Micrometeorology

and

Hang Gliding

An excellent account of an original subject: an ideal paper for this course: something that the author likes to do and how it is influenced by weather. Good writing style; <u>fine</u> diagrams. I learned something (wind over ridges).

by

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PHYS 383

December 10, 1982

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Since before the advent of written history, man has looked with longing at the majestic hawk soaring high overhead - wings all but motionless, floating effortlessly on the breeze. But only in the past century has man realized the dream of flight. Before the late 19th century, it often appeared that the nay-sayers ('if man were meant to fly, he'd have wings') were correct. Most attempts by brave or crazy men to fly in their own contraptions ended in disaster. In the 1890's, Otto Lillienthal built and flew mankind's first successful gliding craft.

He and his brother were the first men to fly with wings of their own devising. They were the first men to 'hang glide.' Otto, unfortunately, was hang gliding's first fatality - victim of a sudden gust that lifted his fragile craft and plunged him back into the small hill he had leapt from. He died a few days later from the injuries sustained.[1]

Flight was dangerous business - but man was not long content to glide down a hillside. Powered flight was now the goal; using the work of the Lillienthals and others, the Wright brothers accomplished this in 1903 at Kitty Hawk, North Carolina (still a popular spot to learn to hang glide). Progress in flight was swift thereafter; flying faster and higher, man quickly outdistanced the birds that inspired him. Aviation grew into the commercial industry that we know today. Aviation grew - and with it, the science of meteorology; for as man strove to fly farther and higher, he needed to know more about the air through which he was flying. This led to an increased understanding of large-scale weather systems and high-altitude effects. Meteorology on the small scale no longer seemed to be of great concern to pilots.

In the early 1970's hang. gliding was 'rediscovered' in California. Starting with bamboo and plastic, young fliers relearned the skills and techniques pioneered three quarters of a century earlier. With new technology like the flexible wing designed by Francis Rogallo for NASA in the early sixties, and new materials like lightweight aluminium tubing and dacron, hang gliding evolved from 'bamboo bombers' skimming a few feet over the dunes in California to high performance soaring craft capable of riding successive thermals on flights over a hundred miles long.

With the return of low-and-slow flight, and the tremendous increase in performance and popularity of hang gliding, there has been a resurgence in the study of weather on the local scale. This is micrometeorology. It is a fairly new branch in the study of weather and the motion of air, and it borrows from as well as fills the gap between meteorology and fluid dynamics. Aerodynamics and weather have both been well studied as a by-product of aviation; hang gliding crated the need to form a synthesis between the two disciplines for every hang gliding enthusiast becomes a student of the weather by necessity. His sport depends wholly upon understanding the effects the wind has on his flying site. As his flying skills improve and he flies from different and more challenging hills, his need for a working understanding of weather and air currents expands.

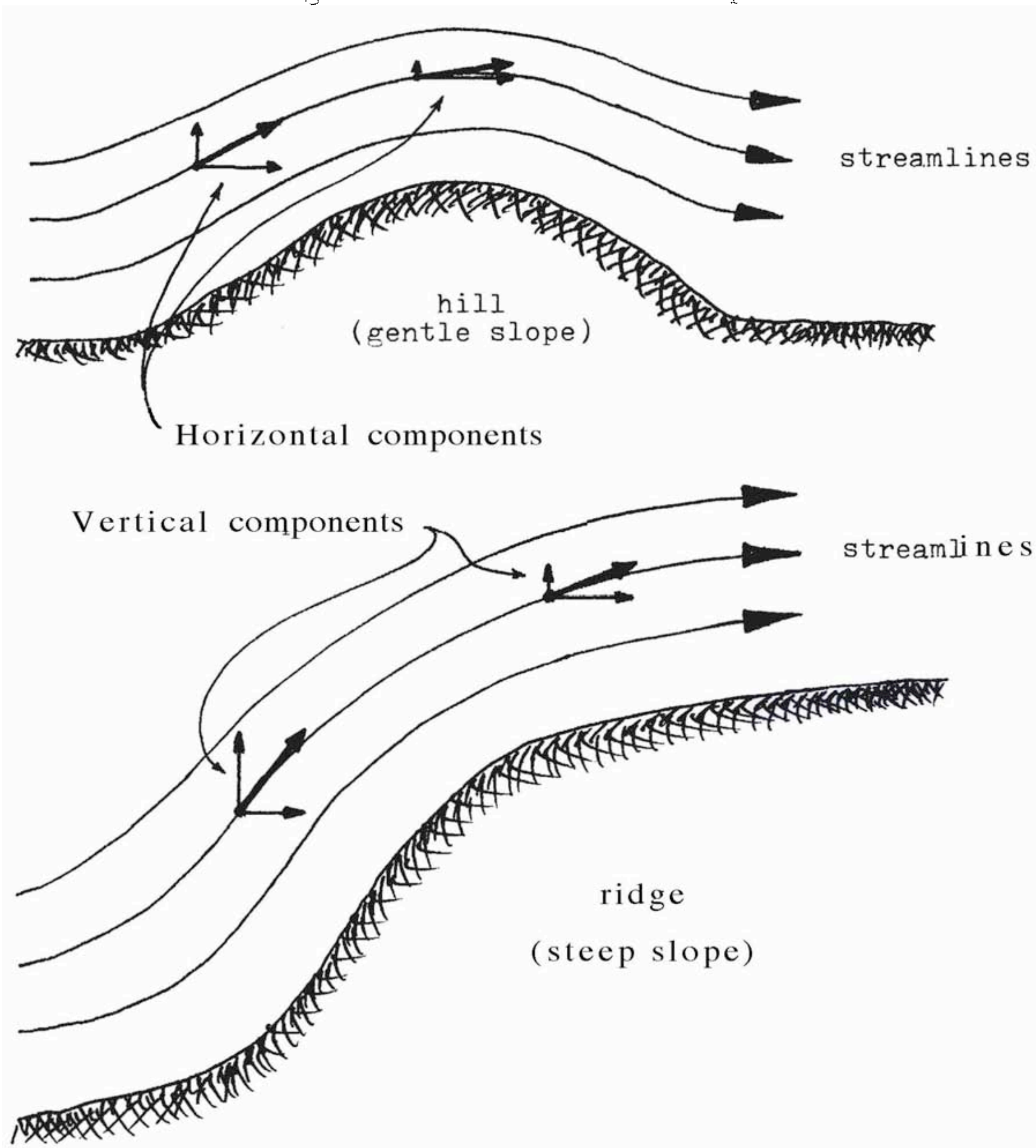
By the time he makes his first few soaring flights, he will have first-hand experience with atmospheric effects that most people neither encounter nor think about. And once he has made a few cross-country flights, a pilot will have developed a great knowledge of and healthy respect for the forces of nature at work in the atmosphere from the lift-giving thermal to the glider-crushing thunderstorm. Weather is one of the most important influences on hang gliding, and it is inter-related with the other primary concern of the hang glider pilot: topography. Other than the condition of his glider (or kite as it is sometimes called), these two effects rule the flier's actions.

As Otto Lillienthal sadly discovered, the wind is the weather element most critical to a hang pilot. The realm of flight for a typical hang glider ranges between about 15 mph minimum flying speed to a maximum of 40 to 45 mph. Needless to say, this is an extremely narrow range when compared to the known wind speed ranges observed on earth. A 200 mph wind would make short work of both man and glider, and even a 70 mph wind would strain even the sturdiest hang glider. Until he reaches expert status, an average hang pilot will think twice about even a 20 mph wind.

As with all aircraft, a hang glider is most at risk at take-off and landing during the transition to or from flight. This is especially true of hang gliders, whose landing gear are the legs of the pilot, which are also the kite's sole (no pun intended) means of propulsion at take-off. The need for some wind becomes apparent; if the glider needs at least 15 mph of airspeed to fly (assuming the wind speed is less than this) the pilot has to make up the difference at launch by running. With an average 45 pounds of kite, it is easy to see why some breeze is nice. For the beginner (like myself) a steady ground breeze of about 10 mph is ideal. Nature being what it is, though, a nice breeze like this is not likely to be sufficient, for the other basic requirement to hang glide is a hill to launch from.

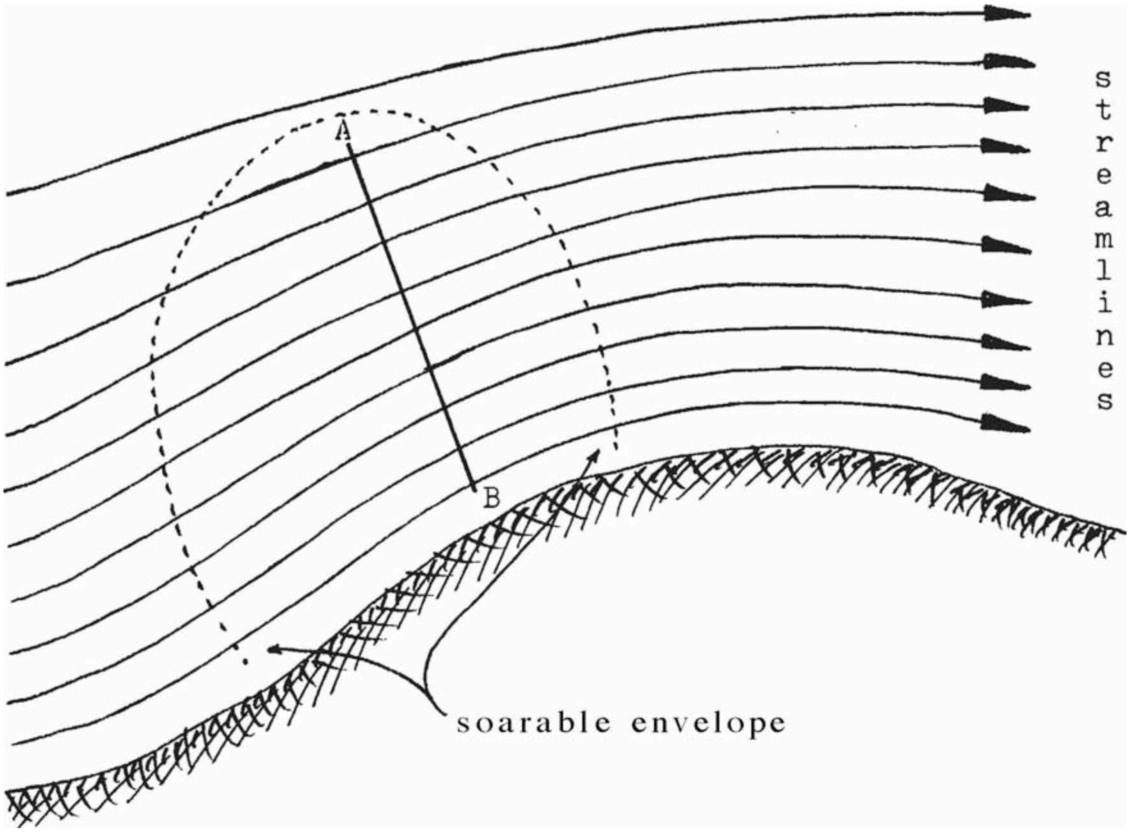
The interaction between air in motion and the terrain below it is one of the primary concerns of micrometeorology. When air moving at constant velocity and direction encounters an obstacle, such as a hill, the air is forced either around or over the obstruction. Air, being a viscous fluid, will seek the smoothest path, which for anything much larger than a house, is over. This produces an effect called orographic lifting. If conditions are right, the airflow up the face of a hill or ridge can have a vertical component of velocity greater than the sink rate of a hang glider; the ridge is then theoretically soarable. Different combinations of wind speed and hill slope produce different vertical components - otherwise known as lift. The steeper a slope for a given wind, the greater and wider in area is the lift produced. And correspondingly, the greater the wind velocity on a given slope, the greater the 'soarable envelope.' These effects can be seen in Figures 1 and 2:

Figure 1: Lift on various slopes



In Figure 1, wind velocity vectors are shown broken down into their separate horizontal and vertical components. For a identical wind speed (the sum of the components) it is easily seen that the steeper the slope, the greater the lift.

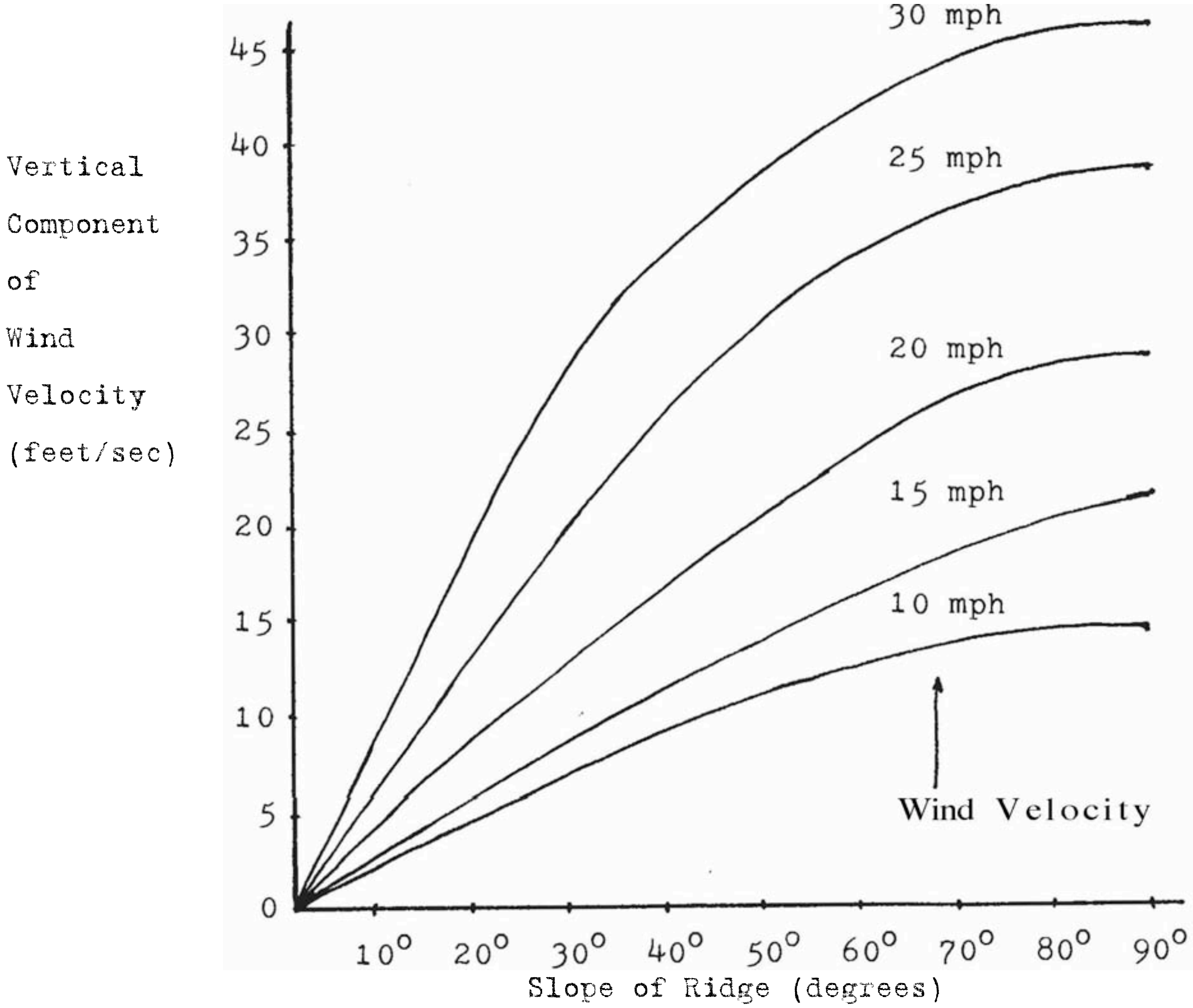
Figure 2: Area of greatest lift



In Figure 2, the line AB represents the line of greatest lift on a typical hill, which occurs where the total wind velocity is greatest. The Bernoulli effect of fluid dynamics states that a fluid will speed up when flowing through a venturi; a hill is the same sort of object. The region of greatest wind velocity produces the region of greatest vertical velocity; when the upward velocity exceeds the minimum sink rate of the glider, the hill is soarable. The boundaries of this region define the soarable envelope.

Figure 3 shows the vertical component of air velocity at various wind speeds, produced by slopes of different steepness:

Figure 3: Lift as a function of slope angle

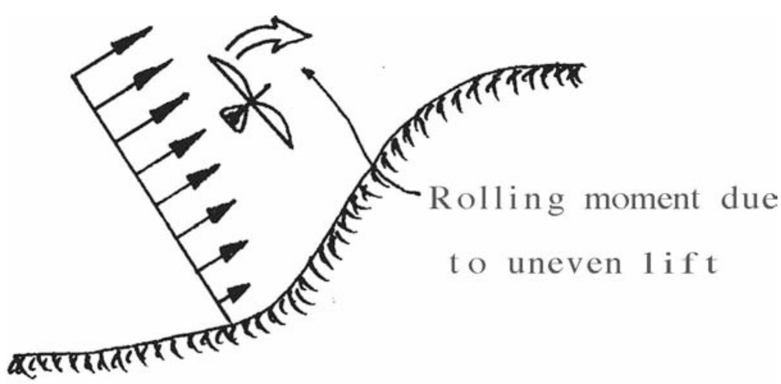


These curves are proportional to the sine of the slope angle, and all assume ideal flow at right angles to a ridge very large in extent - i.e., large enough to insure laminar flow.

So far, we have considered only highly idealized slopes - hardly a common find in nature. Quantitative study of these phenomena is very difficult because of the impossibility of completely modeling all of the factors present in real topographies. And the criteria for selecting flying sites include such factors as proximity and ownership of the land - even the quality of the road (if any) to the top of the hill. These are obviously beyond the scope of this paper. There are, however, a few more additional factors which are part of any consideration of orographic lift: frictional effects and wind directional effects.

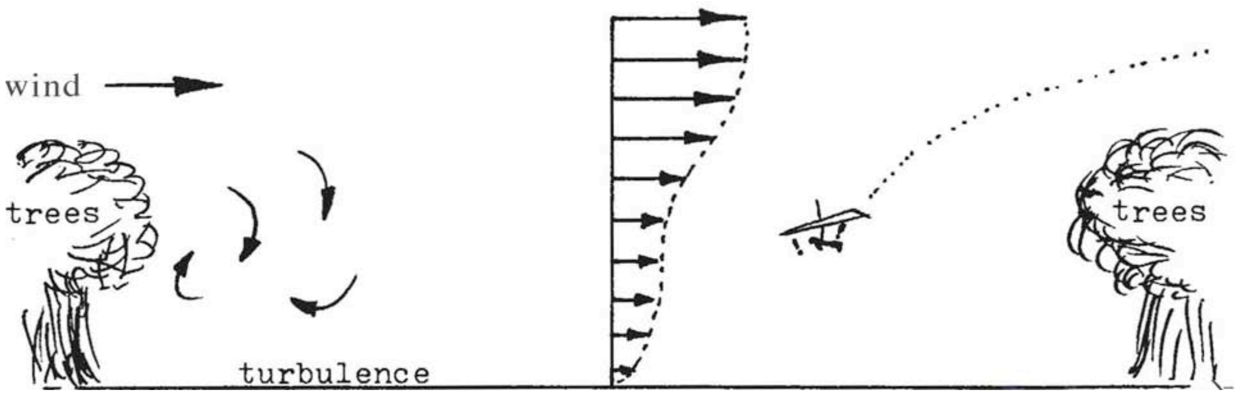
Frictional forces and turbulence result from the rough surfaces which the lowest layers of air strike as they are carried over a slope. If the surface irregularities approach the scale of the hang glider's wing span, i.e., feet to tens of feet, dangerous swirls of air will result. The danger lies in the sudden changes of wind speed and direction that occur in such turbulence. The larger these effects become, the more they disturb the air above and behind them, forming invisible glider traps. Another low-level effect is the wind gradient that forms near the ground. This too is a result of the friction between the-ground and the .moving air. Air velocities taper off nearer to the groundcompared to the flow well above the hill. To a pilot flying along the lane of soarable air in front of the hill, this can produce a rolling moment on the glider that the pilot must continually adjust for, as seen in Figure 4:

Figure 4: Wind gradient effects



This effect is reduced the higher a glider goes, so it is only a hazard in marginal conditions. Wind gradient can affect a glider again when it nears the ground to land. In this situation, sometimes called wind shadow, the wind speed close to the ground is nearly zero (see Figure 5). This is almost always due to trees upwind of the landing field;

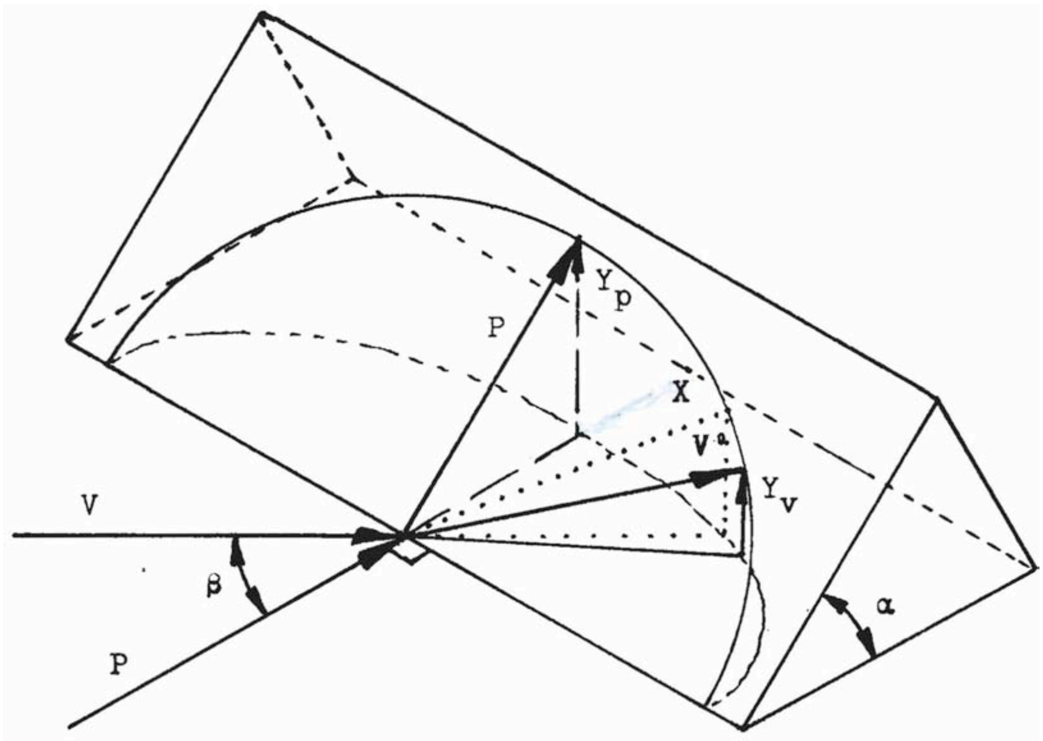
Figure 5: Wind shadow



Such an area is often the only option a flier has to land in; the gradient can approach the severity of a wind shear on a small scale. If the glider's airspeed is too close to minimum flying speed, the pilot could find himself in a serious stall when he enters the slower-moving air.

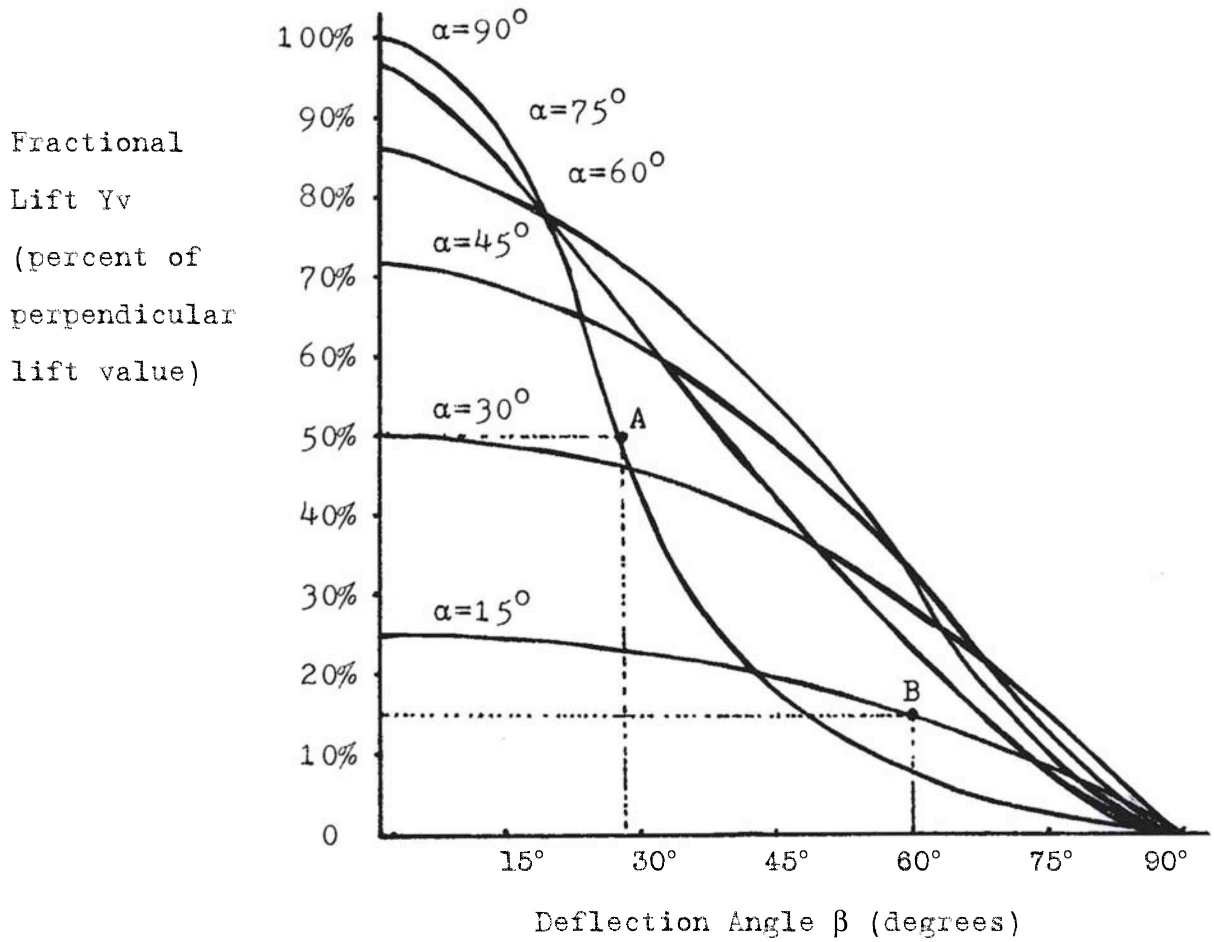
In nature, the winds almost never cooperate and blow right up a slope. When the prevailing winds do not strike a slope perpendicular to it, the lift is somewhat reduced, because the effective slope angle is reduced. This reduction increases the greater the deflection angle, approaching zero when the deflection is 90°. This is a complicated phenomenon, and it does not submit easily to analysis; a highly idealized form is shown in Figure 6:

Figure 6: Wind deflection on a slope



The vector P represents the perpendicular wind discussed and shown in Figure 3 as a function of the slope angle α. Y_p is the lift resulting from P. When the wind velocity vector shifts to V through an angle β from the perpendicular, the wind flowing up the slope is deflected. The wind does not simply maintain the same compass heading and remain in the same vertical plane, however. (This path is shown labelled X in the Figure.) Fluid dynamics tells us that an idealized fluid, when deflected, will choose the path that causes it to make the smallest total angular change in its velocity vector. This is shown as V' on the slope. Thus, the final value for the lift as a function of α and β is Y_v . The analytical solution for this quantity is quite involved and goes through several directional derivative minimizations[2] but a plot of Y_v versus β at several values of a is shown in Figure 7:

Figure 7: Fractional lift vs wind deflection[3]



Some general trends can be seen from this graph. Point A represents a 90° (vertical) slope with a wind 30o from perpendicular blowing over it. The lift component is about 50o of the peak value for that curve - indicating that a cliff is particularly sensitive to wind direction. Point B shows a 15o sloped hill with a wind 60° from perpendicular; here the value still above half the peak for that slope, indicating that a gentle slope's lift is less sensitive to the wind direction. But note also how much greater the lift is for a cliff. These graphs show quantitatively the difference between the beginner's 'bunny slope' and the experienced flier's soarable ridge.

Another difference between a gentle hill and a sheer cliff is in the way the wind flows over the top. Just as orographic lift is produced upwind of a slope, sinking and often turbulent air is produced downwind of a hill. A particularly dangerous phenomenon is known as a rotor, an unstable swirl produced by the boundary layer flow over an obstacle suddenly detaching from the surface. This can occur near the ground, as when air flowing up a slope reaches the upper edge. Rotors more familiar to aircraft pilots are generally found in the lee of a mountain range when high, stable winds form a mountain wave system. Under each rising crest of the wave flow is a rotor of turbulent air that acts almost like another mountain to the smooth air flow above. Mountain waves are generally the realm of sailplanes, which can handle the higher velocities and stresses produced. World records for endurance aloft - over 50 hours - have been set in wave conditions in Europe. Wave conditions can also be flown by hang gliders. Roger Ritenour, a local flier with over six years of experience, uses upper level wind data to predict soarable wave conditions on the Blue Ridge.

Wave conditions are potentially more dangerous than more simple orographic conditions because they produce equal amounts of sinking air that have no visible cause. Getting caught in the down side of a wave could lead directly to being deposited in the rotor under the next wave - if a mountain isn't encountered first. A device called a variometer has long been used in sail-planes for detecting the rate of change of altitude induced by the air the glider is flying in. To fly safely in wave conditions, hang glider pilots use more sensitive versions of the same device. (Hang gliders have a tighter turning radius and are smaller and much lighter than sailplanes, and can ride smaller thermals; this is why they use more sensitive variometers.)

Variometers all use the principle that mean air pressure is a function of altitude. Using a small reference pressure vessel, the vario measures the rate of flow through a small tube open to the outside air. If the pressure outside is falling, the glider is assumed to be gaining altitude. Since other factors such as temperature also affect differential pressure measurements, all variometers are temperature stabilized and calibrated to give reasonably accurate information. Most have electronic circuitry to amplify the pressure signal measured and to produce a tone that indicates rising air. The tone increases in pitch the greater the lift - and a warning tone sounds during rapid descent. These devises are even sensitive enough to detect being lifted slowly from floor to ceiling; this is so acute a measurement that state-of-the-art variometers are designed to compensate for sink and climb caused by the attitude of the glider. Present variometers can fit in the palm of a hand and weigh less than a pound. With one of these mounted on the control bar and an altimeter borrowed from skydiving technology strapped to his wrist, a hang pilot has the basic tools necessary for cross-country flight. Hang gliding has evolved greatly over the past decade - and one of the areas most improved is lift/drag ratio. This is usually expressed as a ratio, and can be considered the same thing as glide ratio - the horizontal distance a craft would glide for each unit distance lost in altitude. This performance specification has been improved from 4:1 to 10:1 and more in only ten years, making hang gliding the most rapidly growing form of air transportation.

But for true cross-country flight, a hang glider needs a renewable source of lift. Orographic lift is by nature dependent on the structure of the landscape beneath. To fly great distances in such lift requires a continuous stretch of slope more or less perpendicular to the wind. Gaps in the ridge as small as half of a mile wide are effective barriers to hang gliders due to their low top speed and low penetration capabilities. What is needed is lift from flat land - thermals.

Thermals have long been used by sailplane pilots, and because they are a major source of thunderstorms, they are relatively well understood by meteorologists. Thermals are a form of convection caused usually by radiant heating; of a small parcel of air near the ground. As the ground is heated by the sun, the air above it begins to rise. The layer of air is said to be absolutely unstable - the lapse rate of the rising air parcel is greater than the average dry adiabatic rate. As the bubble of warm air starts to rise, cooler air moves in from the surrounding area to fill the void left by the warm air. This leads to the instability - the air remains warmer than the air surrounding it, so it continues to rise until it reaches a layer of air with a lapse rate less steep than the wet adiabatic rate; in other words, an absolutely stable layer. If the combination of these two layers' lapse rates is still greater than the wet adiabatic rate, then the two are conditionally unstable. Once it moves upward, the bubble of warm air will continue to rise. To halt the upward flow of air, a totally stable subsidence inversion is required.

If the rising bubble of warm air reaches the convective condensation level, the water vapor carried upward condenses into a culmulus cloud. The height of the tops of these clouds is determined by the stability of the upper air. The thicker the conditionally unstable air layer, the higher the condensing vapor-laden air can rise. Thus the fair-weather culmulus humilus can change to -congestus or even -nimbus if the unstable layer is thick enough. It is rapid changes in upper air stability that give rise to thunderstorms - the nightmare of every thermal-soaring pilot.

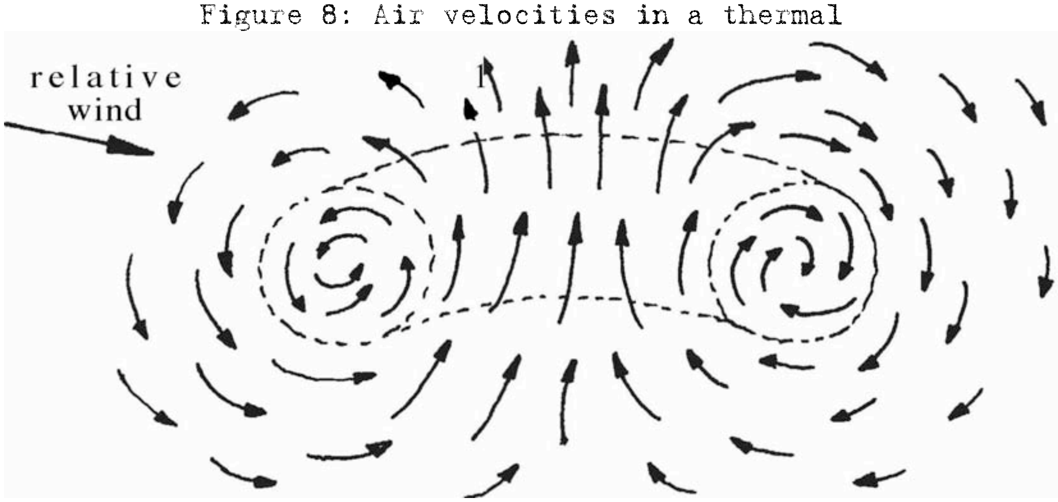
When the surface feature that first produced a thermal heats the cool replacement air, another thermal forms. If the winds aloft have a slight shear relative to the lower level winds, it is possible for the cumulus clouds forming over a particular thermal to align themselves into 'cloud streets.' These conditions are the ultimate for cross-country hang flight. After an upwind slope launch and the use of a few orographically assisted thermals, it is possible for a pilot to turn downwind and follow the rows of continually-forming thermals under the clouds for distances limited only by the continued production of thermals and the distance the pilot's driver is willing to go to retrieve him.

There is an infinite variety of thermals, and no two are alike, but certain conditions are perfect for their formation. If strong solar heating occurs in a sheltered valley when winds are light, a large reservoir of warm air can build up. When the downwind edge of the bowlful of air is perturbed, a column thermal may form on the upwind slope of the lee side of the bowl. By tapping the great supply of warm air in the valley, such a thermal can last almost indefinitely, and is only destroyed by changes in the wind or a break in the constant heating in the sheltered inversion in the valley. This could happen if the warm air is fairly moist - when enough clouds form, they block the sun's rays to the ground, cutting off the supply of warm air.

Real thermals will, more often than not, have multiple cores[5], which result when the wind pulls the forming bubble of warm air away from its source. Another bubble quickly forms from the remaining warm air and follows the first cell. It is even possible in polar regions for thermals to form over water.[6] In this condition, the water temperature is higher that that of the air above it, and bubbles of warm air coalesce until they reach sufficient size or are forced upward over a ridge. An interesting characteristic of water thermals is that from sufficient height the bubbles of warm air are visible by how they alter the surface of the water. Since each little pool of warm air is like an inversion (as long as it stays on the surface), they can be spotted by the calmness of the water. Depending on the relative humidities of the warm air with the cool air around it, the bubble may also have traces of radiation fog in it.

A typical thermal is structured like a torus - a donut of air continually turning inside out as seen in cross-section in Figure 8:

Figure 8: Air velocities in a thermal

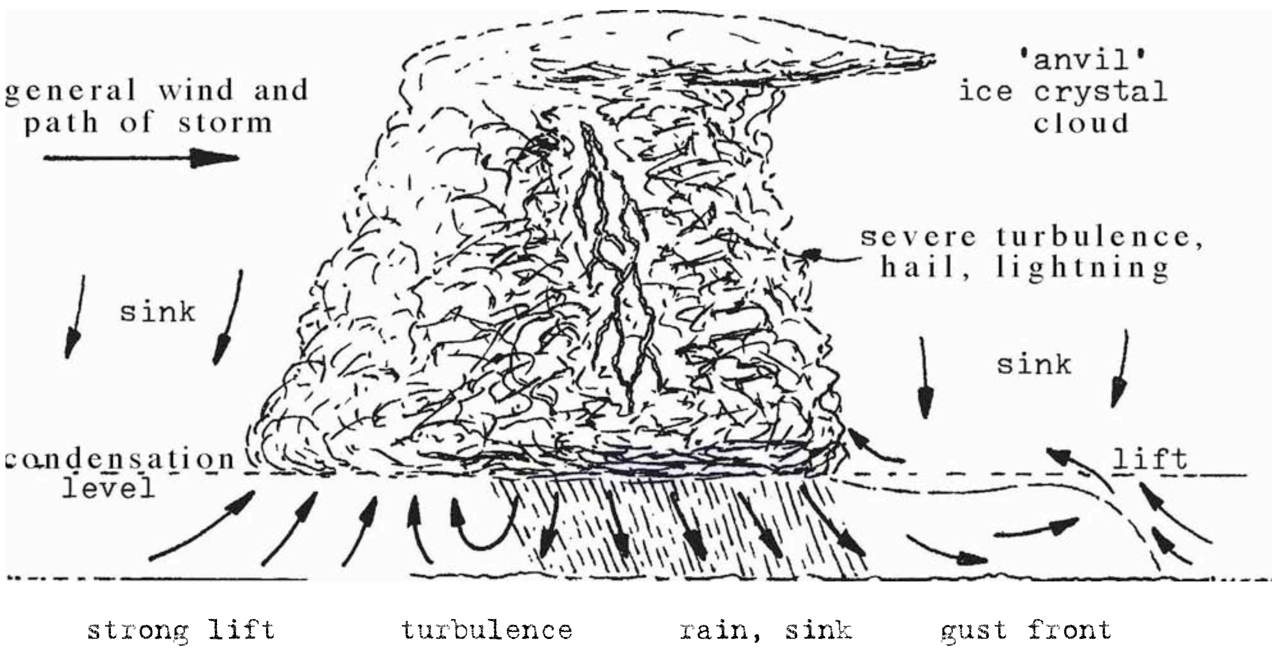


When the rising thermal encounters a horizontal wind, the result is increased lift in the upwind portion of the core and increased sink in the downwind area outside the donut. When several sources of thermals are close enough together, a multicelled thermal can come into being. The lift and sink in such a thermal can be very unpredictable. There is always sinking air between thermals; the energy balance is maintained by its presence. The trick to staying aloft using thermals is to stay in the lift as long as possible and in the sink as short as possible. On a good long flight, a hang pilot will work scores of thermals, gliding through the sinking air between them until he finds the next one. Vertical velocities as high as 1500 feet per minute can occur on a gusty, unstable day.

Such conditions also lead to the production of thunderstorms. It is unfortunate that the same conditions that produce the best possible lift for hang gliders also represent the greatest danger to them.

Often, a pilot's first warning that he is being drawn into a thunderstorm is the very thing he has been trying to find--steady, wide-spread lift. The pilots that have experienced this call it 'cloudsuck.' The first visible sign may be the condensation of vapor into cloud beneath the glider. This means that the pilot is already in the strong updrafts that go right up the heart of the new thunderstorm, and he is already above the convective condensation level. If the hapless pilot cannot get out ahead of the cloud or out the side, he has only a few choices left. One would be to ride it out - this is, needless to say, his worst choice unless the brewing storm dissipates before it becomes severe. Riding it out could mean that the pilot becomes a seed for the formation of a nice, large hailstone, if the freezing temperatures or lack of oxygen don't do him in first! But the violent turbulence would probably destroy the glider long before that. The strong updrafts might then draw the re-mains of kite and flier into the regions of hail, lightning, and ice formation - eventually downbursting whatever was left. This would not be a fun ride. If he acted early enough, it would probably be possible to avoid this fate by calmly disconnecting his harness and falling to an altitude where his small parachute could be used without the risk of getting drawn back up into the maw of the storm. Figure 9 shows a mature thunderstorm:

Figure 9: A maturing thunderstorm



These aerial dreadnoughts represent the greatest threat to the growing sport of hang gliding.

As hang gliding increases in popularity, the conditions that represent great potential danger will be encountered more often. Only through an understanding of meteorology, including the micro-scale effects, can one maintain a good level of safety in the sport.

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