Dr. Terry Clark

By ingenious and carefully selective simplification of the complexities of such modelling Dr. Clark was able to simulate significant features of turbulence, convective instability, wave breaking and periodicity in mountain waves in a realistic way. The results of such simulation enables us to get a better understanding of these features and will pave the way for further extension of our knowledge of the subject."

Dr. Terry Clark was born in 1943, studied first Electrical Engineering at the University of British Columbia, Canada, then Meteorology at the University of Toronto, Canada, were he finished his Master of Science and his 'Philosophical Doctorship' with a Thesis on convective clouds and numerical cloud modeling.

A Post Doctoral Fellowship of nearly two years at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, followed with work on numerical modeling of convective clouds.

Very consequently-regarding his engagement in modeling and cloud physics – he spent approximately four years at the Atmospheric Environment Service in Downsview, Ontario, where he was involved with developing a general three-dimensional small scale convection model.

Then he changed 1977 to the National Center for Atmospheric Research, (NCAR), Convective Storm Division, at Boulder, Colorado, where he was appointed as Senior Scientist, supervising a modeling group mainly working in numerical simulation of convective storms.

Together with Dr. Joachim Kuettner, Honorable Member of OSTIV and also working with NCAR, Dr. Clark's interest is directed also on the theoretical treatment of the 'thermal waves', observed and wellknown to most of the glider pilots. Hopefully they will report in future congresses about good simulations and explanations of that phenomena.

KEYNOTE ADDRESS

by
Dr. Joachim Kuettner
National Center for Atmospheric Research
Boulder, Colorado
U.S.A

50 Years of Wave Soaring Adventure, Research, and Challenge

"Ladies and Gentlemen,

50 years ago, on the 3rd of March 1933, the great soaring pioneer, Wolf Hirth, made the first wave soaring flight in Grunau, Germany. This flight brought a new type of adventure of the sport of soaring, namely the very high altitude flights. It also presented a remarkable scientific discovery that stimulated a new type of research resulting in a still continuing stream of scientific papers. Finally it presented a challenge which is as strong today as it was 50 years ago because the potential of wave soaring has in no way been fully exploited. It is on these three aspects of wave flight – adventure, research, and challenge – that I wish to talk about today with a view towards the second half century of wave soaring.

Adventure

Let us take a look at the mountain profile where Hirth's first flight was made (Fig. 1). All that was surprising about this flight was that the sailplane kept climbing over the slope, very slowly in smooth air, to about 4,000 ft. and the updraft area extended far upstream from the slope. More surprising was that Hirth immediately suspected the higher mountain range of the Sudeten, 25 km further upwind as the source of a wave lift and that he saw a connection with a stationary high cloud which hovered over this mountain range. This was the celebrated "Moazagotl" cloud, known locally as an indicator of bad weather, but made famous among glider pilots as a symbol of high altitude soaring by Hirth's later sailplane designs "Moazagotl" and "Minimoa", the beautiful gull-winged craft. Soon the heights reached at the gliding school in Grunau increased to world record altitudes first achieved by the school's exploration minded instructor, Paul Steinig. I remember myself a record flight to 23,000 ft. without oxygen in an open sailplane. With blue face I landed somewhere in Poland, not eager to repeat this adventure. A few years later the stratosphere was reached by Klöckner in the wave-lift of the Alps.

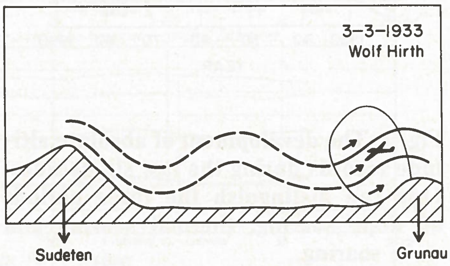

Fig. 1: First wave soaring flight over Grunau (Germany) by Wolf Hirth and his interpretation of airflow induced by upstream mountain range of Sudeten.

Fig. 2 shows an interesting curve of altitude records vs. time. We notice 3 regimes: slope soaring, thermal soaring, and wave soaring. Each starts steeply then flattens out temporarily. We recognize the limitations by the need for oxygen, then pressure oxygen, and finally, pressurization. This last barrier will soon be overcome and another climb to 55,000 ft. can be expected; but not much higher, because at these levels the wind velocity usually decreases – except in the circumpolar jetstream of the arctic winter, where we find the "mother of pearl clouds" near 80 to 100,000 ft over mountains. Notice

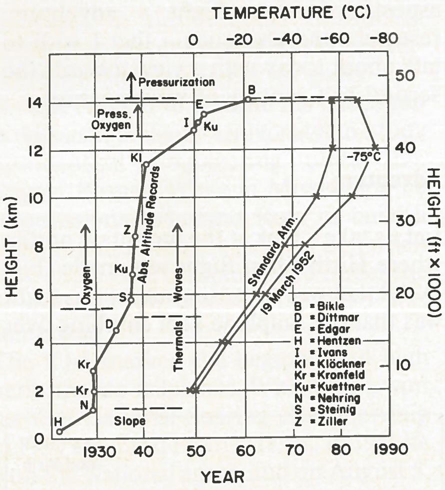

Fig. 2: The development of absolute altitude records during the last six decades. One can distinguish the three periods of slope soaring, thermal soaring and wave soaring.

that World War II separates the series of altitude records flown by the German pilots from those by the American pilots - the latter ones all conducted over the Sierra-Nevada.

Today practically all diamond altitudes are flown in mountain waves and there are regular "diamond mines", such as the Black Forest Gliding School in Colorado, which has produced well over 5000 diamonds.

Waves also occur over flat ground. They are still somewhat mysterious to most glider pilots who call them "Thermal Waves". Although they have not yet been systematically explored, we know at least that much: they form over and upwind of cumulus clouds when the wind increases with height, as well as over cloud streets if the direction of wind changes with height. In this contest, here at Hobbs, thermal waves have been used to altitudes of nearly 18,000 ft., about 7,000 ft. over the tops of shallow cumuli. The thermal wave phenomenon is not fully understood yet and awaits scientific exploration. Australian glider pilots have already tried that and Ingo Renner, our wourld champion, has described a thermal wave flight at 20,000 ft. which allowed him to reach his 600 km distant goal without the help of mountains or thermal techniques. This brings me to my second topic: the research aspects of wave soaring.

Research

It is no exaggeration to state that the majority of atmospheric scientists of repute have, at some time in their life, worked on mountain waves or - as they are called today - "lee waves". It is still a favored scientific subject, and, although the number of papers exceeds now 800, it is not fully solved yet. But we should look 50 years back.

After the discovery of wave lift and its connection with the stationary high altitude clouds - the lenticular clouds - the questions were the following:

Do we have lift (and cloud) over a large lee vortex? Or do we have a high-reaching slope updraft tilted backwards and crowned by the wave cloud? Or do we have a wave updraft in the lee (separated from the mountain) which is leaning forward against the wind?

The three possibilites are illustrated in Fig. 3. At the time of the discovery of the mountain wave the first two alternatives were considered most likely. Today we know that the third alternative is correct, but it was a gliding contest in Grunau in 1937 that provided the proof. All pilots were asked to make accurate reports of their positions at various times, of the up- and downdraft values encountered in the wave, and to carry barographs or barothermographs. Luckily enough, a strong wave occurred. The results can be seen in Fig. 4 and 5. Vertical cross-sections clearly show the wave motion of 8 km wave length, the down-draft area upwind of the first wave and the position of the Moazagotl cloud and the rotors in the lee (Fig. 4, I-III). Looking upwind against the mountains (Fig. 4, A-C) we notice lift values of up to 7.5 m/s and record-altitudes near 6 km with 4 m/s updraft.

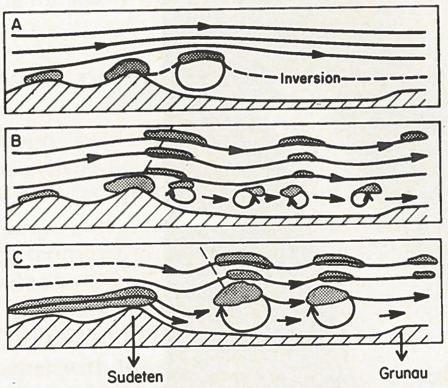

Fig. 3: The three original concepts of the origin of the high, standing wave cloud ("Moazagotl"). A = Lee vortex. B = Displaced slope updraft. C = Lee wave flow.

In the plane view (Fig. 5) the picture is even clearer. The slopes of Grunau are under the third wave, the first wave being induced by the Riesen-Gebirge (the highest part of the Sudeten range) as suspected by Hirth.

Here we had a gratuitous research project with 22 sailplanes in the wave. In one day they cleared up the nature of the mountain wave.

Theory followed soon, first assuming a basic role of low-level inversions and of the tropopause, later providing evidence that the normally present internal stability of the atmosphere is sufficient to produce lee waves. Today lee waves are considered to be primarily internal gravity waves rather than inversion waves. This is important because glider pilots often think one can either have cumulus clouds or one can have waves, but not both. Not so! The air inside a cumulus cloud is unstable due to condensation heat but the dry air surrounding the cloud is still stable and can oscillate up and down, even though it may contain some convective clouds.

The early observations were still semi-quantitative. It was the "Sierra Wave Project" of the 1950's that provided, for the first time, solid, quantitative scientific information from well-instrumented sailplanes and powered aircraft devoted entirely to the problem of lee waves. It was a unique cooperation of top-pilots of the Southern California Soaring Association and top-scientists of the University of California in Los Angeles.

Fig. 6 shows a typical example of the wave structure as measured by a radar tracked sailplane in much detail on the 10 to 30 km scale (note the contrast between terrain contours and stream lines), while the larger-scale of 100 to 200 km was explored by instrumented B-29 and B-47 aircraft. It showed the descending motion of the higher layers upwind of the Sierra crest and their ascent on the lee side. Thus the classical picture of the mountain wave (Fig. 7) evolved from the Sierra Wave Project. Some of the best film footage of the air flow over mountains was taken during this project.

The field project also provided important information on the destructive power of the rotor and the condition under which it develops. Larry Edgar who established the still existing multiplace record of 44,000 ft. in this project experienced the break-up of one of our project gliders as you may have heard.

Important research was also conducted in southern France by Norbert Gerbier and his coworkers, using radar, balloons, aircraft, and gliders near St. Auban, the well-known gliding center, and by Denise Cruette. Not only the lee waves, but also their connection with the Mistral were thoroughly explored.

Excellent and detailed observations of lee wave characteristics in Sweden were reported by L. Larsson in the 1950's from glider flights, soundings and time-lapse pictures.

Another step in wave research was taken in the 1960's and 70's using vertical "stacks" of highly instrumented powered planes traversing the wave from near ground to 60,000 ft over the Rocky Mountains near Boulder, Colorado. NCAR scientists (Lilly and Zipser) documented some of the most spectacular extremes of mountain waves with surface winds of over 100 knots (Fig. 8). The enormous amplitudes of these waves and the fact that the stratosphere was sucked down 6 km (from 40,000 to 20,000 ft.) can only be reproduced by very advanced non-linear theories and computer models. Usable wave lift was found to extend to about 55,000 ft.

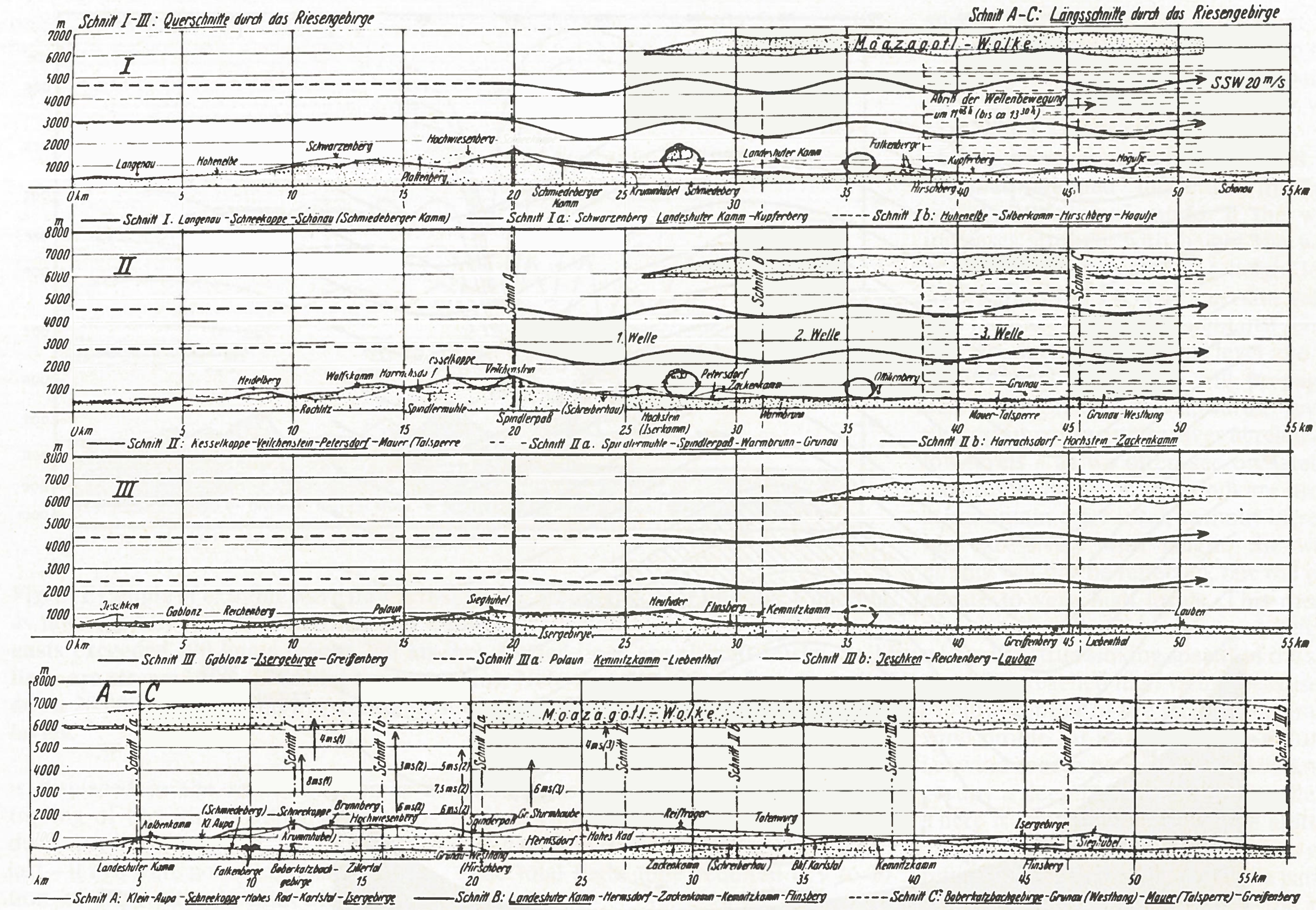

Fig. 4: Establishment of actual wave flow by simultaneous flights of 22 gliders near Grunau in May 1937. Three vertical cross-sections in wind direction across the Sudeten mountain range (I to III) and one vertical cross-section normal to wind direction (A-C, lower part). The numbers are measured values of updrafts.

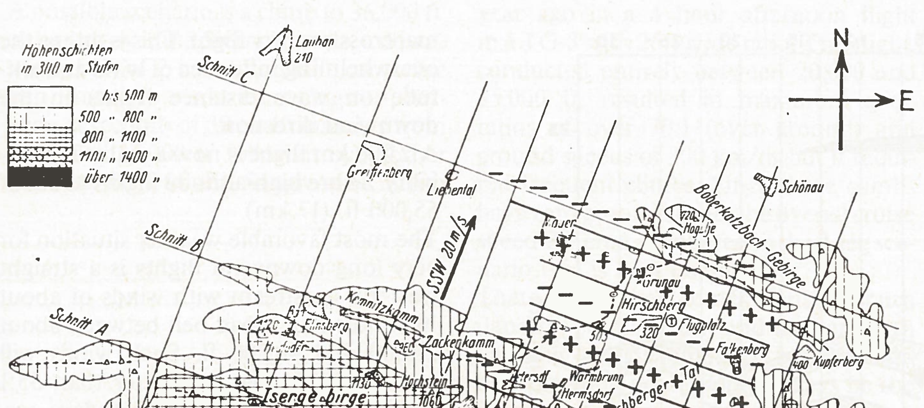

Fig. 5: Plane view of updraft (+) and down draft (-) distribution during glider flights of Fig. 4. This flight day confirmed concept C of Fig. 3. Wavelength = 8 km (5 stat. miles).

The forward tilt of the wave is also understood now. It provides the mechanism which transports strong winds from higher to lower levels, i.e. what is called a "negative momentum transport". The reason is that a wave tilted against the wind has lower wind velocities in the updraft areas than in the downdraft areas. This affects the global circulation if we consider all the mountains around the world.

The last major project exploring the entire problem of air flow over mountains was ALPEX, the Alpine Experiment of 1982, in which 20 nations participated. It investigated, among other problems, the lee waves of the Alps and Pyrenees, as well as the Bora over the Yugoslavian coast. This will be discussed in a separate paper.

The rotor phenomenon and the associated sharp contrast between its turbulence and the adjacent, totally laminar flow of the wave is not fully understood yet due, in part, to the danger of a direct in-situ exploration. It remains a scientific challenge – which brings me to the final point: the now existing challenge of wave soaring.

The Challenge

I believe that this challenge is as strong as it ever was. It is based on the fact that the great advances achieved on the technological and performance side of the modern sailplane have not yet been integrated with the atmospheric possibilites and the optimal meteorological navigation. What

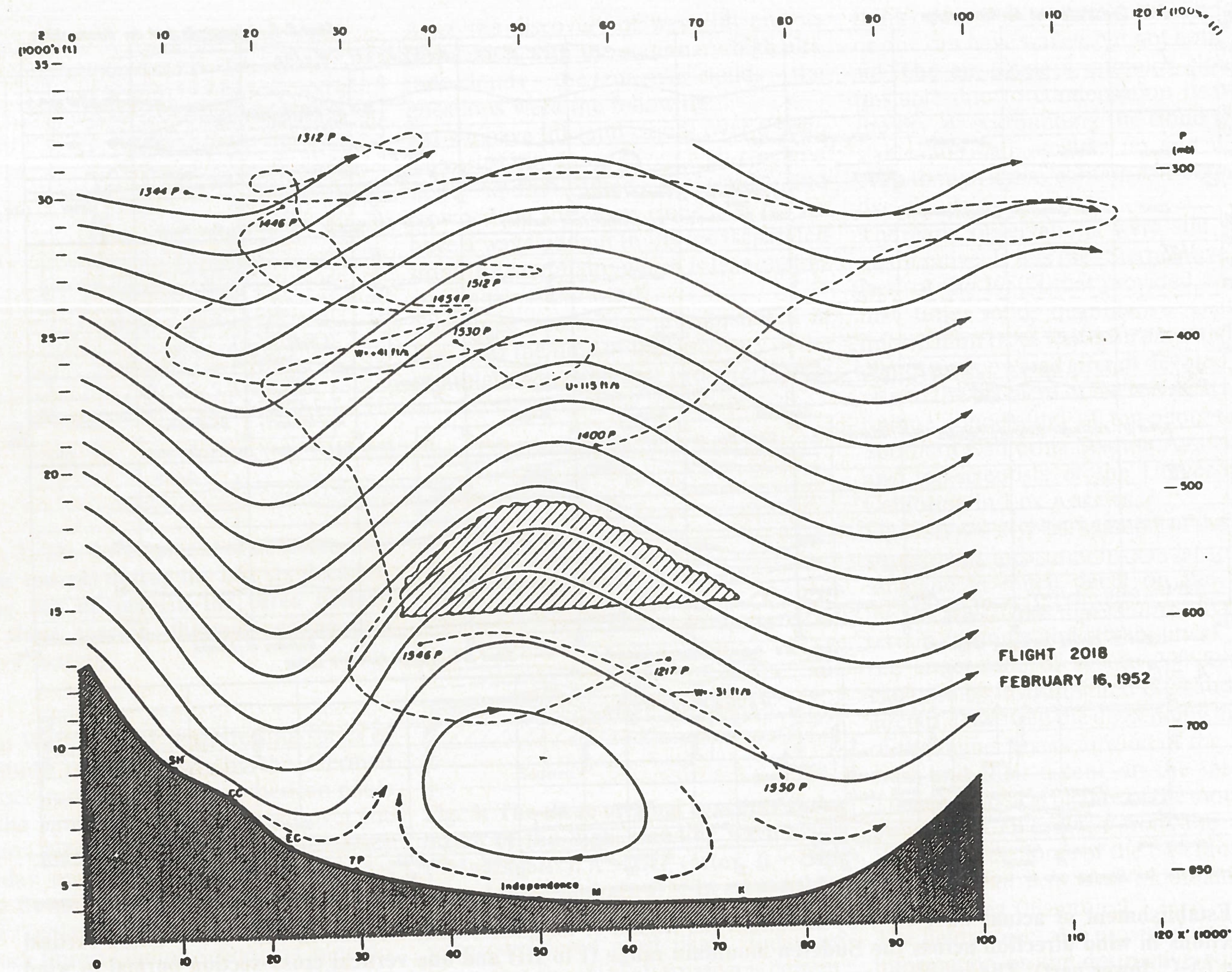

Fig. 6: Airflow in the lee of the Sierra Nevada, California (left) according to radar tracked glider flight (dashed line) during "Sierra Wave Project" (1952-55).

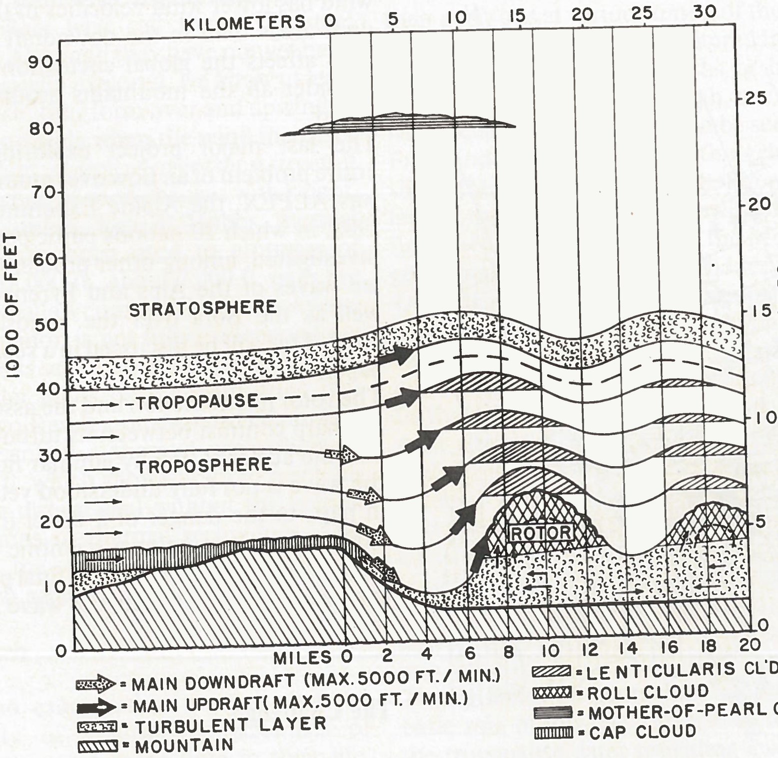

Fig. 7: The classical picture of a typical mountain wave.

is needed now is to combine our latest knowledge on wave and wind characteristics with the aerodynamic behavior of high performance sailplanes in the upper atmosphere. As will be shown, the results are markedly different from those of thermal cross country flight. This is due to the overwhelming influence of wind and altitude on wave distance flights in the downwind direction.

A 2,000 km flight is now a realistic possibility. So are high-altitude flights to about 55,000 ft. (17 km).

The most favorable weather situation for very long downwind flights is a straight westerly jet stream with winds of about 100 knots in a broad belt between about 25,000 and 40,000 ft. Such winds will more than double the better than 55:1 glide ratios achievable with todays carbon-fiber sailplanes.

To optimize the glide angle over ground one has to follow a very simple rule, namely to fly at indicated speeds between minimum sink and maximum L/D, i.e. between about 45 and 50 knots. This will result in glide ratios of about 125:1 over ground and ground speeds of over 300 km/hr (between 150 and 200 knots). Flying faster will penalize the glide angle. With this technique it is possible to stay in the optimum (and most comfortable) altitude range between 20,000 and 35,000 ft. while using only the strongest wave producing mountain ranges. The high ground speed results from a combination of tailwind and high altitude effect on true air speed. Actually a sailplane at 35,000 ft. behaves like a glide bomb: its flight polar

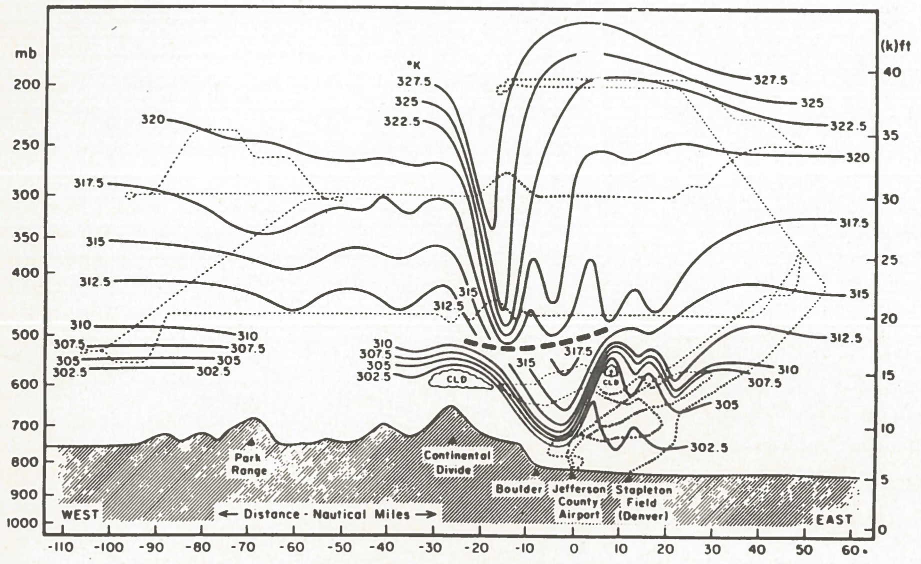

Fig. 8: Example of extreme wave flow across Rocky Mountains near Boulder, Colorado, as measured by NCAR Sabreliner and Queen Air aircraft in January 1972. Surface gusts exceeded 100 knots (about 200 km/hr). Dotted lines are aircraft tracks. Solid lines are stream lines (potential temperatures). Note that the stratosphere is sucked down 20,000 ft. in the wave resulting in severe turbulence in the lowest and highest levels.

is displaced in the same manner as a tripling of the wing loading would produce corresponding to a 2-ton water ballast – if this were possible. This combination of high altitude and wind effects makes it possible to fly 500 to 600 km downwind legs between climbs, without having to descend below 20,000 ft. where winds, glide ratios, and ground speeds rapidly decrease.

A possible scenario is a climb to 36,000 ft or higher over the Sierra Nevada, a downwind dash of 2 hours and 600 km to the San Francisco peaks near Flagstaff, Arizona, a reclimb of 30 to 40 minutes from 20,000 to 33,000 ft followed by another 600 km dash to the Sangre de Christo mountains and a final glide of about 3 hours and approximately 900 km from 35,000 ft to Oklahoma or Kansas (Fig. 9). The total flight time required is 9 to 10 hours.

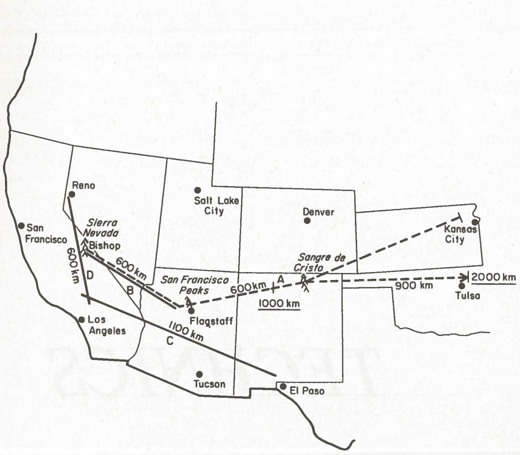

Fig. 9: Scenario of possible 2,000 km downwind flight in the western United States (A). Other wave distance flights are also shown (B = 1955 flight of J. Kuettner; C = 1982 flight of M. Koerner; D = Cross-wind race track used for out-and-return flights along Sierra Nevada).

In other words, only 3 climbs are needed to accomplish this feat – provided one is able and patient enough to wait for the right weather situation. The first leg (600 km) was already flown by the author 30 year ago in a 4 hour afternoon flight in a TG-3 with 26:1 glide ratio. This flight, conducted entirely between 20,000 and 35,000 ft, resulted in maximum glide ratios of over 70:1 (over ground) and ground speeds of 300 km/hr but it required frequent climbs. Since these climbs have zero ground speed, the overall cruise speed suffered, compared to the 3-leg scenario that is now possible.

There are other routes farther south (landing point: Texas) and farther north (landing point: Nebraska), but the optimum starting point would always be the Sierra Nevada.

Weaker waves in-between which occur frequently on such flights should not be used for climb, but taken advantage of by a "modified dolphin" technique, further increasing the glide ratio over ground.

High altitude flights to about 55,000 ft are also possible now, provided care is taken that certain technical problems (pressure suit, inside icing of cockpit, etc. are solved).

We know now a little more about the vertical extent of mountain waves and the conditions that allow very high altitude flights. Both low and very high velocities are not favorable for record altitudes. Everybodys knows that low wind velocities will not produce high-reaching lift because vertical air motions are roughly proportional to the horizontal wind speed. Disregarding for a moment the fact that extremely strong winds can present a penetration problem for a soaring pilot, there is another reason why very high winds are also unfavorable.

Mountain waves occur in two modes, the so-called "trapped" mode and the "vertically propagating" mode. If the wind increases strongly with height the wave energy will be reflected at a height level where the wind exceeds a certain value. The lee waves then are caught in a „channel" or „duct" between this level and the ground and the energy will propagate downwind instead of upwards, giving numerous consecutive waves at relatively low-levels – as we often see on satellite pictures. If, however, the winds are strong at mountain crest level, without increasing excessively with height, the wave energy will not be reflected, but will propagate to very high levels. This means that the lift will still be strong at heights where the "true sinking speed" of the sailplane has reached high values because of the low density of the air. The favorable wind profile for this situation is "blunt", i.e. wind speeds between 80 and 90 knots occupy a deep layer of the troposphere.

There is another barrier to high altitude lift: the tropopause itself. It also acts as a reflecting layer, but will only trap a part of the wave energy below, letting the rest penetrate into the stratosphere. Therefore, a day with a very high tropospause is favorable for high-altitude flights. One can see this from an upwind sounding. Over the Sierra Nevada, tropopause heights near or over 45,000 ft occur occasionally.

We should be careful, however, with record flights above 55,000 ft. The strong decrease in wind velocity on top of the jet stream often leads to "wave breaking" at these levels – like an over-turning surf on the beach – causing violent clear air turbulence. This has been born out by U-2 research flights in the Rocky Mountain lee waves. There could be structural damage or loss of control.

Summarizing then, sailplane flights to altitudes of about 55,000 ft (near 17 km) are possible if (1) the jet stream has a blunt profile (deep layer of near constant height winds), (2) the tropopause is high, and (3) stratospheric levels at which the lee waves break are avoided.

This, then, is the challenge that wave soaring offers 50 years after the discovery of the mountain wave: long-distance flights of 2,000 km and altitude flights of up to 55,000 ft.. While refinements in sailplane design and in the – already sophisticated – flight techniques may still bring small incremental improvements to thermal flight, wave soaring can be expected to produce a quantum jump in soaring performance. The time for such accomplishments is now."