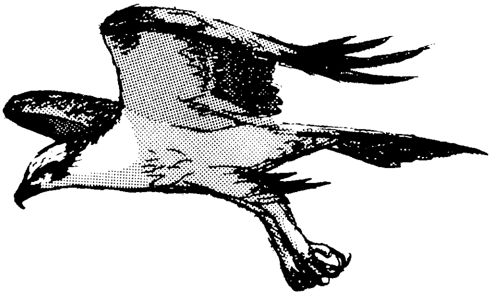
UNDERSTANDING THE SKY

by DENNIS PAGEN

A SPORT PILOT'S GUIDE
TO FLYING CONDITIONS



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I wish to thank Kathy Lee of Taos, New Mexico for her generous offering of photographs. She has truly captured much of nature's beauty with her discriminating eye.

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Dennis Pagen
January, 1992

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Dennis Pagen
Claire Vassort-Pagen

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PREFACE

In the closing decades of the twentieth century a fortunate coincidence of timing and technology has allowed our species—designed for life on the surface of planet earth—to enter the atmosphere and cavort among the clouds. Flying for fun has come into its own as a reasonable and legitimate pastime. But inhabiting the realm of the sky requires a certain amount of understanding. The air is an ever-changing environment and we must know its ways and wiles in order to fly safely and become excellent pilots.

This book is designed to present a clear picture of how the atmosphere works. Naturally some simplifications must be made, for the subject of weather is a complex one requiring many years of study to master. Consequently we have distilled the important lore and knowledge necessary for pilots who fly for fun. The best way to use this book is to read it through, experience flight then reread the pertinent portions to gain a deeper understanding.

We have tailored the material to suit the needs of balloonists, RC modelers, paraglider, hang glider, sailplane and ultralight pilots alike. Hopefully each reader will discover new insights and ideas within these pages to enhance the enjoyment of flight.

Besides embracing all air sports, the material herein is written with an international viewpoint, for many pilots today travel in pursuit of their aerial endeavors. We include the perspective of both the northern and southern hemispheres, where appropriate, and give some attention to regional and continental specifics. We also use both English and metric equivalents in the text as well as the charts and figures.

While we begin the chapters on the air's properties and general weather, we would like to point out that the emphasis in this book is on smaller-scale conditions known as local effects or micrometeorology. The reason for this emphasis is that recreational flying normally takes place within a relatively small volume of airspace where local effects play a major role. Most weather books written for general aviation do not address the small-scale conditions in enough detail to satisfy recreational pilots. This book is intended to fill this void.

The background material for the information in the following chapters comes from many sources. Certainly textbooks have been very useful, but most important is the experience of almost two decades of flying and the sharing of ideas with other pilots from all forms of aviation. It is my wish to pass on some of the knowledge I have gleaned from these experiences so that we can all better savor our time in the sky.

CHAPTER I

The Air Around Us

We grew up on a planet that is surrounded by a life-giving mixture of gases. We call this mixture air and we refer to the entire gas cloud around the earth as the atmosphere.

Most of us take this air and atmosphere for granted as we pass it through our lungs to borrow some oxygen, or slip through it while on the move. For the most part, the air is just simply there. But give us a set of wings and a whole new world opens up. New challenges, new vistas and new experiences alter our viewpoints forever. We become pilots with the realm of the sky to explore.

We quickly become aware of the constant changes that take place in the atmosphere and the need to understand what these changes mean. With understanding we become comfortable in our new environment. With understanding we leave our fears behind and free ourselves from the limitations of an earthbound existence.

In this chapter we begin to study the nature of the sky so we can later predict its behavior as we enter its domain and cast our fate to the winds.

THE BIG PICTURE

The atmosphere is held to the earth by gravity. Although the total thickness of the atmosphere exceeds 500 miles (800 km), most of the air is packed near the earth's surface since air is compressible and gravity pulls each molecule downward. In fact, fully half of the atmosphere's total weight of over 5.6 quadrillion (5,600,000,000,000,000) tons is below 18,000 feet (5,500 m)!

The atmosphere can be divided into different levels like the layers of an onion according to certain characteristics. We are mainly interested in the lowest layer which is known as the troposphere (tropo means change). It is here where the changes take place that we identify as weather. It is here that we live and breath and fly.

The troposphere extends from the surface to 5 or 6 miles (7 to 9 km) at the poles and 10 to 12 miles (17 to 20 km) at the equator. The reason for this difference is centrifugal effects due to the earth's spin (see figure 1). The extent of the atmosphere is greatly exaggerated in the figure for clarity. To put matters in perspective, the entire atmosphere compared to the earth would only be about the same relative thickness as the peel of an orange while the troposphere's thickness would be equivalent to the skin of an apple.

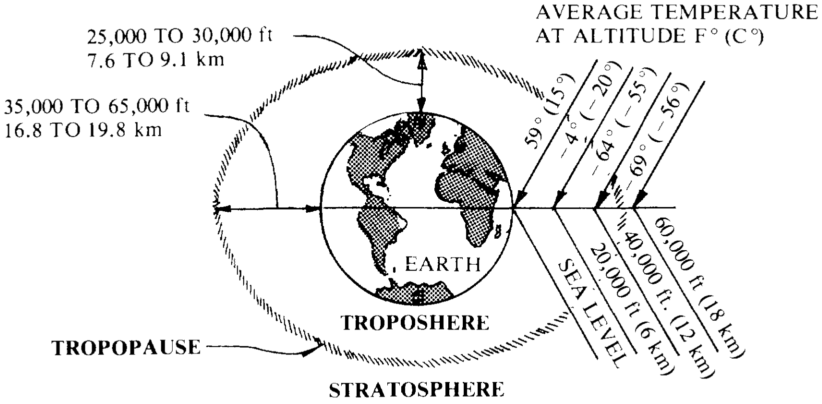


Figure 1 - The Lower Atmosphere

On top of the troposphere lies the stratosphere and the transition between the two is known as the tropopause. The way we differentiate these two lower layers is that the temperature drops steadily with height in the troposphere but it remains nearly constant as we climb into the stratosphere. Thus the stratosphere is stable and clear but the troposphere exhibits clouds and a wide variety of conditions. The troposphere is our sphere of interest in this book.

THE STRUCTURE OF THE AIR

We know that the air is a mixture of gases. Most of it is nitrogen (78%) and oxygen (21%) with the remaining 1% being mainly argon with a little carbon dioxide and some pollutants thrown in.

Water vapor is also a highly variable constituent of air. It can be from zero (dry air) to 4 or 5 percent by weight (saturated air). As we shall see later, water vapor is an extremely important part of the weather process for without it there would be no clouds or rain. Almost all the water vapor in the atmosphere is concentrated in the troposphere for it enters the atmosphere through evaporation from ground sources and is carried aloft by vertical air currents which are limited to the troposphere. Ninety percent of all water vapor remains below 18,000 feet.

The pollutants mentioned above, including smoke, dust, salt particles and industrial exhaust, are important for they serve as condensation nuclei which promotes cloud formation. Clouds are of great interest to us creatures of the sky for they help point out lift and generally give us clues to the atmospheric behavior as we shall see in chapter III. Clouds and pollutants in general can also present visibility problems which are pertinent to our flying.

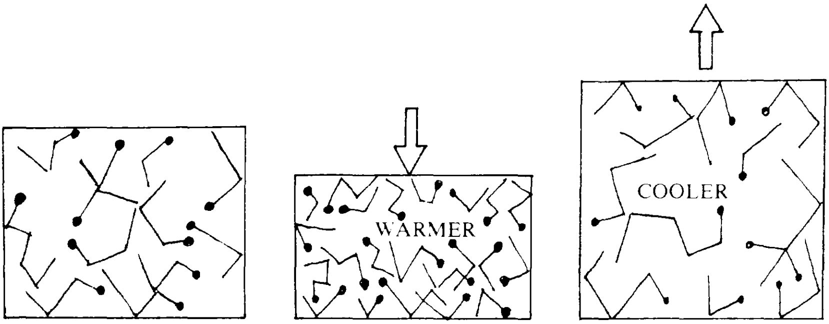
PROPERTIES OF THE AIR

The air is fairly wispy stuff, but just how insubstantial it is depends entirely on its density. As we noted earlier, the air can be compressed so its density depends on its composition and how much compression takes place. It is this density that interests us most for it directly affects our flying.

The three features that determines the air's density are its *temperature, pressure* and *water vapor* content. The two main factors that control these features are *gravity* and the sun's *heating.* Before we look at the importance of each of these items, let's review what we know about how a gas (air) works.

The molecules in a gas are bouncing around like hyperactive kids on a chocolate diet. All this scurrying about causes them to knock into their neighbors and ricochet off in random fashion. If the molecules encounter a solid they leave some energy behind as they hit the solid. In fact, this exchange of energy is what we feel as heat. The more excited the molecules are in the gas, the faster they are moving and the more energy they impart to any solid they contact so the warmer the gas feels. What we know as temperature is simply the state of excitement of the gas molecules.

It isn't too hard to imagine that if we add heat energy to a gas we raise the temperature by causing its molecules to move around more vigorously which in turn makes it want to expand, for each madly careening molecule is knocking its neighbors farther apart with each contact. Also we can see that if we allow a portion of gas to expand the molecules will spread out so it becomes less dense and at the same time cooler since there are fewer molecules in a given volume to knock into one another or a nearby solid. Conversely, if we compress a gas it becomes denser and its temperature rises as the molecules become more jittery (see figure 2). These properties should be well understood for they are of great importance to soaring pilots.



NORMAL ATMOSPHERE

COMPRESSED—
PATHS SHORTER,
MORE FREQUENT
RICOCHETS.

EXPANDED—
PATHS LONGER
LESS FREQUENT
RICOCHETS.

Figure 2 - The Properties of Air

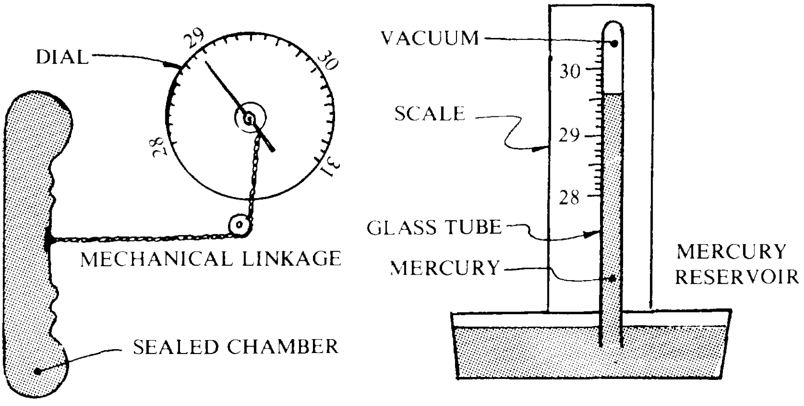
PRESSURE IN THE ATMOSPHERE

We all do our daily chores under considerable pressure—from the atmosphere. In fact, at sea level we experience about 14.7 pounds per square inch (1.03 kg/cm2) on our bodies. That's almost 200 tons (!) on an average size adult. Of course, the air pushes on us equally from all directions, and we are basically water balloons with a rigid internal framework, so we don't notice atmospheric pressure unless it changes suddenly.

We can think of presssure in the atmosphere as simply a measure of the weight of air above us. This weight is caused by gravity pulling down on the air's mass as mentioned previously. At sea level the air weighs .076 pounds per cubic foot (1.22 kg/m3) so a medium sized bedroom (20x10 ft floor plan) contains over 120 lbs. of air. When we consider how high the atmosphere extends, it is no wonder there is so much pressure here at the bottom of the ocean of air.

It stands to reason that the lower our altitude, the higher the pressure since more air is pressing down above us. Likewise, the higher we go the lower the air's pressure. We can also see that higher pressure results in more dense air since the air's molecules will be compressed together by the greater weight they must support.

We measure the air's pressure with a barometer which is simply a cavity with some of the air removed so a partial vacuum exists. As the outside pressure changes (the air's weight changes) the walls of the cavity move in or out in response. A suitable linkage turns a needle to register the correct pressure (see figure 3). Another type of barometer uses a tube filled with mercury suspended by a vaccum at the top of the tube. The mercury moves up and down the tube to register pressure changes. Weather reports for the public often report pressure in inches of mercury in the English speaking countries. On the other hand, the rest of the world and weather maps use millibars to report pressure (1 millibar equals 1000 dynes per square centimeter).



ANEROID BAROMETER **MERCURIAL BAROMETER**

Figure 3 - Barometers

The altimeters we use as pilots are nothing more than sensitive barometers. They sense the pressure drop as we go up and the pressure increase as we go down. Some altimeters used by sport pilots can detect the difference in pressure of as little as one foot of altitude change—that's remarkably only .03 millibar or .001 inch of mercury at sea level.

Here is a summary of some important points:

When air is *lifted* it feels *less pressure* because there is less air pushing down above it, so it *expands* and *cools* and becomes *less dense*. Conversely, when air *sinks* it experiences *more pressure*, which *compresses* it, *heats* it and makes it *more dense* (see figure 4).

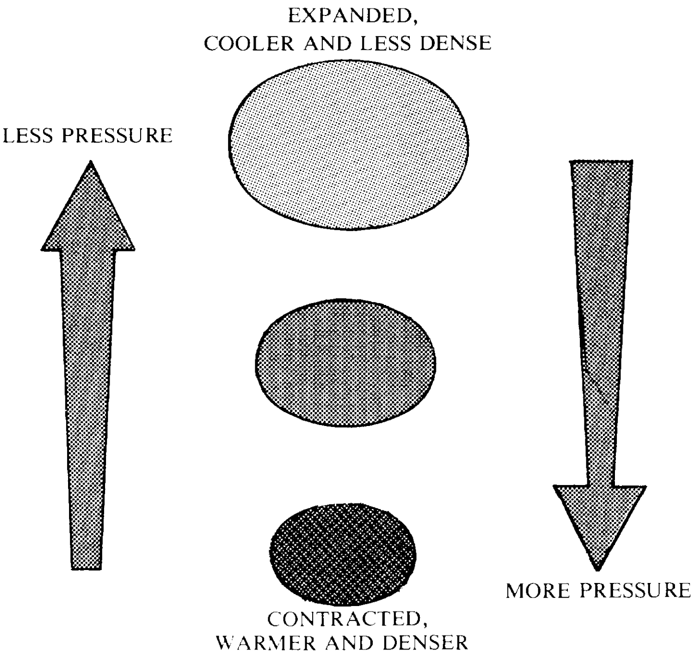


Figure 4 - Expansion and Compression of Air

TEMPERATURE IN THE AIR

We are not used to thinking that cooler air is less dense and warmer air is more dense as we indicated in the box above. However, it is the compression or expansion of the air that causes the temperature change. When the air changes temperature through compression or expansion alone—without the addition or subtraction of outside heat—it is known as an *adiabatic* process. This is the case in general when a thermal rises or convergence, ridge and frontal lift occur. In later chapters we will explore the cause and use of such lift.

Near the earth's surface the air is heated indirectly by the sun. This is a non-adiabatic process since the heat is from an outside source. Such solar heating is the main generator of motion in the atmosphere because air warmed from the outside expands and becomes less dense while air cooled by the surface becomes more dense. In general, air flows from the cool areas to the warm areas.

The sun's radiation does not heat the air from above, but passes through the air to heat the ground which in turn heats the air from below.

We measure this heat with a thermometer which reads in either Celsius (C) or Fahrenheit (F). Water freezes at 0° Celsius or 32° Fahrenheit and it boils at 100° Celsius or 212° Fahrenheit. The conversion formula is: $9/5\ C + 32 = F$.

To avoid the direct effects of reflection from the ground and other objects, the standard temperature reading is taken from a thermometer located 1.25 to 2.0 meters (3 3/4 to 6 ft) above a short grass surface. The thermometer should be shielded with a well-ventilated white box and located in the shade. Only by these means can we acquire a true air temperature reading.

SOLAR HEATING

Most of the sun's radiation passes through the air to the ground. It heats the air directly only 0.5 to 1 °F per day, depending on the amount of water vapor and pollutants present. Much of the sun's radiation is absorbed or reflected back into space by clouds. The amount of reflection naturally depends on the amount of cloud present. Only about 43% of the sun's insolation actually reaches the ground as shown in figure 5.

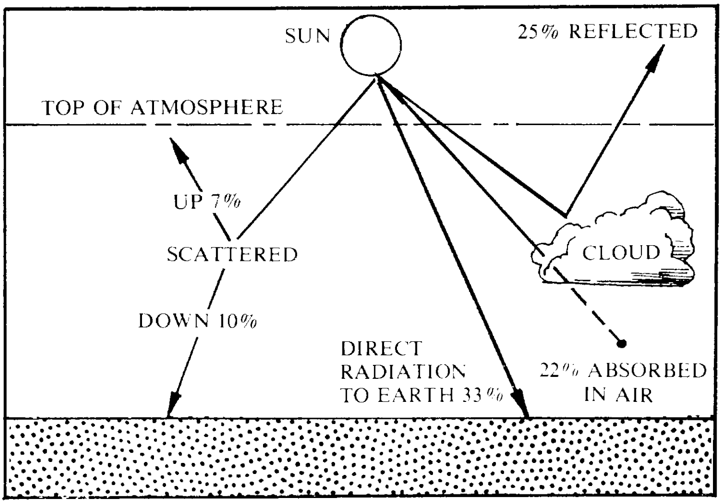


Figure 5 - Solar Heating

The fate of all this sunshine depends on what it meets at ground level. South facing slopes absorb more heat than level ground or northerly slopes. Concave shaped areas take on more heat than flat or convex areas. Trees and grass reflect light in the green wavelengths while sand reflects about 20% of the incoming radiation. Snow and ice reflect from 40% to 90% while dark surfaces such as parking lots or plowed fields reflect only 10 to 15% of the incident radiation. Water reflects the sun's rays according to their angle of arrival—about 2% when the sun is straight up and over 35% when the sun is just above the horizon.

All the radiation that is absorbed by the ground is spent in the process of making heat. Some of it directly heats the air next to the ground by conduction. Some of it heats the lower atmosphere through convection whereby currents or bubbles of warm air rise and spread outward. Some of it evaporates water which later gives back the heat to the atmospere as the water vapor condenses to form clouds.

The nature of the surface of the earth affects how the heat is absorbed or imparted to the air. For example, sand heats up in a shallow layer very readily while water allows the sun's rays to penetrate deeply so the surface temperature doesn't rise significantly. Generally, the hotter the earth's surface, the warmer the air will become above it.

It should now be clear that different types of surfaces heat at greatly different rates given the same incoming radiation. We shall study such properties in detail in Chapter IX for they are extremely important to thermal generation. For now let us note that the daily dose of sunshine keeps our atmosphere warmed from below and this is the main source of energy for our weather and soaring conditions.

COOLING CYCLES

Just as the air is heated from below by the sun heating the ground, so too is the air cooled. When the sun drops from the sky, heat from the ground radiates off into space in the form of infrared radiation. This radiation passes readily through the dry air with little absorption. Consequently the ground cools steadily through the night and in turn cools the air above it.

If a wind is blowing at night, the mixing of the air spreads the loss of the heat upward so it doesn't become as cold near the ground. If clouds or humidity are present they scatter the escaping radiation, sending some of it back down which slows the cooling process. This is the reason it takes a clear, still night to produce dew or frost. This is also the main reason that desert areas get so cold at night. The nighttime air and earth heat exchange is shown in figure 6.

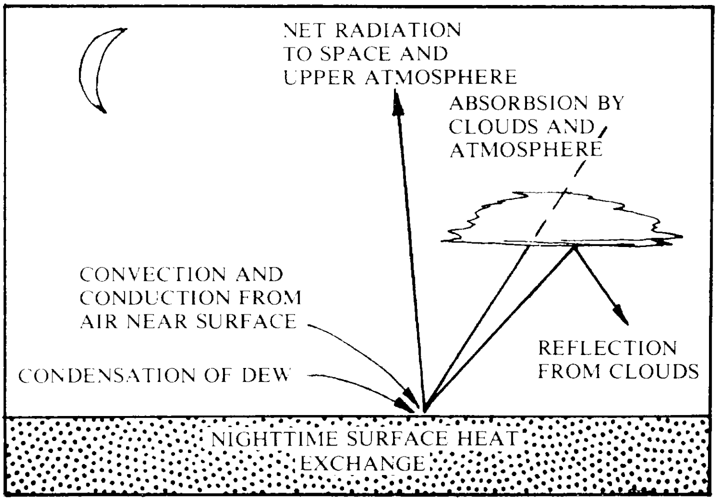


Figure 6 - Heat Radiation

DAILY CHANGES

The daily or diurnal variation of solar heating is an important concept to pilots whether they are looking for soaring conditions or smooth air. To see how this works we need to note that the sun's heating effects begin as soon as it looks upon the surface in the morning and increases to a maximum at noon (local sun time) when it is directly overhead, then diminishes to zero as the sun sets.

As long as more radiation is incoming than outgoing, the surface will heat. Now the outgoing radiation varies directly with the temperature of the surface, so the sun's heating reaches a maximum before the outgoing radiation does and thus the maximum surface heating occurs around 3:00 pm as shown in figure 7. This is also the usual time of maximum thermal production.

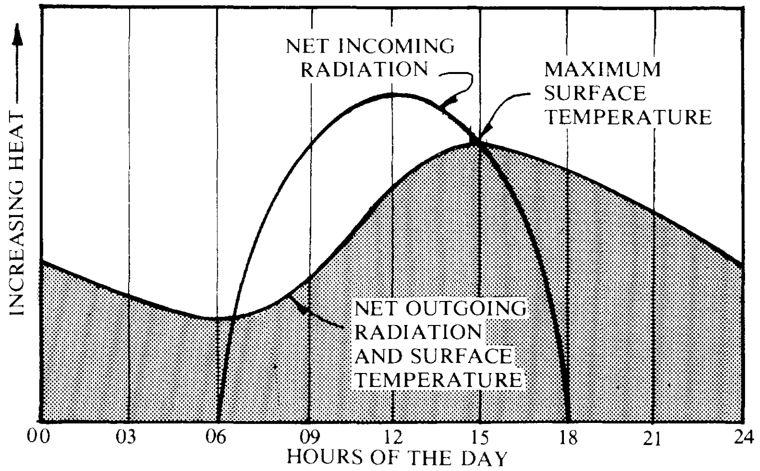


Figure 7 - Surface Heating Cycles

SEASONAL CHANGES

In figure 8 we see the seasonal differences in solar heating. The peak heating during the day is still at noon (local sun time) but it is much less during the winter solstice (when the sun is the furthest away) and at a max-

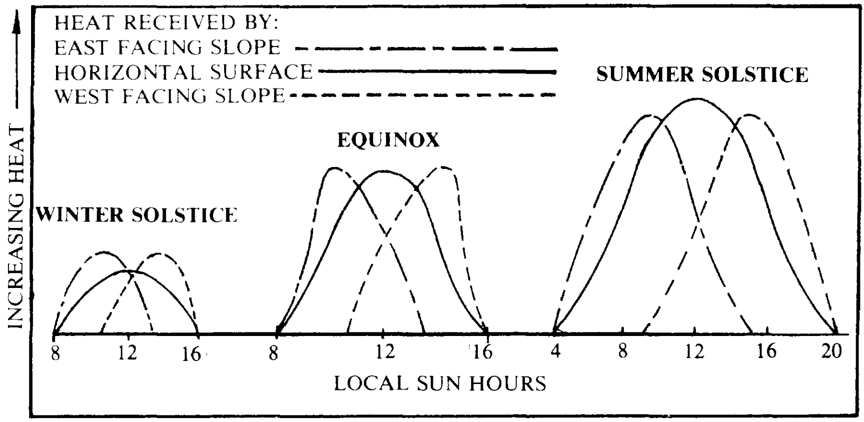


Figure 8 - Seasonal Heating

imum during the summer solstice (when the sun reaches its maximum height in the sky). The time of the equinox is when the sun is passing above the equator. Naturally this is when the heating is maximum at the equator. Note that during all these different heating cycles the maximum ground temperature and thermal production lags the maximum sunshine just as it does in figure 7.

A very important matter to see from these graphs is the difference in heating on various slopes. For example at the time of the equinox the east-facing slope receives the same heat at 8:00 AM as the horizontal surface at noon and the west-facing slope at 4:00 PM.

The cause of the seasonal change in solar insolation is twofold: the tilt of the earth's axis of rotation with respect to the plane of its orbit around the sun and the elliptical shape of this orbit. These features are illustrated in figure 9. Here we see that when the earth is tilted away from the sun in the northern hemisphere, the sun shines less directly on this hemisphere and it shines for a shorter time each day. At the same time it is summer south of the equator and the sun's rays are more direct with longer days.

At the other side of the orbit summer visits the north and winter assails the south. The interesting part of this discussion is that when the northern hemisphere is tilted away from the sun the earth is actually closest to the sun in its orbit as shown in the figure. When the north is tilted toward the sun the earth is furthest away in orbit. This results in making the winters milder and the summers less torrid. This arrangement wasn't always so as past ice ages testify.

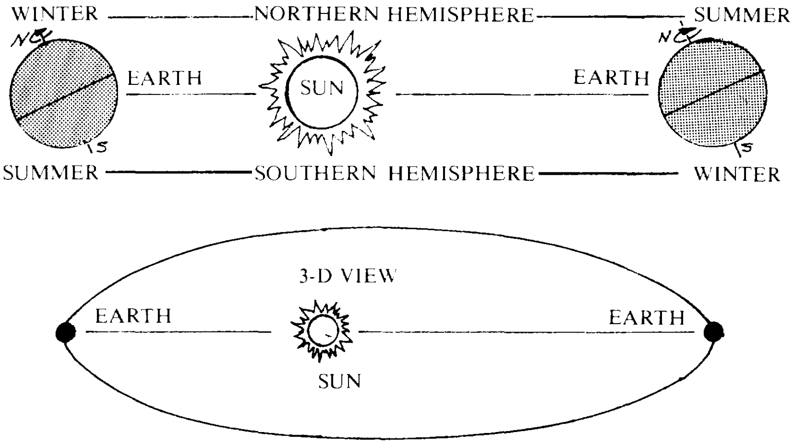


Figure 9 - Orbital Heating Changes

The opposite situation occurs in the southern hemisphere: the sun is closest in the summer and furthest in the winter. This would create more severe weather for southern pilots except there is much more ocean compared to land mass in the southern hemisphere which tends to moderate the temperature. Furthermore, not many people live below the 38th parallel in the southern hemisphere so the most severe winter weather is avoided.

These seasonal changes are important to pilots for the well-known general conditions they bring:

Winter—Cold, dense air, strong winds at times with stable air.

Spring—Changing conditions with cold fronts bringing unstable air and great thermal soaring.

Summer—Hot and humid with poor soaring in the wetter areas but good thermal production due to intense heating in desert areas.

Fall—A return of the cold fronts and unstable air with thermals in northern areas.

WATER VAPOR

Water continuously and universally affects the weather because of its widespread presence both as water vapor and cloud. An estimate of the total amount of water vapor drifting across our land is more than six times the amount of water carried by all our rivers! Even the smallest shower involves thousands of tons of water and one inch of rain falling over an area the size of Oregon state is equivalent to about 8 million tons. All this water vapor and rain comes from evaporation from open bodies of water and transpiration from vegetation.

Water vapor is the gaseous form of water and clouds consist of tiny water droplets that have condensed from water vapor. Water vapor forms clouds when the vapor is cooled to the point of condensation. This point is called the *dew point* and is given as a temperature. The dew point for a given parcel of air depends on its relative humidity.

HUMIDITY

Absolute humidity is a measure of the amount of water vapor in a given volume of air. This is frequently given in pounds per 1,000 cubic feet or grams per cubic meter. Absolute humidity varies from 1 part in 10,000 to 1 part in 40 according to the air's evaporation and temperature history.

Relative humidity is a measure of the percentage of water vapor present compared to how much the air can hold at its present temperature. Relative humidity is given as a percentage and ranges from near zero for warm, dry air to 100% for saturated air.

We must understand that warm air can hold more water vapor than cold air. Consequently the warm air will have a lower *relative* humidity than the cold air even though their *absolute* humidity (actual vapor content) is the same. For this reason we can increase the relative humidity by cooling a parcel of air. If the air is cooled enough its relative humidity reaches 100% or saturation and cloud forms. This saturation temperature is the dew point identified earlier. We will look deeper into this cloud-producing process in Chapter III. For now we note that the most common way that air is cooled in the atmosphere is by lifting which causes expansion and cooling.

The cold air of winter is always more nearly saturated than summer air because it can hold less water vapor. This fact is bad news to a pilot for the result is more clouds and precipitation in winter in general and also lower cloud bases because less lifting is needed to cool the air to saturation. When we heat this cold air and bring it into our homes in winter we decrease its relative humidity and our bodies lose moisture to the air causing us to think of winter air as dry. Relative humidity, not absolute humidity is in charge here.

WATER'S AMAZING PROPERTIES

Water in its various forms—solid, liquid and gas—has some unique properties that give it a special place in our understanding of weather (see figure 10). To begin, water has a high heat capacity. This means it is very happy to accept and store heat. Water absorbs all the sun's radiation it can get without increasing much in temperature. Consequently it tends to be cooler than land areas in the day but warmer than land at night when the lands quickly releases its stored heat. At night the slow release of heat from water can warm the air at the surface to cause instability and convection. The stored heat of water can likewise warm cold winter air moving across it to create "lake thermals," a topic we explore in Chapter IX.

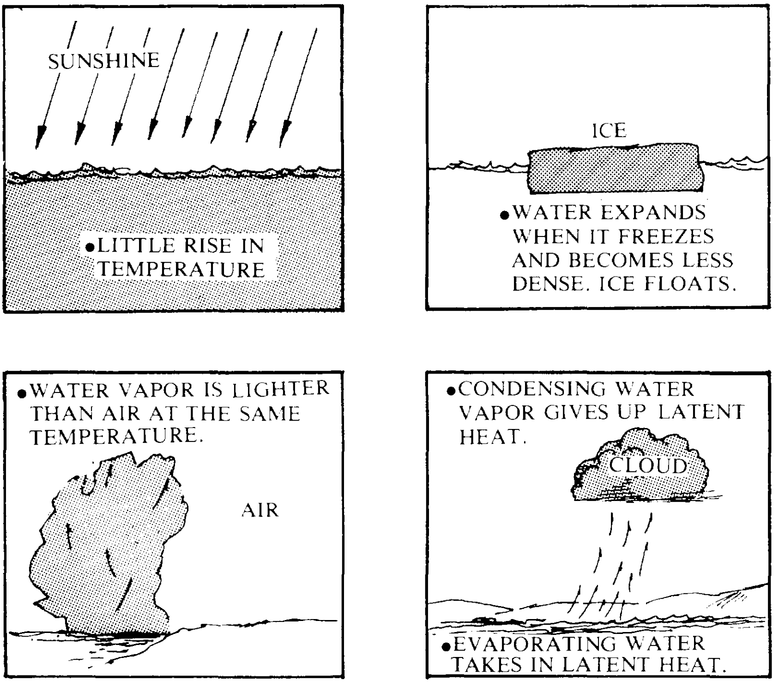


Figure 10 - Properties of Water

The temperature modifying effects of water result in warmer winter air and cooler summer air in its immediate locale. This gives England and France their mild climates despite their high latitudes and allows northern areas such as New York state, Ontario, and British Columbia to support orchards and vineyards. But the next property of water is even more important in terms of modifying our climate.

Water has the unique behavior of expanding when it becomes a solid (ice) so that it is actually lighter as a solid than a liquid. Ice floats. As a result, only a relatively thin layer of ice rests on the top of open bodies of water—a layer that can easily be melted with the return of warm weather.

If ice didn't float it would gradually accummulate on the lake bottoms and build up until the lakes were frozen solid. They would barely thaw in the course of a summer and worldwide temperatures would be considerably cooler, at least in the temperate areas.

The next property of water is its relative lightness as a gas (water vapor). Water vapor is only about 5/8 as heavy as the rest of the air due to its lighter molecules (two hydrogen atoms and one oxygen atom compared to two united nitrogens or two oxygens). As a result, humid air rises in the presence of dry air. This property accounts for the continued progress of thermals and thunderstorms in many instances.

LATENT HEAT

The final property of water we'll investigate is its latent heat. Latent means hidden and this heat is acquired by water vapor during the evaporation process and is "hidden" or stored away to be released later to the surrounding air when the vapor condenses back into water.

The process of releasing heat upon condensation or absorbing heat during evaporation is very important to the behavior of clouds, thermal formation and downdrafts (see Chapter XI). Since the source of the latent heat is usually the air into which the water vapor evaporates, the air above water tends to be cooled and thus rendered more stable (unless the water is much warmer than the air as noted previously). The subject of stability will be explored in more detail in the next chapter.

SUMMARY

In this chapter we have gained an understanding of the makeup and mechanics of the atmosphere. We separate each aspect of the air so we can investigate it, but really all facets of our study are intricately affected by one another. The composition of the air along with its temperature, pressure and humidity all interact and are modified by the sun's input to our little planet with further alterations by that planet's gravity.

As we gain understanding we begin to put together the big picture that allows us to make predictions and judgements as to what we may encounter in the sky. But before we can look at general weather conditions we must learn about a few more forces and effects that take place in our atmosphere. We do this in the next chapter.