HERBERT RIEHL

Intrepid and Enigmatic Scholar

BY JOHN M. LEWIS, MATTHEW G. FEARON, AND HAROLD E. KLIEFORTH

After escaping Germany in 1933 followed by a venture on Wall Street, Riehl was drawn into meteorology by war, found his calling in Rossby's School, and went on to become the "father of tropical meteorology."

The pathways that led thousands of scientifically and mathematically inclined young people into meteorology during World War II (WWII) exhibited a wide variance as might be expected. The course followed by Herbert Riehl (1915–97) was one of the most unusual—a passageway that began in 1933 when his Jewish mother realized that escape from Nazi Germany was critically important to the welfare of her only child, 18-year-old Herbert. And although it would be another seven years before Riehl entered the field of meteorology, once he embarked on this course it quickly became apparent that he possessed a natural talent for understanding the complex atmospheric system.

In the immediate post-WWII period when dynamics of midlatitude weather was the rage, Riehl ventured into the study of low-latitude weather—the weather of the tropics and subtropics, that region of limited observations and poorly understood dynamical constraints.[1] His foray into this challenging scientific landscape set the stage for others to follow and he became known as the "father of tropical meteorology" (Gray 1998).

We explore the roots of Riehl's broad-spectrum view of meteorology and identify those who exerted great influence on this view. We pay particular attention to Riehl's ▶

PHOTO. Herbert Riehl (1915–97) in a contemplative mood on Montgomery Peak, White Mountains on the California–Nevada border. (June 1961) (Courtesy of H. Klieforth).

[1] In this manuscript, we assume the following latitudinal boundaries for the subtropics and midlatitudes: subtopics adjacent to the tropics (23.5°N/S to 35°N/30°S) and midlatitudes from 35N°/30°S to 60°N/S).

accomplishments during the first two decades of his career, from the mid-1940s through the late 1950s. It was during this time period that he established himself as an original thinker about the global atmospheric system. We examine his experiences as an instructor at the Institute of Tropical Meteorology in Puerto Rico during WWII and follow with his experiences in the milieu of "Rossby's School" at University of Chicago (U of C).

As a professor of meteorology at U of C following WWII, he drew a cadre of exceptional graduate students into his zone through the eminently successful course in tropical meteorology. And from this course came his classic text, *Tropical Meteorology* (Riehl 1954). Through presentation of vignettes from several of these students, Riehl's style of mentorship is revealed. The interactions between Riehl and one of his students, Joanne Simpson,[2] are examined in detail.

Beyond the first two decades of Riehl's career, we briefly examine his disconnection from the computational age of research in meteorology and his role in the foundation of the Department of Atmospheric Science at Colorado State University (CSU). We end with an epilogue that strives to assess his unique scholarship in meteorology.

ESCAPE FROM GERMANY. Herbert Riehl was Jewish and the only child of a wealthy German couple. With the rise to power of the fascist National Socialist German Workers Party (Nationalsozialistische deutsche Arbeiterpartei or Nazi Party) in the early 1930s, the Riehl family began planning for departure from Germany. As remembered by William Gray, one of Riehl's doctoral students at U of C during the late 1950s:

> Riehl's mother [Olga Betha (née Bach) Riehl][3] was Jewish and his father [Herbert Anton Maxamillon Riehl] gentile. His mother came from wealth and his father was a medical doctor serving with the German Army where he died of pneumonia on the western front in 1915 [when Herbert was about 1 month old]. Riehl attended a lyceum[4] [the Humanistisches Gymnasium in Berlin with accents on classics] and he finished this education around the time that Hitler came to power [Hitler was named Chancellor in March 1933]. I recall Riehl telling me that the day after he graduated from the lyceum, Hitler announced that no more Jews could graduate from high schools in Germany (Zentner and Bedürftig 1991; W. Gray 2011, personal communication).

Upon Herbert Riehl's graduation from the Humanistisches Gymnasium in March 1933, his mother sent him to England to perfect his use of the English language. And in the absence of his family, he immigrated to the United States in September 1933.[5] He immediately began work for the J. S. Bache and Co. stockbrokerage firm on Wall Street. His uncle, Jules Semon Bache,[6] was the gifted entrepreneur behind this eminently successful investment company [discussed in Birmingham (1967)]. Between late 1933 and 1936, Herbert worked all stations on the stock market floor, but arrogance and a condescending attitude toward his uncle led to his dismissal and disinheritance (J. Riehl 2011, personal communication). With the writing skills that came with his classic education, he had the desire to become a scriptwriter for the film industry. According to Gray, "… because of his fluent German and issues related to the war in Europe, he achieved his dream of becoming a scriptwriter in Hollywood" (Gray 1998; W. Gray 2011, personal communication). In fact, Riehl bought a car in 1936 and drove to California by way of Route 66. He had a "letter of introduction" in hand and obtained a job as tour guide at Metro-Goldwyn-Mayer (MGM) in Culver City, California. He advanced to scriptwriter at MGM and remained there until 1939 (J. Riehl 2011, personal communication).

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[2] In this paper, reference is also made to Joanne Malkus, her name before marriage to Robert Simpson in 1965.

[3] The authors have inserted the bracketed information within the quotes.

[4] Lyceum is the English word for an advanced secondary school ("prep school")—referred to as *Gymnasium* in Germany and *Lycée* in France.

[5] Riehl managed to get his mother and stepfather (Dr. Ernst Moll) out of Germany in 1939 through work with the Marlene Dietrich "underground" (transport from Germany to Cuba). (J. Riehl 2011, personal communication)

[6] Bache was the Americanized version of Bach.

Fig. 1. Athelstan Spilhaus (left) and Gardner Emmons at NYU (c. 1940) (Courtesy A. Spilhaus).

Upon his return to New York City in 1939, Riehl was granted U.S. citizenship. He then worked for a wholesale Italian greengrocer until he saw a newspaper advertisement for Army Air Corps cadets to serve in various branches of engineering.[7] Riehl passed their first test and chose electrical engineering, but he was told that every category was filled except meteorology. Riehl then spoke with Professor Athelstan Spilhaus, head of the Department of Meteorology and Oceanography at New York University (NYU), one of the five universities chosen to offer the Cadet Program in meteorology. The other universities offering this program were the California Institute of Technology, the University of California at Los Angeles (UCLA), the University of Chicago, and the Massachusetts Institute of Technology (MIT).[8] Riehl had graduated *Abitur* from the gymnasium in Berlin and his high academic achievement qualified him for the Cadet Program at NYU (Riehl 1983). He enrolled in fall 1940. Although there is scant information about Riehl's education and experiences at NYU, we know he finished first in his class. Riehl's later prowess as a synoptic analyst also leads one to believe that Gardner Emmons, an outstanding NYU teacher of synoptic meteorology, put his mark on Riehl.[9] Emmons is shown beside Spilhaus in Fig. 1. Not only did Riehl complete the Cadet Program at NYU, he did sufficient extra work to earn the M.S. degree. Although promised a commission in the Air Corps upon completion of the program, Riehl was given an honorable discharge. He never knew what happened to create the change.

Riehl's top rank in the graduating class and receipt of the M.S. degree was undoubtedly related to his strong foundation in logic and excellent performance in mathematics (J. Riehl 2011, personal communication; Riehl 1983).[10] In the absence of a commission in the Air Corps or appointment as an instructor in the Cadet Program at NYU, he visited Rossby at the U of C's Institute of Meteorology (founded in fall 1940; Byers 1976). As he recalled,

> My first acquaintance with Rossby was in 1941 when I visited him just starting in Chicago. He had obtained my first meteorology job for me at the U. of Washington after finishing the 1-year course at NYU. One year later I came back as instructor in the lab in Chicago (H. Riehl 1991, personal communication).

IMMERSION INTO METEOROLOGY.

Instructor in the cadet program. To fortify the instructional staff for the large "A" classes in the Cadet Program at U of C, Horace Byers (Rossby protégé and administrator of the Cadet Program at U of C) added Phil Church and Herbert Riehl to the Officers of Instruction for the 1942–43 academic year (Fig. 2).[11] As noted in Fig. 2, Riehl was an instructor (most likely a lab instructor based on the oral history statement given at the end of section 2). Information in Fig. 3 lists Byers and Riehl as instructors for Meteorology 211 (Synoptic Meteorology) and Church is listed as the instructor for Oceanography (Meteorology 221). In Fig. 4, we find a photograph

[7] Most of the information in this paragraph comes from three letters sent to the authors by Janis Riehl, Herbert Riehl's widow.

[8] The Cadet Program prepared students for the job of weather forecaster (primarily in the U. S. Army Air Corps or U. S. Navy). The "A" school was a nine-month program for students with the equivalent of a baccalaureate in science. The "B" school was a 6-month program for those without the bachelor's degree—a preparatory course for the "A" program where the subjects of math, science, and communication were included. This Cadet Program was started in October 1940 (Walters 1952).

[9] Personal communications with the following meteorologists attest to Emmons' talent as a forecaster and analyst: R. Fleagle (1993), P. Clapp (1994), and A. Spilhaus (1994).

[10] In addition to Riehl's classic education at the Humanistisches Gymnasium, he attended and excelled in mathematics at the Grunevald Science Gymnasium in Berlin.

[11] Church was professor of geography at University of Washington before the war and would play a major role in the post-war establishment of the meteorology department at University of Washington.

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INTRODUCTORY

The Institute of Meteorology has as its objectives: (1) advancement of the understanding of atmospheric processes and measurements, (2) instruction in the principles of meteorology, and (3) training of graduate students for professional work in meteorology. To meet the need for great numbers of newly trained professional meteorologists in the military and civil weather services, the Institute has geared its instruction to a highly intensified, productive program. A majority of the students are officers and men of the United States Army Air Forces. In addition to its all-out war instruction program, the Institute of Meteorology has taken a forward position in research directed toward the solution of problems of foremost importance in both war and peace.

FACILITIES

For meteorological instruction and research, the University provides complete synoptic-analysis laboratories, including files of several years of analyzed weather maps and upper-air charts for various regions of the world. The usual meteorological instruments and equipment for pilot-balloon observations are used by the students, and a completely equipped laboratory for radiosonde observations of the upper atmosphere is provided. A special feature is the mobile weather unit which, mounted on a truck, provides experience similar to that encountered in combat areas. The mobile unit is equipped with pilot-balloon and radiosonde apparatus, and weather-charting equipment permitting a complete weather observation, analysis, and forecast in the field. A complete hydrodynamics laboratory is used in the instruction and research. An official observatory of the United States Weather Bureau is located on the Quadrangles. Well-equipped shops make possible construction of special apparatus for research. A special library of meteorological books and journals is in the Institute of Meteorology.

Fig. 2. Officers of Instruction, Department of Meteorology, U of C, academic year 1943/44 (Courtesy of Special Collections, U of C Libraries).

of graduating students in the 3rd Cadet class at U of C and officers of instruction including Church and Riehl. The nine-month period of study for the 3rd Cadet class was from March through November 1942. Line drawings copied from this photograph are used to identify some of the individuals. The line drawings are found in appendix A.

Epiphany at Rio Piedras. By 1942, the Japanese had overrun Burma, Malaysia, the Netherlands East Indies, the Philippines, and Thailand. Japan's steady expansion led to the urgent need for knowledge of tropical weather. In response to Japan's military expansion into the tropical latitudes, Rossby approached the U.S. Army Air Corps Directorate of Weather and asked them to consider an augmentation to the 9-month Cadet program at the five universities: the addition of a tropical meteorology component. Rossby had support from some of the commanding officers in the field, who said, "… there is a lack of ability in analyzing and forecasting upper-air flow and other problems peculiar to the tropics" (Walters 1952, p. 87).

By early 1943, the Directorate authorized specialized training in tropical meteorology at Rio Piedras, Puerto Rico, home of the University of Puerto Rico.[12] Rio Piedras is located about 10 km inland from San Juan on the northern coast of this Caribbean island. The training took place at the Institute of Tropical Meteorology (ITM), an on-campus institute jointly operated by the University of Puerto Rico and the University of Chicago. Puerto Rico, then as now a U.S. Protectorate, spans ~0.5° of latitude (18°–18.5°N). Thus, it is positioned farther south than the Hawaiian Islands and comes under the influence of the Atlantic Trades and of course experiences the passage of hurricanes. In short, this was the Atlantic Ocean counterpart to the active islands of war in the central Pacific (e.g., the Northern Mariana Islands and the Philippines).

Clarence Palmer and Gordon Dunn, meteorologists with extensive experience in tropical analysis, established the course of instruction at the ITM during the months of March–May 1943 (Burpee 1989). By mid-1943, the ITM began offering courses.

[12]The Directorate also approved specialized training in oceanography (at Scripps Institution of Oceanography, La Jolla, California) and in chemical warfare (at Dugway Proving Grounds, Utah).

Although the ITM was officially an extension of the U of C Cadet Program, graduates from any of the cadet-program institutions were eligible for assignment at the institute. Palmer was appointed director of the ITM after he had gained fame as a tropical analyst and forecaster before and during the war (Palmer 1951). Prior to his appointment as director, he served as a Royal New Zealand Air Force Officer at Guadalcanal.[13]

Although there is an absence of information on the ITM in the archives of the U of C, we have relied on input from Reid Bryson and Riehl. Bryson was assigned to the ITM in October 1943. After completion of his training, he was retained as an instructor at the ITM until May 1944.[14] We quote from Bryson's reminiscence:

COURSES OF INSTRUCTION

For information concerning quarters when courses are given, see "Schedule of Courses" above. Courses 312 to 319, inclusive, offer credit either in Meteorology or in Physics. Courses marked * require payment of a laboratory fee (see p.21).

201. Introductory Meteorology.--Structure of the atmosphere; atmospheric motions and meteorological processes; air masses and fronts; tropical and extratropical cyclones. Tu-F, 10, BYERS, STARR.

203. Applied Climatology.--The climates of the world with special emphasis on war theaters. Tu-F, 9, LANDSBERG, BIEL.

205. Field Course.--Instruments and technique of weather observations; special atmospheric measurements at the observatory and in the field. ½C. Hrs to be arranged, LANDSBERG, STAFF.

211. Synoptic Meteorology.--Radiation, convection, evaporation, etc., in relation to the properties of air masses; formation and structure of fronts; the tropical and extra-tropical cyclones. Tu-F, 11, BYERS, RIEHL.

212. Synoptic Meteorology.--Details of frontal activity; motions on isentropic surfaces; lateral divergence and vorticity; physics of condensation and precipitation; phenomena affecting aeronautics. Tu-F, 11, BYERS.

***216. Meteorological Laboratory.**--Synoptic weather observations; decoding and plotting of synoptic messages; isobaric and frontal analysis of the weather map and practice in the utilization of upper-air data. 2Cs. Afternoons and evenings, MEANS.

***217. Meteorological Laboratory.**--Three-dimensional synoptic analysis, including isentropic and other upper-air charts; displacement of pressure systems and fronts; forecasting practice. 2Cs. Afternoons and evenings, OLIVER, MEANS.

***218. Meteorological Laboratory.**--Complete three-dimensional synoptic analysis, including isentropic and other upper-air charts; displacement of pressure systems and fronts; forecasting practice. 2Cs. Afternoons and evenings, OLIVER.

***221. Oceanography.**--The physical geography of the sea; elementary dynamics of ocean currents ½C. Tu-F, 9, CHURCH.

***246. Advanced Calculus for Meteorologists.**--Selected topics in advanced calculus, including partial derivatives, line and surface integrals, and the elements of ordinary and partial differential equations with emphasis on applications to mechanics and physics. [Not given 1943-44].

312. Hydrodynamics.--Review of classical mechanics including equations of motion in rotating coordinate systems. Hydrodynamics of nonviscuous fluids, Euler's equation, potential flow, vortex motion. Concepts illustrated with experiments. Tu-F, 8, FERENCE.

313. Hydrodynamics of Viscous Flow.--Continuation of classical hydrodynamics with emphasis on special problems in potential flow. Navier-Stokes' equation, creeping motion, applications to lubrication, introduction to boundary layer theory. This course includes a few laboratory experiments. Tu-F, 10, FERENCE.

314. Hydrodynamics of Turbulent Flow.--Special topics in turbulent motion, including laboratory work. Hrs to be arranged, FERENCE.

315. Dynamic Meteorology.--The general circulation of the atmosphere; thermodynamics and statistics. Prereq: Physics 105, 106, 107, and preferably Math 247. Students without Met 312 are urged to take it simultaneously. Tu-F, 11, ROSSBY, STARR, PLATZMAN.

316. Dynamic Meteorology.--Introduction to the dynamics of the atmosphere. Prereq: Met 315, 312. Tu-F, 8, ROSSBY, STARR, BELLAMY.

317. Dynamic Meteorology.--Application of dynamic concepts to forecasting and special problems related to warfare. Tu-F, 8, ROSSBY, BELLAMY.

318. Physics of the High Atmosphere.--Composition and properties of the atmosphere at great heights; atmospheric ozone; radiation and ionization. Tu-F, 10, WULF.

***319 Technique of Upper-Air Observations (laboratory).**--The various types of radiosonde and other instruments for observations in the upper air. ½C. Hrs to be arranged, BELLAMY.

341, 342, 342, 344. Experimental Meteorology.--Introductory courses leading usually to a Master's thesis. Problem will be assigned in consultation with the instructor. Prereq: Met 216, 217, 218, 319. Hrs to be arranged, ROSSBY, BYERS, LANDSBERG, FERENCE, STARR.

399. Professional Forecasters' Course.--A special, intensive course for professional meteorologists, involving mainly individual study of the application of results of new research to weather forecasting. Registration only after consultation with appropriate instructor. 3Cs. Each qr, hrs to be arranged, STAFF.

406, 407, 408, 409. Research Course.--For students prepared to undertake special research, leading to a Doctor's thesis. Hrs to be arranged, ROSSBY, BYERS.

420. Reading and Research in Foundations of Meteorology.--Prereq: Facility in reading German. Each qr, STAFF.

* Optional.
† May be taken first quarter.
‡ Geography 203 and Meteorology 221 are two half-courses in sequence.

Fig. 3. Course listing, Department of Meteorology, U of C, academic year 1943/44 (Courtesy of Special Collections, U of C Libraries).

Fig. 4. Graduation photograph of the 3rd Cadet Class at U of C in Nov 1942. A chart identifying graduates and teachers is found in appendix A (Courtesy of Noburo Nakamura and the Department of Geophysical Sciences, U of C).

[13]Clarence Palmer (1911–73) was appointed Associate Professor of Meteorology at UCLA in 1948 and remained there until retirement in 1972.

[14]Following WWII, Bryson returned to the U of C where he received his Ph.D. (meteorology) in 1948. He was instrumental in establishing the Department of Meteorology at University of Wisconsin—Madison in 1948.

> It [ITM] was really controlled by Rossby … even to choosing the instructors. There were about 30 students in each class … [and] the training program was two months … I remained as instructor after completion of the two-month program.… [The two months] really exhausted what the instructors had to say. Basically little was known, and much of what was "known" was subsequently found to be either wrong or inapplicable. The instructors busily tried to produce small papers for text purposes (e.g., Civilian Staff of the Tropical Institute of Meteorology 1945). Among the military instructors were Carlos Bonnot and George Duncan, who had worked in Panama, and my roommate Phil Allen (Bryson 1993, personal communication).

Riehl's memory of the ITM is contained in a letter sent to the author (J. L.) in 1993. A copy of this letter is found in appendix B.

It appears that Riehl's assignment was justified through his examination of records obtained from Pan American Airlines and other airlines that flew into tropical latitudes. He arrived at the ITM in July 1943 as an instructor but replaced Palmer as director in early 1945 when Palmer's health deteriorated in response to contracting malaria (J. Riehl 1991, personal communication).[15]

When one reads the preface of Riehl's opus, *Tropical Meteorology* (Riehl 1954), it becomes clear that he had a transformative experience soon after he arrived in Rio Piedras. In what comes close to poetry in a scientific book, Riehl describes his first encounter with tropical rain in the book's preface:

> On the first evening some of the staff walked along the beach and admired the beauty of the trade cumuli in the moonlight. Well schooled in the ice-crystal theory of formation of rain, they had no suspicions about these clouds with tops near 8,000 feet where the temperature is higher than +10°C. Suddenly, however, the landscape ahead of them began to dim; then it disappeared; a roar approached as from rain hitting roof tops. When some minutes later they stood on a porch, drenched and shivering, they had realized that cloud tops with temperatures below freezing were not needed for production of heavy rain from trade-wind cumulus (Riehl 1954).

THE MILIEU IN U OF C'S METEOROLOGY DEPARTMENT. *Riehl's early research theme: Disturbances at the tropical/subtropical boundary.* Riehl's first taste of research came with his assignment to the ITM. Here he came under the influence of Dunn, not by direct contact, but through Dunn's seminal paper: *Cyclogenesis in the Tropical Atlantic* (Dunn 1940). In his lectures on tropical meteorology at UCLA in the late 1940s, Palmer expressed the opinion that Dunn's paper was the outstanding contribution to tropical meteorology up to that point in time (Palmer 1949). Even when read today, Dunn's paper is filled with vitality and the reader feels the excitement of a meteorologist trying to unravel the mysteries of a wave pattern (labeled the "isallobaric wave" by Dunn but later referred to as the easterly wave). The wave was detected by analysis of surface pressure changes (therefore the term "isallobaric") in the absence of upper-air observations—other than wind estimates from cloud drift and pilot balloon (pibal). The wave disturbance was often associated with heavy rainfall and the development of tropical cyclones. Riehl extended Dunn's exploration of this wave through use of data he collected at the ITM.

The strength and originality of Riehl's contribution (Riehl 1945), published in the well-known series of University of Chicago Miscellaneous Reports, rested on his analysis of temperature structure accompanying the wave as a response to evaporative cooling in the rain areas and adiabatic descent/warming in the rain-free areas. He also relied on Rossby's vorticity conservation principles to estimate the phase speed of the wave relative to the typical wind speed of the current.

Upon his return to the U of C in autumn 1945, Riehl complemented the easterly wave work with a study of interaction between the tropics and subtropics, especially as the interaction was related to thunderstorm activity along the Gulf Coast (the coast of the Gulf of Mexico) (Riehl 1947). Support came from the U. S. Weather Bureau (USWB) and the work was intimately tied to the Thunderstorm Project under the direction of his doctoral advisor Horace Byers and Roscoe Braham (Byers and Braham 1949; Braham and Malone 2001). A photo of Byers in the company of associates involved in the Thunderstorm Project is shown in Fig. 5. In essence, the study examined the summertime upper-air flow patterns that typified two synoptic regimes: a "polar days" regime where midlatitude structures dominated the subtropical weather, and "tropical days" where the easterly flow aloft dominated the subtropical weather. The research was a form of synoptic typing and he submitted it to the U of C as

[15]The third and final director of the ITM was John Bellamy, one of the officers of instruction at U of C (see Fig. 2) (Byers 1970).

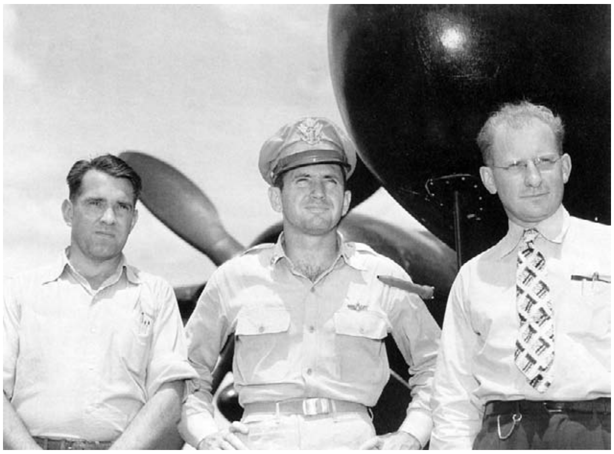

Fig. 5. Thunderstorm Project personnel (left to right): Ferguson Hall (Field Research Coordinator), Colonel Lewis Meng (Air Force Operations), and Horace Byers (Project Director). Background: P-61 aircraft used for flights through thunderstorms (c. 1947) (Courtesy of Douglas Allen).

Fig. 6. Photograph taken near Mirror Lake, CA, en route to Mt. Whitney summit (31 Jul 1951). Mountain climbers (circling clockwise from the bottom left) are Jim Angel, Harold Klieforth, Leon Sherman, Larry Eber, Harry Thompson, Einar Hovind, Herbert Riehl, and Art Belmont (Courtesy of H. Klieforth).

partial fulfillment for the doctoral degree. He was awarded the Ph.D. in 1947. He was listed as assistant professor with the M.S. degree in the *Division of Physical Sciences Catalog* (1946–47). In the 1948–49 catalog, he was listed as assistant professor with the Ph.D. It thus appears that he was promoted to assistant professor before he received his doctoral degree.[16] A photo of Riehl shortly after receipt of his degree is shown in Fig. 6.

Eric Palmén. Carl Rossby was well known for the liveliness he injected into the institutes and university programs that he led from the late 1920s through the late 1950s—at MIT and Woods Hole Oceanographic Institution (WHOI) during 1928–39, at U of C during 1940–54, and at University of Stockholm during 1948–57.[17] The parade of impressive scientific visitors was a major source of the vitality that defined "Rossby's Institutes." Among the visitors for short and long periods at the U of C were Eric Palmén, Zdenek Sekera, Tor Bergeron, Erwin Biel, Alf Nyberg, Einar Hoiland, and Halvor Solberg—Biel and Palmén taught formal classes and Bergeron assisted in synoptic meteorology (W. Saucier 1991, personal communication). For stimulating discussions of the *esprit de corps* at the U of C during this time, the reader is referred to first-hand reminiscences by Chester Newton and Riehl. We excerpt from these reminiscences:

Fig. 7. The building that housed the U of C's Meteorology Department at 5727 University Avenue. The map briefings were held in the lower level room facing the street, and the Quadrangle Club tennis courts are shown in the foreground.

> … it was a small department consisting of a half dozen people and not much more than a half a dozen graduate students. It was greatly enriched by these visitors … the atmosphere in the department was remarkable … interaction on a very informal basis (Newton 1990).

> The most enduring visitor, at first accompanied by Dr. Alf Nyberg, was Palmén, who kept returning to Chicago for 20 years … In the whole winter of 1946–47 there was a veritable forum in the Chicago meteorology department, centered on the first floor of the building [see Fig. 7]. There George Cressman offered daily discussions and forecasts

[16]These details were obtained from the Special Collections Research Department, U of C.

[17]Rossby had affiliations with both U of C and University of Stockholm during the late 1940s through the early 1950s.

with all available maps … and there was no end of arguments about general and cyclone circulations which followed the initial discussions…. Rossby and Palmén were almost always present and they joined in leading the arguments (Riehl 1990).

Figure 8 displays one of these discussions at a U of C map briefing. It seems to fit George Platzman's memory of these events: "It was delightful to see Palmén, an easygoing and somewhat irreverent gentleman, interrupt and argue with Rossby" (G. Platzman 1990, personal communication).

Key arguments centered on 1) respective roles of the mean meridional circulation and transient eddies in the momentum and energy budgets, 2) the mechanism(s) for maintenance of the westerlies (jet stream), and 3) the dynamical basis for alternation of the wind regimes at the surface (pattern of easterlies, westerlies, and back to easterlies, respectively, from equator to pole). By the late 1940s, there was a consensus on the three-cell meridional circulation pattern (Bergeron 1928; Palmén 1951): the thermally direct Hadley cell that spanned the tropics into the subtropics, the thermally indirect "Ferrel" cell (the "reverse" cell) that straddled the poleward part of the subtropics and extended into the midlatitudes, and the thermally direct cell poleward of the midlatitudes.[18]

The controversy that had bearing on Riehl's later work was the issue of meridional circulation vs. transient eddies in transporting momentum and energy from the tropics to midlatitudes and to the pole. It was an emotionally charged controversy that found its way into the correspondence section of the *Journal of Meteorology* (Rossby and Starr 1949; Palmén 1949; Starr 1949). The reader is referred to an informative discussion of this controversy in Wallace (1978). It would take more than a decade for the controversy to be resolved and part of the resolution came with Norman Phillips' simulation of hemispheric circulation (Phillips 1956). The simulation indicated that both mechanisms were operative. As recalled by Phillips,

Palmén and [V. P.] Starr had missing features in their respective views. Starr could not explain the low-level westerlies without the indirect meridional circulation, and Palmén could not explain the upper-level westerlies without the eddies (N. Phillips 1997, personal communication).

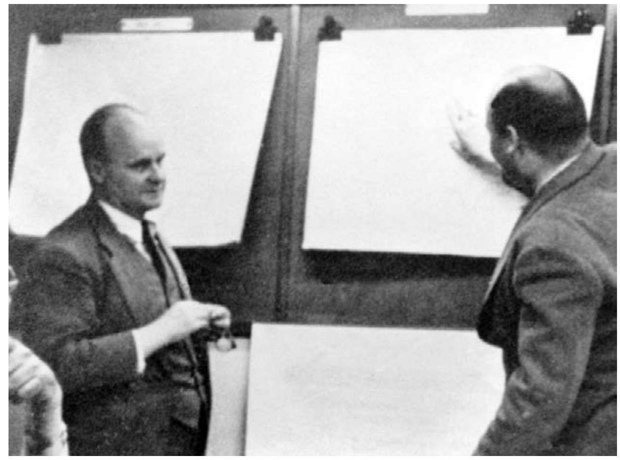

Fig. 8. Eric Palmén (middle), C.-G. Rossby (right), and Tor Bergeron (seated left) at a U of C weather briefing (c. 1947) (Courtesy of George Cressman).

Amidst this controversy, Riehl and fellow doctoral student Tu Cheng ("T. C.") Yeh sided with Palmén and decided to observationally search for evidence of the Hadley circulation.

Rossby with his dynamic personality and Byers with his obvious business/management acumen had strong influence on Riehl, but it was Palmén with his manner and style of research that most influenced Riehl (H. Riehl 1991, personal communication). As recalled by Riehl,

Palmén certainly was one of the most pleasant people we, one generation younger, encountered. He did not throw his weight around, helped people on various problems, and also was a very personable entertainer. The stress in research always remained on the physics and the nature of events, not the prediction (H. Riehl 1994, personal communication).

A photograph of Palmén and Sverre Petterssen is shown in Fig. 9.

RIEHL'S EXPANSIVE VIEW. *Jet stream.* Shortly after completion of his doctoral research, Riehl was entrained into the General Circulation and Jet Stream Project sponsored by the Office of Naval Research (ONR) (administered by Dan Rex, a Rossby protégé who received his D.Sc. at Stockholm under Rossby in 1951).[19] In one of the project's principal publications, the authorship appears as "staff

[18]See Lorenz (1967) for a stimulating history of atmospheric general circulation including a discussion of Bergeron's modification of Hadley's one-cell direct circulation from equator-to-pole into a three-cell pattern.

[19]Dan Rex's doctoral thesis was titled "On atmospheric blocking action: A study in climate dynamics" (Rex 1950a,b). His name is remembered through reference to the synoptic-scale "omega" blocking pattern—often referred to as "Rex blocking."

members" (Staff Members 1947).[20] Riehl recalled his first experiences with the jet stream and the associated activity at U of C:

> I first heard that term [jet stream] when coming to Chicago … to be sure we were most impressed by the news, that B-29's were sent westward to Tokio [Tokyo] became almost stationary over the target! It [the term "jet stream"] first was used tentatively but soon was taken seriously, as it indicated not only the speed of a current but also the narrowness. From the first Rossby was the chief scientist and we all followed along (H. Riehl 1994, personal communication).

Riehl's earliest independent work on the jet stream focused on multiple cases of westerly jets that overlaid weak low-level disturbances (Riehl 1948). He found that the likelihood of cyclogenesis was directly tied to the strength and latitudinal narrowness of the westerlies. He further explored the narrowness of the jet stream via observations aboard Navy aircraft (Riehl et al. 1955). The enjoyment he took in the jet stream work, especially the 1948 contribution, is evident in his following retrospective statement:

> … the prime article [on the jet steam] was by Rossby in BAMS [Bulletin of the American Meteorological Society], 28, 53–68, 1947 early. Later that year we had Staff Members, BAMS, 28, 255–280, 1947, now Palmén and Rossby as Principal Scientists and myself and others also contributing. I had a follow-up article in TAGU [Trans. Amer. Geophys. Union], 29, #2, 175–186, 1948 (still reads well, I should have stayed with that type of work) (H. Riehl 1994, personal communication).

The technical report titled "Jet streams of the atmosphere" (Riehl 1962) is a tribute to Riehl's comprehensive knowledge of the stream and this large volume is impressive for its pedagogical slant.

Hadley circulation. In parallel with his work on the jet stream, Riehl instigated two research efforts that further defined his macroscopic view of the atmosphere: 1) analysis of the Hadley circulation as a means of supporting Palmén's view on the global transport of momentum and heat [Riehl and Yeh (1950) and Riehl et al. (1950)], and 2) an elaboration on the ideas in his dissertation that connected the large-scale upper-air flow in the tropics, subtropics, and midlatitudes (Riehl 1950). And as stated in the Yeh vignette below, the study of the Hadley circulation spurred Riehl and Yeh to investigate the trade wind regime—a phenomenon that spanned the midlatitudes, the subtropics, and the tropics.

Fig. 9. Eric Palmén (left) and Sverre Petterssen in discussion at the Scandinavian–American Meteorological Society meeting in Bergen, Norway (Jun 1958) (Courtesy of H. Klieforth).

The Pacific trades. One of the twentieth century's celebrated contributions to meteorology is the study of the Northeast trade winds of the Pacific Ocean by Riehl, Yeh, Joanne Malkus, and Noel LaSeur (Riehl et al. 1951). The structure of the surface streamlines associated with the trades had been well known since the mid- to late-nineteenth century through the combined efforts of Maury and Köppen [reviewed in Lewis (1996)]. The summertime streamline pattern for the Pacific trades is displayed in Fig. 10a.

Understanding the trade wind inversion, the extremely stable slab between the lower-level marine air, cool and moist, and the upper-level potentially warm and dry air was central to the investigation.[21] In its most elementary form [as found in explanations for stratus and fog off the California coast by Petterssen (1938), Neiburger (1944), and Lilly (1968)], the inversion can be viewed as that interface between potentially warm and dry air in the large-scale descending branch of the Hadley circulation and the substantially cooler ocean surface. Because of the ocean's large

[20]Staff members: Jule Charney, George Cressman, Dave Fultz, Seymour Hess, Alf Nyberg, Eric Palmén, Herbert Riehl, Carl-Gustaf Rossby, Zdenek Sekera, Victor Starr, and Tu Cheng Yeh.

[21]The use of the word "potential" refers to potential temperature, a derived temperature that is especially valuable in tagging or marking air parcels because of its conservative property (see Saucier 1955).

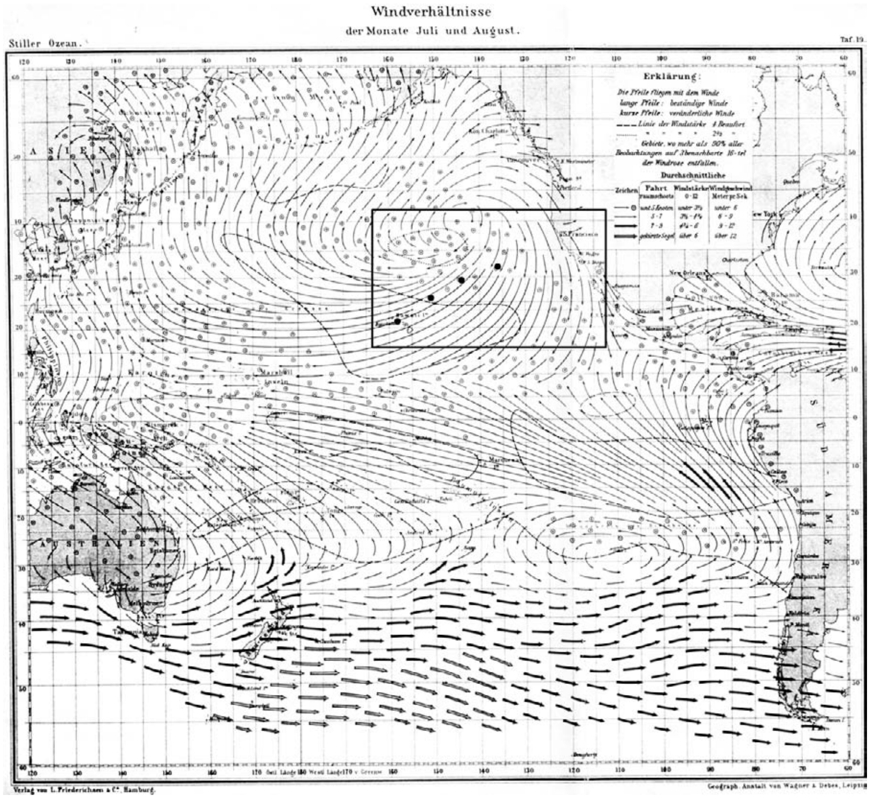

Fig. 10a. Wind analyses for the Pacific Ocean in summer (extracted from the *Segelhandbuch für den Stillen Ozean*). Average winds during the period are denoted by arrows (that "fly with the wind"). Steadiness of the wind is indicated by the length of the arrows (longest arrows are the steadiest). Categories of wind are distinguished by speeds in both m s^{-1} and numbers for the Beaufort scale. Translation: Fahrtraumschoots: "flowing sheets" under favorable winds, and Gekürzte segel: "reduced sheets" in the presence of gale-force winds. The dotted and dashed lines are isotachs of Beaufort Force 2 1/2 (no breaking waves: speed 6–7 kt) and 4 (numerous whitecaps: speed 11–16 kt), respectively. The circles indicate speeds under 5 kt.

heat capacity (extreme heat gain or loss is necessary to change its temperature), a temperature inversion or stable layer must form between the two air masses. Riehl and collaborators were most interested in understanding this stable layer and its role in the heat balance of the atmosphere, and answering the question: How do the trades support restoration of thermal equilibrium in the global atmosphere? As stated in the introduction to Riehl et al. (1951),

> Since the net radiational heat balance of the higher latitudes is negative and that of low latitudes positive, a poleward export of heat from the tropics takes place in the atmosphere that maintains approximate thermal equilibrium. The thermodynamic processes in the trade-wind belt are a principal link to this heat exchange.

But how would they contribute to understanding this transfer process? The availability of a unique set of observations helped define their line of research. They came into possession of upper-air observations from stationary U.S. Navy ships that operated from July to October 1945 [with twice daily radiosondes and frequent pilot balloon observations (up to 3 km)]. The ships were aligned with the flight track from San Francisco to Honolulu that in turn follows along the mean surface streamlines in summer (see Fig. 10b). And when the upper-air observations from Hickam Field

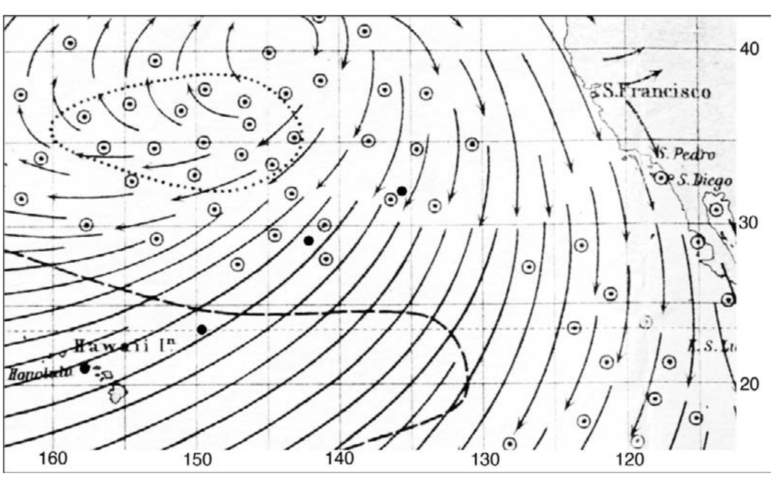

Fig. 10b. A zoom of the rectangular area outlined in Fig. 10a. The four upper-air sites used in the Riehl et al. (1951) study are denoted by the black circles. The sites east of the Hawaiian Islands are stationary U.S. Navy ships, and the westernmost site is Hickam Field. The stations fall along a curved path close to the mean surface streamlines and cover a distance of approximately 2,500 km.

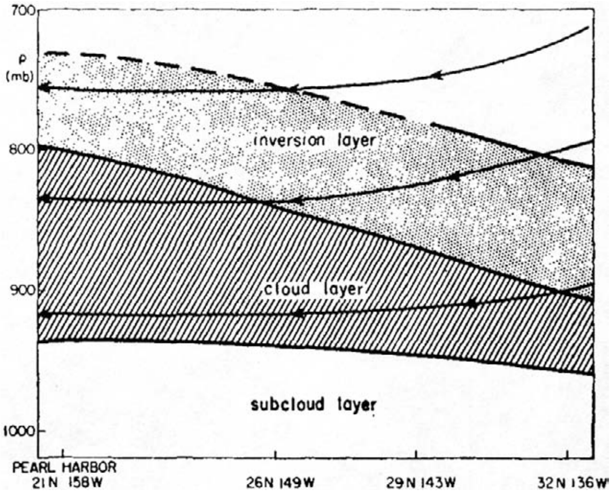

Fig. 11. Figure 8 from Riehl et al. (1951) defining the lower-level structure of the atmosphere along a cross section that follows the average streamlines in the trades.

(close to Honolulu) were added to the set, the upper-air data extended over a distance of approximately 2,500 km. Because of the steadiness of the stream, Riehl and collaborators were able to examine average conditions associated with the trades along the cross section connecting the upper-air sites.

A schematic cross section from Riehl et al. (1951; their Fig. 8) is shown in Fig. 11. This helps define atmospheric structures central to discussions that follow. The major result from their analysis was a gradual increase in the height of the inversion from inflow to outflow end of the section despite continuous divergence and sinking of air columns (the section ran from the position of the easternmost ship at 32°N, 136°W to Hickam Field at 21°N, 164°W). And in the face of earlier conjectures that the inversion was nearly impenetrable (Riehl 1954, ch. 2), these results indicated that a continuous influx of mass occurred across the inversion (from top to bottom). To use Joanne Simpson's term, the inversion was a "leaky wall" (J. Simpson 2009, personal communication). And associated with the leaky wall was the formation of cumulus cloud that pushed into the inversion and lifted it. In essence, the latent and sensible heat from the ocean had a way to escape into the levels above the inversion. As recalled by Simpson,

> One day we [Riehl and I] were just sitting there discussing the aircraft and sounding data from that line of ships.… I was trying to relate my ideas surrounding cumulus clouds forming around the trade wind inversion and the fact that the clouds were there not uselessly but probably serving a function of transporting something [see Fig. 12] … then Riehl drew this picture of a cumulus cloud with the top of it cut off. That diagram was published in the paper [Fig. 24 in Riehl et al. (1951), shown herein as Fig. 13]. I worked out the mathematical and physical basis for how these clouds were responsible for raising the height of the trade wind inversion and then wetting the cloud layer and making it deeper as the air flowed from the subtropical high down to the equatorial trough.… Clouds are a key part of the atmosphere's engine and in the regions where there is a trade wind inversion it makes holes in it and gradually lifts it up and in the equatorial trough, clouds transfer some of the heat energy from the ocean surface to the high troposphere (J. Simpson 2009, personal communication).

Despite significant advances in parameterization of the boundary layer over the ocean and associated parameterization of cloud in the decades following Riehl's study of the trades, climate models are unable to faithfully simulate the stratocumulus clouds in the trade wind regime (Moeng and Stevens 2000).[22] The incorrect simulation of cloud leads to erroneous estimates of the radiation—that is, incorrect albedo

Fig. 12. Aerial photograph of trade wind cumulus near Puerto Rico taken during the Wyman–Woodcock expedition in 1946 (Courtesy of the Schlesinger Library, Radcliffe Institute, Harvard University).

[22] Science historian Paul Edwards has written a stimulating article on the history of GCM development that includes discussion of parameterization (Edwards 2000).

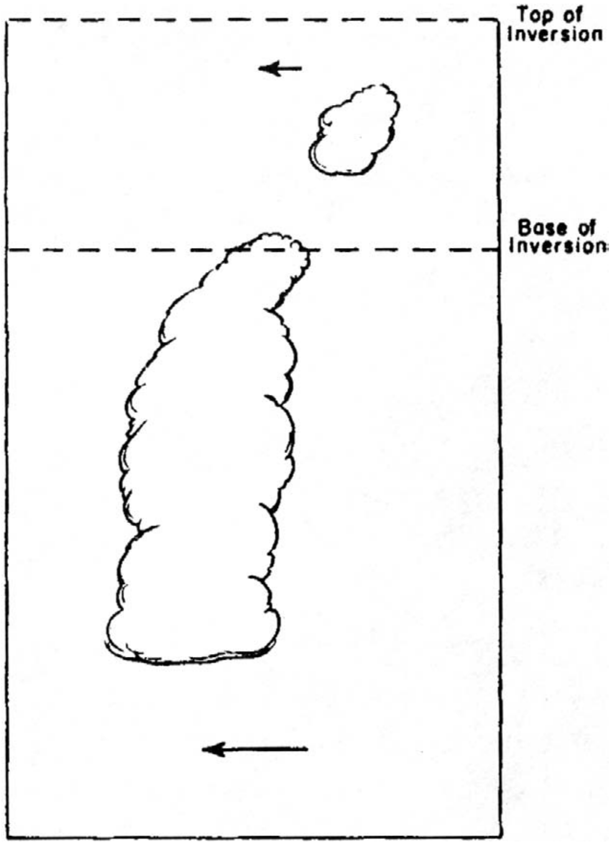

Fig. 13. Riehl's line drawing of a cumulus cloud breaking through the trade wind inversion [Fig. 24 in Riehl et al. (1951)].

that affects the amount of radiation reaching Earth's surface and incorrect estimates of the outgoing long-wave radiation. The incorrect radiation in turn leads to poor simulation of the global circulation.

In response to a question about the difficulty of forecasting cloud in the trades, Akio Arakawa (personal communication, 2009) said that "… most GCMs [general circulation models] do not do well with prediction of the planetary boundary layer and then they cannot make good predictions of the cloud. Dave Randall showed this in his thesis [i.e., Randall 1976] … simulating the transition from stratiform to cumulus is especially challenging … One must be careful and try to unify the boundary layer with the upper levels of the model." A recent publication by Arakawa and Jung (2011) offers another line of attack that couples the GCMs with cloud-resolving models in the hopes of improving the forecast of cumulus clouds such as those in the trade wind regime.

Hydrodynamics Laboratory experiments. Further evidence of Riehl's interest in the "big picture" of the atmospheric processes was his linkage with fellow faculty member and hydrodynamicist Dave Fultz. Together, they conducted laboratory studies of global circulation (Riehl and Fultz 1957, 1958). A photograph of Fultz in the U of C Hydrodynamics Laboratory is shown in Fig. 14. The apparatus for the Riehl–Fultz experiments consisted of a small rotating water-filled dishpan (radius: 15.6 cm, depth: 4 cm, rotation rate: ~1 revolution per 3 seconds). As noted in the abstract of the 1957 paper, "… the flow pattern resembles the basic features of the midlatitude atmosphere in a remarkable way. Mobile long waves in a jet stream overlie cyclonic and anticyclonic vortices further down." This work was indeed gratifying to Riehl and it was complementary to his earlier work on the jet stream (Riehl 1948). As he recalled: "Now some of my happiest memories are of working with Dave Fultz and the rotating dishpan in the hydrodynamics laboratory at the University of Chicago; it was a pity that funding for this dried up with the advent of numerical modeling" (Riehl 1983).

VIGNETTES AND RIEHL–SIMPSON COLLABORATION.[23]

While Riehl pursued studies depicting hemispheric-scale processes in the atmosphere, he did not neglect studies of tropical cyclones and other smaller-scale phenomena in the tropics. Some of the strict tropical meteorology themes are featured in the next two sections that highlight Riehl's interaction with doctoral students and colleagues.

Protégés' verbal portraits of Riehl. T. C. Yeh. I got the Ph.D. in 1948 [dissertation published as Yeh (1949)]. My advisor was Professor C.-G. Rossby. Besides Professor Rossby, Professor Starr and Professor Riehl influenced me. I got a part-time job with Professor Riehl and his group. He was the lead of the group and I was second to him. This group was the most active group [in the U of C's Department of Meteorology]. Many scientists from the world came to U of C and the exchange was exciting. The problem of interest was the process of transferring momentum from the tropics to the midlatitudes. There were two ideas, one from Professor Starr and the other from Professor Palmén. Palmén's idea was that the Hadley circulation was the important part of the transfer. Professor

[23] A list of doctoral students at U of C who studied with Riehl is found in Table 1. The first Ph.D. in meteorology at U of C was awarded to Morris Neiberger in 1945. By 1961, the year that Riehl left U of C, 38 Ph.D.'s in meteorology had been awarded (U of C Archives).

Riehl and I proved the existence of the Hadley circulation examining all the winds from a ship in the tropical area, and we believed the Palmén idea was the most important [Riehl and Yeh (1950); Riehl et al. (1950)]. This also gave us interest in the trade winds and so we started that project…. One of my memories of Professor Riehl's group was that he asked us to write down our ideas on what should be studied and put these ideas in a little box. At the beginning of each month he took these ideas out of the box and we discussed them. This had a great influence on me in my career after I returned to China. I kept a small book with me and wrote whatever I think is important to study. After each month, I make a review of my thoughts. This is a very good way to think what ought to be done.

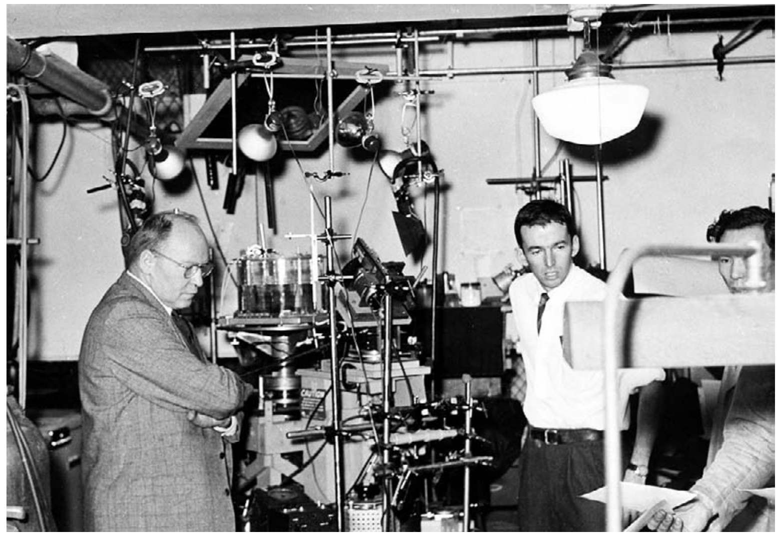

Fig. 14. C.-G. Rossby (left), Dave Fultz (center), and post-doc Yoshi Nakagawa (right) in the hydrodynamics laboratory (basement of Rosenwald Hall on the U of C campus) (c. 1955) (Courtesy of D. Fultz).

Robert Simpson. My first acquaintance with Herbert Riehl was through our exchanges of correspondence during my four Weather Bureau years in Hawaii, and his early exposure to tropical meteorology as an instructor at the Navy's (then) new Institute of Tropical Meteorology in Rio Piedras, Puerto Rico. This acquaintance soon devolved from a collegial friendship into a student–professor relationship, *I* the student, as Riehl rapidly gained recognition as a budding young scientist and prolific author of significant papers in meteorology, who finally established his preeminence in tropical meteorology with publication of his widely acclaimed textbook on that subject (Riehl, H., 1954: *Tropical Meteorology*) [see references].

Table 1. Protégés of Herbert Riehl who received their doctoral degrees in meteorology at University of Chicago. Although C.-G. Rossby was T. C. Yeh's thesis advisor, we include him in this list since he can be considered a junior colleague of Riehl. Year that the degree was granted is given in the left column.

Year	Name	Title of dissertation
1948	Tu-Cheng Yeh	On energy dissipation in the atmosphere
1949	Joanne Malkus	Certain features of undisturbed and disturbed weather in the trade wind region (Malkus 1949)
1953	Noel LaSeur	On the asymmetry of the circumpolar vortex in temperate latitudes
1955	Mikhail Alaka	A case study of an easterly jet in the tropics
1956	Charles Jordan	An experiment in low-latitude prediction with the barotropic model
1959	Tiruvalam Natarajan (T. N.) Krishnamurti	The subtropical jet stream in winter
1960	Jose Colon	On the heat balance of the troposphere and water-body of the Caribbean Sea
1962	Robert Simpson	Analysis of a large-scale atmospheric disturbance in the lower mesosphere
1963	William Gray	On the scales and internal stress characteristics of the hurricane

In my view Riehl, like many others with exceptionally creative minds, was basically a meticulous explorer in setting the stage for his research, the plan for which usually emerged from his personal assessment of the problem as displayed in exploration or from earlier research. I found Riehl quick—sometimes abrasive but fair—in responding to the worthiness of his own work, or that of his Ph.D. students, most of whom regarded him as an outstanding mentor. Yet as a classroom lecturer he had a reputation for making life quite difficult for students he considered unworthy, or who showed little interest in his lectures. However, while Riehl and I often found reason to disagree on procedural matters of scientific interpretations, we enjoyed a lifelong friendship, marred only by a single occurrence:

In 1954 [1956], to my surprise, I was appointed director of the National Hurricane Research Project, a position which Riehl had hoped to receive. It was understandably a major career blow for him, and in disappointment he resolved to have nothing to do with NHRP. But thanks to the Finnish scientist Eric Palmén, and Joanne Malkus, Riehl was soon convinced he needed to contribute to the NHRP program, which he promptly did. At West Palm Beach he was greeted with open arms, and arrangements were immediately made for him to plan and direct several hurricane research missions: Therewith a friendship was rescued; the Riehl–Malkus collaboration using NHRP research data was resumed; and a little later Riehl became sponsor of my Ph.D. program.

Years later, Riehl joined me as co-author of a book *The Hurricane and its Impact* (Simpson and Riehl 1981) during which Riehl rekindled our common zest for exploration, and mountain climbing as the two of us mused the future of hurricane prediction.

T. N. Krishnamurti. I moved to Professor Riehl's lab in 1955. He was most gracious in accepting me. As a Ph.D. student, I had felt that a global rendition of wind analysis of the subtropical jet was needed to describe its global extent. Professor Riehl was most supportive of that idea. My dissertation topic was "The subtropical jet stream of winter" [Krishnamurti 1961] and my committee included Riehl, Palmén, Petterssen, Platzman, and Fultz. That was a heavy defense and followed up with a usual warm up at the Tropopause Room[24] (of Rossby's fame) at the Windermere Hotel at the lake shore of Chicago. One of the highlights of my Chicago schooling days was also watching, at first hand, the science of Riehl and Malkus (Joanne was a part of the Riehl's lab and a constant visitor from Woods Hole) on hurricane and equatorial trough's heat budgets. We watched often the experienced style of Herbert Riehl where he could remove the noise from the important signal.

William gray. During the summer of 1958, I received tremendous encouragement from Riehl. He took me to Florida and got me a flight into a hurricane. I started working with aircraft data and just kept going. As I completed my master's and pursued a Ph.D., Riehl left for Colorado [State University]. Sverre Petterssen and Horace Byers became my direct supervisors. Riehl still provided support and offered me an associate position at CSU in 1961 which partially funded my dissertation work on the internal structure of hurricanes [Gray 1964]. However, Riehl's discontent with folks in Miami [National Hurricane Research Project (NHRP)], a funding avenue for me, caused trouble for me. Through this fallout, Riehl wanted me to completely change the direction of my Ph.D. I pondered the idea of switching to western water (a relevant topic to Riehl at that time) in order appease him, but in the end, I decided I could not. When I finished in 1963, I joined the faculty at CSU per encouragement from Riehl.

Nobody supported and encouraged me more than Herbert did in my M.S. and early Ph.D. days at Chicago from 1957 to 1960. He saw a potential in me that many others did not. Later on when I developed ideas which were different from Riehl's we had some problems. Herbert did not like (and took offense) to have his ideas challenged and not given the highest possible regard by former students that he had previously mentored. I think most of his former Ph.D. students (except for Joanne) had some problems in this regard that other of his associates did not have. However, Riehl encouraged me, and I have great respect for his scientific philosophy and approach. I am a disciple of his observational methodology.

Riehl–Simpson collaboration. During the spring semester of 1947, nearly finished with his Ph.D., Riehl taught his first course in tropical meteorology at the U of C.[25] The course began with a two-week review

[24]This was a lower-level lounge in the hotel that was so frequently used by Rossby and associates that the hotel unofficially called it the "Tropopause Room" in honor of Rossby (C. Newton 1990, personal communication).

[25]The course titled "Tropical Meteorology" first appeared in the Department of Meteorology's catalog in 1944–45. Riehl taught the course at the ITM during that year.

of the Wyman–Woodcock field program (Woodcock and Wyman 1947; Blanchard 1986) and ended with a compilation of Riehl's experiences and research at the ITM. Impressed by the course material and the teacher, doctoral student Joanne Malkus established her first connection with Riehl and he agreed to be her thesis advisor. A photo of Malkus is shown in Fig. 15.

With a long history of interest in aviation and clouds, Malkus began her doctoral research that included the subject of entrainment into developing cumulus—the exchange of mass between the rising column of cloudy air and its environment. Henry Stommel, oceanographer at Woods Hole, had just published what would become the cardinal contribution to this area of research (Stommel 1947). Following Stommel's general line of reasoning regarding entrainment, Malkus added terms to the governing equations that accounted for the differential horizontal wind speed between cumulus cloud and the environment—a differential speed that was estimated from time-lapse photography. Results indicated that if the cloud's horizontal speed is greater than the environment's speed, cloud droplets are detrained and left behind the advancing cloud and vice versa for the case when the cloud speed is less than the environment's speed. In her remembrance (J. Simpson 2009, personal communication), she made the succinct statement referring to this process: "The clouds shed moist air and thereby moisten the environment."

Riehl knew little about tropical clouds but sensed their importance and connectivity to meridional circulation and the trade wind inversion. Excerpts from an unpublished journal housed with the Malkus–Simpson oeuvre expand on this aspect of the Riehl–Malkus interaction:

> Riehl agreed to be my supervisor while insisting he did not know much about cumulus clouds…. The entrainment hypothesis by Stommel was revolutionary, but also very controversial at first. Once it was recognized that cumulus clouds exchanged air with their surroundings, a whole new area of research was opened. On this foundation, we could pioneer in recognizing the essential role of cumulus convection in tropical circulations…. Actually Riehl learned about cumulus clouds very fast, because he soon suspected they might play a crucial role in the Pacific trade-wind layer … (Joanne Simpson Archive, Schlesinger Library/Radcliff Institute, Harvard University).

Fig. 15. Joanne Malkus in the cockpit of a D.C.-3 in preparation for taking observations over the Caribbean (1956) (Courtesy of the Schlesinger Library, Radcliffe Institute, Harvard University).

The landmark paper on the Pacific Trades with Riehl as lead author and Malkus as coauthor was their first in a long series of joint publications through the decade of the 1950s.

Malkus took a full-time position at WHOI in 1951 and the geographical separation served to make collaboration more challenging. Nevertheless, Joanne made regular short-period visits to U of C where the research sessions with Riehl were intense and sometimes contentious, but never unproductive.[26] A working manuscript would generally follow the visit. Although Riehl detested challenging arguments from his protégés as mentioned by Bill Gray and Bob Simpson (personal communications, 2011), he begrudgingly tolerated these exchanges with Malkus. His dependence on her knowledge of clouds was at the heart of his tolerance. Some idea of the exchanges between Riehl and Malkus can be gleaned from Riehl's oral history with Joanne as interviewer (Riehl 1989). The exchanges are sharp 30 years after their collaborative work!

One of the major contributions that stemmed from the Riehl–Malkus collaboration was formulation of a hypothesis related to the equator-to-pole heat budget. They proposed that hemispheric thermal equilibrium could be achieved in the presence of select

[26]Despite the contentious interaction, there is evidence that Riehl exhibited a strong sense of "paternal protection" towards Malkus (J. Simpson 2009, personal communication; Reiter 1998).

[27]The name "hot towers" does not imply that cloud tops near the tropopause were necessarily warmer than their environment. The name more reflects the depth of the undiluted cloudy air (Joanne Simpson Archive, Schlesinger Library, Radcliff Institute, Harvard University).

cumulonimbi that they called "hot towers."[27] These hot towers were conjectured to effectively transport latent and sensible heat from the low-level marine layer to the upper levels of the atmosphere. Further, the select cumulonimbi were assumed to be undiluted (i.e., free from entrainment of environmental dry air) and to rise to levels of the tropopause and higher. A series of papers on the subject appeared in the mid- to late 1950s (Malkus and Ronne 1954; Malkus 1956; Riehl and Malkus 1957, 1958) with a follow-up paper in the late 1970s that benefitted from improved observations (Riehl and Simpson 1979). Researchers continue to actively investigate this subject (e.g., Tao et al. 2003; Fierro et al. 2009, 2012).

The Riehl–Simpson collaboration on hurricanes was extensive, with a focus on genesis and structural maintenance of storms (Malkus and Riehl 1960, 1964; Riehl and Malkus 1961). These contributions have been thoroughly reviewed in Yanai (1964) and more informally in Zipser (1976). Much of this research was tied to support from the NHRP. But prior to this active period of contributions to the subject of hurricanes, Riehl distanced himself from the NHRP after failure to be named director of the Project in 1956 [discussed earlier in Robert Simpson's vignette]. Riehl's failure to be named director was due in large part to USWB Chief Francis Reichelderfer's opinion that Riehl lacked diplomacy in dealing with the tropical meteorological community (R. Simpson 2009, personal communication). The strength of the relationship between Riehl and Malkus is exemplified by Malkus's "rescue" of Riehl after this great disappointment.

The value of teamwork between Riehl and Malkus is exhibited in the following vignette from Michio Yanai, a visitor to CSU soon after Riehl arrived there in 1960:

> In 1962–1964, I visited CSU by Professor Riehl's invitation. We never met before, probably he heard about my work from Charney. They were good friends…. My salary at CSU came from Riehl's contract with NHRP. During my stay at CSU, Professor Riehl was busy as first chairman of the department. He was too busy and I was mostly left to do whatever I wanted … but the best thing happened when Joanne Malkus visited Riehl and told me she wanted me to write a review paper on the formation of typhoons. I was surprised. Why did she pick me? I'm only a post-doc. I wrote it as an extension of my dissertation [for dissertation, see Yanai (1961); for review, see Yanai (1964)]. That was really interesting for me (M. Yanai 2009, personal communication).

The respect and mutual admiration between Riehl and Joanne Simpson lasted their lifetimes. It is an example of strong personalities joining forces and where the excitement of research and complementary talents reigned supreme.

U OF C DEPARTURE. Herbert Riehl was promoted to full professor at U of C during the 1956–57 academic year. However, he was open to other opportunities, as indicated by his interest in the directorship of NHRP.

A key factor in Riehl's decision to leave the U of C was the groundswell of support for a broad-based geosciences department that would merge geology and meteorology (Goldsmith 1991). Scientific justification for the merger rested on unification of the U of C's diverse talents in fluid dynamics. As stated by Goldsmith, a long-standing professor of geology at U of C: "Why shouldn't fluid dynamicists talk to paleontologists?" Riehl viewed these suggested changes with skepticism and it contributed to his decision to leave the U of C as he stated years later:

> … after Rossby had gone back to Sweden, his department of meteorology was combined with geology into a geophysical department [Department of Geophysical Sciences]. I felt that there would not be the same future for me in meteorology in Chicago anymore (Riehl 1983).[28]

The efficacy of this change to a geophysical sciences department at U of C in 1961 has been debated in a thought-provoking article (Wakefield 1994). The pros and cons appear to balance out in this article, but it is clear that the new philosophy was inconsistent with Riehl's strict synoptic–dynamic approach to meteorology.

In the face of imminent changes likely to take place in the meteorology program at Chicago, Riehl decided to take a leave of absence from U of C during the academic year 1960–61. He spent the year as a visiting professor in the department of civil engineering at CSU. His connection with CSU indirectly came from Walter Orr Roberts, the scientific leader of the University of Colorado's (CU's) High Altitude Observatory in Boulder, Colorado, during the 1950s. Roberts invited Riehl to give summer courses in meteorology at CU in 1955 and 1957 (Riehl 1989; Reiter 2011, personal communication). As Riehl recalled:

[28]Riehl made a similar statement in his interview with Joanne Simpson (Riehl 1989, p. 17).

> At that time [summer of 1955], I also went around and visited Fort Collins, Colorado State University. Looked around there on the campus and went on again. Nothing further…. [But] in 1957, we [Riehl and family] came back for another summer session and then also went to CSU. That coincided with the time that I had been doing the work with Dave Fultz and the rotating basin in Chicago. And in Fort Collins, they [Professor Jack Cermak and team] were doing wind tunnel work on the flow of the air across mountains, from the front range of Colorado, in particular, over Long's Peak and down. So they were interested in model experiments on that subject … so some time after that I had the inquiry from them whether I wouldn't like to come there and essentially open a meteorological activity (Riehl 1989).

Riehl formally resigned from U of C in 1961 and became a faculty member in CSU's department of civil engineering during the 1961–62 academic year. His move to CSU was not solely based on academic considerations, however, as he recalled in oral history:

> Anyway there was this invitation [to join the faculty at CSU], and then there came another factor, in the form of my then 5-year old daughter [Natalie] … [who] contracted pneumonia in Chicago and wound up in an oxygen tent, so for her the much drier climate was suggested. That was a real factor in accepting there. I mustn't leave the personal factor out of it. It wasn't just purely a university political or scientific decision (Riehl 1989).

With strong support from CSU's upper-level administrators including President William Morgan, a Department of Atmospheric Science—a graduate program—with Riehl as chair was created in 1962. His vision for the department had "observational methodology" at the forefront where students had opportunities to make observations (highlighted in Gray's vignette). And in the tradition of Rossby, theory underpinned analyses of observations in the Atmospheric Science Department at CSU where Ferdinand Baer and Desiraju Bavanarina ("D. B.") Rao, theoreticians out of the Chicago School, were among the first faculty hired by Riehl. Regarding Riehl's vision, it is eminently clear that he had great reservations about the cultural research change that came with the "great mutation," the phrase used by Lorenz to signify research based on the products of numerical simulation (Lorenz 1996). He was not strictly opposed to numerical simulation as a tool in research, rather he was opposed to the emphasis and the disproportionate government funding for numerical simulation at the expense of his observationally-based approach that included laboratory work in hydrodynamics (Pulwarty 2012, personal communication).

Despite the challenges of building the new department at CSU, Riehl found time to take part in the Barbados Oceanographic and Meteorological Experiment (BOMEX) and Venezuelan International Meteorological Hydrological Experiment (VIMHEX) field experiments from the late 1960s to early 1970s that had tropical air–sea interaction and tropical cumulus as central themes. And once again, his ability to inspire the young scientist was paramount as remembered by Alan Betts, an advanced doctoral student from Imperial College who took part in VIMHEX:

> Riehl was not a hands-on mentor. He would explain what he thought should be done and believed that students and post-docs would produce if they were capable…. [The problem he gave me] was calculating mesoscale vertical transports by convective systems…. He suggested it and left me to it for two years, showing little further interest—except that I knew I was expected to produce a publishable analysis! [The resulting publication is Betts (1973)] (Betts 2011, personal communication).

EPILOGUE. The first easily accessed document from Herbert Riehl's hand is the paper that he published in the series of University of Chicago miscellaneous reports (Riehl 1945). The paper is impressive for several reasons including a meaningful extension of Dunn's classic work (Dunn 1940). But beyond the extension of the earlier work, there is an indication of adroit expression with language and argument. It is thus easy to understand why Riehl took the job as a scriptwriter for MGM in Culver City. For whatever reason, that line of work was terminated and imminent war opened a narrow pathway into academic training in meteorology, a subject which was little known to him based on the following reminiscence:

> They told me that one place was still available at New York University in a course in meteorology, whatever that was (Riehl 1983).

Although it is doubtful that he could foresee a career in meteorology after the short one-year course of study at NYU, the milieu at "Rossby's School," and more particularly the independence and joy of youthful discovery that he experienced at Rio Piedras made him realize he could contribute to this field.

And while others rushed into the exciting field of midlatitude dynamics where the governing equations were amenable to the power of mathematical physics, Riehl ventured into the tropics and subtropics where the poorly understood cumulus cloud and weaker pressure gradients were central to the dynamic constraints. Here he found a scientific home that was little populated and it suited his fancy.

His primary teachers were Rossby and Palmén. But Riehl's view was more in line with Palmén, the deep-thinking synoptician whose forte was investigation of global circulation and the imbedded extratropical cyclones (Newton and Holopainen 1990). Through Yeh and Riehl's effort to more clearly understand the action of the Hadley circulation, they realized it was the trades that needed further investigation. The study of the trades by these young researchers in the company of Noel LaSeur and Joanne Malkus connected weather across a wide swath of latitudes—an approach reminiscent of the Jacob Bjerknes–Eric Palmén investigation of a midlatitude depression through the simultaneous release of radiosondes ("swarm ascents") from 11 European countries (Bjerknes and Palmén 1937). Riehl and collaborators made a major advance in understanding the transport of heat and moisture from the sea surface to the upper level of the troposphere and from thence to the midlatitudes. And as found in recent publications, the solution to this challenging problem remains evasive yet attracts a host of researchers equipped with multiscale models and observations that dwarf those available 50 years ago.

When one examines Riehl's oeuvre with subject matter ranging from first-hand accounts of traverses through the jet stream to his venture into search for the Hadley circulation, and that Herculean effort to connect the tropics/subtropics with midlatitudes, his trademark is careful analysis of observations as a means to understanding the physical processes behind the phenomenon. And although Riehl exhibited a hard-edged elitist attitude that complicated his interaction with students, he was true to the principle of mentorship as espoused by Harriet Zuckerman in her study of celebrated physicists: "… it is not knowledge or skills that protégés acquire from their masters so much as a 'style of thinking.' It is problem finding as much as problem solving" (Zuckerman 1977).

Herbert Riehl stands out as a unique thinker about the complex working of the Earth–atmosphere system. His uniqueness stems from a pioneering spirit in the exploration of tropical meteorology, but in the context of a global view. Palmén was his guide, but Riehl followed a separate path and the boldness of his scientific expeditions inclined others to follow.

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Expansive letters from Herbert Riehl's widow, Janis Riehl, supplied critical information on the life of her husband. Vital details on Riehl's life, some included in the manuscript, are a gift to all readers. The capital suggestion to contact Mrs. Riehl came from BAMS editor Edward Zipser and Ferd Baer.

We are indebted to the former students and associates of Herbert Riehl who provided oral history related to his life and work. Those who contributed are the following: Ferdinand Baer, Alan Betts, Russell Elsberry, William Gray, T. N. Krishnamurti, Robert Maddox, Roger Pulwarty, Elmar Reiter, Joanne and Robert Simpson, Michio Yanai, and T. C. Yeh. Beyond input from these close associates of Riehl, the following input was critically important to the project:

1) Four letters from Herbert Riehl in the early to mid-1990s detailing his experiences at the U of C and the ITM,
2) Reid Bryson's remembrances of the Tropical Institute of Meteorology and his identification of faculty and students in the 3rd Cadet class at U of C (Fig. 4),
3) Information from Phillip Clapp, Robert Fleagle, and Athelstan Spilhaus concerning the NYU meteorology program in the 1940s,
4) Reminiscences from Chester Newton, Norman Phillips, George Platzman, and Walter Saucier concerning the milieu in "Rossby's School,"
5) Oral history interviews with Akio Arakawa and Michio Yanai related to GCMs and tropical clouds, and
6) Cogent suggestions from formal reviewers that were followed and led to an improved manuscript.

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Photo credits are as follows: Fig. 1, Athelstan Spilhaus; Figs. 2 and 3, Special Collections, U of C; Fig. 4, Noburo Nakamura; Fig. 5, Douglas Allen; Frontispiece and Figs. 6 and 9, coauthor Harold E. Klieforth's collection; Fig. 7, author John Lewis's collection; Fig. 8, George Cressman; Fig. 10, Monika Stutzbach-Michelsen, Bundesampt für Seeschiffahrt (Seewarte), Hamburg, Germany; Fig. 12, Radcliffe Institute, Harvard University; Fig. 14, Dave Fultz; and Fig. 15, Radcliffe Institute–Harvard University. Figures 11 and 13 were copied from the *Quarterly Journal of the Royal Meteorological Society* and we are grateful to John Wiley & Sons Ltd. through Verity Butler for permission to reproduce these figures. We also thank Erin Gleason for her careful and skilled work that prepared photographs for electronic submission.

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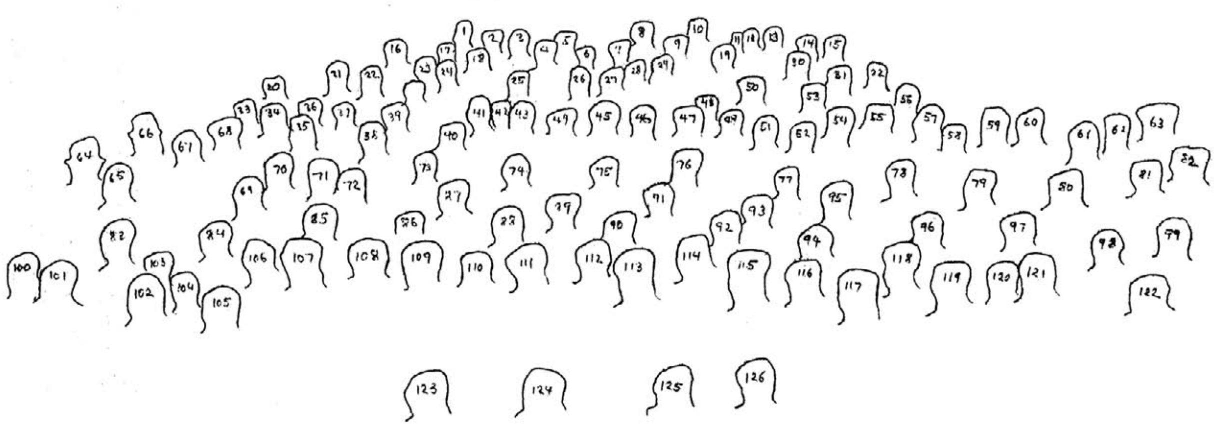
APPENDIX A. A refined version of line drawings of the heads that correspond to Fig. 3 (Original Courtesy of the Department of Geophysical Sciences, U of C). Reid Bryson identified the following faculty and students in Fig. 3: Verner Suomi (16); Reuben Belongia (41); Reid Bryson (45); Ben Bullock (49); Lynn Means (52); Oscar Singer (54); Robert Beebe (58); Ralph Nelson (59); John ? (62); Fred White (63); Bill Plumley (65); Micheal Ference (66); John Finch (67); Chidley [Ken] Johnston (69); Larry Curtis (72); John X. Jamrich (75); Mike Chancellor (80); Glenn Stout (81); Phil Smith (82); Earl Fowler (83); Vince Oliver (98); W.T. Reid (101); Phil Church (102); Herbert Riehl (103); Victor Starr (104); Leonid Hurwicz (105); Raymond Wexler (106); Joshua Holland (108); Lawrence Markus (110); Robert Bentley (112); George Haltiner (113); George Platzman (114); Massey (115); Jack Indritz (116); ? Stanley Beloy (118); Frank Snodgrass (121); Earnest Bice (122); Oliver Wulf (123); Capt. Starbuck (124); Carl Rossby (125); Horace Byers (126).



APPENDIX B (FACING PAGES). Letter sent to the author (J. L.) in 1993 by Herbert Riehl containing Riehl's reminiscences of the ITM.

18 October 1993

John Lewis, NSSL
1313 Halley Circle
Norman OK 73069

Dear Mr.Lewis,

Thank you for your recent letter inquiring about of University of Chicago's Institute of Tropical Meteorology at the University of Puerto Rico, Rio Piedras P.R This was an event now 50 years ago and my recollection about it is very poor.

The institute functioned from the middle of 1943 to the autumn of 1945 when the war ended and the U of Chicago cancelled funding.Your copies of the history leading to the founding of the institute is very interesting. I had heard some of it,but the main reason then was support for the SE Ferry route from Miami along the coast of Brasil to Ascension Island and N to the African coast, From there the planes could fly to North Africa to take part in the military campaign there. I don't think this objective was ever accomplished what with total lack of data from Puerto Rico to Recife, Ascension etc. Later, there was no need as larger aircraft stopped using this route.

For the two years of its existence the institute mainly served instruction in the SE Asian theatre, from which the first director Clarence Palmer was drawn and where he had experienced fighting until he became a victim of Malaria.I was assigned on the basis that I had been collecting microfilm from PAA mostly and other airlines lso wherever such records then existed in Washington archives about the tropics, their weather and flying methods.practised. There was general agreement that polar front cyclone weather as then taught everywhere did not serve at all in the equatorial zone.The prevailing concept was that,hurricanes apart, convection was randomly distributed with a seasonal and diurnal rhythm and stationary effects of topography.Thus the energy stored in the air in form of water vapor could only made available to the middle latitude turbulent systems through advection of air at very high levels from the tropics having high potential energy from the ascent in the random cumuli with conversion of water vapor through condensation and freezing, plus vapor transport in the surface layers.Because of the random aspect the vapor transport could only be shown by averages around latitude circles.Models of that type,dating from the time of Hadley,were the exclusive. presentation of the energy transport from low to high latitudes until about 1945 and this oversimplified concept still has not disappeared entirely as yet.

I think that the institute has contributed to pointing up the fallacy of the random convection theory through noting that the principal occurence of heavy deep convection occurs in organized weather patterns with scale of 1000 miles plus, called the synoptic scale in middle latitudes. In contrast to the usually widespread precipitation in extratropical storms,the tropical convection often occurs in banded forms that yield high amounts of precipitation not unlike summer middle latitude systems, also convection, where squall lines with duration of an hour may produce substantial percentages of mean monthly precipitation, in dry areas the whole monthly average or more.The bands are moving,mostly westward to northwestward.In the course of several days they can deliver an average of 2 cm+ of water over wide areas,Interaction between such rain events in the West Atlantic and the higher latitude storms was noted quite early. The tropical rain systems, and also what has been called "intertropical front" are not fronts in the sense of airmass differences but convergence zones related to the mechanisms initiating convection on various scales.

Special mountain effects are known worldwide. Quite extreme events could be seen near the institute from clouds derived from a mountain some 15 miles to the SE.Under right wind conditions a narrow cloud remained stationary for some hours, precipitation up to 7 inches in a one-mile wide zone, length perhaps 30 miles,and very clear skies to N and S. The cloud top was near 3 km, below freezing, with strong rotation about the horizontal axis(horizontal tornado?). With no data for quantitative analysis,nothing has ever been published.

Finally, the mere existence of the institute appears to have acted as a stimulus for a worldwide start of tropical research abandoning the random hypothesis.

I hope to get a write-up of your output again,

Sincerely,

Herbert Riehl

Herbert Riehl

P.S. If the war had lasted longer, more would have come from the ITM.