3

RADIATION AND TEMPERATURE

Chapter Highlights:

- ✓ Learn the difference between shortwave and longwave radiation.
- ✓ Excursion- Why is the sky blue?
- ✓ Temperature cycles explained.

There is no free ride in the earth's atmosphere: energy is required to produce weather. As you probably already know, the sun provides the earth with energy that drives the atmospheric circulation system. The sun emits massive amounts of energy in the form of electromagnetic radiation (i.e.- photons), of which the earth receives only a fraction. The energy level of this radiation is directly related to its frequency; the higher the frequency the higher the energy level (Figure 3.1). It turns out that the frequency of energy emitted by the sun is a function of its temperature; higher temperatures produce radiation at higher frequencies. The sun, like any other star consists of a large quantity of very hot hydrogen gas. The temperature of the hydrogen in the sun varies significantly, gas near the core is thousands of times hotter than gas in the outer layers. Therefore the sun does not emit radiation at a single frequency, rather it emits radiation across the entire electromagnetic spectrum. However, since the layer of hydrogen in the sun's outer atmosphere is about 5,000^{o} C, many of the photons it emits are in the visible portion of the spectrum.

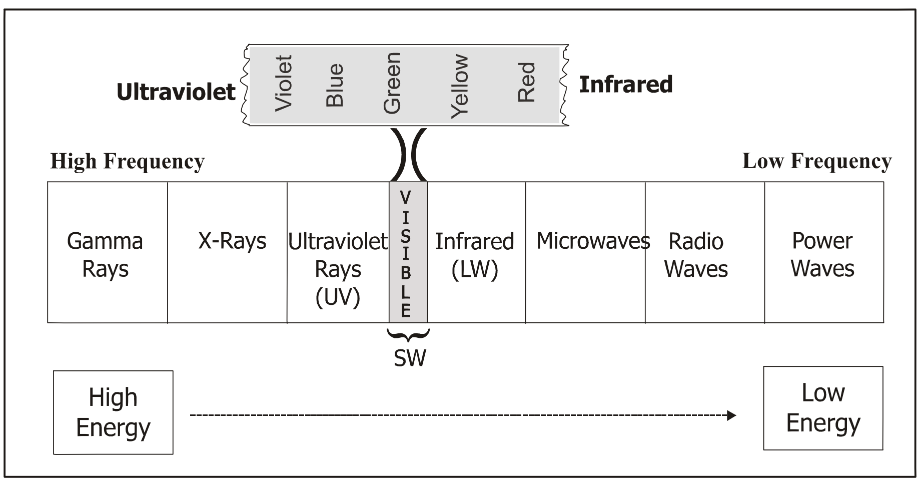


Figure 3.1- The electromagnetic spectrum. The human eye only sees the visible portion of the spectrum. Light appears white because it contains equal amounts of all colors.

Shortwave Radiation

In meteorology we use the terms shortwave (SW) and longwave (LW) radiation to designate the visible and infrared portions of the spectrum, respectfully. Visible radiation has shorter wavelengths (higher frequency) than infrared radiation, hence the names shortwave and longwave. Since the earth is on the average 150 million km (93 million miles) from the sun, it only intercepts a very small amount of the sun's total energy output. The amount of shortwave radiation that reaches the top of the earth's atmosphere is called the *solar constant*, it has a value around 1370 Wm^{-2}. It does vary slightly from season-to-season since the earth's orbit is not a circle, but rather an ellipse. The solar constant also varies with sunspot activity, however these variations have little effect on daily weather patterns, although they may have some influence on the earth's climate

Over the course of let's say a year, on average about 70% of the shortwave energy that enters the top of the earth's thermosphere, is transmitted through the atmosphere and reaches the ground (i.e. sunlight). The 30% that is 'lost', is reflected back out of the atmosphere off of cloud tops and highly reflective surface features such oceans, lakes, glaciers and snow covered regions of the planet. On any given day however, much more than 70% can reach the ground while on other days much less. The actually amount of course depends on a number of factors.

As sunlight passes through the atmosphere some of the photos are absorbed by nitrogen and oxygen molecules. These molecules then re-emit a photon at the same frequency as the original, however it can be emitted in any direction. Since this process occurs billions of times per second, photons are moving in every conceivable direction, giving the sky its bright appearance. Some photons however travel through the atmosphere without being absorbed. Sunlight therefore has two components: diffuse-the part that is absorbed and re-emitted, and direct-the part that is not. On an overcast day there is no direct sunlight, its all diffuse, hence it is difficult or impossible for an object to cast a shadow.

Not all areas of the earth's surface receive the same amount of shortwave radiation on any given day; the amount received is primarily a function of latitude and secondarily on cloud cover. This dependency on latitude is a result of earth-sun geometry. The path of the sun across the sky is confined between the Tropic of Cancer (23.5^o N) and Tropic of Capricorn (23.5^o S). Over the course of a year the tropics of course receive far more shortwave radiation than any other region on the planet.

The amount of energy that is incident on the earth's surface can be approximated by the following little equation:

$$\textbf{shortwave radiation} \quad \mathbf{X} \quad \textbf{cosine}(\theta)$$

where θ is the angle that the sun makes with the vertical, called the sun angle. Since cosine(0^o)=1 and cosine(90^o)=0, any unit area of the earth's surface receives the largest amount of radiation when the sun is directly overhead (on the zenith). You may be asking yourself the question, "what happens if the ground is not horizontal or the sun is not directly overhead"? Have no fear, Figure 3.2 shows what occurs in a valley that is positioned at 45^o N, on June 21st.

At solar noon the sun's zenith angle is 45^o-23^o= 22^o, remember that since we are in the Northern Hemisphere that the suns' path will be an arc across the southern portion of the sky. If we allow the symbol SW to stand for the maximum amount of shortwave radiation that would reach any surface in this example, then the following holds true.

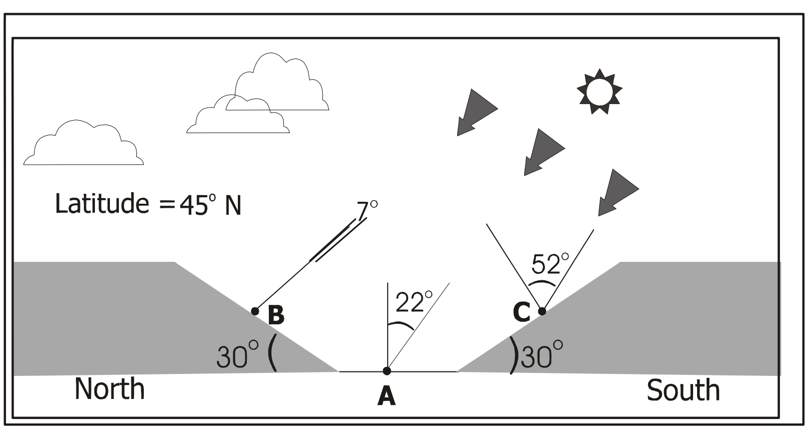


Figure 3.2- Hypothetical shortwave radiation scenario.

at: **A** shortwave radiation X cosine(22^o) = SW X 0.93

at: **C** shortwave radiation X cosine(30^o + 22^o) = SW X 0.61

at: **B** shortwave radiation X cosine(30^o - 22^o) = SW X 0.99

It turns out that the south facing aspect of the northern slope

(**B**) receives the largest amount of instantaneous shortwave radiation. If position **B** was on a slope of 22^{o} instead of 30^{o}, at solar noon it would receive 100% of the available shortwave radiation. Keep in mind that this scenario only holds true at solar noon. At other times of the day the sun angle is a little more difficult to calculate.

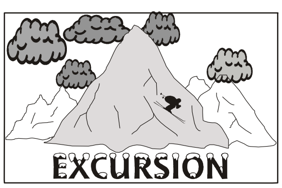
Now if you can imagine making this calculation every minute over the course of a day, include shading of the ground due to clouds, mix in different types of vegetation and surface characteristics, and it should not be difficult to understand why certain terrain features heat up or cool down much faster than adjacent ones.

Why is the preceding discussion important? Because our weather is driven by temperature differences that exists between one region and the next. This occurs at all scales, from a small plot of dirt to continents. This differential heating of the land becomes very important when we consider local-scale winds generated in mountainous terrain (Chapter 4). The heating of snow covered south facing slopes in the spring is important to mountain travelers because the additional heating and subsequent production of melt water weakens the bonding within the snowpack, increasing the potential for avalanches. Furthermore because the troposphere is heated from the ground up, any temperature differences that exist at the surface are often transferred to the lower troposphere. If the earth was covered by a uniform surface type such as water, or light brown dirt, grass, or pink flamingos, it's weather would be much less energetic then it currently is. The net result would be less frequent and less intense storms, while the earth's climate would be considerably more uniform.

Why is the Sky Blue?

As shortwave radiation travels toward the surface from the top of the atmosphere, as noted above, it strikes molecules of nitrogen and oxygen. These molecules absorb the radiation and immediately re-emit it in process called scattering. It turns out that nitrogen re-emits shortwave radiation that is rich in the blue wavelengths, and since nitrogen is more than three times as abundant as oxygen, the sky appears blue. Nitrogen selectively scatters blue wavelengths due to the size, spin, and vibrational modes of the molecule (Rayleigh scattering).

High altitude climbers know that the sky turns increasingly darker shades of blue as they ascend. The explanation for this is as follows: as a climber gains elevation, air pressure and hence the density of nitrogen and oxygen molecules decreases. As a result, the amount of scattering occurring at these higher altitudes is also reduced. As scattering decreases, the sky becomes progressively black because the only source of illumination is the narrow shaft of direct sunlight. The extreme example occurs on a place like the moon where there is no atmosphere, and hence no scattering. Photographs of the astronauts walking on the moon show the "sky" as being black with the sun appearing as a bright disk in the background.



Longwave Radiation

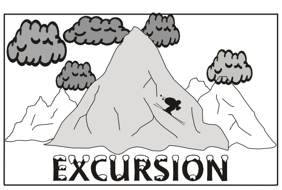
Once shortwave radiation is absorbed by the earth's surface (dirt, rocks, vegetation, water, etc.), the surface warms-up and emits longwave radiation (note that the terms longwave, infrared, and terrestrial radiation are synonymous). Since the temperature of the earth's surface ranges somewhere between -50^{o} C and +65^{o} C (-60^{o} to 150^{o} F) , the longwave radiation it emits has less energy than shortwave radiation emitted by the sun. Unlike shortwave radiation which is transmitted through the atmosphere without very much loss of energy, longwave radiation is absorbed by clouds and many atmospheric gases like water vapor, carbon dioxide and methane. This results in most of the longwave radiation which is emitted by the surface being absorbed within the atmosphere. Due to the nature of atmospheric gases, those that are good absorbers of longwave radiation also have the tendency to re-emit it as well. When clouds and gases re-emit longwave radiation, most of it stays in the lower troposphere. As a result, the total radiation balance (SW and LW) of the earth and atmosphere is pretty complex.

Because clouds are great absorbers and emitters of longwave radiation, the coldest temperatures over the course of a year at any given location generally occur on cloud free nights (or days). A layer of low-level clouds can cause the air temperature near ground level to be roughly 5^{o} C (9^{o} F) warmer than under clear sky conditions. Probably the best way to illustrate the total radiation balance is to consider a high elevation site that is also arid, such as the Tibetan Plateau or the Altiplano of Bolivia. On a typical summer day with few clouds to interfere with incoming shortwave radiation, the surface of the ground heats up considerably. At night the surface emits large amounts of longwave radiation, but since there are no clouds and there is little moisture in the air, this radiation moves higher into the atmosphere. As a consequence, air temperatures during the day are warm for the elevation, but cool rapidly during the evening, and are quite cold at night. Therefore these high elevation sites experience a larger day-to-night (diurnal) temperature range than air in the free atmosphere does at the same elevation.

Conduction and Convection

Conduction is the transfer of thermal energy (heat), from a hot to a cold object. If a warm motionless air mass resides over a cold body of water, heat is transferred from the warmer air to the cooler water. Given enough time, the two temperatures become equal and reach a state called thermal equilibrium**.** Conduction only occurs when the two bodies (air masses in our case) are in direct physical contact with each other, and there is a transfer of heat energy from the warm body to the cooler body.

Convection is more abstract than conduction, it signifies the transfer of thermal energy through the movement of a fluid. Consider a patch of dirt that absorbs large amounts of shortwave radiation and becomes warm in the process. There are a number of possible ways for heat to be transferred to the atmosphere. First, if the air is initially motionless, then conduction transfers heat from the warmer ground to the cooler air. Once the air near the ground is heated to a temperature that is warmer than the surrounding air, it becomes less dense and positively buoyant. As a result the air begins to rise, and new air moves into replace the air (parcel) that is positively buoyant.



In a slightly different example, suppose air is moving over a warm surface. The air molecules that are in direct contact with the surface are heated by conduction, but the carrying away of energy as they move past the heat source is convection.

Conduction and convection are not only fundamental to the atmospheric energy balance, but they are critical in many other geophysical processes. Consider the formation of ice on a mountain lake. In Autumn, as air temperatures decrease, the upper layers of water in the lake lose heat to the atmosphere through longwave radiation, conduction and convection. Fresh water reaches its maximum density at +4^{o} C (39^{o} F), so once the water at the surface of the lake cools to +4° C, it sinks because it is negative buoyancy. During this process, warmer water moves to the surface to replace the sinking water. Ice does not form on the lake until the upper water layers have cooled to the freezing point. Deep lakes take longer to form a layer of ice than shallow lakes or ponds.

Once a layer of ice forms the rate of continued ice growth is a function of the rate at which the water directly beneath the ice layer can lose its heat. Water loses its heat by conduction through the ice, the ice in turn has to lose this heat to the atmosphere. The thicker the ice layer the slower its growth rate since the layer of ice insulates the water below. Since snow is a very good thermal insulator as well, a layer of snow on top of the ice will further inhibit ice growth.

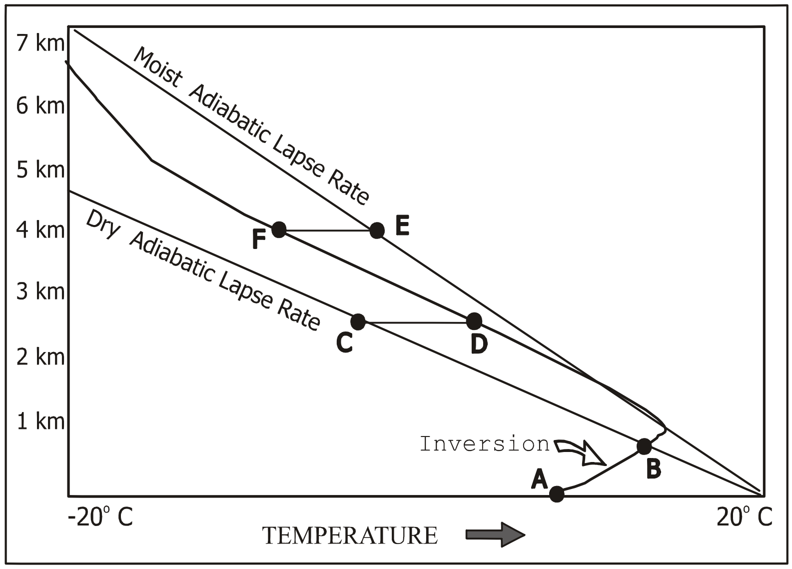


Figure 3.3- Hypothetical vertical temperature profile.

Air Temperature

Since the troposphere is heated from the ground up as noted earlier, on average, tropospheric temperatures decrease with height. This decrease is not constant or uniform, it varies both in space and time. Air temperatures above the earth's surface have been traditionally measured via weather balloons which are released from weather stations all over the globe, two times per day (at 0 and 12 Greenwich Mean Time). Attached to the bottom of a weather balloon is a light weight package of instruments (called a radiosonde) which measure the temperature, humidity, wind speed and wind direction. A plot of temperature versus height from a balloon flight shows the environmental lapse rate (solid line in Figure 3.3), which typically varies between 4° and 10° C km^{-1} (2° to 5.6° F per thousand feet). When the environmental lapse rate is less than about -9° C km^{-1} (5° F 1000^{-1} ft), the atmosphere is considered *stable*, at higher lapse rates (>-9° C km^{-1}) it is *unstable*. Stability refers to how easy it is for a lifted parcel of air to become positively buoyant. <u>A stable atmosphere restricts vertical motion</u>, so that even if a parcel is forced to flow over a mountain or up a frontal boundary, it will have a difficult time maintaining positive buoyancy. <u>When the atmosphere is unstable, positively buoyant parcels may ascend to the upper troposphere without difficulty</u>.

As a parcel ascends it cools independently of the environmental lapse rate. Likewise, when a parcel descends it warms independently of the environmental lapse rate. The rate at which the parcel cools or warms, depends on the amount of moisture contained within the parcel. When a parcel is saturated (contains a maximum amount of water vapor), it cools at a rate called the *saturated adiabatic lapse rate*, which is around 6.5° C km^{-1} (19° F mile^{-1}), but varies with moisture content. If the ascending parcel is not saturated, the rate of cooling is around 9.8° C km^{-1} (29° F mile^{-1}), which is referred to as the *dry adiabatic lapse rate*. The term *adiabatic* means that a parcel does not exchange any mass or energy with the ambient air it is moving through. This is an assumption, but it turns out that it is a pretty good approximation of how the atmosphere works.

A parcel cools when it rises because it expands, like a helium balloon set adrift (the balloon eventually bursts as it ascends because it expands beyond the elastic limit of the rubber). Parcels of air and balloons expand because air density decreases with height. Descending parcels experience an increase in temperature because they are being compressed Therefore, descending parcels warm at either the dry or saturate adiabatic lapse rate, depending on their moisture content.

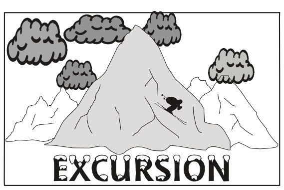
In Figure 3.3 a parcel at **C** is cooler then the ambient air (**D**), therefore it is more dense and negatively buoyant. A parcel at **E** on the other hand is warmer than ambient air (**F**), therefore it is less dense and positively buoyant. The cooling of air as a parcel moves higher works regardless whether it is a thermal or air being forced up the side of a mountain range.

At saturation, water vapor begins to condense and form water droplets. Because condensation releases heat into the parcel (latent heat of condensation), the amount of cooling is reduced. As a result the saturated adiabatic lapse rate is considerably less than the dry adiabatic lapse rate. Likewise when an initially saturated parcel of air begins to descend and warm, water droplets begin to evaporate, this process requires energy for the change of phase from liquid to vapor (latent heat of vaporization). This heat is taken out of the parcel, therefore the parcel warms at a slower rate than when it is not saturated.

Wind Chill

Modern wind chill charts are constructed from data collected in laboratory experiments. You will notice that the wind chill temperature given on a chart is a function of not only the true air temperature, but the wind speed as well. When skin is exposed to air, it not only ‘feels’ the actual air temperature, but it also experiences an additional heat loss due to convection. The wind chill temperature is a measure of both the actual air temperature and that part which is due to convective heat loss via the wind. For example, you are in an environment where the ambient air temperature is -15^o C (5^o F), and the wind speed is 15 ms^{-1} (33 mph), then the combination of wind and cold is equivalent to being in a windless environment where the air temperature is -40^o C (-40^o F). If you happen to be all bundled up, you should only ‘feel’ the actual air temperature. Since most outdoor clothing is not 100% wind proof, the temperature you ‘feel’ may lie somewhere between the actual and wind chill temperature.

Credit for wind chill temperature concept belongs to two Antarctic explorers, Siple and Passel. In the late 1940's they measured the time it took for 0.25 kg (9 oz) of water to freeze, under various wind and temperature regimes. After considerable experimenting, Siple and Passel were able to develop a equation that related the rate of heat loss from exposed human skin to wind speed and ambient temperature. This was the beginning of the wind chill chart.



The work of Bluestein and Zecher (1999) has shown some of the deficiencies of the original Sipel and Passel study. This newer work suggest a revision of the wind chill chart in such a manner that wind chill temperatures would increase by roughly 2-3^o C (3-5^o F). This increase in temperatures in the chart is a result of the fact that most ‘surface’ wind data is actually collected on a tower 10 m (33 ft) above the ground. The net result is that wind speeds at the height of a human above the ground, is considerably less than at 10 m (33 ft).

Temperature Inversions

There are times the temperature of the lower troposphere increases with height, which is of course opposed to the general trend in the troposphere for warm air to be located below cooler air. When this occurs it is called a ‘temperature inversion’ or just ‘inversion’. In the vicinity of an inversion the atmosphere is very stable (resists vertical motion) often trapping pollutants, haze particles, or small cloud droplets. Inversions can be located at any height in the troposphere, although they are frequently within 1-2 km (6,600 ft) of the surface. Often the tops of marine stratus clouds for example, occur at an inversion.

There are two ways which inversions form: the first is by the radiative cooling (longwave) of air closest to the ground; and secondly, by warmer air moving over cooler air (or cooler air moving under warmer air). Inversions that form due to radiational cooling are very common in mountainous terrain. Inversions form in small alpine valleys as well as large intermontane valleys. In a small mountain valley they may form in the evening and dissipate by mid-morning as the surface begins to warm (Figure 3.4). In intermontane valleys, like those in the central Rockies, inversions that develop early in the winter often persist for many weeks or even months. In these large valleys, inversions can be several kilometers deep and can only be destroyed when a new airmass moves into the region. Inversions that form when warm air moves over cooler air usually occur in association with frontal boundaries.

<u>Day-Night Temperature Trends</u>

Everyone is familiar with the diurnal (day and night) change in air temperature that occurs near the surface of the earth. Near the ground the diurnal temperature cycle is a result of daytime heating and nighttime cooling, with the maximum temperature occurring sometime in the afternoon, and the minimum in the early morning hours. There are many times when this scenario does not hold true; for example when a front moves through, when there is considerable cloud cover, or during extended periods of high winds to name a few.

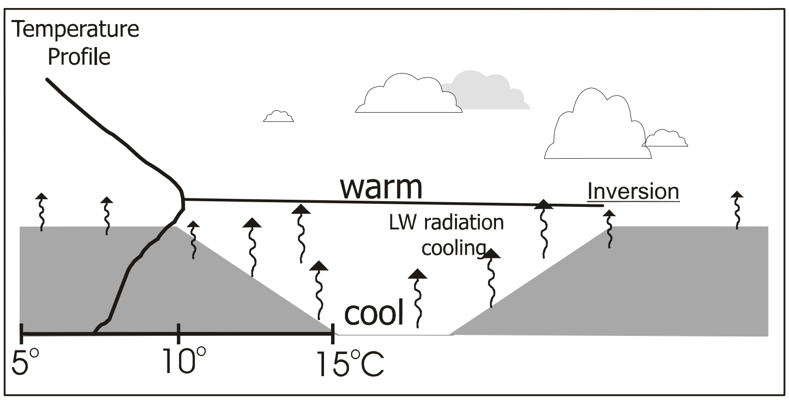
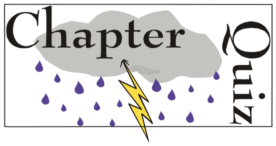


Figure 3.4- Formation of a temperature inversion in a valley.

On mountains that have a permanent snow or ice cover the temperature regime can be more complicated because of the presence of low lying inversions induced by the snow and ice. The work of Ludecke and Kuhle (1991) on the lower slopes of K2 and Everest (between 5000 and 6000 m) indicates that the diurnal temperature range is larger over bare ground (dirt and rock) than over snow or ice. However, the diurnal regime over snow and ice still exceeds the regime in the free atmosphere because at night the longwave cooling of the snow exceeds the cooling of the free atmosphere. During the day near surface, the temperature of the air may or may not exceed the free atmosphere, depending on the presence of inversions and the strength of the wind.

In summary, <u>air temperatures near the ground will tend to be more extreme than free atmospheric temperatures at the same elevation</u>. Actual temperatures are site specific and are a function of surface characteristics and the prevailing weather. Temperature extremes occur on days and nights with little cloud cover and little moisture. In addition, dry climates (deserts) experience larger diurnal and seasonal temperature regimes than wet climates. At night in wet climates, the presence of large amounts of moisture in the lower troposphere effectively blocks outgoing longwave radiation emitted by the surface. During the day clouds block a portion of the incoming shortwave radiation, and in addition a large part of the shortwave energy that reaches the surface is used for

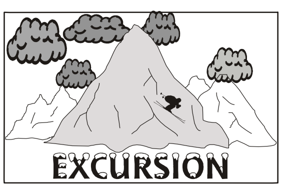


evaporation instead of heating the air.

How Warm Do You Feel?

Next time you are in the mountains on a sunny day, notice how warm it feels when you are in direct sunlight. If the sun goes behind a cloud or if you walk into the shade, you experience a rapid drop in skin temperature. Do you think the air temperature changes this rapidly as well? Here is an brief explanation of what occurs. When you are standing in direct sunlight, your body absorbs considerable amounts of shortwave radiation. Hence you warm-up a lot more than the air. While in the shade, you experience a rapid cooling simply because you are no longer absorbing direct sunlight and because your emitting large amounts of longwave radiation (yes-people emit longwave radiation!). Meanwhile, the air temperature has remained pretty much constant.

This heating/cooling pattern is very noticeable to any one who travels on a glacier on a sunny day, especially when the wind is light. The intense heat that you feel is due to the large amounts of shortwave radiation that is being reflected off of the snow and ice, and absorbed by your body (and its dark clothing). In reality the air temperature is not as warm as you think it is based on how warm you feel, in fact the air temperature is considerably cooler than you would guess it to be.



This illustrates an important point about the proper way to site an outdoor thermometer. We see lots of the thermometers mounted in the sun, there is one word for this: BOGUS. This also applies to those little mercury key-chain jobs that most of us carry. Keep it out of the sun for a accurate measurement. Real thermometers, that is those used to collect weather data, are placed in some type of ventilated shelter which allows good air flow but keeps the instrument shaded.

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1. True/False: The sky appears blue because oxygen decreases with elevation?
2. _______________ is the transfer of heat from a hot to a cold body.
3. Clouds absorb and emit ______________ radiation.
4. True/False: In the Northern Hemisphere, south facing slopes generally receive less shortwave radiation than north facing slopes?
5. For a given air temperature, the wind chill temperature ______________as the wind speed increases.