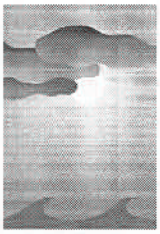
The Lettau–Schwerdtfeger Balloon Experiment: Measurement of Turbulence via Austausch Theory



John M. Lewis
National Severe Storms Laboratory, Norman, Oklahoma

ABSTRACT

In the early 1930s, Heinz Lettau and Werner Schwerdtfeger made direct measurements of air motion in the lowest 4 km of the troposphere by using the manned free balloon as an instrumented platform. The experiment was motivated by Wilhelm Schmidt's and Ludwig Prandtl's work on *Austausch* (exchange) theory in the second and third decades of the twentieth century. As a prelude to investigating the Lettau–Schwerdtfeger experiment, historical developments that had bearing on the field program are reviewed. Following this review, the experiment is analyzed by 1) documenting the scientific goals, 2) discussing the strategy for data collection, 3) examining one flight in detail (the flight of 25 February 1934), and 4) summarizing results from the experiment. The paper ends with a retrospective view of *Austausch* theory.

1. Introduction

In the first few years of the twentieth century, two remarkable papers were written that would change our view of fluid flow adjacent to bounding surfaces. In 1902, at the suggestion of Fridjof Nansen and Vilhelm Bjerknes, Vagn Walfrid Ekman (1874–1954) solved the problem of drift currents in the ocean (Ekman 1902, 1905; Eliassen 1982). The wind flow and its resultant stress at the ocean surface drags the top layers of the ocean with it. This layer in turn influences the next lower stratum of ocean, and because of the earth's rotation, these currents are deflected relative to the surface wind. Additionally, the current's magnitude is progressively damped with depth in response to frictional dissipation. This is the way that Ekman so eloquently argued his case that gave rise to current described by a three-dimensional equiangular spiral . Ekman was exceptional for his ability to combine theory with practical implementation. He is shown in Fig. 1 with the current meter that he developed.

To the south of Stockholm where Ekman completed his drift current work, Ludwig Prandtl (1875–1953) was conducting fluid dynamical experiments in Hannover, Germany. He was interested in the stress in a fluid as it flowed past solid boundaries. His research results on this problem were first presented at the Third International Congress of Mathematicians in Heidelberg, in August 1904 (Prandtl 1905; Tani 1977). In this presentation, he introduced the terms *Grenzschicht* (boundary layer) and *Übergangsschicht* (transition layer). Prandtl showed that the effects of viscosity are significant only within a thin transition layer next to the bounding surface when the flow is laminar (nonturbulent). The smaller the viscosity, the thinner the transition layer. But the steep velocity gradient that forms in this layer, in spite of the small viscosity, produces a force comparable to the inertia force. Prandtl was an adept experimentalist and a master at simplification when it came to theory (von Kármán 1954, 50). In Fig. 2, he is shown conducting an experiment while at the University of Hannover. At the invitation of eminent mathematician Felix Klein, Prandtl joined the faculty at *Göttingen* in 1905, where he established the renowned Institute for Fluid Dynamics (*Institüt für Strömungsforschung*).

Corresponding author address: Dr. John M. Lewis, National Severe Storms Laboratory, NOAA/ERL, 1313 Halley Circle, Norman, OK 73069.
E-mail: lewis@nssla.nssl.uoknor.edu
In final form 1 August 1997.

FIG. 1. Ekman is shown making an adjustment to a current meter while on board a research vessel (ca. 1915). Courtesy of Jan Mattson and Ulf von Barth, Lund University.

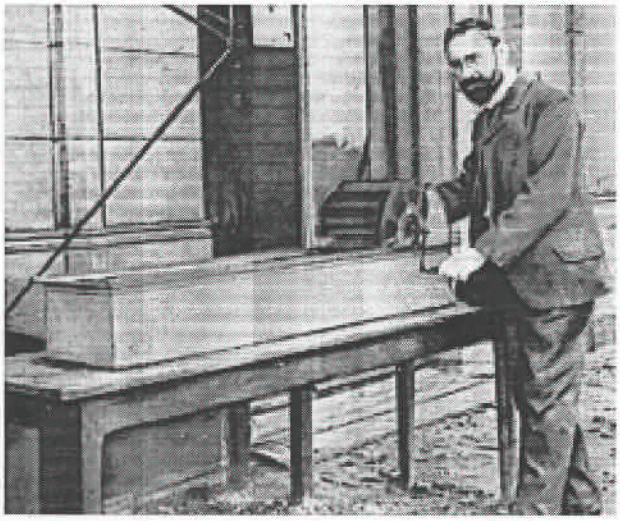


FIG. 2. Prandtl, at age 29, is shown performing a fluid dynamics experiment with a "hand-operated water channel" [*handbetriebenen Wasserkanal*]. Courtesy of Bundesamt für Seeschiffahrt und Hydrographie, Hamburg, Germany.

These theoretical developments would stimulate investigations of wind structure near the earth's surface. Prandtl's work went unnoticed by meteorologists for more than a decade, but Ekman's work had an immediate impact. In concert with Ekman's theoretical work, an evergrowing set of upper-air observations were made available through measurements from instrumented towers (notably the Eiffel Tower), instrumented kites, and pilot balloons. The determination of the virtual or eddy viscosity of air in the lowest levels of the atmosphere became the dominant theme of research during the first two decades of the century. This led to turbulence parameterization via *Austausch* or K theory (K becoming the standard notation for the empirical coefficient of eddy viscosity).

By the late 1920s, the *Austausch* coefficients had been indirectly estimated in a variety of synoptic situations. The first known effort to *directly* measure/estimate these coefficients (and associated turbulent structure) in the boundary layer took place in Berlin, Germany, during 1933–34. Stimulated by Prandtl's theoretical and experimental work on turbulent boundary layers and Wilhelm Schmidt's work on *Austausch* theory, Heinz Lettau and Werner Schwerdtfeger planned a bold experiment to study atmospheric turbulence using the manned free balloon as their platform. The idea was to become a "parcel" in the circulation and to make measurements of turbulent structure in the lowest several kilometers of the atmosphere. In this paper, we explore the events that led to this field program. Further, we discuss the strategy for data collection and summarize the research results. As a prelude, we review historical developments in atmospheric turbulence that had bearing on the Lettau–Schwerdtfeger balloon experiment.

2. Pioneering work in atmospheric boundary layer flow

The individuals listed in Table 1 played an important role in the development of atmospheric boundary layer theory. We will elaborate on their work, but first we introduce some notation and formulas to facilitate the discussion. For details and derivations, the following books are recommended: Prandtl (1952, chap. 3) and Schlichting (1968, chap. 19).

Viscous forces in air arise because of both laminar and turbulent shearing stress. In laminar flow, the

TABLE 1. Late nineteenth- and early twentieth-century research related to atmospheric boundary layer wind.

Scientist(s)/ affiliation	Year	Contribution	Comments
Cato Guldberg and Henrik Mohn (Norwegian Meteor. Inst.—Christiania)	1876	Role of friction in the balance of forces at the earth's surface	Data from Norway, Germany, England, and the United States used to estimate the frictional force
Thomas Stevenson (Scottish Federal Service)	1880	Analytic form of wind profile in the lowest 50 ft of atmosphere	Seasonal wind speed observations from an instrumented pole fitted to a parabola
A. Angot (French Weather Service—Paris)	1890–95	Published tables and figures of observed wind velocity and temperature obtained from instruments on Eiffel Tower	Data collected at various levels from 21 to 302 m
Filip Åkerblom (Uppsala Univ.)	1908	Following Ekman (1902), seasonal variation in eddy viscosity calculated in lowest 300 m of the atmosphere	Angot's data from the Eiffel Tower used to make estimates
Th. Hesselberg and Harald Sverdrup (Leipzig Geophy. Institute)	1913–15	Via Ekman's model and pilot balloon observations, eddy viscosity found as a function of height	Extensive set of pilot balloon observations from the Lindenberg Observatory used to make the estimates
G. I. Taylor (Cambridge Univ.)	1915	Theory of eddy viscosity and conductivity developed (mixing length concept introduced)	Calculations of eddy coefficients based on theory and upper-air observations from *Scotia* and Upavon Air Field
Wilhelm Schmidt (Vienna Zentral Anstalt)	1917	Concept of turbulent mass exchange developed ("*Austausch* coefficents")	Wide-ranging application of turbulent exchange to geophysical and life sciences

mathematical form of the shearing stress τ_l is given by

$$\tau_l = \mu \frac{du}{dz},$$

where μ is the molecular *dynamic* viscosity of air and du/dz is the vertical shear of the horizontal wind (z positive upward). The vertical transport of horizontal momentum (= mass × u) is due to molecular motion, but the resulting stress is expressed in terms of a macroscopic distribution, namely, the vertical gradient of mean flow multiplied by the known physical parameter μ. When du/dz is positive, momentum is transferred downward. In general, the momentum is transported from regions of larger values to those of smaller values (sometimes referred to as "gradient" or "downgradient" transport). For air at 0°C (20°C), $\mu = 1.71\ (1.82)\ 10^{-5}\ \mathrm{m^{-1}\ kg\ s^{-1}}$ (List 1966). The value of μ as a function of temperature was well known by the late nineteenth century. In the governing equations for viscous flow (Navier–Stokes equations), viscosity generally appears in the form of *kinematic* viscosity, $\upsilon = \mu/\rho$ (units of $\mathrm{m^2\ s^{-1}}$), where ρ is air density.

For turbulent flow, there is an additional stress represented by τ_t, where

$$\tau_t = -\rho\overline{u'w'}.$$

This product of density with the negative time correlation of vertical (w) and horizontal (u) perturbation components of velocity is called the Reynolds' stress; the perturbation velocity is the instantaneous gust minus the average wind, where the overbar represents an average over many gusts or turbulent eddies.[1] By analogy with laminar flow, the turbulent stress is parameterized as

$$\tau_t = \mathcal{A}\frac{du}{dz},$$

where $\mathcal{A}$ is called the *Austausch* coefficient (this is the counterpart of molecular dynamic viscosity in laminar flow). The turbulent counterpart of kinematic viscosity is "eddy viscosity," often denoted by K, that is, $K = \mathcal{A}/\rho$. The tacit assumption in this latter form of the turbulent stress is that macroscopic masses of air behave similarly to molecules in laminar flow. Prandtl called these macroscopic masses *Flussigkeitsballen*, balls of fluid that move as a whole (Prandtl 1925, 137; 1952, 117). In contrast to μ, $\mathcal{A}$ varies most significantly with the distance from the boundary.

Reynolds is credited with introducing the idea of eddy viscosity into fluid dynamics; he postulated its existence to account for the increased resistance to fluid flow in pipes when the regime changed from laminar to turbulent (Reynolds 1886; Stewart 1972). It was left to J. Boussinesq, however, to relate the eddy viscosity to the mean flow gradient (Boussinesq 1897; Prandtl 1952, 119).

a. Guldberg–Mohn and Stevenson

Guldberg and Mohn [professor of mathematics at the University of Christiania (now Oslo) and director of the Norwegian Weather Service, respectively] discussed their work in *Études sur les Mouvements de l'Atmosphère,* a book devoted to their theory of cyclone development (Guldberg and Mohn 1876). Their discussion of friction was limited to effects on the surface wind field, with the end result a useful parameterization of frictional deceleration (known as the Guldberg–Mohn hypothesis). This frictional deceleration was proportional to the wind's magnitude and directed opposite to the motion. Kutzbach (1976) has thoroughly examined the contributions of these two men, including their studies of the frictional force, in her scholarly work on nineteenth-century meteorology.

Stevenson's work (Stevenson 1880) is little known but is noteworthy because it appears to be the first collection of observations that clearly show the steep vertical gradient of wind immediately above ground level. The paper is terse and begs for elaboration, but the wind profiles collected from instruments on a 50-ft pole over a field of oats are impressive, bearing a strong resemblance to the logarithmic profiles that were theoretically derived and validated in the early 1930s (Rossby and Montgomery 1935, e.g., and others referenced in Sutton 1953, chap. 7).

b. Åkerblom and Hesselberg–Sverdrup

These studies are grouped together because they both rely on Ekman's model (augmented by the pressure gradient force) and estimate the air's eddy viscosity by coupling the model with upper-air data.

Åkerblom had training in both oceanography and meteorology: a *filosophie licentiate* (fil. lic.) from Stockholm University in 1889 and a doctoral degree in oceanography from Uppsala University in 1904.[2] He was a protégé of Alfred Nathorst at Uppsala, a naturalist who specialized in the geography, geology, and biology of the Arctic. In the late 1890s, Åkerblom worked as an assistant meteorologist under Léon Teisserenc de Bort at the Observatory for the Study of Dynamic Meteorology at Trappes (near Paris). Teisserenc de Bort, along with William Dines in England and Wladimir Köppen in Germany, were actively involved in developing instruments and platforms for upper-air observation at that time.

While employed as docent at Uppsala University, Åkerblom (1908) published his work on the seasonal variation of eddy viscosity in the lowest few hundred meters of the atmosphere by using data collected from the Eiffel Tower (published by A. Angot 1897). In his estimate of the eddy viscosity, Åkerblom anchored the profile to the observed winds at the 21- and 302-m levels of the tower. The viscosity then appeared as an unknown in the equations for the wind spiral. This transcendental equation was solved iteratively, giving the following values of eddy viscosity: 8.7 $m^{-1}\,kg\,s^{-1}$ (winter), 11.3 $m^{-1}\,kg\,s^{-1}$ (summer), and 9.5 $m^{-1}\,kg\,s^{-1}$ (winter–summer average). The estimates of viscosity exhibited a wide range of spatial and temporal variability. Thus, Åkerblom showed that the appropriate value of eddy viscosity for use in Ekman's model was

---

[1] Named in honor of Osborne Reynolds (1842–1912), professor at the University of Manchester, who, along with the German engineer Gotthilf H. L. Hagen (1797–1884), made fundamental studies of the transition from laminar to turbulent flow. Reynolds's work was more systematic, but Hagen first discovered the phenomenon in 1854 (von Kármán 1954, 83).

[2] The fil.lic. is an academic degree intermediate to the American M.S. and Ph.D. Extensive course work and a thesis are required.

roughly six orders of magnitude greater than the molecular viscosity. He did not elaborate on the reasons for this difference, nor did he mention turbulence as a probable cause of the orders of magnitude increase in viscosity.

Surprisingly, Åkerblom does not mention Ekman or his work in the 1908 paper. It could not have been ignorance of the earlier work, since these two men were oceanographers in Sweden, both receiving doctoral degrees from Uppsala University (Ekman in 1902, Åkerblom in 1904). There also appears to have been communication between the two men, based on a footnote in Ekman's paper (Ekman 1905, 8). Quoting from this footnote: "with this remark, a criticism put forward by Dr. Filip Åkerblom (Recherches oceanografiques, Upsala Universitets årsskrift 1903) has been answered." Åkerblom became professor of meteorology at Uppsala University in 1909, and in this same year Ekman was appointed professor of mechanics and mathematical physics at the University of Lund (Sweden).

Theodor Hesselberg and Harald Sverdrup were "Carnegie assistants" under V. Bjerknes at the Geophysical Institute in Leipzig from 1913 to 1915, just prior to Bjerknes's move to Bergen in 1917.[3] They made use of an extensive archive of pilot balloon observations from the *Aeronautisches Observatorium* at Lindenberg (near Berlin) to estimate the eddy viscosity. Their work is much more expansive than Åkerblom's, with reference to Guldberg and Mohn, and Ekman, as well as the lesser-known works such as Stevenson's. They obviously knew that it was turbulent transport that accounted for the magnified value of eddy viscosity. They solved the equations by using power series expansions in z (height) and were able to account for the vertical variation of the viscosity. Their results were presented in the form of layer averages (their Table 7), summarized as follows: eddy viscosity increased from 9×10^{-2} m^{-1} kg s^{-1} at anemometer level (9 m) to 6.0 m^{-1} kg s^{-1} at 500 m and, thereafter, assumed a uniform value of 5.0 m^{-1} kg s^{-1} to 3 km. This result is consistent with the linear increase of eddy viscosity in a neutrally stratified surface layer as discovered by Prandtl in the early 1930s (Schlichting 1968, 548). In the atmosphere, however, the "surface layer" (layer of constant stress) is limited to a few tens of meters.

c. *Taylor*

Shortly after becoming Schuster Reader at Cambridge University in 1911, G. I. Taylor's growing interest in turbulent transfer was given impetus by the British government's investigation of the *Titanic* disaster (in 1912).[4] Taylor was appointed meteorologist on an expedition to the Grand Banks of Newfoundland on the renovated whaling ship *Scotia* during the summer of 1913. Understanding the formation of fog was a primary scientific goal of the expedition, and Taylor gathered upper-air observations from instrumented kites while aboard the ship. When he returned to England, he augmented his dataset by adding pilot balloon records from Upavon Air Field in Salisbury Plain. As a result of analysis of these upper-air data in conjunction with ground-based measurements of turbulence, Taylor formulated a theory of turbulent transfer analogous to the molecular transfer in the kinetic theory of gases.

Quoting from his reminiscence:

> To complete a theoretical analogy between molecular and turbulent transfer it is necessary to think up some length connected with turbulence which is analogous to the mean free path of molecules. I was driven to imagine a purely hypothetical process to represent the collisions which terminate each molecular free path, and in 1915 I put out the idea that coherent fluid masses move a certain distance up or down vertically carrying all their transferable properties and then mix with the surroundings in which they find themselves. In that paper (Taylor 1915) I also showed that a numerical value for the virtual viscosity can be determined by measurements of the height to which the variation of wind direction from the lines of constant pressure extends. This is the principle of the Ekman layer but unfortunately at that time I had never heard of Ekman who had published his paper 10 years earlier (Ekman 1905).[5]

---

[3] Between 1905 and 1940, Bjerknes received a yearly grant from the Carnegie Institution in Washington, D.C., which enabled him to employ a considerable number of research assistants, all of whom became well-known geophysicists (Eliassen 1982).

[4] G. I. Taylor had been trained in physics under J. J. Thomson but turned to fluid dynamics and geophysical science, in part, because of the newly created post of Schuster Reader. Arthur Schuster, a wealthy man and professor of physics at Manchester University, donated money for a position that would encourage the application of mathematics to meteorology (Batchelor 1976).

[5] It is important to note that Taylor's development differed from Ekman's in one important respect. Taylor allowed some slippage of the wind at the lower boundary (the wind velocity was required to be directed along the stress vector). This boundary condition yielded a solution that was more faithful to the observed angular deviation between the surface wind and the geostrophic wind.

The salient features of Taylor's paper follow:

> 1) A "mixing length" is postulated. This distance is used to derive an expression for the eddy viscosity. This eddy viscosity is written as "$1/2(\overline{w}\, d)$, where d is the average height which an eddy moves before mixing with its surroundings, and $\overline{w}$ roughly represents the average vertical velocity in places where w' [perturbation vertical velocity] is positive . . . the divisor 2 is inserted because the air at any given point is equally likely to be in any portion of the path of the eddy, so the average value of $z - z_0$ [vertical displacement] should be approximately equal to 1/2 d" (Taylor 1915, 4 and 13). The eddy viscosity is assumed constant in the layer of frictional turning (approximately the lowest kilometer of the atmosphere).
>
> 2) By matching the Upavon pilot balloon data with his model, Taylor found the eddy viscosity in the lowest ~1 km to range between (2.8–6.2) $m^2\ s^{-1}$, or in the units of dynamic viscosity ~(2.8–6.2) $m^{-1}\ kg\ s^{-1}$. This range of values is in general agreement with the results of Hesselberg and Sverdrup cited above.

Taylor's introduction of mixing length into turbulence theory preceded Prandtl's contribution on this subject by 10 years (Prandtl 1925). There is a difference in the details, however; Prandtl claimed that momentum was the transferable property, while Taylor argued that vorticity was the important property. According to Batchelor (1976, 573): "Neither supposition is correct in any exact sense for turbulent flow, although Taylor's would be in a purely two-dimensional motion."

Figure 3 shows a photograph of Taylor shortly after he published his paper on the eddy motion in the atmosphere.

d. Schmidt

Wilhelm Schmidt received his Ph.D. (1905) in physics at Vienna, Austria, and served as scientist with Felix Exner at the Austrian Central Bureau for Meteorology and Geodynamics from 1905 to 1919. He was appointed full professor at *Hochschule für Bodenkultur* in Vienna in 1919 and returned to the Austrian Central Bureau, as director, in 1930. A photograph of Schmidt in the mid-1930s is shown in Fig. 4. His publications covered a wide variety of subjects, including physical meteorology, limnology, city climate, and mountain meteorology. His crowning achievement, however, came in the form of a booklet titled *Der Massenaustausch in freier Luft and verwandte Erscheinungen* [Mass exchange processes in free air and related phenomena; Schmidt (1925)]. It had a forerunner, an abbreviated version of the same paper, in the proceedings of the Viennese Academy of Sciences (Schmidt 1917). The fundamental underpinning of this work held that fluid properties—momentum and admixtures such as water vapor, condensation nuclei, for example—are transferred with the mass elements in turbulent motion, called "disorderly flow" (*ungeordneten Strömung*) by Schmidt.

The working hypothesis was nearly identical to that of Taylor; namely, when turbulence displaces a parcel of fluid, it moves a certain distance before it loses its "individuality," that is, property, as a result of mix-

FIG. 3. Taylor is shown on the roof of the British Meteorological Office in South Kensington (ca. 1917). The tower in the background belongs to the Imperial Institute. Taylor was serving as meteorological advisor to the Royal Flying Corps at the time. Courtesy of Lady Jeffreys and the Cambridge University Archives.

FIG. 4. Wilhelm Schmidt (ca. 1936). Courtesy of the Bundesamt für Seeschiffahrt und Hydrographie, Hamburg, Germany.

ing with its surroundings. Schmidt developed his ideas independently of Taylor (Gold 1936).

The parameterized governing equation for transfer took the form of the familiar diffusion equation:

$$\frac{\partial S}{\partial t} = \frac{1}{\rho}\frac{\partial}{\partial z}\left(\mathcal{A}\frac{\partial S}{\partial z}\right),$$

where S is the property being transferred and $\mathcal{A}$ is the exchange or *Austausch* coefficient. By tracking fluid elements ("eddies" in Taylor's terminology) through a level surface, Schmidt derives the form of the *Austausch* coefficient $\mathcal{A}$:

$$\mathcal{A} = \frac{\sum m \cdot l}{F \cdot t},$$

where mass is assumed to be transferred through a horizontal area F in an amount of time t.[6] The mass elements (m) move a distance l (from above or below the level in question) before mixing with the surroundings. In this expression, l is counted positive and the summation accounts for all elements passing through F in time t. When the exchange of momentum is considered, that is, S is set equal to the wind component, then $\mathcal{A}$ is the coefficient of viscosity (units of molecular dynamic viscosity).

A near equivalence between $\mathcal{A}$ and Taylor's expression for eddy viscosity can be obtained by setting $m = \rho V$ (density × volume) in the above expression. We then note that V/F is a vertical dimension (proportional to mixing length) and that $V/(F\,t)$ represents vertical displacement per unit time (i.e., w). Thus $\mathcal{A} \propto \rho\, w\, l$.

Schmidt's booklet had a profound effect on Heinz Lettau (H. Lettau 1994, personal communication). In fact, as will be seen, the form of the *Austausch* coefficient and the governing equation were instrumental in the design of data collection aboard the manned free balloon.[7]

3. Experiment design

a. Motivation/preparation

In 1925 as a tenth-grader in high school, Heinz Lettau became fascinated with wind structure while a summer student at the Rossitten hang glider school. In his reminiscence (Lettau 1990), he makes it clear that the instructor at Rossitten, Ferdinand Shultz, challenged him to investigate gustiness and wind while aboard his hang glider. As a result of the experience, he chose meteorology (and geophysics) as his field of study. Toward the end of his formal education [Ph.D. (1931) at Leipzig University under the direction of Ludwig Weickmann], he contemplated the use of the manned free balloon as the vehicle to study wind structure. As he recalled:

> In the departmental libraries, I learned about wind structure and vertical "*Austausch*" processes. . . . [Most stimulation I found in the publications of Wilhelm Schmidt and Prandtl-Tietjens. Specifically, Schmidt's "Austausch-Primer" entitled, in translation, "Mass exchange processes in free air and related phenomena"; Prandtl had published text-

---

[6] Haurwitz (1941, chap. 11) has a detailed derivation of Schmidt's formula for the *Austausch* coefficient.

[7] Lettau and Schwerdtfeger knew little of Taylor's work, only what was mentioned in Schmidt's (1925) booklet (H. Lettau 1997, personal communication). Schmidt references Taylor (1915), but there is little discussion of this work in the booklet.

> books which I found very instructive (H. Lettau 1994, personal communication).] I concluded that a suitable vehicle for the measurement of eddy vertical wind components would be the manned balloon, because when drifting horizontally, the mean motion of the atmosphere would be eliminated [Lettau 1990; H. Lettau 1994, personal communication (bracketed)].

For the planned balloon project, Lettau enlisted the help of Werner Schwerdtfeger (Ph.D. 1931, Leipzig), another Weickmann protégé. Schwerdtfeger had already established himself as an exceptional synoptician at the Bureau for Flight Safety in Berlin (*Reichsamt für Flugsicherung*). Neither one of these men had experience with free ballooning, however. Reinhard Süring, director of the Meteorological Observatory at Potsdam and renowned early-century aeronaut, came to their aid. Quoting Lettau:

> Suering provided valuable technical advice, whole hearted moral support and modest but highly appreciated funding for my plans to use manned balloon flight to measure vertical eddy wind components in the lower troposphere. Suering brought me into contact with R. Petschow, an experienced balloon pilot who could skillfully maintain altitude during the 10–15 minute intervals necessary for the planned measurements (Lettau 1990).

Figure 5 shows Süring, Weickmann, and other prominent meteorologists at a meeting of the International Aerological Commission in Leipzig.

FIG. 5. The following words appear on the back of this picture: "World meeting of the Upper-air [Aerology] Commission 1926 (7?) [1927] in Leipzig. President: Sir Napier Shaw (Engl.)." Members of the commission and others at the meeting are grouped according to rows: the front row (seated), the back row (four younger men standing to the right and rear), and a middle row consisting of the other attendees. Numbering from left to right in each row, the following people (and their affiliation) have been identified.

Front row—R. Lempfert, England (1); H. Hergesell, Germany (3); N. Shaw, England (6); V. Bjerknes, Norway (8); R. Süring, Germany (9); L. Weickmann, Germany (10); A. Wallén, Sweden (11).

Middle row–E. Alt, Germany (1); H. Arctowski, Poland (2); G. Marczell, Hungary (4); L. Lammert, Germany (5); Moltchanov, Russia (7); Th. Hesselberg, Norway (8); E. Fontseré, Spain (10); G. Walker, England (11); E. Mariolopoulos, Greece (12); L. Richardson, England (13); E. von Everdingen, the Netherlands (15); A. Schmauss, Germany (17); F. Linke, Germany (18); W. Oishi, Japan (19); H. von Ficker, Austria (20); S. Róna, Hungary (21).

Back row—Enge (1); P. Mildner (2); K. Keil (3); and H. Hermann (4) (courtesy of Marianne Schwerdtfeger).

b. Balloon characteristics/pilot

Figure 6 is a schematic drawing of the component parts of a free balloon typical of those used in the 1920s–1930s. The gas bag (envelope) was usually rubberized cotton fabric, linen, or silk, with a valve at the upper apex, and an appendix or neck at the lower end. The bag contained the lifting gas [hydrogen or coal gas ("cooking gas")—both flammable] that was subject to free expansion through the appendix that was open during flight. Control was achieved through the concerted use of ballast (sand in gunny sacks hooked to the basket) and "valving" (release of lifting gas). A rope was attached to the valve and hung down through the appendix. When the pilot pulled on the rope, the valve opened. Automatic closing springs normally kept the valve shut. [See Upson and Chandler (1926) for more details.]

The hydrogen-filled balloon used by Lettau and Schwerdtfeger had a volume of 1200 m^3 and lift of 1100 kg. This mass was approximately distributed as follows (units of kg): basket, 100; four people, 300; 35 ballast bags, 350; rope, 50; gas bay, 250; and netting, 50. Planned flight duration was 6–8 h. Figure 7 shows the balloon basket as it is prepared for launch, and a view of liftoff is displayed in Fig. 8.

Because of the primitive state of balloon technology in the 1920s–1930s, the maintenance of constant

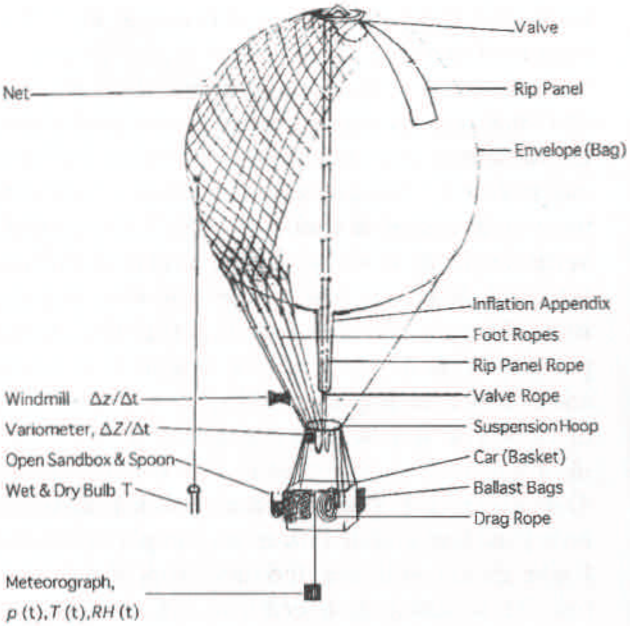


FIG. 6. Schematic diagram of the free balloon and its component parts. Courtesy of H. Lettau.

elevation was most challenging.[8] Meisinger had been unsuccessful in his efforts to fly at constant elevations as he circumnavigated cyclonic and anticyclonic circulation systems during the early 1920s (see Lewis and Moore 1995). In contrast to Meisinger's experiments, which called for maintenance of constant elevation for 12–24 h, the Lettau–Schwerdtfeger flights would require measurements at fixed altitude for ~15 min. Lettau recalls the technique of pilot Robert Petschow:

> Suering told me that Petschow could control the height of the trajectory within a meter or so. We saw how he did it. He kept his eyes continuously on the vertical anemometer (windmill type) and on the rate-of-climb meter [variometer],[9] counteracting a sensed tendency to rise by a light pull with his left hand on the gas release or vent-line [valve rope] and a downward tendency by discharging ballast sand "tablespoonwise" with a small gardener's shovel in his right hand. (H. Lettau 1993, personal communication)

FIG. 7. Assistants remove ballast from the basket as the manned balloon *Von Tschammer und Osten* prepares for liftoff. Pilot Robert Petschow is shown in the basket next to the placard labeled "400" (indicating that this would be his 400th flight), and Lettau is shown jumping into the basket on the right side. The storage tanks in the background contain hydrogen that was used to inflate the bag. Courtesy of H. Lettau.

c. *Calculation of the* Austausch *coefficient*

Ertel (1932) developed an alternate form of Schmidt's vertical *Austausch* coefficient ($\mathcal{A}$ defined in section 2). This formulation rests upon the calculation of the perturbation vertical velocity, w'. The calculation begins by determining the average vertical velocity at a given level over a time period T (a time that is long compared to the lifetime of an individual eddy). This average is denoted by $\overline{w}$. The perturbation, w', is the difference between the vertical velocity (w) and $\overline{w}$, that is, $w' = w - \overline{w}$. Next, the time series of w' is divided into a series of intervals (each denoted by τ) in which w' has the same sign (called "conditional sampling" in modern terminology). Within each interval τ, the mixing length l, and "local average vertical" velocity w^* are defined as follows:

---

[8] The opacity of the balloon envelopes allowed the lifting gas to expand/contract in response to changes in the solar radiation. This problem was minimized in the late 1940s when improved materials for the balloon envelope were developed (Moore et al. 1954).

[9] The variometer determines the rate of climb via differential pressure between air in a bottle (or Dewar flask) and the atmosphere. The air in the bottle is connected to the atmosphere through a capillary leak. As the atmospheric pressure changes, the differential pressure is converted to a rate of climb (C. B. Moore 1997, personal communication; Moore 1997).

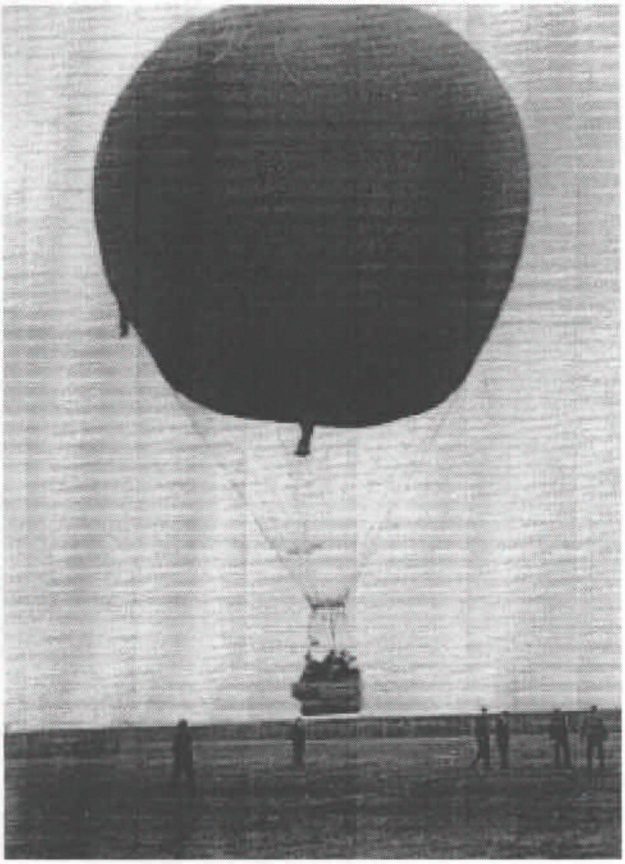


FIG. 8. View of liftoff at Bitterfeld Aerodrome on 25 Feb 1934. Courtesy of H. Lettau.

$$l = w^*\tau = \int_{t}^{t+\tau} w' dt .$$

Ertel's form of the vertical *Austausch* coefficient then takes the form

$$\mathcal{A} = 0.5\rho\overline{(w^* l)} = 0.5\rho\tau\overline{(w^*)^2} ,$$

where $\overline{(\cdot)}$ represents the ensemble time average (over the sequence of time intervals τ within T). This is consistent with Taylor's development cited earlier (see section 2).

To calculate vertical velocity (w) and its perturbation w', simultaneous measurements were collected from the vertical anemometer and the variometer. The variometer measures the time rate of change of balloon height. The vertical anemometer gives the balloon's rate of rise (time rate of change of balloon height) *relative* to the vertical motion of the air (w). Thus, by subtracting the vertical anemometer measurement from the variometer measurement, the vertical motion of the air is obtained.

Lettau and Schwerdtfeger (hereafter LS) (1933, 253) indicated that the root-mean-square (rms) errors in the variometer and vertical anemometer were ±7 cm s^{-1} and ±12 cm s^{-1}, respectively. Since these observations were independent of each other, the net rms error in vertical velocity is ~±14 cm s^{-1}. To get error estimates for $\overline{w}$, w^*, and $\mathcal{A}$, we assume the following characteristics of a typical record shown in LS (1933): 1) a sampling interval Δt = 10 s (a variometer and vertical anemometer reading every 10 s); 2) a nominal value of $\tau = 50$ s (w' has the same sign for 50 s); 3) T = 600 s, the total time of observation at a fixed level; and 4) measurement errors in w are unbiased (zero mean error) and uncorrelated from one sample to the other. Under these conditions, the rms errors of $\overline{w}$ (average over T), w^* (average over τ), and $\mathcal{A}$, are 1.8 cm s^{-1}, 6.2 cm s^{-1}, and 6.10^{-2} m^{-1} kg s^{-1}, respectively. The rms errors of $\overline{w}$ and $\overline{w^*}$ were found by recourse to the standard formulas in Mosteller et al. (1961, chap. 9). The error variance of w^* was used to find the error in $\mathcal{A}$.

d. Case studies

The experiments focused on turbulence in fair (nonstormy) weather. Safety, of course, was a prime consideration, but the maintenance of constant elevation for 10–15-min periods also dictated flights in more quiescent weather regimes.[10] The situation is remembered by Lettau:

> We operated financially on a shoestring, could only start Sundays [when Petschow was available]. The hydrogen was produced (as a by-product) of the Chemical Works at Bitterfeld. We were charged about 0.1 M per cubic meter, about $40 (U.S.) equivalent for the 1200 cubic meter volume of the balloon bag. We had to decide on Fridays on "go" or "no go," using synoptic forecasts merely to avoid storms and thunderstorm situations (H. Lettau 1994, personal communication).

During 1933–34, seven flights were made on the following dates (listed chronologically): 5 March

---

[10] Lettau and Schwerdtfeger were unaware of Meisinger's work (and his death in the balloon crash of 1924). However, the death of aeronauts in Brussels at the 1923 Gordon Bennett Race was well known. Lightning strokes originating from thunderstorms ignited three of the hydrogen-filled balloons while in flight and caused the death of five aeronauts.

1933, 25 February 1934, 11 March 1934, 25 March 1934, 19 August 1934, 9 September 1934, and 23 October 1934.[11] The first four flights took place in cold maritime air masses that had long residence times over Germany; they were relatively free from horizontal inhomogenieties. The summer dates were chosen as representative of conditions under strong solar heating, and the fall experiment took place on a tranquil (but not calm) night characterized by a well-defined surface inversion. Thus, there was a reasonable spectrum of nonstormy weather conditions that could be used to examine the variability of $\mathfrak{A}$.

FIG. 9. Crew and ground-support team pose for a picture prior to the 25 Feb 1934 launch. The two men on the left are graduate students at Leipzig University, H. Koch holding the meteorograph and R. Faust; these men served on the ground-support team. The four crew members are on the right (listed from left to right): Marianne and Werner Schwerdtfeger, Robert Petschow, and Heinz Lettau. Courtesy of H. Lettau.

4. Experiment results

We first examine the calculations from a particular flight in some detail. Following this case study, synthesis of results from the various flights are reviewed.

a. Flight of 25 February 1934

This flight took place over Berlin in a cold air mass associated with an extratropical cyclone. The crew and ground-support team assembled for a photograph prior to launch. They are shown in Fig. 9. The instruments used to measure vertical velocity are held by Petschow (the variometer under his right arm and the vertical anemometer in his left hand). Werner Schwedtfeger holds the Assmann psychrometer (for humidity measurement), and the assistant on the left holds the aerometeorograph (for pressure and temperature measurement). Marianne Schwerdtfeger (wife of W. Schwedtfeger) holds the logbook.

The time–height plot of the balloon's trajectory is shown in Fig. 10. Temperature and humidity profiles are displayed at the left edge of the diagram. Some changes in these profiles occurred during the flight (a period of ~3 h). These changes were confined to the lowest 500 m. The profiles on ascent (morning) are shown by the solid lines, while those associated with descent (early afternoon) are dashed. The stable/saturated layer next to the ground, which was present on ascent, disappeared by the time the balloon landed. The surface temperature rose by ~4°C between 1030 and 1330 local time.

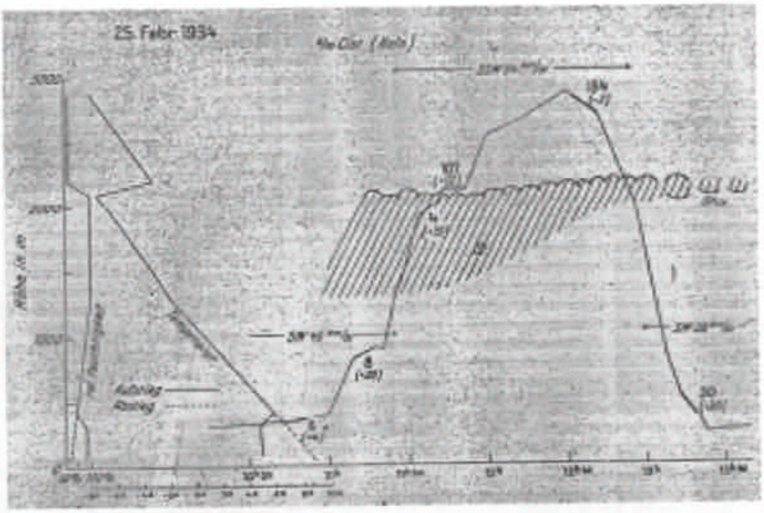


FIG. 10. Reproduction of Fig. 1 from LS (1934). Time–height cross section of the flight of 25 Feb 1934. Thermodynamic profiles are on the left. The *Austausch* coefficients ($cm^{-1}\ g\ s^{-1}$) and vertical velocity ($cm\ s^{-1}$ within parenthesis) are displayed at various points on the flight path. The wind speeds encountered are SW (45 km h^{-1}), SSW (54 km h^{-1}), and SW (38 km h^{-1}) at times 1030–1130, 1130–~1300, and ~1300–1330 (local time), respectively. The type and thickness of clouds are indicated by hatching and symbols [stratus (St), stratocumulus (Stcu), and cirrostratus (Cist)].

Following the surface warming, the thermodynamic structure between ground and cloud base was slightly less than dry adiabatic (~–8°C km^{-1}) and ex-

---

[11] The 23 October 1934 flight was the only flight made at night, and it took place on a Tuesday. All other flights were made during daylight hours on Sundays. Petschow was the pilot on all flights.

hibited a nearly constant mixing ratio of ~3 g kg^{-1}. Within the stratus deck, the lapse rate was moist adiabatic. A pronounced but shallow inversion was present at ~2 km, near the top of the stratus layer. The air above the inversion was stable and relatively dry (compared to the subcloud layer). A view of the stratus overcast shortly after the balloon penetrated the inversion is shown in Fig. 11.

The thermodynamic structure encountered by the balloon on the afternoon of 25 February 1934 was typical of what has come to be called a stratus-topped well-mixed layer (see Lilly 1968). In this case, maritime cold air was undergoing modification over the European continent. Based on fact that the low-level winds were SW at 10–15 m s^{-1}, it is likely that the center of the cold anticyclone was situated to the south and east of Berlin.

The time series of vertical velocity at two levels, one just below the inversion and the other just above it, are shown in Fig. 12 (Fig. 2 in LS 1934). The time resolution of the data is 10 s (displayed as bars) and the duration of measurement at these levels is ~500 s. [To simplify the subsequent discussion, we use the notation ()/() to indicate information at the 1950-m/2150-m levels, respectively.] The average value of the vertical velocity is indicated by the dashed line on each chart (19 cm s^{-1}/12 cm s^{-1}). These lines divide the traces into segments where w' is either positive or negative.

Following the calculation procedure described in section 3c, the mixing length is found to be 5 m/33 m. Since mixing length has the same sign as w' in a given segment (Ertel's convention), the quoted value of mixing length is found by taking the ensemble average of the absolute value of l. The corresponding values of $\mathcal{A}$ are 0.4/10.7 m^{-1} kg s^{-1}.

Referring again to Fig. 10, one sees that the estimated value of $\mathcal{A}$ gradually increases from 0.5 to 0.8 m^{-1} kg s^{-1} as the base of the stratus deck is approached from below. This occurs in the presence of mean upward motion from 4 to 20 cm s^{-1}. Just above the "humpbacked" upper boundary of the stratus deck, $\mathcal{A}$ jumps to the value of 10.7 m^{-1} kg s^{-1}, while the upward motion decreases. Quoting from LS (1934, 250):

> The vertical motions here [at 2150 m] were stronger and remained in the same direction for longer periods, i.e., the mixing lengths associated with the turbulent eddies [*Wirbelkörper*] were from a totally different regime.

The authors were hard pressed to explain the extreme value of $\mathcal{A}$ at ~2800 m (13.4 m^{-1} kg s^{-1}). At this level, the lapse rate was approximately moist adiabatic and the air was ~50% relative humidity; that is, the stratification was stable.

b. Synthesis of results from the various flights

Lettau and Schwerdtfeger made an effort to stratify the *Austausch* coefficients on the basis of the thermal lapse rates that prevailed at the location of measurement. As they said (LS 1934, 253):

> The first thought (at least of the authors) is that the vertical temperature gradient would account for the scale of mixing . . . and that the smallest values [of $\mathcal{A}$] would be expected in an inversion whereas the largest values would be found in the vicinity of adiabatic and moist-adiabatic gradients. . . .[12]

FIG. 11. A view of the stratus deck shortly after *Von Tschammer und Osten* passed through it on 25 Feb 1934. Another manned free balloon is shown in the background (balloons were typically rented to recreational aeronauts on weekends at the Bitterfeld Balloon Aerodrome). Courtesy of H. Lettau.

---

[12] Richardson (1920, 1925) discussed the growth of turbulence in the atmosphere from an energetics perspective; in particular, he established a criterion for the generation of turbulent motion in terms of the vertical wind shear and the vertical temperature gradient. Lettau and Schwerdtfeger were apparently unaware of Richardson's work. [See Sutton (1953, 152) for further information on Richardson's criterion.]

Their discussion referred to a scatterplot of estimated $\mathcal{A}$'s in the lowest 2–3 km of cold anticyclones (Fig. 13). In this figure, each plotted point is identified by a symbol representing the date of observation. The lapse rate [in units of °C $(100\ \mathrm{m})^{-1}$]/wind speed (in units of $\mathrm{m\ s^{-1}}$) associated with the observation is displayed beside the symbol. Adiabatic lapse rates are identified by "a" and moist adiabatic lapse rates by "f" (*feucht:* moist). There was no clear-cut relationship between *Austausch* values and wind speed. Quoting again from LS (1934, 253):

> On the day with the greatest wind speed [25 February 1934], the values of the *Austausch* coefficient were not generally larger than on the day with the small horizontal air motion [5 March 1933] . . . in several instances we noted that on the same day, small values [of $\mathcal{A}$] in the presence of both strong and weak gradients. Also, on different days, the same gradient at a given height gave values from 6–8, and the other 44–91 $\mathrm{cm^{-1}\ g\ sec^{-1}}$ [4.4–9.1 $\mathrm{m^{-1}\ kg\ s^{-1}}$]. [See data from 11 March 1934 and 25 March 1934 at the ~100-m level in Fig. 13.]

In (LS 1936), the distribution of $\mathcal{A}$ above and below the inversions was presented in tabular form. This is reproduced as Table 2. The results from four cases indicated that $\mathcal{A}$ was greater above the inversion. The relationship between *Austausch* coefficient variation above/below the inversion and strength of the inversion (temperature jump), however, was not obvious from the limited sample.

Lettau and Schwerdtfeger also presented their results in terms of $\mathcal{A}$ versus height (LS 1936). The set of 60 observations from the seven cases were sorted by height interval and averaged (with the admonition that these averages were not to be viewed as "climatological"). The results are reproduced in Table 3 and show an increase in $\mathcal{A}$ through the 2–3-km stratum, followed by a decrease in the overlying 1-km layer. When compared with Hesselberg and Sverdrup (1915), there is close agreement up to the 3-km level. The averages from Hesselberg and Sverdrup's study were associated with a wider variety of synoptic conditions and they processed hundreds of pilot balloon records.

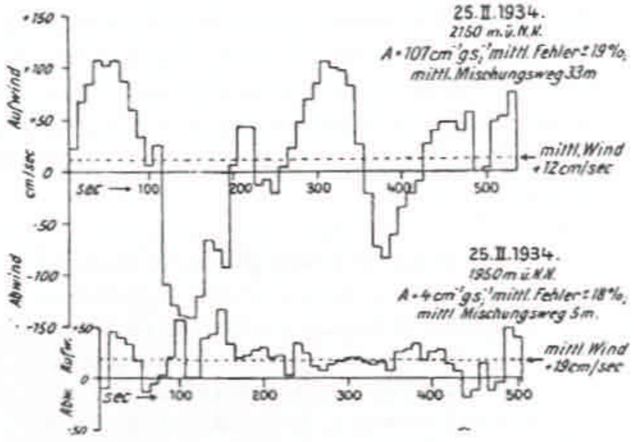


FIG. 12. Reproduction of Fig. 2 from LS (1934). Two time series of vertical velocity measured from the balloon on 25 Feb 1934. The upper plot represents data collected at the 2150-m level, and the lower plot shows data at the 1950-m level. The labels on the vertical axis, *Aufwind* and *Abwind,* indicate upward and downward motion of the air (units of $\mathrm{cm\ s^{-1}}$), respectively.

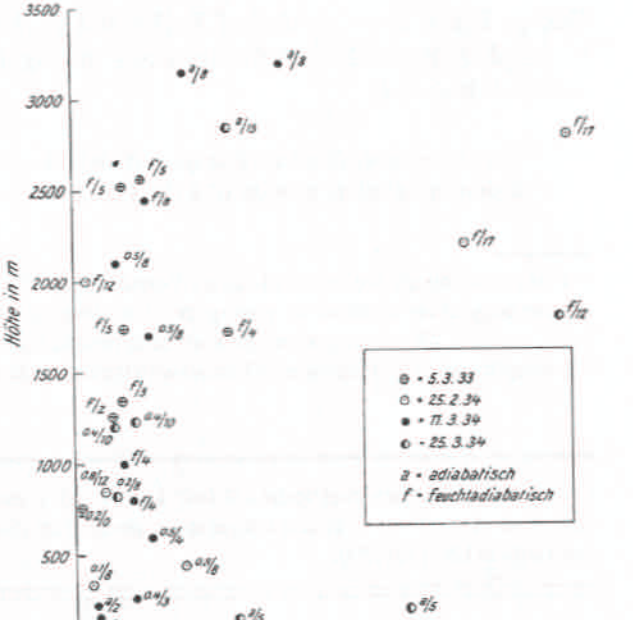


FIG. 13. Reproduction of Fig. 5 in LS (1934). Scatterplot of $\mathcal{A}$ as a function of height from four flights. Data from a particular flight are identified by unique symbols shown on the inset (date given as *day/month/year*). The lapse rate and wind speed associated with a given *Austausch* coefficient appear beside each symbol.

5. Retrospection

The limitations of *Austausch* or transfer coefficient theory in the boundary layer have become evident in recent years. The basic problem is that the eddying mass interacts with others in a continuous manner, unlike molecules in the kinetic theory of gases. Furthermore, observations in the planetary boundary layer (PBL) indicate that the turbulent eddies can scale with the height of this layer; that is, the scale height of the eddies can be comparable to the depth of the layer where turbulent interaction takes place.[13] This problematical aspect of the theory seems to have been anticipated by Taylor, as evidenced by the following remarks:

> Strong winds have been chosen for the comparison [theory vs observations] in preference to light winds, because it is less likely that heat-convection currents will persist through such a distance before mixing takes place, as to prevent the resistance, due to eddy motion from obeying the ordinary laws of viscosity (Taylor 1915, 20).

Finally, there now appear to be a large class of geophysical phenomena, including transport in the PBL, where momentum and heat are transferred locally from regions of small values to regions of large values, called "countergradient flow." [See Starr (1968) for a concise discussion and applications to the larger scales of flow.] In effect, this implies a negative viscosity (or infinite in the case of transport in the absence of a gradient) (see Stull 1993).

The seeds for the decline of the *Austausch* theory were sown by Taylor in the early 1920s (Taylor 1921). George Batchelor, a protégé of Taylor and Taylor's biographer (Batchelor 1996), discusses the significance of this work:

> The movements that lead to transport and diffusion in turbulent motion of a fluid are continuous, in contrast to the motions of molecules in a gas, and Taylor realized that a mathematical study of the properties of random functions would be needed before turbulent diffusion could be described quantitatively. He made the first steps in such a study, and perceived the simplifications possible when the velocity of a fluid element is a stationary random function of time. The main result of the paper is the now classical formula . . . relating the mean-square of the displacement of the fluid element in one direction to the coefficient of correlation of its velocity at two different times . . . this relation accounted for the observed general features of the smoke plume from a chimney in the wind, conical spreading near the source and a paraboloidal shape far downstream. . . . The paper was well ahead of its time, and it was not until 14 years later that laboratory experiments on diffusion in turbulent flow were related to this simple theory or that the idea of using probability theory methods in the description of turbulent velocity fluctuations was taken up. And it was Taylor himself who made these further developments (Batchelor 1976, 580).

By the early 1940s, Andrei Kolmogorov and his school of fluid dynamicists joined Taylor as prime contributors to the statistical theory of turbulence (Batchelor 1990; Yaglom 1994).

Despite the setbacks suffered by *Austausch* theory, this method is not obsolete and, indeed, provides for an effective way of parameterizing turbulence in the surface layer (*Bodenschicht*). The impressive work of Woodrow Jacobs on evaporation over the world sea using the *Austausch* exchange concept is a testament to its value in climatological studies (Jacobs 1942, 1943).

Lettau said, "while Taylor developed statistical theory, my work remained concentrated . . . on physical process from surface layer to stratosphere to exosphere . . ." (H. Lettau 1994, personal communication). He has steadily contributed to studies of world climate through use of balloon research during the late 1930s (see, e.g., Lettau 1939, 1951, 1952, 1969, 1990). The late 1930s phase of the "ballooning" research included accurate wind profile evaluation, airmass modification, downwind diffusion of condensation nuclei, and dust

TABLE 2. *Austausch* coefficients $\mathcal{A}$ (m^{-1} kg s^{-1}) above and below inversions (Inv) with ΔT(°C) = the vertical temperature spread. Translated and rearranged from data in LS (1936, 53).

Date of flight	25 Feb	19 Aug	9 Sept	23 Oct
ΔT (°C)	2	1	1.5	sfc inv
$\mathcal{A}$:above inv	10.7	7.5	35.6	3.6
$\mathcal{A}$:below inv	0.4	3.8	1.7–6.7	0.3

---

[13] Lettau introduced the term "planetary boundary layer" into meteorology in his textbook on atmospheric turbulence (Lettau 1939, sect. 29). This layer couples the surface or ground layer of 50-m depth (called *Bodenschicht* by Lettau) with the Ekman layer.

particles. This led to the O'Neill Experiment in the 1950s (Lettau and Davidson 1957).[14]

In the same spirit that Batchelor praised Taylor's work on statistical theory, it is appropriate to say that the Lettau–Schwerdtfeger experiment, and in particular, the strategy for measuring turbulent structure via the manned free balloon, was well ahead of its time. Don Lenschow, a protégé of Lettau's, comments on the balloon experiment:

> Lettau and Schwerdtfeger's method seems to have not been pursued after their experiment. Yet the accuracy of their technique for measuring w has not yet been achieved by, for example, aircraft sensing techniques. Interestingly, the Naval Research Laboratory has been pursuing a somewhat similar technique in recent years using a blimp (Blanc et al. 1989). This Lagrangian approach is inherently very complementary to aircraft measurements.

We now know that in a stably stratified region (e.g., above the boundary layer) turbulence is not the major source of the vertical wind. Rather the preponderance of evidence is that what they sensed with the balloon was gravity wave activity. This is borne out by the periodic nature of w in Fig. 12, which in retrospect could have been used to measure the Brunt–Väisälä frequency and thus the lapse rate more accurately than they could measure it directly (D. Lenschow 1996, personal communication).

Elaborating on Lenschow's statement, gravity waves that form in a stably stratified atmosphere have a frequency given by

$$\sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial z}},$$

where g, θ, and z represent gravity, potential temperature, and height, respectively. The frequency is known in the meteorological literature as the Brunt–Väisälä frequency [see, e.g., Dutton (1976, 468)]. This formula was known to early twentieth-century aeronauts, but not by the name "Brunt–Väisälä" (Dietzius 1920). It was used by Lettau and Schwerdtfeger in LS (1936, 48) to theoretically calculate the oscillations of the balloon. Although they used this formula for calculating the balloon's periodic motion, its association with the dynamics of internal gravity waves in the atmosphere was unclear in the early 1930s.[15] Following World War II, the French meteorologist Paul Queney visited the University of Chicago and made one of the first systematic studies of internal waves in the atmosphere (Queney 1947).

Based on research conducted during the last half of the twentieth century, we now have a clearer picture of the turbulent processes that occur in the convective boundary layer [where notable contributions have been made by Ball (1960), Lilly (1968), and Deardorff (1966, 1972)]. Deardorff's research has been especially effective in shedding light on countergradient transport through the concerted use of hydrodynamic models and three-dimensional numerical simulations.

6. Epilogue

Since our youth, we have mused over the wind flow close to the earth's surface—its invisible action causing a kite to flutter and its powerful sweep over the ocean surface generating white caps and sea spray. To be sure, this same sense of majesty filled the spirit of sixteen-year-old Heinz Lettau as he held fast to his hang glider and soared over the sand dunes of Rossitten.

The atmospheric boundary layer envelopes us and we have a set of experiences and observations that beg

TABLE 3. *Austausch* coefficients $\mathfrak{A}$ (m^{-1} kg s^{-1}) by height intervals from the four balloon flights of 1934. Translated and rearranged from data in LS (1936, 53).

Height interval	No. of runs	Average $\mathfrak{A}$	Smallest–largest
0–1 km	26	3.5	0.1–14.2
1–2 km	18	4.8	0.2–35.6
2–3 km	11	5.1	1.1–13.4
3–4 km	5	2.5	0.3–5.7

---

[14] Lettau was awarded the Carl-Gustaf Rossby Research Medal in 1974 "for the outstanding research achievements leading to a fuller understanding of the atmosphere's first mile. . . ." (AMS 1992, 1204).

[15] Ekman (1904) and Taylor (1931) had theoretically investigated internal waves in the ocean where the assumption of incompressibility was justified.

for scientific explanation. More than almost any branch of meteorology, understanding came through the concerted efforts of fluid dynamicists like Taylor and Prandtl, from the painstaking efforts of practical-minded scientists like Hesselberg and Sverdrup, who labored over the archival records of pilot balloon observations, and from the field experimenters like Heinz Lettau and Werner Schwerdtfeger, who demanded measurements in the "thick of the medium."

Acknowledgments. I extend my thanks to Heinz and Katherina Lettau for allowing me to visit their home in Madison, Wisconsin, and collect oral history on the balloon experiment. Marianne Schwerdtfeger, one of the crew members on the flights of 1933–34, is also acknowledged for her support.

Review of the manuscript at the early stage by Don Lenschow (National Center for Atmospheric Research) and Alan Shapiro (University of Oklahoma) helped define the scope of the paper; Lenschow's thorough review at the final stage led to a sense of completeness; and Charles Moore (New Mexico Institute of Mining and Technology) is thanked for his review of the scientific ballooning aspects of the paper.

Heinz Lettau, Dian Gaffen (Air Resources Laboratory/NOAA), Judith Torres (World Meteorological Organization), and Stanley Cornford (Royal Meteorological Society) are credited with help that led to the identification of many of the scientists in Fig. 5. The photograph is the property of Marianne Schwerdtfeger, and Professor Lettau alerted the author to its existence.

Much of the material for this project came from late nineteenth- and early twentieth-century journal articles published in Britain, western Europe, and Scandinavia. The acquisition of these materials was made possible through the conscientious efforts of Mary Meacham and Katherine Day, NOAA librarians, and Monika Stutzbach-Michelsen, archivist at Seewarte (Germany). To these dedicated and industrious library science specialists whose assistance came with a most cooperative spirit, I offer my heartiest thanks.

References

Åkerblom, F., 1908: Recherches sur les courants les plus bas de l'atmosphère au dessus de Paris [Research on the lowest currents (flow) in the atmosphere above Paris]. *Nova Acta Reg. Soc. Sci. Uppsala,* Ser. IV, Vol. 2, No. 2, Edv. Berling, 1–45 pp.

AMS, 1992: The Society's awards. *Bull. Amer. Meteor. Soc.,* **73,** 1199–1241.

Angot, A., 1897: Résumé des observations anémométriques faites au bureau central et à la Tour Eiffel pendant les six années 1890–95 (Summary of anemometer observations made from the Central Bureau at Eiffel Tower during the six years 1890–95). Annales du bureau centr. météorol. de France, 171 pp.

Ball, F. K., 1960: Control of inversion height by surface heating. *Quart. J. Roy. Meteor. Soc.,* **86,** 483–494.

Batchelor, G., 1976: Geoffrey Ingram Taylor, 7 March 1886–27 June 1975. *Biog. Mem. Fell. Roy. Soc.,* **22,** 565–633.

——, 1990: Kolmogorov's work on turbulence. *Bull. London Math. Soc.,* **22,** 47–51.

——, 1996: *The Life and Legacy of G. I. Taylor.* Cambridge University Press, 285 pp.

Blanc, T. V., W. J. Plant, and W. C. Keller, 1989: The Naval Research Laboratory's Air–Sea Interaction Blimp Experiment. *Bull. Amer. Meteor. Soc.,* **70,** 354–365.

Boussinesq, J., 1897: Théorie de l'écoulement tourbillonant (Theory of turbulent flow). *Mém. Prés. Acad. Sci.,* **XXIII,** 46–51.

Deardorff, J., 1966: The counter-gradient heat flux in the lower atmosphere and in the laboratory. *J. Atmos. Sci.,* **23,** 503–506.

——, 1972: Theoretical expression for the countergradient vertical heat flux. *J. Geophys. Res.,* **77,** 5900–5904.

Dietzius, R., 1920: Schwingungen des Freiballons (Oscillations of free balloons). *Beitr. Phys. Freien Atmos.,* **7,** 167–178.

Ekman, V., 1902: Om jordrotationes inverken på vindströmemar i hafvet (On the influence of the earth's rotation on the wind-driven current in the ocean). *Nytt. Mag. f. Naturv.,* **40,** 37–63.

——, 1904: On dead water. *Norwegian North Polar Expedition, 1893–1896 (Scientific Results).* Vol. 5, No. 15, 152 pp.

——, 1905: On the influence of the earth's rotation on ocean currents. *Arkiv für Mat. Astr. och Fysik,* **2,** 1–52.

Eliassen, A., 1982: Vilhelm Bjerknes and his students. *Annu. Rev. Fluid Mech.,* **14,** 1–11.

Ertel, H., 1932: Allgemeine theorie der Turbulenzreibung und des austausches (General theory of turbulent friction and the austausch process). *Sitzung phys.-math. Klasse Preuß. Akad. Wiss. Berlin,* **26,** 436–443.

Gold, E., 1936: Dr. W. Schmidt (obituary). *Nature,* **138,** 1086.

Guldberg, C., and H. Mohn, 1876: *Études sur les Mouvements de l'Atmosphère.* Parts 1 and 2. A. W. Brøgger, 39 and 53 pp. (Report, 1910, *Smithsonian Misc. Coll.,* **51,** 122–248.)

Haurwitz, B., 1941: *Dynamic Meteorology.* McGraw-Hill, 365 pp.

Hesselberg, T., and H. Sverdrup, 1915: Die Reibung in der Atmosphäre (Friction in the atmosphere). *Veröff. des Geophysik Inst. Univ. Leipzig,* Spezialarbeiten aus dem Geophys. Inst. [Special Contributions (Works) from the Geophysical Institute], 2d ser., Vol. 10, Spezialarbeiten d. Geophys. Inst., 241–309.

Jacobs, W., 1942: On the energy exchange between sea and atmosphere. *J. Mar. Res.,* **5,** 37–66.

——, 1943: Sources of atmospheric heat and moisture over the North Pacific and North Atlantic Oceans. *Ann. N. Y. Acad. Sci.,* **44,** 19–40.

Kutzbach, G., 1976: *The Thermal Theory of Cyclones: A History of Meteorological Thought in the Nineteenth Century. Hist. Monogr.,* Amer. Meteor. Soc., 255 pp.

Lettau, H., 1939: *Atmosphärische Turbulenz.* Akad. Verlags., 283 pp.

——, 1951: Diffusion in the upper atmosphere. *Compendium of Meteorology,* T. Malone, Ed., Amer. Meteor. Soc., 320–333.

——, 1952: Astronomie und Geophysik. *Landdolt—Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, und Technik,* J. Bartels and P. Ten, Eds., Vol. III, Bruggencate, 666–674.

——, 1969: Evapotransporation climatonomy 1. A new approach to numerical prediction of monthly evaportranspiration, runoff, and soil moisture storage. *Mon. Wea. Rev.,* **97,** 691–699.

——, 1990: The O'Neill experiment of 1953. *Bound.-Layer Meteor.,* **50,** 1–9.

——, and W. Schwerdtfeger, 1933: Untersuchungen über atmosphärische Turbulenz und Vertikalaustausch vom Freiballom aus, I [Investigations of atmospheric turbulence and vertical austausch from the free balloon, Part 1]. *Meteor. Z.*, **51**, 250–256.

——, and ——, 1934: Untersuchungen über atmosphärische Turbulenz und Vertikalaustausch vom Freiballom aus, II. *Meteor. Z.*, **52**, 249–257.

——, and ——, 1936: Untersuchungen über atmosphärische Turbulenz und Vertikalaustausch vom Freiballom aus, III. *Meteor. Z.*, **54**, 44–53.

——, and B. Davidson, Eds., 1957: *Exploring the Atmosphere's First Mile.* Vols. I and II. Pergamon Press, 578 pp.

Lewis, J., and C. Moore, 1995: Leroy Meisinger, Part II: Analysis of the scientific ballooning accident of 2 June 1924. *Bull. Amer. Meteor. Soc.*, **76**, 213–226.

Lilly, D., 1968: Models of cloud-topped mixed layers under a strong inversion. *Quart. J. Roy. Meteor. Soc.*, **94**, 292–309.

List, R., 1966: Meteorological Tables. *Smithsonian Misc. Collection,* Vol. 114, 6th ed., Smithsonian Institution Press, 527 pp.

Moore, C., J. Smith, and A. Gaalslwyk, 1954: On the use of constant level balloons to measure horizontal motions in the atmosphere. *J. Meteor.*, **11**, 167–172.

Mosteller, F., R. Rourke, and G. Thomas, 1961: *Probability with Statistical Applications.* Addison-Wesley, 478 pp.

Prandtl, L., 1905: Über die Bewegung der Flussigkeit mit kleiner Zähigkeit (Motion of fluid with small viscosity). *Verh. Int. Math. Kong,* 3d ed., Heidelberg, 484–491.

——, 1925: Bericht über Untersuchungen ausgebildeten Turbulenz (Report on the investigation into the modeling of turbulence). *Z. Angew. Math. Mech.*, Vol. 5, No. 2, 136–139.

——, 1952: *Essentials of Fluid Dynamics: With Applications to Hydraulics, Aeronautics, Meteorology, and other Subjects.* Hafner, 452 pp.

Queney, P., 1947: Theory of perturbations in stratified currents with applications to air flow over mountain barriers. Meteorology Dept. Misc. Rep. 23, University of Chicago, 76 pp. [Available from Joseph Rogenstein Library, University of Chicago, 1100 E. 57th St., Chicago, IL 60637.]

Reynolds, O., 1886: On the theory of lubrication and its application to Mr. Beauchamp Tower's experiments, including an experimental determination of the viscosity of olive oil. *Philos. Trans. Roy. Soc. London,* **186**, 123–141.

Richardson, L., 1920: The supply of energy to and from atmospheric eddies. *Proc. Roy. Soc. London, Ser. A,* **97**, 354–373.

——, 1925: Turbulence and vertical temperature difference near trees. *Philos. Mag.*, **49**, 81–90.

Rossby, C.-G., and R. Montgomery, 1935: The layer of frictional influence in wind and ocean currents. *Papers in Phys. Oceanography and Meteorology,* Vol. 3, No. 3, Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, 100 pp.

Schlichting, H., 1968: *Boundary-Layer Theory.* 6th ed. McGraw-Hill, 747 pp.

Schmidt, W., 1917: Der Massenaustausch bei der ungeordneten Strömung in freier Luft and seine Folgen [Mass exchange by disorderly (turbulent) motion in the free air and its consequences]. *Sitzungsber.-Oesterr. Akad. Wiss., Math.-Naturwiss. Kl. Abt 2a,* **126,** 757–803.

——, 1925: *Der Massenaustausch in freier Luft und verwandte Erscheinungen* (Mass exchange processes in free air and related phenomena). H. Grand, 118 pp.

Starr, V., 1968: *Physics of Negative Viscosity.* McGraw-Hill, 256 pp.

Stevenson, T., 1880: Observations of the force of wind. *J. Scot. Meteor. Soc.,* **5**, 348–351.

Stewart, R. W., 1972: Atmospheric boundary layer. *Meteorological Challenges: A History,* D. P. McIntyre, Ed., Crown, 267–281.

Stull, R., 1993: Review of nonlocal mixing in turbulent atmospheres: Transilient turbulence theory. *Bound.-Layer Meteor.*, **62**, 21–96.

Sutton, O., 1953: *Micrometeorology.* McGraw-Hill, 333 pp.

Tani, I., 1977: History of boundary layer theory. *Annu. Rev. Fluid Mech.*, **9**, 87–111.

Taylor, G., 1915: I. Eddy motion in the atmosphere. *Philos. Trans. Roy. Soc. London, Ser. A,* **215,** 1–26.

——, 1921: Diffusion by continuous movements. *Proc. London Math. Soc., Ser. 2,* **20**, 196–212.

——, 1931: Internal waves and turbulence in a fluid of variable density. *Rapp. P.-V. Réun. Cons. Int. Explor. Mer.*, **76**, 35–42.

Upson, R., and C. deF. Chandler, 1926: *Free and Captive Balloons.* Ronald Press, 331 pp.

von Kármán, T., 1954: *Aerodynamics.* McGraw-Hill, 203 pp.

Yaglom, A., 1994: A. N. Kolmogorov as a fluid mechanician and founder of a school of turbulence research. *Annu. Rev. Fluid Mech.*, **26**, 1–22.