2.1 ANOTHER LOOK AT THE SIERRA WAVE PROJECT: 50 YEARS LATER

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1. INTRODUCTION

In early 20th century, the sport of manned balloon racing merged with meteorology to explore the circulation around mid-latitude weather systems (Meisinger 1924; Lewis 1995). The information gained was meager, but the consequences grave—the death of two aeronauts, LeRoy Meisinger and James Neeley. Their balloon was struck by lightening in a nighttime thunderstorm over central Illinois in 1924 (Lewis and Moore 1995). After this event, the U.S. Weather Bureau halted studies that involved manned balloons. The justification for the use of the free balloon was its natural tendency to move as an air parcel and thereby afford a Lagrangian view of the phenomenon. Just after the turn of mid-20th century, another meteorological experiment, equally dangerous, was accomplished in the lee of the Sierra Nevada. This Air Force-funded experiment made extensive use of the sailplane, another flying platform whose movement is dictated by the air currents. The experiment was called the Sierra Wave Project, and it took place in two phases, the first in 1951-52 to investigate the well-known "Bishop Wave" or "Sierra Wave", and in 1955 to study the jet stream as it traversed the Sierra Nevada. In this paper, we retrospectively examine this major mountain meteorology experiment. Our investigation has multi-faceted purpose: to uncover the scientific motivation for the experiment, to examine the coupling of sport and science in this experiment, and the impact of the experiment on the meteorological and soaring communities.

2. SAILPLANES

As part of the Treaty of Versailles, Germany was strictly prohibited from flying motorized craft, and was not allowed to engage in the design and construction of aircraft. Nevertheless, in this post-WWI period of intense activity with airplanes, the aerodynamically-minded Germans found a way to contribute to this field—via the development of the glider or sailplane. In the pre-WWI period, gliders were biplanes whose two wings were held together by struts. But in the early 1920s, Wolfgang Klemperer designed and built a cantilever monoplane glider that removed the outside rigging and used "...the Junkers principle of a wing with internal bracing" (von Karmán 1967, p. 98). Theodore von Karmán gives a vivid and lively account of the technical accomplishments of these aerodynamicists, many of them university students, during the 1920s and 1930s (von Karmán 1967).

Since gliders are non-powered craft, a considerable skill and familiarity with local air currents is required to fly them. In his reminiscences, Heinz Lettau also makes mention of the influence that experiences with these motorless craft, in his case hang gliders, had on his interest in meteorology (Lettau 1990). Most of the flying with the gliders in Germany took place in the Riesengebirge mountains in Sudetes (then eastern Germany, today southwestern Poland), the Wasserkuppe in the Rhön Mountains (central Germany), and at Rossitten dunes in the Kurische Nehrung (the 100 km tongue of land in the eastern part of the Baltic Sea), where sailplanes were launched from the high sand dunes (∼70 m above sea level) and flown over the Baltic. With these aerodynamically designed gliders, competitions were the vogue in the 1920s where time/distance records were the primary goals. Interest in gliding was sparked in other European countries, notably Sweden, as well as in the United States. Elmira, NY, became the hotbed of activity in the US, where the terrain around this city in upper-New York state was nearly identical to that around Wasserkuppe. As will be seen, some of the pilots who served in the Sierra Wave Project gained their experience at the gliding schools that developed in the vicinity of these sailplane centers.

3. FLOW OVER MOUNTAINS: EARLY OBSERVATIONS

During this period of interest in sailplane development, a series of contributions related to airflow

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over mountains appeared in the scientific literature. Some of the observations were made with the aid of the sailplane, but the earliest studies of note were simply made with time-lapse photography. Masano Abe, a physicist trained at the University of Tokyo, used a dry photographic plate process to take pictures of clouds that formed over Mount Fuji (Abe 1929). He paid particular attention to the rotary motion of the clouds (rotation about the vertical axis) as the air traversed the 3.7-km high mountain. Sukuei Fujiwara of the Central Meteorological Office had theoretically studied this generation of vorticity in the lee of Fuji and Abe obtained observations in support of the theory (Fujiwara 1927). During the 1930s, several notable observational studies of airflow over mountains were completed. These were: (1) flow over the Atlas Mountains, mountain range parallel to the north African coast (Queney 1936a,b), (2) flow over the Riesengebirge in Sudetes (Kuettner 1938, 1939), and (3) flow over the Northern Pennines, near the border of England/Scotland (Manley 1945)[1]. We briefly discuss these contributions with some background information on the investigators.

Queney's study was the most comprehensive with attention to surface and upper-air observations (from pilot balloon) as well as analytical theory. These papers, Queney (1936a,b), formed his doctoral thesis at the University of Paris. As remembered by his colleague, Pierre de Felice:

> After the competition of Agregation de Physique (he was first), he went to Tamanrasset (Algeria) at the Geophysical Observatory (seismology, magnetism and meteorology). There he met Jean Dubief. . . PQ [Paul Queney] and Dubief made several measurements in Tamanrasset, specially of winds aloft with pilot balloons and 2 theodolites. PQ went to the Institute de Physique du Globe d'Alger, where he regularly drew meteorological maps and he observed the change of direction of the surface wind, south of Mount Atlas when the wind was blowing from the North or Northwest.(de Felice 2002, personal communication)

Queney examined a number of cases of what represented strong synoptic weather systems (including those forcing Mistral) that traversed France and Spain and passed over the Mediterranean and abutted the Atlas Mountains. He delivered detail maps of horizontal pressure perturbations and airflow modifications induced by this mountain range. From observations associated with these systems, he had the basis for his analytical studies. The solutions he obtained—via linearization of the basic equations, assuming sinusoidal variation of orography and constant mean wind and stability—exhibited the importance of interplay between the wavelengths of the mountain profile, speed of the current over the mountain, and the stability of the atmosphere. While Queney himself did not observationally document mountain waves, he predicted their existence theoretically as one possible solution of his analyzed set of equations.

Kuttner's work (Kuettner 1938, 1939) was also comprehensive, with great attention to observations of mountain waves, some of which had been carried out by sailplanes, and conceptual modeling. The key signature in Kuettner's work is the "Stehende Wolken im Gebirgeslee" (the stationary clouds in the lee of the mountain—sometimes called the Moazagotl). These clouds were revered by soaring enthusiasts who knew that the appearance of the Moazagotl portended supreme lift for their craft. The associated vertical currents helped the gliders attain heights the order of 7 km. They had discovered that the lift was not associated with thermals nor the mechanical lift of air over mountain barriers, rather with the stationary cloud downstream of the range. In Kuettner's doctoral thesis (the combined contribution from the two papers referenced above), he begins by making reference to Wolf Hirth's altitude record over Grünau in the lee of the Riesengebirge. His aim is to understand the stationary wave that Hirth used to set an altitude record in March of 1933. Kuettner had been particularly influenced by the work of English classical dynamicists Lord Kelvin (William Thomson) and Lord Rayleigh. They had both studied the generation of standing waves downstream of obstacles in rivers and other bodies of water. Quoting Kuettner:

> You know, those English physicists really did outstanding work. I remember reading Lord Kelvin's work [On the stationary waves in flowing water (Kelvin 1886)]. He motivated the study by recalling the horse-drawn canal boats where speeds exceeding the gravity wave speed led to less resistance on the boat. So clever. (Kuettner 2002, oral history)

The flow of water past obstacles had appeal to Kuettner, yet he realized that the Moazagotl was

[1]Manley's observations were conducted during 1937–1939 but the publication of his results was delayed because of the national security reasons during WWII.

more complicated and would require more in-depth investigation. He enlisted the services of many sailplane pilots (he was a pilot himself) and they made observations of the stationary wave in the lee of the Riesengebirge in 1937. In accord with Queney's work, Kuettner emphasized the importance of stability in the air above the mountain. He also noted the appearance of a rotary motion at low levels, later referred to as the "rotor".

Gordon Manley begins his paper (Manley 1945) by quoting from the Meteorological Glossary (Glossary 1930):

> The Helm wind is a violently cold easterly wind blowing down the western slope of the Crossfell Range [N. Pennines, maximum altitude ~1km]...when the helm is blowing, a heavy bank of cloud, the Helm Cloud, rests along the Crossfell Range, and at a distance of three to four miles from the foot of the Fell, a slender, nearly stationary roll of whirling cloud, the Helm Bar, appears in mid-air and parallel to the Helm Cloud. The cold wind blows strongly down the steep fell sides until it nearly comes under the Bar where it suddenly ceases. . . The space between the Helm Cloud and Bar is usually quite clear although the rest of the sky may be cloudy.

Over a period of several years (1937–1939), Manley painstakingly collected data from the ground on the Helm wind and attendant meteorological features to develop a detailed description of the Helm wind phenomenon. He suspected (with the aid of a limited number of upper air observations) that the Helm Cloud was associated with a strong inversion and stable layer immediately above the Helm Cloud. He also noted that on some occasions, not only one, but as many as four or five standing waves were present downwind of the mountains—equally spaced at distances of about 4 miles. The Helm Bar, a rotor cloud, was also observed as a regular feature positioned not too far from the foot of the range.

The WWII brought intensive field investigation of mountain waves to an almost complete standstill. During the 1940s only a few smaller field investigations took place, most notable among them the field studies by Krug-Pielsticker (1942) in the eastern Alps, and Förchgott (1949) in the mountains of, then, Czechoslovakia. The 1950s announced a new era in the mountain wave field investigation that started with the Sierra Wave Project in the United States.

4. SIERRA WAVE PROJECT

As mentioned in the Introduction, the Sierra Wave Project was a major undertaking designed to study mountain waves and rotors generated in airflow over the southern part of the Sierra Nevada, or High Sierra, in eastern California. This project, funded primarily by the U.S. Air Force but also by the Office of Naval Research[2], involved several organizations including the Geophysics Research Directorate of the Air Force Cambridge Research Center, the University of California Los Angeles, and the Southern California Soaring Association. The project had both theoretical and observational programs. Our discussion of the Sierra Wave Project is based largely on the comprehensive overview of the experiment by Holmboe and Klieforth (1957) and Queney et al. (1960). Here we focus on the impact of the 1951–1952 observational phase, during which large-amplitude mountain waves and rotors were explored in Owens Valley in the lee of the Sierra Nevada.

4.1 Observational Techniques and Instrumentation

In the 1951–1952 experimental campaign, the main observational platform was a sailplane, most of them two-seater Pratt-Read, equipped with a clock, altimeter, indicators for the rate-of-climb, airspeed and direction (compass), accelerometer, an outside (fuselage) thermometer, and a barograph. In order to produce a continuous record of the flight data, the instrument panel was photographed at 1- or 2-second intervals on 16 mm film by two cameras in the rear of cockpit. The number of measured physical parameters and the recording system appears to be quite modest compared to capabilities of modern research aircraft whose data recording systems are capable of recording high-frequency data (up to 10 Hz) for dozens of variables simultaneously and even displaying them during the flight. Yet this system afforded the Sierra Wave researchers with a continuous record of sailplane flights for the post analysis. The total flight time of the sailplane was limited to 4.5 hours by the oxygen supply, and the tracking operation was limited by the film length to 1.5 hour.

The tracking of sailplanes from the ground was carried out by a network of 3 photo-theodolites, a radar and a Raydist (all-weather radio location) system. The instruments were manually operated in tracking the sailplanes but the readings of the photo-theodolites and the radar were photographed

[2]The Navy pulled out of the Sierra Wave Project during 1951 because of demands of other higher priority research.

simultaneously and automatically at 5-second intervals on 35 mm film. The Raydist tracking system produced electronic signals which were recorded directly. Compared to the automatic inertial navigation system (INS) and GPS tracking systems on board of modern research aircraft, the methods for determining the position of sailplanes used by the Sierra Wave researchers were painstakingly complex. Due to the limitations of both the ground tracking and the data recording system onboard sailplanes, useful data were obtained in only 50% of the conducted research flights in the 1951-1952 season (11 research flights on 9 different days).

The corrected quantities derived from the airborne measurements alone and their estimated accuracies were: i) time (± 0.5 s), ii) pressure altitude (± 12 m at MSL to ± 30 m at 12,000 m), iii) true air speed (± 1 m s^{-1}), iv) heading (± 3 deg), v) sinking speed (± 0.1 m s^{-1}), and temperature (± 1.5° C). The synthesis of tracking and airborne data, in which assumptions of steady state and two-dimensionality in a coordinate plane perpendicular to the Sierra crest were introduced, produced the following physical quantities at estimated accuracies: i) horizontal component of wind perpendicular to the Sierra crest (± 5%), vertical wind speed (± 5%), potential temperature (± 2° K), and D-value (i.e., altimeter correction) (± 30 to ± 60 m).

Other sources of data included the following:

(a) Radiosonde ascents from Lodgepole, Sequoia, and Merced upwind of the Sierra crest,

(b) Still photographs and time-lapse films, from air and from the ground, of the Sierra Wave clouds,

(c) Surface measurements from recording instruments (barographs, thermographs, and anemographs) from a number of points across Owens Valley, the eastern Sierra and the western Inyo slopes,

(d) Surface measurements from mobile observations (altimeter, aneroid barometer, thermometer, anemometer, and photo cameras) across the Owens Valley,

(e) Meteograph flights made by the aircraft used for sailplane towing,

(f) Double-theodolite pilot-balloon ascents made by the Weather Bureau at the Bishop Airport in Owens Valley, and

(g) Weather logs and synoptic data.

4.1 Major Observational Findings

Mountain waves observed over the Owens Valley by the Sierra Wave researchers were classified into three categories:

1. *Strong Waves* with wavelengths of 13–32 km, 1,200–2,400 m maximum altitude variation of a streamline, and vertical wind speed of ±9 to ±18 m s^{-1}. As stated in Holmboe and Klieforth (1957) "the near-legendary reputation of the Sierra Wave derives from the spectacular phenomena associated with the lee waves of strong intensity". An example of a strong wave is illustrated in Fig. 1,

2. *Moderate Waves* with wavelengths of 8–13 km, 600–1,200 m maximum altitude variation of a streamline, and vertical wind speed of ±4.5 to ±9 m s^{-1}, and

3. *Weak Waves* with wavelengths of 4–8 km, 150–600 m maximum altitude variation of a streamline, and vertical wind speed of ±1.5 to ±4.5 m s^{-1}, marginally strong to support a sailplane.

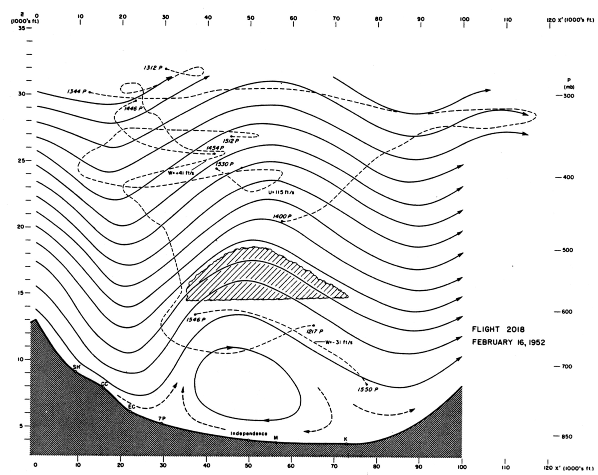

Figure 1: Results from the Sierra Wave Project. Streamlines in a strong mountain wave and "normal" rotor on 16 February 1952. Dashed lines (without arrows) show the sailplane trajectory projected onto a west-to-east vertical cross-section perpendicular to the axis of the Owens Valley near Independence (from Holmboe and Klieforth 1957).

Rotors and zones of low-level turbulence were frequently found beneath strong mountain lee waves (cf. Fig. 1). Two basic types of rotor clouds were identified by the Sierra Wave investigators: i) a "normal" rotor cloud associated with lee waves paralleling the topographic divide and following its bends, and ii) a severe rotor cloud forming a straight, almost vertical wall a considerable distance downstream from the base of the lee slope. In the latter case there is no apparent trailing edge to the rotor, the cloud extends eastward over the White and Inyo Mountains, and the flow is similar in appearance to a hydraulic jump (Kuettner 1959).

4.2 Major Theoretical Accomplishments

From the early contributions on the theory of mountain waves by Queney (1936) and Lyra (1940, 1943), the theoretical treatment of mountain waves had been considerably advanced by Queney (1947, 1948) and Scorer (1949) during the late 1940s. Analytical or semi-analytical steady-state solutions, both hydrostatic and nonhydrostatic, for flow over two-dimensional orography for atmosphere with constant mean wind and stability and a two-layer atmosphere with constant but differing values of wind speed and stability in each layer, had already been known before the start of the Sierra Wave Project.

The observational campaigns of the Sierra Wave Project had, however, provided new impetus for the theoretical work on mountain waves. The theoretical program of the Sierra Wave Project was based at UCLA where it had involved Holmboe, Höiland, Knox, and Wurtele. Some theoretical work was also carried out by Kuettner at the Cambridge Air Force Research Center, as well as by Queney at the University of Paris, and Palm, Foldvik and Fjortoft at the University of Oslo, Norway who all visited UCLA on several occasions.

Of the UCLA group, the most significant contributions came from Morton Wurtele who had introduced vertical wind shear in the previously studied steady-state, two-dimensional, one- and two-layer atmospheric models (Wurtele 1953a). The two-layer model, with a Couette-flow (constant shear, constant stability) in the troposphere, and uniform stratosphere, which was motivated in part by the observed atmospheric structure upwind of the Sierra Nevada, was particularly successful in reproducing the observed wavelengths for a number of strong wave cases from the Sierra Wave Project. This model was further extended by Palm (1955) to include multiple layers. Wurtele also made a contribution to the solution of the initial-value problem for airflow over corrugated bed (Wurtele 1953b,c), continuing the earlier work of Höiland (1951).

4.3 Contributions to Aviation Safety

One of the major accomplishments of the Sierra Wave Project was the formulation of the aviation safety hazards associated with flying in mountainous terrain, and their widespread circulation within the soaring communities in the U.S. and abroad. The latter is not surprising given the pivotal role the California Soaring Association pilots played in this experiment.

The combined phenomenon of wave and rotor flows was found to present serious hazards to aviation. In the order of severity, these hazards were: i) downdrafts, ii) turbulence, iii) local change of upper-level winds, and iv) altimeter errors.

The most significant areas of downdraft were found on the lee slope of the mountain range and the downwind end of the rotor cloud at the height of the mountain crest. Typical values encountered were 10 m s^{-1} with the maxima of 15 to 25 m s^{-1} in extremely severe cases. Similarly, turbulence was found in two distinct layers downwind of the mountain range under wave conditions: i) as the omnipresent low-level turbulence extending from the ground to $\sim$600 m above the mountain tops, and ii) the upper-level clear-air turbulence. One of the major contributions of the Sierra Wave Project was to decisively determine that the altimeter errors in flying over mountainous terrain were smaller than what was widely thought prior to the experiment. This finding came as a result of cancellation of two large sources of error, a thermal and an inertial one, producing the total error on the order of hundred meters (maximum 300 m).

5. SUMMARY AND CONCLUSIONS

The confluence of interest in mountain waves by the soaring community and several scientific investigators was the stimulus for the Sierra Wave Project. With little doubt, the primary impetus came from the Southern California Soaring Association and its contingent that flew the Bishop Wave. Funding for research, however, demanded that an academic component be added and thus the UCLA team headed by Jorgen Holmboe entered the project. There appears to be no other major meteorological field experiment that was or has been spearheaded by a sporting group. With this backdrop, it does not come as a complete surprise that the results of the experiment had more impact on the soaring community than it did on the scientific community. Aside from numerous technical reports and a few excellent "final" reports written by the

UCLA and the Air Force Cambridge Research staff, very few publications in the mainstream scientific literature came out of this project.

Lyra's (Lyra 1943) and Queney's (Queney 1947) theoretical work went far to lay the solid foundation for the interpretation of analyses that came from the project. Holmboe's contribution to the theory was minimal, although he is certainly credited with scientific oversight of the experiment. The reason for his limited theoretical contribution is difficult to unravel. We can only speculate that his "perfectionist" approach to meteorology and an enamorment with simple analytic theory, did not lend itself to explaining aspects of the Bishop Wave that went beyond earlier rather comprehensive work. However, it was another theoretician from the UCLA team, Morton Wurtele, who had made significant contributions to the theoretical advancement of the field as a result of his involvement in the Sierra Wave Project.

In many ways, the project had the flavor of a military science project, i.e., one where specific operational objectives were at the forefront. In this case, it was the safety of the military aircraft that was paramount. Wartime loses of aircraft in mountainous terrain needed to be understood and similar accidents avoided if at all possible in the future. Publication of scientific results in the refereed literature is often secondary in these projects as was the case in the exploration of radioactivity in the atmosphere following nuclear detonation during the 1950s (Stockwell and Lewis 2001).

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