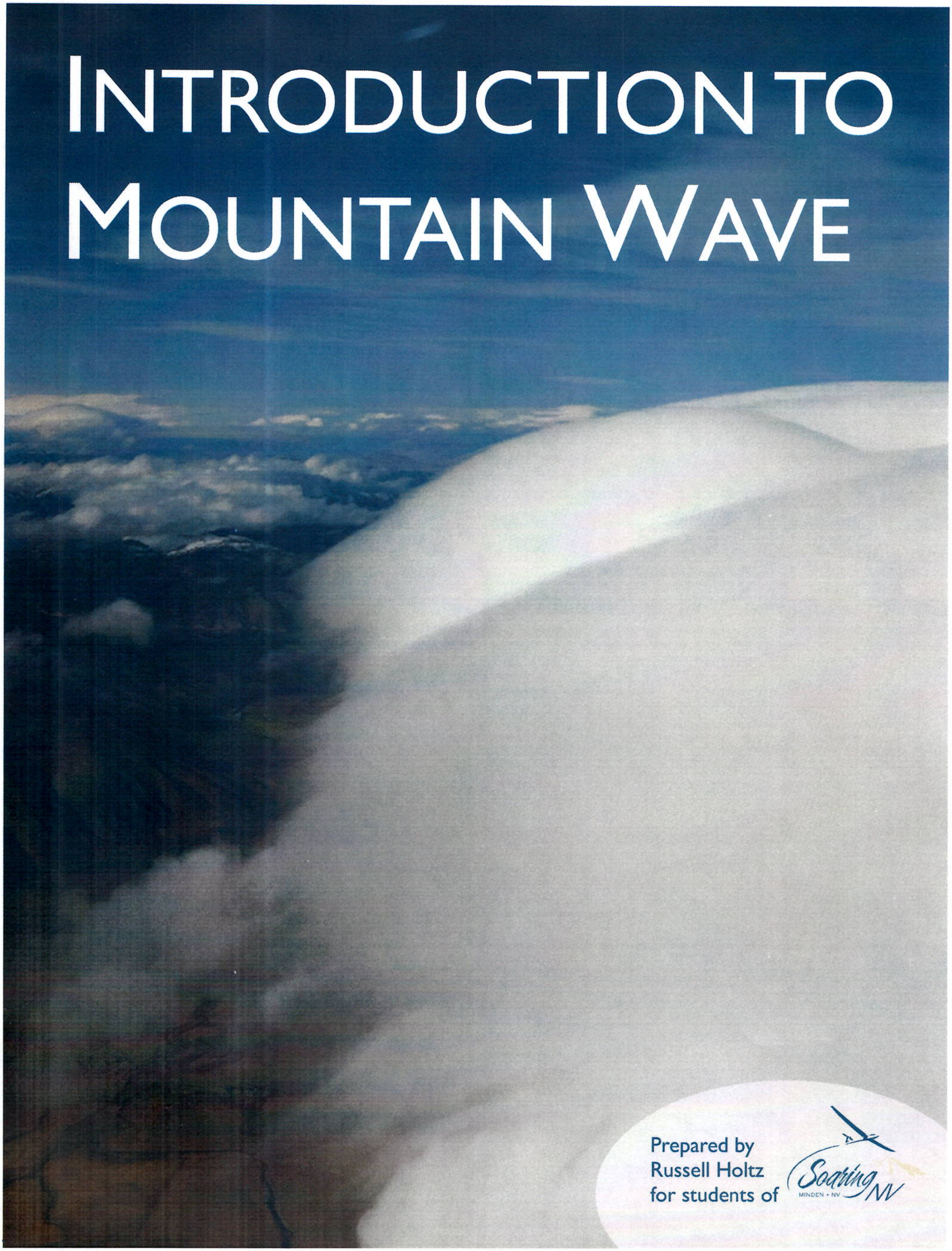
# INTRODUCTION TO MOUNTAIN WAVE



Prepared by
Russell Holtz
for students of

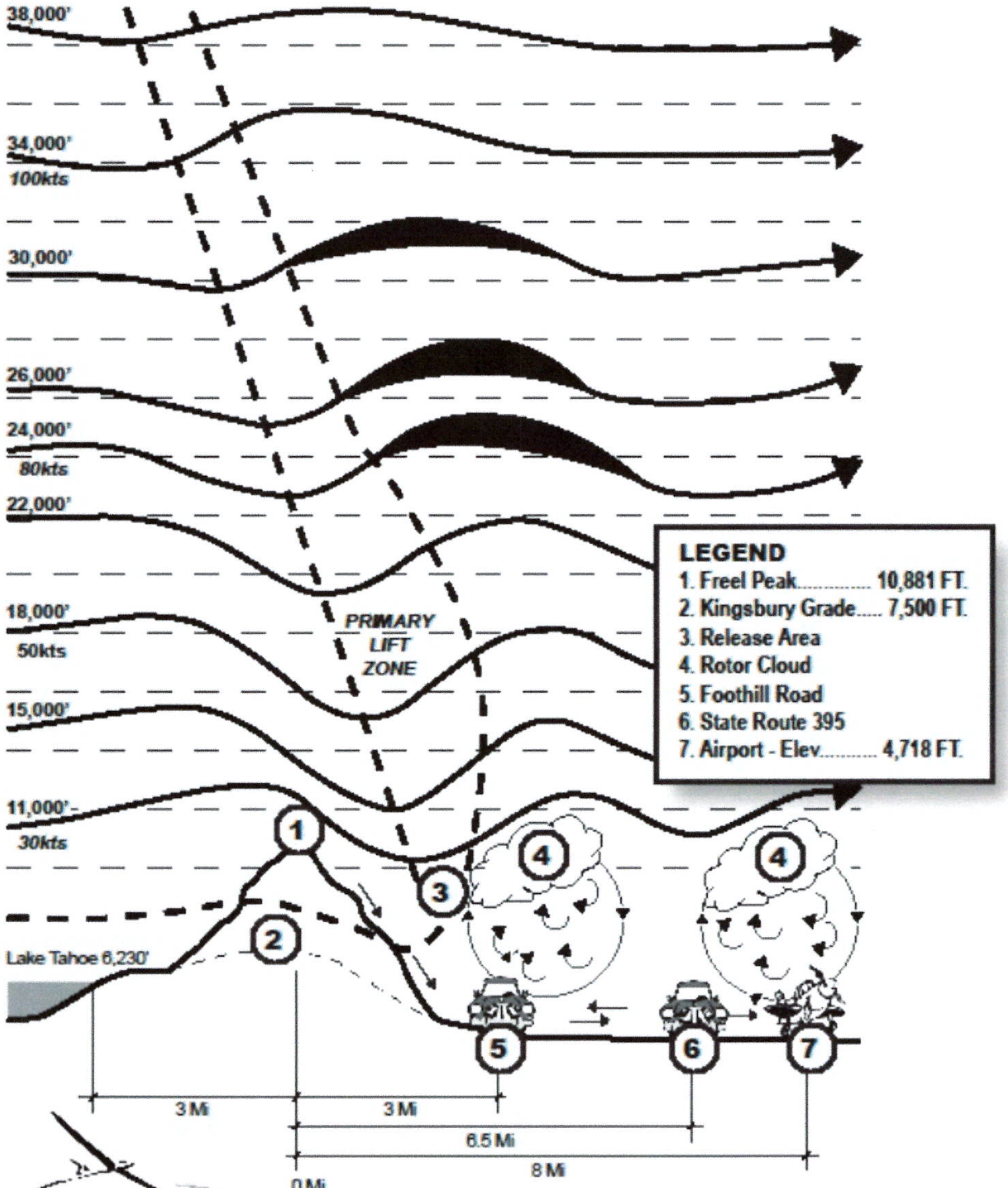
## WAVE CHECKOUT FORM

Soaring NV
MINDEN • NV

Name: ______________________________

| | |
|---|---|
| Glider flying experience (last 3 months/total) | hours: #flights: |
| Mountain flying experience (circle one): | none some extensive |
| Wave flying experience (circle one): | none some extensive |
| Wave theory | Completed |
| Airspace and regulations | Completed |
| Wave window check out (optional) | Date accomplished: CFI Initial |
| Hazards: | |
| Weather | High surface wind, Turbulence, Clouds, Foehn Gap Closure |
| Medical | Oxygen, Temperature, Dehydration, Urination |
| Aircraft and aircraft systems | Oxygen, Electrical, Vne and Va |
| Minimum arrival altitudes for return to Minden | at least 7,000 ft MSL over KMEV |
| Emergency procedures | Emergency descent, benign spiral (gap closing), oxygen failure, air brake freezing canopy frost/visability |
| Personal limits as established during the wave check out | Light wave (gentleman's wave) or higher limits need to be demonstrated to at least 80% of limits |
| Maximum surface wind (take off and landing) | Light wave (15 kts.) or higher kts. |
| Maximum crosswind | Light wave (10 kts.) or higher kts. |
| Maximum wind at ridge level (9,000ft) | Light wave (20 kts.) or higher kts. |
| Maximum wind at 18,000ft | Light wave (40 kts.) or higher kts. |
| | |
| Maneuvers: | |
| Safe high wind ground handling | Completed |
| Peflight inspection (high altitude flight) | Completed |
| Aero tow | Completed |
| Slack line recovery from altitude upset | Completed |
| Cross wind takeoff | Completed |
| Cross wind landing | Completed |
| High wind landing to PTS standard | Completed |
| Situational awareness | Completed |
| Cloud/changing conditions awareness | Completed |
| Sound decision making and discipline | Completed |
| | |
| Date and signature of pilot | |
| I am aware that wave flying in stronger than light wave conditions printed above involves higher risk than other soaring flights. I will stay within consiervative limits to minimize these risks. | |
| | |
| Date and signature of CFI | |

# Minden Wave Camp

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Concept & Design: Carl Herold

## WEATHER TO FLY

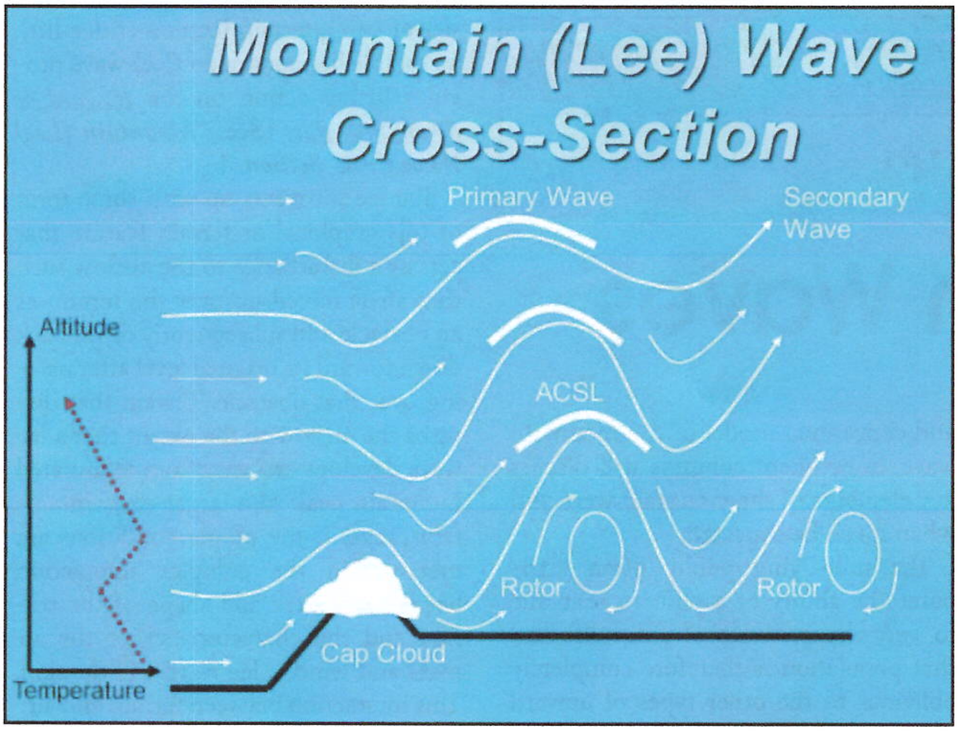
BY DAN GUDGEL

# Mountain Waves

My intent for this column was to provide some insights into the atmosphere's mechanisms for vertical motion that are useful for soaring flight. I also base my subject matter or comments on points-of-misunderstanding that are encountered from student pilots or applicants in the course of conducting glider flight checks. Despite the mountain wave being one of the significant sources of strong lift for soaring, the mountain wave conceptual model is often confused by pilots. This month's "Weather-To-Fly" will focus on the definition and conceptual model of the mountain wave. Subsequent columns will discuss key elements of the mountain wave and when it can be expected.

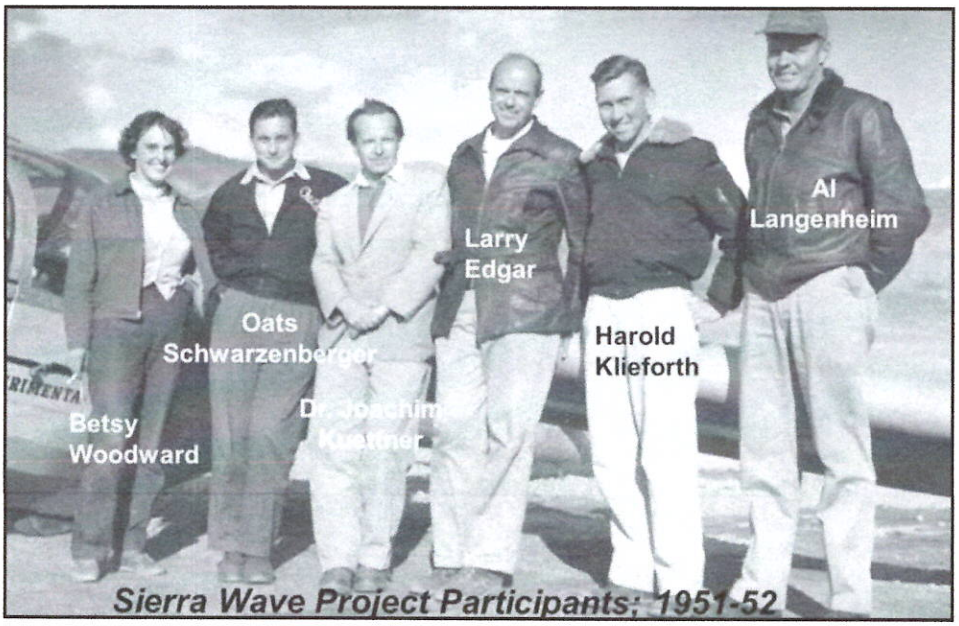
The non-flying public often attributes the ability of a pilot to soar due to *only* the presence of ridge lift and that population is therefore completely oblivious to the other types of upward vertical atmospheric motion due to temperature differential (thermals), convergence or shear lines, and the mountain or lee wave. While the interaction of airflow with terrain can support lifting air motion on the *windward or upwind side* of rising terrain features (ridge lift), an established mountain (lee) wave provides lifting action on the *leeward or downwind side*. [See: ***"Mountain (Lee) Wave Cross-Section."***]

The lee wave sets up with some form of topographical or terrain feature that acts as a disturbance to the airflow such that air is forced up over the terrain as an obstacle and subsequently drops back down toward its original level after passing over that obstacle. Terrain that disturbs the airflow to the extent that a lee wave develops can vary from an isolated mountain peak to a larger-scale mountain range. If the proper conditions are met within the complex interaction between the size and shape of the terrain and the characteristics of the air mass and wind, a lee wave will develop. This interaction between terrain and airflow can be described through a series of complex mathematical equations. I will defer any further points for mathematical description of the mountain wave to another time. Suffice it to say that the interaction of the wind veloc-




ity and atmospheric stability are crucial to the development and formation of a mountain wave. The two primary factors for development of mountain lee waves are temperature stratification and the vertical wind profile.

From a historical perspective, modern meteorology began to get a fundamentally sound understanding of the mountain wave due to the efforts and subsequent documentation of wave flights conducted around Bishop, California, under the auspices of the "Sierra Wave Project" during the 1951-1952 time period. As a young aviator and meteorologist in the National Weather Service's Reno Forecast Office in the mid-1970s I initially had no idea that a frequent office visitor from the Desert Research Institute, very unassuming, knowledgeable, kind, and quick to share his insights about Sierra Nevada meteorology, was one of the key personnel, Mr. Hal Klieforth, in that famous project. [See: ***"Sierra Wave Project Participants."***] Since the publication of the final report on the Sierra Wave Project in 1957 and the development of computer technology, there has been a continuous gain in the knowledge of mountain waves around the world




Sierra Wave Project Participants: 1951-52 through numerous research papers. Mountain wave(s) descriptions in modern research papers are often expressed in great mathematical detail along with sophisticated model simulations of atmospheric motion that includes terrain feature interaction.

For reference, I have listed some mountain (lee) wave definitions and vocabulary [See: ***"Mountain (Lee) Wave Terminology."***] Fundamentally, the development of clouds in and around a mountain wave are consistent with the same conditions needed for cloud development within the general atmosphere, i.e., a lifting action that cools air to the point where water vapor in that air condenses to its liquid state (suspended water droplets) or sublimates to its solid state (suspended ice crystals). In the mountain wave regime, clouds are often seen "capping" the airflow-disturbing mountain range or isolated peak, as "rotor" or "roll" clouds, and/or as the altocumulus standing lenticularis clouds (ACSL or "lens" clouds).

In looking at the cross-section of a mountain wave, wind speeds over the airflow-disturbing terrain must be sufficiently high to make "local" influences in the wind flow insignificant. Typically, a minimum wind speed threshold over the mountain peak or range crest for mountain wave development is in the 25 to 30 knot speed range. The wind direction should be within 30 degrees of perpendicular to the orientation of the mountain range. Because the mountain wave exists as a "standing" wave in the atmosphere, the cloud features remain stationary over a geographic point. However, the wind speed through the wave is anything but stationary. Since a mountain wave can be vertically propagating, wind speeds at the higher altitude within the wave can seasonally approach those of higher speed jet streams, i.e., often in excess of 120 knots. A lenticular cloud develops in the

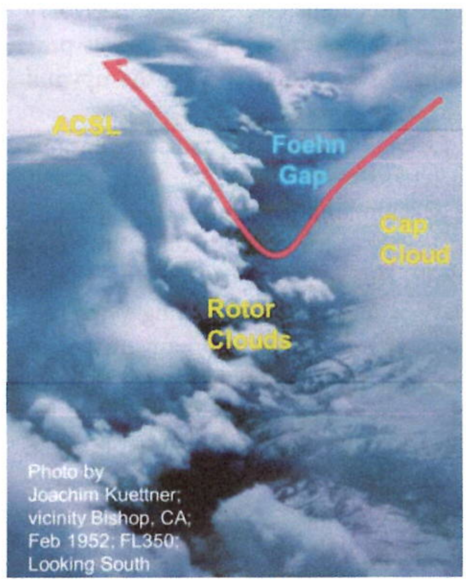


Photo by Joachim Kuettner; vicinity Bishop, CA; Feb 1952; FL350; Looking South

## Mountain or Lee Wave Terminology

**Lee Wave** – Any wave disturbance that is caused by, and is therefore stationary with respect to, some barrier in the fluid (air) flow.

**Cap Cloud** – An approximately stationary cloud, or standing cloud, on or hovering above a mountain peak or range crest. It is formed by the cooling and condensation water vapor within that air as it is forced to rise over the mountain peak or range (upslope/orographically formed).

**Altocumulus Standing Lenticularis** (ACSL) – A cloud species at the middle levels (6,500 to 20,000 feet mean seal level) of the troposphere, of which the elements have the form of more or less isolated, generally smooth lenses or almonds. The outlines of the ACSL are often sharp and sometimes exhibit brilliant spots or borders of coloration. The soaring community often will refer to this cloud type as a "lennie" and the description "pagoda cloud" is used to describe the appearance of vertically stacked ACSL clouds that have formed due to air layers of varying moisture content within a mountain wave.

**Rotor Cloud** – (Sometimes called Roll Cloud.) A turbulent, altocumulus-type cloud formation found in the less of some large mountain barriers, particularly the Sierra Nevada Range near Bishop, California. The air in the cloud rotates around an axis parallel to the range.

**Foehn** – A warm, dry wind on the lee side of a mountain range, the warmth, and dryness of the air being due to adiabatic compression upon air descending the mountain slopes.

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**Primary Wave** – The first atmospheric wave crest leeward and downwind of the mountain range or peak in an established lee wave.

**Secondary Wave** (tertiary, quaternary, etc.) – A repeating atmospheric lee wave downstream of the primary wave that has resulted from airflow over a disturbing topographic feature such as a mountain range or peak.

**Vertically Propagating Wave** – A mountain (lee) wave that may reach all the way into the stratosphere (above 35,000 feet MSL) but has few or no secondary wave crests farther downstream.

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area of rapidly rising air on the upwind side of the wave crest. With adiabatic cooling, water vapor within that rising air condenses or sublimates to visible moisture (cloud). The laminar flow in the wave keeps the cloud quite stratified but the cloud depicts the shape of the airflow over the wave crest, thus the lens shape. After crossing the peak of the wave crest, air begins a descent on the downwind side of that wave crest. Now undergoing compressional heating with descent into the higher pressure of lower altitudes the air warms enough to evaporate the visible moisture (water droplets or ice crystals) that had formed the lenticular cloud. Again, the cloud may appear stationary over a geographic point on the ground but the air is moving with high speed through the cloud.

Two types of flow mark the airflow within a mountain wave; turbulent and laminar. The rotor region is turbulent with rapid changes in both speed and direction of the airflow across the region. Typically, the rotor altitude is near the altitude of the upstream terrain crest. The dangers of the rotor region for pilots of all aircraft categories is two-fold, the existence of severe to extreme turbulence and the inconsistency of wind direction and speed in the rotor region due to turbulent eddies. Typically above the altitude of the upstream mountainous terrain or peak, the airflow in the lee wave transitions to smooth, laminar flow. Although the airflow may be laminar, wind speeds are high. Significant wind correction angles and high-indicated airspeeds are necessary for sailplanes to remain in regions providing upward motion, i.e., the upwind side of the wave crests.

One of the frequent misconceptions in regard to the mountain wave is that it develops and propagates *directly vertical over* the airflow-disturbing mountain range. This is not the case. The mountain wave is a ***downstream*** lifting phenomenon caused by an upstream mountain range or peak interacting with airflow! The reason for the misconception by Student Pilots is understandable. In a deep, vertically propagating lee wave, the wave crest tilts upwind with an increase in altitude. This upwind tilt of the primary wave crest can result in ventricular clouds marking the location of the primary wave crest at that high altitude and over the disturbing terrain thousands of feet below. A pilot flying in the lee wave, without understanding the proper conceptual model of the wave, could mistakenly assume that he is flying in some form of vertically propagated ridge lift.

Within the mountain wave regime, the cap cloud is formed due to cooling in upward vertical air motion akin to ridge lift over the airflow-disturbing mountain range or peak. Likewise, the descent of air on the downwind side of the mountain range results in compressional warming and the subsequent evaporation of the cap cloud. A Foehn Wind refers to this warming, drying air descending from higher terrain. The often impressive "wall" of clouds capping a mountain range as seen looking upwind from a downwind location is referred to as the Foehn Wall and the cloud-free area between cap clouds and leeward rotor and/or lenticular clouds is the Foehn Gap [See: ***"Mountain Wave Foehn Gap"***]. Having described the mechanism for formation and location of clouds in a mountain wave, sufficient air layer moisture is a necessary for any wave cloud development. In the absence of adequate air layer moisture and/or insufficient cooling during any wave lifting process, a mountain wave can still exist but with no visible moisture to mark wave features, i.e., no clouds! Due to severe-to-extreme turbulence in the vicinity of the wave rotor and large downdrafts downwind of the airflow-disturbing mountain range, a "blue" or cloud-free wave is extremely dangerous to the unwary aviator.

The conceptual model of a mountain (lee) wave works well for soaring flight. Like water flowing over smooth rocks in a stream bed, the fluid we know as the air in the atmosphere oscillates like the water waves downstream of those streambed rocks. With visualization of the wave conceptual model, the soaring pilot can use the uplift side of the rotor rotation thus transitioning to the lift in the laminar flow on the upwind side of the mountain wave crest. In the next issue of *Soaring*, I will show more examples of mountain waves and discuss some of the physics behind the wave development.

**References:**

"*Glossary of Meteorology*," Published by the American Meteorological Society, Edited by Ralph E. Huschke, copyright 1959 and corrected 1970.

"*Investigation of Mountain Lee Waves and the Airflow over the Sierra Nevada. Final Report*", Holmboe, J.R., and H. Klieforth, 1957, Department of Meteorology, UCLA, Contract AF 19(604)-724, 283 pp.

"*Stalking the Mountain Wave*", Published by the Alberta Soaring Council,

Written and compiled by Ursalu Wiese, copyright 1988.

"*Weather Forecasting for Soaring Flight, Technical Note No. 203*"; World Meteorological Organization; Prepared by Organisation Scientifique et Technique Internationale du Vol a Voile (OSTIV); 2009 Edition; (Mountain Wave Characteristics, detailed on pp. 40-48).

**Acknowledgments:**

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# WEATHER TO FLY

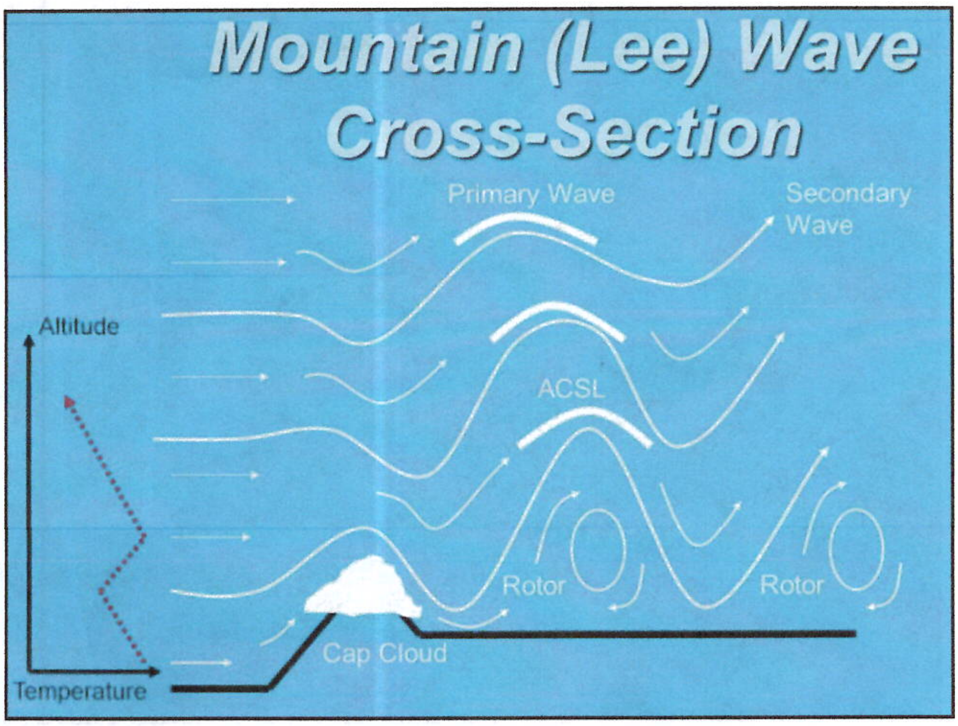
**BY DAN GUDGEL**

# Mountain Wave Forecasting

We introduced the 'Mountain Wave' as an atmospheric lift mechanism, its conceptual model, some history on its exploration, and wave terminology in the December 2011 issue of *Soaring*. Because of frequent confusion in regard to the location of the primary wave lift zone, I emphasize that the mountain wave is a "downwind" lift phenomenon, i.e., the upward vertical motion associated with the primary wave for purposes of soaring flight is downwind of the disturbing mountain boundary to the mean wind flow.

The conceptual model of the mountain wave **[See Diagram #1: *"Mountain (Lee) Wave Cross-Section"*]** is quite sound and has been known for several decades. What has changed is the power and speed of technology to run complex mathematical equations that enable meteorologists to graph and provide visualizations of atmospheric air motion within a wave. Deferring discussion further on the physics of the mountain wave to a future article, I wish to itemize some of the "forecast rules" that have been empirically derived by pilots and soaring meteorologists. There is nothing-new under-the-sun (pun intended!) in regard to these simple rules for forecasting a mountain wave. In fact, parameters that would lead to a mountain wave were posted with a date in the late 1950s in the old Riverside (California) National Weather Service (NWS) Office of Agriculture and Fire Weather.

Meteorology texts are consistent in their listing of the parameters necessary for the development of a mountain wave. Physically some favorably shaped topographic feature is needed to disturb fast moving air. Typically, a terrain feature that can establish a wave is presumed to be a mountain range but it can vary to that of a single mountain peak. The minimum threshold wind speed over the top of the mountain boundary varies among textbooks but it is generally stated to be in the 25 to 30 knot range. To provide conditions favorable for a wave to exist over long distances, a long mountain range of nearly constant height aligned nearly perpendicular to the wind flow is necessary to have the air go up and over the terrain rather than flow around the disturbing boundary. Within some reference sources, the angle of the mountain range to that of the wind direction may vary up to +/-30 degrees from perpendicular for a wave to still be feasible. The shape of the mountain range is also very important for optimum mountain wave development. A shallow angle of terrain increase providing airflow uplifting is necessary up to the mountain range crest; and then marked by a steep decrease in the terrain height from that crest. The air mass wind speed needs to be sufficiently fast such that turbulent eddy wind speeds are negligible when compared to the overall wind speed over the mountain crest. Upon reaching the top of the mountain range the terrain "drop-off" leads to a katabatic wind, i.e., wind blowing down an incline. As the air descends, it rapidly warms due to compressional heating in response to the higher pressure at lower altitudes. The atmosphere's response to this heating and rapid loss of altitude in the wind flow results in a "hydraulic jump" and initiates the mountain wave. While the terrain features sufficient to develop a mountain wave are numerous around the United States, the most classic terrain feature is the "Sierra Front" along the California-Nevada border. **[See Satellite Photo: *"Full Range Sierra Nevada Wave"; 6:15 PM PDT, June 15, 1999.*]** The escarpment or rapid drop from the high Sierra Nevada and Tehachapi Mountain crest eastward to the high desert floor provides arguably the best terrain conditions for mountain wave development in the country. Established airfields such as the Minden Airport south of Reno, Nevada, or Bishop Airport, Inyokern Airport, or California City Airport in California are positioned frequently beneath mountain waves. Again, any mountain barrier can

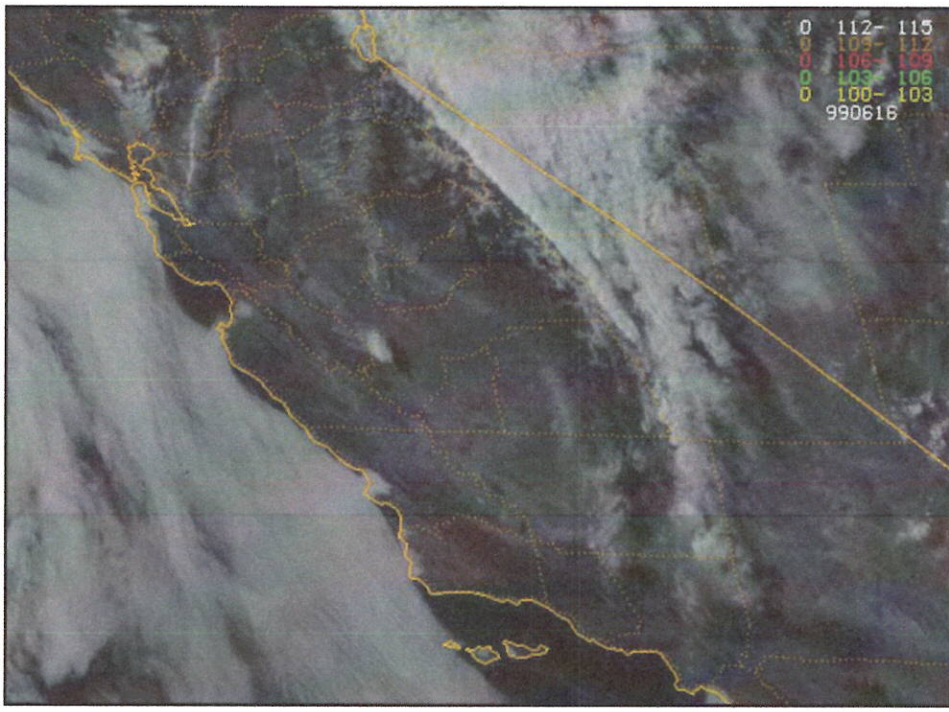


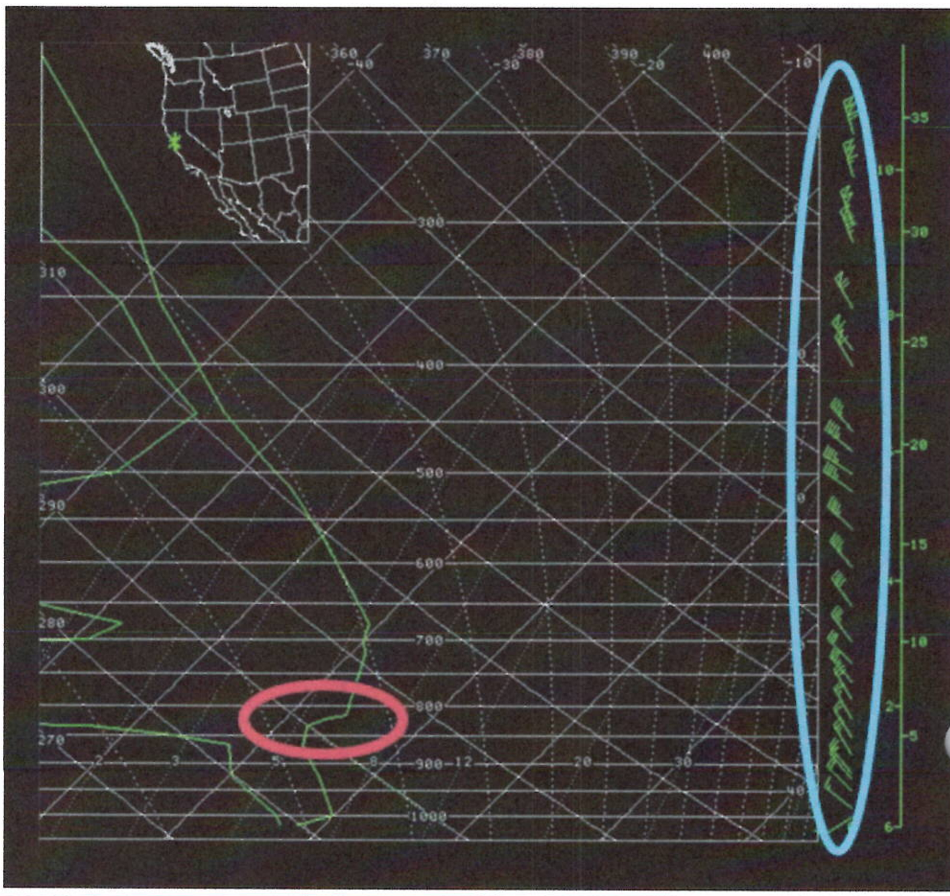
develop mountain wave action whether it is a range such as the Sierra Nevada or a single peak like Mt. Shasta in Northern California.

Intuitively, the faster the wind speed then the greater the uplift in a mountain wave. The fastest wind speeds occur in upper air jet streams (relatively strong winds concentrated in a narrow stream in the atmosphere). By definition, a wind speed of 50 knots at the 500-millibar pressure level (approximately 18,000 feet Mean Sea Level) is a minimum threshold for defining a jet stream. Despite the fastest winds speeds occurring in the jet stream, the presence of too much atmospheric uplift results in widespread cloudiness when the jet stream is directly overhead. Therefore, the best mountain wave conditions are often ahead of an approaching trough of low pressure before the arrival of its supporting jet stream, or just south of the axis of the jet stream (in the Northern Hemisphere). The presence of too much wind shear will not allow mountain wave development. Therefore, some degree of consistency is necessary in wind direction with a gain in altitude through the troposphere, the lower portion of the atmosphere, along with some degree of wind speed consistency. With less frictional influence from the earth's surface, wind speeds typically increase with a gain in altitude. **[See Diagram #2; *"Mountain Wave Upper Air Sounding"; Oakland Raob; 4 AM PST, March 16, 2001 (blue circle around the wind speeds)*].** This referenced upper air sounding was upstream of a large and sustained mountain wave in the lee of the Tehachapi Mountains.

It is known that "stable air" is also a necessary ingredient for mountain wave development. However, that stable air needs to be positioned in an atmospheric mid-level layer approximately at or just above the altitude of the mountain range crest or peaks. Remember that any isothermal layer (no change in temperature with a gain in altitude) or temperature inversion (temperature increases with a gain in altitude) is deemed a stable atmosphere by definition. [Referencing the ***"Mountain Wave Upper Air Sounding"***, note the ***red circle*** at a mid-level stable layer around 6,500 feet MSL]. Recalling our aviation meteorology training, there is a temperature inversion associated with any frontal passage. Therefore, the approach of a warm front or passage of a cold front as depicted on surface weather charts conveys the expected arrival or presence of some form of temperature inversion aloft due to the fronts. The presence of frontal boundaries contributes to meeting the conditions for mountain wave development when combined with terrain and other meteorological parameters.

One last issue in regard to mountain wave flying that I wish to address is that of cloud cover. If the atmosphere contains a deep layer of moist air then the likelihood of getting Visual Flight



Rule (VFR) conditions is not likely to occur due to widespread cloudiness. Aforementioned, the best mountain wave conditions are often ahead of an approaching jet stream, or just south of the jet stream axis, so that the uplift and resulting widespread cloud development associated with a trough of low pressure does not remove VFR flying conditions. If the observed or forecast atmospheric sounding, on the other hand, shows well-separated vertically spaced layers of moist air then VFR conditions may exist so that the wave can be accessed for soaring flight. The absence of moist layers and resultant clear skies does *NOT* mean that a mountain wave may not exist… only that it may be "blue" or unmarked due to a lack of cloud features. The "blue wave" is one of the most threatening of meteorological situations. Not being marked by wave cloud signatures, lenticular or roll clouds, the presence of large downdrafts on the lee side of mountains and/or the extreme turbulence associated with mountain wave rotor poses danger to an unwary aviator.

Therefore, in summary and courtesy of decades of empirical knowledge, here are some "guidelines" for the development of a mountain wave:

1) Terrain: Ideally some degree of asymmetry for a high mountain range or peak with a "flat" windward slope and a steep leeward slope;

2) Wind direction perpendicular (or nearly perpendicular) to the mountain range. Typically the range is a north-south oriented mountain range resulting in a perpendicular boundary to the mid-latitude westerly or zonal wind flow;

3) Wind direction that remains consistent in direction or only changes slightly and smoothly with an increase in altitude;

4) Wind speed that smoothly increases with a gain in altitude starting with wind speeds in the 25 to 30 knot range over the mountain range crest or peak;

5) Optimum wave development occurs close to the axis of the jet stream or highest wind speeds aloft. Minimum winds speeds at the 500-millibar pressure level (approximately 18,000 feet Mean Sea Level) are close to 50 knots;

6) A frontal inversion that provides for a mid-level stable layer close to the crest level of the mountain range or peak; and,

7) Layers of moisture rather than a deep layer of moisture over the mountain range that provide some "marking" of the wave with cloud features.

In the next issue of *Soaring*, we will continue discussing mountain waves and describe some of the physics behind the wave development.

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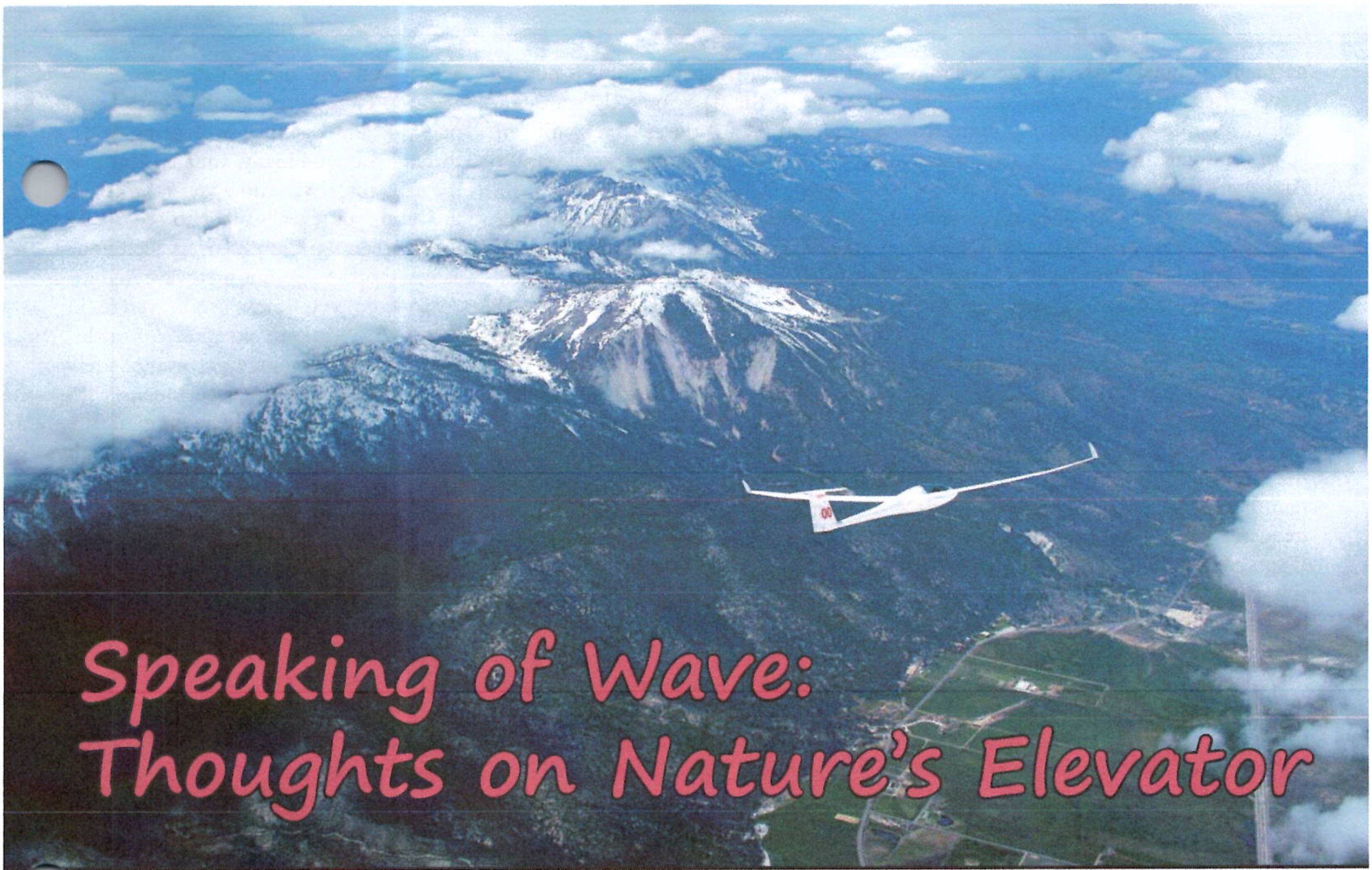


# Speaking of Wave: Thoughts on Nature's Elevator

**By Fred LaSor**

*Reprinted from SoaringNV's 2011 Wave Camp Binder*

Mountain Wave. Lee Wave. Sierra Wave. Standing Wave. Call it what you will, the right combination of topography and atmospheric conditions will create some of the most dynamic soaring conditions a pilot can experience. And although it happens year-'round, winter and spring create the most wave days in northern Nevada – a perfect complement to our traditional thermal soaring during the summer months.

Mountain wave occurs on the lee, or downwind side, of whatever obstacle is generating it; hence the name "lee wave." Minden has what it takes to create reliable wave, and we believe we fly in the world's "sweet spot" for wave.

### What Makes Wave?

Mountain wave needs four conditions:

1) A stable air mass,

2) Wind speed of a certain value that increases with altitude,

3) An obstacle to fall over and that obstacle should be...

4) Nearly perpendicular to the wind.

Perhaps the most important feature for Minden is the obstacle, which in our case is the Sierra Nevada escarpment. The eastern slope of the Sierras is steep, oriented essentially north/south, and extends for several hundred miles. This steepness means the air "tumbles" over the top with a great deal of force. The north/south orientation of the mountain range means it lies perpendicular to the prevailing westerly, and the continuous run means pilots can anticipate a steady source of lift from Herlong, 100 miles north of Minden, to Inyokern, 350 miles to our south.

People sometimes envision wave as an undulation created by some barrier (a mountain ridge, for example) "pushing up" on the moving air. This is how ridge lift is created, but it is really the falling action that results in the up and down motion, we recognize as mountain wave. Think of standing waves in a river: it is the falling action that creates the wave below the dam or the submerged log. Similarly, it is not the air being pushed up by the Sierra ridge that creates our wave – it is the air falling down the lee side of that ridge, where it is heated (by land temperatures, katabatic action, and compression). This is why we think of the steepness as being more important than the sharpness or height of the ridge to our west.

Stability adds coherence to the wave. It is not impossible to see wave at higher altitudes when there are thermals (a creation of unstable air) down low in the Carson Valley, but the very strongest wave is usually a product of stable air. On days when we see both stable and unstable air during the warm months we anticipate the thermal activity will break up the wave. Our experience is that the strongest lift is from stable wave or unstable thermals – not a mixture of the two.

### Where to find lift

If conditions for wave are good, we want to determine where to find the rising band of air, also referred to as the lift band. This is a line of lift that lies parallel with the Sierra ridge about three miles east of the mountains. Other locations will have their own reliable lift line, normally parallel with the geographic feature that triggers it, and once that line is identified, it is reliably going to be in the same location from day to day. And don't forget that we commonly see secondary and tertiary lines of lift over our valley, with the secondary being just a little east of the airport and the third line being at the base of the Pine Nut Mountains.

The actual distance from the mountains to the primary wave is a function of wind velocity at the ridge top – higher wind speed will move the lift further from the mountains. We in Minden expect to find the first lift band west of the airport, frequently right over U.S. Highway 395. If you are planning a long flight in wave, you will not go far wrong if you look for the lift band very close to that highway the entire length of your flight.

Depending on wind direction and speed, you might find lift broken into smaller "wavelets" that do not parallel the ridge. A wind from a more southerly direction (190° or 200°) might trigger wave off Job's Peak that shows up in patches between the airport and Heavenly ski area, often with a northwest/southeast orientation. In addition, a wind from a more northerly quadrant (300° or 310°) might trigger wave off Genoa Peak or the mountains around Spooner Summit, oriented northeast/southwest. It is instructive to remember that tall peaks not associated with mountain ranges (Mt. Shasta is a good example) can generate wave on any side depending on the wind direction.

Try to get a feeling for wind direction at altitude before you tow. Ask your tow pilot, other glider pilots, or examine the lenticular clouds in the valley. An experienced tow pilot will usually be able to tell you where and how high you'll have to tow to find reliable lift, especially if it is not the first tow of the day. Some days a 9,000' tow (4,500' AGL) toward Heavenly will put you in wave; other days you'll want to tow to 10,000' over Jack's Valley.

In a classic wave situation lenticular clouds will line up parallel with Runway 34, more or less over the airport, and extend to Reno (or beyond) in the north and to the end of the Carson Valley to our south. It is common at this point (just a little south of Job's Peak) for the primary wave to jump east several miles as the Sierra escarpment also moves east by Lake Topaz.

We normally try to tow to the leading (western) edge of lenticulars to place ourselves in the climbing side of the cloud. The cloud itself appears to be standing still, but as you get closer, you will see it forming at the leading edge as the moist air reaches the dew point, and dissipating at the trailing edge as the air descends below the condensation level.

Rotor tow is something you will remember for a long time. You will likely find it hard to maintain position behind the tow plane as it abruptly climbs and descends in front of you. Be patient: in about two seconds, you will find yourself in the same air that just bumped the Pawnee up or down 100 feet. The more daunting feeling is the severe rolling action you will occasionally encounter. Here again, strong control pressure and patience will bring you through safely. Finally, your typical tow through rotor will show you more slack line than you ever wanted to see, so do brush up on slack line recovery technique as you prepare for your first wave flight.

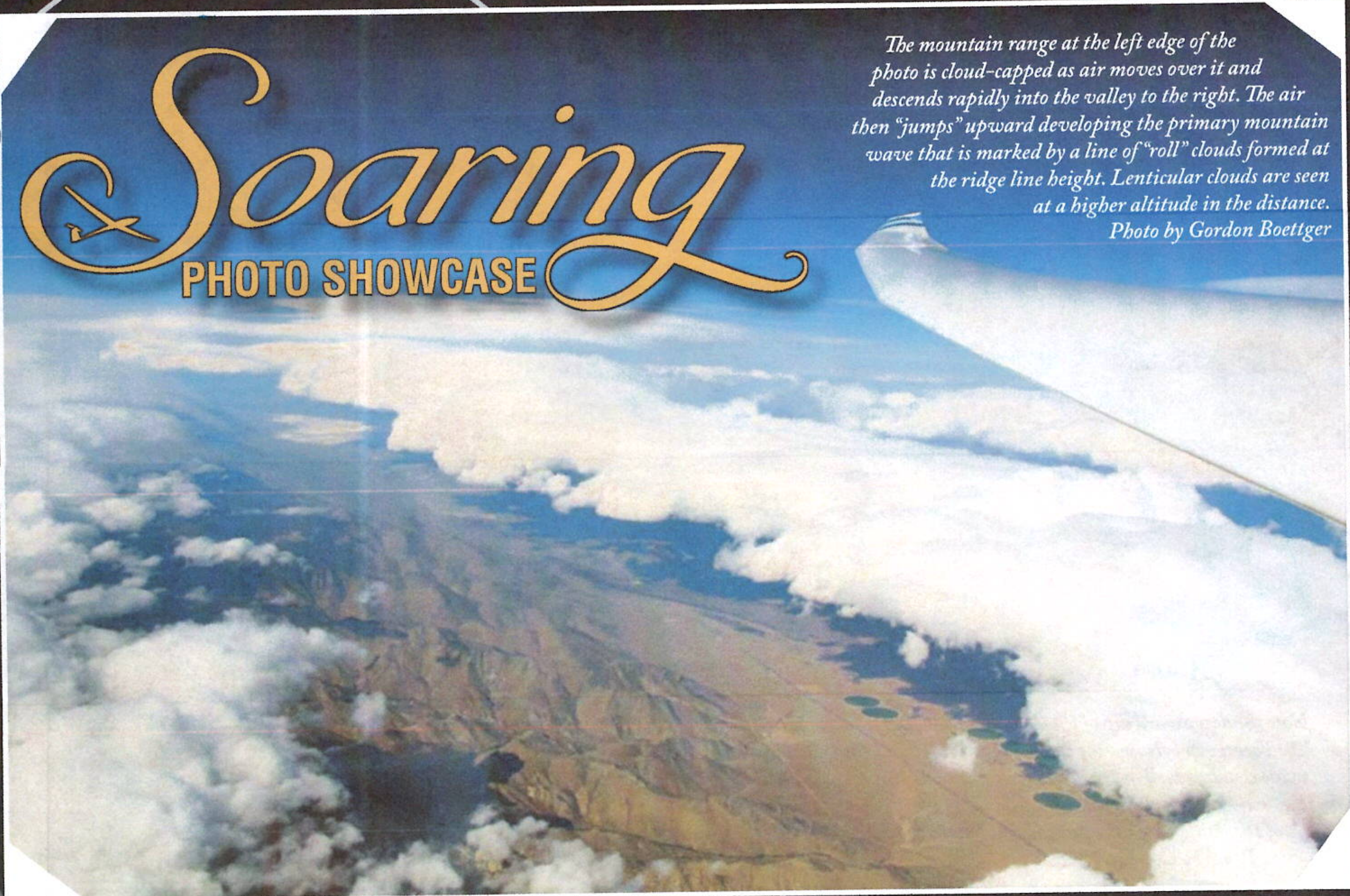
How do you know when you're in wave? As with chickenpox or rattlesnakes, you'll recognize it immediately the first time you come face-to-face with it, only your reaction will be dramatically positive. To begin with, the tow through rotor, which has been rowdy, all of a sudden it feels like you're on an elevator in a high-rise building. The air will probably be the smoothest you've ever flown in, with 600 FPM climb common and a pegged vario needle not at all unusual. Looking over the nose will give you a definite sensation that the close mountains are dropping away below you as you climb without turning at all. If you are in laminar flow and the climb rate is not above 500 FPM, you are probably not in the strongest lift. Our advice would be to fly faster and move west to see if the lift increases. Chances are good you're being blown east (downwind) and need to penetrate into the wind to find the strongest lift.

*Continued on page 32*

*Opposite page: Oscar Oscar (Devin Bargainnier) over Minden at 24,000'. Photo by Fred LaSor*

*Right: Headed home to Minden after a long day in wave. Lots of moisture below, and cap cloud spreading out into the Carson Valley. Cloud can fill in below you very quickly! Photo by Hugh Milne*

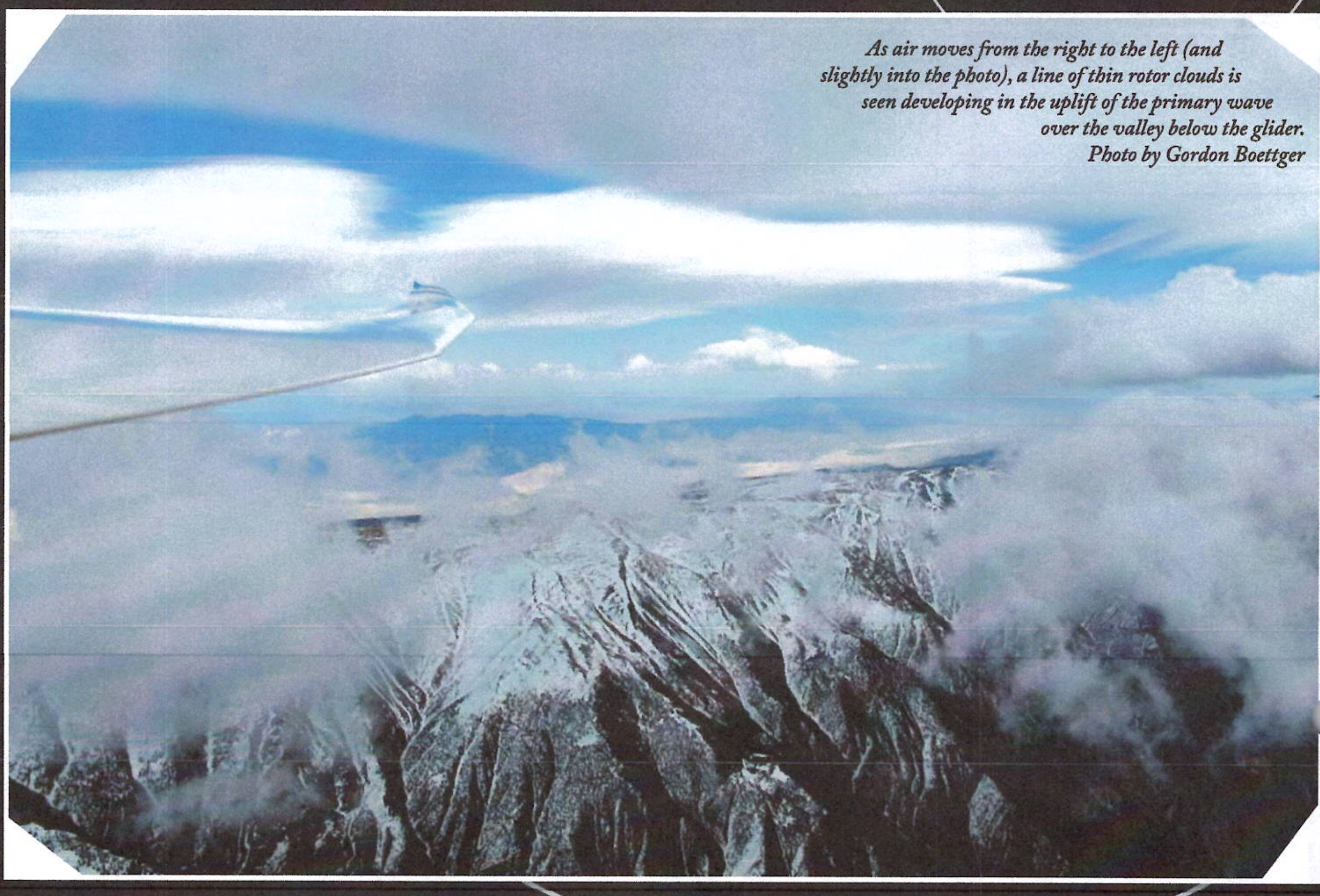
# Soaring PHOTO SHOWCASE



*The mountain range at the left edge of the photo is cloud-capped as air moves over it and descends rapidly into the valley to the right. The air then "jumps" upward developing the primary mountain wave that is marked by a line of "roll" clouds formed at the ridge line height. Lenticular clouds are seen at a higher altitude in the distance.*
*Photo by Gordon Boettger*

*Airflow is moving from the right to the left. The line of clouds at the ridge level marks the primary wave at that altitude. Note the smooth top of the cloud line as the airflow is laminar.*
*Photo by Gordon Boettger*

*Note the downward dip of the clouds as air moves from right to left. The Foehn gap between the cloud-capped ridge and the primary wave clouds is well-marked. A lenticular cloud line is seen above the "roll" or rotor cloud line thus providing visual markings of the rising air in the primary mountain wave.*
*Photo by Gordon Boettger*



*As air moves from the right to the left (and slightly into the photo), a line of thin rotor clouds is seen developing in the uplift of the primary wave over the valley below the glider.*
*Photo by Gordon Boettger*

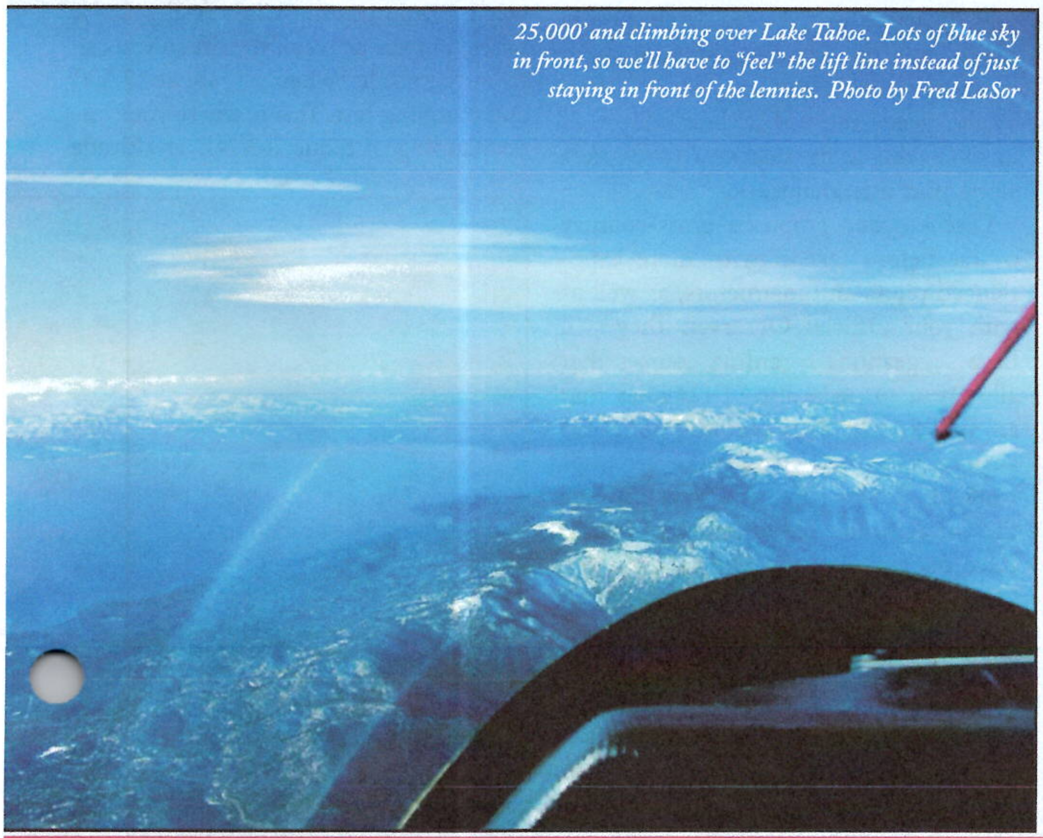
As you climb above the level of the lenticular cloud, you will want to stay on the upwind side of the cloud. In addition, since wind speeds increase with altitude you will need to increase your airspeed merely to stay in the same place over the ground. If you don't concentrate on staying west of the lennie, you will gradually find yourself being moved back to the east and into the cloud itself. Moreover, should you ever turn east chances are good you will be blown through the back of the wave window if you are up that high or certainly well away from the airport if you are below the window.

**Blue Wave**

Our escarpment creates Wave; lennies are created by moisture. It is possible to have wave without lenticulars because the air has lost its moisture climbing the Sierra Nevada range between the Pacific Ocean and us. In fact, even on days with plenty of moisture it is common to see a line of clouds on the top of the Sierras (the "cap cloud"), then a space of blue east of that (the "Foehn gap") before the first roll cloud or lenticular occurs. Foehn is a Swiss word describing a dry wind, and the gap that bears its name is an illustration of air losing its visible moisture – first by being cooled, then by warming – as it falls into the valley downwind of the Sierra escarpment. The lesson to take from this explanation is that wave can occur without cloud, and we frequently experience this "blue wave" when the moisture has been stripped out of the air.

The advantage of flying on a blue wave day is that you don't have to worry about cloud clearance and visibility; the disadvantage is that you don't have lenticulars to mark the lift line. If you will think of the lift as being a function of the air falling over the crest of the Sierras you will have an idea of where it should occur over the valley east of the barrier creating it. You can fine tune this image of the lift line by flying east and west approximately over U.S. Highway 395, but remember: the wind is always pushing you east, so the chances are that you need to fly west to get into the best lift.

The point is lenticular clouds are an indication but not an absolute precondition of wave. When atmospheric conditions are right for mountain wave, we will likely experience it whether we see those clouds or not. Experienced pilots generally prefer a day with lennies, both to show us where the lift should be and because let's face it: they're downright beautiful! However, if the wind is the right direction and speed you should be trying for wave even if there are no lennies in the valley.



*25,000' and climbing over Lake Tahoe. Lots of blue sky in front, so we'll have to "feel" the lift line instead of just staying in front of the lennies. Photo by Fred LaSor*

**Flying for altitude in the Wave Window**

If you are flying for an altitude diamond, you will need to gain 16,405' above your release point. Obviously, we need to know where your release point is on the GPS trace. The most visible means of marking that is to make a 360 degree turn when you release so we will see a sharp circle (smaller than you normally fly on tow) at the beginning of soaring flight. Our wave window extends to 28,000' so you can tow above 11,000' and still have space for a diamond climb. You might consider giving yourself a little challenge, though, by releasing as soon as you feel decent rotor lift and working it into laminar flow. Diamonds have been flown from Minden with a tow to less than 8,000' (≈3,000' AGL.)

If your goal is a diamond altitude, you'll be climbing into one of the three wave windows above our valley. These windows are precisely defined "boxes" of airspace approximately 15 miles north to south and 5 miles east to west. Oakland Center likes to open only one at a time and we find Minden West to be the most useful as the primary wave is usually found there.

A local instructor will brief you on the procedure we use to open the window. If you are the first pilot into the window that day, please establish yourself in laminar flow before requesting the window. Somewhere around 12,000' you should definitely be solidly in wave and have an indication of how soon you'll reach 18,000'.

Air Traffic Control does not want to hear from individual pilots. Call Soaring-NV on 123.05 with information about current altitude and how fast you're climbing, and they will arrange with Reno and Oakland Center to open the window and call back to let you know. You should also be prepared for the possibility that air traffic is currently in the airspace crossing through the window so there will be a delay while that clears out.

Use of the Wave Window comes with certain responsibilities and you will be briefed on these. Most important, obviously, is that you need to stay inside the lateral boundaries of the window so separation can be guaranteed from other air traffic. You will also need to know who to communicate with, on what frequency, and when. All this information will be included in your preflight briefing and you must adhere to the rules so we can continue to have access to the window.

A line of lenticular clouds oriented northwest to southeast, triggered by winds from the southwest. Photo by Fred LaSor

## Staying Safe in the Wave Window

You must stay clear of clouds inside and outside the wave window, just as you do on normal VFR flight. If it appears you are approaching cloud you should probably consider moving somewhere else and descending because increasing moisture can close the clouds below you very quickly and you do not want to be caught on top.

You should also anticipate that your exhaled breath will condense inside the canopy when you get to about 22,000' and the higher you go the worse this will get. Do NOT try to clear this with a glove or a rag: you will only make it worse. The best action you can take is to direct outside air from your vent window on a small patch of the canopy and to try to keep it clear.

Another consideration is reduced VNE at altitude. The issue here is flutter, which is a function of True Air Speed, not Indicated Air Speed, and so decreases as you climb. You need to know what your VNE is at various altitudes and not exceed that value while high above the Carson Valley. Your glider ASI should be marked for VNE at altitude: make sure you observe those limits. In addition, if you have any question about this talk to an instructor so you understand what's at stake.

## Flying Long Distances in Wave

The lift we use for diamond altitude flights can also be used for very long cross-country flights. These are either "yo yo" flights up and down the face of the Sierras or a straight out downwind dash. Occasionally they include a little of both: a long flight south along the Sierras, back to the north, then downwind to the east. Whatever you choose there is a lot of advance preparation needed; including knowing landout locations if you are unable to return to Minden, dressing warmly enough to withstand hours of sub-zero temperatures, navigation, and aero medical factors and how to recognize lift lines as you jump downwind from one to the next. Remember to carry a SPOT tracker and have it turned to the breadcrumbs feature so ground crew will know where you are as you progress on course.

The north/south flight along the Sierras will always involve strong crosswind, so ground track and heading differ quite a bit. Obviously, there is a wind speed at which heading will be so far off track that forward progress is prohibitively slow. The ideal wind speed appears to be somewhere in the area of 50 MPH. Wind speeds above that threshold result in you having to fly "sideways" to progress along your intended track.

Discuss your proposed cross-country course before takeoff with more experienced pilots and instructors, as well as with your Official Observer. They will have suggestions regarding courses that allow you to make use of lift lines that are well known. They will also point out airports you can land at if the lift stops working. Make sure you have entered the correct information into your Flight Recorder and that your Official Observer knows your intended course, especially if you are flying for a badge that requires advance declaration.

Finally, remember that climbing above 18,000' MSL outside the wave window will disqualify the flight for a badge or record unless you have a Letter of Agreement with Air Traffic Control Centers responsible for the airspace you will be in. If climbing through 18,000' sounds fanciful, rest assured it is remarkably easy to do and you need to guard against it. One way to avoid busting Class A airspace is to feel out the edges of the lift so you can fly out of the lift when you are at 17,500' and climbing fast. This is where your understanding of reduced VNE at altitude

22,000' above Minden with extensive rotor cloud marking the lift line. Photo by Fred LaSor is important: you cannot merely point the nose down and fly at sea level Red Line when you are at 18,000'.

If you are flying north and south parallel with the Sierras, you will have airspace considerations. For most of your flight north of Carson City, you will need to be in communication with the NorCal controllers who sequence air carriers into Reno International Airport. Pilots and instructors who fly wave out of Minden regularly have worked extensively with Air Traffic Control to let them know how and where gliders will be, and we have a good working relationship we want to preserve. Please follow our guidance on this aspect of your flight.

In addition, if you go more than 60 miles to the south you will be in airspace managed by Joshua Approach and will be talking to them on a different frequency and squawking a different transponder code. By common agreement, gliders change squawk codes at the north shore of Mono Lake. It is your responsibility as PIC to familiarize yourself with these details before departure.

**Getting out of the Wave**

Descending out of strong wave is sometimes harder than you anticipate. As the day progresses and the wave spreads out you might find there is lift everywhere you fly. You have two options: fly over the lenticulars if you are high enough to clear cloud and descend in the sinking air on the east side, or fly to the south end of the Carson Valley, where the wave usually jumps 10 miles east and there is a non-wave area to descend. We frequently begin our descent headed south over the town of Genoa, flying fast and with spoilers out, toward Woodfords and Markleeville. Usually about the time, you are even with Job's Peak you'll be running out of lift and can slow yourself as you fly into the turbulence associated with rotor.

Plan to turn east when you are below the lenticular cloud and fly under it. About the time, you reach the back edge of the cloud you'll fly into the descending part of the wave and will be coming down at something like 2,000 FPM. Make a large circle to the east side of the airport and plan your flight path so you can fly over the center of the airport to check the wind tee. Listen to Minden AWOS (119.325) and plan to fly a high, fast pattern so you have plenty of altitude and speed to fly through the wind gradient as you get near the ground. You should be comfortable with the idea of shedding your excess speed and energy in the last few feet before you touch down so you make a normal landing. Do not get slow on final as the wind gradient will drop your wind speed even further leaving you too slow on short final. Wind speeds on the ground will likely be high enough that you will experience very short ground roll, so landing long is not a problem.

**Get Home before Sunset**

Finally, you need to return to the field by official sunset, which appears in the daily weather forecast. Unlike thermal lift, wave lift occurs independently of solar heating and so can be present any time of the day or night. If you are flying late in the day you will still be in full daylight at altitude when shadows are filling the valley below you, especially because the mountains will block late afternoon sun. Note official sunset before you depart so you can be on the ground before dusk. Landing after sunset is illegal, unsafe AND will result in invalidation of a badge or OLC claim. Remember to carry clear glasses with you if you normally fly with prescription sunglasses – you will likely need them when you return in the late afternoon.

*Left: Lennie over Carson Valley. Lasor photo.*

*Below: Climbing in solid wave. Photo by Brad Bullion*

**The Flight's not over until the Glider is tied down**

Mountain wave frequently precedes a cold front with all the weather considerations such a front brings: rain, snow, high winds, and clouds. As the front approaches, weather conditions often deteriorate. It is not uncommon for the wind on the ground to be benign when you depart and to have picked up speed and changed direction when you return. If the rotor is touching down when you land, the wind will sometimes be 180° opposite from the wind only a thousand feet higher. Checking with AWOS while still 2,000' high will let you know what the wind is doing on the ground.

Strong winds on the ground mean you might have to stay in the glider "flying" it on the ground while you wait for ground crew to secure it so you can exit the cockpit. Securing a glider in high wind is not a one-person task.

If this is a badge flight, you will want to secure the Flight Recorder and get it to your Official Observer to be downloaded. S/he must attest with his/her signature that he has maintained custody of the secure file since your landing. If you will be submitting the flight trace to the OLC, you will want to upload the file before the end of the day.

We who fly out of Minden think our mountain wave is the best in the world. You can find wave elsewhere, but nowhere as close to the airport as here, and few places that have as long a continuous run. We think of wave as Minden's special treasure and while we're happy to share it with other pilots, we hope you'll take advantage of our experience to make your flying safer.

*Fred LaSor moved to Minden in 2005 for the soaring. He is a Master CFI-G and was a co-founder with Laurie Harden of SoaringNV. For the past five years, he has towed glider events at the Hilton Ranch and for Hugh Bennett and Gordon Boettger. He also instructs with the Civil Air Patrol.*

# WEATHER TO FLY

BY DAN GUDGEL

# Mountain Wave Comments

The past couple of installments of "Weather To Fly" has concentrated on the lee or mountain wave phenomenon: 1) defining it; and, 2) guidelines to assist in anticipating its development. Before continuing with some of the more academic aspects of the mountain wave, I would like to simply address some miscellaneous aspects of the subject.

Previously mentioned, a "classic" lee or mountain wave is an atmospheric lift phenomenon providing uplift for the soaring pilot in the downwind area of a mountain range (as a disturbing boundary in the face off a moderate to strong wind). But even a single mountain peak can act as that required topographic feature needed to establish a "local" wave under the right circumstances ***(See Photo #1: Mauna Kea Wave; Photo courtesy of Woody Woods)***. All of the wave characteristics, including cloud features, can be present in just a small geographic area: cap cloud, Foehn gap, rotor cloud, and altocumulus standing lenticularis (ACSL) or "lennies." Under what circumstance airflow decides to move vertically in response to the lone mountain peak and develop a mountain wave rather than simply flow around that peak horizontally cannot be described by this author. However, the phenomenon does exist and if the meteorological situation seems to fit wave development soaring pilots should remain aware of the possibility of a "lone peak" wave even if the topography doesn't look "classic." Along the thought *of "lift is where you find it,"* lee wave action may simply exist at the lowest levels of the atmosphere and not extend to high altitudes. On many occasions in the Tehachapi Valley of Interior South-Central California, a moderate-to-strong low-level southeast wind flows across a NE-to-SW oriented 1000-foot high ridge just southeast of Mountain Valley Airport. Departing with glider-in-tow into the wind on Runway 09, I have often utilized a "wave bounce" climbing out on the crosswind leg to enhance the tow plane climb rate and subsequently soared in the same area after release from tow as a glider pilot. The "wave bounce" does not extend typically to very high altitudes, but the effect has been observed up to 3,000 feet AGL and often times only a primary wave is usable for soaring flight. While not objectively measured by instrumentation, the line-of-lift runs parallel to the mountain ridge and a small, low altitude atmospheric lee wave appears to be the only mechanism for such lift. Remember that the atmosphere is a fluid so visualizing airflow behavior like one might see water wave behavior downstream from a smooth rock in the stream is advantageous for a soaring pilot to find lift areas in mountainous terrain.

*Mauna Kea Wave*

While focusing on the features and airflow action associated with the mountain wave, descriptions have concentrated largely on the primary lee wave. However, it is important to remember that the sinusoidal action of the lee wave, if no other terrain influence interferes, can lead to multiple wave crests (and troughs) downstream before the action dampens. In the open Mojave Desert southeast of the Tehachapi Mountains, multiple wave crests are often seen when the lee wave develops. But anywhere in the country that frequently supports mountain wave development, multiple wave crests are often marked by parallel lines of clouds ***(See Photo #2: Stratocumulus Standing Lenticular Clouds over the Southwest San Joaquin Valley)***.

While I have addressed the mountain wave as a meteorologist, I feel compelled to mention a few things from a flight instructor point-of-view in regard to safety considerations:

Per the Federal Aviation Regulations, Title 14, Part 91, visibility and cloud clearance requirements increase in Class E airspace above 10,000 feet mean sea level (MSL) in the contiguous United States. Mountain wave altitudes above 10,000 feet MSL are commonplace and glider pilots operate under Visual Flight Rules (VFR). At those altitudes, the horizontal distance from any cloud feature is mandated to be one statute mile for VFR flight. However, the ability to use lift provided by the mountain wave may not be available more than one mile in front of the rotor/roll clouds or lenticulars. While I am <u>*not*</u> endorsing or encouraging pilots to break this regulation to accomplish soaring flight, I do wish to put the strongest emphasis on *why* that regulation is in place and the safety threat that results from violating cloud separation requirements. Aircraft above 10,000 feet MSL are allowed to fly above the 250-knot speed limit up to Mach One speed. Therefore, a pilot loitering "close" to a lenticular in soaring flight could near instantaneously find themselves in a mid-air collision with any one of a number of fast-moving jet aircraft legally flying under Instrument Flight Rules. I admonish anyone violating this very practical rule to consider the aforementioned situation and avoid the risk of disaster from such a violation!

*Stratocumulus Standing Lenticular Clouds over the Southwest San Joaquin Valley*

The loss of visual references for VFR flight is ever-present in mountain wave conditions in a couple of ways. Since the presence of cloud features is dependent upon a moist layer of air or sufficient moisture to form clouds in the uplift of the wave, cloud features develop and dissipate as the moisture field varies. An unobservant pilot flying in unrestricted visibility below or abreast of clouds might suddenly find that an undercast quickly forms trapping the airman in VFR-on-top conditions. Since cloud layers can form quickly in the mountain wave, soaring pilots must respond at the first indications of cloud layers developing below them to plan for sufficient time to descend in a safe manner. Further threatening loss of visibility is that of canopy frost! Air temperatures aloft in a winter mountain wave will easily reach 30 degrees below zero Celsius at altitudes above 18,000 feet MSL. In combination with the super-chilled canopy from this very cold air, moisture from a pilot's respiration and perspiration inside a glider cockpit results in sublimation and frost on the glider canopy inhibiting visibility for VFR flight in the least; and in the worst, frost obscures all outside visual references. Be prepared for canopy frost in wave flight by constructing "clear panels" that will keep sections of the canopy clear for VFR flight.

Wind speeds aloft increase with a gain in altitude but the mountain wave is essentially a stationary phenomenon. A pilot will need to increase his airspeed to remain in proper position in the wave as he/she climbs. Aircraft "Never Exceed Speed" (Vne) design limitations are established to avoid aircraft control surface flutter and are a function of true air speed (TAS). With flight at much higher altitudes comes much faster true air speeds and the threat of control surface flutter. Consider even a wave flight reaching a "modest" altitude of 18,000 feet MSL. Applying the old "rule-of-thumb" of a 2% increase in TAS per 1000 feet of altitude gained for the same indicated air speed (IAS), a sailplane flying at 100 knots IAS would have a TAS of 136 knots. Therefore, wave conditions subsequently flown in very high winds aloft pose a threat to the sailplane due to the high TAS experienced in soaring such a wave. Strong winds aloft are often prevalent in the deep winter months when the Jetstream is farther south and speeds are frequently in excess of 100 knots at altitudes above 18,000 feet MSL. Pilots utilizing "wave windows" for soaring altitudes above 18,000 feet must especially be cognizant of their aircraft design speed limitations in relationship to TAS. ☛

Often mentioned in my post-check flight discussions with check ride applicants, one of the ironies of gliding is that our "simple" soaring aircraft puts a pilot into a harsher environment, aeromedically, than that of a "complex" airplane that is altitude-limited due to carburation. Therefore, the prudent and safe soaring pilot must "think ahead" of the aircraft and be prepared for the harsh environment of high-altitude mountain wave flight. Preparations for such flight must consider, but not necessarily be limited to, oxygen requirements and equipment, very low outside air temperatures, large air temperature variations (mild temperature conditions at launch but becoming frigid aloft), and physiological triggers from the very cold air aloft (increased kidney function, etc.).

Mountain wave flying can be exhilarating! The ability to fly in wings-level attitude while still climbing 1,000 feet per minute without an engine is quite enjoyable for those who often twist and turn for the meager reward of a 100 foot per minute climb in weak thermals. There are many fine books and individuals who provide solid information in regard to mountain wave flying. Pilots such as Jim Payne, Gordon Boettger, Kempton Izuno, and instructor pilots around the Truckee, Minden-Tahoe, California City, and Tehachapi areas are walking encyclopedias for mountain wave flying. Since I am the most familiar with those folks who fly the Sierra Nevada and Tehachapi Mountains, my personnel bias reflects the referenced geographic area. Nonetheless, consider taking the opportunity to read some of the reference materials and listen to the advice from wave-knowledgeable pilots in wave soaring areas around the country before undertaking high-altitude wave flying. Better yet, participate in one of the many "wave camps" that are annually offered around the country. Such camps teach wave-flying lessons developed over years of experience.

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## WEATHER TO FLY

BY DAN GUDGEL

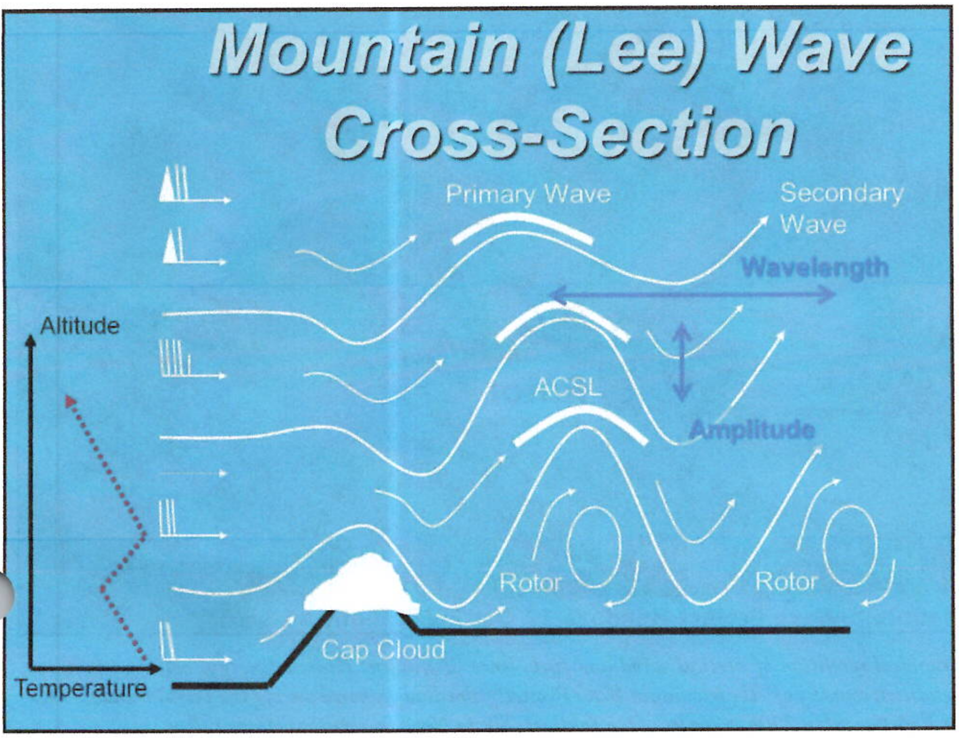
# Mountain Wave Parameters

In previous renditions of Weather to Fly, we discussed characteristics and the conceptual model of the mountain wave, mountain wave forecasting, and implications of flight in and around the phenomenon. To close out the topic, a little discussion on the complexity of numerical forecasting is appropriate. When the subject of mountain waves is discussed very often someone eventually asks, "Why does the mountain wave form?" A complete explanation of why the wave forms and a numerical description requires advanced mathematics and physics. This is the reason for the vague answer that is often given regarding the appropriate question "why?" from inquisitive aviators.

The complexity of a comprehensive numerical description for a mountain wave cannot be overstated. In keeping with the meteorology profession's reputation of subterfuge – along with the complexity of atmospheric interactions that lead to the development of the mountain or lee wave – I use this month's installment of Weather to Fly to just give just a taste of the theory. I will point out a few of the assumptions, and numerical equation terms and variables that only begin to describe the atmospheric motion that results in the development of the mountain wave. I am also including a more extensive, yet still abridged, reference section for those who wish to see examples of wave research continually underway. Personal recommendations for further information about mountain wave would be the "The Mountain Wave Project" [7] and any research conducted by the University Corporation for Atmospheric Research (UCAR) and National Center for Atmospheric Research (NCAR).

In looking at the conceptual model of the mountain wave, the definition of the (vertical) wavelength is the distance between the crests of the waves. Reliably this is the distance between the first and second waves (not the distance from the disturbing terrain feature to the first wave crest). The amplitude of a wave is the measure of the air's vertical change in its oscillation (See ***Diagram #1: "Mountain Wave Conceptual Model"***).

Courtesy of Holton [4], a mountain or lee wave develops when air is forced to flow over a mountain under statically stable conditions. Individual air parcels are displaced from a level where they were at an equilibrium level. As a result of the displacement by terrain, the air parcels undergo buoyancy oscillations as they move downstream of the mountain. An internal gravity wave system is excited in the lee of the mountain. A *gravity wave [5]* is defined as a wave disturbance in which buoyancy (or reduced gravity) acts as a restoring force on parcels of




**Hydrostatic Equation [5]**

Underscoring just some of the assumptions and yet considerations that constitutes the complexity of attempting to describe the motion of the atmosphere in regard to mountain waves, this meteorological formula derivation represents the vertical component of the vector equation of motion. All Coriolis, earth curvature, frictional, and vertical acceleration terms are considered negligible compared with those involving the vertical pressure force and the force of gravity.

Thus $\delta p / \delta z = -\rho g$

where $p$ is the pressure, $\rho$ is the density, $g$ the acceleration of gravity, and $z$ the geometric height. For cyclonic-scale motions the error committed in applying the hydrostatic equation to the atmosphere is less than 0.01%.

**NOTE:** Strong vertical accelerations in thunderstorms and ***mountain waves*** (editor's emphasis) may be 1% of gravity or more in extreme situations.

air displaced from hydrostatic equilibrium. *Hydrostatic equilibrium [5]* is the state of a fluid (the air) with consistent horizontal surfaces of constant pressure and constant mass (or density). In this equilibrium, a balance exists between the force of gravity acting on the mass of air and the pressure force (Note: Remember pressure changes with altitude height gain or loss). With assumptions, the relationship between the pressure and any geometric height in the atmosphere is defined by the *Hydrostatic Equation* (See ***Text Box #1: Hydrostatic Equation [5]***).

The first term that must be addressed by numerical modelers of the atmosphere is stability, and in the mountain wave case, static stability. *Static Stability [5]*, also called hydrostatic stability or vertical stability, is the ability of air at rest to become either turbulent or laminar due to the effects of buoyancy. A fluid - the air - tending to become or remain turbulent is said to be statically unstable; a fluid tending to become or remain laminar is statically stable. A fluid on the borderline between the previous two (which might remain laminar or turbulent depending on its history) is statically neutral. The most prevalent type of the mountain wave, commonly known as a "trapped wave," typically requires static stability. With the aforementioned basic concepts and definitions, meteorologists begin to numerically describe the atmosphere's stability.

The concept of static stability can also be applied to air not at rest by considering only the buoyant effects and neglecting all other shear and inertial effects of motion. *Shear* and *inertial effects of motion* result in dynamic stability contributions, or the measure of the ability of the air to resist or recover from finite perturbations of what was a steady state condition. However, if any of these other dynamic stability effects is indicative that the flow is dynamically unstable, then the flow will become turbulent regardless of the static stability. In other words, turbulence has a physical priority in the atmosphere when considering all possible measures of air flow stability (e.g., the air is turbulent if any one or more of static, dynamic, inertial, etc., effects indicates instability). Turbulence that forms in statically unstable air will act to reduce or eliminate the instability that caused it by moving less dense air up in height and more dense air down thus creating a neutrally buoyant mixture. Thus, turbulence will tend to decay with time as static instabilities are eliminated in the mixing (unless some outside forcing such as heating of the bottom of a layer of air by contact with the warm ground during a sunny day) continually acts to destabilize the air.

By mathematical derivations and assumptions (See ***Text Box #2: Wavelength Relationship***), the vertical wavelength of the gravity wave excited by zonal flow (westerly flow) over a mountain is *proportional to the zonal wind speed, and inversely proportional to the square root of the stability* [4]. Mountain lee waves are stationary with respect to the ground. The initial energy source for disturbing the air flow is the ground and this disturbing energy must be transported vertically. At the same time, the phase velocity relative to the mean wind flow has a downward component. In the mathematical derivation of the wavelength, the constant phase velocity of the wave shows a westward (or upstream) tilt of the wave crest with height. When viewed within a coordinate system moving at the speed of the mean zonal wind, constant phase lines of lee waves set up by westerly flow appear to progress upstream toward the west (the direction from that the wind is coming from).

As mentioned, early wave modeling work proceeded with a series of assumptions to keep the Lee-Wave Equation [8] simplified. It was assumed that the amplitude of the waves is relatively small compared to the wavelength (wavelengths ~6 miles or 10 km), and that the effect of the earth's rotation could be dis-

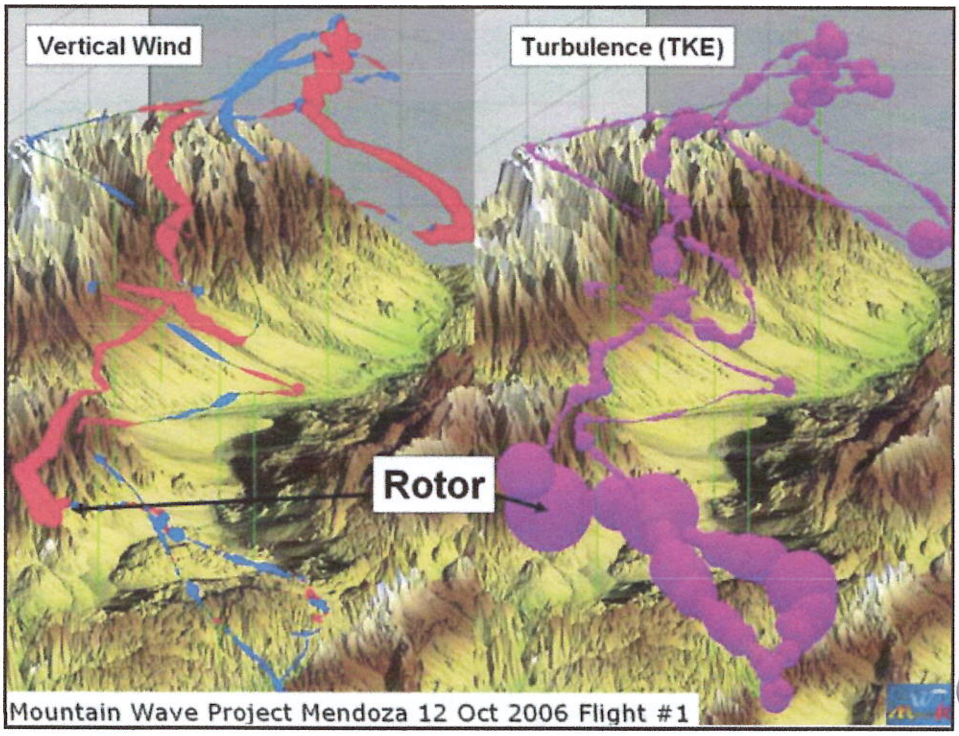
**Wavelength Relationship [4]**

$$\lambda = [S/u^2 - 1/4H^2]^{1/2} \approx S^{1/2}/u$$

where:

λ = vertical wavelength of the gravity wave;
H = a constant scale height
S = stability; and,
u = zonal wind speed.

By derivations of numerical equations, this relationship shows that the vertical wavelength of the gravity wave excited by zonal flow over a mountain is ***proportional to the zonal wind speed** **and inversely proportional to the square root of the stability.***




*Graphical rendition of vertical wind and turbulence (Turbulent Kinetic Energy) observed in wave. Rendition courtesy of "The Mountain Wave Project" from data gathered during the Terrain-Induced Rotor Experiment in 2006 in the lee of the Southern Sierra Nevada over the Owens Valley.*

regarded. The air motion was described in a coordinate system where the wind was relatively undisturbed, and along an axis perpendicular to a mountain ridge considered to have an infinite extension. Other assumptions were that the motion would be described as non-viscous, laminar, and isentropic. *Isentropic* implies that potential temperature is constant with respect to space, in this regard [4].

Turbulent flow is not the type of air movement desired for soaring wave flight. As such, the "trapped wave" regime of air that is relatively stable provides for the laminar flow. Numerical work must account for the effects of both variation of wind and stability with height. Early work by R.S.Scorer and the subsequent development of an older wave forecast tool, the *Scorer Parameter* (See ***Text Box #3: Scorer Parameter [6]***), underscores the importance of *temperature, temperature lapse rates*, and *wind shear* in the generation of mountain wave laminar flow. As observed, some degree of stability is desired at lower atmospheric levels with increasing destabilization aloft that often approaches the dry adiabatic lapse rate.

What else makes mountain wave numerical description complex? The basic structure of the mountain wave is initially determined by the size and shape of the mountain. Downwind terrain can interfere with the wave. Constructive interference occurs when the downwind terrain features align favorably within the wavelength to support the updraft of the wave; or destructive interference occurs when the downwind terrain is out of phase with the wavelength. Terrain shape and size must fit in with the functions of the vertical profiles of temperature, wind speed, and moisture in the impinging flow [3] for wave development. Linear theory fits well for the assumption that mountain waves are generated by terrain relatively small compared to the wavelength. If the aforementioned assumption is not the case, then *nonlinear dynamics* play a significantly larger impact on the low-level wave field over the lee slope.

The role of stability as a function of temperature and temperature changes has been discussed. Wind shear is also a key term in the development of the mountain wave. If numerical simulations change only the vertical wind shear, then the following wave development occurs [6]:

- If a wave structure develops that occurs with *weak wind shear* (change in wind speed), on the order of 10 meters/second or 20 knots from mountaintop to the Tropopause (the top of the lowest atmospheric level extending upward from the surface to around 30,000 feet MSL at mid-latitudes in the winter), the waves are primarily in a vertically propagating mode with wave response mostly higher than the mountain ridge. Only minimal disturbed flow is noted downwind of the mountain;
- *Moderate wind shear* with winds increasing 20m/s or 40kts leads to lee waves occurring farther downwind with longer wavelengths aloft. The primary wave has a very pronounced upwind tilt. The mountain wave system then has both high-level vertically propagating and low-level trapped-wave modes. This is an optimum wave condition for pilots looking for maximum altitude or altitude gain; and,
- *Strong wind shear* through the Tropopause, winds increasing 45m/s or 90kts, results in wave energy that is largely trapped in waves in the lower troposphere and minimal disturbed flow at higher altitudes. Wave updrafts develop farther downwind of the mountains.

One other flow structure can develop from terrain influence that is different from the trapped-wave considered above. This type of mountain-wave is referred to as an *atmospheric jump* (or hydraulic jump as studied in engineering and fluid-dynamics). The atmospheric jump is analogous to a shock wave in a compressible fluid. The jump develops one large wave oscillation downwind of the lee slope of a mountain with no resonant waves. Rotor or turbulence forms not only under the wave crest, but also occurs downwind as well. Atmospheric jumps are much less frequent than trapped-wave systems. They tend to favor development with the presence of *high, steep lee slopes*, *strong near-mountain top inversions*, and *relatively weak vertical shear* environments [6].

In summary, accurate and comprehensive numerical descriptions and modeling of a mountain wave (and subsequently the ability to numerically forecast) is quite complex for all aspects of wave development, especially if one is striving for 3-dimensional representation of the wave. The understanding of the complex interactions within the atmosphere has been aided immeasurably by high-speed computing along with technological advances in observation capabilities to the extent that we can graphically display air motion (See ***Diagram #2: "Mountain Wave Project Rotor Depiction [7]"***). In order to model the mountain wave, atmospheric stability and its variation must be defined and measured, any changes in the wind's character (wind speed and direction changes, including eddy development) must be noted and calculated, and the variation of terrain in regard to shape, height, and its influence the initial air flow disturbance must all be numeri-

**Scorer Parameter ($I^2$), [6]**

A wave forecast tool that emphasizes the importance of *wind speed, stability*, and *shear* throughout the troposphere in the generation of mountain waves:

$$I^2 = [g(\gamma^* - \gamma)/(Tu^2)] - [1/u(d^2u/dz^2)]$$

where;

$g$ = acceleration due to gravity;
$\gamma^*$ = dry adiabatic lapse rate;
$\gamma$ = ambient lapse rate of the layer;
$T$ = average temperature in the layer;
$u$ = average wind speed in the layer; and,
$d^2u/dz^2$ = curvature term, specifically the vertical derivative of the vertical wind shear

If the Scorer Parameter decreases with height, trapped waves are likely. The Scorer Parameter will decrease with height if: *stability decreases with height, wind speed increases with height,* and *vertical wind shear increases with height*.

**Rules:**

- A sharp decrease of $I^2$ with altitude indicates lee waves; or
- A sharp increase of $I^2$ with altitude indicates turbulence or rotors.

cally described. And even as the wave is generated, downwind terrain features then interfere with the wave. Given the "introduction to numerical modeling of the mountain wave" in this article and for the sake of my compatriots in the meteorological field, please be a little understanding if we seem elusive when answering questions about "why" a mountain wave forms :) .

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# PURPOSE

Learn how wave is formed

Learn how to identify structures of the wave

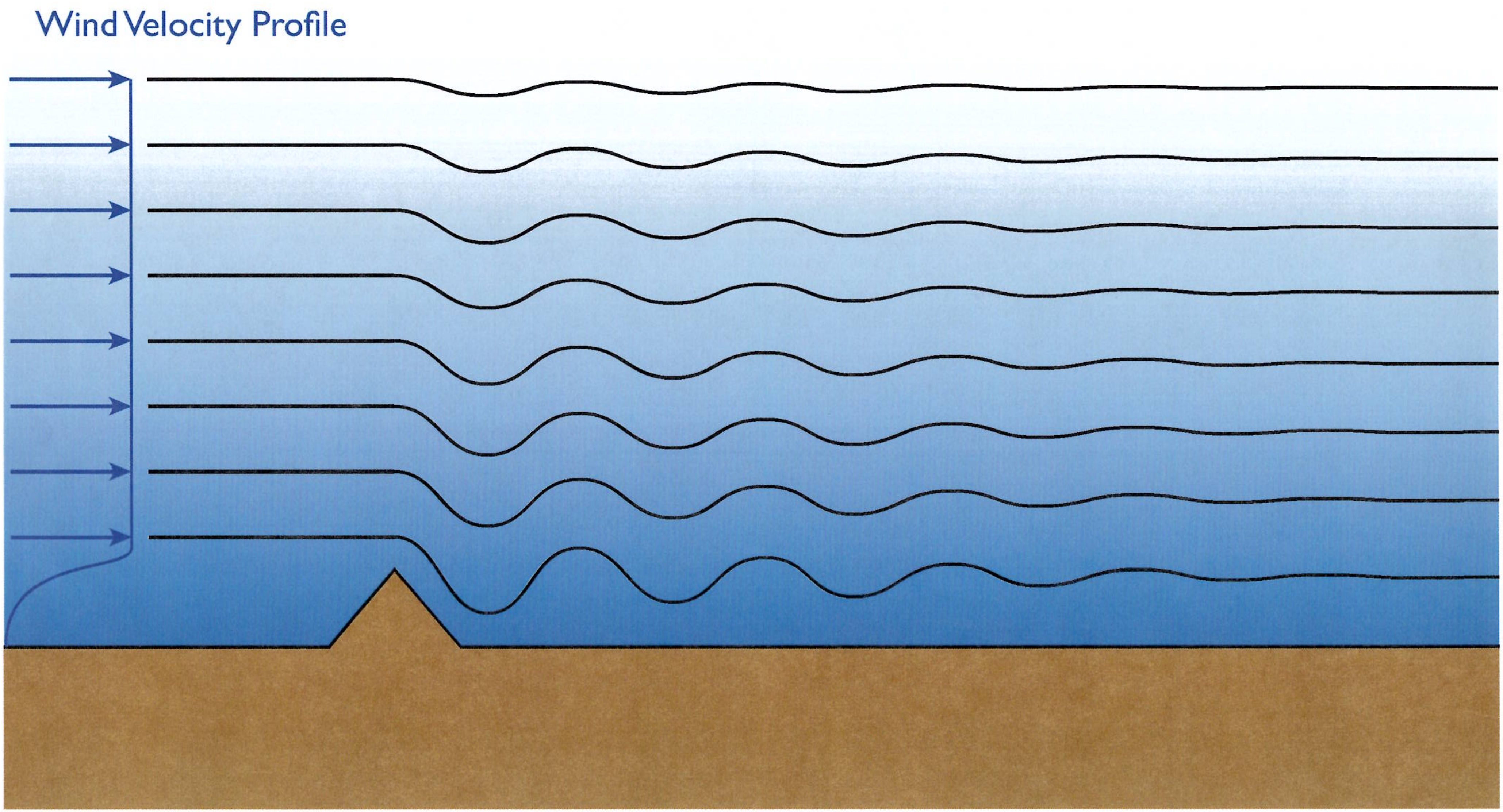
Learn how to safely fly in the wave environment

Learn how to find and use wave lift

# HOW WAVE IS FORMED

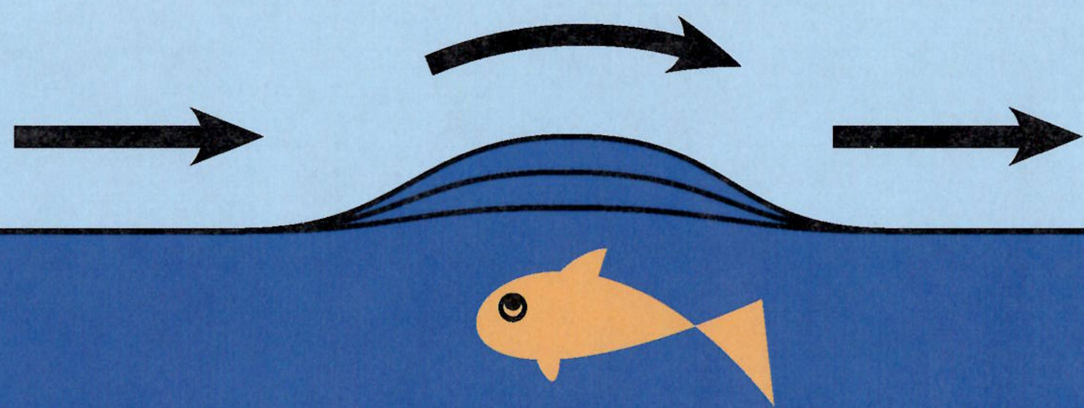
# DAMPED WAVE

## Stable Atmosphere - Constant Wind

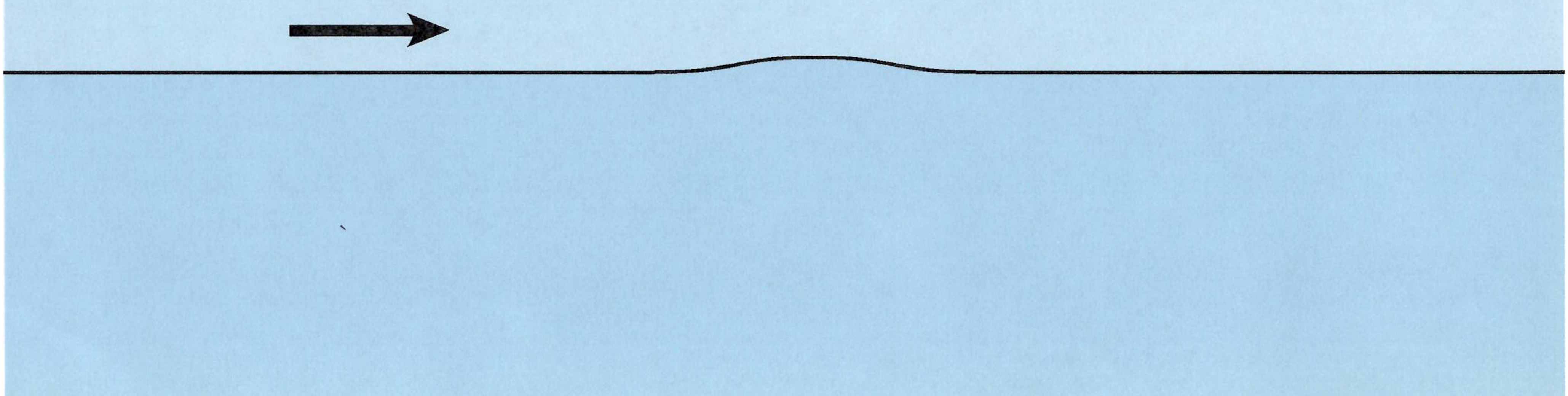


# AMPLIFIED WAVE

Air flowing over the top of a wave speeds up,
creating decreased pressure which amplifies the wave.

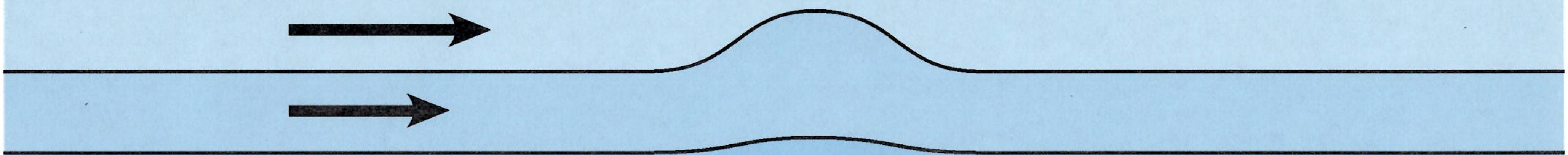


# AMPLIFIED WAVE - WIND GRADIENT



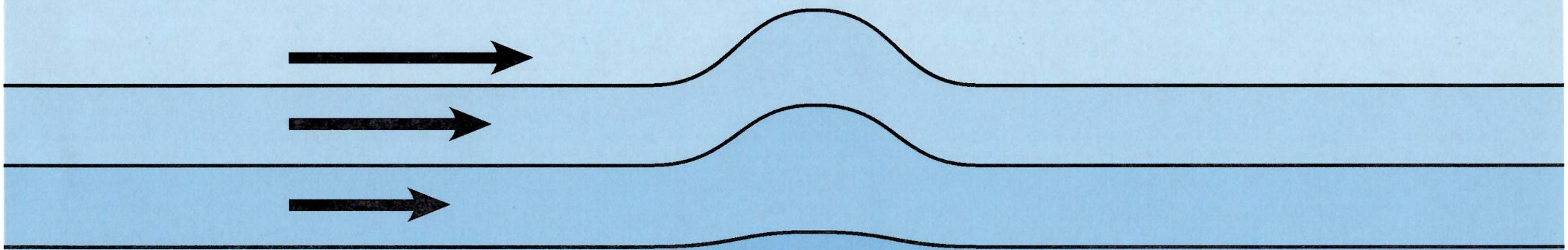
# AMPLIFIED WAVE - WIND GRADIENT

As long as the wind speed continues to increase with altitude, the wave will continue to increase in amplitude



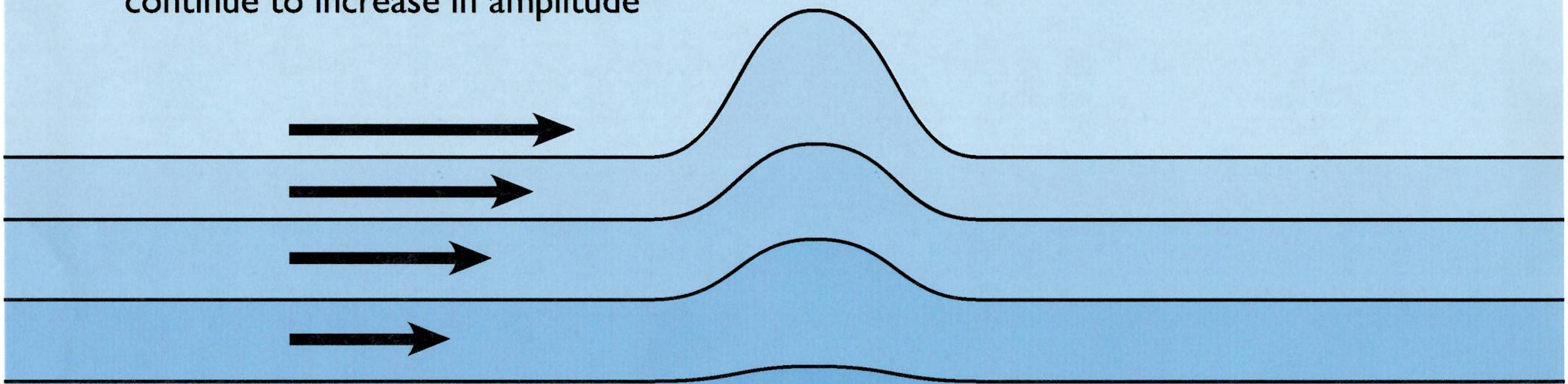
# AMPLIFIED WAVE - WIND GRADIENT

As long as the wind speed continues to increase with altitude, the wave will continue to increase in amplitude



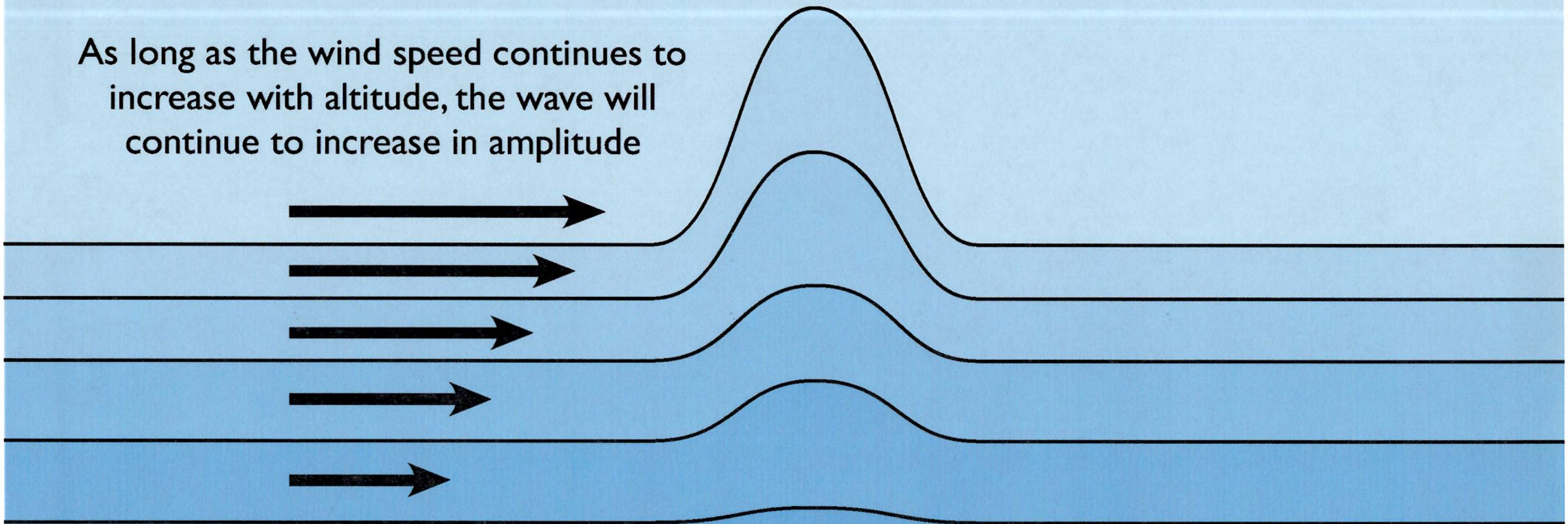
# AMPLIFIED WAVE - WIND GRADIENT

As long as the wind speed continues to increase with altitude, the wave will continue to increase in amplitude



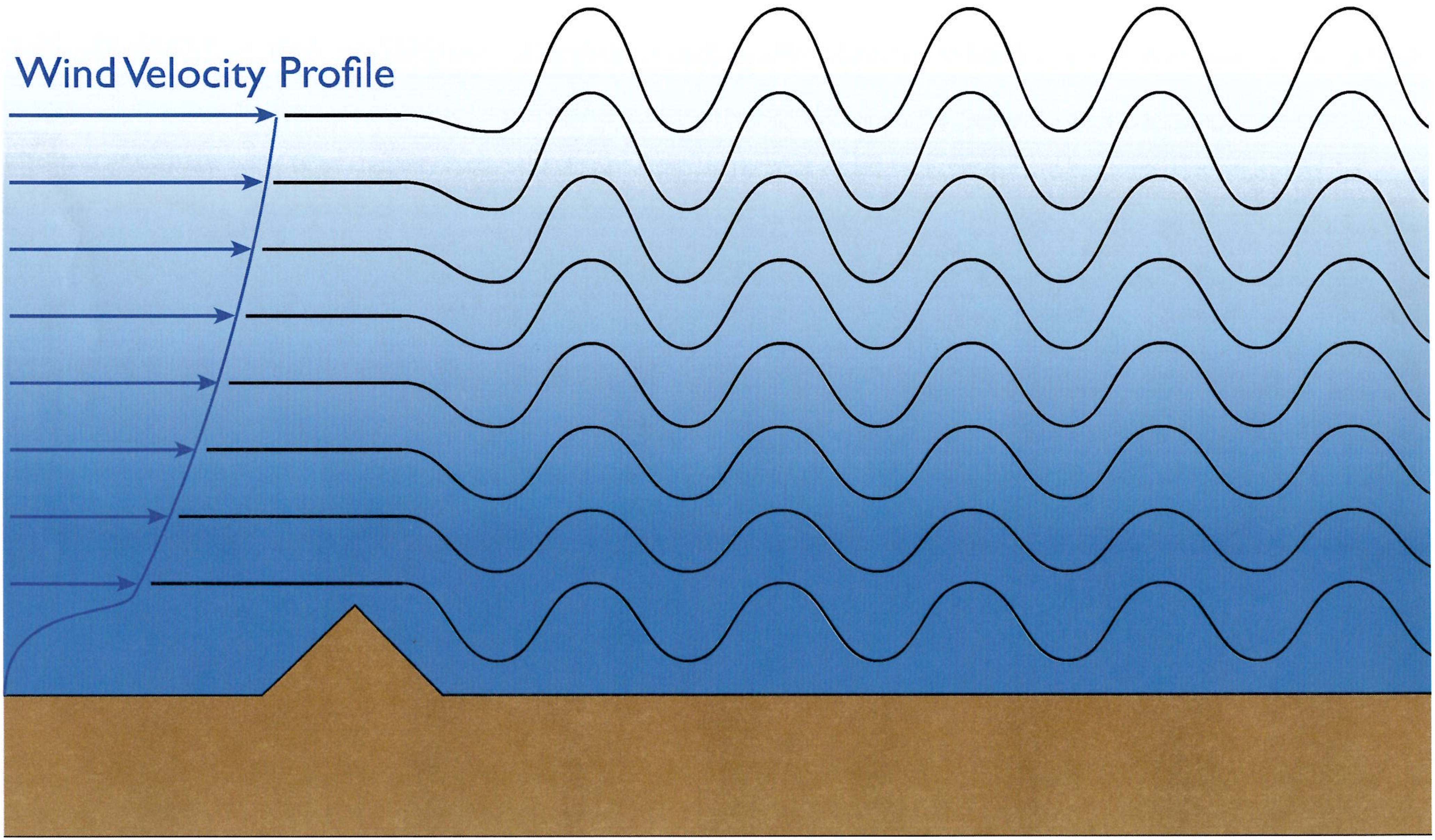
# AMPLIFIED WAVE - WIND GRADIENT

As long as the wind speed continues to increase with altitude, the wave will continue to increase in amplitude

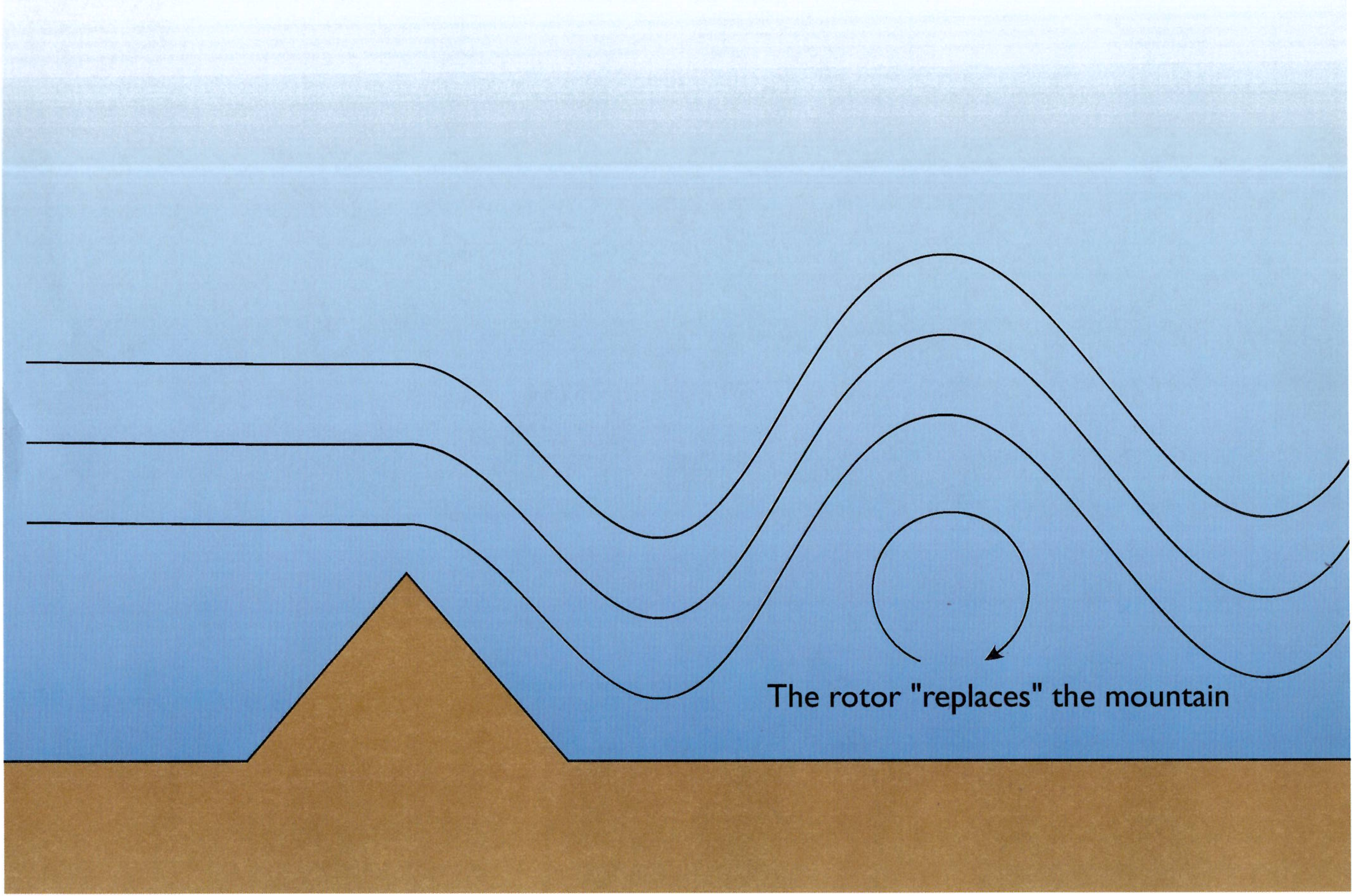


# AMPLIFIED WAVE

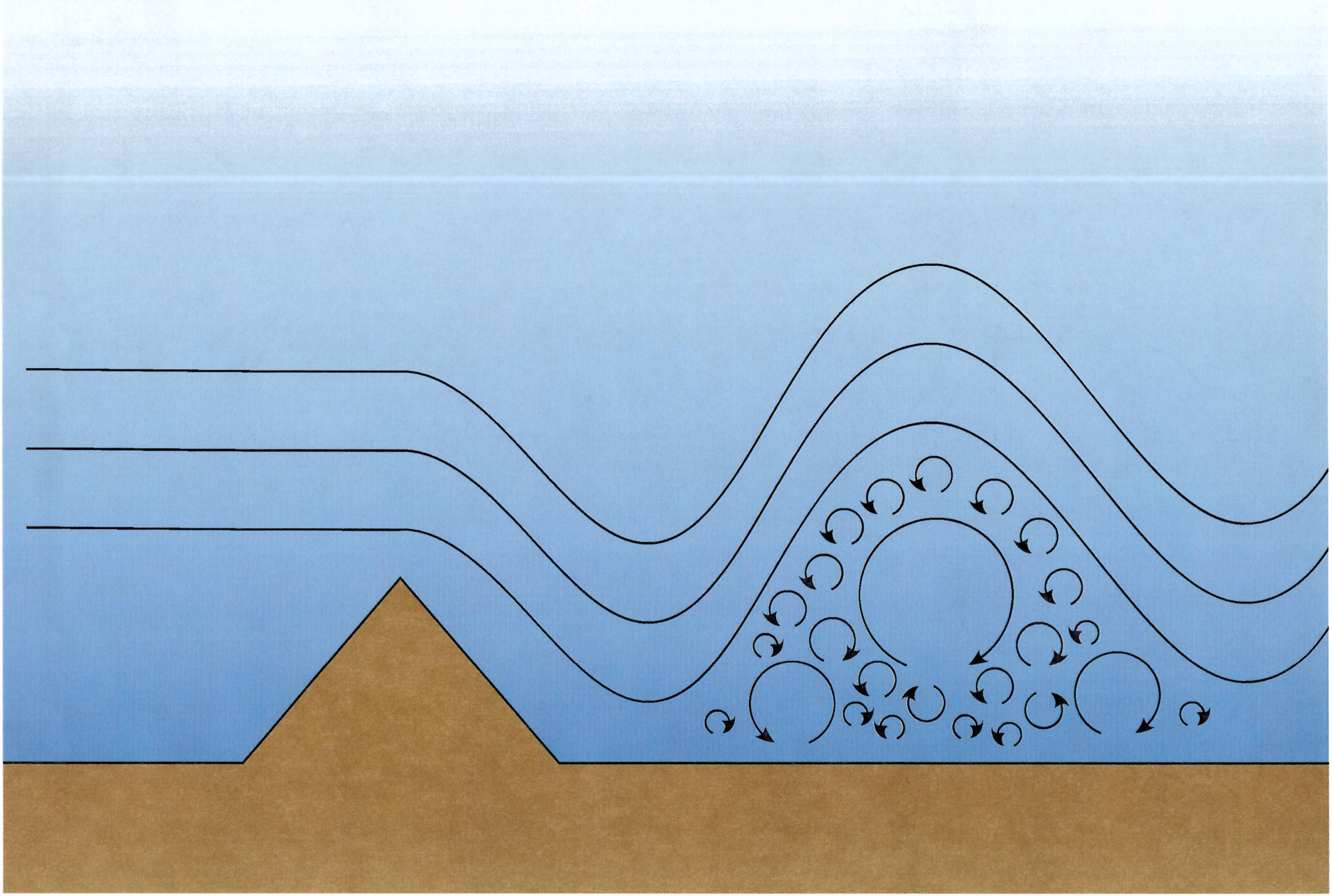
Stable Atmosphere - Increasing Wind with Altitude



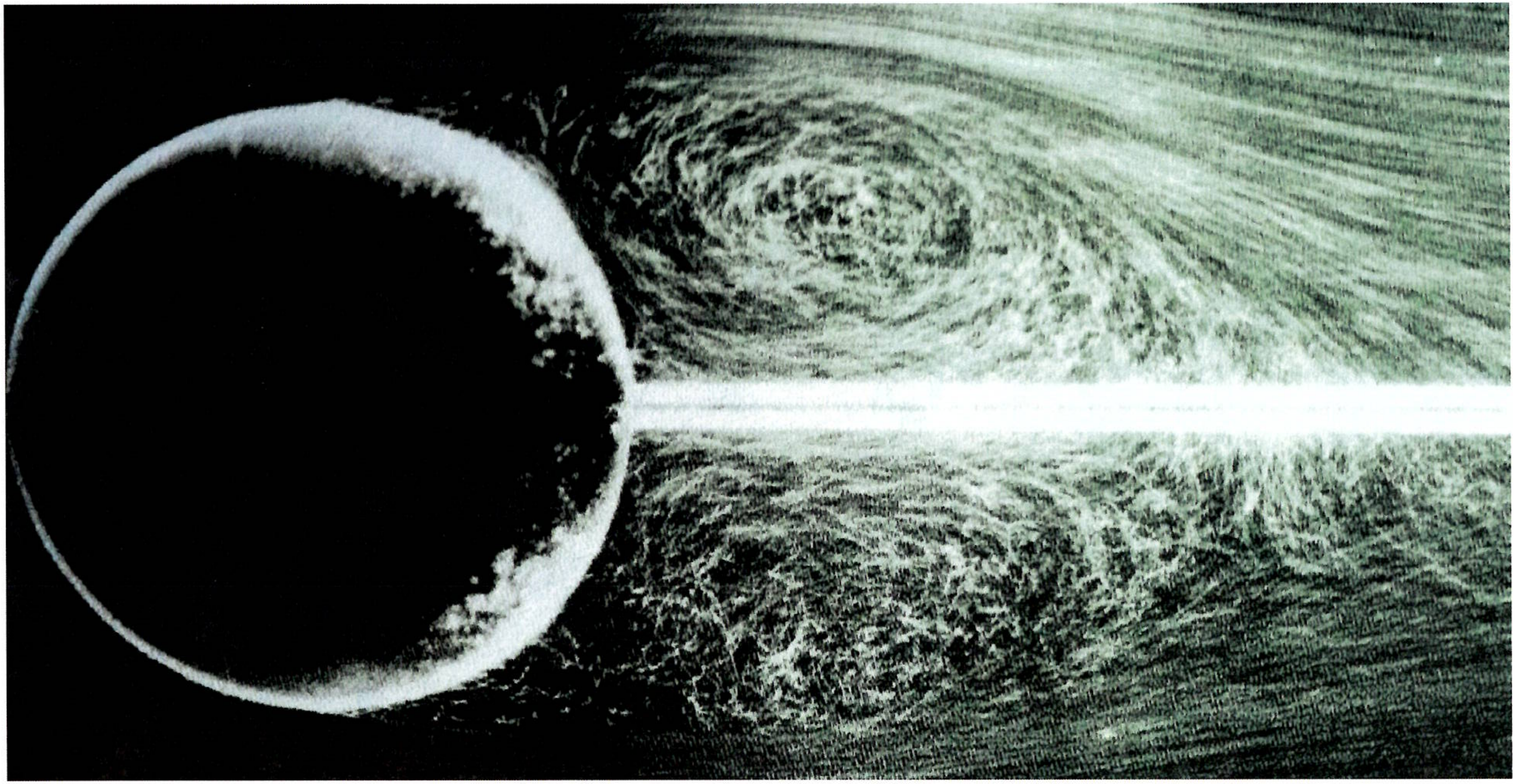
# ROTOR FORMATION



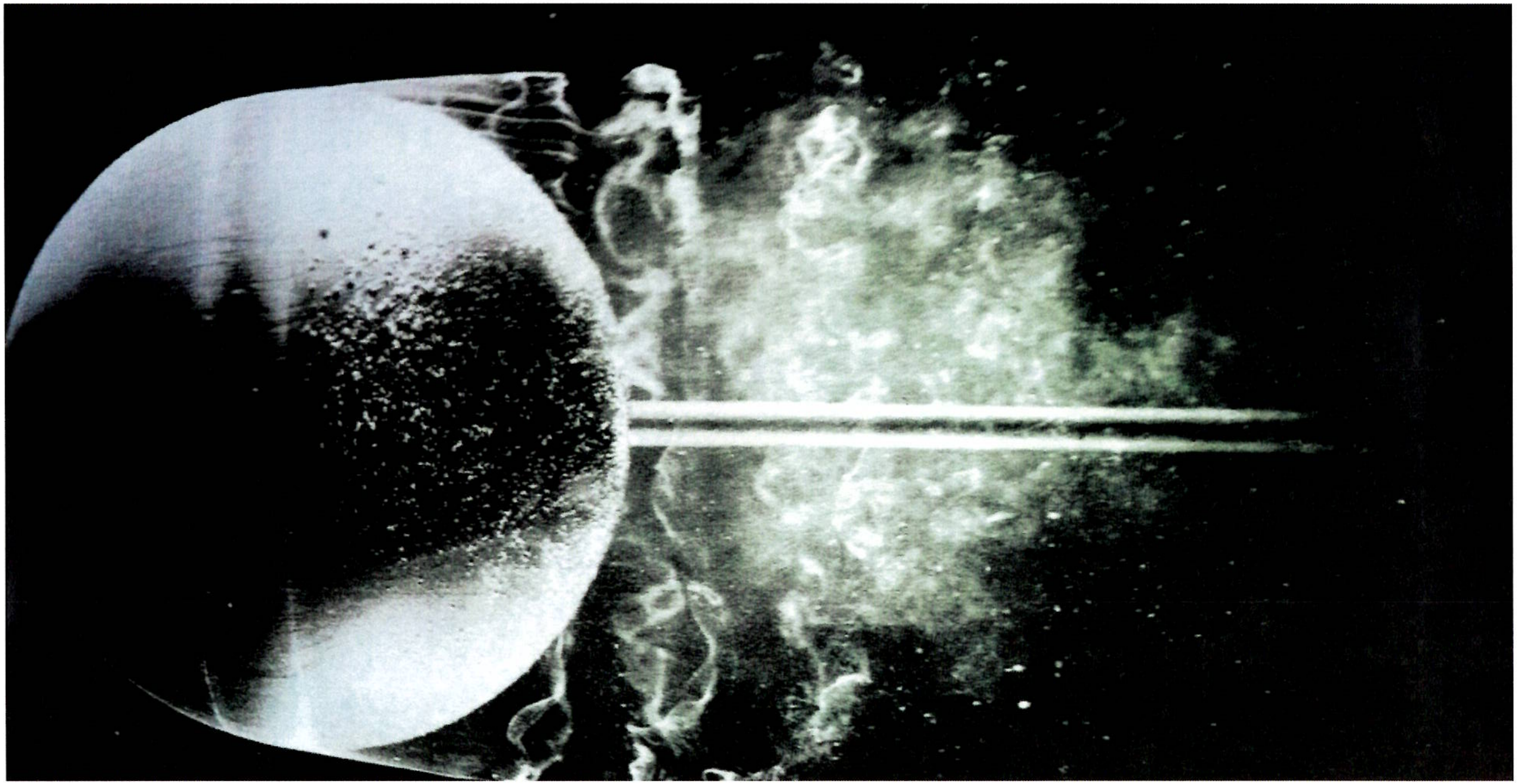
# ROTOR - REAL LIFE



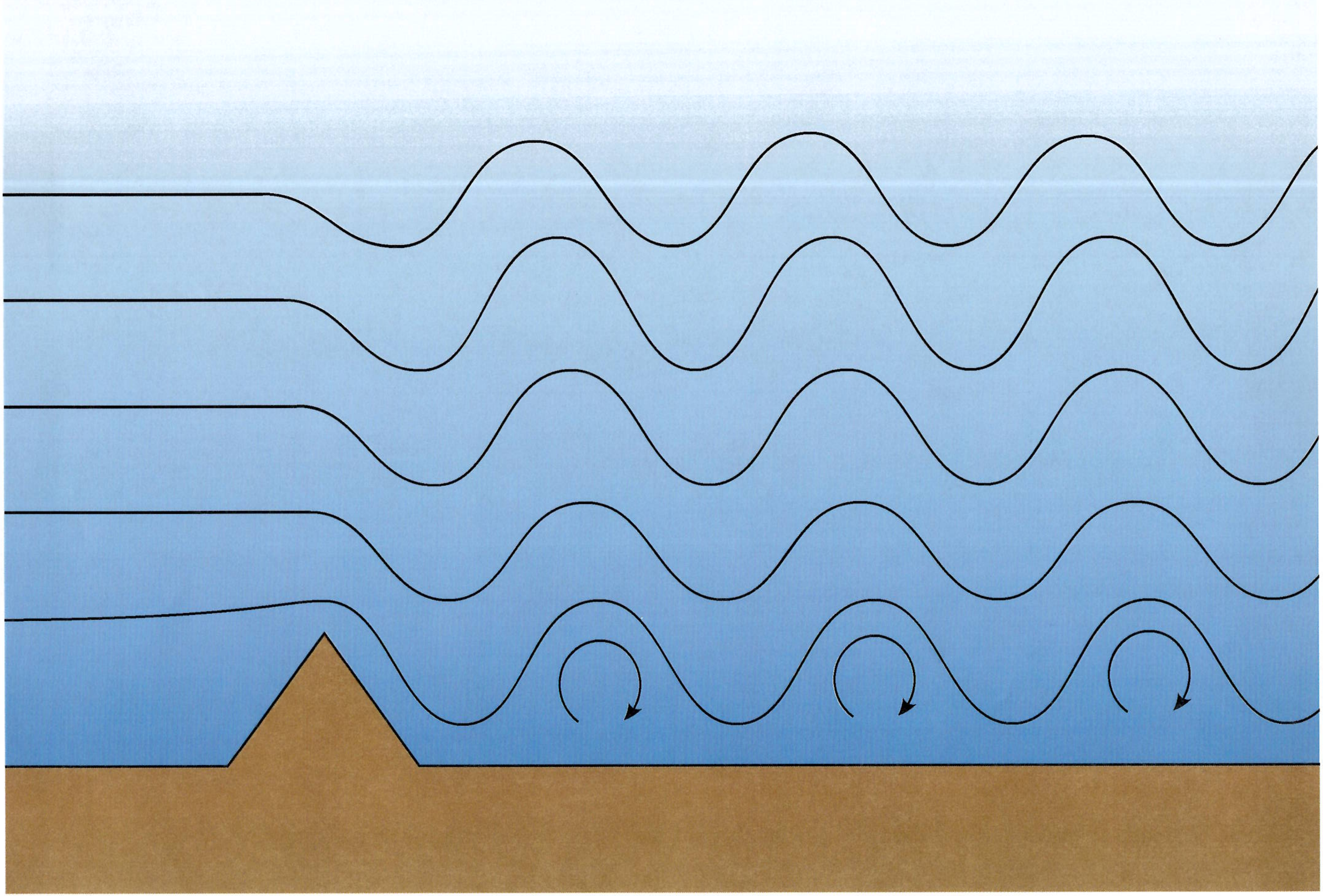
# MEAN FLOW PATTERN



# INSTANTANEOUS FLOW PATTERN

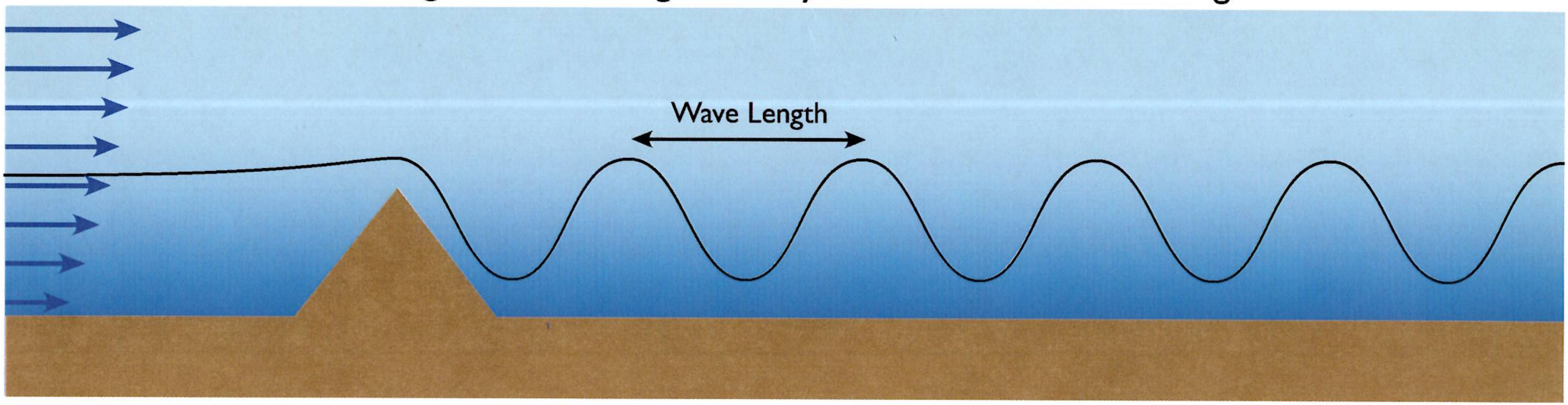


# SIMPLIFIED WAVE SYSTEM

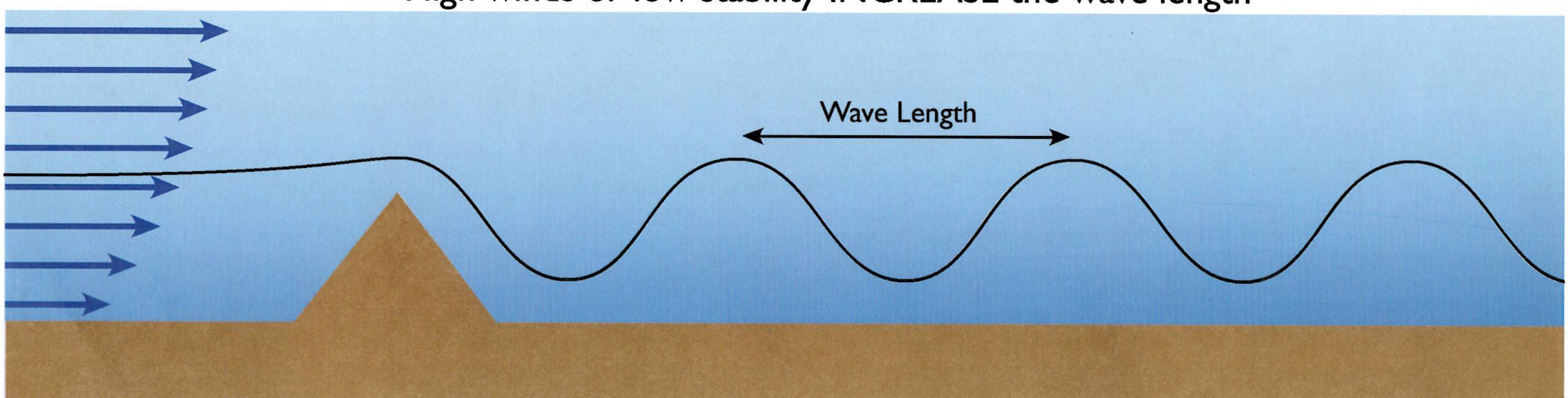


# WAVE LENGTH

Light winds or high stability DECREASE the wave length

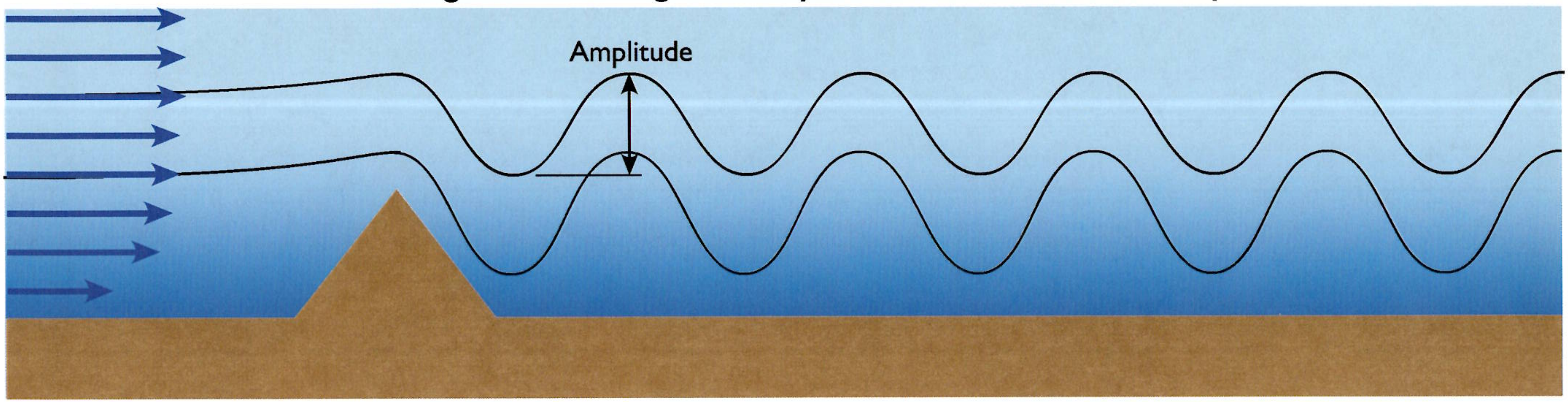



High winds or low stability INCREASE the wave length

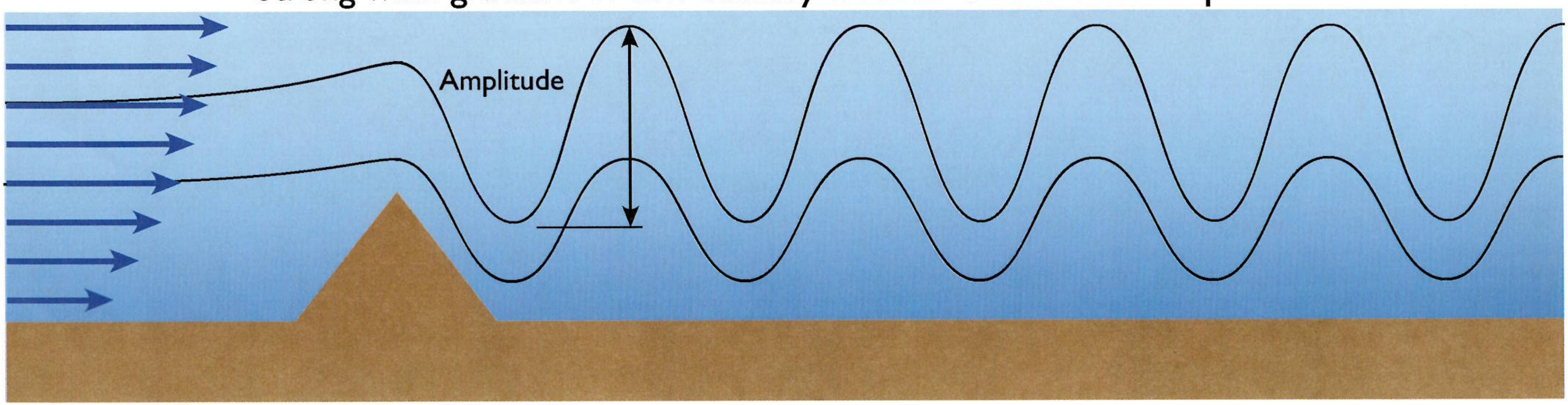


# WAVE AMPLITUDE

Weak wind gradient or high stability DECREASE the wave amplitude

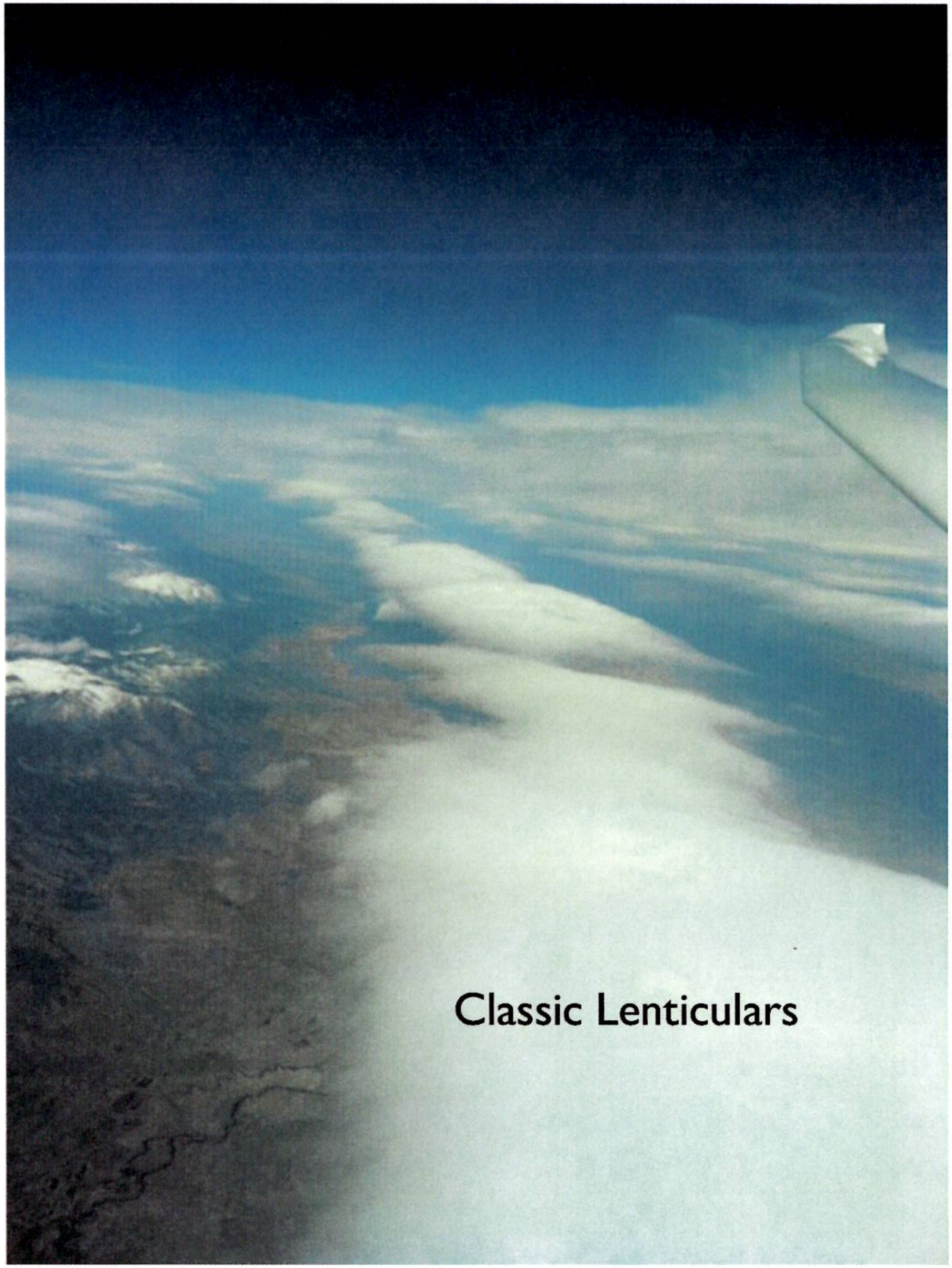



Strong wind gradient or low stability INCREASE the wave amplitude

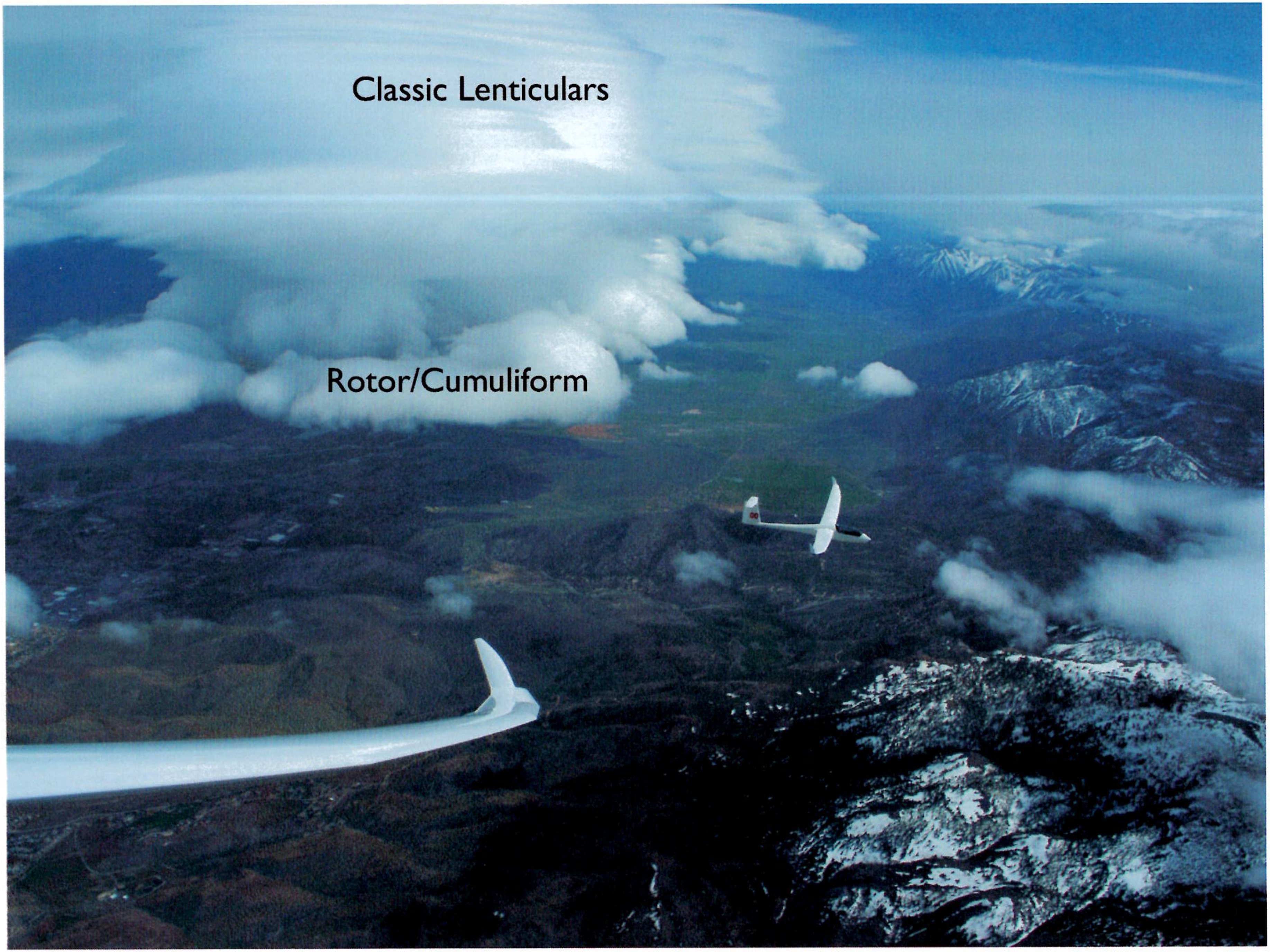


# CLOUDS ASSOCIATED WITH WAVE

# CLASSIC LENTICULAR CLOUDS



# LENTICULAR/ROTOR/CUMULIFORM

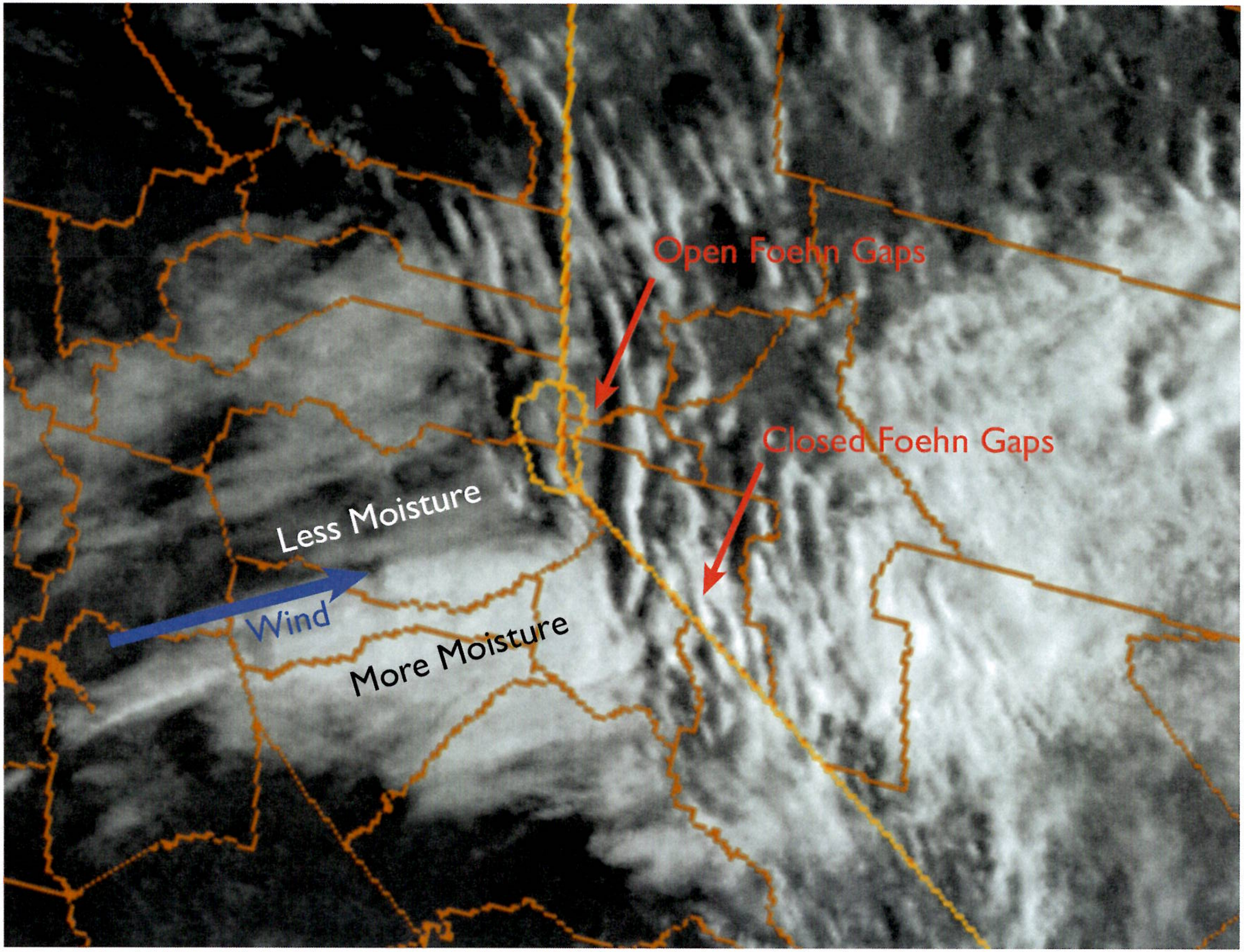


# TRANSPARENT WAVE CLOUDS

# TRANSPARENT WAVE CLOUDS II

# STACKED LENTICULARS

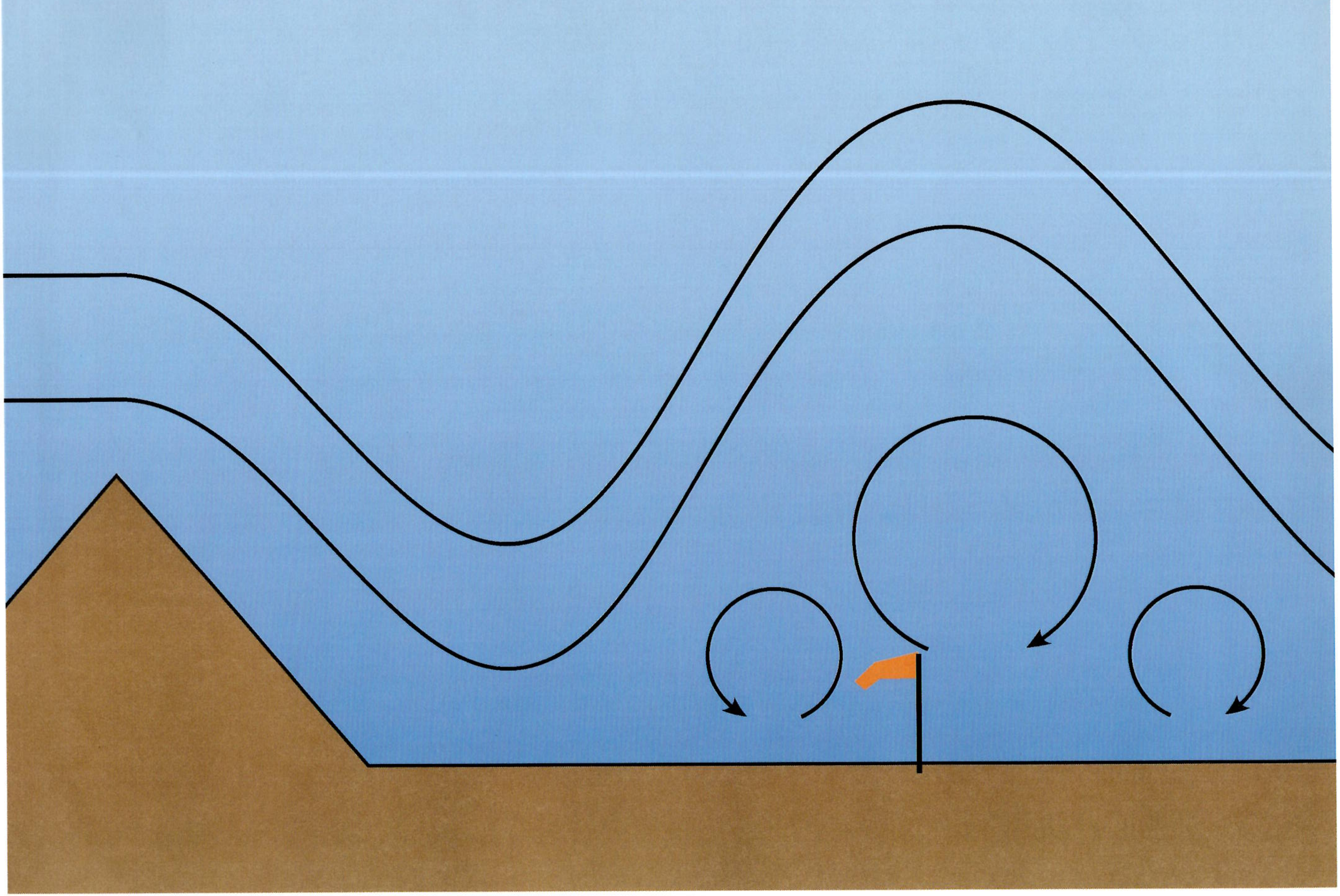
# FOEHN GAPS



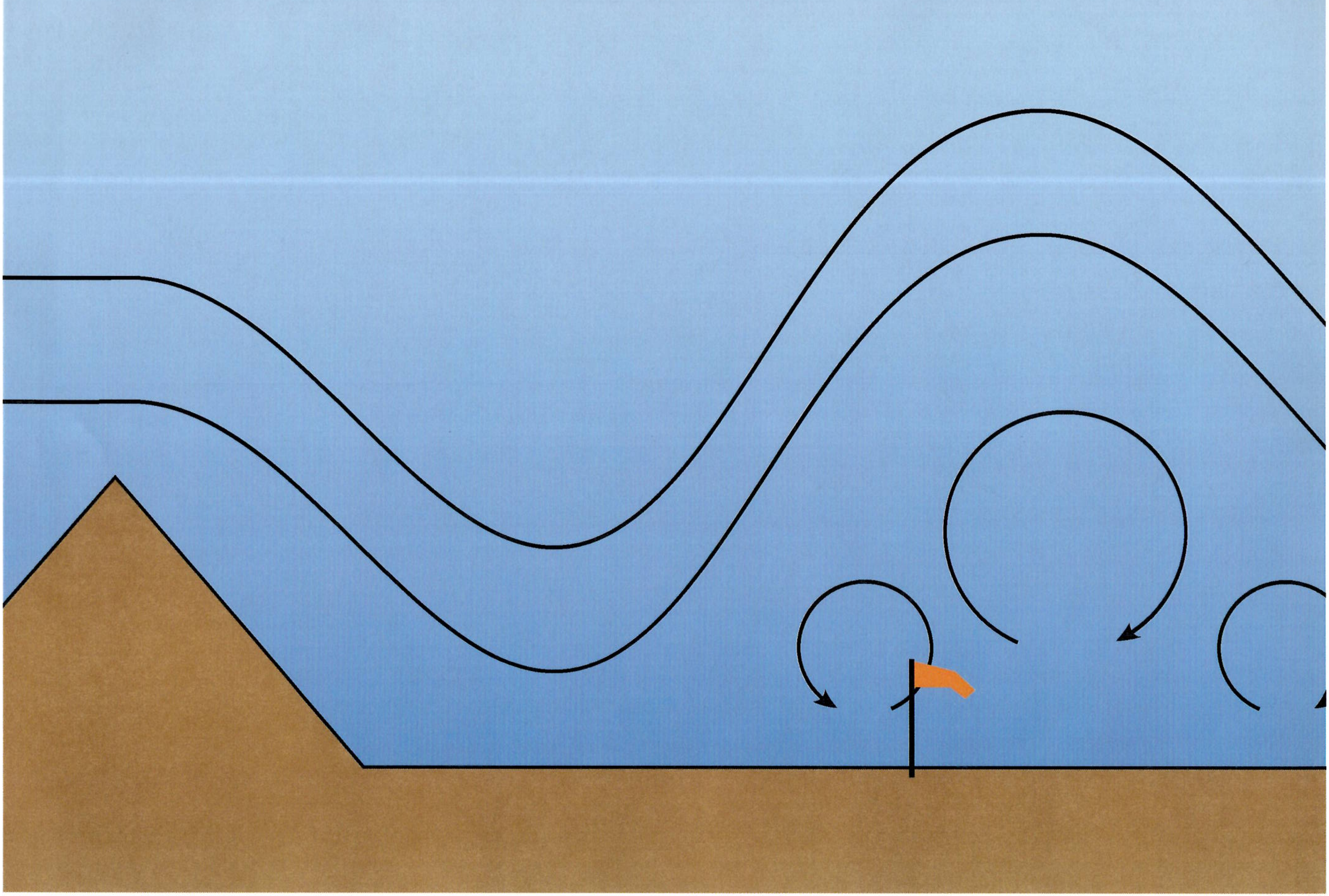
Open Foehn Gaps
Closed Foehn Gaps
Less Moisture
Wind
More Moisture

# DANGERS OF FLYING IN WAVE

# SHIFTING WINDS



# SHIFTING WINDS



# BEFORE TAKEOFF

Secure all loose objects.

Make sure belts are very tight.

Control check - extra clothing could limit movement.

Verify that oxygen is on and regulator is working.

Emergency Plan - high winds may prevent a safe downwind landing.

# ALL TAKEOFFS ARE OPTIONAL!

All takeoffs are *optional*, landings are NOT!

If you take off in conditions that are at the EDGE of your abilities, you may land in conditions that are BEYOND them.

# TAKEOFF

Gusts

Wind direction change

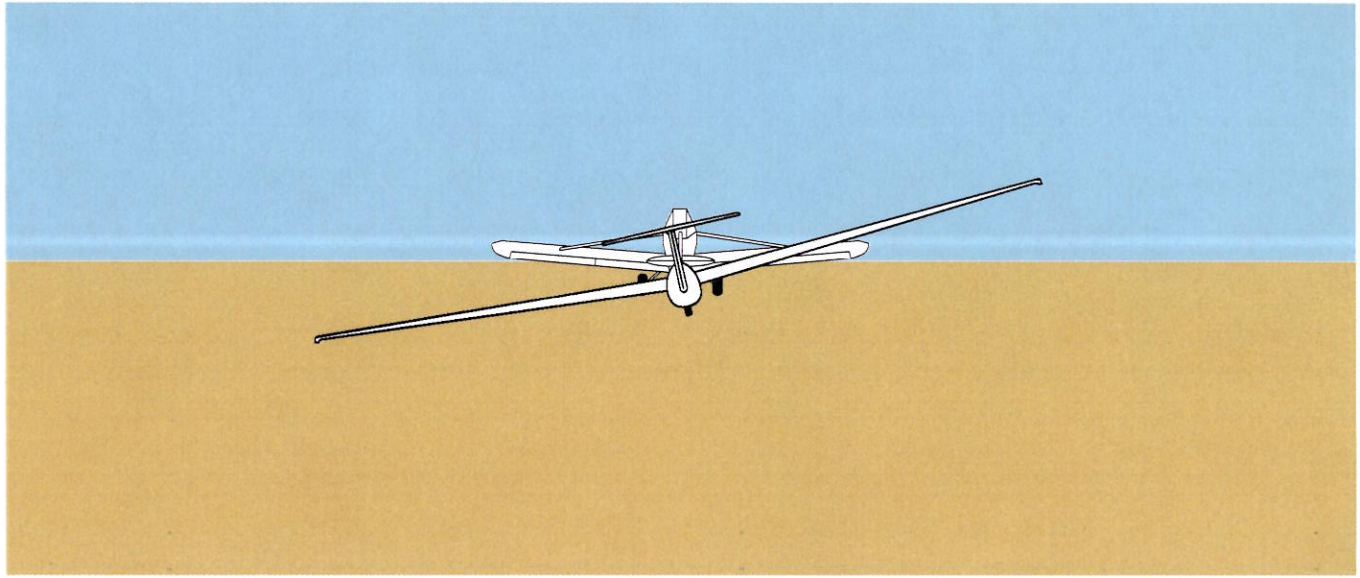
Crosswinds

Be prepared to release if things start to go bad

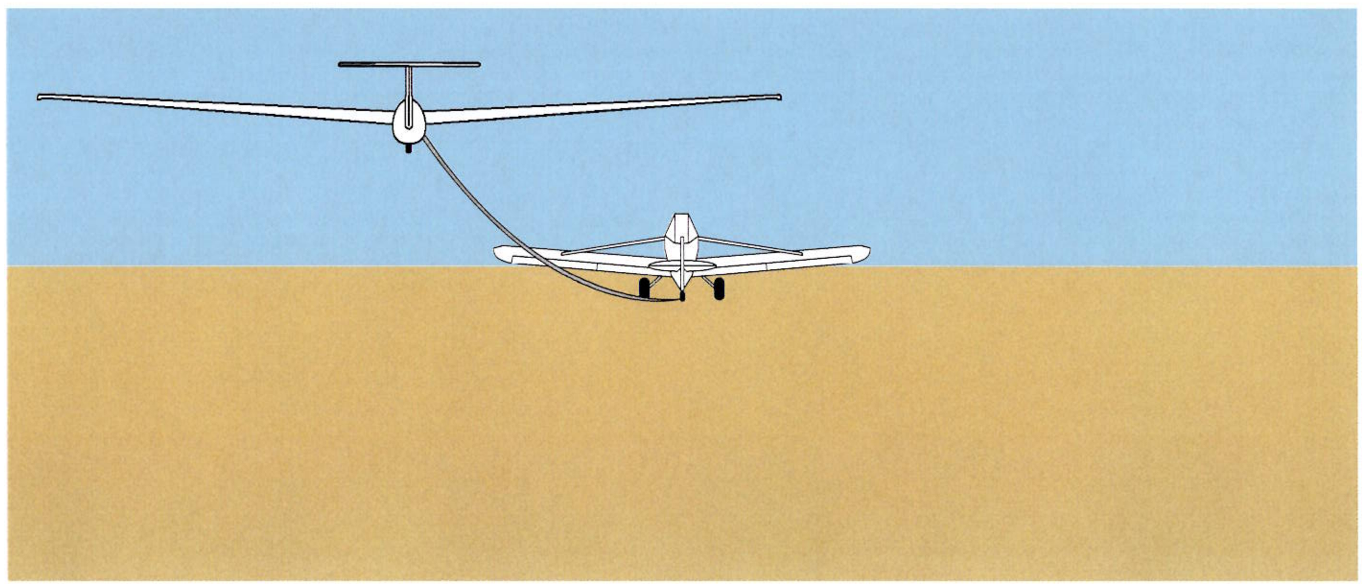
Do NOT have your hand on the release or airbrake handle

# CORRECTING TOW ERRORS

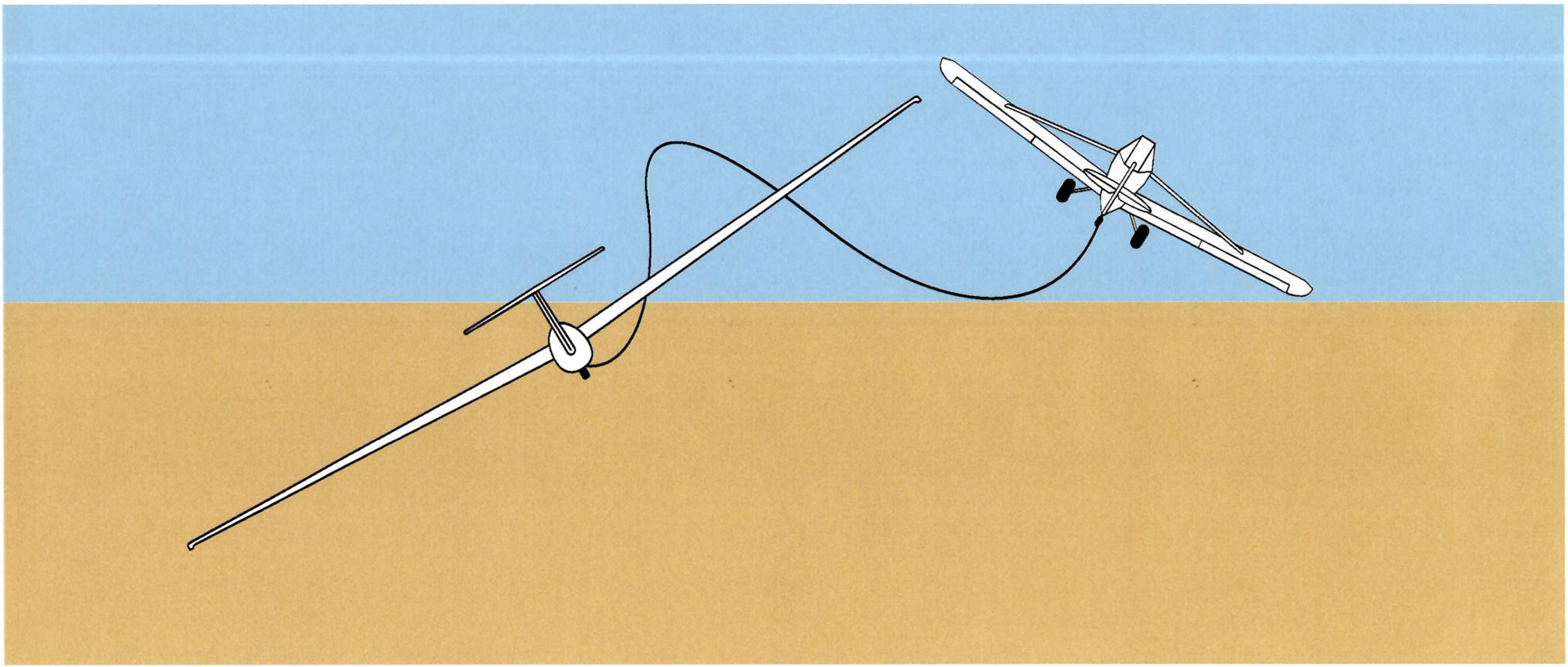
Be aggresive in correcting ATTITUDE (pitch/bank) errors.



Be patient in correcting POSITION errors.

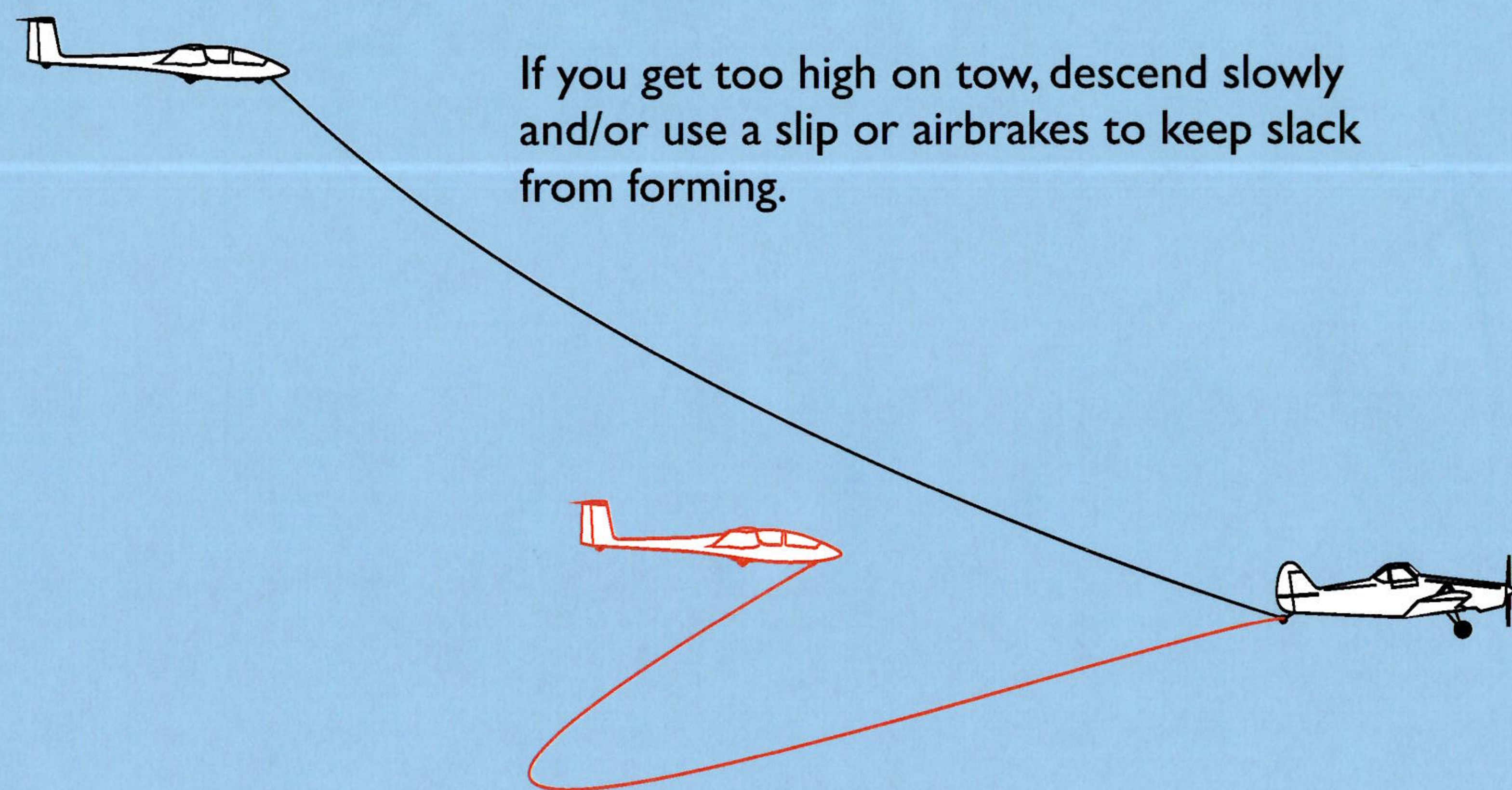


# RELEASING CAN BE THE BEST OPTION



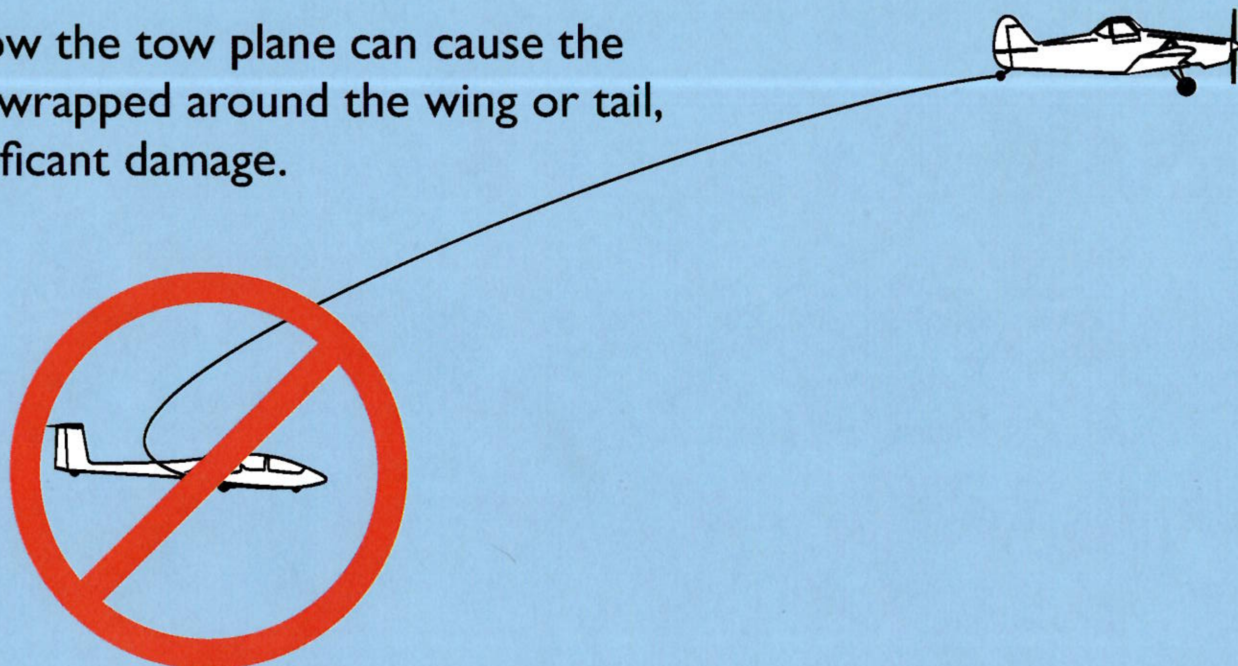
# TOO HIGH ON TOW

If you get too high on tow, descend slowly and/or use a slip or airbrakes to keep slack from forming.



# AVOID GETTING BELOW THE TOW PLANE

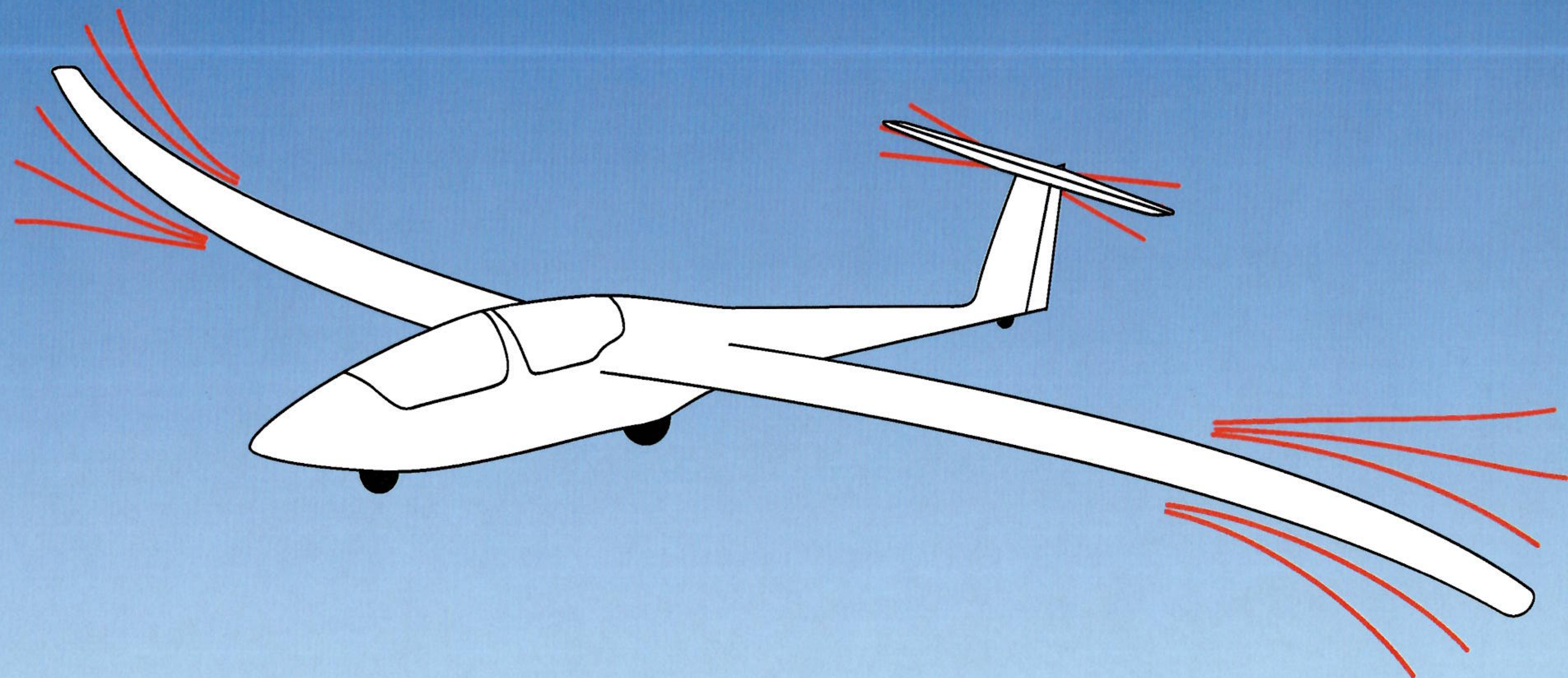
Getting below the tow plane can cause the rope to get wrapped around the wing or tail, causing significant damage.



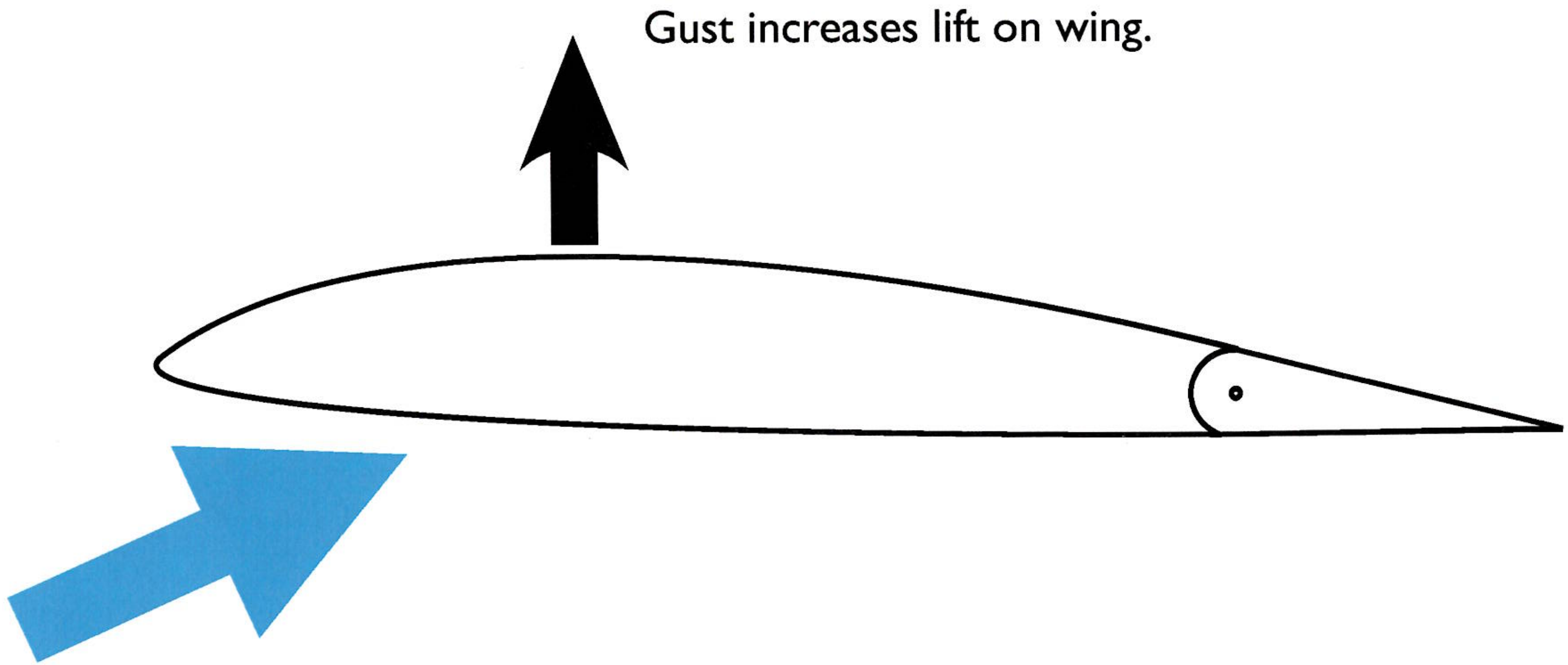
If you are low with slack, maintain position until the tow plane removes the slack.

If you are low without slack, you can immediately start climbing back into position.

# FLUTTER



# FLUTTER

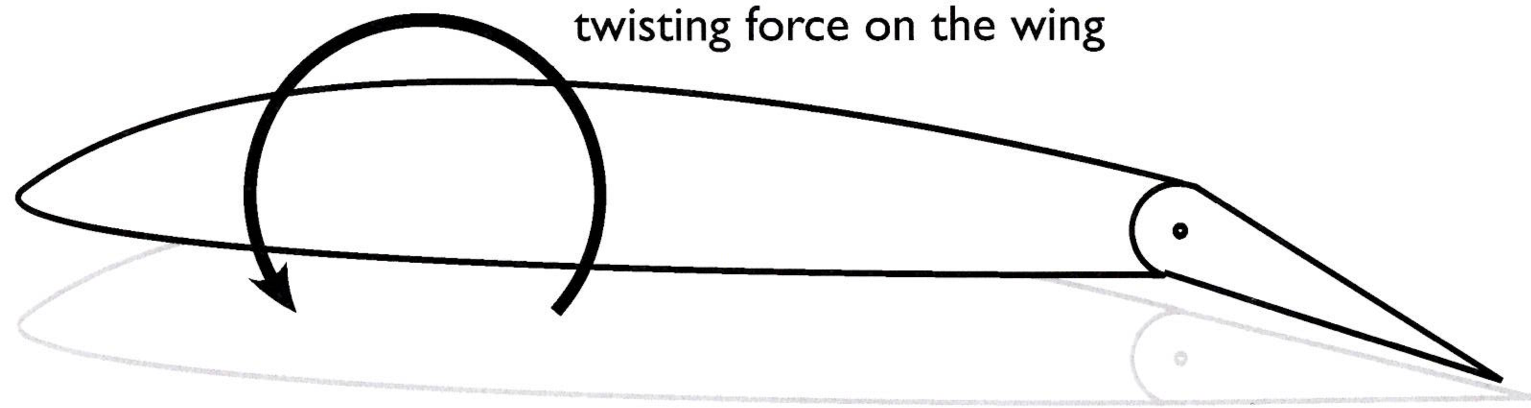


# FLUTTER

As wing deflects upward, inertia of the aileron causes it to be left behind, deflecting down.

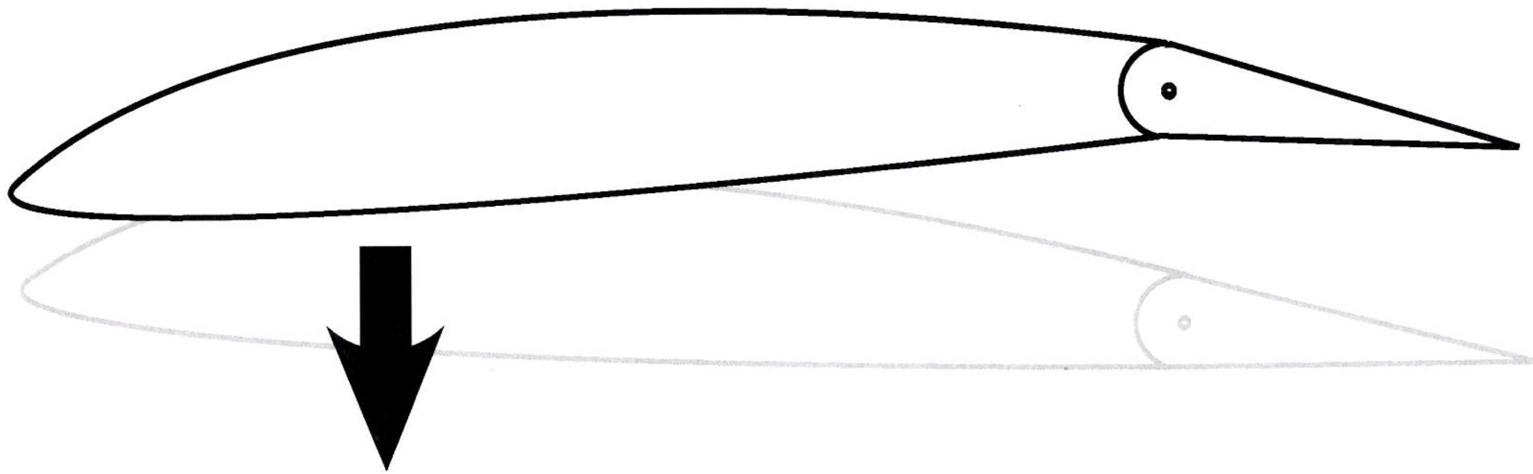
# FLUTTER

The down aileron causes a nose-down twisting force on the wing

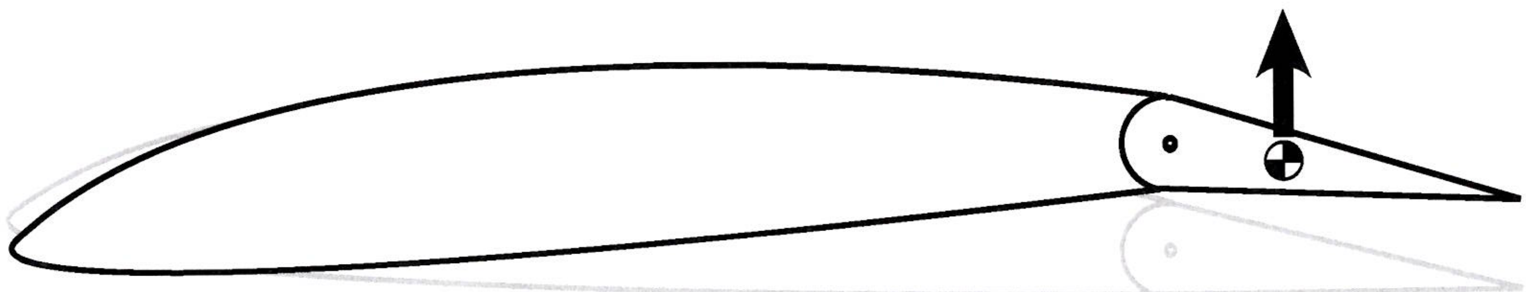


# FLUTTER

Wing twists to a lower angle of attack, decreasing the lift.

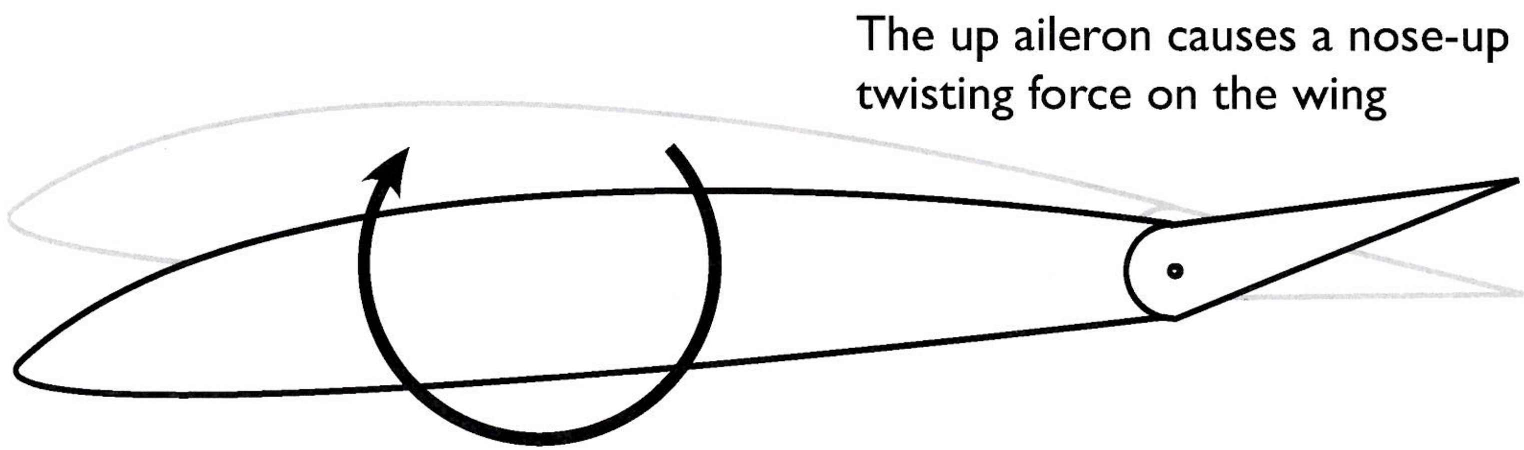


# FLUTTER



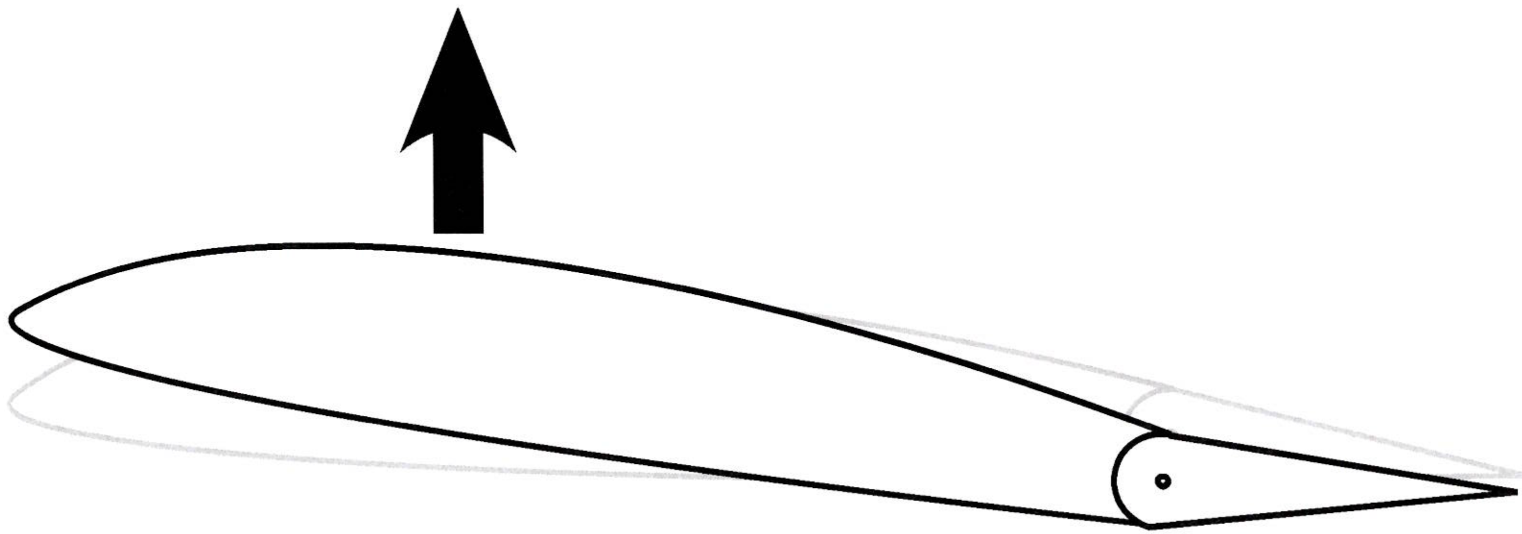
As the wing deflects down, inertia of the aileron causes it to be left behind.

# FLUTTER

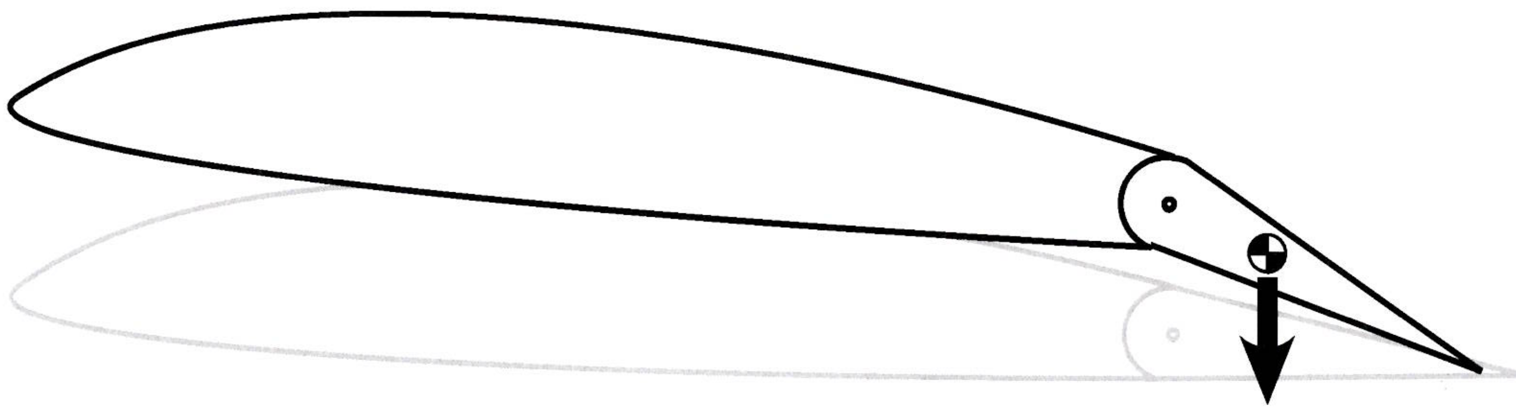


# FLUTTER

Wing deflects to a higher angle of attack, increasing the lift.

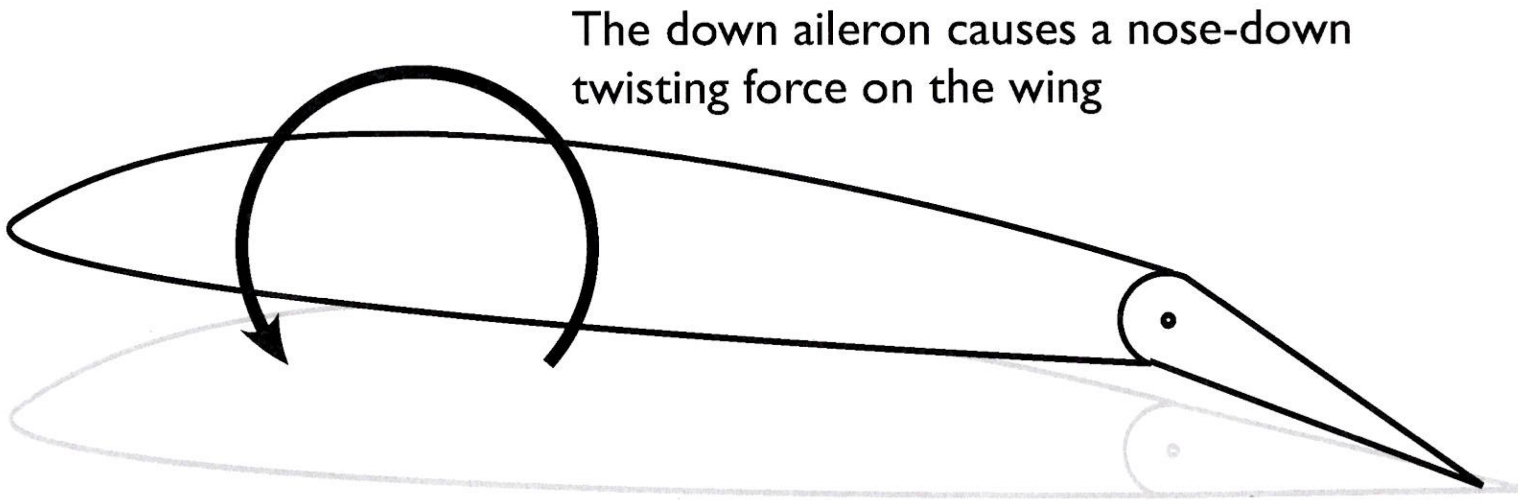


# FLUTTER



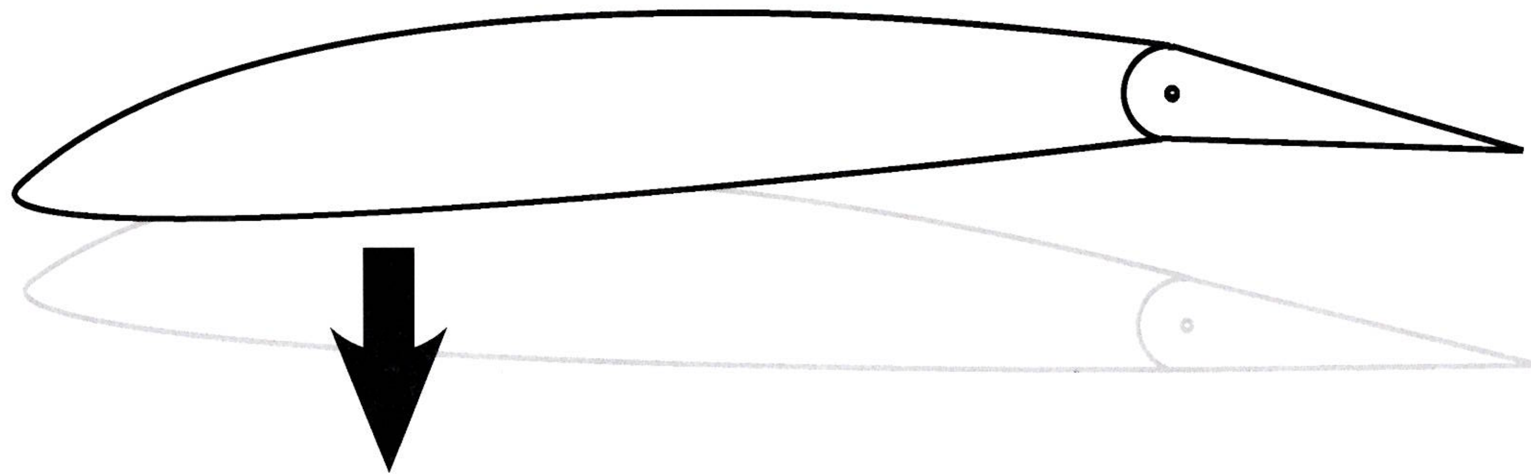
As wing deflects upward, inertia of the aileron causes it to be left behind, deflecting down.

# FLUTTER


The down aileron causes a nose-down twisting force on the wing

# FLUTTER

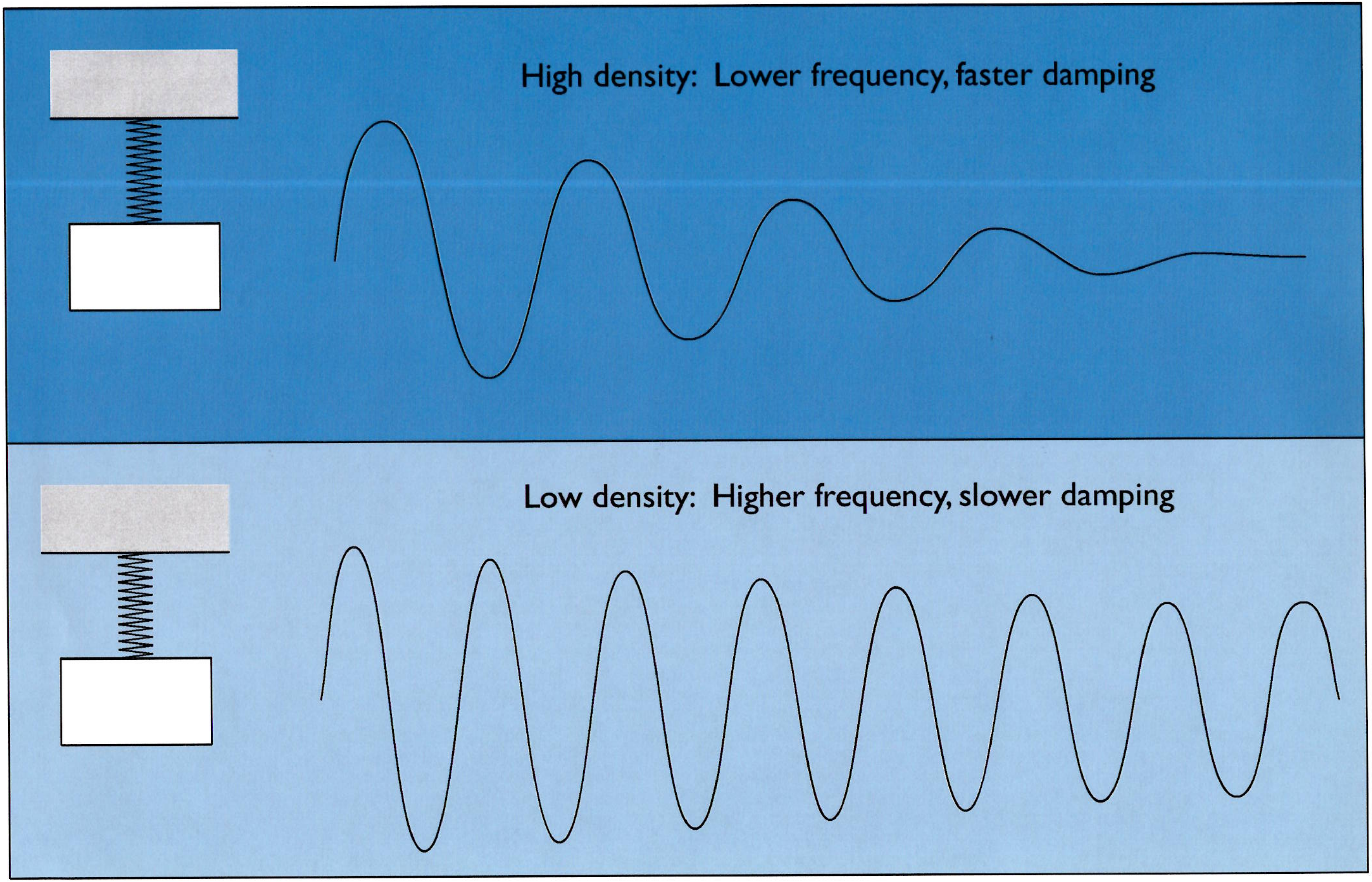
Wing twists to a lower angle of attack, decreasing the lift.



# FLUTTER

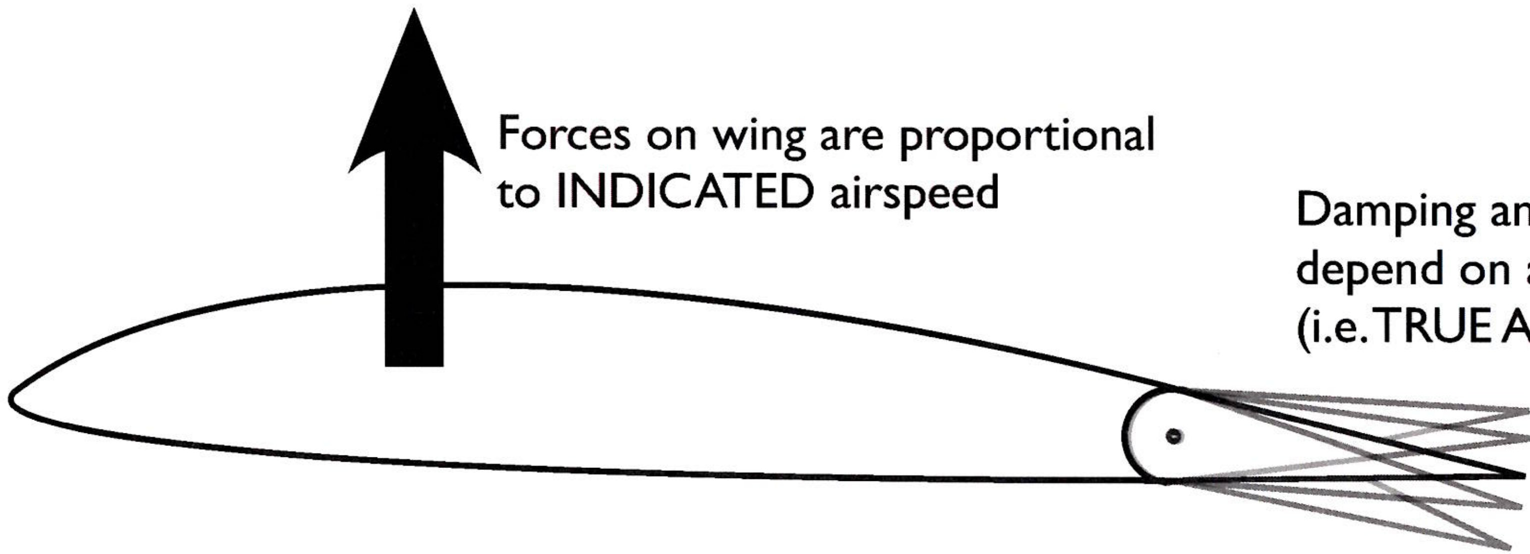
As the wing deflects down, inertia of the aileron causes it to be left behind.

# EFFECTS OF DENSITY ON FREQUENCY/DAMPING



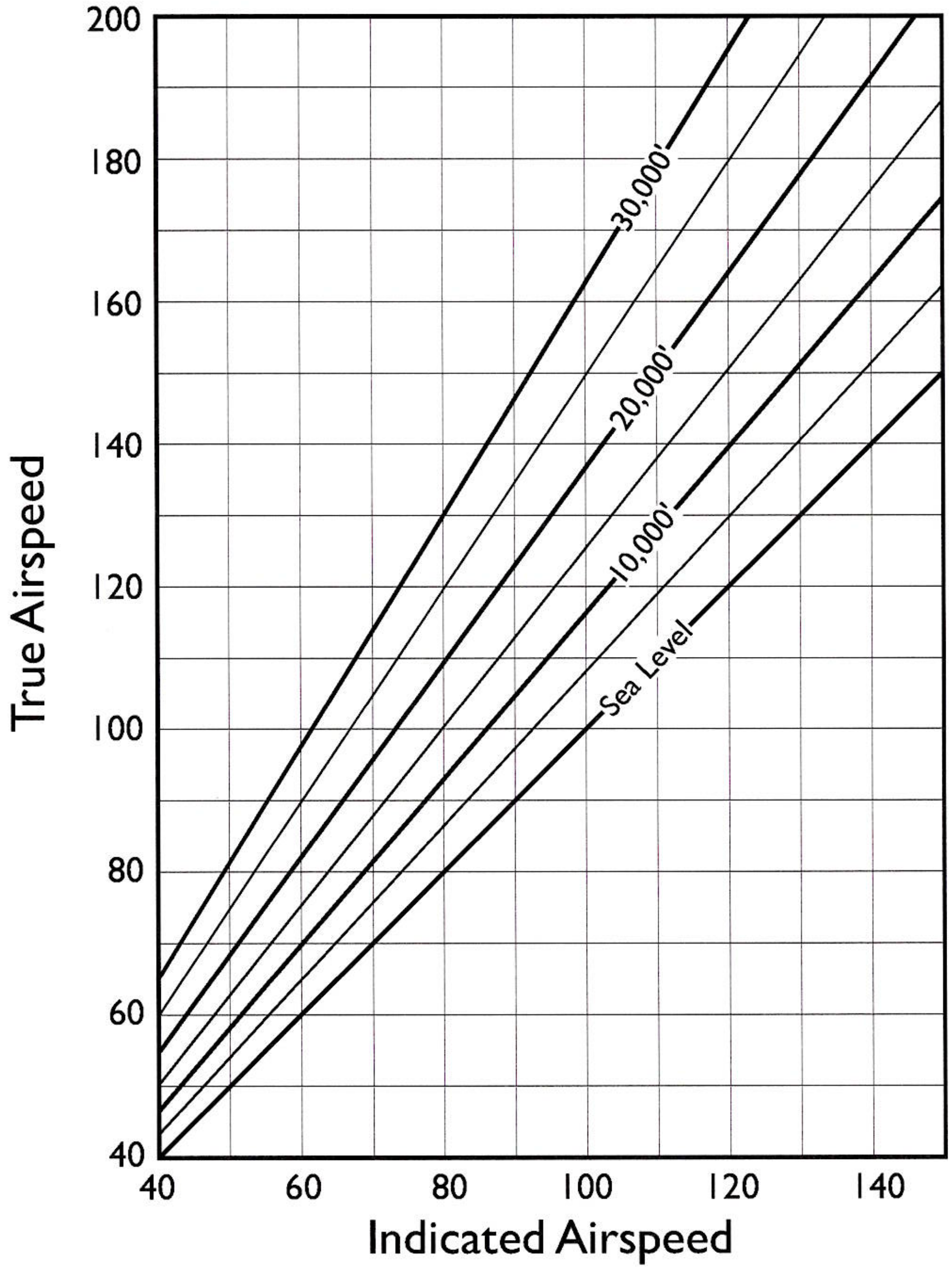
# DENSITY EFFECTS ON FLUTTER

$$\text{True Airspeed} = \frac{\rho_{\text{Sea Level}}}{\rho} \times \text{Indicated Airspeed}$$




The torsional frequency of the wing is relatively high.
As the frequency at which the aileron osciliates increases,
it can start to match the wing frequency, causing flutter.

# EFFECT OF ALTITUDE ON TRUE AIRSPEED



# SYMPTOMS OF HYPOXIA

- Headache
- Difficulty processing numbers
- Loss of coordination
- Decreased reaction time
- Impaired judgment
- Euphoria
- Apathy

***Prevention is crucial!***

# TIME OF USEFUL CONSCIOUSNESS

| Altitude (Feet MSL) | Time of Useful Consciousness |
|---|---|
| 30,000 | 1 to 2 Minutes |
| 28,000 | 2.5 to 3 Minutes |
| 25,000 | 3 to 5 Minutes |
| 22,000 | 5 to 10 Minutes |
| 20,000 | 30 Minutes or More |

# SYMPTOMS OF HYPOTHERMIA

- Shivering
- Clumsiness or lack of coordination
- Slurred speech or mumbling
- Confusion or difficulty thinking
- Poor decision making
- Drowsiness or very low energy
- Apathy or lack of concern about one's condition
- Progressive loss of consciousness
- Weak pulse
- Slow, shallow breathing

A person with hypothermia is usually not aware of their condition.

Persons 65 and older are more vulnerable.

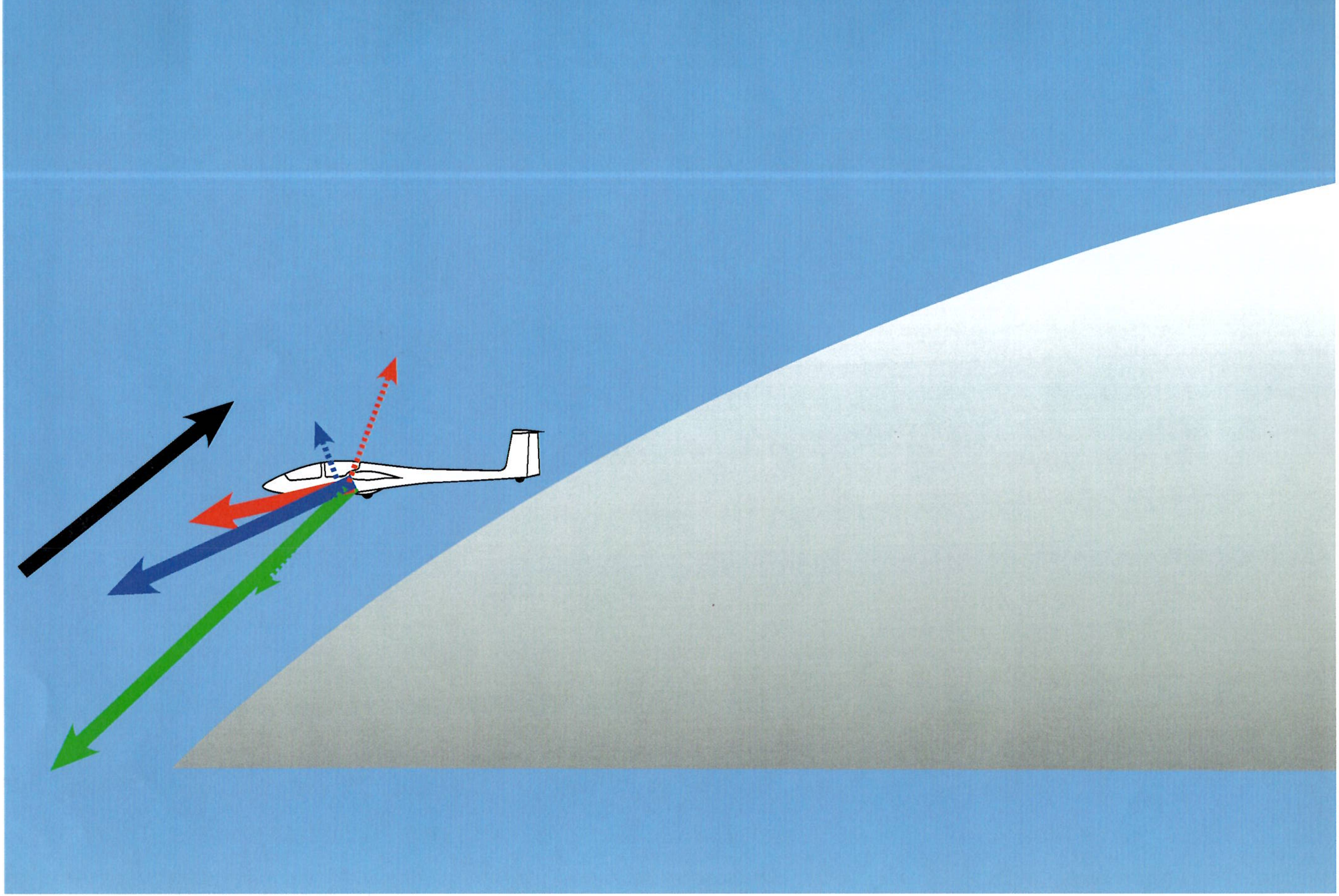
# SYMPTOMS OF DEHYDRATION

- Fatigue
- Dizziness
- Weakness
- Nausea
- Decreased physical and mental performance

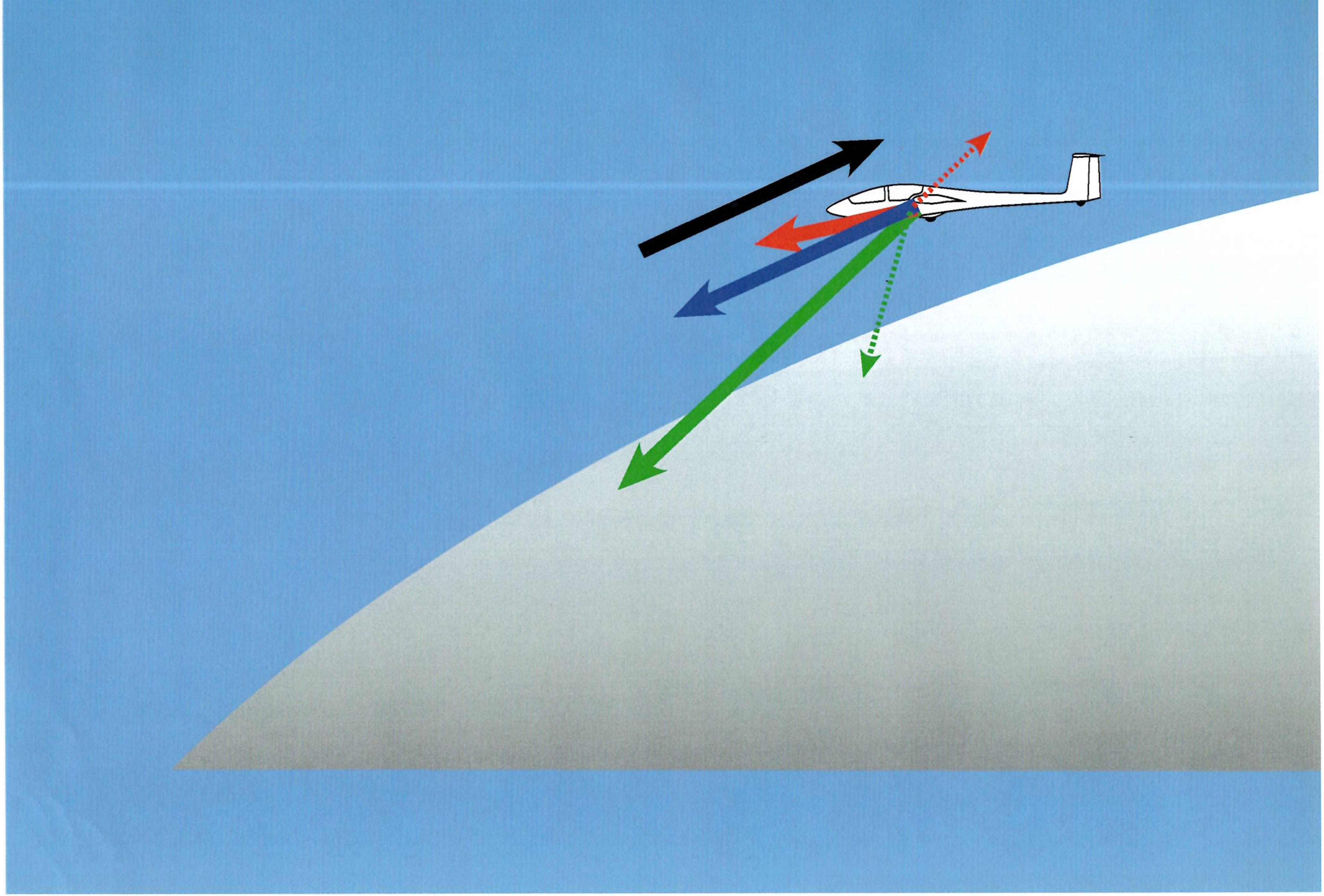
Blood vessels constrict when you are cold, increasing urine production, removing liquid from your body.

When you descend and start to warm up, blood vessels dilate, decreasing blood pressure, and increasing dehydration

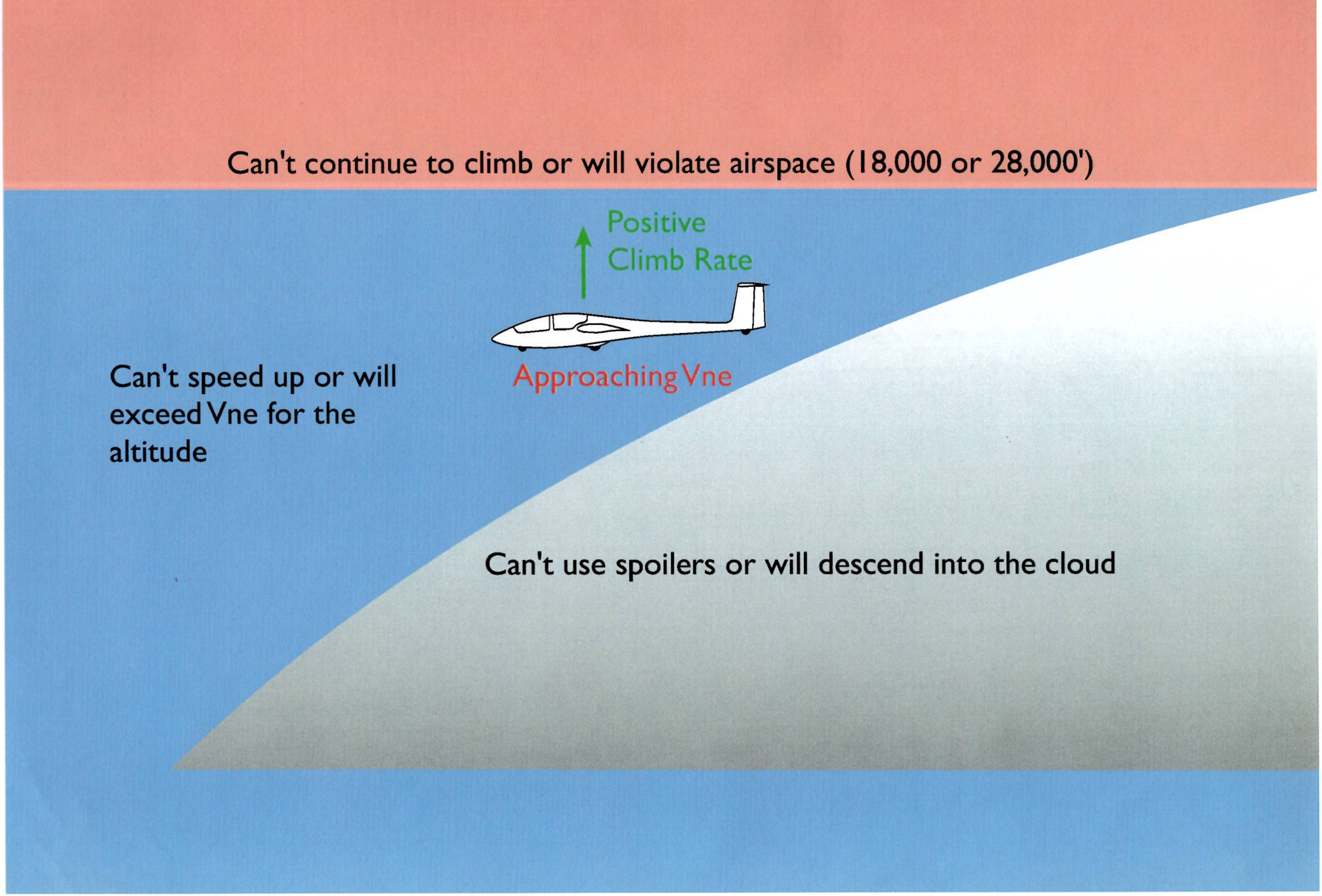
# GETTING BLOWN OVER THE TOP



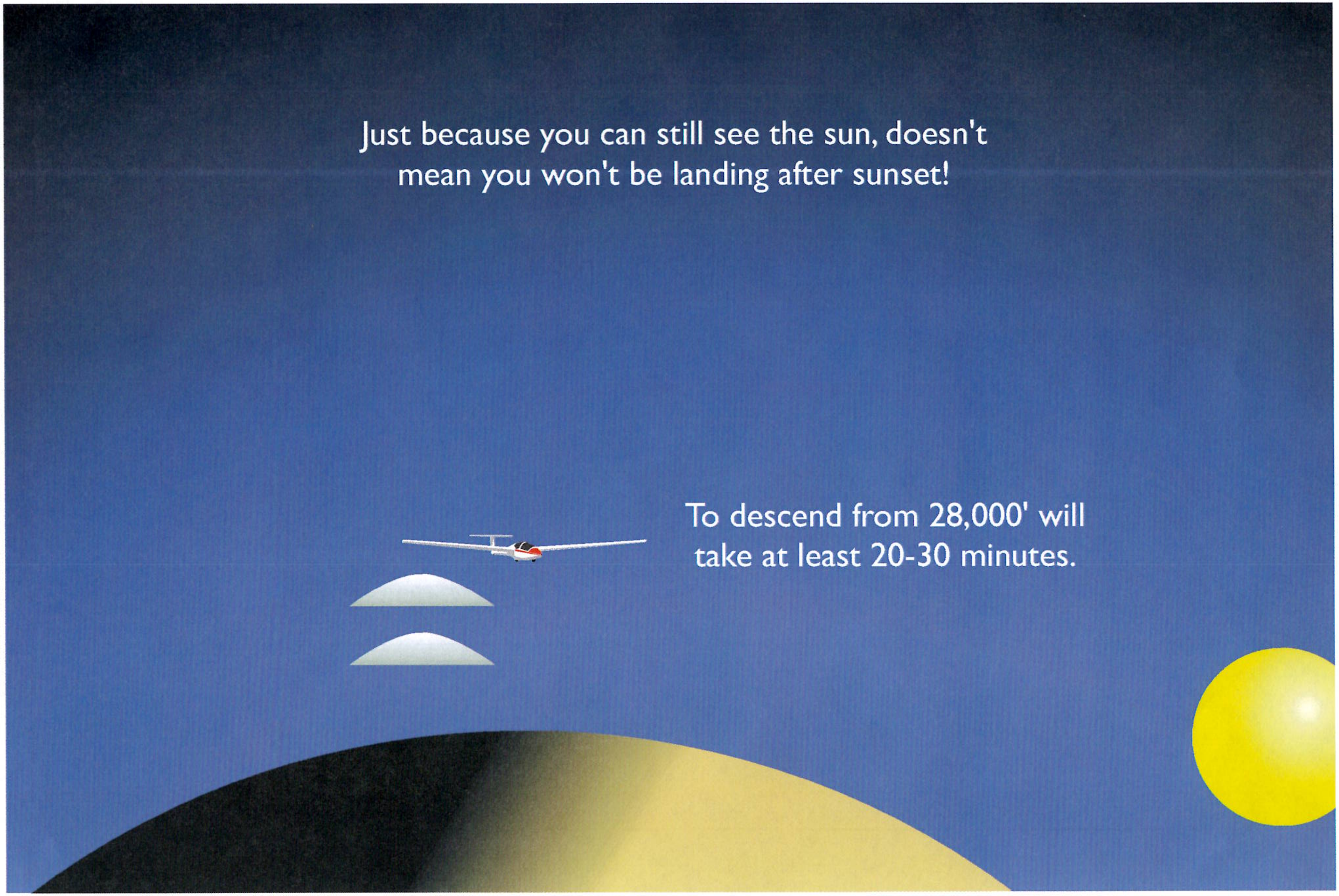
# GETTING BLOWN OVER THE TOP



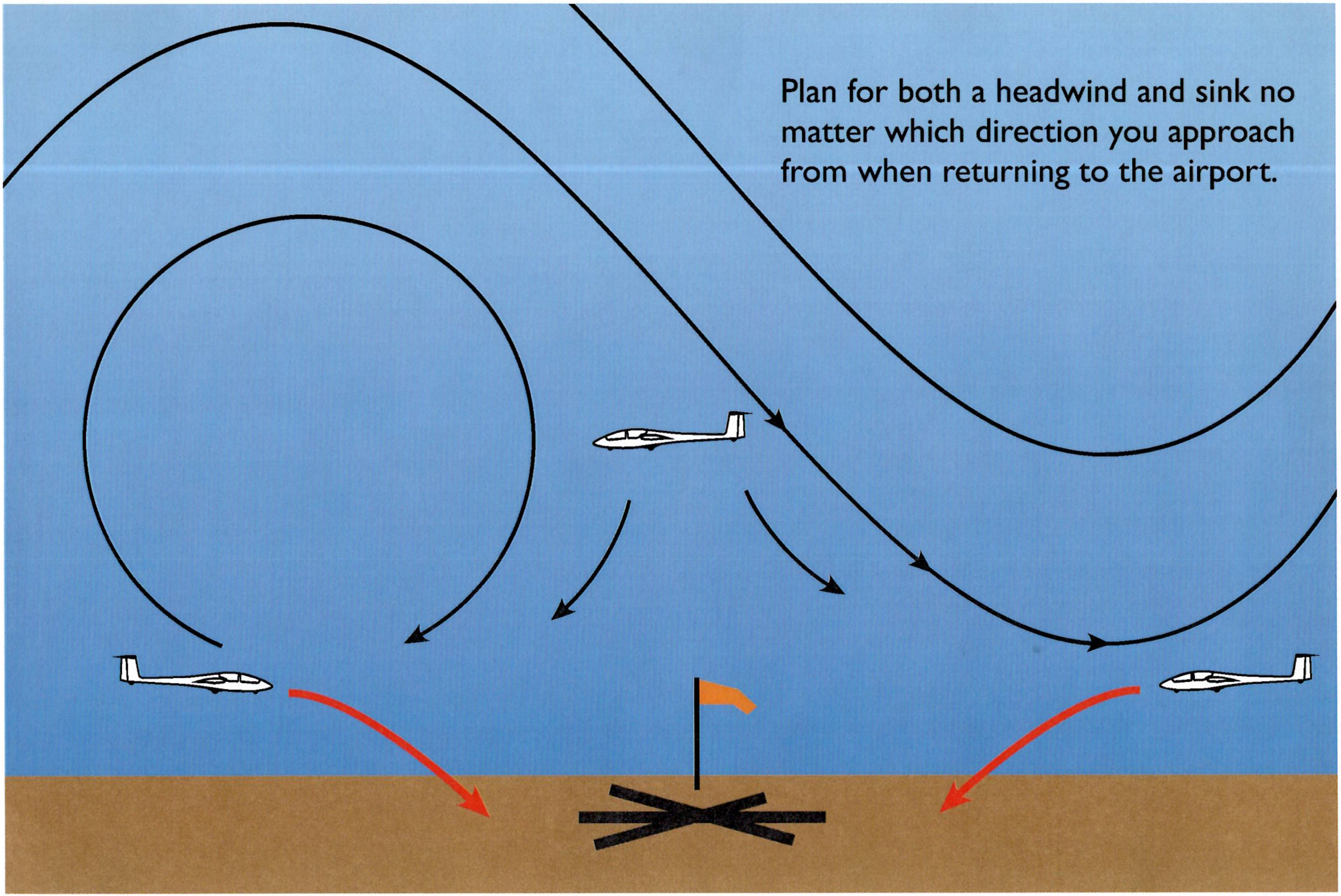
# THE "SQUEEZE"


Can't continue to climb or will violate airspace (18,000 or 28,000')
Positive
Climb Rate
Approaching Vne
Can't speed up or will exceed Vne for the altitude
Can't use spoilers or will descend into the cloud

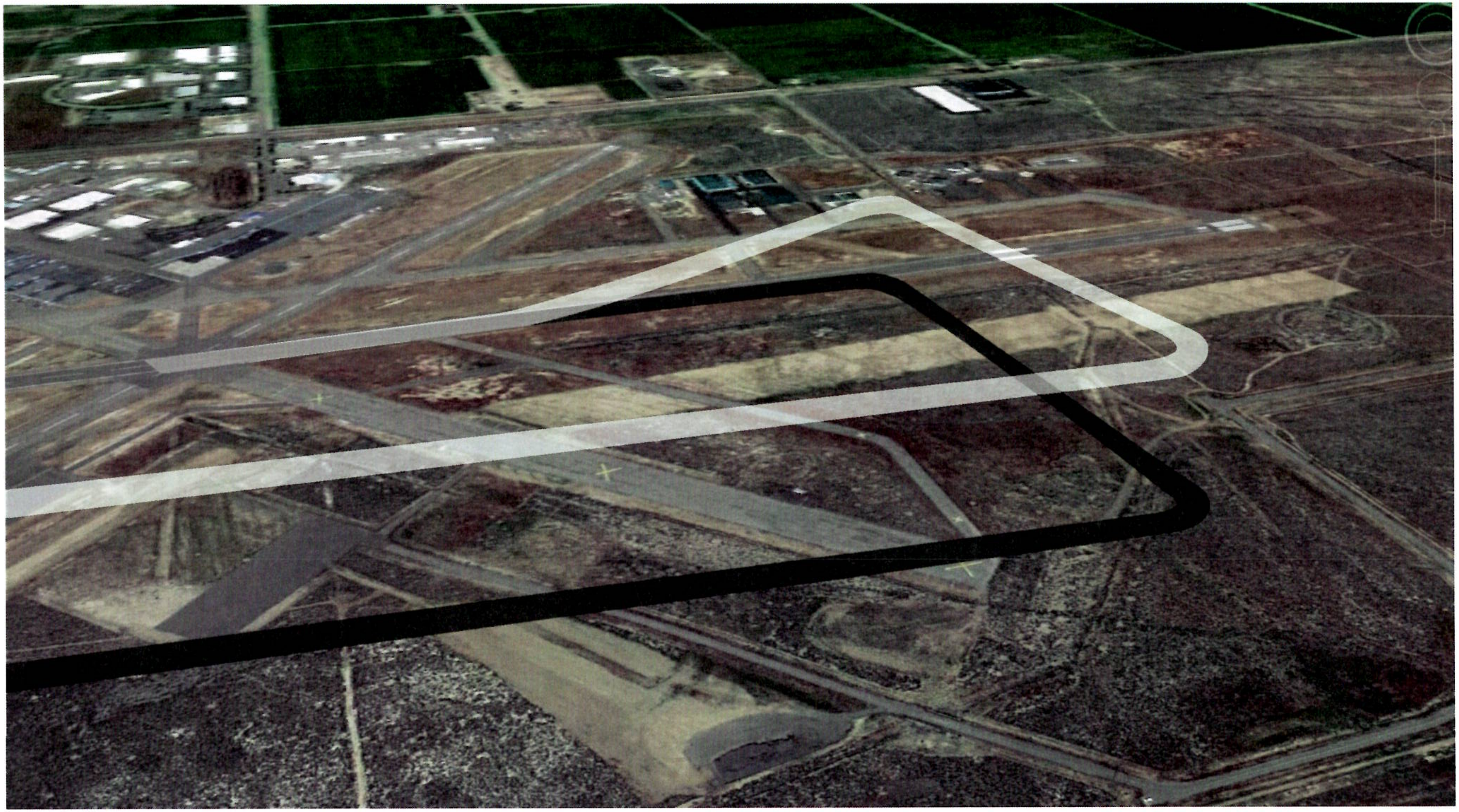
# SUNSET


Just because you can still see the sun, doesn't mean you won't be landing after sunset!
To descend from 28,000' will take at least 20-30 minutes.

# HEADWIND AND SINK



# FLYING THE PATTERN



The location of your aim point and where you turn base is determined by the wind speed.
In strong winds, it is difficult to turn base too early, or be too high on final

# TOO LOW ON FINAL

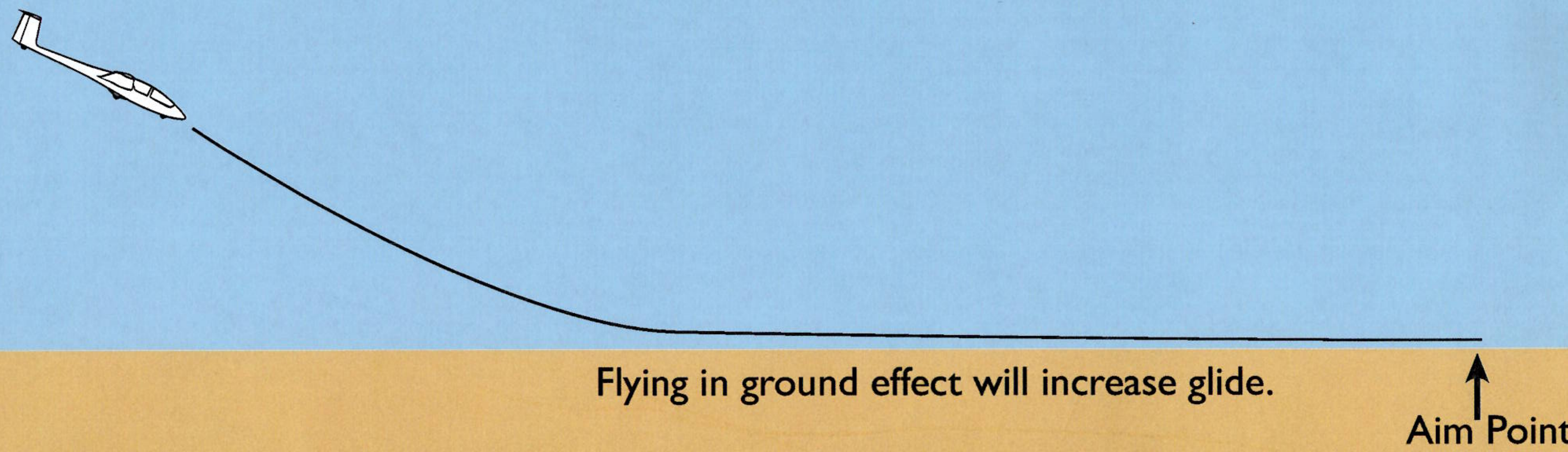
Cause: Unexpected Headwind - Remedy: SPEED UP to penetrate wind

or

Cause: Sink - Remedy: SPEED UP to get out of the sink

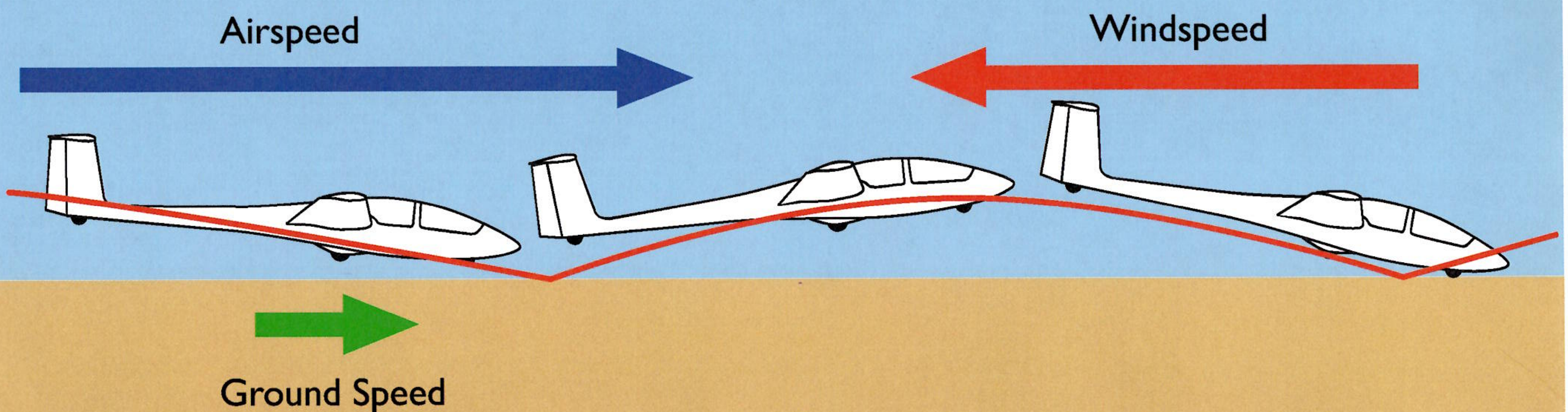
or

Cause: Misjudged - Remedy: SPEED UP to get into ground effect



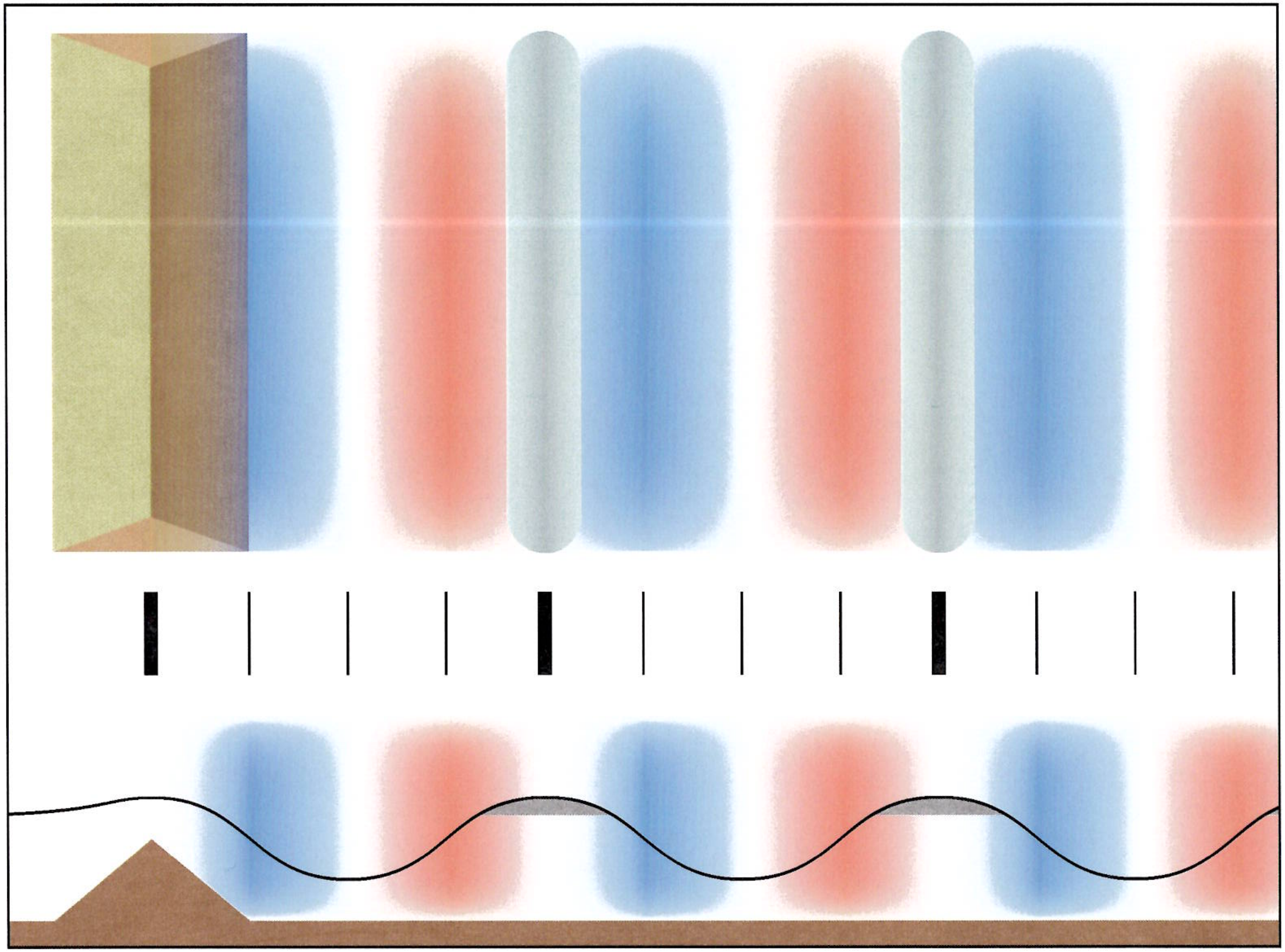
# PILOT INDUCED OSCILLATIONS

Strong headwinds can fool you into landing with more airspeed than expected, leading to a PIO.
Don't let the glider touch down until reaching a "normal" landing pitch attitude.



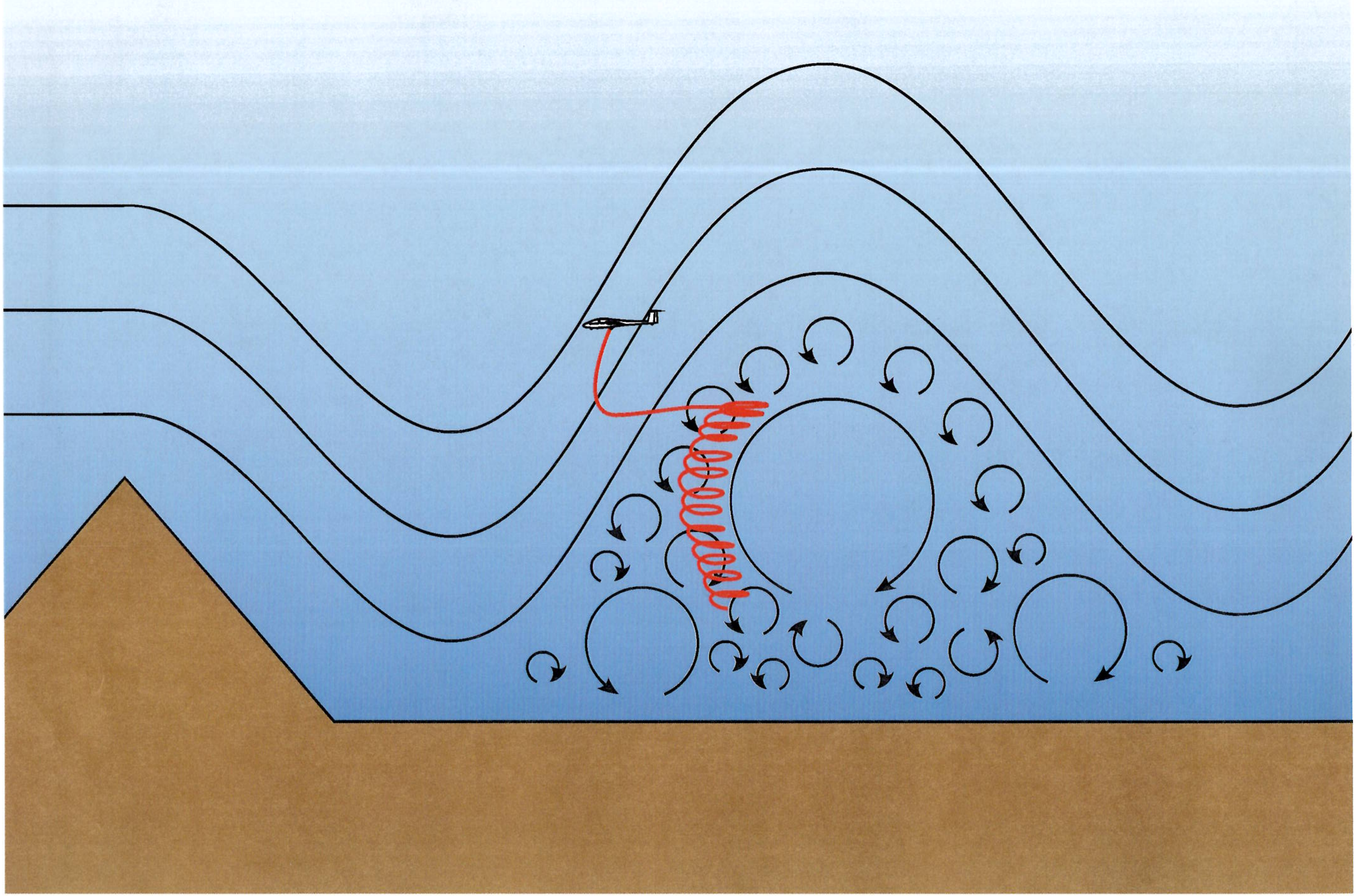
# FINDING AND USING WAVE LIFT

# STRONGEST LIFT

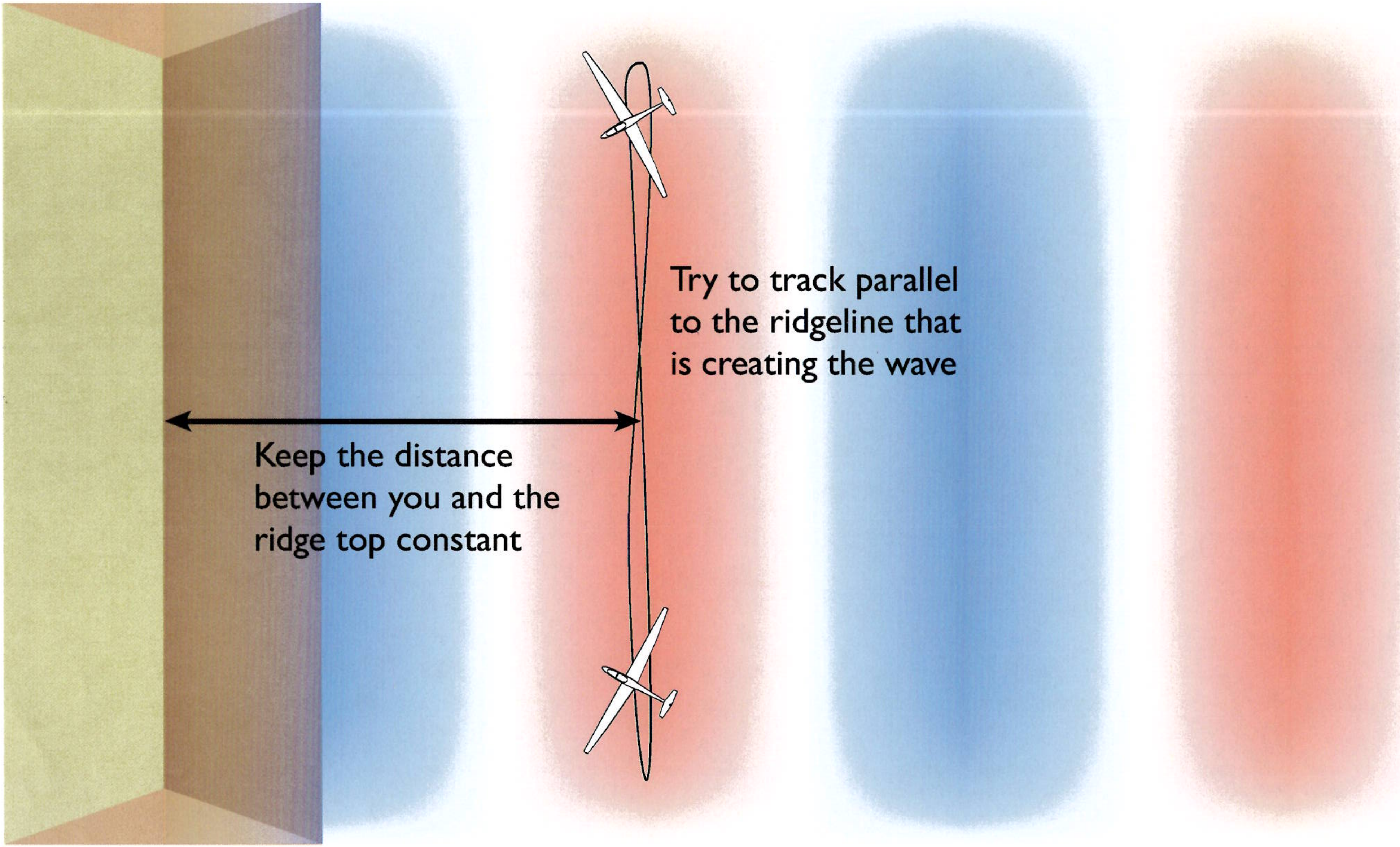


The strongest lift will generally be 3/4 of the wavelength between the peak of the mountain and the center of the lenticular cloud.
At higher altitudes the best lift tends to move upwind.

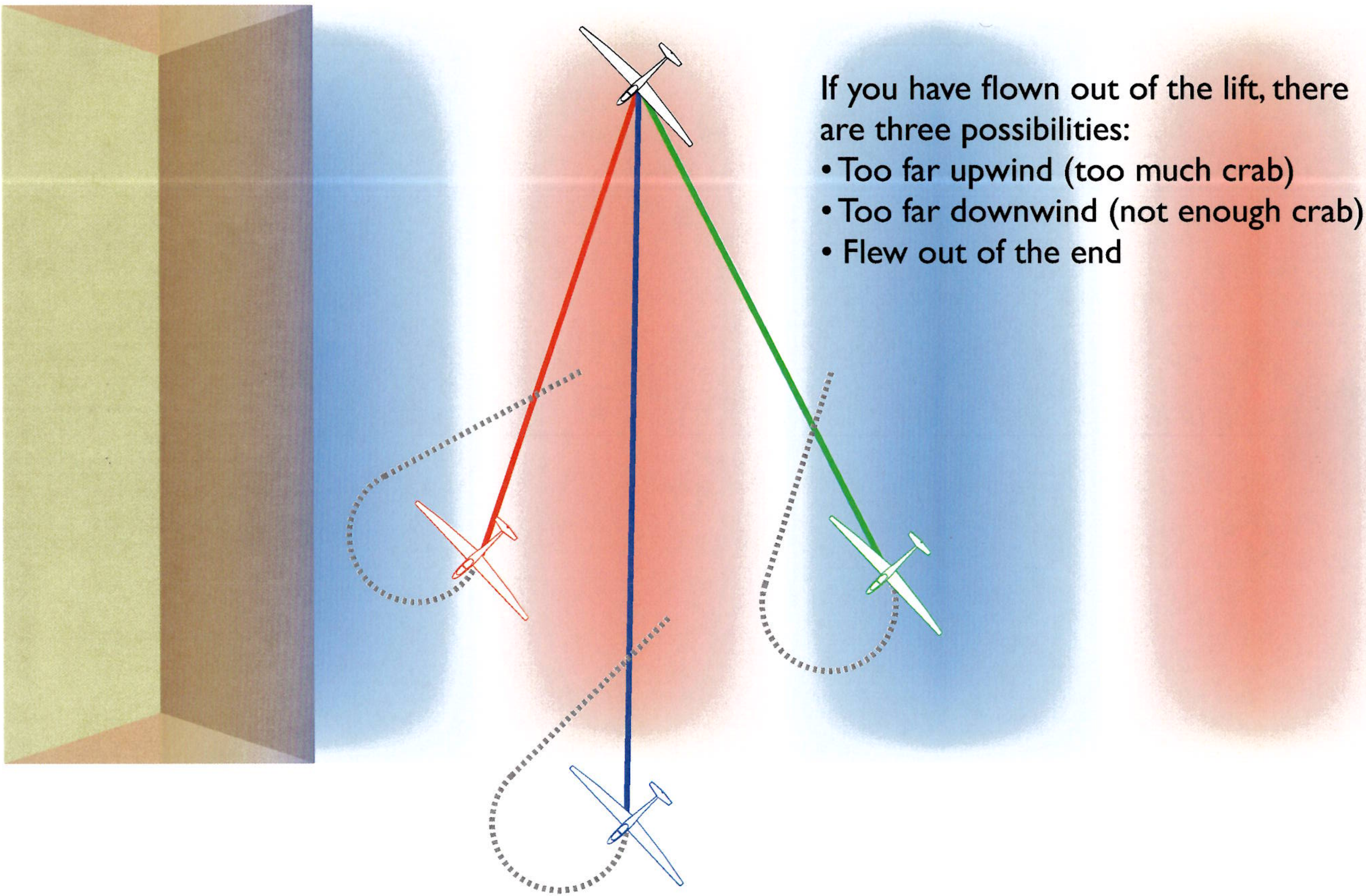
# CLIMBING IN ROTOR



# WORKING WAVE LIFT



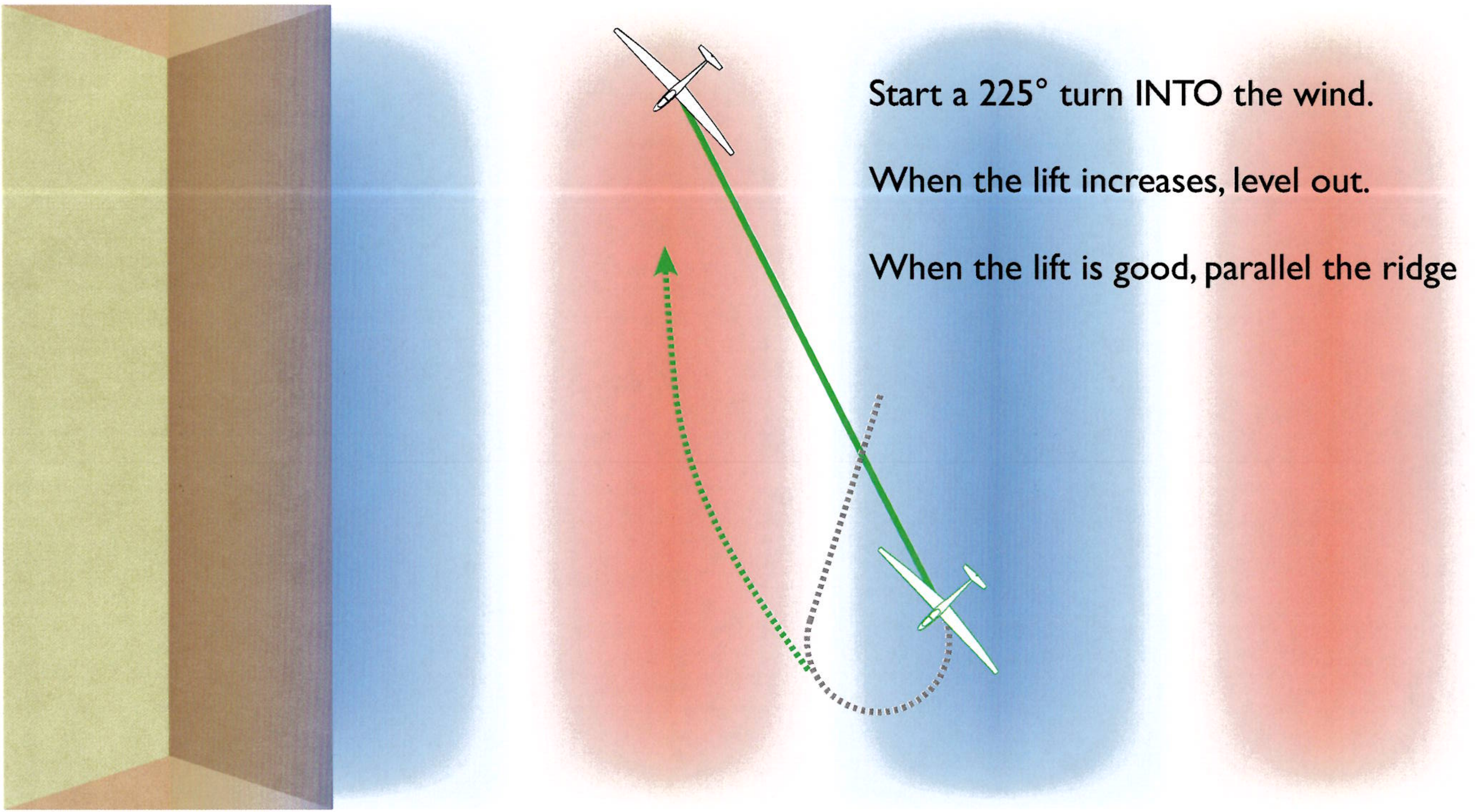
# FLYING OUT OF THE LIFT



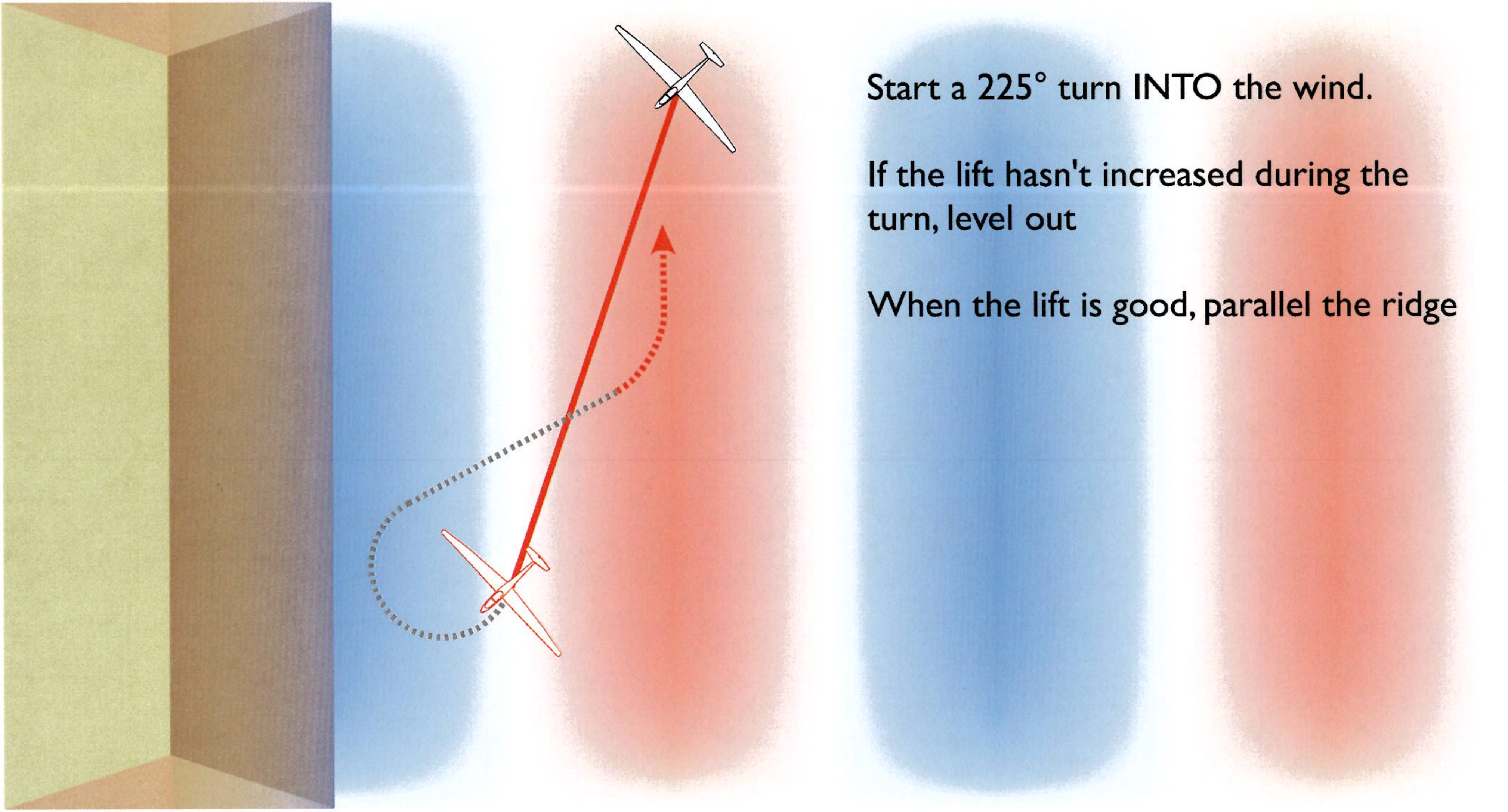
If you have flown out of the lift, there are three possibilities:

- Too far upwind (too much crab)
- Too far downwind (not enough crab)
- Flew out of the end

# FLYING OUT OF THE LIFT - TOO FAR DOWNWIND



# FLYING OUT OF THE LIFT - TOO FAR UPWIND

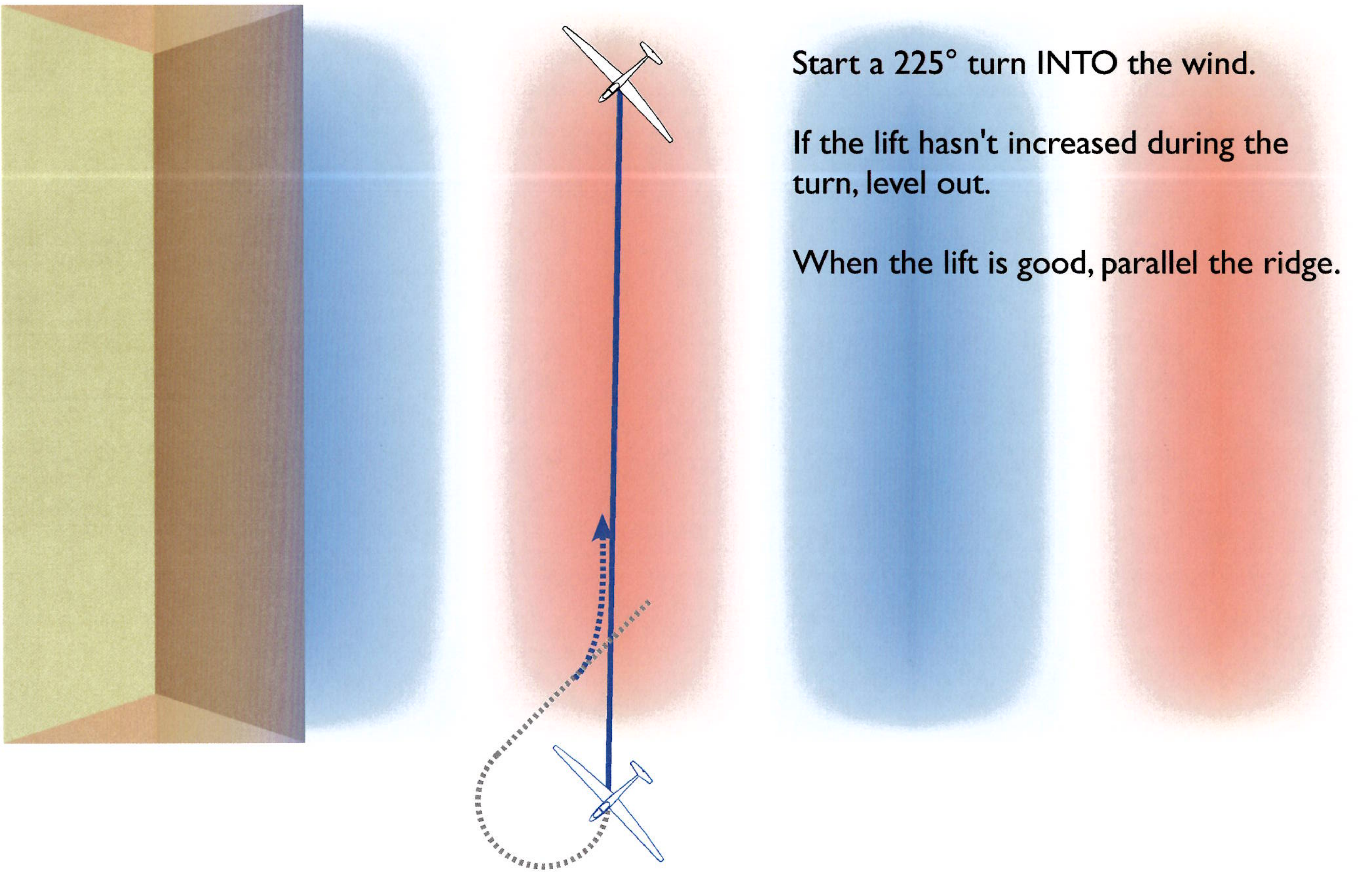


Start a 225° turn INTO the wind.

If the lift hasn't increased during the turn, level out

When the lift is good, parallel the ridge

# FLYING OUT OF THE LIFT - OUT THE END

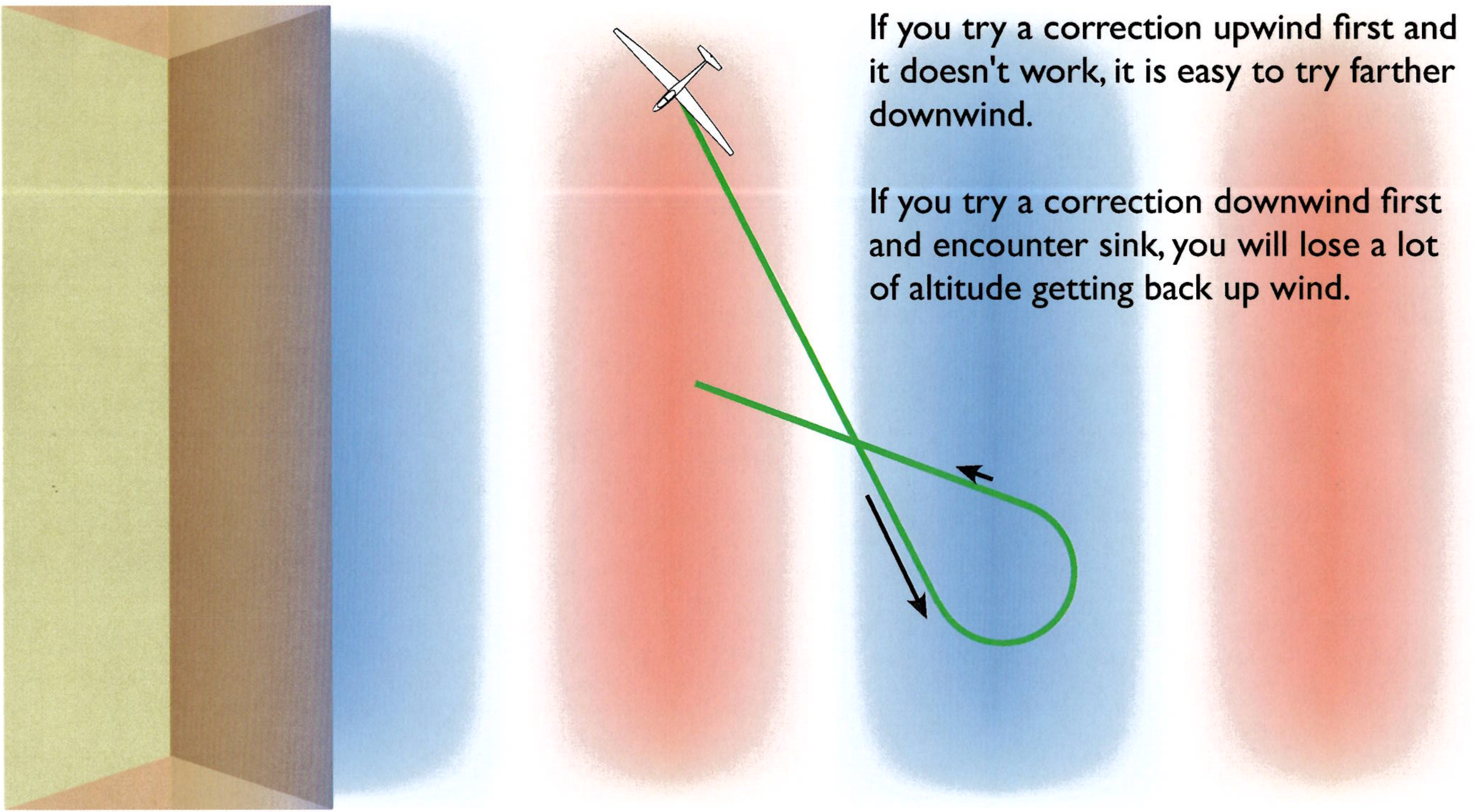


Start a 225° turn INTO the wind.

If the lift hasn't increased during the turn, level out.

When the lift is good, parallel the ridge.

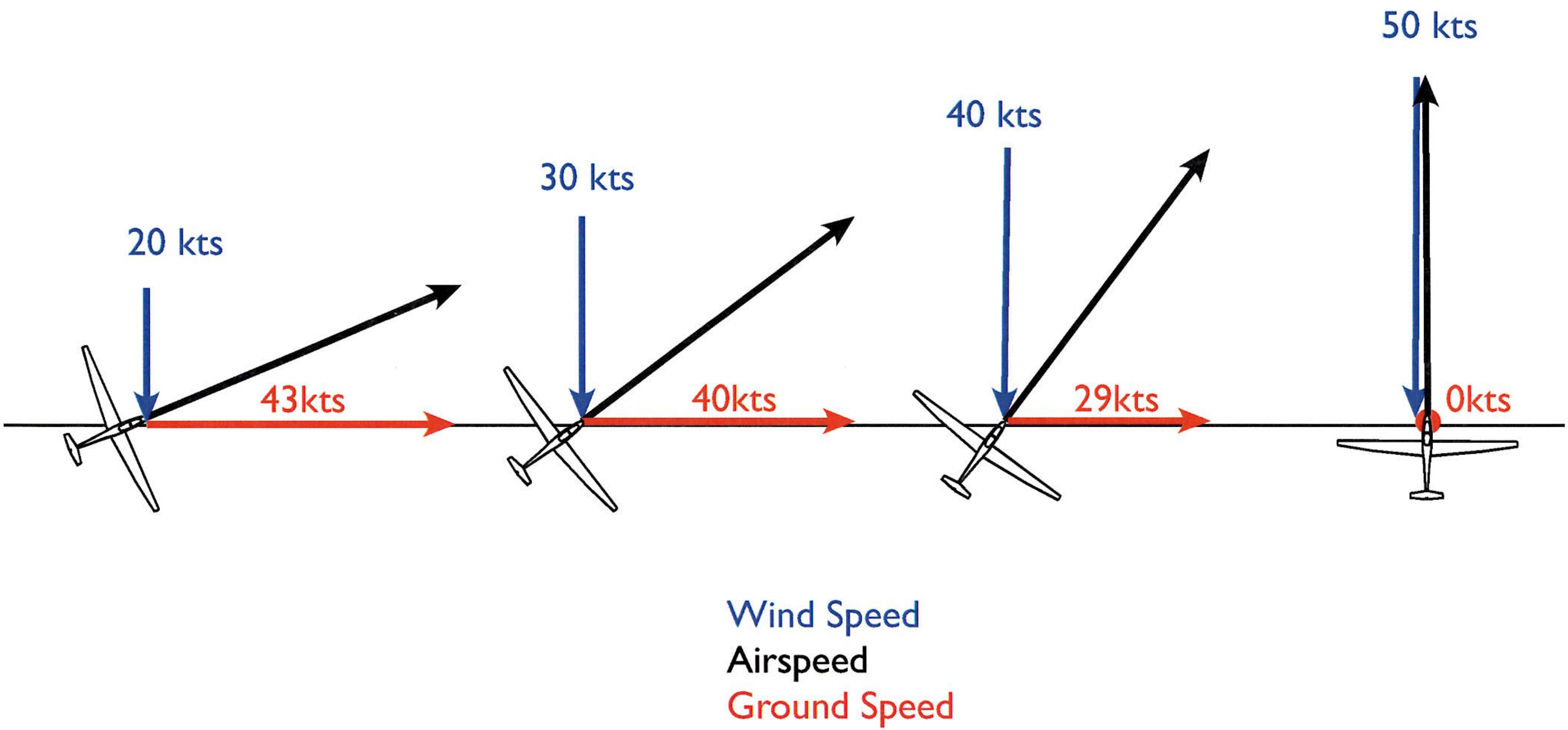
# TRY UPWIND FIRST



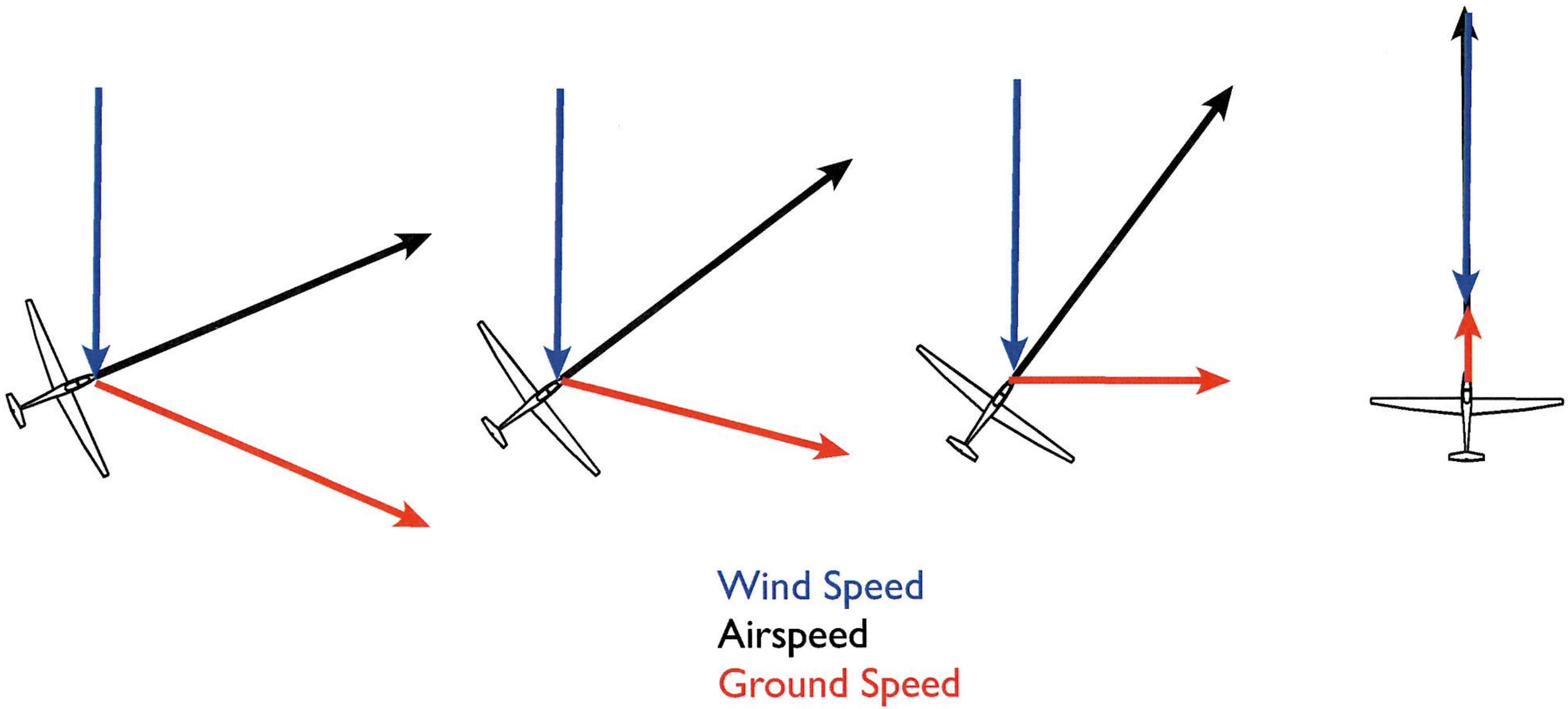
If you try a correction upwind first and it doesn't work, it is easy to try farther downwind.

If you try a correction downwind first and encounter sink, you will lose a lot of altitude getting back up wind.

# EFFECT OF WIND SPEED ON CRAB



# EFFECT OF CRAB ANGLE ERRORS ON TRACK



# MENTAL MODEL

Create a mental model of what you think is happening in the atmosphere

See how well your model explains the lift/sink you are encountering

Adjust your model

Repeat

# THE END
# (GO FLY)