Know the Sky:
A History of Interaction between Meteorology and Soaring

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From Orville Wright's 1911 flight to Jack Glendening's 2013 Thermal Index Prediction software program, pilots, designers, engineers, and meteorologists have contributed to the knowledge of soaring meteorology. The paper shows the knowledge flowing not solely from meteorologists but rather from different groups at different times, depending on numerous geographic, technological, or political circumstances. With a few exceptions, the interaction has been positive, dynamic, and frequent. The paper is organized chronologically according to the discovery of the primary forms of soaring lift: ridge, storm, thermal, and wave.

Introduction

Until now, no one has attempted to describe the interactive relationship between the knowledge of soaring meteorology and the pilots, designers, and engineers who fly sailplanes. I will show how this relationship has benefitted the soaring community, and that often advances in sailplane technology also have contributed to the study of soaring meteorology.

First Soaring Flights

> "Since he depends entirely upon the elements, the soaring pilot's skill is determined by the ingenuity with which he matches his wits against them. This immensely interesting and sporting method of exposure soon makes him as good a weather smeller as an old salt who has sailed the seas all his life. Meteorology has become second nature instead of a necessary evil that must be learned." (Ref. 1, p. 14)

On 24 October 1911, Orville Wright soared in a glider for nine minutes and 45 seconds into the teeth of a 64 km/h (40 mph) wind above the sand dunes at Kitty Hawk, North Carolina (Fig. 1). His flight set a world record for motor-less aircraft that remained unbroken for ten years. In addition to the flying skill and experience Orville had acquired during the previous decade, the 1911 flight depended a great deal upon the steady winds blowing against the dunes to produce the required lift. Orville's brother, Wilbur, had decided on Kitty Hawk in 1900 as the place to test the Wright's aircraft after studying the tables of average hourly wind velocities recorded at 120 weather stations managed by the U. S. National Weather Bureau (Refs. 2, pp. 182, 444 and 3, p. 12). The data showed the wind velocities at Kitty Hawk to be the sixth highest in the nation. This fact, and the site's isolation from news reporters, led Wilbur to choose the site. This was however not the first time that knowledge of meteorology had influenced soaring flight. Otto Lilienthal, the first person to make repeated short gliding and soaring flights from 1890-96, relocated his flying experiments to the Rhinow Moun-

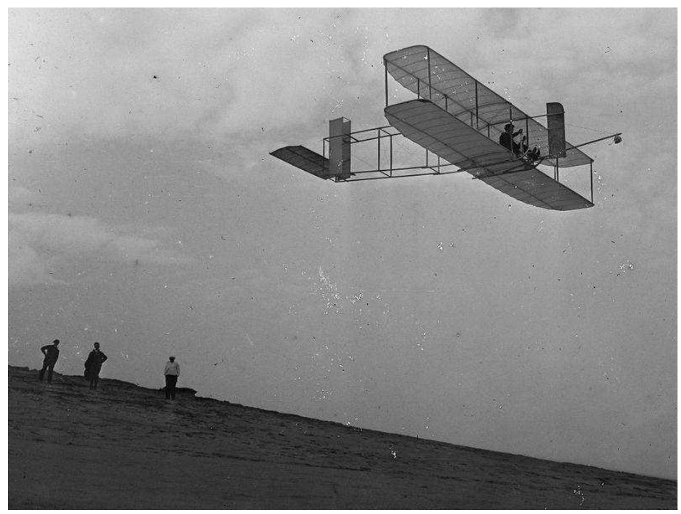

Figure 1 Orville soaring for nine minutes 45 seconds above the sand dunes of Kitty Hawk, North Carolina, on 24 October 1911 (Source: Library of Congress, Prints & Photographs Online Catalog, LC-USZ62-56250).

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tains near Berlin in the early 1890s, in part to take advantage of more favorable winds (Ref. 4, p. 22).

One decade and a world war passed before anyone seriously challenged Orville's record. In 1920 atop the Wasserkuppe mountain in south central Germany, flyers organized the first gliding competition as a means to continue flying after the Treaty of Versailles had barred them from operating nearly all types of powered aircraft. Only 10 gliders flew and most sustained damage during landing but the overall results encouraged the enthusiastic participants to meet again. They did so the following year and one of the 11 pilots in the competition more than doubled Orville Wrights 1911 endurance record. Still, many contestants gave little thought to soaring for distance or altitude, not from lack of basic piloting skills or technical deficiencies in the aircraft, but rather because they lacked a sophisticated understanding of the meteorological conditions required for soaring (Refs. 5, p. 9; 6, p. 122; and 7, p. 9).

On 18 August 1922, following advice from German meteorologist Walter Georgii, pilot Arthur Martens soared to 108 m (354 ft) above the Wasserkuppe and remained airborne for an hour and six minutes. Georgii was largely responsible for this remarkable improvement. He had counseled Martens to seek the strongest lift above the mountain slope facing the prevailing winds, and to keep to this narrow region by flying a figure-eight pattern. In later years, Georgii declared that true soaring began with Martens' flight. Before the meet ended, another pilot soared more than three hours.

News of these events swept across Europe, increasing the number of participants soaring in many countries and encouraging Georgii to specialize in soaring meteorology. He took charge in 1926 of the Rhön-Rossitten Gesellschaft, or RRG, an organization responsible for maintaining and developing the two centers of German soaring research at Rossitten on the Baltic Sea coast and atop the Wasserkuppe. Georgii instructed his staff to focus on mining knowledge of the atmospheric conditions required to soar aircraft, developing efficient sailplanes and improving the methods for teaching pilots to soar (Refs. 8, p. 57 and 4, pp. 58–59, 63). He employed science to expand the practical limitations to soaring with greater effect than any other individual working between the world wars, but despite many successes, Georgii's ideas did not always prove valid. He speculated incorrectly that favorable soaring weather could be found over the tropical oceans and at night (Ref. 9, pp 6–7).

Storm Soaring

> "The approach of a nice clean thunderstorm makes the soaring pilot's heart jump with delight." (Ref. 1, p. 14)

Georgii prioritized soaring research just as a "serious crisis" gripped the sport and threatened its future (Ref. 10, p. 260). From 1922 to 1926, Allied authorities charged with restricting German aeronautical activities in accordance with the Versailles Treaty began gradually to relax prohibitions on the design and development of civil aircraft. A small but vigorous industry in

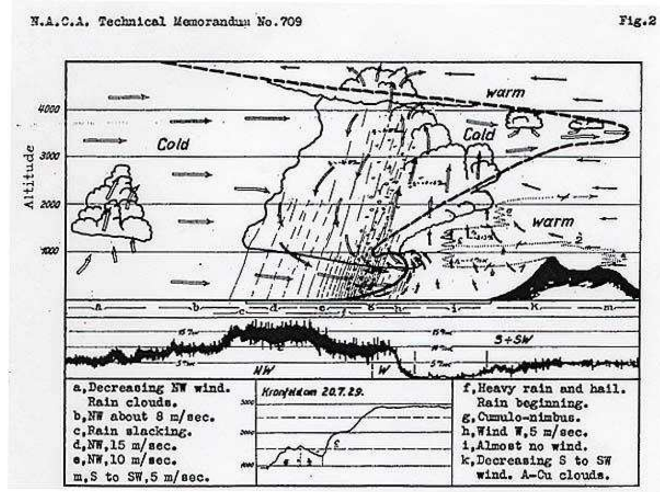

Figure 2 By 1932, pilots had pinpointed the strongest and smoothest lift within a narrow region 2-3 km (1.2-1.9 miles) ahead of the storm (Source: Technical Memorandum No. 709, National Advisory Committee for Aeronautics, NACA translation, Washington, D. C., May 1933, Fig. 2).

light powered aircraft sprang up in Europe as sailplane pilots became bored with skimming the hillsides and frustrated by the slow and difficult retrieves that followed most landings away from the home airfield. Affordable light powered airplanes lured many away from soaring and the sport might have disappeared if meteorologists and pilots had not discovered and mapped new forms of lift (Refs. 11, pp. 3–4; 6, p. 123; and 8, pp. 69–70).

In 1926 during the German national contest, Max Kegel naively surrendered his glider to powerful updrafts entrained ahead of a fully developed thunderstorm (Fig. 2). Although the glider's open cockpit left Kegel's head unprotected, he managed to survive extreme turbulence, rain, and hail to double the world soaring distance record to 56 km (35 miles). Three years later, German pilot Robert Kronfeld soared inside several rain clouds when he nearly tripled the world record for distance in July 1929 with a straight-line flight of 150 km (93 miles). Cloud and storm soaring was perilous and could be fatal but it helped sustain the sport by sparking favorable publicity (Ref. 12, pp. 65, 77–78).

By the early 1930s, the pilots of sailplanes instrumented for flying 'blind' without reference to landmarks had begun to explore cumulonimbus clouds and thunderstorms. They gained new knowledge that enabled meteorologists to better understand storm meteorology, led the soaring community to work out special routines for soaring in clouds and storms, and provided designers with data they needed to design sailplanes capable of withstanding storm turbulence (Refs. 13, p. 26 and 14, p. 86). Alexander Lippisch specifically designed the Fafnir sailplane in 1930 to withstand storm flying by strengthening the airframe and partially covering the cockpit to protect the pilot from the elements (Refs. 12, p. 79 and 5, p. 66).

Yet the risks involved and the commitment in time and money necessary to train and equip a pilot to soar in clouds and storms always limited its appeal. Despite stronger aircraft and better equipment and training, the practice continued to cause casualties throughout the 1930s and after World War II. When more accurate weather forecasting methods allowed pilots to soar in cloud and avoid thunderstorms, the number of casualties decreased but in 1966, the Soaring Society of America, an organization that has sanctioned and regulated the sport in the USA since 1932, banned the blind-flying instruments necessary to soar in clouds from the cockpits of sailplanes flying in contests sanctioned by the SSA. The society wanted to maintain fair competition and prevent federal airspace violations by pilots soaring in clouds without the complete and correct complement of instruments required for such flying (Refs. 6, pp. 37–38 and 7, pp. 216–217).

In 2012, the USA Federal Aviation Administration still allowed cloud soaring by pilots with proper training, flying gliders with the correct equipment and proper clearance from the air traffic control specialists, and Europe and England permitted it, too, but the forces of nature unleashed inside a thunderstorm remained formidable.

Thermal Lift

What was safer than cloud soaring and drew recreational and cross-country soaring within reach of sailplane pilots of virtually any skill level was the discovery of thermal lift. The term 'thermal' is generally credited to the soaring community and defined in the context of sport soaring as a "relatively small-scale, rising current of air produced when the atmosphere is heated enough locally by the earth's surface to produce absolute instability in its lowest layers" (Ref. 15, p. 572). Pilots had routinely encountered thermals since Lilienthal's day without knowing their cause and characteristics. Georgii began studying thermals at Griesheim airfield near Darmstadt in spring 1928, and in April and June, research pilot Johannes Nehring used thermal lift to maintain altitude for more than ten minutes in a small powered aircraft with the engine switched off. Later that year, the meet organizers made soaring in thermals an official event at the German national contest held at the Wasserkuppe (Ref. 8, p. 73).

Proving that thermals could lift sailplanes led to another question. How would pilots navigate their way into the thermal lift? When soaring the slopes, they could determine their position relative to the strongest lift by sighting along nearby peaks and ridges yet thermals were often encountered many thousands of meters above such landmarks. This problem grew more difficult after experiments confirmed that puffy cumulus clouds did not always mark thermals, that thermals could be potent and widespread even under a cloudless sky.

Within weeks of Nehring's flight in spring 1928, sailplane designer and pilot Alexander Lippisch, who had once worked for the Zeppelin airship company, suggested that Nehring try using an instrument called the variometer that registered minute changes in altitude by very precisely measuring fluctuations in air pressure. Sailplane pilot Robert Kronfeld used a variometer to locate thermals and circle within them as he soared 8 km (5 miles) to a nearby mountain and back during the national meet on the Wasserkuppe in August 1928 (Refs. 12, pp. 71-72 and 5, pp. 59–61). The following year, Kronfeld more than doubled the record for distance by soaring 150 km (93 miles) using a combination of thermals marked by cumulus clouds and those detected with his variometer. Following a 164-km (102-mile) research flight made in August 1931 to gauge the variometer's sensitivity, Georgii concluded that thermals "are apparently so plentiful that if the weather is favorable and the sailplane has enough altitude, a short gliding flight [from one thermal] leads again to [the next]" (Ref. 5, p. 65).

Over the years, pilots and engineers improved the variometer's accuracy and reduced the "lag" time that passed before the instrument registered altitude changes. The United Kingdom's team victory in the 1952 world soaring contest was credited to refinements they had made to the instrument. A major improvement occurred a decade later when engineers gave the device an audible chirp that varied in pitch with the rate of altitude change and permitted pilots to monitor the variometer with their ears while focusing their eyes outside the cockpit to maneuver the sailplane and avoid other aircraft (Ref 16, p. 38).[1]

By the early 1930s, meteorologists and pilots understood that the characteristics of topography influenced the formation of thermals. They knew that cumulus clouds formed more often above wide valleys dotted with bodies of water, mountain slopes heated by the sun, and swamps and other areas likely to produce water vapor as well as open fields and meadows. (Refs. 17, p. 23 and 9, p. 3). Meteorologists could say by the 1960s that sun angle, surface dampness and ground moisture, the type and condition of crop fields, architectural elements, and construction materials of fabricated structures, transportation infrastructure, and other factors could influence the formation and strength of thermals (Ref. 18, pp. 130–133).

Observations made from sailplanes in flight continued to yield new findings, too, and contribute to the weather knowledge on soaring. During the spring 1938 Southwest Soaring Expedition to Wichita Falls, Texas, Lewin Barringer carried equipment aboard his sailplane to measure the atmospheric conditions, including temperature and humidity at various altitudes, above the high plateaus of the North American Great Plains region. His team discussed fitting sailplanes with a radio device for transmitting weather readings to a ground station (Ref. 19, p. 15).

German meteorologist Karl O. Lange accompanied Barringer's expedition to help interpret the results, and by one account, the data collected helped the designers of commercial aircraft to understand better the extent, frequency, and strength of clear-air turbulence (Ref. 19, p. 15). Barringer set a national distance record during the expedition and the publicity that followed, together with the meteorological data collected, collated, and disseminated, helped encourage pilots to abandon the ridges

[1] *Soaring* magazine first advertised an audio variometer inside the front cover of the March 1963 issue.

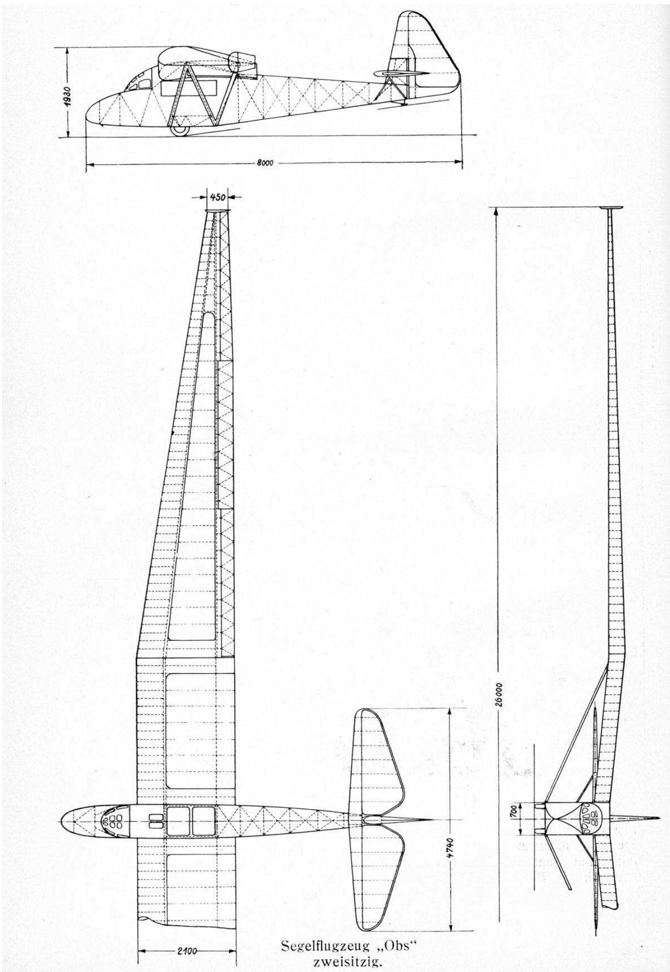

Figure 3 D-OBS (Source: *Flugsport*, vol. 25, no. 1, 4 January 1933, 16).

and hills and begin to soar the flat lands of the Southwestern United States (Refs. 7, p. 59 and 20, p. 40).

There were limits to how much useful information one pilot flying one sailplane could gather so in 1931, Georgii asked Alexander Lippisch to design a special sailplane capable of carrying aloft, in addition to the pilot, two passengers, or a technician and a meaningful complement of scientific equipment. Meeting these requirements dictated a sailplane with a wingspan of 26 m (85 ft). Lippisch completed the design in 1932 but its large size forced artisans to build it in a workshop at Poppenhausen. Engineer Egon Scheibe contributed to the project by designing one of the first steel-tube fuselages used in a glider. The Rhön-Rossitten Gesellschaft named it *Urubu* and the government assigned the registration code D-OBS (Fig. 3) with a play on its intended function as an atmospheric 'Observatorium.' After appearing at the Wasserkuppe in 1932, Georgii moved the *Urubu* to Griesheim airfield near Darmstadt the following year where crews flew the aircraft "extensively" for research purposes (Refs. 21, p. 64; quote on p. 65).

Experiments had already shown that around Griesheim airfield, "frequent and almost stationary regions of rising [air] currents develop, which even in the absence of any tell-tale clouds, can be easily sought out by a sailplane [pilot]" (Ref. 22, p. 13). Georgii planned to use the *Urubu* to expand the search around Griesheim airfield for these local, or 'house' thermals, and then explore the conditions at other airfields by making detailed temperature records at various altitudes. Once mapped, pilots flying sport sailplanes should then be able to reach these house thermals using tows aloft from automobiles, a less expensive method and at that time considered less difficult than towing with powered airplanes.

Georgii also planned to conduct general meteorological research after towing the *Urubu* to an altitude of 5-6,000 m (16-20,000 ft) using a powered airplane. A flight of several hours was possible from this height even without thermal lift. The *Urubu* crew could gather data undisturbed by engine vibrations or hot exhaust gases. The latter in particular was thought to interfere with research on electricity in the atmosphere. There is no record of further investigations on the house thermal phenomenon or the work at high altitude but the D-OBS remains the world's only sailplane designed and built specifically to conduct meteorological research.

The possibility that thermals could form nearly anywhere inspired scientists and pilots to mount soaring expeditions to distant lands. Georgii led a German group to South America where Heini Dittmar set a world height record when he ascended to 4,621 m (15,200 ft) through the core and out the top of three developing cumulus clouds in rapid succession during a flight from the Campos dos Affonsos airfield outside Rio de Janeiro on 16 February 1934 (Refs. 23, p. 164, and 24, p. 92). The first Frenchman to soar beneath a cumulus cloud, Georges Abrial, led an expedition in 1954 to Brazzaville in the African Congo. Abrial's group spent nearly two months in Africa flying and studying soaring meteorology (Ref. 12, p. 151).

Germany not only investigated conditions in other lands, it also shared much of its vast knowledge of soaring with other countries to promote the growth of soaring and to enhance the competition between German pilots and those of other nations. Members of the Dunstable Gliding Club northwest of London progressed rapidly from slope to thermal soaring primarily through the information imparted in Wolf Hirth's lectures during the winter of 1932-33. Two years earlier, Hirth had worked a similar transformation at the hub of American soaring in Elmira, New York (Refs. 25, pp. 121, 144 and 26, p. 166).

Georgii took a leading role in sharing information. On 14 June 1930 after Georgii had proposed the idea, six countries established the Internationale Studienkommission für den Motorlosen Flug (International Commission to Study Motorless Flight, or ISTUS) and wisely made the German meteorologist its first president. One of the commission's primary tasks was sponsoring and promoting study of the atmosphere as it related to soaring. Efforts succeeded to reestablish the organization after World War II and led to a new name, the Organisation Scientifique et

Technique Internationale du Vol à Voile (OSTIV, the International Scientific and Technical Organization for Soaring Flight), but studying soaring meteorology remained a critical purpose (Ref. 12, pp. 125–126; 155).

Contest Soaring

Scientific data took time to digest whereas competition pilots needed speedier reporting and analysis. As early as the First International Gliding Competition held in Asiago, Italy in October 1924, contest organizers set up a radio station to rapidly collect and disseminate meteorological information (Ref. 12, p. 49). Mr. C. G. A. Rossby of the MIT Meteorology Department sent a special team to the third USA national meet held at Elmira, New York, in July 1932. Led by meteorologist Lange, the group took "soundings ever morning, which made it possible to give much improved weather briefings" and may have aided pilots to set two national records (Refs. 7, pp. 34–35 and 27, p. 44).

Competitive soaring took a hiatus during World War II but beginning in 1947 with the first postwar USA national contest, the sport resumed and continued to evolve using thermal, ridge, and occasional wave lift. By 1953, pilots competing in regional or national meets could often fly as far in one day as pilots had flown during an entire contest held before the war. Increases in pilot skill, aircraft performance, and weather knowledge in turn pushed meet directors to devise more challenging tasks. To the simple free distance and straight-line races common before the war, directors tasked pilots to soar the longest distance within an area defined before take-off, using 4-7 turn points chosen by each pilot while in flight during the task (Ref. 28, pp. 390–391).

Organizers of international and national contests found it relatively easy to attract professional meteorologists with sophisticated and expensive equipment. Local soaring clubs had no access to such professional support. Writing in the 14 March 1933 issue of *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, Roland Eisenlohr offered one solution when he advised club pilots to "promote the spread of distance and cloud flying" by studying local cloud formations (Ref. 17, p. 23). He explained how developing cumulus had been studied using high-speed film exposed at a rate of one frame every 5 seconds to reveal the "really dramatic evolution in the turbulence, disruption, and piling up of the cloud[s]." The film record could be made available for pilots to study before taking off.

Eisenlohr acknowledged the film technique was impractical for many clubs so he described how to sketch on paper the clouds as they formed. Eighteen of his sketches accompanied the article. For scale reference, and to help consistently plot over time where in the sky the clouds formed, Eisenlohr suggested that the observer could simply sight the clouds through a hanging net (Fig. 4). Club members, he said, should continue these "systematic observations" throughout the year and from different locations in order to build a three-dimensional map of where the clouds most conducive to soaring formed and how they changed with the seasons (Ref. 17, p. 24).

Even as the performance of pilot and sailplane improved after

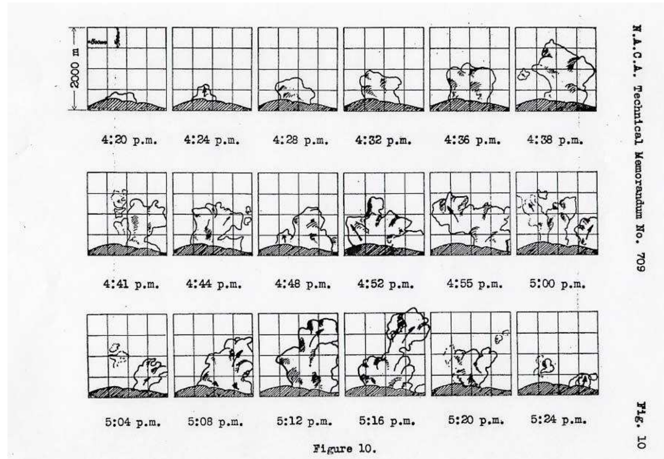

Figure 4 Each side of Eisenlohr's grid covered about 2,000 m (6,560 ft) of the sky (Source: Technical Memorandum No. 709, National Advisory Committee for Aeronautics, NACA translation, Washington, D. C., May 1933, Fig. 10).

World War II, there remained a market for inexpensive soaring aids. Using a circular slide rule called the Thermal Forecaster developed in the late 1960s, a pilot could bypass the more laborious calculations required to forecast thermals using the standard adiabatic lapse rate charts. A linear slide-rule called the Weather Guide combined pictures of various cloud forms with inserts corresponding to the weather sequences found in six different regions of the USA to help a pilot forecast local wind direction. The Weather Guide was most accurate when used in conjunction with the national weather map published in many newspapers (Ref. 29, pp. 39–40).

Following Lewin Barringer's spring 1938 Southwest Soaring Expedition to Wichita Falls, TX, Barringer travelled to New Hampshire in the fall to explore soaring conditions near Mt. Washington where meteorologists had measured the world's highest wind gust to 372 km/h (231 mph) on 12 April 1934. Barringer planned his flights around the daily weather reports received via short-wave radio from the Mt. Washington weather station. (Refs. 30, p. 2 and 31, p. 58). Forty kilometers (25 miles) south at White Mountain Airport on 25 October 1938, Barringer took off in tow behind a light airplane and soon began climbing in the strongest lift he had ever encountered. Although not completely understood at the time, Barringer had made the first soaring flight in the USA using a form of lift called mountain lee wave (Refs. 32, p. 159 and 7, p. 222).

Wave

Wind blowing against a ridge, mountain, or mountain range can trigger atmospheric waves to form and propagate downwind for long distances and to reach high altitudes. Meteorologists often call the basic and widespread form a 'standing' wave because it remains stationary relative to the ground and can persist for days. The hydraulic mechanism that forms the waves down-stream from stones or other submerged obstructions in shallow, fast-flowing water resembles the mechanism that forms these waves in the sky (Ref. 29, p. 27). Although birds had first hinted at the possibilities of soaring aircraft in ridge and thermal lift, pilots flying sailplanes discovered the powerful lift potential of standing waves when Hans Deutschmann and Wolf Hirth first soared in wave lift flowing leeward from the Riesengebirge mountain near Grunau, Germany, on 3 March 1933 (Refs. 32, p. 159 and 33, p. 110).

Four years later in May 1937, Joachim Küttner mapped in three dimensions the lee wave system near Grunau to earn his first doctorate in meteorology, using data collected by 25 sailplanes flown by pilots competing in a local soaring contest. Küttner himself soared a sailplane to 7,387 m (24,300 ft) in the Riesengebirge wave four months later. This world record ascension bettered the old mark by a wide margin but the flight earned Küttner no formal recognition after National Socialist politicians questioned his ethnic background (Refs. 34, p. 1129 and 32, pp. 10–11).

While studying the region from 1937-39, British Meteorologist Gordon Manly observed the fierce 'Helm' wind producing standing wave clouds above and to leeward of the Cross Fell, highest peak in the Pennine hills in northern England. Noel McLean verified Manly's observations in June 1939 when he found the lee wave at this spot and soared to more than 3,000 m (10,000 ft) (Ref. 34, p. 1127 and 8, pp. 144-145). No one conducted significant lee wave research during World War II but after the war, interest in the phenomenon shifted to the western USA where military and civilian pilots flying both powered aircraft and sailplanes had encountered wave over the Sierra-Nevada Mountains surrounding the Owens Valley in central California near the Nevada border (Ref. 32, p. 32). By 1951, a partnership had formed to study the Sierra wave comprising the following organizations: the U. S. Air Force Cambridge Research Center in Massachusetts, U. S. Navy Office of Naval Research, U. S. Weather Bureau, Los Angeles branch of the American Meteorological Society, and the Meteorology Department at the University of California, Los Angeles (Ref. 34, p. 1127).

Personnel from each of these organizations contributed, but the group of amateur pilot members of the Southern California Soaring Association (SCSA) proposed the Sierra Wave Project and pushed it through a tedious definition and validation process. The SCSA also supplied the sailplanes used to record most of the data gathered during the program, two surplus U. S. Navy training gliders called Pratt-Read LNE-1s. Members of the SCSA modified the Pratt-Reads to carry special instruments and equipment, and then furnished from its own ranks the pilots to fly them (Refs. 32 pp. 62–68, 74–79; 34, pp. 1127, 1129). German meteorologist Joachim Küttner, the most experienced wave scientist in the world at that time, joined the project in 1948 while working for the U. S. Air Force Cambridge Research Center (CRC) (Ref. 35, p. 3).

The CRC funded the Sierra Wave Project from 1 November 1950 to 31 October 1952. Project personnel spent the first year preparing the sailplanes to gather test data and organizing the ground tracking teams. The first sailplane test flights to establish and refine the cooperation between ground observers and sailplane flight crews needed to measure the wave began in December 1950 (Ref. 32, pp. 66, 69, 80). Ground teams made the first attempt to track a Pratt-Read flying at 7,620 m (25,000 ft) in November 1951 and in December, pilots made the first project flight to exceed 12,192 m (40,000 ft). However, months earlier, enough was known about the wave to begin vigorously exploring its upper reaches. William "Bill" Ivans set the world altitude mark in the single-seat glider category with a flight to 12,823 m (42,070 ft) in December 1950 but he never participated in the Sierra Wave Project (Ref. 36, p. 99). Ivans was just one of many caught up in the enthusiasm for flying the Sierra wave that engulfed the soaring community after *Soaring* magazine began publishing accounts in 1949 of other record-breaking wave flights (Refs. 32, p. 56 and 37, p. 2).

It is worth noting that the soaring potential of the Sierra lee wave dawned first on the members of the SCSA and well before it was widely known among meteorologists. For example, early in 1949 when the Los Angeles branch of the American Meteorological Society invited members of the SCSA to speak at a monthly meeting, they greeted the tales of tremendous lee waves emanating from the Sierra Nevada Mountains with incredulity. This attitude stemmed perhaps from the utter remoteness of the Sierra Nevada area and the near total lack of commercial and general aviation activity there (Ref. 32, pp. 44, 63).

The year 1952 saw research flying that gathered important data and directly led to world altitude records. On 19 March 1952, project pilots Klieforth and Edgar set the world record for two-seat sailplanes at 13,453 m (44,255 ft), this after gaining 10,465 m (34,426 ft) following disconnect from the tow aircraft, another world record (Ref. 32, pp. 108, 161). More record flights followed but mapping the wave in detail also led to deeper understanding of wave characteristics with an enduring impact on the flight safety of military, commercial, and general aviation. The Sierra Wave Project is the only "major meteorological field experiment that was or has been spearheaded by a sporting group" (Ref. 34, p. 1139).

The Sierra Wave Project generated one of the first detailed analyses of the hazards of wave flying including "downdrafts, turbulence, spatial and temporal changes of upper-level wind speed and direction, in-flight icing in the roll and lenticular clouds, and strong winds and wind shear near mountain crest level" (Ref. 34, p. 1139). A key finding was that turbulence itself, not altimeter error, caused rapid unusual, and unexpected, height fluctuations in aircraft. With these new hazards in mind, the U. S. Government considered the preliminary findings of the project important enough in 1953 to disseminate 42,000 copies of a report titled *Flight Aspects of the Mountain Wave* to "operations departments of every U. S. airline, every U. S. airline pilot, and every air-transport-rated U. S. pilot whether an airline employee or not," plus copies to each military service and the

Civil Aeronautics Authority (Ref. 32, pp. 145, 158, note 1).[2]

Following on the Sierra Wave Project, the Jet Stream Project began in 1955 to study how the Sierra wave influenced the jet stream and severe weather (Refs. 32, p. 127 and 7, p. 144). Again, the SCSA provided pilots and aircraft. On 14 April, SCSA member Betsy Woodward set the world altitude record for female pilots flying sport sailplanes when she reached 12,158 m (39,994 ft) after a record gain of 8,510 m (27,994 ft) (Refs. 38, p. 20 and 7, p. 147). Later that month, the wave demonstrated its power to destroy when severe turbulence tore apart the Pratt-Read sailplane piloted by SCSA pilot Larry Edgar (Refs. 7, pp. 147–148). Undeterred, the SCSA proposed to design a sailplane with pressurized crew cabin called the *Stratosailplane* to study wave at 21,280 m (70,000 ft). A company built a crew cabin mockup but the projected $250,000 cost kept the work from progressing beyond preliminary design (Refs. 39, p. 26 and 32, p. 123).

The early wave studies and record flights encouraged many pilots to seek out and fly in wave the following decade, not only to set records but also to experience an exciting new type of motor-less flight. The Soaring Society of America (SSA), Federal Aviation Administration (FAA), and the U. S. Air Force began the Altitude Training Program in 1964 to help prepare sport pilots for wave flying at high altitudes. The air force allowed 120 SSA member pilots to 'ride' a pressure chamber on simulated trips to high altitude to experience the effects of oxygen deprivation and extreme temperatures they were likely to encounter during wave flight. By 1966, seven commercial sailplane operators located across the USA offered wave flying to sport pilots (Ref. 7, pp. 218, 222).

Forecasting mountain lee waves and other soaring weather phenomenon across the United States and over much of the world improved dramatically after the launch on 1 April 1960 of the first Television and Infrared Observation Satellite, TIROS I, dedicated to observing and transmitting meteorological images and data from space. These images allowed meteorologists for the first time to see entire patterns of the telltale lenticular clouds that mark wave activity. The satellite sometimes imaged lenticular patterns that no one on the ground had reported seeing, which is not surprising because ground observers could not see more than about 62 km (100 miles) horizontally even in the clearest conditions. Whenever the atmosphere contained sufficient moisture to form lenticular clouds, meteorologists could measure a wave's horizontal area using satellites but as late as 1968, to determine height, they still needed the data gathered by radiosondes, helium-filled balloons carrying devices aloft to gather information about the atmosphere and transmit it via radio signals, as well as the information in pilot reports that frequently appeared in the pages of *Soaring* magazine (Ref. 40, pp. 8–9, 11, 12).

Innovations in the efficiency and cost of satellite technology sometimes originated from the bottom up. When the Tiros VIII satellite launched in December 1963, it carried into orbit the Automatic Picture Transmission system, which could transmit complete weather images in just a few minutes. Access to the pictures was limited to those who possessed about $40,000 worth of equipment until UCLA lab technician Dan Dibble improvised a receiver using a few hundred dollars' worth of surplus and discarded parts (Ref. 41, pp. 122-123). Satellite photos soon began to reveal long lines of thermals called 'cloud streets' that sometimes covered entire countries (Ref. 16, p. 60).

By the mid-1980s, government bureaucracy impeded wave flying more than meteorologists' forecasting capabilities, according to Paul Bikle, retired director of the NASA Dryden Flight Research Center, CA (Ref. 42, p. 1F). Since late 1963, pilots wanting to soar in wave above 7,315 m (24,000 ft) across most of the nation and down to 5,486 m (18,000 ft) in some areas, were required to ask their local federal air traffic control authority to set aside a block of airspace called a "wave window" for a designated period.[3] The wave window allowed pilots to soar without violating federal laws that required aircraft to carry expensive avionics equipment and maintain radio contact with air traffic controllers. Bikle's comment specifically referred to the sailplane world altitude record (14,899 m/49,009 ft) set on 17 February 1986 by Robert R. Harris who took off on his record attempt without waiting for the FAA wave window, which Harris claimed would take longer to establish than the very rare weather conditions required to set the record would persist.

Soaring on wave lift high into the stratosphere continues to fascinate and challenge the soaring community. The most promising work ongoing in 2013 is the Perlan Project begun in 1991 by Einar Enevoldson, sponsored by Steve Fossett, and supported by NASA meteorologist Ed Teets. Enevoldson has set ambitious and important meteorological research goals for the project: map and analyze the structure of the stratospheric mountain wave (SMV) and breaking waves; investigate how the tropopause changes during SMV activity; and determine how the tropopause interacts with the polar vortex and SMV. Attempts are expected the summer of 2013 in Argentina to soar to 27,400 m (90,000 ft) aboard a specially designed and purpose-built sailplane, but another three years may pass before the right weather conditions occur to reach this altitude (Ref. 45, p. 18).

Even as the number of electronic eyes orbiting the Earth grew, soaring pilots continued to find wave in new locales by observing lenticular clouds from the ground. A soaring club in Cumberland, MD, began exploring wave conditions generated by the Allegheny Mountains late in 1962 (Ref. 46, p. 17). Early in March 1968, pilots soared wave above Mount Mitchell in North Carolina, said to be the first wave soaring done south of Roanoke, VA (Ref. 47, p. 27). Five years later, soaring pilots began to investigate the previously unexplored 'Chinook Arch' wave over Montana in 1973 (Ref. 48, p. 18). In April 1975, meteorologist Charles V. Lindsay wrote in his monthly column in

[2]Vic Saudek also cites the 42,000 figure, see Saudek quote in Ref. 7, p. 148.

[3]Soaring Society of America proposed the wave window procedure late in 1963 and the FAA agreed to adopt it early in December, see Refs. 43, p. 7 and 44, p. 21.

Soaring magazine that "mountain wave soaring has become almost second nature to sailplane pilots who live near mountains, whether it be near the Appalachians in the east or the Rockies in the west" (Ref. 49, p. 42).

The new technologies improved the accuracy of forecasting not only wave but ridge lift as well, for example Bill Holbrook's 1973 record distance flight along the ridges of the Appalachian Mountains that furrow the east central USA. Responding to the pilot's written request, the National Weather Service assigned meteorologist Charles Lindsay to help Holbrook plan the flight. After discussing weather, routing, departure and arrival times, and other details nearly every day from February to May, the men devised a plan that called for Holbrook to fly 1,314 km (816 miles) along a precisely calculated route at 113 km/h (70 mph). May 5, 1973, dawned with favorable weather conditions and after officially declaring that he would fly to a certain spot before returning to his point of origin, Holbrook took off. Lindsay's forecast was so accurate that Holbrook was able to remain within a few miles of the planned course. He landed 11 hrs 54 minutes later and missed his estimated time of arrival by just 4 minutes (Ref. 50, p. 20).

In 1978, contest directors used photographs made with the Meteosat weather satellite to plan tasks during the World soaring competition at Chateauroux France (Ref. 8, pp. 190–193). Faster and more accurate weather forecasting paralleled steady increases in sailplane performance and by 1971 in the USA, 200-mile flights during contests had become routine. This distance was about as far as ground support crews could drive in a day to retrieve a pilot and glider. When more challenging out-and-return flights began to replace traditional and less demanding tasks such as free-distance, duration, and altitude gain, retrieval crews could more often remain at the airfield. Contests flying became safer when crews and pilots had more time to rest between tasks (Ref. 51, p. 40).

Computers and the Internet

> "It is conceivable that computerized soaring weather flight plans could be developed" (Ref. 52, p. 32)

Meteorologist Charles V. Lindsey made this prescient 'forecast' in June 1990 but even he could not have foreseen that within a few years, pilots in flight would be holding computers small enough to fit their shirt pockets that displayed in real-time and bright colors layer upon layer of soaring weather information, all blended seamlessly with detailed maps of the surrounding terrain.

The race to digitize data for soaring meteorology began in the USA in the late 1960s when meteorologists started using mainframe computers to analyze the sky readings beamed from radiosondes. It began as a job for 2-3 people but in the mid-1980s, only one person was required after the National Weather Service started using personal computers to analyze the radiosonde data and then disseminate it. The digitization revolution took a dramatic turn with the introduction of the IPM PC, or personal computer, in the 1980s. Early in the 1990s, Pan Am Weather Systems marketed a software program to various state aviation agencies called WeatherMation that allowed anyone with a PC, modem, and telephone line, access to meteorological data (Ref. 52, p. 30).

In 1992, the Swiss physicist Olivier Liechti wrote a computer software algorithm that could integrate the readings from many radiosondes to model atmospheric convection over a geographic region shaped by the homogeneity of the weather above it. This convection model, "ALPTHERM," is described in Ref. 53. Liechti explained that ALPTHERM "used radiosonde-measured vertical profiles from remote locations and modified its near surface section with surface observations at close stations." He added, "No advection was used initially during model runs... In the first operational setup at MeteoSwiss National Weather Service, trends (advection) obtained from [a] series of predicted model soundings were applied during model runs. Model initialization was still based on measured soundings modified by observations."

Liechti continued, "Operational runs at the German National Weather service (TOPTHERM) initially used the same setup as in Switzerland. Initialization was still based on measured soundings... At some point model initialization was migrated from measured to [numerical weather prediction] model soundings — still modified by local surface observations... The development of TopTask started only after the migration from measured to model soundings for the model initialization had become operational" (Ref. 53).

To pilots planning soaring flights, the algorithm provided the optimum time to take off and land and the height and strength of thermals expected along a particular course by correlating height of convection, cloud base altitude, and lift rate over the region with the glide ratio and glide speed characteristics of the type of sailplane a pilot planned to fly (Ref. 54).

By mid-2005, a meteorologist could load 120 homogenous regions in Western Europe and Scandinavia into the TopTask Competition computer program built around the Liechti algorithm. Contest pilots reported that half of the TopTask Competition forecasts ranged from good to excellent. At the Colorado State University in the USA, work began in 2005 to combine Liechti's TopTask Competition (TTC) logarithm with a system called Regional Atmospheric Modeling System (RAMS) to predict soaring flight conditions in the American Southwest where some of the world's best soaring conditions prevail. Test flights gave quite positive results but there remained room to improve the forecasts (Ref. 55, pp. 68–71). By Fall 2006 and Spring 2007, Hindman, Saleeby, and Liechti had moved to the east coast of the USA and begun testing conditions in Fairfield, PA, and Reedsville, PA, and to Warren, VT, the following year. The scientists determined that the accuracy of the RAMS-TTC forecast was highest on days when the wind remained below 20 kts (23 mph), but suffered because the program made errors when estimating surface temperatures and dew points (Ref. 56).

In 2000, Dr. John W. "Jack" Glendening launched a website that provided access via the Internet to weather prediction models developed by Glendening that forecast thermal strength and height for sailplanes pilots. Now in 2013, Glendening provides several different models to forecast conditions in the USA and around the globe. The three versions of Glendening's Boundary Layer Information Prediction (BLIP) model are the Regional Atmospheric Soaring Prediction, or RASP model, and the TIP (Thermal Index Prediction) and WINDIP to predict upper level winds and mountain wave for pilots who fly in California and Nevada.

Chris Galli opened the XCSkies website in 2005 and in 2013 used it to market and support software programs that users could download and install on a variety of platforms, from desktop and laptop PCs to portable devices such as the iPhone. Like Glendening, Galli's programs allow users to forecast soaring conditions at nearly any location in the world.

Conclusion

Knowing the sky has driven progress in soaring since Lilienthal. Often the knowledge flowed from meteorologists to designers who created stronger and faster sailplanes, and to pilots who soared them higher, faster, and farther. Sometimes pilots discovered sky conditions previously unknown to science but regardless of its source, the new knowledge nearly always expanded the possibilities for soaring flight. Pilots today achieve remarkable altitudes, distances, and times aloft but the future also rings with the potential for the Perlan Project to soar into the lower stratosphere. Much more is possible as the soaring community continues to interact with science and technology.

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