THE O'NEILL EXPERIMENT OF 1953

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Abstract. The official report on this first comprehensive field experiment in boundary-layer meteorology was published 1957 in two volumes, edited by Lettau and Davidson (hereafter L&D). The official report is supplemented in this paper by relevant pre-history developments and a discussion of some selected post-history interpretations and follow-up experiments.

1. Introduction

O'Neill, Nebraska, is located in prairie country at 42.5° N, 98.5° W and about 600 m elevation. The terrain is flat but ascending gradually by a slope of about 1:500 from the Mississippi in the east to the foothills of the Rocky Mountains in the west. The boundary-layer experiment was run between 1 August and 9 September, 1953. Recordings of subsoil parameters, surface fluxes and surface-layer profiles of temperature, momentum, and mass admixtures were made by participants from nine US Universities. Measurements of the boundary-layer profiles of wind components, air temperature and humidity were made by participants from six US Government agencies. Use of diverse types of sensor systems for the most frequently measured meteorologcial variables was encouraged in order to establish to what degree an instrument output approximated faithfully the behavior of the atmosphere and what proportion might be due to unwanted response characteristics of the instrument itself.

To simulate as nearly as possible the quality of wind tunnel experiments, I had concluded that three precautions would be necessary: Firstly, the site must be carefully chosen on flat terrain of high uniformity on the 5-km scale and of at least moderate uniformity on the 50-km scale; secondly, synchronized intensive round-the-clock data collection by all participating teams should be made on "General Observation Days" with clear skies and a steady driving force of air motion; thirdly, the frequency of occurrence and direction of a steady driving force should be established by a statistical analysis of surface-level geostrophic winds. The first requirement was satisfied by the grasslands of the Great Plains area where O'Neill is located; the second requirement meant a restriction to the 6-week period of late-summer university vacations; the third one meant a restriction to southerly flow, as a result of a statistical analysis of synoptic weather charts from previous years; see article by P. Davis (L&D, Volume II, pp. 384–387).

On location after 1 August, 1953, general observations were initiated four hours in advance when, by special arrangement with the US Weather Service in Kansas

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City, Ben Davidson acting as program coordinator at O'Neill was advised of favorable synoptic conditions expected to prevail for the following 30 hours. During the six weeks on location, seven general observation days were initiated and in six cases the full diurnal course of boundary-layer structure was documented.

Definite planning of the experiment began in 1952 at the Air Force Cambridge Research Center. This last phase of the history is reported in some detail (L&D, Volume I, 1–6) with an outline of the general objectives. I would like to supplement the record by the 'pre-history' which can be dated back to 1925, relating to events and decisions during the years before 1953, without which the O'Neill experiment probably would not have taken place, or would have occurred at a later time and under different conditions.

2. Earliest Impressions, 1925–1931

In 1925, as a high-school tenth-grader in my home-town of Koenigsberg, East Prussia, I attended summer camp at the hang-glider school Rossitten. The location was adjacent to the nearly 10 km long wall of sand dunes with crest heights of 40 to 50 m, forming the backbone of the narrow isthmus separating the Baltic Sea in the west and Kurisches Haff in the east. Life on this protected nature preserve was controlled by the wind. The few conifer trees near the seashore were stunted and wind-trained. With strong westerly gales the sand drifted in sheets and streamers, causing a slow eastward migration of the dune wall. Fishermen's cottages and graveyards near the lagoon shore had been buried two centuries ago, and had re-appeared to the west of the dune a century later. Stretches of 300 to 500 m length on the gentle western slope served for beginner's training in the primitive hang-gliders of the 1920's. On days with east winds, the air current above the steeply descending slipface was the domain of the experts. Here, a few years earlier, our instructor at the camp, Ferdinand Schulz, had established an endurance record by staying eight hours aloft. Schulz inspired us to try to understand wind structure and gustiness above terrain slopes. I was impressed and decided that after graduation from high school, I would study physical and mathematical sciences, and relate my education to environmental problems.

I studied geophysics and meteorology, attending university courses by F. Errulat in Koenigsberg, by F. Baur, B. Gutenberg, F. Linke, R. Muegge, and G. Stueve in Frankfurt, and by B. Haurwitz and L. Weickmann in Leipzig. In the departmental libraries, I learned from the literature about wind structure and vertical 'austausch' processes. 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.

3. Boundary-Layer Meteorology, 1931–1947

Having graduated in the depression year of 1931, I was fortunate to receive a postdoctoral research stipend from "Deutsche Notgemeinschaft der Wissenschaft" for work on gravimetry at the Geodetic Institute near Potsdam, located on 'Telegraph-Hill'. My assignment permitted me to get acquainted with the other research institutes on the 'Hill'. Most fruitful was my contact with the director of the Meteorological Observatory, Reinhard Suering. In 1901 he had reached by balloon an altitude of 10,800 m, a record not surpassed for 30 years. Suering provided valuable technical advice, wholehearted moral support and modest but highly appreciated funding for my plans to use manned balloon flights 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.

In all seasons during some of the years 1932 to 1938, we completed ten successful scientific 'saw-tooth' flights, with repeated altitude changes between ground and 3000 m. The first five were devoted to the measurement of eddy up-and-down drafts, with a time resolution of 10-s. Werner Schwerdtfeger was co-investigator, whom I had met as fellow graduate student at Leipzig. The second series beginning in 1935 was devoted to quasi-Lagrangian studies of downwind changes resulting from ground sources of Aitken nuclei, or dust particles, and water vapor. This method also yielded data on vertical eddy mass-exchange and air mass transformation over time-scales of 10 h, or trajectories of 150 to 300 km length; see Lettau and Schwerdtfeger (1933, 1936) and Lettau *et al.* (1937).

Incidentally, analyses of strip chart recordings from the Telegraph-Hill tower anemometer (about 70 m above the surrounding plain) provided two statistical results that are relevant for the discussion of post-historic interpretations of the O'Neill experiment. Firstly, the maximum of the average diurnal course of wind speed occurs during the daytime in summer but at night in winter (Hann and Suering, 1926); this is a significant variant of the Espy–Koeppen paradox (Lettau, 1979, p. 460). Secondly, F. Defant (1941) found that inertial oscillations are very rare, occurring only in 12 cases on more than 9,000 daily stripcharts from Telegraph-Hill

Back at Leipzig University, from 1933 to 1938, first as research assistant, later as dozent, I continued balloon flights. Besides geophysical investigations of earth-tides, I was in charge of counseling graduate students at the Geophysical Observatory on micrometeorological thesis research. Ludwig Weickmann, the director of the Institute and the Observatory, suggested 'Atmosphaerische Turbulenz' as the topic of my first lecture course which I gave at Leipzig University in 1937. The material collected and evaluated for these lectures was later published under the course title. Chapter 7 of this monograph (Lettau, 1938) was headed 'Atmosphaerische Grenzschichten' and the term translated 'planetary boundary layer' appeared for the first time in the literature.

Following a call to my old home-town 'alma mater', I returned to Koenigsberg by the end of 1938. However, the war interrupted my university teaching. The German Air Force drafted me into service and found use for my experience with boundary-layer wind structures; I may refer to an introductory note in Schwerdtfeger (1986). After the war, my home-town was annexed by the USSR without any possibility for my return. I resumed theoretical studies on atmospheric diffusion processes as head of the research unit. German Weather Service in the US-Occupation Zone. I renewed contact with Ludwig Prandtl, the father of aerodynamic and hydrodynamic boundary-layer theory and the concept of eddy mixing length. In 1946, during a brief visit at Goettingen, Prandtl re-emphasized his interest in atmospheric applications of his theory. Incidentally, he found it confusing that meteorologists used the term 'jet stream' for flow driven by internal force fields, while an aerodynamic jet is driven out of a nozzle by an initial pressure excess, and decomposed downstream by friction.

4. Preparations for O'Neill, 1947–1953

In the summer of 1947 I accepted an offer to come to the United States to join an Air Force Research unit which later was re-organized as the Geophysics Research Directorate, located in the Greater Boston area. The opportunity arose to justify and prepare a comprehensive boundary-layer experiment. The first step was to summarize from the international literature the results of several 'small-scale experiments' dealing with surface-layer responses to boundary fluxes of heating and cooling. The manuscript was accepted for the first issue of the Directorate's newly established Report series 'Geophysical Research Papers'. A re-analysis of the "Leipzig Wind Profile" (Lettau, 1950) documented the importance of high accuracy in the vertical profiles of shear of the two horizontal mean wind components in the atmospheric boundary layer above the reach of tower equipment.

Recalling the accuracy of mean wind shear vectors when evaluated from altitude steps in quasi-horizontal balloon drift, I concluded that there was a need for a ground-based method of wind profile measurements of similar accuracy. Guenter Loeser, who had joined the Directorate in 1951, agreed to design a double-photo theodolite technique. After testing several possibilities in Wellfleet, Cape Cod, during the spring of 1953, we settled on one method for daytime and another for night-time use; Section 6.1 (L&D, Volume I, pp. 276–282). The exceptional quality of the wind profile structure data obtained by Loeser's technique is evident in Figure 1, showing details of the development of the nocturnal low-level jet flow over the region. To the deepest sorrow of all people who knew Guenter Loeser, he and four others died in a most unfortunate helicopter accident while pre-testing his new method.

To make the planned experiment truly comprehensive, I tried to interest independent university groups in contributing observations of atmospheric admixtures – other than water vapor – for which the atmosphere's lower boundary acts as a natural area-source or sink; for example, carbon dioxide, radon, or others. The result was that ozone profiles were measured at O'Neill by mast-equipment development by V. Regener; see Section 4.4 (L&D, Volume I, pp. 188–198).

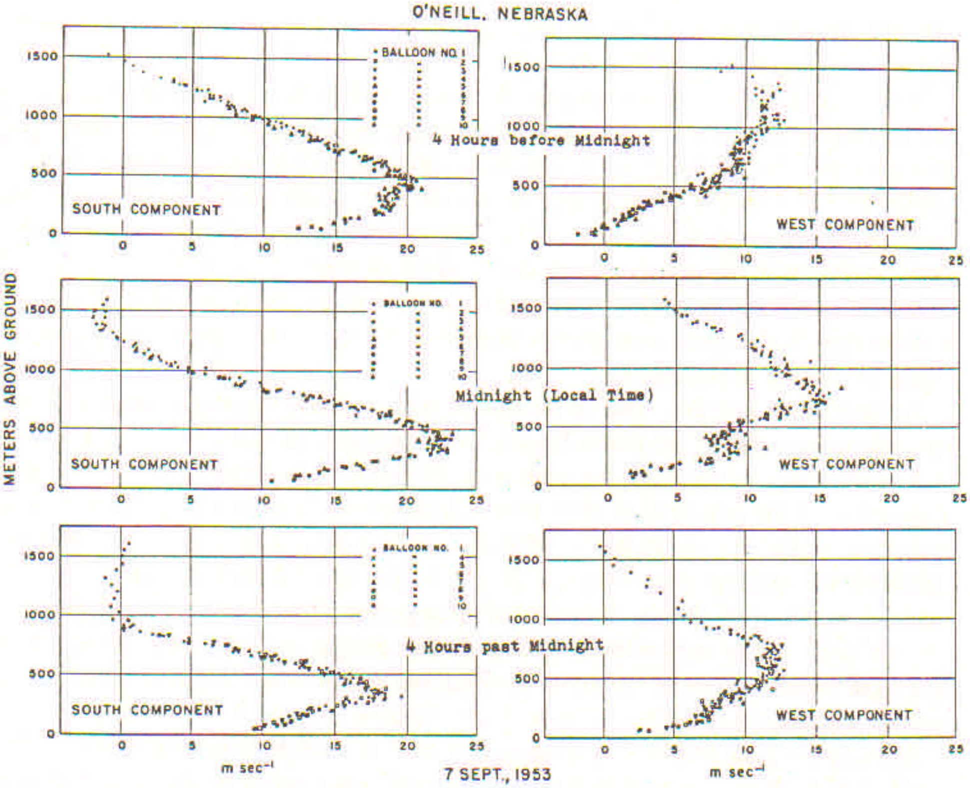

Fig. 1. Profiles of the south and west components of air motion, O'Neill, seventh "General Observation Day". For round-the-clock data on low-level jet buildup and decay after the midnight peak, see tabulations in L&D (1957, Volume II).

According to the prepared plan, observations at O'Neill were to be made under southerly surface wind conditions. The total of nine co-operating universities – for a complete list see L&D, Volume I, pages viii to ix – made it necessary to preassign sites for sensing equipment along an east–west line which stretched over 500 m. Mobile housing and shacks for recorders, and machinery for power generation, also all traffic, were restricted to north of the observing line. For details, see L&D, Volume II, pp. 377–384.

5. Post-History Impressions

5.1. Sensor arrays

In this and the following Section 5.2, a few supplementary thoughts are added to the official report (L&D, Volume I, pp. 4–6). Firstly, some suggestions are made for the array of sensors in future field experiments, and secondly a brief discussion is given of several experiments reported in the literature and significant for understanding the dynamics of the low-level jet delineated for the first time at O'Neill during all general observation days.

Subsoil and Surface Observations. A 'bonus' not foreseen was that during the six weeks on location, the soil lost evaporable water nearly continuously. The Bowen ratio went from 1/2 to 2. Soil heat diffusion and storage changed significantly. The analysis of diurnal courses would have been more conclusive if soil heat flux plates had been paired with soil thermometers at each measurement level. With such an array, depth distribution of daily-mean soil heat capacity and heat conductivity could be determined. Bolometric measurements of surface temperature variations were greatly missed at O'Neill and should always be included in future experiments.

Surface-Layer Profiles. The conventional array of mast-supported anemometers and thermometers by "adjacent double-level spacing" – for example: 3.2, 1.6, 0.8, 0.4, and 0.2 m – is adequate for evaluation of surface roughness length and height correction in the adiabatic surface layer. A conclusive analysis of diabatic profile structure would be significantly improved by available data from "overlapping double-level spacing", for example: 3.2, 2.4, 2.0, 1.6, 1.2, 1.0, 0.8, 0.6, 0.5, 0.3, and 0.2 m; (Lettau, 1967). In cases of strong inversion, only this array permits one to locate the inflection level of temperature-profile curvature and to document the significantly different reactions of wind and temperature profile curvatures to surface heating and cooling (Lettau, 1979, Figures 1, 2 and 3).

Boundary-Layer Profiles. A comparison of O'Neill data obtained by three conventional methods, captive balloon, radiosonde, and airplane suggests that the airplane is the most efficient tool. It permits altitude steps in horizontal sampling of mean temperatures and mixing ratios, measurements of wind components and eddy co-variances, and also the bolometric sensing of surface temperature fields.

5.2. THE LOW-LEVEL JET

According to Blackadar's (1957) hypothesis, the nocturnal wind maximum is caused by an inertial oscillation starting around sunset when the daytime convective turbulence has died down. Then, the oscillation starts from subgeostrophic velocities and passes after 1/4 pendulum day through the supergeostrophic phase. Although widely quoted in later literature as the possible cause of low-level jet streams, the general applicability of the hypothesis must be doubted for reasons enumerated as follows.

(i) Surface layer wind-speed as a fraction of geostrophic speed is relatively large in the daytime and small at night. The normal diurnal wind-speed spread between the heating and the cooling phases is at a maximum no higher than a few meters above the surface. It decreases with height and reverses sign at levels of a few decameters, still within the surface layer – the Espy–Koeppen paradox – and still at subgeostrophic speed; see Figure 2 in Lettau (1979).

(ii) As mentioned in Section 3, Defant has shown that inertial oscillations very

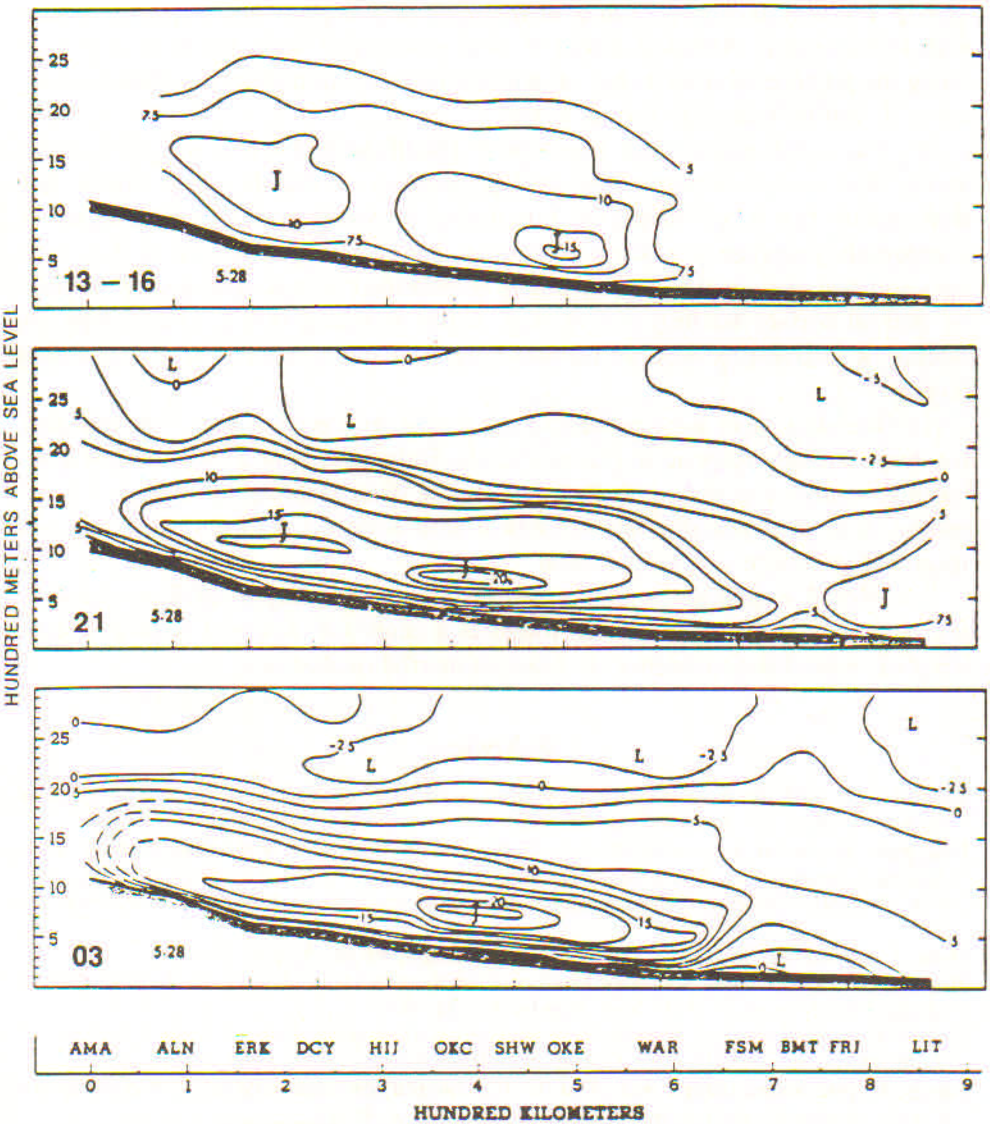

Fig. 2. Isotach (in m/sec) cross-sections at 13–16 (averaged), 21, and 03 CST on 28 May, 1961. For full round-the-clock graphs and explanation of station symbols, see Hoecker (1963). The west-to-east line of special pibal soundings by the US Weather Bureau, from Amarillo, Texas, between 35 and 36° N latitude, to Little Rock, Arkansas, was referred to as "Wexler's Low-Level Jet Stream Experiment" (Lettau, 1983).

seldom occur in anemometer recordings from hill and mountain stations. The cause was always a more or less abrupt cessation of a pressure gradient force.

(iii) A horizontal cross-section of the Great Plains low-level jet is reproduced in Figure 2. For the full round-the-clock development of this case, see Hoecker

(1963). Position and lateral limits of the peak flow suggest a strong relationship with terrain slope. Although about 800 km south of O'Neill, the vertical profile along the jet core resembles that shown on Figure 1. An inertial oscillation would certainly not be related to terrain slope.

(iv) The Antofagasta Field Experiment (Rutlland and Ulrikson, 1979) documents that a north easterly low-level jet persists during the night hours, but shifts within two hours during the fore-noon to a south westerly low-level jet of comparable structure, persisting until about sunset. The profiles are 12-day averages and best explained by forcing due to see-sawing thermal wind fields generated by diurnal surface cooling and heating of the westward-facing Andes slope. A release of restraint by reduced turbulent mixing cannot explain the daytime low-level jet.

(v) Boundary-layer wind profiles in the persistent inversion above the antarctic ice-dome strongly respond to thermal winds. Dalrymple *et al.* (1966) analysed the thermal winds using the South Pole radiosonde data, yielding an estimate for the terrain slope in reasonably fair agreement with altimeter readings from traverses towards the Amundsen–Scott station.

The overall conclusion is that it will be more rewarding to look for possible diurnally varying fields of internal forces as a cause for observed boundary-layer wind extremes than to restrict attention to inertial oscillations.

References

Blackadar, A.: 1957, 'Boundary Layer Wind Maxima and their Significance for the Growth of Nocturnal Inversions', *Bull. Am. Meteorol. Soc.* **38**, 283.

Dalrymple, P., Lettau, H., and Wollaston, S.: 1966, 'South Pole Micrometeorology Program. Data Analysis', *Antarctic Res. Series, Amer. Geophys. Union* **9**, 13.

Defant, F.: 1941, 'Traegheits Schwingungen in den Luftstroemen der Atmosphäre', *Meteorol. Z.* **58**, 53.

Hann, J. and Suering, R.: 1926, *Lehrbuch der Meteorologie*, 4th ed., Leipzig, 333 pp.

Hoecker, W.: 1963, 'Three Southerly Low-Level Jet Systems Delineated by the Weather Bureau Special Pibal Network of 1961', *Mon. Weather Rev.* **91**, 573.

Lettau, H. and Schwerdtfeger, W.: 1933, 'Vertikal Austausch in unmittelbarer Berechnung', *Meteorol. Z.* **50**, 47.

Lettau, H. and Schwerdtfeger, W.: 1936, 'Untersuchungen über Atmosphaerische Turbulenz und Vertikal Austausch vom Frei-Ballon aus (III)', *Meteorol. Z.* **53**, 44.

Lettau, H., Doerffel, K., and Roetschke, M.: 1937, 'Luftkoerper Alterung als Austausch Problem auf Grund von Staub und Kern Gehaltsmessungen', *Meteorol. Z.* **54**, 16.

Lettau, H.: 1937, 'Weiterfuehrung der Frei-Ballon Untersuchungen über effektiven Vertikal Austausch und Luftmassen Alterung mit Anwendung auf die Frage der Land Verdunstung, *Meteorol. Z.* **54**, 406.

Lettau, H.: 1938, *Atmosphaerische Turbulenz*, Akadem. Verl. Ges., Leipzig, 283 pp.

Lettau, H.: 1950, 'A Re-examination of the "Leipzig Wind Profile" Considering some Relations Between Wind and Turbulence', *Tellus* **2**, 125.

Lettau, H. and Davidson, B. (ed.): 1957, *Exploring the Atmosphere's First Mile*, Vols. I and II, Pergamon Press, New York, 378 pp.

Lettau, H.: 1967, 'Problems of Micrometeorological Measurements (On Degree of Control in Out-of-Doors Experiments)', in E. Bradley and O. Denmead (eds.), *The Collection and Processing of Field Data*, Interscience Pub. John Wiley, New York, 222 pp.

Lettau, H.: 1979, 'Wind and Temperature Profile Prediction for Diabatic Surface Layers Including Strong Inversion Cases', *Boundary-Layer Meteorol.* **17**, 443.

Lettau, H.: 1983, 'Thoughts on Priorities in Boundary-Layer Research', *Boundary-Layer Meteorol.* **25**, 429.

Rutlland, J. and Ulrikson, P.: 1979, 'Boundary-Layer Dynamics of the Extremely Arid Northern Part of Chile', *Boundary-Layer Meteorol.* **17**, 41.

Schwerdtfeger, W.: 1986, 'The Last Two Years of ZWG (Part I)', *Weather* **41**(4), 130.