geophysik und Bioklimatologie
Arkiv. f. Math. Astr. och Fys. = Arkiv. för Mathematik, Astronomi, och Fysik
Beitr. z. Phys. d. freien Atmos. = Beiträge zur Physik der freien Atmosphäre
Bul. Am. Met. Soc. = Bulletin of the American Meteorological Society
Geof. Pura e Appl. = Geofysica Pura e Applicata
Geogr. Ann. = Geografiska Annaler
I.U.G.G. Assoc. Met. Gen. Assbly. = International Union of Geodesy and Geophysics, Association of Meteorology, General Assembly
J. Aero. Sci. = Journal of the Aeronautical Sciences
J. Chinese Geophys. Soc. = Journal of the Chinese Geophysical Society
J. Mar. Res. = Journal of Marine Research
J. Met. = Journal of Meteorology
J. Wash. Acad. Sci. = Journal of the Washington Academy of Sciences
Medd. fran Statens Met.-Hydr. Anstalt = Meddelanden fran Statens Meteorologiska-Hydrologiska Anstalt (Stockholm)
M.I.T. Met. Prof. Notes = Massachusetts Institute of Technology, Meteorology Course, Professional Notes
M.I.T. Papers in Met. = Massachusetts Institute of Technology, Papers in Meteorology
M.I.T. and W.H.O.I. Papers in Phys. Oceanogr. and Met. = Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, Papers in Physical Oceanography and Meteorology
Mon. Wea. Rev. = Monthly Weather Review
Proc. 3rd Hydraul. Conf. = Proceedings of the Third Hydraulics Conference
Proc. 5th Cong. Appl. Mech. = Proceedings of the Fifth Congress for Applied Mechanics. Cambridge, Mass.
Quar. J. Roy. Met. Soc. = Quarterly Journal of the Royal Meteorological Society
Sitz. d. D. Ak. Wiss. z. Berlin, Math.-Naturw. Klasse = Sitzungsberichte der Deutschen Akademie der Wissenschaften zu Berlin, Mathematisch-Naturwissenschaftliche Klasse
Tek. Tidskr. = Teknisk Tidskrift (Stockholm)
Toronto Proc. Suppl. = Toronto Proceedings Supplement
Trans. Am. Geophys. U. = Transactions of the American Geophysical Union
U.S. Dept. Agric., Yearb. of Agric. = U.S. Department of Agriculture, Yearbook of Agriculture
Univ. Chi. Dept. Met. Misc. Rep. = University of Chicago, Department of Meteorology, Miscellaneous Reports
Univ. Iowa Studies in Engrg. = University of Iowa Studies in Engineering
Yearb. = Yearbook

BIBLIOGRAPHY

1923

Den Nordiska Aerologiens Arbetsuppgifter. En Återblick och ett Program. Ymer, 43:364.

1924

On the Origin of Traveling Discontinuities in the Atmosphere. Geogr. Ann., 2:180–89.

Thermisches Gleichgewicht in der Atmosphäre. Arkiv f. Math. Astr. och Fys., 18:11–20.

1925

Meteorologiska Resultat av en Sommarseglat Rundt de Brittiska Oearna. Medd. fran Statens Met.-Hydr. Anstalt., 3, No. 1.

Not beträffande Teorin för Flettner-rotor. Tek. Tidskr. No. 2.

1926

With R. H. Weightman. Applications of the Polar Front Theory to a Series of American Weather Maps. Mon. Wea. Rev., 54:485–96.

The Vertical Distribution of Atmospheric Eddy Energy. Mon. Wea. Rev., 54:321–32.

On the Solution of Problems of Atmospheric Motion by Means of Model Experiments. Mon. Wea. Rev., 54:237–40.

1927

Convection in the Free Atmosphere and over a Heated Surface. Mon. Wea. Rev., 55:1–5.

Theory of Atmospheric Turbulence—a Historical Résumé and an Outlook. Mon. Wea. Rev., 55:6–10.

Zustandsänderungen in atmosphärischen Luftsäulen, I. Beitr. z. Phys. d. freien Atmos., 13:163–74.

1928

Studies in the Dynamics of the Stratosphere. Beitr. z. Phys. d. freien Atmos., 14:240–65.

Airways and the Weather. Western Flying, April.

1929

Theoretical part of a monograph by C. M. Alvord and R. H. Smith. The Tephigram, Its Theory and Practical Uses in Weather Forecasting. M.I.T. Met. Prof. Notes, No. 1:7–13.

1930

On the Effect of Vertical Convection on the Lapse Rates. J. Wash. Acad. Sci., 20:33–35.

1932

Thermodynamics Applied to Air Mass Analysis. M.I.T. Papers in Phys. Oceanogr. and Met., 1, No. 3.

A Generalization of the Theory of the Mixing Length with Application to Atmospheric and Oceanic Turbulence. M.I.T. Papers in Phys. Oceanogr. and Met., 1, No. 4.

1934

Comments on Meteorological Research. J. Aero. Sci., 1:32–34.

1935

With R. B. Montgomery. The Layer of Frictional Influence in Wind and Ocean Currents. M.I.T. and W.H.O.I. Papers in Phys. Oceanogr. and Met., 3, No. 3.

1936

With R. B. Montgomery. On the Momentum Transfer at the Sea Surface. M.I.T. and W.H.O.I. Papers in Phys. Oceanogr. and Met., 4, No. 3.

Dynamics of Steady Ocean Currents in the Light of Experimental Fluid Mechanics. M.I.T. and W.H.O.I. Papers in Phys. Oceanogr. and Met., 5, No. 1.

1937

With collaborators. Aerological Evidence of Large Scale Mixing in the Atmosphere. Trans. Am. Geophys. U., 1937, Part I:130–36.

With collaborators. Isentropic Analysis. Bul. Am. Met. Soc., 18:201–9.

On the Mutual Adjustment of Pressure and Velocity Distributions in Certain Simple Current Systems. J. Mar. Res., 1:15–28.

Rate of Turbulent Mixing. In paper by F. B. Wood: The Formation and Dissipation of Stratus Clouds beneath Turbulence Inversions. M.I.T. Met. Prof. Notes, No. 10:9–15.

1938

On Temperature Changes in the Stratosphere Resulting from Shrinking and Stretching. Beitr. z. Phys. d. freien Atmos., 24:53–60.

Note on Shearing Stresses Caused by Large Scale Lateral Mixing. Proc. 5th Cong. Appl. Mech., 1938:379–82.

On the Role of Isentropic Mixing in the General Circulation of the Atmosphere. Proc. 5th Cong. Appl. Mech., 1938:373–79.

Solenoidal Circulations Resulting from Lateral Mixing. Trans. Am. Geophys. U., 1938, Part I: 159–62.

With J. Namias and R. Simmers. Fluid Mechanics Applied to the Study of Atmospheric Circulations. Part I: A Study of Flow Patterns with the Aid of Isentropic Analysis. M.I.T. and W.H.O.I. Papers in Phys. Oceanogr. and Met., 7, No. 1.

With G. Grimminger, C. L. Pekeris, J. Namias, and H. Wexler. Application of Fluid Mechanics to the Problem of the General Circulation of the Atmosphere. Trans. Am. Geophys. U., 1938:159–70, 174–76.

On the Mutual Adjustment of Pressure and Velocity Distributions in Certain Simple Current Systems—II. J. Mar. Res., 1:239–63.

1939

Relation between Variations in the Intensity of the Zonal Circulation of the Atmosphere and the Displacements of the Semi-permanent Pressure Systems. J. Mar. Res., 2:38–55.

1940

Planetary Flow Patterns in the Atmosphere. Quar. J. Roy. Met. Soc. (Toronto Proc. Suppl.), 66:68–87.

1941

The Scientific Basis of Modern Meteorology. U.S. Dept. Agric., Yearb. of Agric., 1941:599–655.

Amateur Forecasting from Cloud Formations. U.S. Dept. Agric., Yearb. of Agric., 1941:656–61.

Comments on the Weather Bureau's Experiment in Five-Day Weather Forecasting. Trans. Am. Geophys. U., 1941:437–437b.

1942

With V. J. Oliver and M. Boyden. Weather Estimates from Local Aerological Data: A Preliminary Report. Univ. Chi. Dept. Met. Misc. Rep., No. 2.

Kinematic and Hydrostatic Properties of Certain Long Waves in the Westerlies. Univ. Chi. Dept. Met. Misc. Rep., No. 5.

With D. Fultz, H. G. Dorsey, and M. Boyden. Forecasting of Flow Patterns in the Free Atmosphere by the Trajectory Method. In V. P. Starr, *Basic Principles of Weather Forecasting,* 268–84.

1943

Specific Evaluation of Pilot Balloon Data in Single-Station Forecasting. Sect. II in Monograph by W. W. Jones and Staff Members: Weather-Map Construction and Forecasting in the Westerlies from Single-Station Aerological Data. Univ. Chi. Dept. Met. Misc. Rep., No. 7.

Boundary Layer Problems in the Atmosphere and Ocean—Introduction to the Conference and Some Applications of Boundary-Layer Theory to the Physical Geography of the Middle West. Ann. N.Y. Acad. Sci., 44, Art. 1:3–12.

1944

Horizontal Motion in the Atmosphere. J. Met., 1:109–14.

1945

On the Propagation of Frequencies and Energy in Certain Types of Oceanic and Atmospheric Waves. J. Met., 2:187–204.

The Scientific Basis of Modern Meteorology. In F. Berry, E. Bollay, and N. Beers, *Handbook of Meteorology,* Ch. 7:501–30.

The Earth Sciences and the Undergraduate Liberal Arts Curriculum. Bul. Am. Met. Soc., 26:1–4.

1947

On the Distribution of Angular Velocity in Gaseous Envelopes under the Influence of Large-Scale Horizontal Mixing Processes. Bul. Am. Met. Soc., 28:53–68.

With Staff Members. On the General Circulation of the Atmosphere in Middle Latitudes. Bul. Am. Met. Soc., 28:255–80.

Notes on the Distribution of Energy and Frequency in Surface Waves. J. Mar. Res., 6:93–103.

Recent Advances and Probable Future Trends in Basic and Applied Meteorology. Proc. 3rd Hydraul. Conf., Univ. Iowa Studies in Engrg., Bul. 31:103–20.

1948

On Displacements and Intensity Changes of Atmospheric Vortices. J. Mar. Res., 7:175–87.

Nyare Riktlinjer inom Meteorologie: de Atmosfäriska Rörelsesystemens Skala och Structur. Kosmos (Yearb. Svenska Fysikersamfundet), 26: 162–82.

The Circulation of the Upper Troposphere and Lower Stratosphere. Science, 108:643–52.

With R. Berggren and B. Bolin. On the Mechanism of Changes in the Upper Flow Pattern. I.U.G.G. Assoc. Met., 8th Gen. Assbly., Oslo.

1949

On the Nature of the General Circulation of the Lower Atmosphere. In G. P. Kuiper, ed., *The Atmospheres of the Earth and Planets,* Ch. 2: 16–48.

On the Dispersion of Planetary Waves in a Barotropic Atmosphere. Tellus, I, No. 2:54–58.

On a Mechanism for the Release of Potential Energy in the Atmosphere. J. Met., 6:163–80.

With R. Berggren and B. Bolin. An Aerological Study of Zonal Motion, Its Perturbations and Breakdown. Tellus, I, No. 2:14–37.

With H. Ertel. A New Conservation Theorem of Hydrodynamics. Geof. Pura e Appl., 14:189–93.

With H. Ertel. Ein neuer Erhaltungs-satz der Hydrodynamik. Sitz. d. D. Ak. Wiss. z. Berlin, Math.-Naturw. Klasse, 1949:No. 1.

Glaciers and Climatology; Hans W:son Ahlmann's Contribution. Glaciers and Climate, Geogr. Ann., 1949, No. 1–2:11–13.

With V. P. Starr. Interpretations of the Angular Momentum Principle as Applied to the General Circulation of the Atmosphere. J. Met., 6:288.

1950

On the Dynamics of Certain Types of Blocking Waves. J. Chinese Geophys. Soc., Vol. 2:1–13.

1951

On the Vertical and Horizontal Concentration of Momentum in Air and Ocean Currents. I: Introductory Comments and Basic Principles with Particular Reference to the Vertical Concentration of Momentum in Ocean Currents. Tellus, 3:15–27.

Note on Cooperative Research Projects. Tellus, 3:212–16.

Über die Vertikalverteilung von Windgeschwindigkeit und Schwerestabilität in Freistrahlbewegung der oberen Troposphäre. Arch. f. Met. Geophys. u. Bioklim., Series A, 4:3–23.

1952

With Staff Members. Preliminary Report on the Prognostic Value of Barotropic Models in the Forecasting of 500-mb Height Changes. Tellus, 4:21–30.

Wanted: A Government Policy towards Research. Statens Naturvetenskapliga Forskningsråds Årsbok, 1951–52.

1953

A Comparison of Current Patterns in the Atmosphere and in the Ocean Basins. I.U.G.G. Assoc. Met., 9th Gen. Assbly. Brussels, pp. 9–30.

1955

With H. Egnér. On the Chemical Climate and Its Variation with the Atmospheric Circulation Pattern. Tellus, 7:118–33.

1957

Aktuella Meteorologiska Problem. Statens Naturvetenskapliga Forskningsråds Årsbok, 1956:15–80.

1959 (Posthumous)

Current Problems in Meteorology. In B. Bolin, ed., *The Atmosphere and Sea in Motion* (Rossby Memorial), New York, Rockefeller Institute Press, p. 25.