Weather 2 Fly

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Pilot
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Personal Introduction

I'm Dan Gudgel. Just to give you evidence that I might possibly know what I'm writing about here, and to prove that I haven't been letting the grass grow under my feet, here's what I've been up to for the last 5 or 6 decades.

I was born to a crop duster farmer and raised on a farm and airport in California's fertile Central Valley. My formative experience fostered a fascination with meteorology, so I got a meteorology degree from San Jose State University. Meanwhile, I worked with my dad as a professional agricultural and charter pilot in the family business. I continue to hold a current journeyman agricultural pilot certificate for the state of California. For several years, I've been a California Agricultural Aircraft Association Board Member and have been actively participating in the Professional Agricultural Aircraft Safety System Program (PAASS).

I worked after college for the U.S. National Weather Service (NWS) for 36 years in varying roles, an aviation meteorologist, a station manager, or a program manager while continuing to expand my aviation interests.

While working in the Reno Office of the NWS in Western Nevada in 1975, I assisted with soaring-weather forecasts – this piqued my interest, and I took my first soaring flight at Minden.

This led to a keen interest in soaring, and I contributed to the soaring community by routinely providing on-site weather support for local and regional soaring contests in California and Nevada beginning in 1979.

Shortly after that, I became active as a tow pilot and as a gliding instructor. I've flown somewhat more than 1500 hours in gliders and 4500 hours in airplanes. I now hold flight instructor certificates in gliders, single and multi-engine airplanes, instrument airplane, and rotorcraft-helicopters.

I serve the soaring community also as an FAA-Designated Pilot Examiner for the glider category. I also serves on the Board of Directors of the Central California Soaring Club, and I split my service as instructor and tow pilot between this club and Skylark North Flight School in Tehachapi, CA.

I enjoy working with the soaring community as a soaring meteorologist at local, regional, national, and international soaring events. Often I also am concurrently the chief tow pilot. I have served at more than 60 events so far.

It's been an honor to be trusted and respected enough to have been asked to serve as a support meteorologist at the International Masters of Soaring in 1986 and 1987, Chief Tow pilot and meteorologist for the cross-country Return to Kitty Hawk event in 2003, Lead Meteorologist in the pre-World Gliding Championships (Ameriglide) in Minden in 1990, the lead meteorologist in the WGC in Uvalde in 1991 and 2011, and was privileged to serve Barron Hilton at the Hilton Soaring Cup as meteorologist and tow pilot from 1986 until Mr. Hilton's passing. I also was asked to provide meteorology support to the Earthwinds-Hilton Balloon World Circumnavigation Attempt. I was lead of the team of meteorologists at the World Gliding Championships at Uvalde, TX, in July and August 2012.

During 2018 and 2019, I was asked to work with the Perlan Project in El Calafate, Argentina, in support of the stratospheric record-altitude soaring flights of the Perlan II glider, for which Einar Enevoldson was the inspiration.

Wx-Dan Gudgel

Editor’s Introduction

This is a book about the weather we use to fly gliders (soar sailplanes, if ambitious).

I love to make books. Dan Gudgel and I shared a cabin in El Calafate with Perlan. I lazed around, comparatively speaking, as the team medical advisor. I heard him grumble out of bed at 0400 every morning, and labor at his computer, muttering imprecations at slow software response and conflicting data, grinding coffee beans by hand to make cup after cup of excellent coffee, while I dozed until it was time to make our morning Health Oatmeal.

He taught me a good bit about meteorology; more important, I saw that he was as perfectionistic professionally, and as intolerant of foolishness, as I am in medicine.

He and I had for some years written parallel monthly columns for *Soaring* magazine, I on medical physiology related to flight (https://tinyurl.com/drdanscolumns); he, on incisive basic truths of soaring weather. I encouraged him to create this book from that material, dangling the carrot that I’d do the editorial heavy lifting if he’d to the authorial heavy lifting.

We have tried to add some advice about using weather pragmatically, beyond the theory. Every form of professional practice must go beyond theory to nuanced advice and action. Understanding the physics of weather does not a forecaster make: the forecaster must look out the window, to see whether the models are connected to fact, and to verify his own forecasts. Nor does reading about disease physiology make a competent doctor; experience corrects many wrong assumptions and misconceptions.

Similarly, the soaring pilot can read about and understand weather theory but cannot comprehend strategically the weather through which the glider is piloted without practice and application. *Where’s the next thermal? How do I get out of this sink?* are the questions that test a pilot’s understanding of weather.

We hope that book helps you take some steps in that direction.

Dr-Dan Johnson

Feet on the Ground, Eyes on the Sky, Rulebook Nearby

Before we launch into the interesting technicalities, let's take a couple of pages to discuss why I've written this material down. It's optional reading. I simply want you to be able to understand the "context" in which I write and in which I act as a pilot, instructor, examiner, and meteorologist.

I've seen great angst in student pilots as they look ahead and begin to comprehend the pilot certification process and the depth of learning that must occur before they are ready for certification. Rote memorization of Federal Aviation Regulations (FARs) and trying to understand meteorological phenomena both often seem daunting.

It is necessary to know the FARs because they keep pilots and other aviation professionals on the same page operationally in the national airspace system, and they create limits aimed at flight safety. The FARs, it is sometimes said, are written in blood. But learning the FARs is rather unexciting by nature as it feels simply like a rote learning task to endure.

Unlike learning the FARs, meteorological knowledge has obvious application to flight and therefore is very much of interest for aviators of all categories of aircraft. However, meteorology is a broad and complex subject area that is not quickly mastered. It requires diligent study by the student and can be an intimidating learning challenge, especially for those who do not have a technical background and have not become comfortable with elementary physics and math, and thus do not know the language in which meteorology is described. The Practical Test Standards (PTS) of the Federal Aviation Administration (FAA) require an understanding of meteorology, familiarity with the various text and graphic observation and forecast weather products, and the ability to apply and correlate this information for aeronautical decision-making for safe flight.

Pilots in the Airplane, Rotorcraft, Powered-Lift Aircraft, and Sport Pilot classes chiefly review meteorology for its impact on their flight. Glider category pilots additionally use meteorology phenomena as the aircraft power source gain altitude and to fly cross-country. To their credit, experienced glider pilots are especially attentive and knowledgeable of the weather in comparison to comparably experienced powered-flight colleagues.

There is nothing new under the sun here. My goal is to discuss weather in ways that might help you better understand and use weather and forecasts for safe and enjoyable soaring flights. I will review items that will help any prospective aviator working toward obtaining a pilot certificate go beyond meeting the FAA's test standards for weather knowledge, and to be able to talk about the practical application of that knowledge for soaring flight.

The practical test standards (PTS) require knowledge of "Weather Information" and list "thermal index and thermal production" and "other lift sources" as mandatory. Glider pilots use the atmosphere's various types of upward vertical motions to stay aloft and to proceed with cross country flight.

While thermal lift is the most widespread lift generator used by pilots, and is specifically listed in the FAA PTS, other forms of atmospheric vertical motion frequently occur for glider pilots under the proper meteorological and terrain conditions. The other lift types providing upward vertical motion for gliders are *ridge lift and upslope flow*, *mountain wave,* and various types of *shear* or *convergence* lines.

A rudimentary understanding of these lifting processes in the atmosphere, including those just listed as well as well as frontal boundary discontinuities, helps a pilot soar cross country.

Besides discussions on the atmospheric lifting processes for soaring flight, it is important also to understand weather phenomena that result in hazardous flight conditions. It behooves the soaring pilot to not only observe the weather, but also become short-term forecasters as they fly.

A skilled pilot is one who not only understands the atmospheric lifting processes but also continually observes for severe weather or those conditions that lead to severe weather. For example, pilots are quite aware that a thunderstorm is “Mother Nature’s Severe Weather Generator” that may contain icing, turbulence, poor visibility in heavy rain, low cloud bases, lightning, and other severe weather such as hail, downbursts, or tornadoes. High, gusty, and shifting winds are also present around any cell or thunderstorm complex.

Strong and gusty synoptic-scale winds (affecting hundreds of miles) result in moderate to severe mechanical turbulence and severe wind gradients, creating issues in landing. Flight visibilities can be locally reduced to instrument meteorological conditions due to blowing dust. Increasing atmospheric-layer moisture can rapidly change cloud coverage into overcast and/or undercast conditions. Fog may develop and surround the glider.

Even apparently benign weather can produce insidious dangers to thermal soaring flight in the form of high density altitudes from high temperatures in strong heating conditions, or the detrimental effect of frost on the wings from a clear, cold night before a wave flight is attempted.

The weather forecaster isn’t a prophet: the forecast is an expert projection of the present conditions, and can never be perfectly accurate. The 3-day outlook is like a 3-point shot in basketball: the farther out, the lower is the percentage. The forecast provided should include an indication of the degree of confidence of the forecaster, and is intended to inform a pilot’s initial pre-flight planning.

However, ***lift is where you find it!*** As indicated in a fine series of annual cross-country seminars from the Pacific Soaring Council (PASCO) in the 1999-2003 period, a skilled soaring pilot is one who learns about the atmosphere’s forms of vertical lift (and weather threats), remains alert to and aware of evolution of the local weather during a flight, and keeps an open mind to change flight tactics to accommodate any changes in the course of that flight.

Besides discussing weather phenomena in the next chapters, I will also provide reference sources for more complete information and to assist you in building a library. With assistance from my meteorologist compatriots and soaring peers, I suggest “road maps” and advice on how and where a pilot might find and apply information toward a safe flight. My goal is to lead you to the point that you can confidently find whether you have ***Weather to Fly***.

Library Build:

[I’d propose that most references be placed at the end of the, book. We can easily cross-reference to them in the text.]

1) *Extended Cross Country Soaring Seminar*. Pacific Soaring Council, copyrighted, published, and distributed by CH Engineering, Reno, NV.

2) Soaring Society of America Website. www.ssa.org

---On the Left Side Menu: Click “News and Info”

---On the Drop-Down Menu: Click “Weather”

---Peruse the various tutorials on weather and weather-related info.

3) *Aviation Weather*. *AC 00-6A* FAA/Gov’t Printing Office, 1975

Ridge Lift

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Illustrations:
…Two (2) Diagrams (Lapse Rates, and Slope Flow)
…One (1) Weather Map (April 4, 2006)
…One (1) Temperature Sounding (Pittsburgh on April 4, 2006)
…One (1) Picture
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The atmosphere provides vertical air motion or[1] atmospheric lift in various forms and thereby provides the "engine" for soaring pilots to accomplish cross-country flight. There are four mechanisms of atmospheric lift used for soaring flight:

- ~ ridge,
- ~ thermal,
- ~ mountain wave, and
- ~ convergence.

We begin our discussion of these specific lift mechanisms with a focus on ridge lift, the mechanical lifting of air as it encounters upsloping terrain.

People in the general public typically seem aware that "wind" is necessary to gliding and soaring, as if no other lifting mechanisms exist in nature. This simplistic view is fortuitously accurate with regard to soaring ridges. Among soaring pilots, this has several names – ridge, slope, hill, and orographic all refer to the same process.

In the jargon, upslope and ridge lift is "mechanical lift" because it does not require the buoyancy mechanism behind thermal soaring, that we explain in the chapters to come. "Upslope" lift is wind that has not yet topped a ridge; "ridge lift" typically extends far above the ridge top because a substantial thickness of flowing air is forced upward by the rising terrain upwind of the ridge top.

The *Glossary of Meteorology* says that orographic lifting is "the lifting of an air current caused by its passage up and over mountains." More specifically, the rise or upward flow of air passing over terrain begins on the upwind or windward side of terrain obstructing horizontal air movement (wind).

Importantly, in the lee of a ridge and over the downslope, air is *down-going*, sometimes powerfully, that may trap a glider on the wrong side of a ridge or crash it with whirling turbulence – a *rotor*.

The development and persistence of useful ridge lift is a function of several factors: atmospheric stability, wind direction and speed, and terrain shape.

Strong, "classic" ridge lift is characterized by smooth, upward motion on the windward side of slopes, hills, and ridges. For long-distance soaring it requires synoptic scale *stable* meteorological conditions ("synoptic" = extending across 100s to 1000s of miles). *Why should the conditions be* stable*, and what does this mean?*

Atmospheric Stability and its Effect on Ridge-soaring Conditions

When planning to use ridge lift for soaring flight, it's important to consider atmospheric moisture, because the lifted air cools. If it cools to the dew point, cloud will develop. In the worst situation, steadily cooling clear but humid air may swiftly engulf a glider. This inevitably causes spatial disorientation within 15 seconds and a usually-fatal crash. As the jargon says, "cloud formation may occur, affecting the ability to maintain visual flight rules and meet cloud clearance requirements."

The development of clouds will be addressed in more detail when I explain thermal development. For now, I simply need to admonish you to remember that the orographic lifting process can develop "surprise" instrument flying conditions near a ridge. Here are the essential ideas –

[1] In English, "or" means "and/or." This sometimes creates ambiguity when *or-not-and* is intended.

The meteorological definition of an *unstable* atmosphere is that air raised from its original altitude by any means will tend accelerate upward.

The “stability” of the local atmosphere is chiefly related to the particular decrease in temperature with altitude that happens to exist in the area. This temperature gradient is the *lapse rate*.

Pragmatically, *stable* means “rain clouds won’t form.” *Unstable* means “rain clouds are likely” if there’s enough humidity. If the air is too dry to form clouds, *stable* means, “turbulence only due to terrain” and *unstable* means “turbulence throughout, possibly severe.”

Whether the local atmosphere is stable can be determined by measuring the *prevailing* or *ambient* lapse rate of temperature (measured by a gadget lifted under a balloon – a *sounding*) and comparing this with the *dry adiabatic lapse rate*[2], DALR in the jargon. As a parcel of air is raised in altitude, it expands and cools. The dry adiabatic lapse rate describes the natural decrease in temperature that occurs with the expansion of a parcel of dry air (without visible moisture) that is lifted by any means.

The engine of a hot-air balloon depends on the fact that warm air is more buoyant than cool air at any pressure. Any parcel of air that is warmer than the air surrounding it will buoyantly accelerate upward. This acceleration is *instability*. Conversely, a stable atmosphere is one where the ambient lapse rate is less than the dry adiabatic lapse rate `(insert Diagram #1: Atmospheric Instability Relative to Lapse Rates)`.

Air forced upward by flowing over upsloping terrain in a *stable* atmosphere tends to flow smoothly except for tumbling across obstructions. If it cools below its dewpoint as it rises, stable, fog-like clouds will form that don’t detach from the terrain. The condensation may decrease the parcel’s stability.

Neutral stability means that the temperature lapse rate equals the dry adiabatic lapse rate. The atmosphere becomes neutrally stabile with stronger winds that mix the atmosphere thoroughly near the ground. This is why strong winds on the ridge are not associated with ridgetop fog. With strong and steady winds, long-distance flights using ridge lift are commonplace near long mountain ranges around the world.

Air forced upward by flowing over upsloping terrain in an *unstable* atmosphere departs from smooth, laminar flow across the terrain. As it ascends into temperatures cooler than itself, it accelerates upward. The flow detaches from the terrain and rises as pockets or bubbles – the terrain acts as a trigger for the atmosphere to “turn-over” and rise in pockets – in other words, *thermals*! If the lifted air is moist, cumulus clouds form that are detached from the terrain. I’ll cover the nuances of this in the chapters coming right up.

Slope soaring is still possible in an atmosphere tending toward unstable, but turbulence will be greater. With a lapse rate favoring instability (upward acceleration of lifted air), thermals will form. Thermals disrupt laminar ridge flow. The soaring pilot cannot see these, and *feels* the transition from smooth ridge flow into or out of a thermal bubble or thermal core as a bump. In moist, unstable conditions, clouds will mark these, so the turbulence can be anticipated. In dry unstable conditions, you’ll bang along through it, head against canopy perhaps.

Remember that ***velocity*** is speed + *direction*. Airflow may change in either speed or direction across a distance or with altitude. Change of direction with altitude does affect whether ridge lift is established and how deep it is. Change speed with altitude affects the degree of turbulence, especially downwind of the ridge.

Any change of airflow velocity – direction or speed – across any distance, is termed ***shear***. We want *moderate* speed shear with altitude for best ridge-soaring conditions. Severe change of either direction or speed at the altitudes near the ridge top will cause (`difficulty`).

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[2] The Dry Adiabatic Lapse Rate, DALR, is a physical constant, defined as “the rate of decrease of temperature with height of a parcel of dry air lifted in an adiabatic process through an atmosphere in hydrostatic equilibrium.” The decrease in temperature with altitude in this atmospheric constant is 3˚C./5.4˚F per thousand feet or in the metric system 9.8˚C. per kilometer. A ***parcel of air*** is a fixed mass of air. Within an initial volume no energy is added to or taken away from the parcel’s mass as it moves vertically (up or down) in the atmosphere.

Wind direction for slope lift should be within 10 to 20 degrees normal to (perpendicular to) the ridge axis. Some discussions indicate that oblique angles up to 40 degrees can generate ridge lift. In this case, terrain features (*orographics)* will shape the ridge lift locally, and may cause downdrafts that may surprise the pilot who has estimated wind direction incorrectly. A ridge tends to divert flow along the slope when the wind strikes it obliquely, which terrain details could possibly overcome.

Wind *direction* above the ridge should only gradually change with an increase in altitude (*Vertical shear should be gradual*). Generally, a wind speed of 15 knots impinging on a mountain ridge is considered a typical minimum value for ridge-lift cross-country flight. This generates upward air motion of up to 6 feet per second (360 feet per minute (fpm)). This results in climb rates of 200 fpm for even moderate performing gliders.

Wind speeds under 15 knots with good atmospheric stability conditions and smooth slopes do generate lift sufficient for gliders with lighter wing loading. A moderately steep terrain slope of 30 degrees can provide lift for soaring flight with a wind speed of 10 knots.

An unstable temperature lapse rate in the air flowing across the ridge will favor the development of thermals. In the jargon, "shear in transition between thermals and smooth ridge lift makes for widely varying lift rates and uncomfortable flying conditions." Too much atmospheric instability eventually leads to destruction of steady, reliable ridge lift when the development of thermal lift on the slope becomes the dominant atmospheric lifting mechanism.

Wind flow over a ridge is arguably the easiest of the various forms of lift to visualize as used for soaring (`see Photo and Diagram #2: Wind Flow over a Ridge`). Because the atmosphere is a fluid and therefore behaves much like water in a stream flowing over rocks, a soaring pilot need only pay attention to wind direction at the surface and at the lower atmospheric levels to have a good idea where ridge uplift can be found. Slope lift generation is determined by both wind speed and terrain slope. The steeper the slope of the terrain or the higher the wind speed, the stronger will be the lift. Air passing across rising terrain will show its greatest lift rate on the windward side or front of the hill. The lifting zone extends upward, tilting *windward* about 45˚ to 30˚ off the vertical above the steepest slope on the windward terrain. Generally, the best lift is found at the altitude of the brow or top of the hill. Shallow slopes may not provide enough lift to support soaring, a steep slope can generate turbulent eddies that make slope soaring difficult, dangerous, or impossible at lower points along a ridge, thereby limiting useful soaring only to the area adjacent to the ridge top.

Eddies[3] – turbulent wind currents – pose challenges for the ridge-soaring pilot in several ways. *Turbulent* means that they are variable in direction, speed, and size. Terrain undulations or irregularities lead to the development of eddies on the windward side of the hill in areas that one might otherwise expect smooth uplift. Wind eddy presence also poses a danger by creating (invisible) wind gradients across the wingspan of gliders operating near the terrain that can overcome aileron authority or stall a wing.

Just as rising terrain provides lifting action with possible eddies on the windward side of a ridge, the lee or downwind side of a ridge provides downdrafts and leeside eddy currents, often strong. Since by definition a *stable* atmosphere is one in which air disturbed from its original altitude will want to return to that altitude, there is a powerful tendency for air to descend along the lee side of a ridge. Because of the neutral to stable conditions of the atmosphere that provide ridge-lift conditions, soaring pilots need to plan for heavy sink on the lee side of a ridge as air tries to return to its original altitude before it was lifted on the windward side of the ridge, and for possibly severe turbulence overpowering control surface authority.

[3] "Eddy" is the jargon term; "whirlwind" is the lay term that more accurately describes a strong eddy. The strongest eddy is the tornado…

Slope-soaring factors

Slope soaring courtesy of the World Meteorological Organization's *Weather Forecasting for Soaring Flight* cites three factors that help to determine ridge lift conditions:

1) The stronger the wind flow, the greater the tendency for air to flow over rather than go around a mountain barrier;

2) Air with neutral stability has a greater tendency to flow over a small barrier while stable air would seek to flow around a such a barrier; and,

3) Air flow tends to go over wide barriers, while it will seek to flow around small or narrow barriers. More insight is provided from Helmut Reichmann in *Flying Sailplanes*.

Favorable terrain features:

~ The terrain undergoes a gradual steepening of the slope from the valley floor, and
~ There are no obstacles to the wind flow upwind of the slope.
~ The smoothest ridges also provide the best flights utilizing ridge lift.

Varying amounts and heights of trees or irregular slope features on the ridge slope affects surface friction. With this increased friction, eddies form that weaken the ridge lift. The greater the turbulence, the deeper the layer of eddies and disturbed flow along the slope.

1) For more information on mountain flying in respect to ridge lift, suggestions can be found for soaring in and around complex terrain in Dale Master's book, *Soaring Beyond the Basics*. `[Out of print and unavailable.]`

An Example of Great Ridge-Soaring Weather

The typical weather scenario for classic ridge soaring in the U.S. is following cold-frontal passage in a mid-latitude wave[4] across the Appalachian mountain ranges. A good example of such a scenario for ridge lift occurred on April 4, 2006 `(see Surface Weather Map and 500mb Upper Air Chart)`. The associated post-frontal temperature sounding for Pittsburgh is also provided (`see Upper Air Profile`).

Behind the cold-front surface pressures rise ahead of the oncoming high-pressure center with an axis of higher pressure extending eastward over the mid-Atlantic area. While the atmosphere tends toward instability near low pressure centers and fronts, the atmosphere tends toward stability with the presence of higher pressure. The reason for this stability of the air is that the air is sinking or subsiding through the troposphere within the high-pressure center and ahead of it. Concurrently, large pressure differences (the pressure gradient) between the center of the oncoming high and the center of the departing low support strong, low-level, or surface winds. Steady surface wind speeds and wind direction changing minimally with altitude, and atmospheric stability from stable (for lower or threshold wind speeds) to neutral (with stronger wind speeds) are the atmospheric ingredients for development of consistent ridge lift. The vertical temperature profile of April 4, 2006, depicts a generally neutral-stability atmosphere, with wind speeds of 30-40 knots range below 10,000 feet.

You may have noted in the upper air profile a surface-based nocturnal temperature inversion and light wind right at the surface. This this sounding was taken before the inversion broke, after which the higher winds aloft mixed down to the surface.

How Do I Know When to Expect Ridge Lift?

Now that you have a basic grasp of the conditions necessary for ridge lift development, go to the following web locations to discover the area-side the synoptic scale weather situation and upper air temperature profile:

Surface Synopsis

NOAA/NWS Aviation Weather Center, www.aviationweather.gov

[4] Jargon alert: a synoptic-scale ***wave*** is a low-pressure center with its associated fronts.

- ~ On the top-bar Menu, choose *FORECASTS*,
- ~ then choose *Prog Charts* from the dropdown,
- ~ then click *Sfc* in the menu bar.
- ~ Click *Thumb* for a grid of 12 forecast charts extending out a week.

Upper Air Soundings

- ~ https://weather.rap.ucar.edu/upper/ Simply click on any map location for current or past sounding skew-t graphs.
- ~ Or https://www.windy.com/ - right-click on any map location, choose “sounding” from the dropdown picklist.
- ~ Alan Walls has created a skew-t viewer for android devices that shows the skew-t forecast for any US location, that allows the user to modify the anticipated daytime high, to see the effect on potential thermal development. https://apkpure.com/skew-t/com.ajw.skewt

Acknowledgement:

Thanks to pilot John Good in providing background and comments on a fine example of a long-distance soaring flight utilizing primarily ridge lift on the Appalachian Ranges on April 4, 2006, in which he set a U.S. Standard Class Record. John Good, Richard Kellerman, and John Seymour flew from Eagle Field to Tazewell, VA, and a point south of Charlottesville, VA, for a 1049 km triangle. Karl Striedieck also flew long distance on the day.

Library Build:

1) *Glider Flying Handbook*. FAA-H-8083-13, FAA, Gov’t Printing Office, 2013.

2) *Soaring Beyond the Basics*. Dale Masters, © 2006 (Out of print, not available used)

3) *Weather Forecasting for Soaring Flight*. World Meteorological Organization Technical Note #203; WMO-No.1038; ©2009. Available only in pdf.

Atmospheric Gradients

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Additions:
…Four Diagrams.
 …Diagram #1: Surface Area per Unit Energy
 …Picture #1: Temperature Inversion
 …Picture #2: Slope Winds
 …Picture #3: Mountain-Valley Winds
 …Picture #4: Favorable Terrain for Strong Slope Winds
12/13/2020: -- I find only 3 illustrations in the source folder:
LapseRateStability.bmp, sfx_map_03z_04122011.bmp, and WindGradi-
ent.bmp
I cannot find separate files holding these text boxes, and I believe
they're incorporated in the text.
In 2011_07, (elevated heat sources) I find Pic#2_SlopeWindDiagra-
omPic.bmp and Pic#3_StrongSlopeWinds.bmp
Text Box #1: Energy to Evaporate Water versus Raising Water/Air
Temperatures (255 Words)
Text Box #2: Equation of State for Dry Air (129 Words)
Text Box #3: Difference in Mass at 850mb vs. 1000mb (264 Words)
```

Much of the mystique of meteorology can be attributed to the vernacular of the trade. Hopefully, a little insight into a couple of common key meteorological terms will help soaring pilots to better understand weather charts and the processes they portray.

This chapter focuses on the definitions and concepts regarding atmospheric pressure and temperature lapse rates, to better understand lifting processes and master them in flight.

Gradients

In aviation meteorology, a key concept is *gradient*. The *Glossary of Meteorology* defines gradient as "the space rate-of-decrease of a function." Gradients are everywhere in the atmosphere, so you will see it applied to many features, for example, the wind gradient, the pressure gradient, temperature lapse rates, and so on.

Pressure gradients determine wind velocity. The differences in pressure from one point to another, the rate of decrease (the gradient) of pressure across distance at a fixed time determine speed and direction of air flow (wind velocity). We often refer to the magnitude of the pressure gradient or the pressure difference across a certain distance. Though frictional influences change wind direction, air movement over the earth (wind) is the direct result of atmospheric pressure[5] differences.

This pressure gradient results in a force that moves air from areas of higher pressure to lower pressure. Note that I did not say "high pressure" or "low pressure." The gradient force that moves air only needs the pressure difference to be relatively higher at some point, thereby providing force that moves air toward a point with a lower pressure. The presence of a pressure gradient results in horizontal air movement, or wind. Intuitively, the larger the pressure gradient and resulting force on the air over a point on the earth, the higher the wind speed over that point. Conversely, a weak pressure gradient over a given point leads to a lower wind speed. Wind speeds on a surface weather chart reflect the influence of the patterns of high and low pressure and the resulting pressure gradients. The spacing of the lines of equal

[5] The Glossary of Meteorology defines Atmospheric Pressure as, "the pressure exerted by the atmosphere because of gravitational attraction exerted upon the 'column' of air lying directly above the point in question." The air in a column over a given point has a certain mass. And that mass is under the influence of the earth's gravity like every other object. The barometer is an instrument that is used to assign a value to the atmospheric pressure at the point of measurement.

pressure (shown as *isobars*) on the chart illustrate the intensity of the pressure gradient across them. Each isobar is four millibars different from the adjacent isobar. The closer the isobars are together, the higher are the wind speeds at the observation points near them. [See: Surface Weather Chart, Southeast U.S., at 03Z, April 12, 2011.]

Obviously in its effect on the lifting processes, wind speed is an essential ingredient for the development of ridge lift, mountain wave lift, and shear/convergence lift. But pressure gradient force also influences the growth or detracts from thermal lift development. Discussions on mountain wave lift and shear/convergence lift are in the chapters ahead.

Wind Gradient: Vertical Change

The *vertical* component of wind is called *wind gradient*. This is the change in wind speed, with altitude, through the layer of air immediately over the surface. In the true definition of a gradient, wind gradient refers to the *decrease* of wind speed as an aircraft descends toward the ground. Wind gradient is most noticeable in windy conditions and of most concern in the landing phase of flight. Surface or ground roughness causes this decrease in wind speed through friction while descending in the lowest 100 to 150 feet of altitude above the landing surface. (This is called, broadly, *the friction layer*.)

When a glider gets close to the surface, flying into the wind, the wind gradient has the effect of reducing the airspeed of a glider. The glider's momentum is relative to the *earth* and its ground speed tends to remain constant. When it descends into lighter wind, its true airspeed decreases. If the glider's approach airspeed has been close to its stall speed, this decrease may stall the glider. This is damaging to gliders, pilots, and passengers. For this reason, the pilot must accurately estimate the wind gradient in the friction layer and *add* this to the normal approach speed so that stall does not occur.

This slowing of true airspeed will also mean that the glider enters a part of its polar that is associated with a greater descent rate, so that it will feel to the pilot as though *sink* has been encountered. Though this is not likely the case – decreased headwind is what has occurred – the pilot's proper response is to *lower the nose* to restore airspeed and control authority, for instinctively raising the nose to arrest the unwanted descent will only increase the rate of sink and risk a stall (and a fall to earth). When the nose is lowered, true air speed will increase thanks to gravity, and the descent will decrease when the glider is within a wingspan height of the ground because induced drag then decreases by 30-50%, allowing the pilot to safely level off and permitting the glider to float low over the ground onto the runway. [See Diagram #2: Wind Gradient.]

This wind gradient is made worse (or decreased, or both) by turbulent eddies in the general wind flow caused by adjacent low-lying vegetation, trees, thermals, or man-made structures such as hangars.

Lapse Rates Determine Whether there are Thermals

Most soaring flight uses *thermals* to remain aloft and to gain the altitude needed to move across country (to the next thermal). The secret sauce that creates thermals is the temperature gradient with altitude, the *lapse rate* (of temperature decrease), and the fact that there are three *different* lapse rates:

- the actual temperatures that currently exist at the altitudes above one's location – the ***ambient*** lapse rate;
- the rate at which air cools as it ascends – the ***dry*** *adiabatic* lapse rate; and
- the rate at which ascending air cools in cloud – the ***wet*** *adiabatic* lapse rate.

The differences between the ambient and the applicable adiabatic lapse rates determine whether a parcel of air lifted from the surface gains buoyance and accelerates (for at least a time). As long as the ambient temperatures around the parcel are relatively *cooler* than the temperatures reached by the rising parcel of air, acceleration of the parcel continues. In the jargon, *when the ambient lapse rate is greater than the adiabatic rate, a lifted parcel is accelerated.* This condition is called *instability*.

In distinction, when the ambient temperatures aloft are greater than the temperatures achieved by the lifted parcel, the lifted parcel is not buoyant, acceleration does not occur, and the parcel descends to an altitude of neutral buoyancy, possibly back to ground. This situation is called *stable*.

Understanding how and why this happens is a nidus for understanding how to progress from being a glider pilot to being a sailplane pilot. All gliders descend at a designed-in rate. They stay aloft – can *soar* – only when in air that is ascending faster than they naturally descend.

This is why the FAA Practical Test Standards (PTS) for the Glider Category examination, the *Area of Operations, Preflight Preparation* section, lists *gathering of weather information* as a specific required task, and within that task, "*knowledge of pressure and temperature lapse rates in their relationship to the lifting process*" and "*atmospheric instability*" are to be demonstrably understood by the applicant.

Lapse Rates Definitions, Explanations

In the previous chapter on ridge lift, we introduced temperature lapse rates.[6] Byers' textbook, *General Meteorology*, states that lapse rate is "the rate of temperature decrease with height in the atmosphere overlying a point on the surface of the earth at any given time." In other words, typical conditions in the atmosphere tend to have the temperature decreasing as altitude is increased. And if a lapse condition with the temperature decreasing with a gain in altitude is typical, then anytime the temperature increases with altitude then conditions are not typical or "inverted" from that normally expected. Hence, the departure from a lapse temperature condition provides the background for the term "inversion" in defining the condition of warm air overlying cooler air. [`See Diagram #1: Atmospheric Instability Relative to Lapse Rates.`]

Throughout the various FAA aeronautical training manuals, especially regarding general airframe and engine performance, the "average" lapse rate of 3.5˚F decrease in temperature per 1000 feet of altitude gained is applied. I must underscore that this particular lapse rate is nothing more than the average decrease in the temperature in the International Civil Aviation Organization's Standard Atmosphere through the troposphere (the lowest 5 to 8 miles of the atmosphere). The average temperature lapse rate is **not** representative of any particular physical process or location in the atmosphere.

As we pointed out, the *Dry Adiabatic[7] Lapse Rate* (DALR) is a constant, as it defines a physical process in the atmosphere. The *Glossary of Meteorology* says it is "the rate of decrease of temperature with height of a parcel of dry air lifted in an adiabatic process through an atmosphere in hydrostatic equilibrium." The decrease in temperature with altitude of this atmospheric constant is 3˚C or 5.4˚F per thousand feet; in the metric system, 9.8˚C loss of temperature per *kilometer* of altitude. Adiabatic changes in temperature occur due to changes in the pressure of a gas (the atmosphere) as the parcel of air moves vertically up or down (the atmosphere) while not adding or subtracting any external thermal energy to that parcel.

This is an essential hypothetical condition. Pragmatically, a rising thermal mixes at its boundaries with surrounding air and entrains some amount. This entrainment may add to or diminish the buoyancy of the rising thermal, depending on the temperature and humidity of the entrained air.

Atmospheric Stability

The DALR defines a *neutrally* stable atmosphere in regard the potential of the atmosphere to tend to move vertically. A packet of dry air that is at the *same* temperature as the surrounding air has *neutral* stability because, obviously it has neither positive nor negative buoyancy.

Positive stability occurs when the lifted packet is *cooler* that the surrounding air. It accelerates downward until it is no longer negatively buoyant. This characterizes wave motion in the atmosphere – the atmosphere is essentially vast leaves of air differing in humidity, temperature, and velocity. At the boundaries of these leaves, velocity differences create lifted packets. Positive stability returns these to their

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[6] A lapse condition is one where the variable of interest is diminishing or decreasing.

[7] *Adiabatic*: Of, relating to, or being a reversible thermodynamic process that occurs without gain or loss of heat and without a change in entropy.

Without transference: used in thermodynamics of a change in volume, whether by expansion or contraction, unaccompanied by a gain or loss of heat.

The American Heritage® Dictionary of the English Language, 5th Edition.

original altitude, creating wave. (This is different from “mountain lee wave” and is seldom of soarable strength.)

Instability occurs when the ambient lapse rate is greater than the DALR – that is, when the temperature decrease with altitude is more than 5.4˚F. This atmosphere is *unstable* because a rising packet, cooling at the DAL rate, becomes progressively relatively warmer than the ambient air it is passing through, and thus more buoyant, so accelerates upward. With this temperature profile, the atmosphere is ready to be “triggered” – to develop upward vertical motion in air that is lifted into it by any mechanism.

An *inversion* is the condition in which a defined layer of air above is relatively warmer than the layer just below it. It does not mean the air has turned upside down; it means that the temperature change is backwards, warmer with altitude instead of cooler. The “leaf” of air above is simply warmer that the “leaf” below. In the stable condition, the temperature at the inversion boundary is significantly warmer that the temperature that has developed within the lifted parcel, so that the parcel is no longer buoyant within the (warmer) inversion. Extreme stability occurs when the temperature increases with higher altitude, and is absolutely warmer than a lifted parcel.

Summarizing, an atmosphere in which the temperature *decreasing more* with altitude than the DAL rate of 5.4˚F per thousand feet is *unstable*; and an atmosphere in which temperature decreases at or less than the DALR of 5.4˚F per thousand feet mitigates toward a *stable* atmosphere.

Humidity Affects Stability

Stability of the atmosphere is heavily influenced by changes in state of the water vapor it contains (humidity). With the release of energy from water vapor (*the heat of condensation*) when water vapor condenses back to liquid, the release of the latent heat that vaporized the water from its liquid state warms the parcel of air containing it.

This does not “dry out” the parcel – the reason condensation occurs is that the cooling air parcel *cannot* any longer retain all the water in as vapor; the excess forms droplets: fog, cloud, snow. When the cooling air parcel’s relative humidity reaches 100%, and visible moisture condenses, the remaining gas is still at 100% humidity, fully saturated. Further cooling will cause more condensation, releasing heat of condensation. This continual, progressive condensation of water from a cooling saturated parcel modifies the lapse rate to a new value – the *saturated* adiabatic lapse rate[8]. This is *approximately* 1.5°C (2.7°F)/1000 ft.

The saturated adiabatic lapse rate is *not* a constant. But, except at low pressure and in extreme cold, it is less than the dry adiabatic rate and less than the average ambient lapse rate, so saturated air is *much* more buoyant than dry air, and therefore much more unstable. This is why cumulonimbi may form explosively, evolving from a lovely puff to a towering, intense small storm in just 5 or 10 minutes.

Regardless, lapse rate gradients and wind gradients are the sauce that spices gliding and creates thermal soaring. Learning to understand their behavior, prediction, and nuances will help you to become an expert soaring pilot.

Library Build:

Daily Weather Maps. U.S. National Weather Service Hydrologic Prediction Center; URL: https://www.wpc.ncep.noaa.gov/dailywxmap/index.html

[8] The rate at which adiabatic cooling occurs with increasing altitude for wet air (air containing clouds or other visible forms of moisture) is called the *wet* adiabatic lapse rate, the *moist* adiabatic lapse rate, or the *saturated* adiabatic lapse rate. The wet adiabatic lapse rate lies in the range of 3.6-5.5°C/1000 m (2-3°F/1000 ft), depending on temperature and pressure. It is lower in hot conditions and higher pressure.

Higher-Terrain Heat Sources

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Diagram #1: Surface Area Covered by a Unit of Incoming Energy
Picture #1: Temperature Inversion
Picture #2: Slope Winds
Picture #3: Favorable Terrain for Strong Slope Winds
Picture #4: Mountain-Valley Winds
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To continue to lay the groundwork for understanding thermal lift development, I'll address a question that has often been asked of me through the years: *Why do thermals start sooner over higher terrain than in adjacent valleys or over flat ground?* With occasional exceptions, convection (thermal generation) generally starts from sloped terrain – hills or mountains – sooner than from flat terrain. Other influences on thermal development include terrain texture and color, and atmospheric stability, and will be discussed later.

All energy on Earth comes ultimately from the sun. Differential surface heating beneath an atmosphere that has a *large* lapse rate – a temperature decrease with altitude exceeds the dry adiabatic lapse rate – results in the development of pockets or streams of rising air called *thermals*. Thermals are buoyant because air within the thermal is less dense than the air surrounding it. There are several factors that speed the initiation of thermals around and on elevated terrain.

Air is a very poor conductor of energy (it's an insulator when trapped in fabric or open-celled material), so air is heated by conduction only within a few inches of its contact with the earth and objects on the earth's surface. This near-surface warming of the air creates a density difference between the warmed air and adjacent air that begins a convection process[9]. (Sailplane pilots experience this convective flow as a *thermal*.) Because surface heating is necessary to warm the air immediately adjacent to the earth's surface, the degree and rate of surface heating determines the rapidity and intensity of thermal development.

Sunlight directly heats objects on and near the ground. Sunlit objects warm the air touching them by conduction (conversely, shaded objects radiate heat through the atmosphere and cool the air touching them by conduction). The rate and intensity of this heating is directly proportional to the amount of energy received per unit of surface area. Highly textured surfaces have more sunlit area. The more directly (closer to perpendicular) that the sun's shines on an area, the more intense is the surface heating. Conversely, the shallower the angle that the sun shines on a given surface area, the weaker is the surface heating and conduction to air.

Given the slope of topographic features such as terrain inclines, small hills, or mountains, solar energy is intensified on surfaces more orthogonal to the sun's rays (`See Diagram #1; Surface Area Covered by a Unit of Incoming Energy`). In the example provided in Diagram #1, a unit of incoming energy with a 55˚ angle is "spread" over a surface length that is twice as long a length with a 75˚ angle.[10]

Overnight surface-based temperature inversions often develop in weather that brings daytime thermal development, because both depend on clear skies. The nocturnal inversion forms because objects – especially the twigs of trees – radiate infrared to space when not blanketed by clouds. Cold objects chill the air touching them (conduction), which flows downward (convection). This continues all night. A valley can fill with cold air, and downslope (katabatic) winds develop. Daytime thermals, conversely,

[9] By convention in meteorology, convection is implied to mean upward vertical motion of air.

[10] For comparative reference, at 45˚ N latitude, the noon sun is at 70˚ at midsummer and 22˚ at midwinter. At 30˚ N latitude, the noon sun is at 83˚ at midsummer and 37˚ at midwinter. (https://keisan.casio.com/exec/system/1224682331)

develop when the same objects absorb radiant heat from sunlight and transfer heat to the air in contact with them, which then rises.

We call the nocturnal cold air an “inversion” because the air above it remains as warm as it was the previous day. On the average, air becomes quickly cooler with altitude, so to have warm air above the nocturnally formed cold air is upside down.

In the morning, the air surrounding ground objects ground is much colder than the air aloft (above the inversion) so solar energy heating the valley ground must warm this cool surface air several degrees to initiate convection that can rise above the top of the inversion layer, to produce soarable thermals. Higher terrain above a surface-based inversion is able to reach convection temperature sooner simply because the surrounding air is already warmer.

Sunlight intensity is diminished by dusts and large molecules in the atmosphere. In the jargon, this is called *atmospheric attenuation.* This, too, may inhibit thermal development in valleys. Nighttime surface-based temperature inversions are *stable*. That is, the air of an inversion does not ascend, and its greater density displaces the horizontal air flow aloft (the *gradient wind*, driven by the synoptic (large-scale) pressure gradient), producing a pool of calm in the valley.

Many types of small particles may enter this pool of air and be trapped by the absence of wind and vertical thermal mixing. Pollutants, smoke, pollen, fog, and dusts added to this near-surface stable atmosphere does not mix-out because of the lack of motion. These molecules and particles in the air reflect, scatter, or absorb incoming solar energy after sunrise. This *attenuation* of sunshine reduces the strength of heating on surfaces and delays thermal formation.

Ridges or mountains protrude above nocturnal inversions, so are bathed in air that has not cooled during the night – so that there’s no warming delay after sunrise – and the atmosphere is drier and cleaner, reducing solar attenuation. (`See Picture #1: Temperature Inversion – 12/13/2020: I don’t find this illustration in the source folder.`) Solar heating of the surface on high slopes is thus more efficient than in valleys.

While higher terrain can have varying degrees of vegetation, that grows from moist ground and tends to trap moisture, slope promotes water run-off, so the surface of higher terrain tends to be dry. Since a large amount of energy is required[11] to vaporize water to change-its-state from liquid to vapor, so moisture presence requires more energy to raise the sensible temperature the same as a dry surface, so dry ground warms quicker.

The Energy Required to Change the State of Water

The *heat of vaporization* is the energy required to change the state of water molecules from liquid (or solid) to gas (water vapor). For molecules of water to evaporate, sufficient kinetic energy must be available to overcome the liquid-phase intermolecular forces. *Sensible temperature* (stated in degrees) is the jargon term for this molecular kinetic energy.

A substance’s *latent heat* is the heat absorbed (or released) per unit mass (by a substance, in a change of phase that is reversible, isobaric (equal pressure), and isothermal (equal temperature).

The *specific heat* of a substance is the energy required to raise the temperature of one kilogram mass by one degree Kelvin (Celsius):

~ The Specific Heat of Dry Air at 0 degrees Celsius = 1.006 Joules /gram-degC[12]

~ The Specific Heat of Water at 0 degrees Celsius = 4.186 Joules /gram-degC

[11] In physics, this is now called *enthalpy of vaporization*. For water, it’s 2257 Joules/gram at 100˚C, at sea level pressure in a saturated atmosphere. More energy is required to convert water to vapor at cooler temperatures. The relationship is non-linear. As a learning exercise, you could research this.

[12] One *Joule* is a unit of measurement of energy equivalent to 0.24 calories.

The Energy Cost of Phase Change

The energy required to change the phase of water varies with temperature and requires a tremendous amount of energy. At 0˚C it takes 597.3 calories/gram (2500 Joules/gram) to change the phase of water from liquid to its gaseous state *without temperature change*.

The Energy Cost of Temperature Change

To change the sensible temperature by 1˚C, we see, by comparing the specific heat of dry air to that of water, that it takes about four times as much energy to raise the temperature of a given mass of liquid-water to that of an equivalent mass of dry air, i.e., 4.186 vs. 1.006 Joules/gram-degC., respectively. Water vapor holds almost twice the heat as dry air, 1.86 Joules/gram-degC. at atmospheric temperatures, so somewhat more solar energy is required to warm moist air than dry air.

The atmosphere encompassing higher terrain is of course at lower pressure and density. These are proportionally related, so that a pressure increase results in a density increase, and conversely a pressure decrease leads to a density decrease. A temperature increase will result in an air density decrease, and conversely a decrease in temperature will increase the air density (more mass per unit volume).

Here's the simple math. Using math adds nuance to principle:

$P = D*R*T$,

where P is pressure, D is density, R is the gas constant, and T is ˚K. The point is that pressure, density, and temperature are related by a simple proportion. This is the *equation of state for dry air*, in case you need to look it up.

There's less mass in any volume of air at altitude: Using this equation, the *difference in density* is

$D_{\Delta} = Pa/Pv$,

where D_{Δ} is the change in density, Pa is the pressure at altitude and Pv is the pressure in the valley. So, to know the change in density (and the change in latent heat), we simply calculate this ratio using any measurement of pressure (lb/sq-in, mmHg, bar, mb). Taking what's handy, standard meteorology mb, we see that the percentage of mass of the air column above a pressure level of 850mb (~4800 feet MSL) versus the amount of mass at a pressure level of 1000mb (~400 feet MSL) is 85/1000 = 0.85, meaning that the amount of energy required to raise the temperature of the mass of air at 850mb of pressure would be only 85% of that required at a surface with an observed pressure of 1000mb.

Thus, the air adjacent to heated surfaces on the mountain has less mass, so is warmed to any given temperature with less specific solar energy than in the valley – or rises to a higher temperature from the same solar energy. Since there is less solar attenuation on the mountain, the sensible temperature will be higher on the mountain than in the valley.

We now understand why a specific volume of air will warm faster and hotter in the air next to higher terrain than at the valley floor. This results in earlier convection or thermal triggering on higher terrain.

The Effect of Wind on High Terrain

Wind is everywhere; the atmosphere is never still except in transition or when air is trapped by physics, such as in the nocturnal inversion. Air movement occurs at every scale. In the jargon, *micro-scale* phenomena are (arbitrarily) those of scale size less than 2.5 miles; *meso-scale* phenomena are those encompassing all distances greater than 2.5 miles.

Temperature driven wind circulations abound that affect aviation and guide decisions. Important circulations are named by their circumstances: sea breezes, shear lines, slope winds, mountain-valley breezes, and so on. I will discuss sea breezes and shear lines later.

Slope winds and mountain-valley breezes may be driven by density or temperature. As we have discussed, density of the air decreases with a decrease in pressure. As you can see by $\Delta = P/ R*T$, density decreases with increased temperature. Differential heating of terrain generates heat-driven density differences in the air along a slope. As the sunlit slope heats quicker than lower terrain, air along the slope concurrently increases in temperature and decreases in density as a result of that surface heating. Being more buoyant the air begins to rise up the slope. This movement of air up a slope is known as *slope wind*.

This slope wind from the differential surface heating may initiate convection (a thermal) upon reaching the top of the slope and releasing packets of warmed air into the atmosphere above. Lower on the slope, air movement up the slope can trigger thermals by kicking pockets of warmed air free from the rising terrain. (`See Picture #2: Slope Winds.`)

Slope winds coursing up steep terrain marked by chutes or gorges can result in large wind gradients close to the surface. This poses a soaring hazard due to the change in the wind component across the wingspan of the glider[13] (`See Picture #3: Favorable Terrain for Strong Slope Winds`). As the day progresses, the more rapid heating of higher terrain surrounding a valley results in a more general up-valley wind flow that manifests itself in winds along mountain slopes angling upward and across slopes (`See Picture #4: Mountain-Valley Wind`). Again, this density-driven wind flow can act as a thermal trigger to pockets of warmed air on mountain slopes or even the valley floor itself.

Summary

Several factors that trigger thermals or support convection earlier from high terrain than from adjacent valleys or lower topography:

1) The slope of the terrain enables the sun to provide more energy per unit area;

2) The lack of surface-based temperature inversions at the elevations of higher terrain results in minimal atmospheric attenuation of incoming energy due to comparably less atmospheric man-made or natural particulates and haze. With the air aloft generally drier, atmospheric haze and its energy attenuating characteristics is minimized;

3) Above a valley's temperature inversion, air adjacent to higher terrain is already warmer than air at the bottom of the temperature inversion on the adjacent valley floor. Less warming of the air is required there to reach thermal trigger temperature[14];

4) The surface of the ground, is drier on mountain slopes so temperature increases faster with less solar energy consumed by water evaporation, though modest amounts of moisture increase bouyancy;

5) With less mass in any given volume of air adjacent to higher terrain compared to the same volume of air over an adjacent and lower altitude valley floor, incoming solar energy is able to raise the sensible temperature[15] faster to thermal trigger; and,

6) Wind is created by gradients of temperature or density, which drive air movement along slopes of hills and mountains. Wind acts as a thermal kicker by its movement along mountain slopes and releases thermals from the tops of mountain slopes, ridges, and peaks.

[13] This danger was outlined by the late Henry Coombs, in *That Beautiful Mountain and Her Sinister Trap*. Soaring, September, 1984. No one should fly in the mountains until this essay is digested. This phenomenon has killed several pilots.
https://www.ssa.org/files/member/ThatBeautifulMtSinisterTrap.pdf

[14] *Trigger temperature* is merely the temperature that a packet of air on the surface must reach in order to have enough buoyancy to release and rise. This temperature is not taken from a local rock; it is the standard 2-meter temperature of meteorologists. This is important because if the 2 meters of air close to the ground is warm enough to rise, then wide, workable thermals will begin to develop.

[15] *Sensible* temperature is the *felt* temperature, as measured by a thermometer. This term specifically excludes any implication about the heat content of a packet of air, the *specific heat.*

Thermal Development

…Diagram: Atmospheric Instability Relative to Lapse Rates

The atmosphere provides vertical air motion or atmospheric lift in various forms and thereby provides the “engine” for soaring pilots to accomplish cross-country flight. In the first chapter, I listed four mechanisms of atmospheric lift commonly used for soaring flight; thermal, ridge, mountain wave, and convergence. Last chapter opened our discussion of thermal lift (small-scale, upward moving, convective air current) regarding elevated heat sources, showing that elevated terrain enhances or speeds thermal development.

When instructing, I ask students questions about why or what is needed for thermals to develop. This brings responses that vary from overly simplistic to quite complicated. A little conceptual-model knowledge of thermals helps an aviation student to grasp several important meteorological principles. There are many fine instructive sources on techniques and strategies of thermal soaring, so my purpose here is to simply mention some very fundamental aspects of thermals to set the foundation for other discussions of thermal lift in the next chapters.

Contrary to the general public’s perception that soaring flight is impossible without wind (horizontally moving air), using thermal lift is generally the most flexible way to accomplish soaring cross-country flight over a given area. I say this because flights using ridge lift or mountain wave demand flight along or near mountain ranges rather than a general geographic area or region.

The ingredients necessary for thermal development are:

~ some form of *differential* surface heating (the ground must warm to *conduct* heat (energy) to the air immediately adjacent to it),

~ an atmosphere that is or can be made *unstable*, and

~ some form of *triggering* to initiate convection.

In the last chapter’s discussion of the energy required to change the state of water, the high specific heat of water explains why large sensible temperature rises are highly unlikely on moist ground. Therefore, dry, dark ground that is open to unimpeded, strong, solar energy has the largest potential to increase its sensible temperature. *Conduction* warms the air immediately in contact with the warmed ground and ground objects, then *convection* mixes the air above this warmed surface. A volume or “bubble” of warmed air develops over this source surface area. The air density (mass of air per volume) of this warmed air will now be lower than adjacent air residing over cooler ground at the same level per the *equation of state for dry air,* P = D*R*T, explained on page 15.

Definition: *Convection*.

“Because the most striking meteorological results of convective motion occur in conjunction with the rising current of air (strong updrafts or thermals, cumulus, etc.) convection often is used to imply upward vertical motion.” (*Glossary of Meteorology*).

Definition: *Convective Condensation Level* (CCL).

“The CCL is the height to which a parcel of air, if heated sufficiently from below, will rise adiabatically until it reaches saturation (condensation of the average moisture content over the approximately lowest 1500 feet of the atmosphere). The CCL approximates the base height of cumulus clouds which are, or would be, produced by surface heating.” (The author, from NWS Reno Internet Website “Soaring Terms and Definitions.”)

Instability

The second ingredient necessary for thermal development is *instability* of the atmosphere. See the previous chapter, beginning page 11, for a discussion of stability. [How much do we want to repeat here?]

The International Civil Aviation Organization (ICAO) Standard Atmosphere specifies a standard sea level temperature of 59˚F (15˚C) with an average temperature drop of 3.5˚F or 2.0˚C per thousand feet of altitude gained. Observed sounding temperatures always differ from this average.

An atmosphere is *unconditionally* unstable when the observed temperatures aloft decrease faster than the dry adiabatic lapse rate (DALR) that is, more than 5.4 ˚F. or 3.0 ˚C per thousand feet of altitude. (`See Diagram #1: Atmospheric Instability Relative to Lapse Rates`). Dry air (unsaturated air) rising in the atmosphere will cool at the DALR due to the decreases pressure with altitude. Heated air adjacent to a warmed surface will behave like a cork held underwater. Being less dense than the water in which it is immersed, the cork will bob upward. Warmed air will tend to bob upward through cooler, denser surrounding air. It will rise as it seeks air of equal density. This is a basic concept.

As long as the rising air's density is less than the surrounding atmosphere (warmer or more humid, though humidity plays a small role), then the rising air still has an upward force, buoyancy, or lift. The terms "warmer" and "cooler" are relative. Just because the air is hot or temperatures are high does not alone make for good thermals. There must be a large temperature *differential* between the lower atmospheric level and the air aloft for the best thermal lift conditions. A winter marsh with water at 40˚F surrounded by forest with air at 10˚F will generate a thermal (to the low top of the winter haze layer).

Since air density differences at any given altitude (expressed in meteorology as a millibar pressure level) are the result of temperature differences, water vapor can have a substantial impact on the temperature of the air if the water changes state. I will address the effect of changing water state later.

When there develops established differential heating of the ground resulting in "pockets" of warmed air relative to adjacent surface area, with extensive cooler air aloft offering a high lapse rate (loss of temperature with altitude gained), then only some form of "trigger" is necessary to begin a thermal lift process. (Air behaves as though it's somewhat sticky.)

Thermal Triggering

Trigger processes can be quite pronounced or subtle in nature. As discussed in the last chapter, terrain heating can result in the movement of air up a slope resulting in the release of rising air off or near ridges or mountains. Light winds can act as a "trigger" that encourages the release of warmed air from its surface source area. Human activity such as vehicular movement or farming operations can trigger convection. At a soaring contest some years back, a towplane was dispatched to retrieve a sailplane that reported low in attitude over a remote airstrip. The tow pilot arrived while the sailplane was still struggling to stay aloft and so he landed, awaiting the sailplane's expected landing. To the tow pilot's amazement, the sailplane climbed away to fly home – the towplane's landing triggered the last thermal of the day off the airstrip.

Summary

The small-scale upward vertical air current known as a thermal is

~ generated by differential surface heating,
~ initiated by a convection process, that is
~ triggered by some disturbance, and
~ propagates vertically as long as the rising column or bubble of air heated at the surface is warmer (less dense) than the surrounding air at its altitude (pressure level).
~ The requirement for a thermal usable for soaring flight is magnitude: speed and size.

Obviously, a sailplane that sinks at 120 feet per minute (fpm) in flight will need the atmosphere to provide a lift rate generally greater than 120 fpm thus enabling the sailplane to climb and fly cross-country, and a thermal diameter about as large as the sailplane's circling diameter.

In the next chapter I'll discuss how to anticipate thermal occurrence and strength (*forecasting*), and in doing this review the concepts of thermal strength, the thermal index, and thermal forecast tools, especially the energy diagram in its own chapter.

Thermal Forecasting

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Diagram #1: The Thermal Index
Diagram #2: The Soaring Index
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In this chapter I provide insights and mechanisms regarding thermal physics and forecasting, based on my empirical observations through the years and those shared by far more experienced soaring pilots and meteorologists. References are noted at the end of the chapter that detail thermal development and thermal strength forecasting, to be studied at the reader's leisure.

In the chapter, *Higher-Terrain Heat Sources*, I explained how elevated terrain enhances thermal development. In *Thermal Development*, I explained the key role of air density differences resulting from differential heating of the air adjacent to the ground, and that the key to thermal formation is that the density of warmer air is less than the relatively cooler air surrounding this. Less dense air is buoyant, resulting in the upward vertical air motion known as a *thermal*.

A majority of cross-country soaring is accomplished by use of thermals that occur in an air mass structured to favor them. Such an air mass contains cool air to a depth of at least 3000 ft, and its surface air responds to surface heating by development strong lapse[16] temperature conditions with altitude over a broad area.

Because thermals develop in an air mass, their development is generally not restricted to the areas of sloping orographics cause ridge and mountain wave lift to develop. Thermal development needs differential surface heating in combination with an air mass that will, when lifted from the surface, develop a temperature lapse rate exceeding the dry adiabatic lapse rate (DALR) over the lower layer of the atmosphere to an altitude sufficient to make cross-country soaring possible in the course of the flying day. Moisture contributions to the development of thermals, or upward vertical air motion, will be addressed in the chapter, *Moisture Effects on Lift*, beginning on page 24.

Evaluating the weather for potential soaring flight has always been a challenge. The most successful long cross-country soaring pilots are those who are good observers and evaluators of the weather situation and are prepared to launch as soon as the lift is available that can support soaring flight. Assisting in this evaluation, the soaring community has relied on the concept of the Thermal Index (TI) for decades (See *The Thermal Index* by Henry Higgins). The TI is intended to be a predictor of dry thermal presence and quantify the maximum altitude of those thermals. The TI is the Celsius temperature difference at a given altitude (often given for the 850-millibar and/or 700-millibar pressure level on an upper air temperature sounding) between the ambient air as measured by a morning sounding and the temperature at that level along the dry-adiabat that intercepts the expected surface maximum temperature. The "Glider Flying Handbook" concisely describes the TI at a given level or altitude as "the temperature of the air parcel having risen at the Dry Adiabatic Lapse Rate subtracted from the ambient temperature" (`See Diagram #1: "The Thermal Index"`). The TI provides some degree of illustration emphasizing the point that air density differences, i.e., air temperature differences and not high temperatures, drive thermal development.

Having been developed from observed and recorded lift rates and the altitudes reached during soaring flights, and subsequent analysis of morning temperature soundings, the TI is a soaring community "standard" for forecasting useful thermal maximum altitudes and inferring relative lift rates. Relative lift strength is deduced that the greater the absolute value of the "negative" TI then likely is the greater thermal lift. For clarification to my students, I always comment in regard to the TI and its meteorological convention of the "minus" number that is necessary for thermal development. Remember what a thermal

[16] In meteorological jargon, *lapse* refers to a *decrease* in a specified parameter. Temperature lapse rate is thus the rate of temperature decrease with altitude.

is all about. At any point where a thermal is rising, the air temperature within the thermal is higher (the air warmer) than the ambient air outside of the thermal's boundaries. The meteorological convention of this situation being a "minus" number is derived from the TI Definition but the physics of buoyancy in regard to the needed temperature difference, i.e., the air in the thermal must be warmer than the air outside the thermal, is the concept to be remembered.

Following on the heels of Higgins' publishing of the TI in 1963, research was done by meteorologist Charles Lindsay in analyzing a series of flights by Mario Piccagli in a Standard Austria from 1963 to 1969 in the mountains around Frederick, Maryland. Piccagli's flights led to empirically derived regression equations that were published under the auspices of the National Weather Service in *Forecasters Handbook No. 3, Soaring Meteorology for Forecasters*. The analysis of those flights attempted to objectively determine and describe the relationships between maximum altitudes and lift rates reached in soaring flight with the depth of the DALR, including relating thermal strength to the initial height of the Convective Condensation Level (See "Definitions; Convection and Convective Condensation Level, CCL").

The results of Piccagli's flights and Lindsay's analysis specified:

1) A correlation of the maximum height of the thermals with the height of the dry adiabatic lapse rate;

2) Lift is stronger in a dry ("blue" or no-cloud) thermal that reaches a greater altitude (deeper) than one that is lower (shallower);

3) Convection (rising air) inside the cumulus cloud is an extension of the thermal's rising air below the cloud;

4) For a given altitude, lift under a cumulus cloud will usually be stronger than for that same altitude in a dry thermal;

5) Air must be heated enough to become dry-adiabatic through at least the lowest 3000 feet of altitude before the sailplane encountered lift rate of 100 ft/min or greater; and,

6) It was Higgins study that suggested a potential temperature increase[17] of 3˚C or greater (a TI of -3 or less) provided a good chance for sailplanes to reach the altitude of that temperature difference.

Following Lindsay and his analysis of Piccagli's flights in the mid-Atlantic Region of the United States, feedback graciously provided by the 1975 Regional Contest Pilots in the Minden area of Western Nevada provided a soaring data set for evaluation by National Weather Service (NWS) Meteorologists Chris Hill and Doug Armstrong that resulted in the development of an objective aid for forecasting thermal strength. Edited by John Joss in *Soar Sierra*, this objective aid was labeled the "Soaring Index, SI". (See *Soar Sierra*, pp. 23-28). Whereas the TI provides a forecast estimate of thermal height and only a relative and very subjective estimate of thermal strength based on the surface temperature in its relationship to the lower atmosphere lapse rate, the SI algorithm quantifies an estimate of thermal strength (See Diagram #2: The Soaring Index). The assumption of the TI and the SI is that the air mass represented by the morning sounding is not influenced by synoptic-scale changes during the soaring day. But even given the ever-changing nature of any air mass, on the average the SI has proved to be a reliable forecast aid in describing the quality of a thermal soaring day for the Intermountain West Great Basin and especially if its output is applied in comparison to previous days' forecasts as a trend.

There are a few interesting notes that need to be emphasized to put these two empirically derived soaring aids, the TI and the SI, into proper perspective. Geography and climate are crucial in understanding the logic behind these aids' outputs. As mentioned, the TI was developed from observations of soaring flight in the mid-Atlantic area with its modest vertical terrain variation (modest in comparison to the Intermountain West), higher average atmospheric relative humidity, more extensive vegetative ground cover, and higher soil moisture content. Conversely the SI was developed utilizing pilot feedback from the Great Basin with its large vertical variation in terrain, dry soil, minimal vegetation, and very low

[17] Perhaps you could explain what is a *potential* temperature increase…

atmospheric moisture. As published in numerous soaring textbooks and articles, the altitude where a TI value of -3 occurs is considered to be the useful "top of the lift." Understanding the climate of the mid-Atlantic region and that the effect of the incoming solar energy in its heating of the surface is mitigated by the amount of moisture present in the air and soil, the top of the useful lift would usually not reach the intersection of the DALR with the morning temperature sounding (given no large scale synoptic atmospheric changes during the day). Observed in the Western U.S. with terrain contributions to enhancing thermal production and drier conditions, incoming solar energy efficiently raises the sensible temperature of the lower atmosphere as the surface heats. The intersection of the DALR with the morning temperature sounding in the SI is quite frequently the top of useful lift as opposed to "capping" thermal altitudes at a value of -3 as depicted by the TI. Observed in Hill's and Armstrong's own data set as well as utilizing one of the results of Piccagli's flights, the strength of thermal lift is a function of the depth of the surface-heated, convectively-mixed, lower atmospheric layer. The deeper the convectively mixed lower atmospheric layer then generally stronger is the lift rate of the thermal. The SI's forecast for thermal strength comprises, and is a function of, two terms, the maximum altitude of the thermals and a solid lapse condition where there is a good decrease in temperature with altitude.

In summary, differential surface heating results in lower atmospheric level temperature differences. These temperature differences lead to air density differences. In combination with a favorable upper air temperature profile that favors development of a strong temperature lapse condition during the day, thermal soaring flight is then possible. The "soaring standard" Thermal Index provides an estimate of atmospheric mixing or thermal height and subsequently an inference of relative thermal strength. The "Great Basin" (author's descriptor) Soaring Index in its quantifying forecast for thermal strength underscores the contributions of both maximum thermal altitude for the day and temperature differential from the surface to aloft. I have addressed these two thermal forecast indices to underscore the concepts that are necessary to understand thermal development. I acknowledge that there are several other soaring indices and forecast aids, and variations of those aids, used around the world. But the meteorological physics and concepts for the thermal process are consistent. An additional factor that needs to be addressed in the future is a discussion of atmospheric moisture in its role of de-stabilizing of the air mass and contributions to thermal development.

Note that I have discussed these particular thermal forecast indices for the express purpose of understanding thermal development. Technological advances in computer speed and the ability to apply more detailed atmospheric physics has resulted in rapidly improving numerical soaring forecasts. The worldwide contributors to soaring in this computer environment are simply too many to know or list but they are appreciated on behalf of all the meteorologists and soaring pilots who now daily use fantastic atmospheric model output for planning soaring flight.

Point to specific references?

Energy Diagrams

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Diagram #1: The Del Rio RAOB 8/13/2011 1200z
Reference and Library Building (45 words)
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In the continuing discussion of determining whether soaring flight is possible from thermal development, I have begun throwing around meteorology terms, definitions, and concepts with some abandonment of constraint. With so many references to "energy diagrams" in defining the atmosphere's stability, I would like to pause with this month's article to simply define and explain a few of the lines that are seen on those constantly referenced energy diagrams. Despite the appearance of complexity, the diagrams actually present a picture that visually simplifies physical processes that impact vertical air motion and, thus, describe the state of atmospheric stability.

There are several different types of energy diagrams such as "Skew-T/Log-P", "Pseudo-Adiabatic," "Tephigram", "Emagram", etc. I am going to focus my explanation on energy diagrams using the Skew-T/Log-P Diagram as the other energy diagrams are similar in function but vary in the way meteorological parameters are oriented on the diagrams. From the recently concluded Pre-World Soaring Championships and the U.S. Open Class Nationals, the atmosphere's temperature and stability was often depicted by use of radiosonde observations (RAOB) over Del Rio, Texas (DRT). A specific example of a Skew-T Log-P Diagram over DRT depicting atmospheric parameters on August 13, 2011, at 1200 hours Coordinated Universal Time (UTC or Z) is shown.

At 92 stations around North America and the Pacific, fast-rising, helium balloons with attached instrument packages are sent aloft twice per day at 0000Z and 1200Z. As the balloons rise with their instrument packages, temperature, humidity, and pressure are measured and, by tracking the balloon, wind direction and speed are also derived. Keep in mind that the sounding data is a weather observation of the upper air. The gathered weather data is plotted and represented on constant pressure weather charts over the launch point. The obtained sounding does not give a true vertical dimension since the wind blows the balloon downstream. The gathered information is assumed to be over the launch point. Neither does the sounding give a true instantaneous measurement since it takes several minutes to travel from the surface to the upper troposphere. As a technical point, a radiosonde observation provides only pressure, temperature, and relative humidity data. When a radiosonde is tracked so that winds aloft are provided in addition to pressure, temperature, and relative humidity data, it has become a rawinsonde observation. Most upper air launch stations around the world take rawinsonde observations. Meteorologists and other data users, including myself, frequently refer to a rawinsonde observation as a radiosonde observation.

In looking at the example of an upper-air Skew-T Log-P diagram commonly distributed on the internet web by the University of Wyoming through a link from the University Center for Atmospheric Research (UCAR), let's define some of the lines seen.

Isobars – Solid, bold lines of equal pressure in a shade of blue (Label: 1). They run horizontally from left to right and are labeled on the left side of the diagram. The vertical coordinate on the energy diagram is that of pressure expressed in millibars(mb). Pressure is given in increments of 100mb and ranges from 1050 to 100 mb. Notice the spacing between isobars increases in the vertical (thus the name Log P). Since pressure as measured at a given point on the surface of the Earth is the result of the mass of air above that point, the greater altitude one goes in the atmosphere then the pressure at that altitude will reflect a decrease as a result of a loss of mass above that point/altitude.

Isotherms – Lines of equal temperature. These solid, blue lines run from the lower left of the diagram toward the upper right across the diagram (thus the name, Skew-T). Increments are given for every 10 degrees in units of Celsius, i.e., 10 degrees, 20 degrees, etc. (Label: 2). The isotherm lines are labeled at the bottom of the diagram.

Saturation mixing ratio lines – Saturation mixing ratio is the dimensionless ratio of the mass of water vapor to the mass of dry air. On the energy diagram it is expressed in a value of grams-per-kilogram. These light green-brownish, dashed lines run from just left of vertical upward to just right of vertical (Label: 3). The mixing ratio line values are labeled on the bottom of the diagram.

Wind barbs – Wind speed and direction given for each plotted barb. The wind information is plotted on the right of the diagram (Label: 4). The wind staff indicates the direction relative to True North from which the wind is blowing. The wind speed is depicted by barbs on the wind arrow and consistent with other weather products, i.e., one-half of a wind speed barb is equal to 5 knots, each full barb is 10 knots, and each solid triangular pennant represents 50 knots of wind speed.

Dry Adiabatic Lapse Rate (DALR) – The DALR is a rate of cooling (9.8 degrees Celsius per kilometer) due to an adiabatic expansion of a rising, unsaturated parcel of air. These slightly curved, light red, dashed lines on the Skew-T Log-P diagram arc to the right from the lower right upward with increasing height. Weather articles often reference the DALR as it pertains to thermals (Label: 5).

Moist Adiabatic Lapse Rate (MALR) – The MALR is a rate of cooling that depends on the moisture content of the air of a rising, saturated parcel of air. Owing to the release of latent heat, the MALR is less than the DALR. However, the MALR does increase with an increase in height since cold air has less moisture content than warm air. With the higher altitude and less water content available in that colder air, the MALR begins to approach that of the DALR. The MALR is indicated by dashed, light green lines that start to run vertical from the lowest portion of the chart but then curve to the left with increasing altitude (Label: 6).

Environmental sounding – This bold, red line represents the actual measured temperatures in the atmosphere (Label: 7). The temperature sounding is the jagged line running from bottom to top on the diagram. The sounding line is always to the right of the dewpoint line.

Dewpoint plot – This bold, green, jagged line runs from the bottom to the top of the diagram and it is the vertical plot of dewpoint temperature (Label: 8). The dewpoint line is always to the left of the environmental temperature sounding. The dewpoint is the temperature to which a given parcel of air must be cooled at constant pressure and constant water-vapor content in order for saturation (condensation) to occur.

With these lines on the diagram identified, I will discuss and elaborate on some of the atmospheric indices, interactions, and relationships that can be derived or described by reference to the various lines on the Skew-T Log-P Diagram in forthcoming articles.

References:

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

"Skew-T Basics", Courtesy of Meteorologist Jeff Haby
<http://www.theweatherprediction.com/thermo/skewt/>

Upper Air Data (RAOBs); University of Wyoming
<http://weather.rap.ucar.edu/upper/>

"Upper Air Data" Background Information
DOC/NOAA/National Weather Service
<http://www.ua.nws.noaa.gov/net-info.htm>

Moisture Effects on Thermal Lift

Text Box: Upper Air Sounding Labeled Parameters (363 words)
Diagram #1: DRT Upper Air Sounding
Diagram #2: De-Stabilization of the Atmosphere
Diagram #3: Change in the Lapse Rate due to the Release of the Latent Heat of Vaporization
Diagram #4: Temperature and Relative Humidity (RH)

In previous chapters I have deferred discussion of moisture as it relates to atmospheric stability and only briefly mentioned the moist adiabatic lines on energy diagrams. Now, more comprehensive explanation is warranted to help the soaring pilot understand moisture contributions or hindrances to thermal lift.

Referencing the previous chapter on energy diagrams, the upper air temperature sounding (See Diagram #1: DRT Upper Air Sounding) over Del Rio, TX, for August 13, 2011, is used as an example of a Skew-T/Log-P energy diagram. The temperature is depicted by the red line (Label: 1) upward in altitude through the atmosphere, and the dew-point temperature is depicted by the green line (Label: 2). The dew-point temperature, by definition, is the temperature to which a given parcel of air must be cooled to reach saturation, i.e., a relative humidity of 100%. Upon reaching saturation, the condensation process begins whereby the water in the air parcel changes from gas (or vapor) to its liquid state. The dewpoint may alternatively be defined as the temperature at which the saturation vapor pressure of the air parcel is equal to the actual vapor pressure of the contained water vapor. (Reference: Glossary of Meteorology)]

The generation of thermal activity for the purposes of soaring flight requires solid lapse conditions or the decrease of temperature with a gain in altitude in the atmosphere. Therefore, any combination of warming at the lowest levels of the atmosphere, and/or cooling aloft increases the atmosphere's lapse rate toward thermal development. (See Diagram #2: De-Stabilization of the Atmosphere). Anything that hinders surface heating or keeps the air next to the surface from warming is a hindrance to the lower atmosphere's de-stabilizing process for thermal development.

Cloud cover blocks incoming solar insolation and obviously hinders surface warming. In looking at our example upper air temperature sounding from DRT, note the closure of the temperature and the dew point temperature values at the 875-millibar and 575-millibar pressure levels (Circled on Diagram #1: DRT RAOB). In any upper air sounding the closure of the temperature and dew point lines depicts a cloud layer at that particular pressure level. At DRT the temperature and dew point closed and thus cloud layers were detected by the fast-rising rawinsonde at approximately one kilometer of altitude (3,300 feet mean sea level) and another at approximately four kilometers (13,100 feet mean sea level). In pre-flight weather analysis, the soaring pilot can get an idea of cloud layers that could hinder initial surface heating for purposes of thermal flight from the 'observed' morning temperature and dew-point temperature plots on the rawinsonde sounding, or forecast cloud layers that could develop during his/her projected flight by looking at the temperature and dewpoints aloft progged by numerical model soundings.

Water present within or on the surface of the ground is detrimental to the rise of the sensible temperature of the surface due to the high specific heat of water (See *Higher-Terrain Heat Sources,* in the section titled, *The Energy Required to Change the State of Water,* beginning on page 14). The presence of standing water, a very moist soil, or a large amount of green vegetation will slow the sensible rise of the surface temperature and subsequently the heating of the lower atmosphere from surface interaction.

What about atmospheric moisture and its influence on the temperature lapse rate in the upper air? Previously discussed the Dry Adiabatic Lapse Rate (DALR) is a constant rate-of-cooling due to decreasing air pressure of an air parcel that is rising in the atmosphere (DRT RAOB Label: 3). This is true only if the rising air parcel remains dry, i.e., no condensation or change of state of the parcel's water vapor occurs. So what happens if the rising air parcel cools to its dew-point temperature and, therefore, the air parcel has reached its water vapor saturation temperature? The water vapor within the rising air parcel begins to condense into suspended water droplets (visible moisture/cloud formation). The energy that was needed to change the state of water into its gas vapor form, the latent heat of vaporization, is released into the parcel and the parcel warms (See Diagram #3: Change in Lapse Rate due to Release of the Latent Heat of Vaporization). The rising air parcel, i.e., buoyant because of its lower air density/higher temperature than the surrounding air will become even more buoyant as the parcel warms from this water condensation process. If buoyancy of a dry, rising air parcel (thermal) was beginning to decrease and weaken due to a smaller temperature difference between the rising air parcel and the surrounding air, the condensation process of the water vapor warms the air parcel and increases rising air parcel/ambient air temperature differential. Therefore, atmospheric high water vapor content provides a potential for de-stabilizing the atmosphere, i.e., an encouragement for upward vertical motion. The upper air observed soundings or forecast soundings quantify atmospheric moisture content by the dew-point temperature values.

Remember that the water vapor saturation value of warm air is much higher than that of cold air (See Diagram #4: Temperature and Relative Humidity, RH). The amount of warmth added to a rising air parcel from the condensation process at lower altitudes and at a relatively higher temperature is much larger than that at higher altitudes where average temperatures are cooler, the water vapor content is subsequently less, and the resulting warming from the condensation process is therefore smaller. Furthermore, the Moist Adiabatic Lapse Rate (MALR) or Wet Adiabat on a Skew-T/Log-P Diagram (DRT RAOB Label: 4) also reflects a pseudo-adiabatic process meaning that the condensed moisture is assumed to precipitate out of the air parcel as it continues its ascent. In looking at the Skew-T/Log-P example diagram, note that the MALR is not a constant. [The DALR is constant temperature rate-of-loss of 3 degrees Celsius (5.4 degrees Fahrenheit per thousand foot/10 degrees Celsius per kilometer gain of altitude). Over the lowest 10,000 feet of the atmosphere, the MALR averages a temperature loss of 2 degrees Celsius/3.5 degrees Fahrenheit per thousand feet gain of altitude or 6 degrees Celsius per kilometer. An atmosphere high in water vapor content and initiating the condensation process is able to maintain upward vertical motion (buoyancy) with threshold temperature decreases of only 2 degrees Celsius per thousand feet in the MALR instead of the higher value of the DALR at 3 degrees Celsius per thousand feet. Our example upper air sounding provides a visible picture to underscore the fact that cooler air holds less moisture before reaching saturation than warmer air. Note how the slope of the MALR lines begin to bend toward that of the DALR at high altitudes, particularly as they approach the 200-millibar pressure level (approximately 40,000 feet mean sea level). With the saturation water vapor pressure much less in air that averages -40 degrees Celsius, the water vapor available to release its latent heat of vaporization when it condenses (or sublimates directly to ice crystals at this altitude) does not appreciably warm the rising air parcel. Therefore, the slope of the MALR and DALR is not that much different at such cold temperatures and altitudes.

With high values of atmospheric water vapor content, the condensation process releases explosive amounts of energy to warm rising air. With significant warming due to high water vapor condensation, large amounts of air parcel warming enables the rising air parcel to boost its temperature higher than any previously blocking atmospheric stable layer or temperature inversion to a rising dry air parcel under a dry adiabatic ascent. Thus, large amounts of atmospheric water vapor are considered the "fuel" for convective (thunderstorm) development. In a less unstable environment, thermals that ascend enough for its dry adiabatically cooling air to reach its dew-point temperature provide more benign but useful conditions for the soaring pilot in the form of visible thermal markers we know as cumulus clouds!

In consideration of our discussion on atmospheric moisture, along with upper air sounding analysis, atmospheric stability indices provide clues to meteorologists and pilots about the fine line that separates benign cumulus development from the dangerous presence of thunderstorms….and leaves room for future discussion.

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Upper Air Sounding Labeled Parameters
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References:

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

"Skew-T Basics", Courtesy of Meteorologist Jeff Haby
<http://www.theweatherprediction.com/thermo/skewt/>

Upper Air Data (RAOBs); University of Wyoming
http://weather.rap.ucar.edu/upper/

Mountain Wave

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Text Box: Mountain (Lee) Wave Terminology (394 words)
Picture: Sierra Wave Project Participants
Picture: Altocumulus Standing Lenticularis (ACSL)
Picture: Mountain Wave Foehn Gap
Diagram: Mountain (Lee) Wave Cross-Section
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My intent in this book is to provide insights into the atmosphere's mechanisms for vertical motion that are useful for soaring flight. I also focus on points-of-misunderstanding that I have encountered with student pilots or glider flight check applicants.

Despite mountain lee wave being one of the significant sources of strong lift for soaring, the mountain wave conceptual model is often confused by pilots. This chapter focuses on the definition and conceptual model of mountain wave. The next chapters will discuss key elements of the mountain wave and when it can be expected.

The non-flying public often believes that soaring is due only to ridge lift and is completely unaware of the other types of upward vertical atmospheric motion – due to temperature differential (thermals), convergence or shear lines, or mountain lee wave. While the interaction of air flow 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".]

Lee wave sets up with some form of topographical or terrain feature – a ridge, a hill, an island – that acts as an obstacle – disturbing the air flow up over the terrain that then drops back down toward its original level (or that drops from a plateau[18] – it's the *drop* that's the key to the bounce). 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 use illustrations and concepts rather than mathematical description so that your head will not ache. The math makes it clear that interaction of the wind velocity and atmospheric stability are crucial to the development and formation of a mountain wave. The two primary factors permitting development of mountain lee waves are temperature stratification and the vertical wind profile.

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 1951-1952. 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 persons in that famous project, Mr. Hal Klieforth. [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 through numerous research papers. Mountain wave(s) descriptions in modern research papers are

[18] Lee wave often forms over Lake Superior: Northern Minnesota is essentially a plateau. the North Shore of this lake is orthogonal to the strong northwest winds that characteristically follow cold front passage. At these times, satellite images usually show lee wave that may continue past the opposite shore.

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[19] 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, or as the altocumulus standing lenticularis clouds (ACSL or "lens" clouds).

Considering mountain wave in cross section, wind speed over the airflow-disturbing terrain must be sufficiently high to make "local" influences on the wind flow insignificant. Typically, a minimum wind speed over the mountain peak or range crest for mountain wave development is 25 to 30 knots. 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 propagate vertically, wind speeds at the higher altitudes 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 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).

Laminar flow in the wave keeps the cloud quite stratified and the cloud reveals the shape of the airflow over the wave crest, thus the lens shape. After crossing the peak of the wave crest, air descends on the downwind side. 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. Thus the cloud appears stationary, but the air is moving with high speed through the cloud.

The airflow associated with mountain wave is marked in different regions by two types of flow, turbulent and laminar. The rotor region is turbulent, with rapid changes in both speed and direction of the airflow throughout. 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 are 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. Above the altitude of the upstream mountainous terrain or peak, airflow in the lee wave is smooth and laminar. 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, the upwind side of each wave crest.

Mountain lee wave is a *downstream* lifting phenomenon caused by an *upstream* mountain range or peak interacting with airflow! A frequent misconception of mountain wave is that it develops and propagates directly vertically over the airflow-disturbing mountain range, so that in cross-section the wave peaks and the downwind sink are vertically aligned. This is not the case.

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 be seen, and its location relative to the disturbing terrain when lenticular clouds mark the location of the primary wave crest at high altitude. A pilot flying in the lee wave, without understanding the proper conceptual model of the wave, could mistakenly assume that the sailplane is flying in vertically-propagated ridge lift. If the upwind slant is not understood, the pilot may fail to navigate upwind while climbing and transition into the strong sink located downwind.

[19] Sublimate: in chemistry, To be transformed directly from the solid to the gaseous state or from the gaseous to the solid state without becoming a liquid. – https://www.thefreedictionary.com/

Within the mountain wave regime, a cap cloud is formed due to cooling in upward vertical air motion 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 evaporation of the cap cloud.

A foehn wind is experienced on the ground, and is due to this warming, drying air descending from high 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 a cloud-free area between cap clouds and leeward rotor 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.

This 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 streambed rocks. With visualization of the wave conceptual model, the soaring pilot can use the uplift side of the rotor rotation to transition to the lift in the laminar flow on the upwind side of the mountain wave crest. In the next chapter I will show more examples of mountain waves and discuss some of the physics behind wave development.

Mountain or Lee Wave Terminology

Special reference:

National Landmark of Soaring (NLS) Program, NLS #12, "Sierra Wave Project", Bishop Airport, California. https://en.wikipedia.org/wiki/National_Landmark_of_Soaring

Lenticular Clouds

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Diagram: Mountain Wave Conceptual Model
Photo #1: Mountain Wave Cloud Features
Photo #2: Well-defined ACSL
Photo #3: 'Stacked' ACSL
Photo #4: Minimal Moisture for ACSL
Photo #5: Multiple Wave Crests
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The late winter/early spring season brings transitory trough passages in the Northern Hemisphere's mid-latitude westerly wind flow that develops lee side or mountain waves with some frequency. When the right conditions are met, one of the more interesting cloud features within the mountain wave is that of lens-shaped clouds, *lenticulars*. This chapter discusses a few points about these – in the jargon, *alto-cumulus standing lenticularis* (ACSL).

Looking at the conceptual model of a mountain wave, [`See Diagram: "Mountain Wave Conceptual Model"`] note the position of the ACSL cloud that soaring pilots call a "lennie." Like all clouds, ACSL forms when the air temperature lowers to its dew point temperature, the air becomes saturated (100% relative humidity), and a change in state of the water molecules occur, i.e., water transitions from its gaseous state to that of its liquid or solid state depending upon the air temperature, forming suspended water droplets or ice crystals. The rapid lifting process on the front side of a lee wave provides the cooling mechanism through the air layer's gain in altitude and reduction of atmospheric pressure. The only requirement for visible moisture is enough water vapor – depicted by a sufficiently small dew point spread at that altitude.

Why is there a smooth, lens shape to the ACSL cloud?

When wave-related clouds develop, there are three distinct cloud types that may be seen: cap clouds, rotor clouds, and ACSL [`See "Photo #1: Mountain Wave Cloud Features"`]. A *cap cloud* resides on the mountain wave-initiating terrain feature, whether it is a single peak or a mountain range. It reflects ridge lift. The cap cloud forms as the result of an air layer lifting over that terrain. The dissipation of the cap cloud on the back or lee side of the lifting terrain feature is due to compressional warming of the air layer as its pressure increases in its descent, leading to the evaporation or sublimation of the cap cloud particles.

*Rotor cloud*s develop as the result of uplift in turbulent flow *below the wave crests*. A common misconception is that rotor clouds form against the lee side of the mountain range. They and the turbulence they mark extend vertically downward from the wave crest, sometimes to the ground. Turbulent flow in its general downward motion in that location does not support cloud development. In fact, the compressional warming and subsequent evaporation dissipates cloud. This creates the clear area known as the *foehn gap*, a break in the lenticular cloud lines , a clear area between the cap cloud of the generating ridge and the primary lenticular.

The smooth shape of the ACSL cloud is the result of laminar air flow. A relatively stable atmospheric layer around the altitude of a mountain peak or ridge provides, to some degree, a buffer layer from the lower atmospheric air – which is characterized by terrain-induced mechanical mixing or surface heating mixing. It is characteristic of mountain wave that wind velocity shear upstream from the lifting terrain is minimal – speed increases only slowly with an increase in altitude and wind direction changes little – with increasing altitude. In the jargon, the wind vector components of direction and speed do not change quickly in the troposphere where the lee wave is resident.

Wind flow at wave altitudes is laminar or smooth because of minimal wind-velocity shear, the temperature lapse conditions (temperature decreasing with a gain in altitude) above the stable layer, and the buffer provided by the stable layer itself. So the characteristic shape of the ACSL, a lens shape, is the visible moisture seen toward the top of each wave crest. The upstream edge of the ACSL is where the water changes state to that of visible moisture; and the back, or downstream, edge of the cloud is where the cloud evaporates as air descends from the wave crest.

Lee wave, and the lenticular cloud, is "standing" because of its static position with respect to the ground. However, the air *through* the lenticular cloud is moving very fast. Depending on the exact altitude and the strength of the overall weather system supporting mountain wave development, wind speeds at Flight Level 180 (about 18,000 feet mean sea level or near the 500-millabar pressure level) typically can range from 50 knots to 100 knots! In high mountain ranges around the globe, with the mountain wave phenomena setting up at high altitudes through the troposphere, wave soaring results in very high true air speeds risking control-surface flutter[20].

The varying degree of ACSL cloudiness in a mountain wave is simply a function of moisture content within layers in the atmosphere. Deeper moisture layers will result in taller ACSL [note the ACSL layer in Photo #1]. A narrower moisture layer with subsequent lifting in a mountain wave may result in a smaller number of lenticular clouds at the wave crests; [See "Photo #2: Well-defined ACSL" Note the cap clouds on the right side of the Photo #2.] and affect whether cloud marks the rotor presence beneath the arching ACSL at the crest of the mountain wave. The development and appearance of ACSL will vary with even minor changes in moisture content from layer to layer. With layered changes of atmospheric-layer moisture content, ACSL will often result in a stack of clouds, nicknamed pagoda clouds [See "Photo #3: 'Stacked' ACSL"].

Of course, insufficient moisture may lead to minimal ACSL development even though other wave cloud features are definitively present [See "Photo #4: Minimal Moisture for ACSL"]. With atmospheric moisture content below the threshold for lifted moisture condensation, a mountain wave may still be present even if not marked by ACSL or other characteristic mountain wave cloud features. This cloud-free wave is sometimes referred to as *blue wave*.

Should the combination of atmospheric stability parameters, moisture, and topography align, a mountain wave may also have several wave crests with each crest marked by ACSL [See "Photo #5: Multiple Wave Crests" and also Photo #4 where rotor clouds mark a secondary wave crest existence].

Summary

The lifting action that results in ACSL in a mountain wave is one of the mechanisms that powers soaring flight. While there are hazards that must be understood before soaring in a mountain wave, the presence of ACSL and an understanding of the conceptual model of the mountain wave is a step toward safely utilizing a smooth form of lift for soaring flight.

Photograph Acknowledgements:

Photograph #1: Courtesy of the "Sierra Wave Project" and Dr. Joaquin Kuettner.
Looking southeast over the Owens Valley in documenting the Sierra Wave.
Photographs #2 and #4: Courtesy of Jim Payne.
Photos taken during his extensive mountain wave flying over the Argentinian Andes.
Photograph #3: Courtesy of Jeff Kirby.
Photo taken of stacked ACSL generated in the lee of the Tehachapi Mountains over California's Mojave Desert.
Photograph #5: Dan Gudgel
Several ACSL marking several mountain wave crests looking downstream from Mountain Valley Airport in the Tehachapi Mountains.

[20] *Flutter* is a 3-dimensional resonance affecting the whole airframe that is most apparent and most damaging when control surfaces flutter and detach.

Mountain Wave Forecasting

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Main Body of Text (approximately 1500 words)
Text Box: Mountain (Lee) Wave Terminology (394 words)
(Wave Picture: To Be Furnished at Chief Editor discretion)
Diagram #1: Mountain (Lee) Wave Cross-Section
Diagram #2: Mountain Wave Upper Air Sounding
Satellite Picture: "Full Range Sierra Nevada Wave"
"Milestones" Section (Jan 2012)
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The previous chapter introduced the mountain wave as an atmospheric lift mechanism, its conceptual model, some history on its exploration, and wave terminology. Because of frequent confusion regarding the location of the primary wave lift zone, I emphasized 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 mountain boundary disturbing the mean wind flow, and that the wave structure leans upwind with altitude.

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 on the physics of the mountain wave to *Mountain Wave Parameters, page* 38 , I wish to itemize here some of the forecast rules that have been empirically derived by pilots and soaring meteorologists. There is nothing new under-the-sun regarding these simple rules for forecasting 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 mountain wave. See particularly *Weather Forecasting for Soaring Flight*, World Meteorological Organization; Prepared by OSTIV; 2009, Mountain Wave Characteristics, detailed on pp. 40-48, References, page 89.

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 even be a single mountain peak.

The minimum threshold wind speed over the top of the mountain boundary 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 ideal. Some reference sources state that 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 upsloping terrain to provide air flow uplifting is necessary, up to the mountain range crest; and then, a steep decrease in the terrain height from that crest.

The air mass wind speed needs to be sufficiently fast 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 (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, compression, and rapid loss of altitude in the wind flow results in a "hydraulic jump" that initiates the wave.

While the terrain features sufficient to develop a mountain wave are numerous around the United States, the most classic terrain 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 beneath frequent mountain waves. A single peak like Mt. Shasta in northern California is also seen to produce wave in favorable conditions.

Intuitively, the faster the wind speed, 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 upper troposphere). By convention, a wind speed of 50 knots at the 500-millibar pressure level (approximately 18,000 feet mean sea level) is a minimum threshold for to be called a jet stream.

Though the fastest wind speeds occur in the jet stream, it also is associated with strong atmospheric uplift, which brings moisture to the jet-stream level and brings widespread cloudiness. So the jet stream itself is usually not useful for wave flight, which is safest and most manageable in visual conditions, with visible markers of rotor and downdraft and avoid them. This need for dry air aloft means that the best mountain wave conditions are typically 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 directional wind shear will not allow mountain wave development. With less frictional influence from the earth's surface, wind speeds typically increase with a gain in altitude. The change of wind direction needs to be modest with increasing altitude through the troposphere. The wind speed also needs to change only modestly with altitude for wave to form. [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.

In addition, a large increase of wind speed with altitude may increase the risk of breaking wave, with its associated severe turbulence.

Stable air is also necessary for mountain wave development. 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. What is meant by this? A stable layer is *isothermal* (no change in temperature with a gain in altitude) or is warmer than the layer below (temperature *inversion*). [Referencing the "Mountain Wave Upper Air Sounding", note the red circle at a mid-level stable layer around 6,500 feet MSL].

There is a temperature inversion associated with any frontal passage. Therefore, the approach of a warm-front or passage of a cold-front (depicted on surface weather charts) implies the expected arrival of some form of temperature inversion aloft with the fronts. The presence of a frontal boundary contributes to meeting the conditions for mountain wave development when combined with terrain and other meteorological requirements.

Clouds and Wave

If the morning sounding shows that the atmosphere contains a deep layer of moist air, then getting visual meteorological conditions (VMC) for visual flight rule (VFR) flights is unlikely due to widespread cloudiness. A local trough of low pressure usually precludes VMC. If the observed or forecast atmospheric sounding, on the other hand, shows well separated, vertically spaced layers of moist air, then VMC may exist, and 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. Blue wave is one of the most hazaardous of meteorological situations because there are not markers of roll clouds and the large downdrafts on the lee side of mountains, and the extreme turbulence associated with mountain wave rotor will be invisible to the unwary aviator.

Summary

1) Courtesy of decades of empirical knowledge, here are some "guidelines" for the development of a mountain wave:
2) Terrain: Ideally some degree of asymmetry for a high mountain range or peak with a "flat" windward slope and a steep leeward slope;
3) 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;
4) Wind direction that remains consistent in direction or only changes slightly and smoothly with an increase in altitude;
5) 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;
6) 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;
7) A frontal inversion that provides for a mid-level stable layer close to the crest level of the mountain range or peak; and,
8) 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 two chapters we will continue discussing mountain waves and will describe some of the physics behind the wave development.

Mountain Wave Comments

Reference Section (112 words)

Diagram #1: Mountain (Lee) Wave Cross-Section (optional editor's judgment)

Photo #1: Mauna Kea Wave

Photo #2: Stratocumulus Standing Lenticular Clouds over the Southwest San Joaquin Valley

The previous two chapters have concentrated on the mountain lee wave phenomenon:

- ~ defining it and
- ~ giving guidelines to assist in anticipating its development.

Before continuing with some of the more analytical aspects of the mountain wave, I would like to simply address some important details.

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 (a *disturbing boundary* in the face of a moderate to strong wind). But even a single mountain peak can act as that required topographic feature 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).

I cannot describe the circumstances that cause airflow to move vertically in response to a lone mountain peak and develop a mountain wave, rather than simply flow around that peak horizontally. However, the phenomenon does exist, and if the meteorological situation seems to fit wave development, soaring pilots nearby should be aware of the possibility of a "lone peak" wave. Remember that the atmosphere is a fluid, so visualizing airflow behavior as seen in water waves downstream from a smooth rock in a stream is advantageous in helping a soaring pilot understand lift areas in mountainous terrain.

In addition, along the aphorism "lift is where you find it," lee wave action may sometimes be found 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 towplane climb rate, and have 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. Often only the primary wave is usable for soaring flight. While not objectively measured by instrumentation, this line of lift runs parallel to the mountain ridge. A small, low-altitude atmospheric lee wave appears to be the only conceivable mechanism for such lift.

Wave also occurs at the boundaries of air masses of different density and wind velocity, particularly at the top of the haze layer. This is not *lee* wave, is usually not stationary with respect to the ground, is usually evanescent, and its location is not predictable, except that generally it is most reliably found, in the northern hemisphere, to the southwest of the center of a low, behind the surface cold front. Wave markers are often seen on satellite images. This is rarely useful for sustained soaring flight.

Descriptions of the features and airflow action associated with the mountain wave concentrate largely on the primary lee wave. But 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 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`).

Safety

While I have addressed the mountain wave as a meteorologist, I feel compelled to mention a few things as a flight instructor, regarding safety:

Cloud clearance:

The Federal Aviation Regulations, Title 14, Part 91, require increased visibility and cloud clearance 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. I am not endorsing or encouraging pilots to break this regulation to accomplish soaring flight, and 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 faster than 250-knots up to mach one. Therefore pilots loitering close to a lenticular in soaring flight could 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 this, and avoid the risk of disaster from such a violation!

VMC into IMC:

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 at least; and at 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.

The late Bob Spielman, a highly experienced pilot, while flying wave over Reno, had cloud form *around* him. He lost spatial orientation quickly, lost a wing, and landed on a hospital parking ramp in high winds, fortunately snagging his parachute on a light pole His experience is not rare: "flight into IMC" sometimes means "cloud forms around pilot" at any altitude with humid air and cooling temperature.

Speed Margin

Wind speeds aloft increase with a gain in altitude, but the mountain wave is essentially a stationary phenomenon. Pilots will need to increase airspeed to remain in proper position in the wave as they climb. Aircraft *Never Exceed Speed* (Vne) design limitations are established to avoid aircraft control surface flutter and are a function of ***true*** air speed (TAS). As we ascend, there's a growing gap between indicated and true airspeeds. The wind noise and control response reflects *indicated airspeed*.

With flight at much higher altitudes comes much faster true air speeds, with deceptively low *indicated* airspeed, and the threat of control surface flutter becomes important. It is useful to own a panel instrument that shows true airspeed when flying wave.

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 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 jet stream is farther south, with 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.

It is useful and safe to have a flight computer in the panel that computes true airspeed.

Be Prepared

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 personal views reflect this 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.

Mountain Wave Parameters

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Text Box #1: Hydrostatic Equation (133 words)
Text Box #2: Wavelength Relationship (80 words)
Text Box #3: Scorer Parameter (142 words)
Diagram #1: Mountain Wave Conceptual Model
Diagram #2: Mountain Wave Project Rotor Depiction
Reference Text Box (256 words)
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In the previous chapters on mountain wave we discussed characteristics and the conceptual model of the mountain wave, mountain wave forecasting, and implications of flight in and near it. I will not let you get away from the topic without a little discussion on the complexity of numerical forecasting. 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 requires advanced mathematics and physics and a numerical description. In this chapter, I will give just a little taste of theory in order to leave undisturbed the meteorology profession’s reputation for being enigmatic.

This complexity is why vague answers are often given by meteorologists when asked, “Why?” by interested pilots. The complexity of a comprehensive numerical description for a mountain wave cannot be overstated. Along with the complexity of atmospheric interactions that lead to the development of the mountain or lee wave, I will point out a few of the assumptions, and numerical equation terms and variables that only begin to describe atmospheric motion resulting in the development of the mountain wave.

At this chapter’s end, I include an extensive, yet abridged, list of references, page 41, for those who wish to see examples of wave research. Personal recommendations for further information regarding mountain wave would be the *The Mountain Wave Project* and any research conducted by the University Corporation for Atmospheric Research (UCAR) and National Center for Atmospheric Research (NCAR). See https://opensky.ucar.edu/ for publications

In the conceptual model of mountain wave, the definition of the *wavelength* is the horizontal 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 (ref 3, page41), 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. 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* is defined[21] as a wave disturbance in which buoyancy (or reduced gravity) acts as a restoring force on parcels of air displaced from hydrostatic equilibrium. *Hydrostatic equilibrium* 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`).

The first term that must be addressed by numerical modelers of the atmosphere is stability. In the case of mountain wave, static stability. *Static Stability*, also called hydrostatic stability or vertical stability, is the relative tendency of air at rest to become turbulent or laminar due to the effects of buoyancy.

[21] Gravity wave, hydrostatic equilibrium, hydrostatic equation, and static stability definitions are from the *Glossary of Meterology*, https://www.ametsoc.org/ams/index.cfm/publications/glossary-of-meteorology/

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. Using these 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, determine *dynamic stability*, the measure of the tendency of the air to resist or recover from finite perturbations of what was a steady state condition. However, if any dynamic stability effect indicates 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 through this mixing – unless an outside force continually acts to destabilize the air, such as heating of the bottom of a layer of air by contact with sunlit ground during a sunny day.

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 (ref 3, page 41). 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 (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 which the wind is coming).

As mentioned, early wave modeling work worked with a series of assumptions to keep the *Lee-Wave Equation* (ref 1, page 41) 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 disregarded. 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 could be described as non-viscous, laminar, and isentropic. (Isentropic implies that potential temperature is constant with respect to space, in this regard (ref 3, page 41).)

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 and provides for laminar flow is sought, and soaring pilots focus on finding the conditions that favor 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, ref 11`), 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 determines wave persistence and strength. C*onstructive interference* occurs when the downwind terrain features align favorably within the wavelength to support the updraft of the wave; *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 (ref 5) for wave development. Linear theory fits well for the assumption that mountain waves are generated by terrain relatively smaller than the wavelength. If this assumption is not the case, then nonlinear dynamics play a significantly larger role in the low-level wave field over the lee slope. These equations confirm the importance of vertical wind shear for mountain lee wave:

~ 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 (ref 11, page 41):

~ 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 from ridge to tropopause 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.

Another 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*, in engineering and fluid-dynamics). Most people have seen the standing wave at the bottom of a dam spillway: this wave is a hydraulic jump. 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. Atmospheric jumps are much less frequent than trapped-wave systems. They tend to develop in the presence of high, steep lee slopes, strong near-mountain-top inversions, and relatively weak vertical shear environments (ref 11, page 41).

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" (ref 7)).

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 numerically described. And even as the wave is generated, downwind terrain features interfere with the wave.

Mountain Wave References

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Wind, Convergence, and Shear

Text Box #1: Equation of State for Dry Air (129 Words in Picture Form)
Diagram #1: Gradient Wind
Diagram #2: Resulting Wind
Diagram #3: Surface Pressure Gradient and the Wind
Diagram #4: Speed and Direction Convergence
Diagram #5: Convergence at Surface Low Pressure
Diagram #6: Shear Lines
Reference Text Box (40 words)

This book began with a listing, on page 2, of the types of lift commonly used for soaring flight. I have reviewed the features of ridge, thermal, and mountain wave lift types. Now I review *convergence*. Convergence lift develops in several ways. and these different forms of convergence lift will be addressed over the next three chapters. This chapter reviews basic meteorology and focuses on providing background for the following convergence lift discussions.

As previously discussed, air (which has mass) moves in a continually failing attempt to reach equilibrium of its mass distribution in the atmosphere. The Equation of State for Dry Air describes the relationship of mass, pressure, and density (See Text Box #1: "Equation of State for Dry Air"). Density is expressed in terms of mass per unit of volume. If temperature remains constant, then pressure is directly a function of the density (the amount of mass in a given volume). Previous chapters have illustrated that vertically oriented density differences in the atmosphere result in vertical motion of the air. Likewise, horizontal density and pressure differences result in the movement of air that we know as wind. Because the atmosphere is impelled by physics to reach equilibrium of its mass concentration, air movement is from an area of higher pressure (higher density) to that of lower pressure (lower density).

The *pressure gradient* (the rate of decrease of pressure over the horizontal plane of the earth's surface) is the magnitude of the decreasing change of the pressure across a field at a specific time (Reference: AMS). This difference in pressure over the surface of the earth results in a force that moves air (mass) from one point to another. Air moves directly from higher pressure to lower pressure.

As the mass of air moves from higher to lower density, an apparent force deflects the air to the right (in the Northern Hemisphere), as seen from an observer's point-of-reference on the rotating earth. This apparent force is called the *coriolis force* (Reference: AMS). The stronger the pressure gradient force and the resulting wind, then the stronger the coriolis force. At altitudes high enough to have minimal frictional influence from the earth's surface on air movement, the resulting wind is called a gradient wind. The wind direction of this gradient wind at altitude generally is tangent to the contour lines of an upper air constant-pressure chart (See Diagram #1: "Gradient Wind"). Close to the earth's surface, frictional effects influence the balance between the pressure gradient force and the coriolis force. Frictional force slows the wind speed even though the pressure gradient force remains. With decreased wind speed, the coriolis force is not as great, and the wind direction does not turn as much to the right (northern hemisphere). The resulting wind moves across the lines of equal pressure (cross-isobaric wind flow) from higher pressure toward lower pressure (See Diagram #2: Resulting Wind).

This is why wind directions reflect air moving at an angle away from high pressure areas on a surface weather chart and subsequently flow at an angle toward low pressure (See Diagram #3: "Surface Pressure Gradient and the Wind").

Convergence, by definition, is the process or act of converging or coming together. In mathematics convergence is defined as "the contraction of a vector field" (Reference: AMS). A vector has both direction and speed components, and in the atmosphere air movement has opportunity for 3-dimensional flow. When convergence of air flow occurs near the surface of the earth, due to the conservation of mass, air is forced vertically upward since the earth below does not allow downward air movement. Thus, the horizontal movement of air (which has mass) with any component of convergence will result in upward air motion (See Diagram #4: "Speed and Direction Convergence"). Aviation textbooks remind us that air "sinks" as it comes from the higher mass concentration of high pressure and moves toward the lower mass concentration of low pressure (See Diagram #5: "Convergence at Surface Low Pressure").

As a point of clarification, glider pilots very often use the terms "shear" and "convergence" interchangeably. Convergent flow, such as air moving into areas of surface low pressure, will result in some form of upward, vertical motion (typically not strong enough to support soaring flight). "Shear" is a sharp, directional difference in air flow that may, or may not, have any convergence associated with it (See Diagram #6: "Shear Lines"). Shear will not necessarily result in upward vertical motion. So-called shear lines that support soaring flight, by definition, have a component of convergent flow that results in upward air motion. Convergent flow can occur in one of, or a combination of, two ways: wind speed changes, speed convergence, and/or wind direction (See Diagram #4: "Speed and Direction Convergence").

The atmosphere behaves like a fluid. The mindset of any soaring pilot should always be envisioning the air around him or her as a fluid. With a vision of forces and mechanisms including convergence possibly at work in the fluid of air, and the use of conceptual models, the glider pilot is better able to use the atmosphere to soar. Having provided the basis for wind movement in this rendition, the next chapters focus on several situations that develop convergent lift.

Convergence along a Sea Breeze Front

Text Box #1: Equation of State for Dry Air (129 Words in Picture Form)
Diagram #1: Initial Atmosphere Pressure Pattern
Diagram #2: Resultant Sea Breeze Pressure Pattern
Diagram #3: Sea Breeze Circulation
Diagram #4: Sea Breeze Inland Movement with Time
Diagram #5: Sea Breeze Convergence Lift Zone
Diagram #6: Sea Breeze Vertical Temperature Profile
Picture #1: Florida Sea Breeze
Picture #2: SE Texas Gulf Coast Sea Breeze
Reference Text Box (94 words)

Convergence in the atmosphere's airflow provides a mechanism for providing useful lift for a soaring pilot. The classic example in soaring aviation texts for convergence lift is often illustrated as that associated with a sea breeze. This chapter is a simple review of the development of a sea breeze and its associated convergence lift. In the atmosphere's constant failing attempt to achieve density or pressure equilibrium, motion results, felt as wind. Differing air masses that flow against one another are *convergent*. When they are of differing density, one flows over the other, creating convergence lift.

Specific heat is a thermal property of a substance, the ability of that substance to absorb and store energy *without raising its sensible temperature*. All ground objects absorb solar energy. Of the various surfaces and materials along coastlines lakes, the specific heat of water is the highest of common materials, about 4.5 times higher than typical earth. Thus at any latitude, and under a upper-air synoptic weather pattern, surface temperatures of earth and water differ primarily because of their different specific heat. Other properties such as color, texture, and opacity are secondary influences.

Imagine a simplified initial state of the atmosphere at dawn where the air immediately above the sea and land are the same in temperature and the isobars of pressure aloft are parallel to the surface. As pressure is defined as the weight of the air molecules above us, the isobars decrease in magnitude with an increase in altitude (See Diagram #1: "Initial Atmosphere Pressure Pattern"). In such a simplified model, with no temperature or density differences, there is no wind (pressure gradient = 0.0 mb). The Equation of State for Dry Air describes the relationship of mass, pressure, and density (See Text Box #1: "Equation of State for Dry Air").

After dawn, incoming solar energy begins to add energy to all surfaces, water and land. But the ocean remains relatively steady in temperature with the water's tremendous capacity to store energy while the land with a low specific heat and as a poor conductor heats much more quickly than the adjacent ocean. With higher surface temperatures, air immediately adjacent to the land warms by conduction and subsequently the lower atmosphere warms by the convection mixing process. With lower atmosphere thermal mixing, mass is transported upward in thermals, thereby raising the pressure altitude aloft. Pressure decreases at the surface of the land with the departure of vertically transported thermal air along with the reducing of the density of the air through sensible warming.

Subsequently, this early, weak thermal mixing of the air changes the orientation of the initial pressure pattern, placing higher pressure aloft over the land in comparison to a point at the same altitude over the ocean. Concurrently, the sensible temperature of the ocean (or large lake) changes trivially, and the density of the air immediately over the water is relatively unchanged.

This creates a density gradient at the surface directed the ocean to the land, thus atmospheric pressure at the surface over the water is higher than surface pressure over the land, an an onshore (ocean-to-inland) pressure gradient. Wind follows this pressure gradient and sea breeze develops. (See Diagram

#2: "Resultant Sea Breeze Pressure Pattern") Empirical evidence shows that air movement can begin with as little as a 2˚F difference in temperature. An onshore breeze is then observed at the surface.

A sea breeze is a *closed circulation*, the pressure gradient aloft favors a return (although much weaker) land-to-ocean air flow. (See Diagram #3: "Sea Breeze Circulation") A typical sea breeze onshore wind flow begins by mid-morning at the coastline and reaches about 20 miles inland by early afternoon. With incoming solar energy received per unit area getting stronger during the morning through mid-day, the surface onshore pressure gradient continues to get stronger and the sea breeze front continues to push inland with time through the afternoon hours. (See Diagram #4: "Sea Breeze Inland Movement with Time".)

Because of the differing air mass characteristics and discontinuities across this front, the sea breeze front is analogous to a synoptic scale front. The air being replaced over a given point inland along a coastal plain or valley reflects the characteristics of the maritime or large lake source region with lower surface temperature and higher humidity.

The common characteristics of a sea breeze front passage include: a sharp temperature drop, wind shift, wind speed increase, gusty wind, and a rise in relative humidity. The passage of a sea breeze front is also marked by a sudden pressure rise (pressure discontinuity), the presence of a line of haze marking the boundary between land and sea air, and a rise in dewpoint temperature.

Because of the speed convergence (see page 43) at the leading edge of the sea breeze, upward vertical motion results in useful lift for the soaring pilot (See Diagram #5: "Sea Breeze Convergence Lift Zone"). The magnitude of the upward vertical motion along the sea breeze front is a function of several factors, including at least the instability of the air mass ahead of the front, the speed of the front, the speed of the wind, and the vertical depth of the maritime influence.

There are a couple of factors associated with the sea breeze front, as a convergence line, that may place an unwary soaring pilot in an unplanned situation who does not understand and plan for its normal evolution.

Since the sea breeze front initially develops at the coastline and moves inland with time in a diurnal pattern, a soaring pilot using thermals for lift at a gliderport on a coastal plain, would in the morning hours transition to steady lift along the sea breeze frontal convergence line when it passages. Frequently, the lifting action associated with the sea breeze front or convergence line will be marked and enhanced by the development of a line of cumulus in an otherwise "blue" or clear air mass. Some typical characteristics of a sea breeze front are as follows:

- ~ The rate-of-advance of the sea breeze is a function of the density difference across the front. Typically, the advance is from 4 to 8 knots, but higher values reach 15 knots;
- ~ The temperature difference across the sea breeze front is often on the order of 15˚F over a distance of 20 miles;
- ~ The sea breeze has wind speeds typically from 8 to 15 knots with higher speeds up to 28 knots;
- ~ The depth of the sea breeze circulation is a function of the coastal marine layer and will vary from 1000 feet(330m) to 3000 feet(1km) mean sea level in altitude;
- ~ Lift rates along such a convergence line (heavily influenced by terrain features) are typically in the 200 to 400 feet per minute (FPM) range. However, other influences such as terrain channeling and especially inland air mass instability can increase soaring lift rates along such a modified convergence line to over 1000 FPM, and,
- ~ Inland penetration of the sea breeze varies tremendously because of terrain features. Inland distances, with questions also involving the definition of 'maritime' air, vary from 3 miles to 125 miles with sea breeze *circulation* effects also observed 60 miles from the coastline over the ocean.

Traps for the unwary

If a pilot chooses to soar the inland-moving convergence line, at least two negative soaring properties of a sea breeze front must be overcome should the soaring pilot decide to return to the departure gliderport:

- ~ A strong headwind in the maritime influenced boundary layer against which to fly to reach the gliderport (`See Diagram #4: "Sea Breeze Inland Movement with Time"`); and
- ~ A change to weaker or even total absence of thermals, hindering or preventing cross-country flight back to the gliderport, due to the cool air at the lower levels snuffing thermal development.

This cool air advection behind the sea breeze front at the lowest levels weakens the vertical temperature lapse rate and provides a low-level "capping" temperature inversion at the transition from the maritime air to the general air mass aloft (`See Diagram #6: "Sea Breeze Vertical Temperature Profile"`). An afternoon weather satellite image of Florida clearly shows the influence of the sea breeze as it changed the resident land air mass with its thermal-generated cumulus cloud field to that of a cleared, stable maritime air mass along the coastlines (`See Picture #1: "Florida Sea Breeze"`). Depending upon atmospheric instability and moisture presence in the resident air mass ahead of the front, sea breeze fronts often result in a third negative property, the development of deep convection due to the initiating lift mechanism of the frontal convergence line (`See Picture #2: "Southeast Texas Gulf Coast Sea Breeze`).

Whether it is truly marine air with its moisture content and reflecting the ocean surface temperature that defines its maritime origins or marine air that has become modified in its inland push and no longer has its initial marine moisture and temperature characteristics, the influence of a coastal sea breeze can be realized far inland. For example, local meteorologists do not consider the increase in wind speeds observed at Uvalde, Texas, around 11 PM CDT as the passage of a sea breeze front. However, the influence of a push of maritime air from the southeast Texas Gulf Coast sea breeze front results in the landward flow well downstream from the coast, over interior, south-central Texas. Even if the air directly involved in that flow is not 'maritime' in nature, it occurs because of the sea breeze at the coast. Such interior convergence lines will be discussed in the next two chapters.

Summary

The closed, thermal-induced circulation system which drives a sea breeze front creates a discrete air mass that flows inland due to the pressure gradient created by sunlight on ground objects. The relationship of temperature, pressure, and density continues to be a driving force for air motion that results in convergence that is useful for soaring flight. The sea breeze front and its variants are examples of convergence.

The soaring pilot flying the sea breeze front must be aware that if the front passes the gliderport, the glider will encounter headwind and an absence of lift on the way home.

Terrain-Induced Convergence

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Diagram #1: Tehachapi Valley and Shear Line
Diagram #2: Tehachapi Shear Line Roll
Picture: Tehachapi Shear Line Cloud Street
Diagram #3: Elsinore Shear Line
Reference Text Box (132 words)
Acknowledgment Text Box (97 words)
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Both meteorology and aviation texts frequently present the sea breeze phenomenon as a source of air uplift. Last month we discussed various examples of sea breezes that lead to convergence. Besides the sea breeze, convergence can also develop due to terrain interaction with air movement. That air movement (or wind) can be either a density-driven (small-scale) wind or due to synoptic (large-scale) features.

With the introduction and explanation of how convergence results in lift in the last chapter, I would like to simply cite two cases in this article as examples of the many terrain-induced convergence zones or lines that regularly occur around the country. One of these examples develops due to synoptic-scale as well as a smaller meso-scale flow; and the other type of terrain-induced convergence is one that develops *within* a coastal plain sea breeze.

The Tehachapi Shear Line

The Tehachapi Shear Line is a terrain-induced convergence line that has been described in soaring texts and articles through the years (`See: References`). It is an example of upward air motion primarily the result of convergent wind flow, i.e., directional convergence, from air passing around a terrain feature.

The Tehachapi Valley in South-Central California (`See Diagram #1: "Tehachapi Valley Shear Line"`) lies at an elevation of 4,000 feet above mean sea level (MSL). The elliptical 8 mile long by 5 mile wide Tehachapi Valley is roughly bounded by the Tehachapi Mountains and specifically Double Mountain at an elevation just under 8,000 feet MSL running generally northwest-to-southeast on the south side of the Valley, a low-lying ridge just under 5,200 feet MSL running southwest-to-northeast for the east boundary, the beginning of the Sierra Nevada Range climbing upward from 6,500 feet MSL as the north boundary, and a combination of two passes and Bear Mountain (and ridge) reaching an altitude of 6920 feet MSL to the west.

These western boundary features lead to the channeling of air that results in a line of convergence in a general northwest-to-southeast orientation over the Tehachapi Valley. Tehachapi Pass and Valley provide a lower elevation terrain gap from the 500-foot MSL Southern San Joaquin Valley to the Mojave Desert at 2,500 feet MSL for wind flow through the south end of the Southern Sierra Nevada and the Tehachapi Mountains. The north side of Bear Mountain Peak and its associated northwest-to-southeast ridge constitutes the west side of the Tehachapi Pass. The south side of Bear Mountain Peak slopes downward to the Cummings Valley that is essentially a same elevation, 6-mile western extension of the Tehachapi Valley. A small 500-foot ridge on the southwest side of Cummings Valley then drops rapidly 4,000 feet to the San Joaquin Valley floor in a horizontal distance of only approximately 4 miles.

Air passing eastward through Tehachapi Pass on the north side of Bear Mountain meets air that has arrived into the Tehachapi Valley coming eastward around the south side of Bear Mountain up from the San Joaquin Valley and through the Cummings Valley. The resultant convergence provides a line of lift through the major axis of the Tehachapi Valley under the right meteorological conditions (`See Diagram #1: "Tehachapi Valley Shear Line"`). Since the scale of the shear line in the Tehachapi Valley is a small meso-scale phenomenon, it lies well inside the resolution of the old National Weather Service (NWS) observation network. No local, high resolution observational networks are in place, in either the vertical or the horizontal plane, to precisely map and document the convergence line configuration. However, soaring activities in the Tehachapi Valley, from Fred and Goldie Harris's Holiday Haven[22] through Larry and Jane Barrett's Mountain Valley Airport, over the past five decades have provided solid empirical information about the convergence.

This line of convergence, the Tehachapi shear line, generated from northwesterly wind flow, generally aligns WNW to ESE over the Tehachapi Valley. The line may oscillate in a serpentine manner downwind of Bear Mountain. Larry Barrett, with his own flying experiences, also references comments made by long-time retired NWS District Ag Forecaster and pilot Darwin Wilkins that this shear line seems at times to exhibit horizontal roll characteristics, with the strongest lift on the south side of the lift line (`See Diagram #2: "Tehachapi Shear Line Roll"`).

While this convergence line has occasionally been observed to have lower atmosphere instability markers, i.e., low-ceiling cumulus, it seems to form most consistently and with the strongest lift when there is a "capping" stable layer below 9,000 feet MSL. This stable layer is produced by the subsidence in high pressure aloft following a winter cold frontal passage, or by the resident high pressure that lies over the eastern Pacific Ocean along the California coast during the warm season. If the moisture content is sufficient, in combination with the shear line uplift, the line of lift will be marked as a cloud street (`See Picture: "Tehachapi Shear Line Cloud Street"`).

Atmospheric moisture for shear line cloudiness can be provided by the air layer at the Tehachapi Valley level or by moisture contributions from upslope air flow from the Southern San Joaquin Valley. Even with widespread cloudiness from upslope air flow on the northwest slopes of the Tehachapi Mountains, often the shear line presence can still be detected by a heavier line of clouds embedded within the low-lying overcast over the valley. The best visual evidence of the shear line, however, is the development of a cloud street formed due to the convergent uplift, with clear conditions prevailing to the sides.

The meteorological scenario for the Tehachapi shear line development starts with a sufficient pressure gradient in the lower atmosphere that supports a northwest wind, typically of 12 to 20 knots through and over the Tehachapi area. Less frequently the shear line has been observed to occur with higher wind speeds. The surface pressure pattern that supports this kind of flow is one where higher pressure resides northwest of the Tehachapi Valley with lower pressure inland and southeast of the area.

This type of surface pressure pattern can come about following a synoptic scale event such as a frontal passage, or the more typical interior California pressure pattern resulting from a large meso-scale Valley-Mountain wind in combination with Mojave Desert heating. The presence of subsiding air aloft associated with high pressure likely supports shear line development by limiting its vertical extent to favor some form of a closed vertical circulation. This "cap" also keeps air flow in the horizontal plane, to thus flow "around" both sides of Bear Mountain rather than pass over it.

The perceived "roll" of the shear line may be attributed to the differential heating of air rising from the South San Joaquin Valley through the Tehachapi Pass north of Bear Mountain versus the air arriving in the Tehachapi Valley after passing through Cummings Valley[23]. A more gradual lifting of air through the Tehachapi Pass on the north side of Bear Mountain does not warm the air as much as that warmed from the steep Tehachapi Mountain slopes south of Bear Mountain and its passage through the Cummings Valley on its way into the Tehachapi Valley. With the air warmer on the south side of the line, it flows over the air converging from the north and, thus, the "roll" of the line (`Again, see Diagram #2: "Tehachapi Shear Line Roll"`).

On days when the Tehachapi shear line is broad, the south side of the convergence line is much sharper in the transition into the line with stronger lift rates. This is in comparison to the north side of the shear line that is characterized by lower lift rates and higher sink rates adjacent to the shear line.

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[22] `[Mrs. Google knows nothing about this. Is the reference still apropos and understandable by the reader?]`

[23] `[And where, pray tell, is Cummings Valley?]`

Flight using the lift of the Tehachapi shear line is like flight using other types of shear lines, typically wings-level flying. Pilot and any passengers are provided comfortable ride conditions in contrast to the circling necessary to use thermals for soaring flight.

The Tehachapi shear line does have some interesting characteristics:

- ~ ***Narrow lift band***. The "lift line" can be narrow at times. In fact, the pilot can perceive the shear line lift as if it were a sharp ridge with a rapid diminishing of lift immediately to the left or right. In this situation, the lift line may be so sharp that a pilot may feel the lift to shift from one wing tip to the other with just a small heading change.
- ~ ***Dolphin technique optimal***. With a narrow line-of-lift, turning in the line is typically unrewarding, as any turn only puts the pilot into sink adjacent to the converging air. Therefore, "dolphin" flight along the line is a far more efficient soaring technique than circling.
- ~ **Irregular lift rates**. The lift rate along the shear line is typically not steady. There are areas of stronger and weaker lift (sometimes absent altogether at "weak" spots). General lift rates without thermal enhancement vary from neutral (zero sink) to 6 knots of lift. During the warm season months, the shear line can enhance thermal development along its axis. In this instance, soaring pilots can circle with positive climb rates for the entire turn, with observed lift rates of 6 to 10 knots not uncommon. However, climbing to altitudes higher than 9,000 feet MSL is generally not productive in the shear line and pilots usually move to adjacent higher terrain in search of thermals that extend higher.
- ~ ***High collision risk***. In thermal lift, gliders circle and are easier to spot. But like all shear line soaring, gliders fly for extended periods of time wings-level. Thus, there is an added difficulty in collision avoidance as gliders approach each other with minimal cross-sectional area exposed. To soar the Tehachapi shear line requires careful adherence to accepted right-of-way practices, with gliders meeting or passing each other on the right. However, it becomes difficult to strictly adhere to this right-of-way rule when the shear line has "lift pockets" from thermal enhancement and gliders are able to circle within the shear line. Thus, flight using the shear line demands an increased awareness for collision avoidance.
- ~ ***Terrain may align thermals***. Flight in a line through the axis of the Tehachapi Valley and farther west is not exclusively from convergent flow. Pilots have been able to fly westward toward the peak of Bear Mountain by transitioning from convergence in the Tehachapi Valley to that of thermals coming off both the north and south slopes of the NW-SE spine of Bear Mountain with some degree of low-level instability supporting thermal development.

Elsinore Shear Line

The Elsinore shear line in Southern California is often cited as the classic example of terrain-induced convergence in aviation textbooks and publications. A quick review of the topography of the Southern California coastal area shows its coastal plain rising to high coastal area terrain features. These features include the Inland Empire plateau around 1,500 feet MSL east of Corona, and the Santa Ana Mountains southeast of Los Angeles that vary from 4000 feet MSL to its high point, Santiago Peak, at 5,720 feet.

I discussed the sea breeze and its density-driven winds in the previous chapter, *Convergence along a Sea Breeze Front*, page 44. The Elsinore shear line develops from terrain channeling and diversions of the Southern California sea breeze as it pushes inland off the immediate coastal plain (See Diagram #3: "Elsinore Shear Line"). As the sea breeze sweeps inland beginning in the mid-morning hours, it pushes through both Santa Ana Pass toward Corona on the northwest side of the Santa Ana Mountains and north of this through Temecula Pass on the southeast side of the mountains (locally known as the Ortega Mountains).

While soaring is possible along any sea breeze front due to speed convergence, the added directional component of convergence near Lake Elsinore makes this particularly distinctive. The air coming from the northwest typically contains more pollutants from the south Los Angeles Basin as well as its denser cool, moist air. At the onset of the sea breeze immediately along the coast, the air pushed ahead of the sea breeze at Temecula Pass is drier, a little warmer, and has better flight visibility associated with it. With the air arriving from the northwest on the east side of the Santa Ana Mountains, there is a very discernible line-of-discontinuity marking the location of the convergence, reflecting differences of air mass moisture, visibility, wind speed, and wind direction. Due to its higher density, the cool marine air arriving from the northwest not only drives under resident inland air but also drives under the arriving air from the southeast.

The best lift zone for soaring literally has the glider pilot placing one wing in the “smog” arriving from the northwest and the other wing in the clearer air to the southeast. Typically, the sea breeze encircling the Santa Ana Mountains meets from opposite directions about 5 miles northwest of Lake Elsinore on the inland side of the mountains around 10-11 AM PDT. However, this initial convergence location is not geographically fixed, as it is influenced by day-to-day changes in the orientation of larger scale surface pressure gradients.

Diurnal changes in the pressure gradient influence sea breeze speed and direction around in the Los Angeles area. In response to the inland advance of the sea breeze toward the Ontario and Riverside areas as well as air pushed through Temecula Pass, the Elsinore convergence line typically drifts southeast and begins extending toward the northeast and Banning Pass during the early and mid-afternoon hours. The sea breeze front generally reaches the vicinity of March Air Reserve Base (ARB) in midafternoon, about 2:30 to 3:30 PM PDT, with typical winds from the west-northwest about 10-15 knots.

Movement of this convergence zone is inland at about 5 knots. The variable location of the Elsinore shear line is generally in the area from March ARB to Hemet. And much like the Tehachapi shear line, the convergence zone usually shows some serpentine characteristics.

This shear line lift is not only the result of the speed convergence of the inland-pushing sea breeze, but the lift rate is augmented by the conflicting wind direction from Temecula Pass. Typical altitudes reached along the Elsinore shear line are 4,000 to 6,000 feet MSL. During summer days, the lower layer air residing over the Inland Empire Plateau de-stabilizes due to strong daytime surface heating. Afternoon thermal development is enhanced along the shear line, so after the shear line arrival thermal climbs to altitudes of 11,000 feet MSL are common.

The shear line tends to focus thermal activity such that thermals adjacent to the line are more widely spaced and weaker, while even as thermals within the line become better organized and stronger. The width of the Elsinore shear line lift may approach one-half mile and it is very often marked by a cloud street. Climb rates due to the shear line are generally 3-5 knots but shear line enhanced thermals reach 8-10 knots.

Conflicting air flow around the Santa Ana mountains typically continues to provide some convergence for useful lift until 6-7 PM PDT, even though the most active convergence has moved southeast and extends more to the northeast. At the end of the afternoon, the northeast side of the Santa Ana Mountains becomes shaded. This late afternoon shading, combined with the long-lived marine air influence, washes out the convergence line, resulting in sink in the vicinity of Elsinore. The active lift of the shear line at this point is typically from Perris and eastward towards Hemet.

Conflicting airspace use

- ~ Much like the Tehachapi shear line, flight right-of-way rules need to be adhered to for safety-of-flight regarding collision avoidance. The proximity of the Elsinore shear line to the complex airspace over the Los Angeles area adds additional burden to the pilot who wishes to fully utilize this convergence lift.
- ~ Consideration must be given to flight rules directly associated with the March ARB Class C airspace that hosts the shear line. Any flights west of March ARB begin to have other airspace considerations for the Ontario Class C and the Riverside and Chino Class D airspaces. Even without the March ARB airspace encumbrance, the airspace to the north becomes quite

busy with lower altitude general aviation traffic, and higher altitude heavy turbine and prop-jet aircraft.

~ The Lake Elsinore and Perris Airports have active skydiving operations adding to the air-space use in the shear line.

Summary

The presence of mountains and valleys often results in winds being channeled, blocked, or diverted. These are present in various forms around the country, I have presented just a couple of simple examples in regard to the interaction of elevated terrain with air flow that results in convergence or shear lines providing upward moving air sufficient for soaring flight.

Terrain-Channeled Convergence

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Chart: "500 Mb Constant Pressure"
Diagram #1: "Mono Lake Shear Line"
Diagram #2: "Flying 'M' Shear Line"
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In the last chapter I introduced terrain-induced convergence by citing the Tehachapi shear line and the Elsinore shear line as examples. This chapter focuses on another couple of scenarios that result in convergence as the result of terrain interaction with density driven winds.

The eastern edge of the southern Sierra Nevada[24] range along the California-Nevada state border is a sharp escarpment dropping from an average elevation of 13,000 feet mean sea level (MSL) down to the Owens Valley at 4,000 feet MSL in just a couple of miles. This tremendous west-to-east variation in terrain height results in large temperature differentials across this region as the result of mountain slope effects, mountain-valley interactions, regional heating/cooling disparities due to surface moisture and vegetative differences, terrain-blocking (influencing regional temperature advection) and typical large-scale (synoptic) atmospheric changes. These effects and interactions can be cumulative, thereby increasing air density differences at various locations along the Sierra Front (the Sierra Nevada eastside escarpment). As detailed in previous chapters, especially page 44, temperature differences change air density and ultimately result in pressure differences. Pressure gradients thus result in a force that moves air from an area of higher pressure to lower pressure, creating wind.

The west side of the Sierra Nevada is a gradual upward slope that lifts air as it moves in its general middle-latitude, hemispheric, west-to-east direction. This west side of the mountain range is forested and moist from winter rains and snow. As the air descends on the lee side of the range, with its dramatic drop in terrain height, it dries and warms adiabatically as it descends to the floor of the Owens Valley and the western valleys of Nevada after crossing the crest of the southern Sierra Nevada.

During the summer months, especially, the air mass over the western Great Basin of Nevada is much hotter and drier than the Californian west side of the Southern Sierra Nevada. However, the southern Sierra Nevada is not a solid, uniform high wall of granite along its range axis. There are gaps (passes) in the range that open to the east side high desert that bring cooler air to the west side of the range, so that local surface pressure is typically higher than the pressure over the intensely heated western Great Basin during the warm-season afternoon hours.

Frequently during the warm season, the synoptic weather pattern is dominated by high pressure aloft over California and the western Great Basin (`See Chart: "500 Mb Constant Pressure" June 14, 1999`). With this high pressure, synoptic pressure gradients are typically weak or "flat" over the region. However, regional average temperature differences develop in daily cycles from the contributions of slope and mountain-valley heating and cooling effects. As each day begins, overnight radiant cooling and subsequent mixing due to overnight slope effects diminish temperature differences at the surface over the region. After sunrise, the dry atmosphere of the high desert of eastern California and western Nevada combined with the dry soils of the basin mountain ranges result in quick rises in sensible temperature. These high-desert temperature rises occur faster than on the moister forested west side of the Sierra Nevada.

With this larger rise in temperature over the western Great Basin during a typical summer day, a density-driven westerly wind is encouraged along the Sierra Front that results in varying types of moving convergence lines as the wind sweeps out to the far-west Nevada Great Basin valleys. The more robust afternoon west wind "Washoe Zephyr" over the Truckee Meadows and Carson Valley, with higher surface pressure due to the cold Lake Tahoe, is a well-known example of this meso-scale phenomenon. In

[24] Sierra Nevada is *snowy mountains* in Spanish.

a similar fashion but smaller in magnitude, this afternoon westerly wind along the Sierra Front is also shaped and locally augmented by the presence of Mono Lake that affects the local pressure field due to its cooler surface as well as contributing some moisture from the lake at the Great Basin valley level to the otherwise drier air adjacent to the high desert surface.

Mono Lake Shear Line

At the start of a typical summer day under the domination of high pressure aloft, skies are clear. Thermal trigger routinely occurs by mid-day with perhaps a few cumuli early over the higher terrain. As the day progresses, the aforementioned density-driven west wind develops over the Mono Lake area focused by the Tioga Pass gap in the Southern Sierra near Lee Vining on the west side of Mono Lake and at the east side base of Tioga Pass. A convergence zone develops where the leading edge of this surface west wind, cooler and more stable, meets the near-calm, warmer, and drier air of the High Desert around Mono Lake. Often the air is so dry that the convergence line is "blue" or cloud-free as the moisture content at the convergence is insufficient to condense and form clouds with the lifting process along the line. Under the right circumstances, however, the lower air layer moisture content is sufficient to result in clouds, revealing the lifting process of the convergence line.

On the afternoon of June 13, 1999, cloud features marked the convergence line's presence and confirmed this concept (`See Diagram #1: "Mono Lake Shear Line" / Photo Inset 1745 PDT; June 13, 1999`). With time, this convergence line continues to spread north, east, and south in the course of the afternoon until the temperature differences across the region begin to diminish after sunset and through the evening hours and winds subsequently subside.

As a result of density-driven winds along the Sierra Front in the afternoon hours during the warm season, area mountain ranges and valleys direct air via terrain channeling that can develop small convergence lines. The formation, timing, exact location, and even the orientation of these convergence lines varies due to day-to-day changes in the synoptic-scale surface pressure field along with the diurnal changes in local temperature fields.

Flying 'M' Shear Line

In the area north of Mono Lake and east of Bridgeport, CA, an additional west-to-east convergence zone often develops. During the late morning hours, thermals develop over the rapidly heating high desert region around Walker Lake. Surface winds are light. As the day progresses and the western Great Basin valleys continue to heat, surface pressure gradients support winds with a westerly component across the area. The cool air pushing across Mono Lake results in a northward-channeled wind of 10 to 15 knots along the East Walker River coming northward from Bridgeport and adjacent valleys. At the same time, an up-valley northwest wind develops by mid-afternoon in the East Walker River Valley well to the north of Mono Lake with typical speeds of 8 to 12 knots in the area. This southeastward-moving air is warmer than that coming northward from Mono Lake. This up-valley wind remains somewhat consistent through the afternoon and very early evening hours, as it is encouraged by the push of west wind through the lower end of the Smith and Mason Valleys.

By late afternoon on June 14, 1999, this channeled southeast-moving air met the northward moving air from the Mono Lake area and a local convergence line marked by a cloud line was established in the vicinity south of the Flying "M" Ranch southwest of Walker Lake. (`See Diagram #2: "Flying 'M' Shear Line" / Photo Inset 1700 PDT; June 14, 1999`).

Summary:

Due to terrain-channeling, density-driven winds can result in converging air flows. The astute soaring pilot needs to picture air moving in and around terrain features like a fluid (air, after all, is a fluid!). Good cross-country pilots keep monitoring surface wind flows for any terrain-channeling that might result in convergence and subsequent areas of lift for purposes of soaring flight.

The El Mirage Shear Line

(Modified Convergence Lines)

Chart #1: Upper Air 500 Mb Pressure Level; June 11, 2012
Chart #2: Surface Pressure Chart; June 11, 2012
Diagram #1: Mojave Desert Shear Lines
Diagram #2: Mojave Desert Late Afternoon Wind Flow
Text Box: Southern California METARs
Visible Satellite Image: Mojave Desert Shear Lines Marked by Cloud Lines

Differing wind speeds or wind directions can result in convergence of air causing lift to develop useful for soaring flight. In previous chapters, we have defined convergence lines and given examples of convergent lift in sea breeze fronts, terrain-induced convergence lines (Tehachapi and Elsinore shear lines), and terrain-channeled convergence lines (the Mono Lake and Flying "M" shear lines). However, one of the most historical and pronounced convergence lines is that of the "El Mirage shear line." Numerous articles and references have documented well this steady, strong lift-producer across the Mojave Desert of Southern California, so this chapter is a review of that history, in order to provide a comprehensive listing of the convergence lift types.

Understanding that air density differences result in pressure differences that subsequently establish pressure gradient forces resulting in inland air movement along coastlines, sea breeze effects on coastal plains can result in air movement well inland from that coastline air mass displacement. Such is the case of the El Mirage shear line. During the warm-season months along the Southern California Coast, a sea-breeze typically develops daily in response to late morning heating over the Los Angeles Basin and the Southern California Coastal Plain. The onset of the sea breeze along the coast generally results in passage of a classic sea-breeze front by 1:00 PM PDT about 10 miles inland through the vicinity of downtown Los Angeles with a continued push inland toward the Inland Empire by 3:00 PM PDT in the vicinity of Ontario, 60 miles inland from the coast.

A classic sea breeze frontal passage typically is marked by a lowering in temperature (cooling), a change in the moisture content (increased dew points), and a wind shift or an increase in the wind speed with increased gustiness of the wind field. Especially regarding Southern California sea breezes, there is also a marked change in visibility as the Los Angeles megalopolis leads to degraded visibilities with the sea breeze frontal passage.

Mojave Desert Shear Line

During the warm-season months along the west coast of the United States with its Mediterranean climate, high pressure tends to dominate the upper air pattern over or just upstream of California (See Chart #1: Upper Air 500 Mb Pressure Level; June 11, 2012). When high pressure dominates the upper air pattern, only small, diurnal or day-to-day changes tend to occur in the mean sea level (MSL) pressure field over Southern California. Intense surface heating in the deserts of Southern California by the late morning hours causes a reduction of surface pressure in Mojave Desert due to the temperature-related decrease in air density adjacent to the superheated desert ground, which establishes an area of thermal low pressure. Thermal low pressure is often depicted on Surface Pressure Charts as a trough axis of low pressure through interior central California that extends into the desert southwest of the United States (See Chart #2: Surface Pressure Chart; June 11, 2012). MSL pressure over the western Los Angeles Basin compared to the MSL pressure over the Mojave Desert by late morning hours reveals a well-defined onshore pressure gradient.

By early afternoon, the sea breeze is already underway on the coastal plain and pushing through the Los Angeles basin on its way through the "Inland Empire" around Ontario, Riverside, and San

Bernardino. This push of air through the L.A. basin associated with the classic sea breeze reinforces the widespread pressure gradient toward the inland desert region of California even while the inland thermal low deepens and intensifies with continued daytime heating.

The lowest MSL pressure from thermal heating develops over the area of strongest heating, the Mojave Desert. With this intense heating over the Mojave Desert, air begins to move inland through the passes of Southern California into the desert regions. Specifically, air is pulled into the Mojave Desert through Cajon Pass, which separates the San Bernardino Mountains and the San Gabriel Mountains of California; Soledad Pass, located in the San Gabriel Mountains, and air from the San Joaquin Valley begins to flow through the Tehachapi Pass and onto the floor of the northern Mojave Desert around the town of Mojave (See Diagram #1: Initial Mojave Desert Shear Line Development).

Mojave Desert Late Afternoon Wind Flow

In a diurnal cycle, the air in the Mojave Desert during the late morning hours is relatively calm. However, the air being pulled into the desert sets up areas of speed convergence. Subsequently "lift lines" develop where this incoming air begins to interact with the calmer desert air. The air flowing through the Cajon Pass initially forms the well-defined *El Mirage shear line* that sets up in an arc from just east of Pearblossom, arching toward El Mirage Dry Lake, and then to the area south of Victorville. (Reference Diagram #1: Initial Mojave Desert Shear Line Development).

At about the same time, convergence lines also begin to appear on the Mojave Desert side of Soledad Passand Tehachapi Pass due to the intensifying pressure gradient. Depending on local pressure gradient forces, sometimes these desert shear lines remain quasi-stationary over the desert floor through mid-afternoon, providing a long-lasting source of convergence lift for the El Mirage area and in proximity to other passes into the desert. However, the convergence or shear lines will eventually push deeper into the desert and subsequently provide a general west-southwest wind flow over the Mojave Desert by late in the afternoon (See Diagram #2: Mojave Desert Late Afternoon Wind Flow).

Reference the METAR weather observations for the Inland Empire and Mojave Desert locations at Ontario (ONT), Palmdale (PMD), Lancaster (WJF), Victorville (VCV), and Edwards Air Force Base (EDW) on June 11, 2012. A classic sea breeze would reflect pressure differences providing the pressure gradient force, a drop in temperatures, a rise in dew point temperatures, wind speed, gust, and direction changes, and an air mass acuity change. The inland moving air from the L.A. Basin into the Mojave Desert may not exhibit all of the features of the classic sea breeze. However, at least one, if not all, of these characteristics will exist to show the change in overall low-level air mass characteristics with shear line passage. Note the highlighted blue METARs that indicated the arrival of a shear line at the observation location (See Text Box: Southern California METARs).

The air that is pulled into the desert is not true marine air, as its arrival time is too early for its source region to be the coast, nor does it have the temperature and moisture characteristics of a marine environment. Certainly the wind speed, gust factor, direction change and visibility degradation do occur with shear line passage. Thermal strength is enhanced on the shear line with convergence. The temperature does not drop appreciably at the shear line location, but cool air advection is occurring behind the shear line, and thermal strength becomes weaker and more diffuse compared to the thermal field in front of the shear line.

Sometimes the moisture field ahead of the desert shear lines depicts the convergence lift with cumulus clouds while the air behind the shear lines reflects the weaker lift conditions marked by cloud-free areas (See Visible Satellite Image: Mojave Desert Shear Lines Marked by Cloud Lines; March 23, 2000; 22Z).

In years spent forecasting for the Region 12 Competition Soaring Contests at California City, thermal strength generally could be reasonably predicted for tasking purposes. But the presence of shear lines dramatically influenced thermal strengths due to the assistance of the convergence uplift. It is was not uncommon for soaring pilots to report that lift rates in thermals in convergence along the El Mirage shear line exceeded 1500 feet per minute (fpm) compared to lift rates over the general Mojave Desert averaging 500 to 800 fpm.

Furthermore, competition tasks that penetrate the shear lines behoove competitors to consider avoiding flight in the weaker thermal environment behind the shear line in favor of “running the shear line” with its strong, dependable lift even if the flight path resulted in an arc between task points. As mentioned, slight changes in the alignment and strengths of the pressure gradients over the Southern California area from day to day result in significant changes in the arrival time, movement, and speed of the shear lines as air was pulled into the desert through the passes.

I want to underscore that the air mass arriving on the Mojave Desert floor is not marine in nature. The air reflects source regions over inland Southern California areas even though its initial push inland may have been encouraged by the more classic marine sea breeze push at the coast. The El Mirage shear line essentially develops due to density differences from the Inland Empire source region to that of the Mojave Desert. The convergence at the El Mirage shear line is a result of the modification of the same driving parameters associated with a sea breeze even though the convergence line is occurring far inland.

Great Soaring or Dangerous Thunderstorms?

nee, The 850-250mb Differential Divergence Chart

Gathering weather information is necessary to determine a day's soaring potential. It is also necessary for safety-of-flight. To do this, a soaring pilot needs to have basic knowledge of weather services and products as well as the concepts of soaring weather. This chapter reviews the weather products that help a pilot understand when forecast parameters indicate strong thermals, and whether there may be a risk of thunderstorms, which are dangerous in the air and on the ground.

When we first look at the forecast, or at current weather observations, in deciding whether a soaring flight will be feasible, we focus on how strong the lift will be, how high will it take us, what difficulties will wind or broad cloudiness create, and where, geographically, will be the good or the poor conditions for the day.

We also need to look at risks. Wind velocity on the ground, whether there is a risk of thunderstorms in our area, when they might develop, and how extensive they might be are all important. We do not want to be caught in the air by a big cu-nim, and we don't want to be caught on the ground out of the trailer or out of strong tiedowns. The reason this is worth checking is that the instability that creates a good thermal-soaring day might be instability that creates thunderstorms.

Assessing thunderstorm risk also must consider that there's a wide range of cumulonimbus, from isolated, mild, easily avoided enthusiastic local cu to area-wide supercells. There are several tools readily available on the web to answer these questions.

Knowing the meaning of the various shapes of the temperature and dewpoint lines on the Skew-T plot is useful in gathering information to answer these questions. Also there are many sources of synoptic soaring information specifically for soaring pilots. These chiefly predict the likelihood of usable lift and don't highlight hazards.

`[Possible additional paragraphs]`

Will there be usable thermals?

How high will there be usable lift?

Will there be markers?

Are widespread clouds coming?

Where not to fly today?

Is there a risk of thunderstorms?

Scattered small cumulonimbus

Severe thunderstorms and cold fronts

Supercell likelihood

Acknowledgement: Background help provided courtesy of National Weather Service Storm Prediction Center Lead Forecaster Rich Thompson.

Storm Prediction Center

The National Weather Service web page, https://www.spc.noaa.gov/products/outlook/ offers forecast charts depicting the convective outlook daily for the next 3 days and a 4-8 day composite and a Thunderstorm Outlooks chart that anticipates the immediate risk of thunderstorms 4 to 8 hours ahead.

References

1) NWS (National Weather Service) Storm Prediction Center Website
< https://www.spc.noaa.gov/ >

2) NWS Storm Prediction Center “850-250mb Differential Divergence”:
< https://www.spc.noaa.gov/exper/mesoanalysis/ >
Rest the cursor on “Upper Air” and select “850-250mb Diff. Divergence” from the dropdown menu

3) Consolidated Storm Prediction for Aviation (CoSPA) https://cospa.wx.ll.mit.edu/login (Requires access permission, secure login)
Massachusetts Institute of Technology (MIT) Lincoln Laboratories.
Aviation Weather Research funded by the Federal Aviation Administration (FAA)
[Note: CoSPA special courtesy of FAA and MIT through the NWS Southern Region Headquarters for safety-of-flight at the World Gliding Championships.]

The Lifted Index Analysis Chart

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Chart #1          Lifted Index Analysis Chart
Text Box #1       Definitions                         (378 Words)
Text Box #2       References                          (81 Words)
Table #1          Lifted Index Values and Atmospheric Instability
Table #2          K-Index and Coverage of General Thunderstorms
Chart #2          Upper Air Balloon Sounding for Fort Worth/Dallas
Web Display #1         SPC Meso-scale Analysis Page
Web Display #2         LI/Radar Chart
Web Display #3         K-Index/Radar Chart
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https://www.instantweathermaps.com/GFS-php/conussfc.php?time=INSTANT&var=LFTX

`This is the only lifted-index chart that I can currently find.`

The state of the atmosphere's stability is an important meteorological parameter to be considered by pilots contemplating possibilities for soaring flight. Historically among the suite of National Weather Service (NWS) pilot weather briefing products was the Lifted Index Analysis Chart [`See Chart #1: Lifted Index Analysis Chart`]. This chart presented the Lifted Index (LI) and the K-Index calculated from the upper air balloon soundings over the U.S. taken at the 0000 UTC and 1200 UTC hours. This so-called "Instability Chart" had its origins in the era prior to that of computer supported meteorological modeling. The indices as presented in this analysis were computed from observed weather parameters. I make this distinction because in this era of meteorology numerical models derive and generate such high-quality graphical weather products that the line between forecast and observed weather products can be easily blurred.

Referencing the sample Lifted Index Analysis Chart, note that it has its origin as the Department of Commerce's National Oceanographic and Atmospheric Administration (NOAA) National Center for Environmental Prediction (NCEP). This chart has been produced at the NWS Numerical Meteorological Center in Washington D.C. and subsequently distributed through the NWS Telecommunications Gateway to NWS Offices and Federal Aviation Administration (FAA) Flight Service Stations. The Lifted Index Analysis Chart presentation remained reminiscent of the facsimile machine era of weather products. On the chart the computed meteorological indices were positioned over the balloon sounding sites and presented onto a Lambert-conformal conic projection of the United States. The indices were presented much like the form of a fraction. The Lifted Index was placed like that of a numerator in a fraction with the K-Index printed below in the place of a denominator. Lifted Index isopleth values of every four were lined on the chart (0, -4, etc.). The date and time of the soundings providing the indices was plainly presented.

A negative Lifted Index indicates that the air closest to the ground is unstable with respect to the middle troposphere [`See Text Box #1: Definitions`]. The more negative the LI the more unstable is the lower atmosphere and convection can occur, i.e., strong updrafts are likely to develop. While soaring flight needs some weak to moderate convection for thermal lift, too much instability can lead to overdevelopment in the form of thunderstorms and severe weather [`See Table #1: Lifted Index Values and Atmospheric Instability`].

The K-Index provides an estimate on the likelihood of thunderstorms and subsequently an estimate on the extent of the coverage. The first term in the K-Index Formula is the temperature lapse rate between the 850 mb level (approximately 5,000 ft Mean Sea Level, MSL) and the 500 mb level (approximately 18,000 ft MSL). The larger this temperature difference in the 850-to-500 mb layer then the trend is toward that layer being more unstable and supporting the development of convection or thermal lift. The remaining two terms of the K-Index Formula were designed to give an idea of lower atmosphere moisture content by looking at two mandatory reporting levels of the balloon sounding at 850 mb and 700 mb (approximately 10,000 ft MSL) rather than analyzing the entire balloon sounding. High water vapor content in the lower air layer combined with a good lapse temperature condition provides for thunderstorm development. The higher the K-Index then the probability of thunderstorms increases [See Table #2: K-Index and Coverage of General Thunderstorms].

This Lifted Index Analysis Chart[25] in the form displayed has not been generated at least since the 2009 time period (indications are that the last chart produced was March 16, 2009). Due to its longevity from the by-gone facsimile machine era, reference to the Lifted Index Analysis Chart mistakenly has been left on NWS weather product lists even among relatively recent FAA and NWS publications. The primary government document for NWS weather products for the aviation community is "Aviation Weather Services; Advisory Circular; AC 00-45" [See Text Box #2: References]. The March 12, 2009 publication date for Change Notice #2 for AC 00-45F still listed the Lifted Index Analysis Chart among the available products. But with the July 29, 2010 publication and distribution of the updated Advisory Circular, AC 00-45G, the Lifted Index Analysis Chart was no longer referenced as an available product. Even with the chart itself no longer available, the Lifted Index and K-Index still have some relevance in providing atmospheric instability information to the soaring pilot.

So, if the reference indices are no longer available per the Lifted Index Analysis Chart, where can a soaring pilot find the information previously provided by that analysis chart? The answer to that question lies still with the original source of the indices as plotted on the defunct chart, the upper air or radiosonde balloon sounding plots [See Chart #2: Upper Air Balloon Sounding for Fort Worth/Dallas]. On this sounding provided by the NWS and distributed onto the web through the University of Wyoming, the top of the example plot for Fort Worth-Dallas (KFWD) displays the K-Index and the Lifted Index along with some other indices and parameters. While the reference indices computed from observed parameters are not available on a nationwide chart display, the calculated Lifted Index and the K-Index are nonetheless obtainable for each individual radiosonde balloon sounding plot.

The development and subsequent implementation of high-speed computers into numerical meteorological forecasting now enables updates of forecast atmospheric instability. Through the auspices of the NWS's Storm Prediction Center (SPC), updated depictions of the Lifted Index and K-Index along with numerous other meteorological parameters and algorithms are produced by the Rapid Refresh hourly-updated assimilation/modeling system. This information is then made available for display on the SPC Meso-scale Analysis Website [See Web Page #1: SPC Meso-scale Analysis Page]. The SPC products displaying the Lifted Index [See Web Page #2: LI/Radar Chart] and the K-Index [See Web Page #3: K-Index/Radar Chart] involve model forecast projections of some parameters combined with recent observations ingested into the model run for the index computations. Despite combining forecast projections for some weather parameters and updated observed data for other parameters, a high degree of reliability for atmospheric stability evaluations results. During the 2012 World Gliding Championships at Uvalde this combination of real-time observations and short-term parameter forecasts gave the weather forecast team a high confidence in its convection-threat assessments. The virtues of one such meso-scale analysis product, the "Divergence Chart", utilizing this assimilation/modeling process, were discussed in the December 2012 issuance of Soaring.

In summary, understanding the background to selected weather analysis and forecast products can provide insight for the educated soaring pilot to assess atmospheric stability (instability) potential. In the case of the Lifted Index and the K-Index computed from direct observations or derived in the Rapid Refresh Numerical Modeling, the projected indices provide information for soaring as well as severe weather potential for safety-of-flight deliberations.

Text Box #2 - References

[25] https://www.instantweathermaps.com/GFS-php/conussfc.php?time=INSTANT&var=LFTX (12/19/2020)

Websites:

“Skew-T Basics”, Courtesy of Meteorologist Jeff Haby
< http://www.theweatherprediction.com/thermo/skewt/ >

“Skew-T: A Look at LI”; Courtesy of Meteorologist Jeff Haby
< http://www.theweatherprediction.com/habyhints/300/ >

Upper Air Data (RAOBs); University of Wyoming
< http://weather.rap.ucar.edu/upper/ >

NWS Glossary of Meteorology
< http://w1.weather.gov/glossary/ >

NWS Storm Prediction Center; Meso-scale Analysis Page
< http://www.spc.noaa.gov/exper/mesoanalysis >

Gov’t Printing Office: “FAA Advisory Circular 00-45F” (Change 2; Mar 12, 2009)
< http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC%2000-45F.pdf >

Gov’t Printing Office: “FAA Advisory Circular 00-45G” (Published July 29, 2010)
< http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC-0045G_chg1_fullDocument.pdf >

Text Box #1:

Definitions

Lifted Condensation Level

(Abbreviated, LCL) - The level at which a parcel of moist air becomes saturated when it is lifted dry adiabatically.

Troposphere

The layer of the atmosphere from the earth's surface up to the Tropopause and it is typically characterized by decreasing temperature with height (relatively thin inversion layers may form and dissipate), vertical wind motion, appreciable water vapor content, and sensible weather (clouds, rain, etc.).

Lifted Index

(Abbreviated, LI) - A common measure of atmospheric instability. Its value is obtained by computing the Lifted Condensation Level (LCL) of the air 50 millibars (mb) or approximately 150 feet above the surface of the ground and lifting it moist adiabatically to the 500 mb level, typically around 18,000 feet mean sea level (MSL), and subtracting that temperature from the actual temperature at that level. Negative values indicate instability; the more negative, the more unstable the air is, and the more buoyant the acceleration will be for rising parcels of air from the boundary layer next to the surface. (As an analogy for the soaring community, the LI is essentially a “Thermal Index” at the 500 mb level!) There are no absolute or threshold LI values below which severe weather becomes imminent. However, there are arbitrary ranges of LI values that describe the relative instability of the low to mid-troposphere [See Haby reference ….]

{LI = 500 mb environmental Temp – 500 mb lifted parcel temperature}

K-Index

The K-Index is a measure of the thunderstorm potential based on vertical temperature lapse rate, moisture content of the lower atmosphere, and the vertical extent of the moist layer. The temperature difference between the 850 mb level, typically around 5,000 feet MSL, and 500 mb is used to parameterize the vertical temperature lapse rate. The 850 mb dew point is used to represent the moisture content of the lower atmosphere. The vertical extent of the moist layer is represented by the difference of the 700 mb temperature and 700 mb dew point (DP). This is called the 700 mb temperature-dew point depression. The index is derived arithmetically and does not require a plotted sounding.

Note the following equation for the K-Index computation:

{K-Index = (850 mb Temp – 500 mb Temp) + 850 mb DP – 700 mb DP depression}

Turbulence

Weather is not merely interesting to aviators – we do fly within and as permitted by weather – iwe must understand it to remain safe while flying, especially in soaring, because turbulence represents the vertical atmospheric motion that is the lift mechanism for soaring flight, and turbulence is a danger that must be understood and managed.

Weather-related accidents plague aviation, past and present. The FAA reviews hazardous weather topics in its “Got Weather” campaign – www.faa.gov/about/initiatives/got_weather.

Turbulence is defined in the Glossary of Meteorology as “a state of fluid flow in which the instantaneous velocities exhibit irregular and apparently random fluctuations so that in practice only statistical properties can be recognized and subjected to analysis.” Ok, now that this is clear, in airman lay terms turbulence is present in wind gusts, shears, and atmospheric eddies of all sizes and velocities. Turbulence is typically micro-scale in size.

Turbulence is simply felt change in the direction or speed of air flow. This creates an accelerating force on any aircraft transiting it. These accelerations are bumps or jolts on an aircraft and crew. In severe form, rapid changes of wind velocity (speed and direction) either vertically or horizontally, can threaten the structural integrity of one’s aircraft. Many years ago, in the early days of wave flight, a pilot stuck one wing into a fluffy cloud. It broke off his wing, he was temporarily blinded by hypoxia after opening his parachute, and fortunately landed next to a highway.

Where can turbulence occur in our soaring? The FAA’s Advisory Circular (AC) 00-6B, *Aviation Weather*, devotes a chapter to atmospheric processes that can develop turbulent flow. Within that chapter on turbulence the AC discusses turbulence in general, convective turbulence, thunderstorms, mechanical turbulence, wind shear, clear air turbulence, and wake turbulence. We must understand the conditions that potentially generate turbulence in order manage its risk. Except for high-altitude clear-air turbulence, all of these turbulence generators are commonplace in soaring flight.

Stress on an airframe from atmospheric turbulence or pilot control input is related to airspeed. Flight in turbulent conditions mandates reducing the aircraft airspeed. On airspeed indicators, the *yellow arc* denotes the *caution* range wherein flight should only be conducted in smooth air. Some rough air can be accommodated with flight speeds within the green arc, the normal operating range, with *the top of the green arc considered the maximum structural cruising speed*.

However, substantially rough air, that which requires full or large control deflections, mandates flight at airspeeds at or below *maneuvering speed* of the aircraft, which may not be marked on airspeed indicators.

Convective turbulence

Convective turbulence is associated with changes in direction of vertical air motion within the atmosphere. Glider pilots seek and require thermals for soaring flight. When we meet airplane pilots after a great soaring day, they typically say, “How was soaring? We got beaten up.”

In flying cross country in any aircraft, even gliders, updrafts and the adjacent downdrafts are felt as turbulence when they are transited because air velocity changes swiftly, causing brief and rapid changes of lift on all flying surfaces. These are sometimes powerful enough to overpower pilot control. It’s important to understand the situations in which such strong turbulence can be expected.

Convective turbulence doesn’t exclusively occur between updrafts and downdrafts. It results also from simple differential heating across adjacent dissimilar ground textures and properties [See Diagram #1: Effect of Convection Currents]. This dissimilar surface heating, causing subtleties in vertical air motion, is one factor that makes every glider landing pattern unique rather than an automatic routine.

The lowest layer of atmosphere, to which thermals are limited, is variously called the *boundary layer*, the *mixed layer*, or the *haze layer*. Once an aircraft is above this atmospheric boundary layer containing turbulence caused by surface heating, gradient wind flow is generally laminar and flight is smooth. Many airplane pilots do not realize that flight is smooth above cumulus cloud base or above the haze layer if clouds are absent.[26]

Because thermal convection requires sunlight, turbulence in the boundary layer is a daytime phenomenon. The remarkable exception is the frontal thunderstorm, which glider pilots must avoid. (It can be safe as well as very useful to soar the uplift along the advancing side of an isolated small thunderstorm. These should be studied and understood before venturing to do this.)

Thunderstorm turbulence

Thunderstorms are essentially Mother Nature's severe weather generator. A couple of aspects of thunderstorms are responsible for generating turbulence. The scale and intensity of the convective updrafts and down-drafts within or near a thunderstorm cell are large. Inflow and outflow winds of thunderstorms cause turbulence due to large changes in wind speed and direction over short distances around any thunderstorm cell [`See Diagram #2: Schematic View of a Tornadic Thunderstorm`].

A downdraft from a thunderstorm cell at the onset of precipitation of a mature thunderstorm can be relatively benign with downward vertical motion of only a few hundred feet per minute. However, in the extreme, such as with microbursts or downbursts, a thunderstorm downdraft can reach 6000 feet per minute. With a tremendous strong vertical downdraft and subsequently abrupt transition to horizontal of air motion on contact with the ground, wind velocity changes cause severe to extreme turbulence. It has often been said that a downdraft will slow before striking the ground, but meteorologic research has shown this not to be true; besides which, an aircraft caught in a downburst will have its own momentum that is not dissipated until striking the ground.

For gliders, the leading edge of the gust front – the "thunderstorm outflow wind boundary," provides useful uplift and that generates cloud at some altitude due to that lifting action. A sailplane using this lift may be engulfed by forming cloud, or the updraft may exceed the glider's maximum descent rate with full spoilers. The pilot should always expect to have to change course out of the strongest portion of the lift line.

Mechanical Turbulence in the Friction Layer

Air is a fluid. Moving air encounters friction from the ground and ground objects, creating eddies that are experienced as any degree of mechanical turbulence. With elevation, wind speed increases rapidly, creating a wind gradient next to the surface that can be dramatic with high gradient wind velocity. [`See Diagram #3: Wind Gradient.`] This requires higher approach speeds for adequate aircraft control, and to prevent the fluctuations of wind velocity from stalling either wing, through touchdown. A landing flare to stall is not safe when gradient wind velocity or thermal turbulence are strong.

One of the dangerous aspects of friction-layer turbulence is that it is generally invisible. Even when a dust devil is visible, the one seen is not alone. Most small whirlwinds do not pick up dust or trash reliably.

[26] So that you can talk like a meteorologist, and get better dates, here's the jargon, from the Glossary of Meteorology:

"The lowest layer of the atmosphere, containing the active weather, is the *convective boundary layer*." This comprises three parts: the *radix* layer in contact with the ground, the *uniform* layer that is its interior, and the *entrainment zone* at the top. The classical *surface layer*, where, as you know, *Monin–Obukhov similarity theory* applies to small shear- driven turbulent eddies, is the bottom subdomain of the radix layer. This is sometimes called the *friction layer*.

"The ABL has a marked diurnal cycle. During daytime, a mixed layer of vigorous turbulence grows in depth, capped by a statically stable entrainment zone of intermittent turbulence. Near sunset, turbulence decays, leaving a residual layer in place of the mixed layer. During nighttime, the bottom of the residual layer is transformed into a statically stable boundary layer by contact with the radiatively cooled surface. Cumulus and stratocumulus clouds can form within the top portion of a humid ABL, while fog can form at the bottom of a stable boundary layer."

Clear-Air Turbulence

Clear air turbulence is used in commercial aviation to refer to cloud-free turbulence associated with mountain lee wave or shear wave (such as Kelvin-Helmholz wave). This turbulence has destroyed commercial aircraft. Yet air is clear unless condensation has occurred, so it is common that there might not be any visible clues to turbulence. Clear air turbulence can be generated in several ways.

A quick change in wind vectors across time or space creates wind shear and turbulence. The surface wind gradient is a gradual wind shear.

Radiant cooling begins when the sun is low and continues as long as the sky is clear until after sunrise. This creates a pool of cool air that grows until morning, first filling swales and valleys. It is typically about 200 or 300 feet deep after a clear winter night over relatively level terrain. Strong surface winds fragment the cooled air and may prevent the layer from forming or delay it. Clouds at any altitude block radiation, acting as a blanket and making an inversion unlikely.

On a long slope, *katabatic* (downslope) flow occurs, which with a long downhill fetch can result in significant wind.

In a valley or plain, this cooled layer creates the *nocturnal inversion*, which is characteristically much colder than the gradient flow aloft, which may remain near the previous day's mean surface temperature. The cold air is denser than the warm air aloft, so is very stable, and except with katabatic flow, is calm.

The nocturnal inversion displaces the warmer gradient air upward. At the top of the cool, calm inversion, the gradient wind continues to flow, so that there is *shear* with sharp discontinuity. This produces a narrow band of turbulence. A pilot descending into a gradient wind of, say, 20 kt for a night landing, will feel significant turbulence at 200 to 400 feet altitude on final, accompanied by a 20-kt drop in airspeed. If his usual airspeed on short final is 75 kt, and stall speed 60 kt, he will descend swiftly and abruptly. This will cause no harm if he allows the nose to drop, or better, pushes the stick. In the pilots' lounge, he's likely to say, "I flew into quite a downdraft on short final." No, *he* sank. Different.

Mountain nocturnal Inversions

A deep inversion of a few hundred feet above the ground occurs frequently on clear winter nights in mountain valleys or basins. Cold air drainage from adjacent higher terrain combined with additional surface radiational cooling on the basin floor through the long night results in very cold air next to the ground creating a strong temperature inversion [`See Diagram #4: Wind Shear at a Temperature Inversion Top`]. Wind shear is often amplified across such an inversion as a scalar wind speed differential of 30 knots or greater can exist in a narrow layer of air. Rarely such a situation may cause a horizontal vortex (a roll without a cloud) that can reach into the nocturnal inversion to an airport runway, affecting an aircraft in an unexpected and alarming way/

A deep nocturnal inversion capped by a strong gradient wind occurs frequently in intermountain areas ahead of oncoming frontal systems with increasing pre-frontal gradient winds aloft and quiescent cold air beneath clear night skies.

Frontal Shear Turbulence

Frontal boundaries are shrouded by cloud much of the time due to air mass lifting, though drier airmasses may not produce much cloudiness at the frontal uplift boundary. The frontal boundary is an area of wind shear due to the differing wind vectors of the conflicting air-masses, which creates turbulence near the frontal temperature inversion.

High-altitude turbulence

The classic phenomenon known for generating clear air turbulence is the jet stream. Typically located at high altitudes (25,000 to 35,000 feet) and well within Class A Airspace, very high wind speeds of 150 knots or more may occur within the jet stream core. This results in strong wind shear all around the lateral perimeter of the jet core that often produces severe to extreme turbulence.

Another phenomenon well noted by alpine soaring pilots to generate clear air turbulence is the mountain (lee) wave [See Diagram #5: The Mountain Wave]. Wind shear and turbulent flow within a mountain wave's rotor zone resident below the wave crests can create severe to extreme levels. Additionally, mechanical turbulence near terrain is also generated due to the high wind speeds associated with mountain wave.

Wake Turbulence

Wake turbulence requires special attention because it is often unexpected. While most glider club and fixed base operations will not typically have glider operations affected by wake turbulence, motorgliders with their increased cross-country flight capabilities or a glider recovery operation at an airport handling larger aircraft can expose aircraft and pilots to wake turbulence. Produced by larger aircraft with high wing loading while at high angles-of-attack, this aircraft-generated turbulence poses a loss-of-control threat to all following aircraft, including gliders, both near the runway and aloft. Intense wingtip vortices develop when larger aircraft are at a high angle of attack, especially while flaring for landing or rotating for take-off. These vortices come off the wingtips of and settle downward around 500 feet per minute. If they encountering the ground, they drift to either side of the aircraft's flight path approximately 5 miles per hour in calm wind, and drift across the runway with a crosswind.

Gliders or towplanes approaching to land behind landing larger aircraft need to stay above the approach slope of the larger aircraft and land beyond its touchdown point; and on take-offs, the rotation point is beyond where the larger aircraft touched down.

If taking off after a larger aircraft, then the towplane or motorglider should rotate and break ground well before the larger aircraft's rotation point, and climb more steeply than the large aircraft if possible, and off the centerline to the upwind side of the runway. Landing behind a larger aircraft's take-off necessitates landing before the rotation point of that departing aircraft. The FAA provides an excellent review of the subject in *Advisory Circular 90-23G, Aircraft Wake Turbulence* https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_90-23G.pdf.

Being a fluid, anything that either impedes flow or provides shear is likely to generate atmospheric turbulence. It behooves the soaring pilot to understand the processes and causes that generate turbulence. The material review presented here hopefully has refreshed our knowledge in regard to turbulence generation and, to some degree, how to mitigate any adverse effects it may have for safer flying.

Thunderstorms: Ingredients for Trouble

To save you the trouble of hunting through this book for the most important points about thunderstorm hazards, in this chapter I briefly roll them up into one ball. They severely threaten both ground activities and flying. A thunderstorm is one of the few things that can winds strong enough to create lift on the wings of a tied-down aircraft that can either break the ropes, chains, or cables, or pull the tiedown themselves from the ground.

Any severe weather that might come to a pilot's mind is present in or near a thunderstorm or Cumulonimbus (Cb) cloud-type [`See Photo #1: "Cumulonimbus (Cb) Cell`]:

~ Icing;
~ Turbulence (severe to extreme);
~ Lightning;
~ Hail;
~ Strong Wind; both straight-line (downbursts) and rotational (tornadic);
~ Lowered Cloud Ceilings (loss of terrain/obstruction clearance);
~ Heavy Rain (degradation of visibility); and,
~ Surface Flash Flooding (runway hydroplaning, sailplane crew dangers).

Life Cycle

Given that the presence of a strong convective cell or Cb cloud-type bodes ill for aviators and ground crew, it behooves us to understand what atmospheric states leads to the thunderstorm development.

The life cycle of a thunderstorm is characterized by three distinct stages [`See Diagram #1: "Three Stages of a Thunderstorm"`]:

~ Towering Cumulus;
~ Mature; and,
~ Dissipating.

The *towering cumulus stage* [`See Photo #2: "Towering Cumulus Stage"`] is typically the most appealing to soaring pilots. At this point in the thunderstorm life cycle, the developing cell is characterized by updrafts only, with wonderful lift rates.

The *mature stage* [`See Photo #3: "Cb Mature Stage"`] begins with the onset of either precipitation or lightning (thunder). Precipitation is either rain or virga (rain not reaching the ground), which marks the presence of downdrafts.

The last stage of the thunderstorm is the *dissipating stage* [See Photo #4: "Cb Dissipating Stage"]. When Cb begins to disappear, only downdrafts are present and the cell is raining or drying itself to destruction. There are risks or challenges in flying near a Cb in either the cumulus or dissipating stages but the mature stage, just as the name implies, is where all the worst dangers can be present. The soaring pilot must understand and recognize the atmospheric mechanisms and the possible adverse conditions in the vicinity of the cell.

Fuel, air, heat

Much like a fire needs three elements to occur (heat, oxygen, and fuel), so does a thunderstorm need three essential elements to mature. The absence or insufficiency of any of these elements eliminates the possibility of thunderstorm development Those elements are:

~ Lift Initiation
~ Instability; and,
~ Adequate Water Vapor.

Lift initiation may be terrain-forcing of air upward (orographic or ridge lifting), frontal-slope lifting, or simply the uneven surface heating that leads thermals. Instability is a function of the vertical temperature profile. If the atmosphere is *unconditionally unstable* over the layer next to the surface, air displaced upward will remain warmer than the ambient (surrounding) air even as the adiabatic process [`See Definition: "Adiabatic Process"`] cools the displaced parcel. Thus, in an unstable atmosphere, the displaced air parcel is more buoyant because its temperature is higher and therefore its density lower than the ambient air.

Adequate Water Vapor acts as a fuel source for thunderstorm growth. A dry parcel of air moved upward will cool at the Dry Adiabatic Lapse Rate (DALR) of 3.0 degrees Celsius (°C) per 1,000 feet of increased altitude [`See Diagram #2: "DALR and MALR"`]. The buoyancy force at any specified altitude or level in the atmosphere of an air parcel rising is directly proportional to the difference between the ambient air s temperature and the rising air parcel's temperature. For any given surface temperature cooling at the DALR, soaring pilots know this temperature difference (°C) as the definition of the "'Thermal Index' [`See Diagram #3: "Thermal Index"`]. If sufficient water vapor is present in combination with instability and lifting, the ensuing dry adiabatic cooling process lowers the temperature of the air to its dew point temperature. When an air parcel cools to its dew point temperature, water vapor saturation occurs and subsequently the water molecules in the rising air change phase from the gaseous phase (water vapor) to their liquid state (small water droplets). The energy that it took initially to have had the water molecule change its phase to the gaseous or vapor state (latent heat) is released with the condensation process into the rising air. This release of energy slows the rate of cooling of that air parcel from the DALR constant 3.0°C/1000 feet to that of the Moist Adiabatic Lapse Rate (MALR) [`See Diagram #2: "DALR and MALR"`]. Unlike the DALR, the MALR rate-of-cooling is not a constant because the amount of water vapor present at saturation is a function of temperature.

The ascent of an air parcel along the MALR is not strictly adiabatic, because loss of mass also occurs due to precipitation [`See Diagram #4: "The Moist Adiabatic Process"`]. Condensed water does not have to fall as rain. Simply transforming from gas to liquid functionally removes the mass of liquid water from the lifted air parcel. This is why further cooler, which brings further loss of gaseous mass through condensation, is called *pseudo*adiabatic.

Warmer air has a greater capacity to hold water vapor before reaching saturation. After a surface-based dry convection process (thermal) has moved air to a high altitude, possibly 24,000 feet above sea level over the Great Basin of Nevada, DALR cooling brings the parcel to its dewpoint and condensation begins. The ascent rate of the dry air updraft is relatively weaker than a similar lifted parcel that has reached its dew point temperature, begun condensation, that then rises and cools at the MALR.

Once condensation has begun, cooling at the moist adiabatic rate is slower, which enhances its buoyancy and enables a rising air parcel in a developing thunderstorm to ascend to a higher altitude at a more vigorous updraft velocity inside the cumulus cloud. The acceleration of the condensing thermal is determined by the lapse rate of the ambient atmosphere. The cooler the surrounding air, the stronger and higher will be the updraft.

This in-cloud acceleration will actually entrain air up to several thousand feet below the development cumulus cloud or incipient thunderstorm, creating spectacular lift rates near burgeoning cloud.

Summary

With an initiating lifting mechanism, an unstable (cool-above) atmosphere, and adequate water vapor, the atmosphere releases a tremendous amount of energy from the latent heat of evaporation to support thunderstorm development. The aviator must wary of the adverse conditions associated with a thunderstorm.

Atmospheric Hydrometeors: Fog

I discussed that flight visibility varies with direction relative to the sun, due to the light-scattering properties of haze. In this chapter I discuss degradation of visibility due to condensation, which is not always so dense as to create instrument meteorological conditions

First, the jargon. A *hydrometeor* is *"any product of condensation or sublimation of atmospheric water vapor, whether formed in the free atmosphere or at the earth's surface; also, any water particles blown by the wind from the earth's surface"* [Glossary of Meteorology]. Hydrometeors can be:

- ~ Liquid or solid water particles formed and remaining suspended in the air such as damp haze, cloud, fog, ice fog, and mist.
- ~ Liquid precipitation (drizzle and rain).
- ~ Freezing precipitation (freezing drizzle or freezing rain).
- ~ Solid precipitation (ice pellets, hail, snow, snow pellets, snow grains, and ice crystals).
- ~ Falling particles that evaporate before reaching the ground (virga).
- ~ Liquid or solid water particles lifted by the wind from the earth's surface (drifting snow, blowing snow, blowing spray).
- ~ Liquid or solid water deposits on exposed objects (dew, hoarfrost, rime, and glaze).

Here I provide a simple review of the hydrometeor phenomenon of fog (related counterparts are damp haze, cloud, ice fog, and mist).

Aviation safety reports have consistently cited through the decades the tragic consequences of unprepared flight from visual meteorological conditions (VMC) into instrument meteorological conditions (IMC). VMC-to-IMC flight constitutes by far the largest type of weather-caused accidents and the highest accident fatality rate. [See Sidebar Box #1: "AOPA ASI Comments" and Graphic, "Types of Weather Accidents".] Many people – pilots, safety experts and rule-makers – do not seem to understand that often the pilot does not fly deliberately into cloud – he flies in humid, cooling air, and the atmosphere around the aircraft at some unexpected point swiftly becomes opaque. Thus it's important to understand the conditions that favor cloud or fog formation at our planned altitude, and to check for these in our preflight briefing

IMC caused by suspended atmospheric moisture can present itself in the form of cloudiness, low ceilings, and decreased flight visibility (often caused by fog).

The atmosphere, even in the driest of climates and environments, always has some moisture present as water vapor. On average, 4% of the atmosphere is water in its gaseous state, water vapor. As a native of the Great Central Valley of California, I am well acquainted with one of the valley's noted weather occurrences, extremely dense and persistent cold-season fog as an atmospheric hydrometeor [See Photos: "VFR-on-Top of Valley Fog" and "Dense San Joaquin Valley Fog"].

Fog is nothing more than a cloud near or immediately adjacent to the surface (land or sea) and comprises small, suspended, liquid or solid water droplets or ice particles. The physical processes that lead to the condensation or the changing of the state of atmospheric water from its gaseous phase as water vapor into its liquid state, water droplets, or sublimate directly to its solid state, ice crystals, are consistent for either cloud or fog development.

The dew point temperature represents the amount of moisture in the air and the temperature to which a parcel of air must be cooled at constant pressure and constant water-vapor content for saturation to occur. Any cooling process that lowers the air temperature to its dew point temperature results in 100% relative humidity of the air at that temperature. The amount of moisture at saturation is a function of temperature. The higher the temperature, the more moisture the atmosphere can hold before saturation is reached [`See Graphic #2: "Temperature and Relative Humidity (RH)"`]. At the point of water vapor saturation, and with sufficient condensation nuclei (suspended liquid or solid particles) present in the atmosphere, water changes its state through condensation or sublimation to result in visible, small, suspended water droplets (or ice crystals through sublimation if the temperature is at or below freezing).

Types of Fog

The types of fog are identified by the process or mechanism that causes it to form:

~ *Advection fog* is formed when warmer, moist air moves across a cold, wet surface, for example, at the juncture of a warm and a cold ocean current, air warmed and humidified by the warm ocean current may flow across the cold ocean current, producing fog. These fogs are famously dense. Or humid gulf moisture, especially in early spring, may move across cold or snowy midwestern prairie, causing durable fog.

~ *Radiation fog* is formed when nocturnal radiant cooling of the friction layer brings the ambient temperature well below the dew point. This is the classic swamp or marsh fog of a summer's night. *Fog in the hollow, a fine day will follow.*

~ *Up-slope fog* forms when humid air is lifted by flowing up a slope. This may flow up from the ocean coast, or maritime air may flow across an ascending plain. *Fog on the hill, water for the mill.*

~ *Precipitation-induced fog*: fog can also form if the temperature remains constant but the dew point is raised to the point of moisture saturation. This may occur when precipitation falls into or through an atmospheric layer. A common fog occurs after a heavy rain on a hot day.

~ *Steam fog*: when air passes over a warm, moist surface or body of water, (less frequent than other types). This type of fog may form over large lakes or ocean estuaries in the autumn before they have cooled seasonally, after a cold front passes.

Fog is distinguished from haze (suspended dry particles and aerosols) by condensed water and a greyer color. In the long-defunct North American Weather Code (prior to 1993), two fog intensitities were recognized. Fog was classed by its visibility degradation and labelled as either *dense fog* or *fog*. Dense fog involves visibility restricted to less than ½-mile or 0.62 kilometer. Fog or light fog involves visibility equal-to-or-greater than ½-mile in a moist atmosphere.

Meteorologically mist may be considered as an intermediate descriptor of conditions between fog and haze. The international meteorological code (METAR) implemented in the early 1990s, classifies light fog as mist (METAR code BR); and dense fog alone as fog, FG.

Conditions that Promote Fog

What are conditions that lead to fog development that inherently and adversely affect safety-of-flight? Outside of certain geographic locations such as coastal areas, the most prevalent type encountered by pilots in the night is radiation fog. Radiation fog develops over land as a direct result of radiational cooling of the earth's surface and subsequently the cooling of the immediately adjacent air to its dew point temperature. Factors favoring the formation of radiation fog overnight are:

1) a relatively moist layer of air next to the ground;
2) clear skies and drier air aloft; and
3) light surface winds.

The exact classification of any fog type can be difficult, as nighttime cooling intensifies all fogs. Valleys and terrain hollows are characteristic and repeated locations for fog when combined with a favorable synoptic or large-scale weather pattern.

Fog often intensifies just after dawn, when the first sunlit heating of small ground objects triggers condensation of supersaturated still air.

The largest nocturnal temperature drops occur during the long nights of the cold season. There is simply more time during the winter for temperature to drop to the dew point. However, high dew points present in warm gulf air that moves northward into the continental United States can lead to radiation fog development throughout the year. Dew points in the 70s˚F can produce fog even in warm-season months. In combination with nocturnal cooling, high pressure aloft that dominates a region provides drier air aloft often due to subsidence warming and typically cloudless skies for optimum surface radiational cooling overnight. Simultaneously, surface pressure gradients beneath high pressure aloft are generally weak and therefore synoptic-scale pressure forces result in light winds. Meso- or small-scale influences accentuate cooling in valleys or hollows as density differences lead to cooler air flowing off slopes during the night and pooling in valleys or basins.

The intensity and area affected by fog depends on the amount of moisture available (higher dew points mean more moisture) and the time available for radiant cooling, ensuring dew point temperatures are reached.

For pilot decision-making, conditions that result in long nighttime hours beneath high pressure aloft with a moist layer of air immediately adjacent to the surface favors fog formation. An old weather rule-of-thumb states that a temperature - dew point difference of 4˚F or less around sunset is a harbinger of fog formation during the evening or night [`See Sidebar Box #2: "Benefit of the 'Remarked' Temperature Group"`].

Obviously, soaring flight demands VMC. And while the conditions that favor fog formation require a stable atmosphere in opposition to soaring flight needing instability for thermal lift, the air-cooling processes that lead to radiation fog are the same as for cloud development.

`Place the Graphic depicting the Types of Weather-Related Accidents along with these comments together in a sidebar box?`

AOPA ASI Weather-Related Accident Comments

Courtesy of the Aircraft Owners and Pilot Association (AOPA) Air Safety Institute (ASI) from the Joseph T. Nall Reports of 2010 and 2011 citing the dangers of flying from Visual Flight Rules (VFR) into to instrument meteorological conditions (IMC):

"The most common type of weather accident, and one of the most consistently fatal, continues to the be the attempt to fly by visual references in IMC…"

"Attempts to fly by visual references into IMC continue to claim pilots at all levels of experience and, worse, their passengers. Those without training to fly by instrument references are highly susceptible to spatial disorientation culminating in the loss of aircraft control, while instrument-rated pilots have a better chance of maintaining controlled flight until they hit structures or terrain. The results are equally deadly either way. Over the past 10 years 86% of Visual Flight-into-IMC accidents have been fatal…"

"As always, attempts to fly by visual references in instrument conditions accounted for the lion's share of fatalities…."

`Place the following narrative information in a Sidebar Box???`

Benefit of the 'Remarked' Temperature Group

METAR CODE Example:
KRNO 230053Z 03003KT 10SM CLR 05/02 A3013 RMK AO2 SLP195 T00450024

METAR for:	KRNO (Reno/Tahoe-International Airport, Nevada)
Time:	23rd Day of the Month at 0053Z/1653PST (winter)
Temperature:	5˚C (41.0˚F)
Dew Point:	2˚C (35.6˚F)
Pressure (altimeter):	30.13 inches of Mercury
Winds:	From the North-by-Northeast at 3 knots
Visibility:	10 or more statute miles
Clouds:	Sky Clear (Below 10,000 feet above the surface)
Remarks:	Denoted by “RMK”
	AO2 = Automated Station (ASOS)
	SLP = Sea Level Pressure 1019.5 millibars
	T00450024 = Temperature to the nearest 0.1˚C
	Temperature 4.5˚C and Dew Point 2.4˚C

Considering that an air temperature (T) and dew point temperature (DP) differential at sunset poses a threat of fog formation during the evening and nighttime hours and that a historical threshold value for that likelihood is 4˚F, the “remarks” section of a station aviation weather report can provide valuable insight for a pilot regarding potential fog formation. The presented example of an encoded Metar report for Reno-Tahoe International shows a 3˚C T/DP spread in the body of the report with readings rounded to the nearest whole degree Celsius. But in this early winter evening observation, decoding the Remarks section of the report that gives a greater resolution of the temperature and dew point, the temperature is seen to be 4.5˚C (40.1˚F) and the dew point 2.4˚C (36.3˚F) – or a T-DP differential of only 3.8˚F!

Reference:

Annual Joseph T. Nall Report; General Aviation Accidents: Aircraft Owners and Pilots Association (AOPA) Air Safety Institute (ASI)
https://www.aopa.org/training-and-safety/air-safety-institute/accident-analysis/joseph-t-nall-report

Advection Fog and Stratus

In the last chapter, the discussion of *atmospheric hydrometeors* (products of condensation or sublimation) focused on fog formation; especially radiation fog. In this chapter I would like to focus on a related type of IMC producer, coastal advection fog and stratus. The same energy exchange mechanisms occur inland, to produce advection fog and stratus far from any coast.

Figure 1: Coastal advection fog and stratus

Before cloud can form, the air must become moisture saturated. This usually occurs through lowering the temperature of air to its dew point. Less frequently, air becomes saturated by adding moisture. After the air becomes moisture saturated, condensation or sublimation results in visible moisture as tiny water droplets or ice crystals.

Classic advection fog occurs regularly along the west coast of the United States during the warm season months from May into October. The prevailing northwest wind in the east Pacific Ocean along the west coast during this time passes across an ocean upwelling of cold, bottom water to the surface immediately offshore. This maritime environment raises the moisture content of the lowest layer of the atmosphere and the ocean cold-water upwelling significantly cools the air immediately adjacent to the ocean surface. This means that the coastal marine air is relatively dense and of higher pressure.

The Mediterranean climate inland, with long, dry summers (provided by dominant higher pressure aloft along the west side of the continent) results in intense inland surface heating beneath clear skies. This daytime heating creates a transient surface low, and thus weak *synoptic* (large-scale) surface pressure gradients prevail, so that density-driven winds from the sea onto land become dominant, drawing moist air over the coast inland.

The low-level cooling of air in contact with the east Pacific waters and added moisture from the ocean creates a sharp temperature inversion over the ocean. This lowest level of air is the *west coast marine layer* [`See Image #1: "West Coast Marine Layer"`]. This cool, moist air readily reaches its dew point temperature and condensation leads to visible moisture, forming fog or a low-level stratus cloud deck, depending mostly on the strength of the gradient wind (stronger wind has more turbulence in the friction layer, creating greater mixing to keep the mean saturation slightly low). [`See Photo #1: "California Coastal Fog/Stratus"`].

The low-level, cooler air over the coastal sea is relatively more dense and correspondingly higher pressure than the warmer, less-dense air inland. This pressure difference between the sea and the land results in an onshore, density-driven wind known as a *sea breeze*.

The moisture in the sea-breeze air will condense to fog or stratus from any of the known mechanisms: orographic lifting, nocturnal radiative cooling, or daytime thermal lifting. Moist air does not need to be lifted far to reach saturation and condense.

By regulation, flight must conform to instrument-flight rules when cloud ceilings are below 1,000 feet or visibilities less than 3 statute miles. Depending on the depth or strength of the marine layer, the cloud *tops* of an associated stratus cloud deck within the marine layer may vary from only 500 feet above mean sea level (MSL) to 3,500 feet MSL [`See Photo #2: "Shallow Marine Layer"`]. The *ceilings* associated with the marine layer stratus typically range from 300 feet above ground level (AGL) to 800 feet AGL. And it is not unusual for the marine layer to provide *obscured* skies – that is, cloud extends to the ground, that is, fog). Stratus ceilings at or above 2,000 feet (AGL) are typical. Aviation safety is jeopardized when impatient VFR pilots elect to continue flight into the marine-influenced air layer with its reduced ceilings or visibilities. This is especially dangerous for pilots along the interface of the ocean and land because of the rising terrain and obscuration of coastal mountain ranges.

Advection fog is common and not limited to the west coast. Movement of air over any type of cooler or uplifting surface, either land or air, can bring it to its dew point. In the central plains of the US, air from the Gulf of Mexico is moist. It is one of the three major air masses creating weather west of the Rocky Mountains. Particularly in the spring, this Gulf air moves northward over cold prairie that in its northern extent is snow covered, which further chills the air in the friction layer and adds moisture. Thus a south wind in the spring often creates persistent dense fog or low stratus over the upper Mississippi Valley into Canada.

In this region, the second major air mass affecting weather is the cold, dry Continental Polar air mass that develops over central Canada. The juncture of the Gulf air mass with the Continental Polar mass forms a semi-permanent front that migrates with the birds in autumn and spring. When this frontal juncture is a stationary front, durable low stratus forms as the moist Gulf air over-rides the cold continental air, snuffing out soaring and creating wide areas of instrument meteorological conditions.

(The third air mass affecting the central US is marine air that has crossed the mountains and in so doing has been wrung out, so that it's warm and dry. It brings upper-level fronts and clear skies with warm temperatures and good soaring generally. Not fog or stratus.)

In general, advection fog forms when temperatures are only relatively lower, that is, the air isn't necessarily cold, just cooler. For example, a common form of advection fog or cloudiness due to marine layer moisture and cooling due to gradually rising terrain occurs in the summer over southeast Texas. Gulf of Mexico marine air reaches deep inland through the Uvalde soaring area due to the onshore pressure gradient from the Gulf to interior Texas [`See Image #2: "SE Texas Gulf Coast Marine Layer" and Image #3: "SE Texas Morning Low Clouds"`]. This is only *relatively* cool, as overnight minimum temperatures are high and humid, around 70˚F.

Compare this to the California coastal marine layer with its morning temperatures around 55˚F. Air moving over any *relatively* cooler surface – ocean, lake, or ground – that results in condensation or sublimation of moisture will form advection fog or stratus with its inherent hazards to flight.

However, marine moisture and elevated dew point temperatures – marked by a stratus cloud deck in the morning courtesy of the previous late afternoon "sea breeze" – [`See Photo #3: "Uvalde Early Morning Stratus Deck"`] is not necessarily detrimental to good soaring conditions. With intense seasonal afternoon sun and the mixing and drying of the lower layer of air, the boundary layer becomes destabilized (clear to permit insolation and cooler than the thermals that the sun creates), so that strong, consistent thermals develop by mid-day. The marine-elevated dew points from the overnight onshore wind over the Southeast Texas Plain create classic soaring conditions with cumulus clouds as thermal markers spread across the southeast Texas plain in the afternoons of mid to late summer. [`See Photo #4: "Uvalde Afternoon Cumulus Field"`].

Summary:

Understanding the atmospheric mechanisms that result in restrictions to visibility and/or restrictive cloud cover is necessary for our safety-of-flight decision-making.

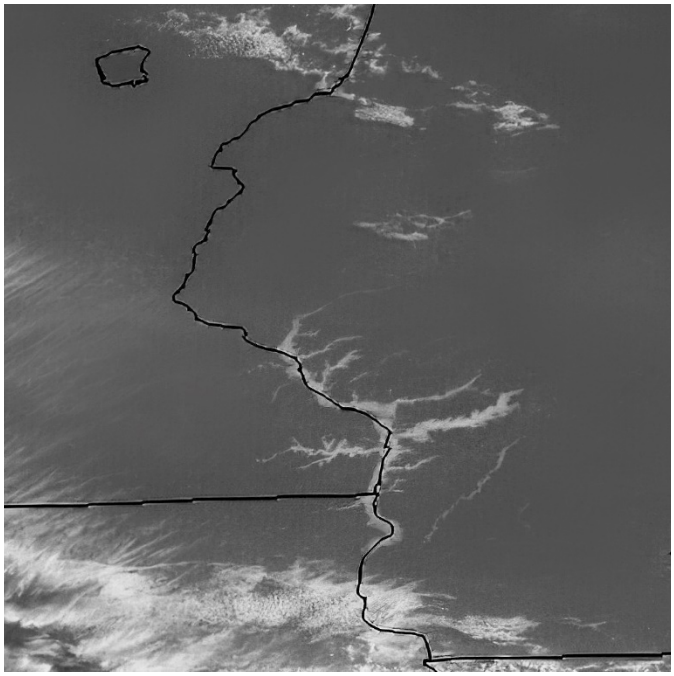


Figure 2: Early-morning radiation fog, MN-WI Mississippi & tributaries

Terrain and Thermals

"The best place to find a thermal
is at the most downwind corner
of a field."
- Letter to Soaring magazine

The nature of the terrain determines the location of thermal lift except with very strong lapse rates and brisk wind (in which case thermal bubbles seem to be swept up and coalesced above about 1000 meters into thermals – often in streets – that are not linked to ground features.

To recognize slope from 5000 ft agl requires studying terrain features to deduce upslope. This is an important challenge over rolling prairie or farmland, and over intermountain basins.

It's also important to understand how air flows up mountainsides, and in guessing where lift may be found, it's important to study the forecast gradient winds throughout one's planned flight area, and to note their expected evolution. These and upslope thermals strongly influence the channeling of wind in valleys and ravines.

On a blue day, the pilot has the choice of simply blundering along on course and working thermals as they are encountered, or of identifying thermal sources, mentally visualizing their slant in the wind, and connecting them. The first method works better when high; we fall back on the second method when low and a save is essential.

Air acts as though it is sticky. Invisible, clear, adherent to surface and self.

When it moves across a surface, friction makes the air rough and tumbly.

When it is heated by sunlit objects on the ground, it gets light and tends to rise, but does not form a tiny streamer from each blade of grass. Instead it mingles and diffuses and there results a swelling layer of heated air next to the ground that sits in place as if waiting for a nudge.

When a nudge does come, air from somewhere must replace it, which takes time to organize itself and move. Many different things can nudge this warmed air – a vehicle, an aircraft, a crowd waving sheets, the wind.

Air is light, but does have mass and must accelerate in order to gain speed. When warm air starts to move, especially when nudged by the wind, it moves sideways more than up.

If you watch a grass fire or brush fire in wind, you will observe that the smoke flows sideways, almost along the ground for a time, then rises ever more steeply. If the fire is burning over moist ground, the water vapor increases the buoyancy of the rising smoke and increases the acceleration. The angle of the smoke column is exactly related to the speed of the wind and the speed attained by the smoke thermal. When the smoke reaches the dewpoint of the air within it, a cumulus cloud may form.

Figure 3:Smoke behavior on a good cloudless soaring day, wind 8 kt, gusting 12 kt.

The Good-Looking Thermal Source

Thermals do not reliably kick off from homogeneous flat ground even if it's dark and sunlit. A soaring pilot many years ago told the story of an anxious time on a dual cross-country flight. They were beginning to get a little low, and nearby, across their course, was an expanse of black lava. They needed a thermal – what more appealing place than that?

They headed out across the lava. Miles floated by without a thermal. "We like our butts were gonna get scratched," he said. We were just holding on, flying minimum sink, hoping. We never got a thermal over that lava. But there was one after we got to the other side that saved our sorry butts."

What happened?

The lava was a flat, homogeneous expanse. Any dark field, any broad. large thermal source is *unlikely* to spring a thermal. The thermal will rise from the "farthest downwind corner." That is, the thermal will rise from the ***discontinuity*** between the heatable source and the adjacent terrain. That may be another field with different vegetation, a tree line, a low rise or a high one. If you need a thermal, you need to be able to reach the downwind side of the good thermal source. If it's a hayfield, and you miss the thermal, you'll be perfectly positioned for an out-landing in that field.

The Importance of Slanted Land

Except near mountains, from cloudbase on a good soaring day, all land looks flat. Yet there are always marks that reveal whether the ground is tilted, though they don't usually reveal the actual slant.

Rule One.

Thermals do not rise from down-sloping terrain.

If you are on the downwind side of a hill and need a thermal, do not make promises to God. Fly to the upwind side of the hill. *I will flee unto the hills, from which cometh my strength*.

Rule Two.

The sun shines brighter on the sunward side of the slope.

If the wind is light, thermals will be somewhere above the highest point of the flat-looking terrain that can be seen by tree shadows or water drainage markings to be leaning toward the sun.

If the wind is strong, you'll be lucky to find a slope that's downwind and tilted toward the sun. That's because, on many good soaring days, the sun shines from the south and the wind blows from the north. On such days there will be no upwind sunny slopes.

Dark Things Soak Up Heat

Terrain features that are dark blue or dark green do not generate thermals. In fact the dark blue ones, if large (more than 5 km / 3 miles wide, often snuff thermals for miles downwind by exhaling cooled air. The mechanisms are detailed in *Moisture Effects on Thermal Lift*, beginning on page 24, and in *Higher-Terrain Heat Sources,* beginning on page 14.

Dark vegetation fails to generate thermals in two ways: the chlorophyll soaks up insolation's energy, and its moisture retards contact heating. Maize (field corn) and deciduous forests are always thermal-free. Hayfields are not only good thermal generators but excellent out-landing fields because there are no bushes or rocks and the vegetation is short.

My observation, having spent 20 years circling low over various fields, is that bare earth doesn't generate thermals as well as short, dry vegetation, presumably because the vegetation has much more surface area with which to warm air by conduction. (See the discussion of conductive heating, page 13.)

Water affects thermal development

Water fails to generate thermals for several reasons: it has little surface area, it absorbs insolation thoroughly, it is cooler than the adjacent land except in mid-autumn, and it cools and humidifies the friction-layer atmosphere when the wind blows across it, snuffing thermal development downwind for many lake-diameters. Thus, *do not expect thermals downwind of lakes or wet river valleys*.

This effect extends far downwind of the wet area, even when the wind is not strong. The this effect is of course larger with big bodies of water or broad, wet river valleys.

Northern Minnesota has several large lakes that demonstrate this phenomenon on days with profuse marking cumuli.

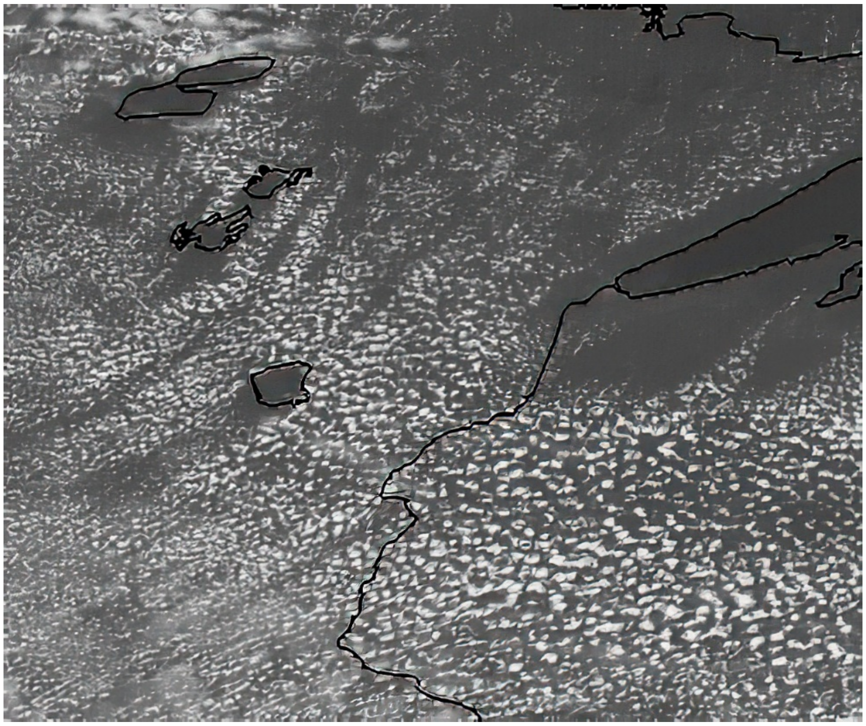
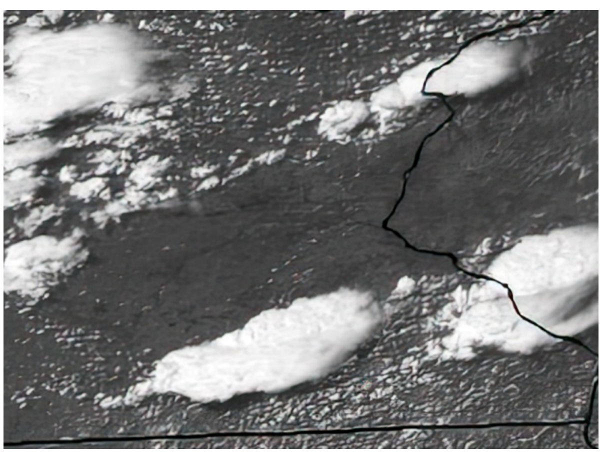


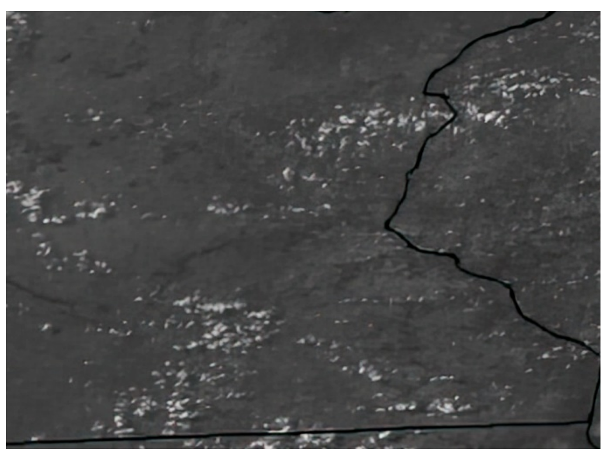
Figure 4: NE MN NW WI - Effect of water on thermal development.

In the satellite photo nearby, of the NW corner of Wisconsin and NE Minnesota, the wind is from the north and northeast, at less than 10 kt on the surface. The western tip of Lake Superior is at the right. The seabreeze front is seen to extend a few miles upwind it seems to extend many miles downwind. But because the sea breeze and the gradient wind are in the same direction along the south, there is no front, and gradual recovery of thermal activity can be seen in the gradation of cloud sizes.

There are four large lakes left of center. Each can be seen to snuff thermal development a long distance downwind despite light wind in the boundary layer. There are many streaks in the lines of clouds that are due to wet surface features that cannot be seen on this image, especially large areas of marsh and, over the NE part of this satellite photo, extensive mature forest.

The Effect of Rain





The sat photos are about 24 hours apart. The left-hand image shows a small thunderstorm moving NW to SE, with a blue hole behind it. The right-hand image shows a blue hole bottom center, next afternoon, where the rain had been heaviest the day before, persistently quenching thermals.

Are all blue holes devoid of lift?

Wet ground creates low-lift blue holes, as illustrated above. Any local high, an area into which air is descending, is a low-lift area. This may be the condition near any large hot area such as a desert.

Blue conditions that develop behind a cold front, on the other hand, tend to exist because progressively dry air is moving across an area. When soaring in this weather, the markers steadily become smaller and eventually vanish while thermals are still being generated. The anxiety for the soaring pilot is that a blue expanse with thermals looks exactly the same as one without. It's a good idea to study the forecast energy diagrams for area of a planned cross-country flight, so this can be anticipated.

Thermal sources in hilly or mountainous terrain

Strongly sloped terrain shapes the flow of wind and thermals. Terrain features were created by water erosion – in thinking about thermal flow, imagine reversing the water flow.

Thermals will originate on the most directly sunlit slopes, and migrate upward along the slope and depart from the peak or ridge.

Thermals will follow the slanted valleys – *but* are modified by the local wind. So the pilot, in interpreting terrain features and the effect of sunlight, must consider both the gradient wind direction and the directions in which large terrain features will shape or direct the gradient wind. This can guide, fragment, or enhance thermal integrity and movement.

So, in hills or mountains, an ideal is a steep slope directly facing both sun and gradient wind, in which is a large, sloping ravine. Of course, local wind oblique to the ravine or the slope is to be expected and as these vary as the terrain varies, the pilot must continually re-imagine the local wind direction and thermal tilt.

Much more could be said…

Cumulus Types and Their Behavior

It's clouds' illusions I recall.
I really don't know clouds at all.
- Joni Mitchell

`This chapter needs technical notes regarding the nuances of clouds mentioned.`

Near the top of the boundary layer, the temperature, humidity (dewpoint), and wind velocity (speed and direction) and observed lapse rates determine whether there are visible markers of lift, what is their lifespan, the strength of the lift, the presence of shear; in general, what the pilot can expect to find. When cu are present, the location of best lift is consistent, depending on the cloud type. By understanding the effects of shear, environmental lapse rate, MALR, and wind gradient, the pilot can use markers more effectively.

This chapter reviews some of those characteristics, which help a pilot decide where to go to avoid sink and encounter lift. Roughly, there is a long continuum of features that has characteristic types that recur often. Each time of day tends to have consistent character. For example, early in the day, every source has a thermal – small, weak, and short. Late in the day, sources are broad, often miles across. There's a transition between these, in which there's a mixture of new, working cu and senescent cu. Early in the day, every wisp marks a thermal (not always worth a turn, often half-a-turn small); after mid-day, wisps are often dying thermals, and the pilot must keep track of those nearby to understand which are coming and which going.

The most important thing to remember is that the top of the haze layer is the altitude of cloudbase if any clouds develop.

Blue thermals and Haze Domes.

The discussion in the last chapter of terrain and thermal sources becomes very interesting on a day without clouds. It's worth carefully studying the current and predicted skew-T to understand what lift rates to expect with altitude, to know where the band of best lift may be, and to understand expected shear, especially direction change with altitude.

It's been said that the strongest lift is generally about two-thirds of the way to the top of the lift. But we don't fly average days, we fly the day that we've got. We can either fly and discover, or we can study the forecast lapse rates and verify.

`Maybe put a sample skew-T from a blue day in here somewhere.`

Some flight computers, such as the SN-10, record and display both thermal strength and wind direction with altitude. Yet since the atmosphere is never frozen, the wind strength and direction and the lapse rates can all change during the day or across the area of a task. Because of this change, we cannot be confident that the wind at 3000 ft agl, 70 km and two hours after last being at that altitude, is unchanged. But unless we've crossed a front (which should be obvious), the change should be evolutionary.

Haze domes are sometimes visible in blue conditions. They are seldom visible when the boundary layer has 50-mile visibility because there ain't no haze to dome up. So the more haze, the more likely reachable haze domes are to be visible. Also, later in the afternoon, when the sun is somewhat low, haze domes are much easier to see when looking toward the sun. When desperate for a thermal, anything helps.

Still and all, on a blue day, it's worthwhile to continually observe the terrain and analyze it for likely thermal sources. Doing so is a different mindset than looking for cloud markers. In addition, when we've gotten low, every day is blue. We are best off to head downwind of good thermal sources while waiting to blunder into something strong enough. So much can be learned that way.

The thermals on a blue day with strong winds will have little apparent connection to terrain features. Lift lines and sink lines are more likely to exist. On any day with strong winds, thermals aren't well organized below about 3000 ft agl, making it important to stay high enough to reach the next thermal before getting low.

Once we get used to the blue, clouds and wisps may be simply a distraction that can lead us uselessly off course, perhaps across sink.

Wisps

Wisps – condensation without formed cloud – are reliable markers at the beginning and the end of the day. Early in the day, thermals are just beginning to top, condensation is scant, and every marker tops a live thermal – there's not been time for any to decay. This being the case does not mean cross-country speed will be high, only that we can stay up, sometimes in the small, weak thermals for only part of each turn. This is typically the situation 4 or 5 hours after sunrise.

Wisps are also reliable late in the day when the atmosphere is drying out, without enough moisture to support clouds but enough to produce evanescent condensation at the peak of the thermal's cycle. Late in the day, thermals are larger and stronger than early, so it's possible to play connect-the-wisps along one's rhumb line and make good cross-country time. While doing this, we always blunder into lift, and while turning in it the wisp may form above us to confirm our good judgment in not passing it up.

During mid-day, there is an assortment of small markers in all stages of the thermal cycle. Some wisps are just beginning to announce a new thermal topping out, others are the last remnants of a dissipating small cloud. These evolve very slowly, so it's important to keep a mental catalog of the markers within reach and check their appearance intermittently for change. Unless the atmosphere above the boundary layer is unstable and tight, heaped-up cumulus form, by the time a distant cu looks attractive, it's past its peak and will be dissipating by the time we arrive on a straight glide.

Small clouds with short cycles

In general, when markers are small, their cycles are relatively short, less than half an hour. Best cross-country progress is made if one strikes out toward new wisps so that there's a chance of using the best part of its cycle. It's dissatisfying to arrive under a nice, tight cu to discover that it's no longer marking a thermal.

It's important, when there are small clouds early in the day, to have checked the forecast to understand what evolution of lapse rates is expected. Typically, the atmosphere becomes drier and clouds more widely separated later in the afternoon. Other times, pre-frontal conditions exist and evolve toward small cu-nim with unstable air above the haze layer.

Small clouds always have sink at the most downwind side, and the thermal is always located at or beyond the most upwind part of the cloud. As the day evolves, finding that the best lift has moved to a different quadrant of the clouds is a reliable sign that the gradient wind just above the haze layer has changed direction. The best lift of small clouds is *not* at the center or darkest part of the cloud.

Wind-blown clouds and possible wave

The wind above the haze layer is usually not in the same direction as below it. If there is speed shear at the top of the boundary layer, there may be wave above cloudbase. This is uncommon, and advice on its location is as varied as the pilots telling of their experiences.

It is commonly said that burgeoning cu may act as an obstacle to the gradient wind, and this is likely true at times. Satellite photos rarely show a grid of cu behind a cold front, with evidence of streeting in the direction of the gradient wind in the boundary layer and evidence of orthogonal wave induced by gradient wind above. Together these influences create order along two axes, with a gridded effect to the cu. I've found no evidence of a soaring pilot chancing upon this and using it.

It's in the nature of wave that it does not require an obstacle to trigger. Shear and friction are enough, though an obstacle that creates upslope and ridge lift, and possibly lee wave, provides stronger soaring. There is often wave at the top of the haze layer, though seldom strong enough to use for soaring. An airplane flying along the top of the haze layer will experience gentle changes of pitch and altitude due to wave that is best managed by asking ATC for an altitude block.

Standard instruction on contacting thermal wave is to fly well upwind of the obstructing cu, partly to respect regulatory cloud clearance requirements. Certainly in some conditions this has been found to be useful. In any case, several soaring pilots have discovered and used deep thermal wave. I do not know whether this is upslope lift in front of a massive cumulus cloud or whether it is harmonic lee wave related to a cloud field. I believe that both conditions sometimes exist, based on studying satellite photos.

Yet shear wave may have its peak strength at the clouds, which in this circumstance are analogous to lenticulars. It may not be possible to use this wave and conform to visual flight rules. One soaring pilot said, "You can get up above those clouds, but you can't do it by flying 1000 ft upwind. You have to circle right at cloudbase to build up speed in the updraft, then, when you're going as fast as you can, pull up sharply into the upwind edge of the cloud. It's not legal, but it's the only way to do it." OK, then. We are not promoting this action, we include the story to support the argument that shear wave sometimes exists at the top of the boundary layer.

It's useful to understand that this is one variety of wave, and we leave it to you to negotiate a way with ATC. In fact, if you are instrument rated and your sailplane is instrument-equipped, and you are flying well away from IFR routes, ATC may be able to accommodate, after a personal visit to Center to have a long, adult conversation about how this might be workable.

Calm days produce wandering thermals

If you study smoke, especially that from large fires, you will note that the flow is not at all laminar, and on a calm day smoke from a large, steadily burning fire ascend continually but is characterized by great rotating globs. Thermals, on light-wind days, are not laminar columns, either. When a thermal seems to have topped out well below the day's predicted maximum, it's worth widening one's turn once. Often we find that the core has simply shifted significantly and can resume a strong climb adjacent to the path we had been flying. This may occur two or three times before the lift actually abates.

At wind speed above about 8 kt, thermals, though slanted, are better organized, and as the wind speed increases, streeting may occur. I would like to add a couple of paragraphs on the mechanisms of streeting, but I do not know them well enough to write a true statement.

Whether streeting occurs depends on instability as well as wind velocity. In addition, clouds often line up, more or less, without the upper-altitude coalescence that characterizes the best streeting.

Vacuum-Cleaner Cu

When there is adequate moisture in the boundary layer to support massive clouds, and sufficiently cold above the boundary layer to provide instability, thermals become actually stronger above cloud base, after condensation begins. This is because condensing air cools more slowly than dry air, becoming relatively much more buoyant. With this condition, the acceleration of the condensing lifted parcel will force additional air into the cloud from below. If this is sufficiently moist, it will augment the acceleration of condensed air.

It appears that an active cu cumulus will actually pull air from the boundary layer to replace the condensed packets accelerating upward. This has two apparent effects.

First, the ascent rate of the thermal that initiated the cloud increases far below cloud base.

Second, are from the boundary layer that was not thermally lifted is entrained to the thermal. To the extent that this air is sufficiently humid to condense within cloud, it will augment the acceleration provided by the condensed thermal. You can imagine that, in optimal circumstances, this process can be very unstable and can result in explosive development of cumulonimbus. In circumstances optimal for soaring, the instability is limited to a narrow band at most a few thousand feet in depth.

In this instance, the less-humid air being drawn into the actively-growing cu forms a dimple in the cloud base. More-humid air being drawn into the cu condenses at a lower altitude, forming virga-like streamers of condensing air.

We need some technical notes about this, particularly how to recognize from a skew-T diagram whether there's enough instability just above the condensation level to support augmented cumulus development, and if so, what will limit cloud height. It's also important to provide a means to judge the risk of explosive tall cu.

I clearly recall, standing at our local airport on a presumably wonderful soaring day, prevented by an air show from launching. During the afternoon, a tall cu rose about 40 miles to the west. The weather radar showed this to be a small but extremely intense cell. It reached the tropopause about five minutes after I first saw it. The radar movement showed it to be moving directly toward our local air show. But it did not grow to be a large thunderstorm. During the next 20 minutes, it completely dissipated, and the air show wasn't inconvenienced.

We can recognize which cu will have augmented inflow – will be sucking air – by their appearance. Such active cu look like cauliflower. Tight, dense, burgeoning. Never wispy or limp. These have a much longer life cycle than the small cu that simply top thermals without augmentation. The fact that both types of cu can exist in the same broad area suggests that there are microscale differences across an area of stability as well as microscale differences in ground heating and available moisture to thermals.

Streets and lines

Ok, I don't feel like writing about these right now.

Clouds may be lined up due to wind and terrain influences. I recall one morning when we were ground-launching, the sky was initially clear blue, the wind was calm. At about 10 am, a small cu appeared nearby. By 11 am, there was a line of small cu extending as far as one could see to the east and to the west, curving slightly to the southeast. I quickly realized that these were precisely following the interstate freeway. I've never seen this since. By early afternoon, the sky was completely blue and cloud-free again. Clearly freeway traffic augmented thermal release on this day. This brings to mind a casual comment I heard decades ago by another glider pilot: "There's always zero sink over freeways after sunset." Why, one wonders, did he need to discover that…

With brisk winds and an unstable lift rate, clouds form connected lines several miles long that we call streets. Much more often, with lighter winds, clouds seem to form lines and the lift is not connected. This could be chance; it could be that thermals are entrained by shear wave at the boundary layer top. I do not know what mechanisms produce this.

Blue Holes vs Dry Lift

The mystery, when clouds are absent over an area, is always, *Are there any thermals there?* A blue hold is viewed pessimistically because so often thermals are absent there. For examples, soaked earth due to recent rain, or the washout of instability far downwind of a large lake, as we discussed on page 78. There are no small-scale forecasts that take into account spotty rain and the associated excessive soil moisture, so it can be useful to keep track of rainfall the day before a task or contest to anticipate this. [I cannot find storm-relative precipitation graphics, as NOAA has overhauled the weather site and site-specific radar history appears to have been removed.]

On the other hand, when dry air is moving across an area, the day may evolve from few clouds to wisps and then to blue, which may contain thermals and not be a dreaded blue hole. It's useful to have studied the forecast skew-T across the area of planned flight, or to use a graphical soaring forecast that predicts thermal strength and thermal clouds.

Safe Cu-Nim

The international weather consortium does not discriminate among the several kinds of convective clouds that may be present. We'll eliminate supercells and frontal thunderstorms as being too dangerous to be worth our time writing and discussing as possibly useful for soaring.

In general, a forecast of lightning and the presence of lightning indicate dangerous convective cloud. But isolated strong cumulus clouds free of lightning (indicates less-vigorous convective turbulence) are not inherently dangerous, and soaring can use them carefully, flying beneath its cloudbase, using the lift shelf along the front, or taking a long final glide through the still air in its wake.

So small isolated cumulus can be used safely.

Post-cold-front Roll Clouds and Wave

We sometimes talk as though mountain lee wave is the only wave. This is not correct. Wave is everywhere in the atmosphere; wave of different types *characterizes* atmospheric phenomena. Mountain lee wave is special because it's so well suited for soaring:

It is stationary (*standing* lee wave), so pilots can return to the well.

It is predictable, so equipment and personnel can be staged.

It is reachable.

It occurs reliably with seasons.

It is strong.

It is present across broad geographic areas, so can be used for speed and distance records.

Shear wave is commonly seen from the ground and in satellite photos, but has none of these qualities. Pilots may by chance encounter it, and it seems to interact with thermal lift, so it's worth a mention.

Shear wave is most common in the quadrant of a low pressure system behind the cold front. In the northern hemisphere, this is to the southwest of the center of the low. It is associated with stronger surface winds, so a high-performance glider is more suited to explore it. From the ground, if there is overcast, regular wave undulations can sometimes be seen in it. When the overcast is broken, sometimes this takes on the appearance of roll clouds.

These phenomena are not stationary, nor is there any attention given to researching this or forecasting it because it does not cause enough turbulence to trouble commercial passengers nor is it useful. Rarely this wave excites the boundary layer below to wave movement strong enough, persistent enough, and deep enough to sustain glider flight. [Reference OSTIV paper on prairie wave?]

When clouds are minimal, this organizes the small cu into rows. [I have not found any research that would say whether this is usable for soaring.] This is *not* streeting, which can occur in the boundary layer at the same time.

Streeting

[I think this is worth a section, or possibly a chapter. I do not understand the conditions necessary to produce streeting, nor the meteorological mechanisms by which it forms, nor its interaction across the top of the haze layer. Gradient wind in the boundary layer of more than about 15 kt and an unstable lapse rate, and enough moisture to produce cloud. It seems, too, that some instability above the haze layer is necessary, to allow "working" cu to develop. Cu that suck air should augment the streeting mechanisms.]

The Pilot Weather Briefing

Ed.'s note: Might it be worthwhile to focus on the tools now available for self-briefing?

What's available at 1-800-wxbrief.com – I don't use this except to file airplane xc.

aviation.weather.gov – I use the surface progs thumbnail view every day to estimate whether coming weather will be unsoarable. Generally it's worth the effort to assemble only for 1-4 days after cold front passage, or if the jet stream is flowing across Canada, bringing Pacific air across the mountains and blue soaring conditions to the plains.

Dr. Jack's BLIPmaps – I find these useful especially for thermal-clouds prediction ("experimental") and boundary-layer winds across a region.

SkySight – I find this useful for projecting XC speed over a course. It's seldom accurate, yet always useful. It must be combined with a study of the visual sat photos, to understand where high clouds are and will be, as they change everything and are barely predictable.

TopMeteo – I find this useful for its detailed spot forecast profile, and the map of thermal heights showing numbers rather than colors. In my area the heights are underestimates by about 1000 ft, but are more useful than pretty colors.

Windy.com – I find this useful for motion of sat imagery and cloud/moisture forecast. The first step in self-briefing is to look at the Windy Clouds forecast (which also shows predicted precipitation) because if it's gonna rain, ain't nobody gonna soar. Importantly, the forecast skew-T sounding can be shown for any location by touching a spot on the windy.com map.

The android app Skew-t is very portable and is designed for soaring pilots.

Any source of regional satellite imagery

Other used frequently

Graphic: The PWB sequence

[I did not edit the remainder of this chapter yet…]

While successful cross-country soaring depends on a pilot using his/her evaluation of the current weather, existing weather threats or the potential for inclement weather provided within the PWB must be understood by a pilot to make a good risk assessment given that pilot's skill and aircraft capabilities.

Recognizing the important connection between weather forecasting and aviation, on May 20, 1926, Congress passed the Air Commerce Act. This Act included legislation directing the Weather Bureau (forerunner to the current National Weather Service - NWS) to "furnish weather reports, forecasts, warnings ... to promote the safety and efficiency of air navigation in the United States." From the late 1920s through the 1940s, the United States military developed a briefing format advising pilots of adverse weather in regard to safety-of-flight as well as mission requirements. By the late 1950s with the development of the Federal Aviation Administration's (FAA) Flight Service Station (FSS) System and the staffs of U.S. Weather Bureau (USWB) Offices, a formal PWB format was instituted to brief the civilian aviation communities. The main components of that format are still in place along with a few extra-meteorological additions given present-day concerns (See Text Box: "Pilot Weather Briefing").

As a young meteorologist in the early 1970s, one of the first professional certificates I acquired within the National Weather Service was that of the "Pilot Weather Briefing Certificate." To be allowed to brief a pilot who called the NWS for weather information under the auspices of regulatory pre-flight knowledge requirements, I was trained, drilled, and then tested by a Weather Service Evaluations Officer to demonstrate proficiency in providing the necessary weather information. Having received the provided information from a weather briefing, a pilot could then make the proper "go" or "no-go" decision for safe flight in consideration of their personal and aircraft capabilities.

The main components of the formal PWB provides information on meteorological flight hazards, forecast weather conditions, and observed weather in a specified order. In using the Internet and specifically the NWS's Aviation Weather Center (AWC) Homepage (See Web Page #1: AWC Home), various formal and experimental weather products are available for pilot weather information. The left menu on the AWC site has a specific header for "Standard Briefing" which is the formal PWB format with one exception. This exception is the acquisition of "background information" by a weather briefer (See Web Page #2: AWC Standard Briefing Page). Background information provided by a pilot enabled the FAA FSS or USWB briefer to better understand the pilot and aircraft capabilities thereby custom fitting the briefing within the limitation of the pilot and plane in an efficient manner. This pilot-furnished information included the type of aircraft, flight limitations (Visual Flight Rules or Instrument Flight Rules), departure and arrival airports, route and altitude of the flight, and the time of departure and estimated time en route.

After the background information was obtained, the pilot weather briefer then proceeded to progress through the PWB format using a variety of weather products appropriate to the requesting pilot's flight parameters. All of the sections comprising the PWB utilize knowledge of weather codes and products that were acquired through ground and flight training (See References: AC00-45G, Aviation Weather Services).

Obviously, telephone briefings had the briefer utilizing text weather products to a large extent. Any information gleaned by the briefer from graphical products or charts had to be verbally described and conveyed to the pilot. The weather information and products pilots were required to study to pass their knowledge and practical tests for their airmen certificate was to be applied toward safety-of-flight decision-making. One of my favorite instruction stories is reminding pilots that we have witnessed a "full circle in weather briefings". In the 1950s and 1960s pilots could call for a weather briefing or had the option of visiting a FAA FSS and/or USWB Office for a "One Call – One Stop" briefing. Pilots began to primarily use only the FAA FSS System for briefings by the early 1970s, but FAA FSS Offices co-located with USWB (now NWS) Offices had the ability to pass briefed pilots through to the neighboring NWS Office. This "pass-over" to the NWS from the FAA FSS for additional insight into occurring or forecasted weather was known as the "one call" briefing option. Pilots who physically visited FSS and NWS Offices could review posted facsimile charts and teletype text weather products in their encoded form on PWB boards and office map displays. The developmental pinnacle of FAA FSS and NWS Offices during the 1970s and early 1980s along with the convenience of the "One Call - One Stop" weather briefing service led to most civilian weather briefings being conducted by telephone. The late 1980s saw the beginning of FSS and NWS Office closures and centralization of service locations thereby making it most inconvenient for pilots to visit FSS and NWS Offices. Pilots then depended almost exclusively on telephone weather briefings. Familiarity and proficiency in reading encoded weather text products and weather charts to gather weather information for a flight seemed superfluous except for successfully passing the airmen knowledge tests. The centralization of the FAA FSS System and the restructuring of the NWS Offices by the mid-1990s pretty much eliminated the pilot "walk-in" self-briefing capability. But then, even with weather services centralization, the development and expansion of Internet capabilities accessible by pilots after the late 1990s now provides for better weather product dissemination than that seen on any map displays and PWB Boards of the 1960s. Therefore, the need for pilots to not only grasp meteorological concepts but be able to personally read and interpret weather products is again operationally very useful … a "full circle" in a pilot's weather briefing knowledge over the years!

Without going into great detail within this article in regard to specific weather products that make up a PWB, I would like to point to a purposeful redundancy within the briefing format. The first weather products referenced in the briefing format are those in regard to "Adverse Conditions", i.e., conditions that may be deemed hazardous to flight. Examples of weather products comprising this section might be AIRMETs and SIGMETs. And yet, these same hazardous conditions will again be briefed within the "En Route Forecast" section in conjunction with the Area Forecast (FA). This redundancy is meant to ensure that the inclement weather information has been adequately conveyed to the pilot.

Since the attack on the United States in 2001, the NOTAM section has a much more robust and comprehensive Temporary Flight Restriction (TFR) bullet within the Notices to Airmen (NOTAM) section. Additionally, due to Internet capabilities, the FAA is able to make available other types of information directly to pilots that would not have been possible in decades past.

In summary, it behooves the soaring pilot to understand meteorological processes that provide upward air motion. But primarily a soaring pilot needs to have basic knowledge of weather services and products that assure him/her that inclement or hazardous weather does not compromise a safe flight…no matter how strong the atmospheric lifting mechanisms. Future articles can address some of these useful products. In the meantime, before any soaring flight is undertaken some form of weather briefing needs to be received. To quote cross-country pilot extraordinaire Jim Payne…" Have Fun and Fly Safe," and (Editor's addition) Get a thorough pilot weather brief !!!)

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Aviation Weather Services, Advisory Circular 00-45G, is published jointly by the National Weather Service (NWS) and the Federal Aviation Administration (FAA). This publication supplements its companion manual Aviation Weather, Advisory Circular 00-6A, which documents weather theory and its application to the aviation community. AC00-45 explains U.S. aviation weather products and services. It details the interpretation and application of advisories, coded weather reports, forecasts, observed and prognostic weather charts, and radar and satellite imagery. Product examples and explanations within the publication are taken primarily from the Aviation Weather Center's Aviation Digital Data Service.

2) NWS Aviation Weather Center Website
www.aviationweather.gov

3) NWS Aviation Weather Center "Standard Briefing":
http://www.aviationweather.gov/stdbrief/
---Go to the NWS Aviation Center Website (reference point #2 above)
---On the Left Side Menu: Click "Standard Brief"
---Note the components of the PWB and various weather products and graphics

References

Soaring Meteorology Publishing Pioneers

While omitting significant contributors to understanding soaring meteorology, as a soaring meteorologist for many years, I would like to acknowledge the published works of those with whom I am familiar. Their compilation of soaring meteorology and pioneering publishing has furthered the understanding of "modern" soaring meteorological concepts for soaring pilots and meteorologists:

- Harry Higgins' work and derivation of the Thermal Index;
- Australian Meteorologist and pilot C.E. "Wally" Wallington, NWS meteorologist Charles V. Lindsay, and British meteorologist and pilot Tom Bradbury on fine pioneer publishing work to describe meteorological elements (not just "thermal" related) relevant to modern soaring flight;
- NWS Meteorologists Chris Hill and Doug Armstrong for their work in development of the *soaring index* and providing the precedent for acceptance of soaring parameters and forecasts within the NWS; and,
- Notable computer-era Navy Research Laboratory Meteorologist and pilot Dr. John "Jack" Glendening for his development and subsequent availability of numerical soaring forecasts. Besides the actual computations, access of "Dr Jack's" internet website also provides excellent definitions of significant soaring meteorological aspects. http://drjack.info/

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Also see the mountain wave references at the end of *Mountain Wave Parameters*, page 41.

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