Figure 4. *A cross-country skier skiing among the ghost trees of Yellowstone National Park. The ghost trees were produced by snowfall collecting on the branches and rime frost.*

2. *What and Where is Winter?*

Humans may perceive winter differently than other organisms. As humans, we know that when the blanket of snow drapes the landscape and the fire is burning in the fireplace, winter has arrived. We perceive the cold, heating bills, inconvenience on the road, beauty, or winter sports. Our exact perceptions, though, are often based on the weatherman on television telling us that the icebox of the nation was Fraser, Colorado, or Cut Bank or West Yellowstone, Montana.

Seldom do we question where weather statistics come from. The figures come from a continent-wide network of observers who maintain instruments in official recording stations known as **Stevenson** screens. A Stevenson screen is a white box standing three feet off the ground surface. The sides of the box are covered with down-sloping slats that prevent the entry of solar radiation but allow the circulation of air. Instruments housed in these shelters are routinely calibrated to ensure accurate readings. Thus standardized, temperature and relative humidity readings provide the official records of the weather bureau that can be used to develop a picture of winter across North America.

Let us characterize winter as we humans, including weathermen, perceive it. Winter is, first, a time of beauty. It is time when the hoarfrost crystals edge the open spots along the creek, when rime frost laces the trees, when cold temperatures hold the smoke-laden temperature inversions to the ground, and a time when the **ghost trees** shelter the small birds deep within their branches (Figures 4 and 5). But to the weatherman, these beautiful scenes are described in numbers reflecting climatic conditions. The human perception of winter occurs on two levels: sensuous and emotional perceptions, and weather patterns delineated by statistics and maps.

To us, winter is **cold**; to the weatherman it is **average** and **record low temperatures**. Official North American weather bureau records provide a perspective describing winter (Table 1). Record lows tend to be located in the high country of the western United States or in the northern regions of the continent. While -63°C (-81°F) may seem low, the world record at Vostoc, Antarctica (elevation 3,490 m, or 11,450 ft), tends to edge lower each year and is currently about -90°C (-130°F).

Large geographic areas may be affected by record low temperatures at a given time. The winter of 1978-79 may have been, in fact, the coldest North American winter in recorded history—certainly the coldest during the last 89 years (Figure 6). Even more unusual, the three winters beginning in 1976-77

Figure 5. *Hoar frost forms an abstract drawing on grass blades in the early morning.*

were all in the extremely cold category. Remember, the winter of 1988-89 brought record cold temperatures across much of North America. Besides affecting a large area, the cold lasted for an extended period of time.

It is cold, however, in more areas than those where the record lows have occurred. The distribution of cold is perhaps better understood by a map indicating the mean January temperatures (Figure 7). Notice in particular the -1.1°C (30°F) **isotherm** (line indicating the boundary of all equal tempera-

Table 1. Official record low temperatures for North America. Data compiled through 1976.

State or Province	Location	Elevation ft (m)	Temperature °F	Temperature °C
Yukon			-81	-63
Alaska			-80	-62
Montana	Rogers Pass	5,470 (1,667)	-70	-57
Wyoming	Moran	6,770 (2,063)	-63	-53
North Dakota	Parshall	1,929 (588)	-60	-51
Idaho	Island Park Dam	6,285 (1,916)	-60	-51
Colorado	Taylor Park	9,206 (2,806)	-60	-51
Colorado	Bennett	5,484 (1,672)	-60	-51

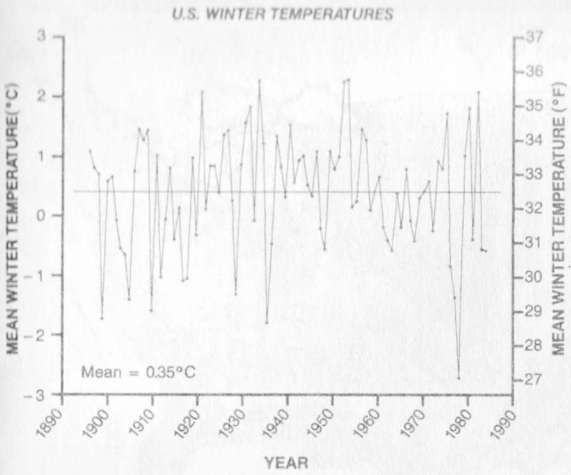


Figure 6. *Mean winter temperatures from the last 89 years for the contiguous United States (°C). The record winter of 1978-79 is apparent (Karl et al. 1984).*

tures), because we will use it for comparisons later in this section. In addition, extreme, life-threatening cold can occur in valley bottoms where it is caused by **temperature inversions**.

Winter is also **wind**. Winds affect organisms in many ways, including mechanical destruction, desiccation, and temperature depression. In Colorado, extreme gusts of wind blowing off the mountains of the Front Range often reach speeds greater than 45 m/s (meters per second, or 100 mph) with records on the high peaks of **Rocky Mountain National Park** reaching 92.5 m/s (207 mph). Winds at **Mt. Washington**, New Hampshire, have reached 103.3 m/s (231 mph). On the

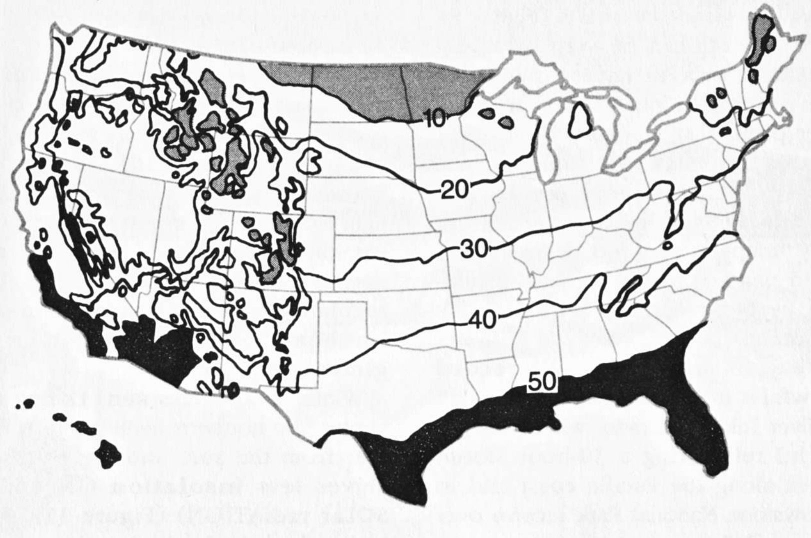


Figure 7. *Map showing mean January temperatures (°F). In January, about half of the United States experiences temperatures below freezing.*

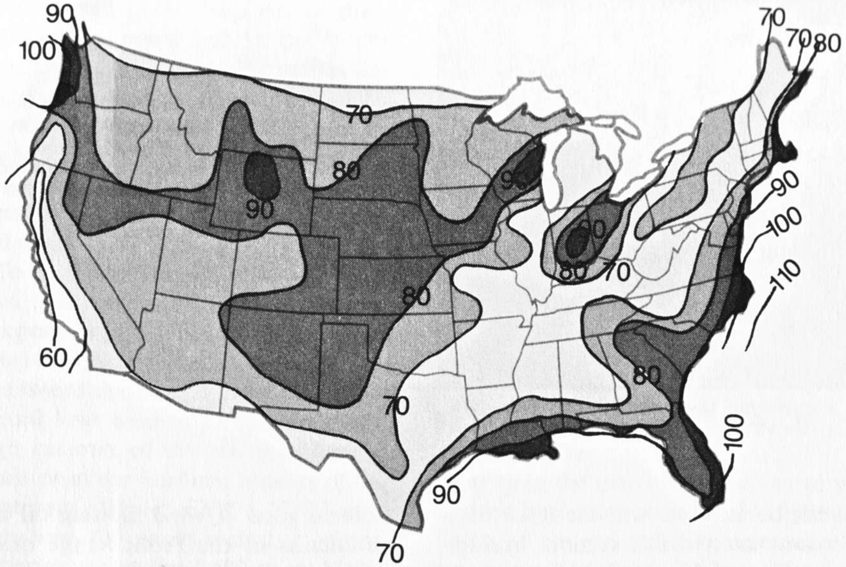


Figure 8. Distribution of maximum expected wind speeds (mph).

average, the **highest maximum winds** in the continental United States blow in the region of Wyoming, with very strong winds also occurring just off the Great Lakes and the coasts (Figure 8). Extreme gusts can be very damaging even to forests, as large expanses of trees are toppled in a "blow." Trees and other plants that are loaded with rime ice are particularly vulnerable to damage. Continuous winds cause extreme **windchills** that may drastically lower body temperatures and desiccate exposed parts of plants. Mechanical erosion by blowing snow particles may also occur.

Winter is **snow**. Dramatic **record snowfalls** include a 24-hour snowfall at Silver Lake, Colorado, where 183 cm (90 in) fell during a 30-hour storm. Places along the Pacific coast and in Yellowstone National Park receive over 600 cm (240 in) per year and even up to 800 cm (315 in) per year. Areas in Newfoundland have snowfalls nearly as high. Mean annual snowfall provides a useful index of the impact of winter. On the map (Figure 9), note the location of the 40-cm (15.7 in) line (called an **isopleth**) for snowfall.

Winter is also **shorter days**. Shorter days resulting from the tilt of the planet earth provide considerably fewer hours of sunlight (Figure 10). The further poleward, the fewer the hours of daylight available. Once past the Arctic Circle, there are periods when the sun does not shine for days at a time. The regularity of annual changes in day length provides a **timing** device for organismal responses.

Winter is also **less sun**. During the winter, the northern hemisphere is further from the sun, and the earth receives less **insolation** (INcoming SOLar radiATION) (Figure 11). The higher the latitude, the less the amount of insolation for any given time and for

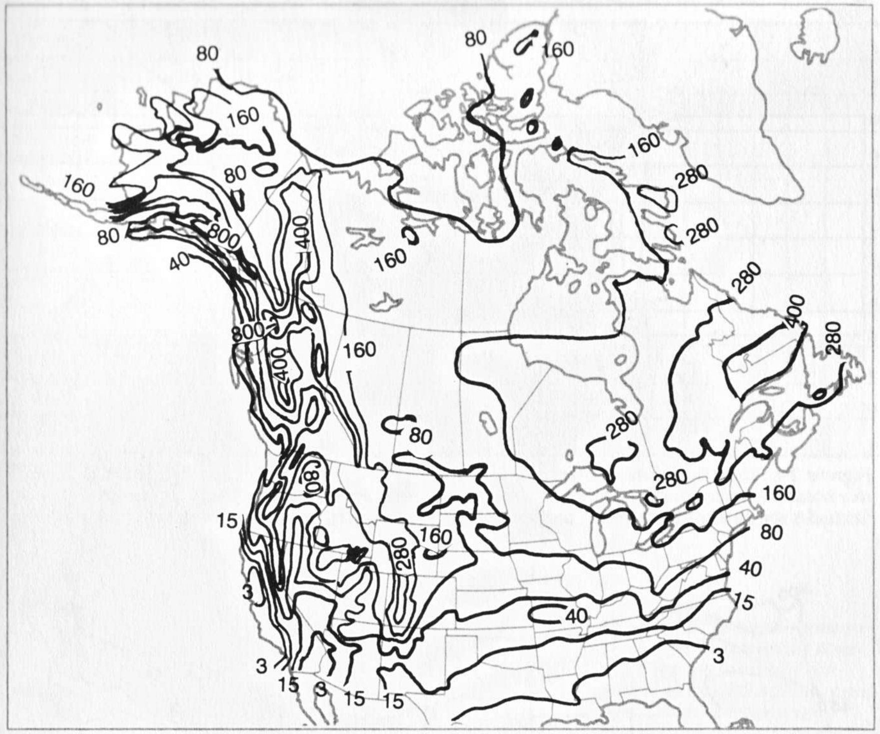
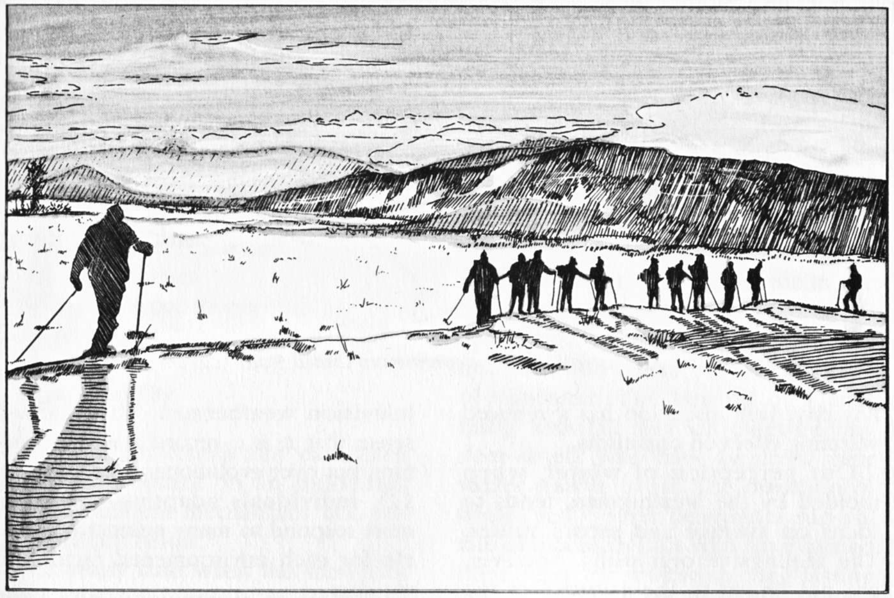


Figure 9. Map showing mean annual snowfall (cm) (after Schemenaur, 1981).



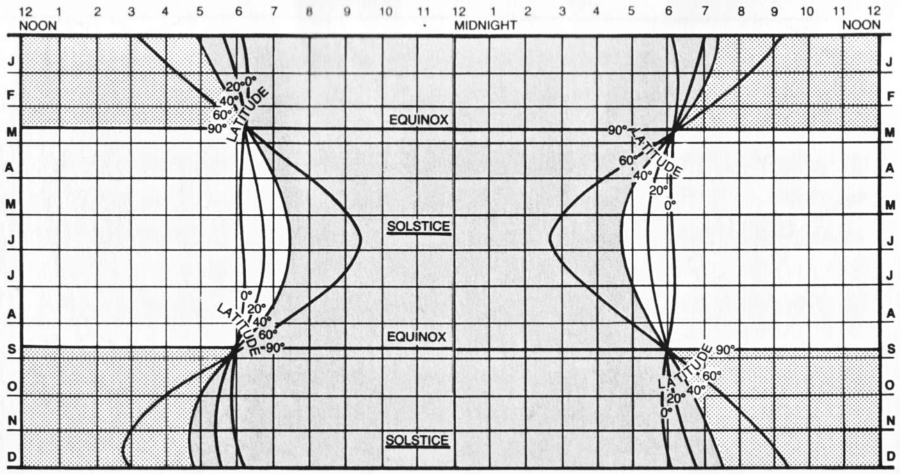


Figure 10. *The Hourglass of Darkness for the northern hemisphere. The emphasized period of darkness (heavier shading) is for 40° north latitude. From September 23 to March 21 at high latitudes the sun remains below the horizon for periods longer than 24 hours (lighter shading).*

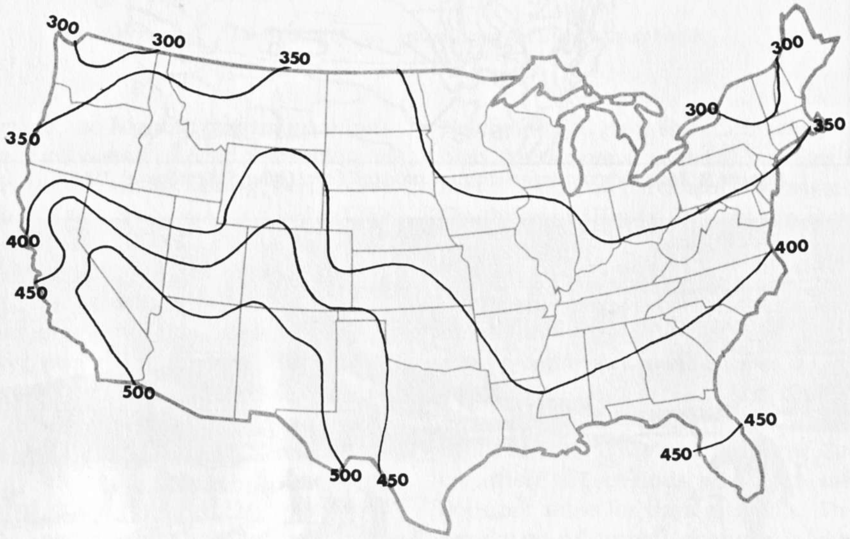


Figure 11. *Insolation for the continental United States (cal/cm²).*

any day. Less insolation has a reduced warming effect on organisms.

Our perception of winter, when molded by the weatherman, tends to focus on average and record values. The feelings of organisms, however, are not linked to the statistics of the television weatherman. They cannot sense that it is a record low temperature. but over evolutionary time (Figure 12), individuals adapting to winter must respond to many **selective criteria** for each environmental factor, including:

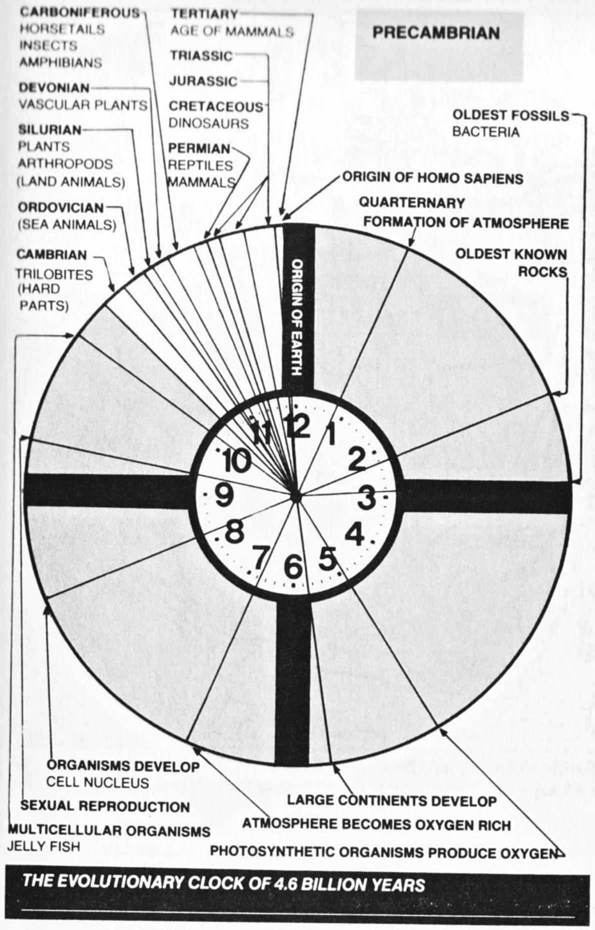


Figure 12. *The evolutionary clock, which represents time since the beginning of the planet earth, 4.6 billion years ago. On a 12-hour scale, people entered the scene at 41 seconds after 11:59.*

1. The mean value (for example, temperature) or total accumulation (for example, precipitation)
2. Extreme values
3. Timing of occurrence
4. Duration
5. Seasonality
6. Repeatability

The last four criteria may each exert selective pressure on an individual through different mechanisms that will be explained below.

The yearly date when the snowpack forms and disappears is of critical importance to organisms (Figures 13 and 14). Individuals must respond to the timing and duration of the snowpack. When cold temperatures occur in the fall before a protective mantle of snow has formed, many of the resident small mammals and plants can freeze or die of exposure. The **timing** of a late, heavy snowfall may kill overwintering deer or elk who have depleted their winter reserve of fat. The **duration** of winter snow cover determines survival rate of mountain pika who have cached their food for winter. A long-lasting snowpack depletes the food supply,

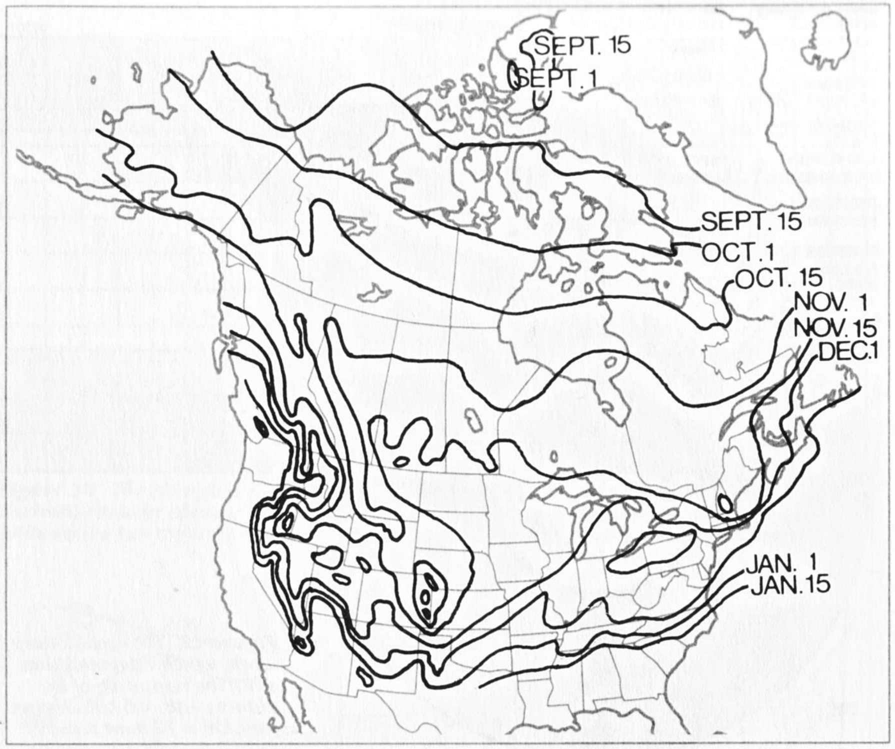


Figure 13. *Map showing the average date of continuous snowcover formation. Compare the locations of the boundary where snowpack formation occurs by December 12 to Figures 16 and 17 (after Schemenaur, 1981).*

causing overwintering animals to die and reducing the reproductive success for the following summer.

When great environmental differences occur between seasons (high **seasonality**), the selective pressure on organisms due to seasonality can be very high (Figure 15). For example, a broad range of temperatures to which an individual has to respond and the abruptness of the change between seasons may necessitate considerable energy expenditure. The opossum, a native of South America, has been extending its range northward in North America. Opossums have been very successful in environments with low **seasonality**, i.e., little change in temperature between seasons. In northern regions, however, it is not unusual to see opossums missing parts of their ears and tails to freezing because of poor adaptation to the high seasonality of temperature change in winter climates.

The frequency of occurrence, or **repeatability**, of an environmental factor interacts with the life span of a species to determine the necessity for and type of adaptation for survival. Species with short life spans may not have to adapt to rare or low frequency events. Deer mice may not develop specific adaptations for -40°C (-40°F) record low extremes, which occur only every 20 years. Allocating energy to adaptations to the extreme but rare cold event is not the best course for deer mice popu-

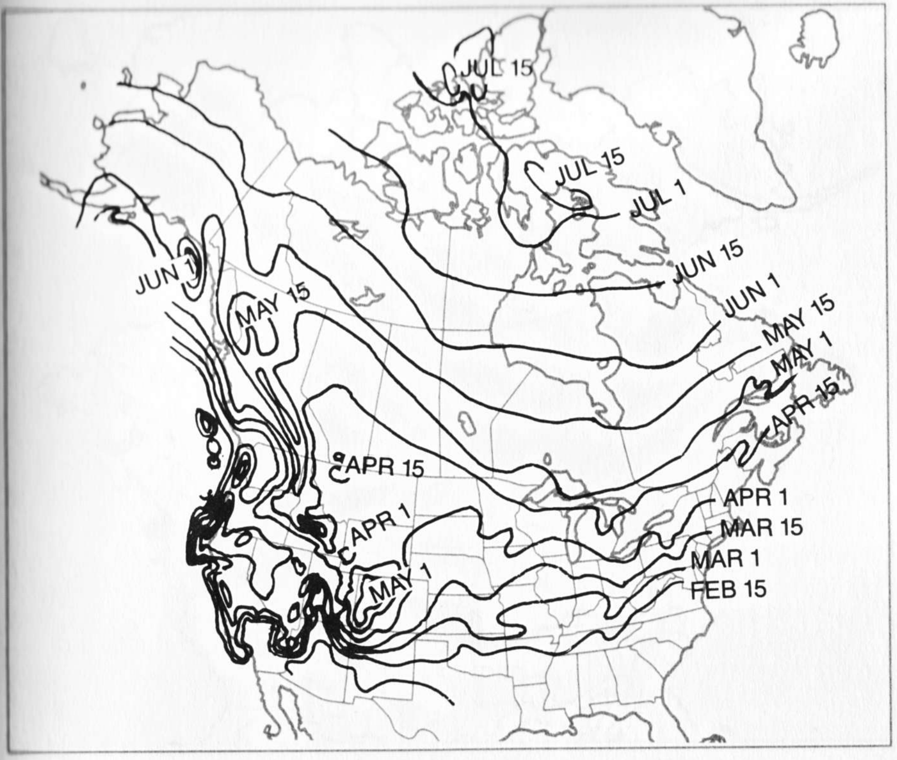


Figure 14. *Map showing the average date of snowcover disappearance. Compare the location of the boundary of the area where disappearance occurs after February 15 to Figures 16 and 17 (after Schemenaur, 1981).*

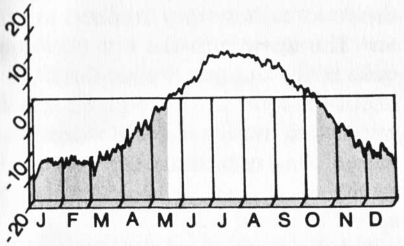


Figure 15. *The mean daily temperatures at the D-1 Weather Station (3,749 m, or 12,300 ft) on Niwot Ridge, Front Range, Colorado, show marked seasonality with large changes in temperature between seasons (adapted from Halfpenny and Clark 1988).*

lations; instead, recolonization following a severe cold snap may depend on the reproductive powers of the few surviving deer mice. Populations may, however, be nearly decimated by low-frequency events, and recovery may take years. Adaptation and energy allocations suitable to yearly extremes may differ considerably from those necessary to survive less frequent events with **return times** of 20 years. Frequent extreme events may require large energy allocations to assure the continuation of the species.

We humans may perceive winter by our interactions with snow or cold. Our perception may be further shaped by the statistics of the television weatherman, a perception that we intuitively

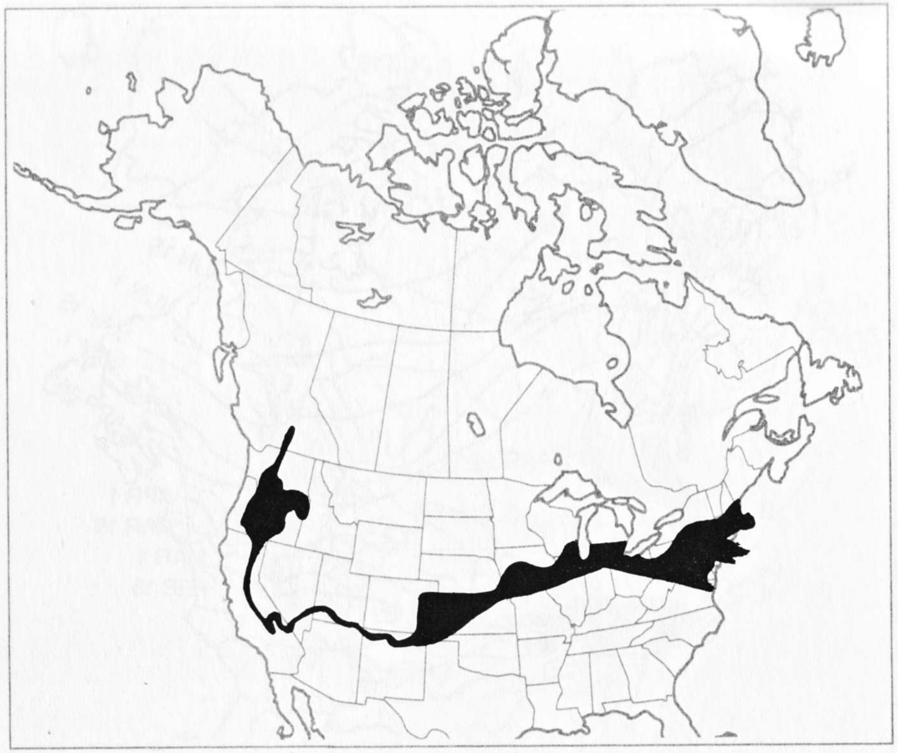


Figure 16. Winter color phases exhibited by the long-tailed weasel in North America. In the northern region, weasels turn white in the winter. South of the shaded zones weasels stay brown, while within the shaded zone weasels of both color phases may be observed during the winter. The narrowness of the band in the west is a product of a small sample size and compressed vertical zonation due to the presence of high mountains (adapted from Hall, 1951).

believe and understand. Humans can control their environment; they can mediate the effects of winter by living in a warm house, by wearing thick jackets, or by vacationing in Florida. Organisms other than humans also must interact with their environment, and they must respond to it. In order to respond, they must sense the environment in some way. For the moment, let us consider this sensing or feeling of the environment by organisms. The body of an individual feels the stimuli presented by winter and responds. Do other organisms sense winter the same way as humans? Do they "recognize" the selective winter criteria mentioned? Do patterns of distribution of plants and animals indicate to us how they respond to winter? The answer to the last two questions is yes and that is what this book is about—the interaction of plants and animals with winter. How do organisms "sense" (in the broadest meaning of the word) the winter environment and respond to it?

For the moment, consider two examples in which the patterns of species respond to the environment. There are three species of weasels in North America: the short-tailed weasel, the long-tailed weasel, and the ermine. In the northern portions of their ranges, the coats of all three turn white during the

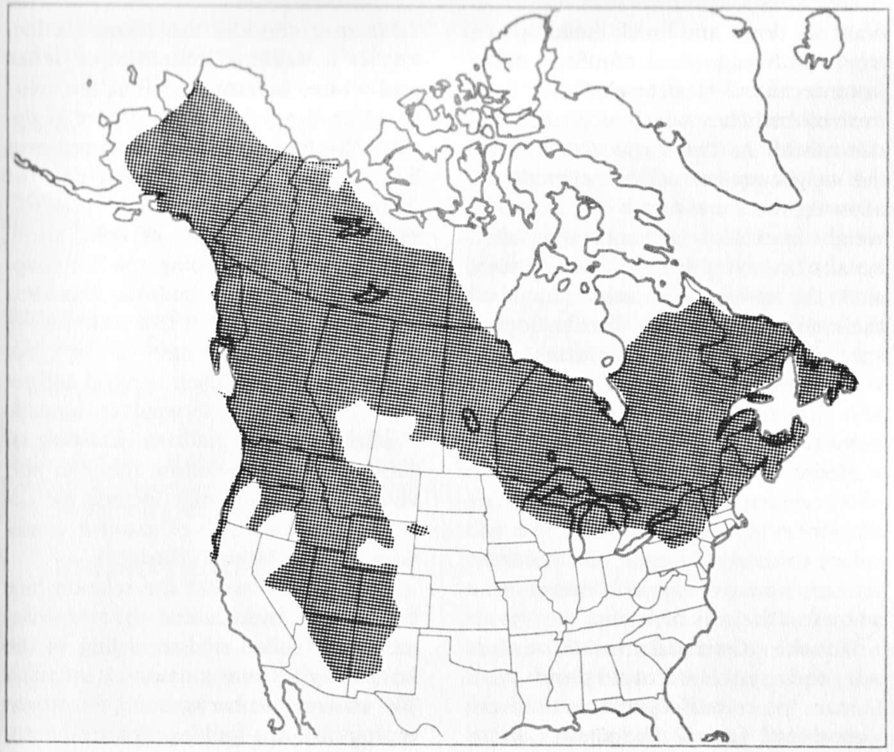


Figure 17. Map showing the distribution of spruce trees in North America.

winter. A weasel in its white color phase is commonly called an **ermine**. The distributional map of the **color phases** of the long-tailed weasel indicates a northern region where weasels turn white and a southern region where they stay brown during the winter (Figure 16). The regions are separated by a zone where weasels of both colors may be found. These traits appear to be genetically fixed; that is, a white-phase weasel taken to Texas would still turn white each winter even though the color would have little selective advantage in the south, and might in fact be disadvantageous to the individual.

Weasels have sensed winter and have responded to it. Those in northern regions expend energy to make two color changes each year. Southern weasels may also perceive winter, but the selective pressures are low enough that they do not respond with a color change. The distribution map shows us the region where selective pressures are great enough to cause selective changes that we can observe in the animals. On the map, we see an ecological zonation of animals expressed by the response of animals to winter.

Plants as well as animals have adapted to conditions of winter. Consider the distribution of spruce trees in North America (Figure 17). The evergreen life form of the spruce is ready to photosynthesize at the first available moment each spring. The large surface area of all the needles, however, provides a collection area for winter snows that could potentially weigh the branches down and break them. Spruce trees, and in general conifers, differ from deciduous trees in that they have evolved branches which slope out and downward. As the snow accumulates, the weight presses the branches down, allowing the snow to fall off. Excessive weight from snow accumulations often breaks branches off deciduous trees, since the upright branches cannot shed their snow load. The distribution of spruce trees is an indication that individuals were able to adapt to winter and survive under the selective pressures of winter.

Many other examples could be given of species whose distribution shows adaptation to winter, but these two will suffice to show that organisms do sense winter, and over evolutionary time adapt to the rigors of winter.

Do the distributions of winter-adapted species correspond with human "perceived" distributions of environmental factors? The answer seems to be yes. Consider now some factors we have illustrated in the figures:

1. Mean January temperature of -1.1°C (30°F)
2. Maximum expected wind speeds of 37 m/s (80 mph)
3. Mean annual snowfall of 40 cm (16 in)
4. Mean annual insolation of about 375 cal/cm^2
5. Continuous snow cover by December 12
6. Snow cover disappears after February 15

Compare these weather patterns to the distributions shown for the weasel and the spruce. Indeed, organisms sense environmental factors that, over evolutionary time, define ranges that researchers can correlate with winter weather patterns.

We may consider the above six factors as a working definition of **what and where is winter**, that is, the areas in which the influence of winter is significant enough to be a dominant evolutionary force. These weather patterns define the area where individuals will respond to the factors of cold, wind, and snow by developing specific adaptations. Individuals outside this area may also sense winter (for example, in the change in the length of day), but the factors do not affect survival and reproduction enough to result in dramatic evolutionary adaptations. Existing or subtle adaptations allow them to survive winter, which may include the occasional major influx of extreme conditions such as snow in Florida.

Before we consider the relationships between individuals and their environment, a detailed understanding of the nonbiological environment is needed. We will set the background for winter ecology by first looking at the sun, energy, weather, and snow.

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THE SUN AND WINTER

The sun provides the source of the energy supporting life on earth, but its influence is not constant. A variety of phenomena cause variations in the amount of solar energy received at any point on our planet. These phenomena include the elliptical orbit of earth around the sun, the tilt and wobble of earth on its axis, the interference of the atmosphere, and the length of day. The tilt of the earth results in the largest variation and causes the winter **season** (Figure 18).

The earth tilts on its axis at an angle of 23°27' (Figure 19). Different portions of the earth are nearer to the sun during its yearly orbit, because of the tilt. This results in different seasons in the northern and southern hemispheres. During the summer in the northern hemisphere, the north pole is closer to the sun, and during the winter the tilt is away from the sun. Winter occurs at opposite times of the year in the southern hemisphere, which is farthest from the sun in June.

In winter, rays of sunlight strike the earth at a lower angle, resulting in a glancing blow which imparts less energy to earth. A given amount of the direct beam of sunlight is spread out over a larger area, therefore providing less energy per unit area. A small reduction in **insolation** also results from the longer path that the beam must take through the atmosphere.

The effect of tilt on the distribution of radiation may be experienced by placing your hand near a fire or furnace. First, hold your hand so the palm is evenly exposed to the heat. Next tilt the top of your hand away from the flame. The effect of the tilt should be obvious as the lower portion of your

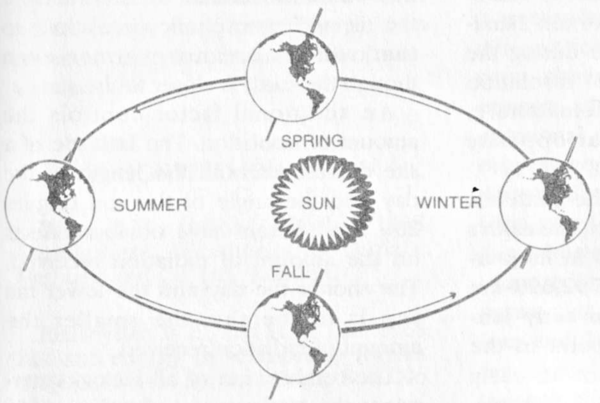

Figure 18. *The earth in its orbit around the sun. The tilt of the earth causes the seasons. During winter in the northern hemisphere, the north pole tilts away from the sun. Earth is closer to the sun in the winter.*

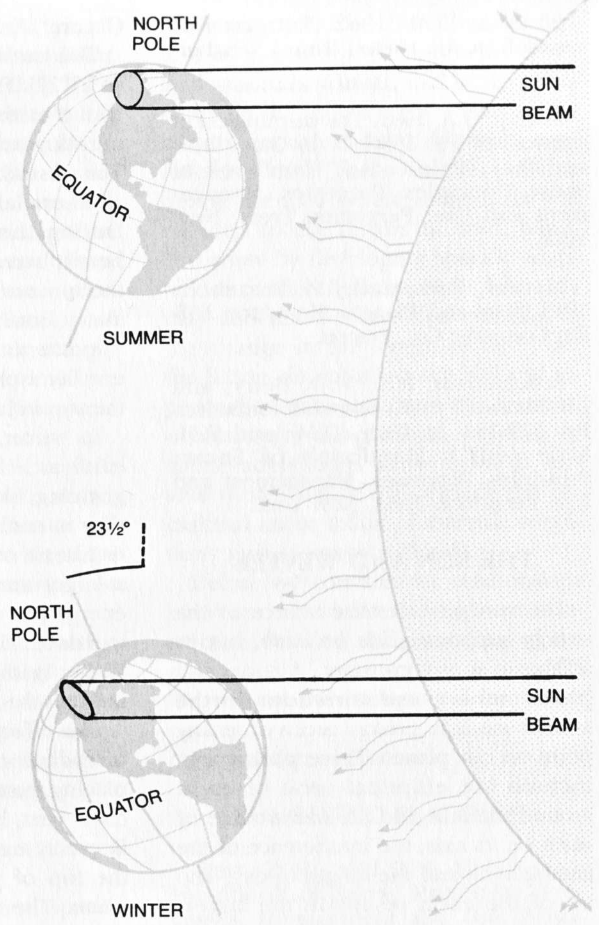

Figure 19. *Close-up of earth in summer and winter. During the winter, insolation arrives at a low angle. Since radiation is spread out because of the tilt of earth, a sunbeam must cover a larger area in winter, and the amount of radiation is less per given unit of area. The resulting differences in the seasonal amount of insolation are dramatic and increase towards the pole.*

hand is now warmer and the upper portion is cooler. This effect is analogous to the tilt of the northern hemisphere away from the sun during the winter. Similar patterns of insolation occur in the southern hemisphere; however winter occurs at opposite times of the year.

The **elliptical orbit** of the earth has little effect on winter. In fact, the earth's closest point (**perihelion**) in its journey around the sun, 56,792,699 km (91,398,990 mi), occurs in early January, while the farthest point in the journey (**aphelion**) occurs in early July, 58,725,661 km (94,509,790 mi). The effect of the closer distance during the winter is masked by the effect of the tilt and atmospheric circulation, so that winters are not warmer even though the earth is closer to the sun.

An additional factor controls the amount of insolation. The **latitude** of a site determines both the length of the day and the angle of the sun (Figure 20). Both factors have obvious effects on the amount of radiation received. The shorter the day and the lower the sun is in the sky, the smaller the amount of radiation received.

The combination of all factors determines the total amount of radiation re-

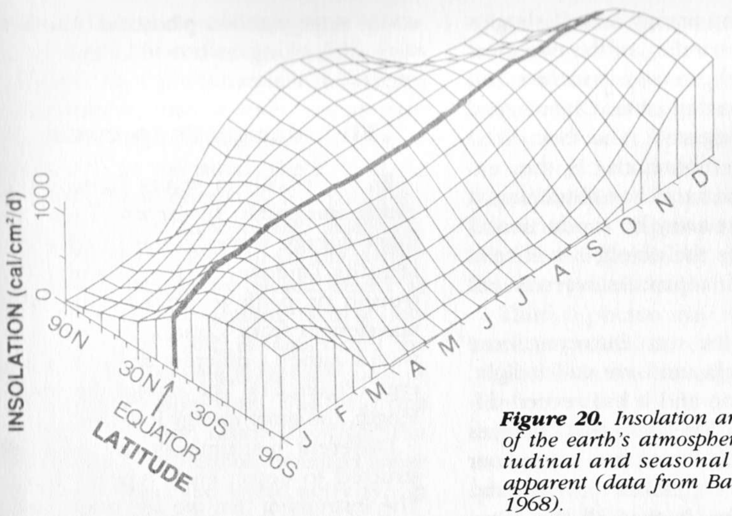

Figure 20. *Insolation arriving at the top of the earth's atmosphere (cm²/d). Latitudinal and seasonal variations are apparent (data from Barry and Chorley, 1968).*

ceived during the winter. The net effect is that winter is a time of reduced insolation and this reduction greatly influences the environment and organisms. The land and its blanketing air mass cools, surface waters turn to ice, and precipitation freezes, covering the land with snow. The amount of energy available to organisms is lowered or may become negative because of reduced energy inputs. The organism may spend more energy than it receives. To do this it must borrow from fat stores accumulated during the summer. Organisms also must conserve what stored energy they have. Energy then becomes the crux of winter and of winter survival.

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ENERGY

Energy is the universal force that flows through the universe in many different ways. Energy is the ability to do work. It is the force that can make things happen. Often we know energy more by its properties than its definition. Energy is the agent of change, yet it is itself changing. Energy tends to move from where there is a lot of energy to where there is less of it. Energy can either be on the move or stored. When energy is in motion, we call it **kinetic energy**. When it is stored, we call it **potential energy**. There are many different forms of energy—**radiant energy**, **thermal energy**, **gravitational energy**, **chemical energy** (including nutritional energy), and **electrical energy**. Energy can neither be created nor destroyed, although it can be changed from one form to another form. How these forms of energy are transported, changed, stored, and utilized is of paramount importance to living organisms and their existence during the winter. Therefore, we need to develop a more detailed understanding of energy.

Understanding energy actually begins with the understanding of the two great opposites in the world: **motion** and stillness or a resting state. Objects tend towards a resting state, and they do so by giving away motion, that is, their energy. If the object touches something, it will give energy away by conduction. If nothing touches the object, it will send the energy off, a process we will call radiation.

We look at the sun. Our eyes sense something bright, and we call it light. Light is radiation and it has several different qualities. We know that our eyes can sense it. We know that having our skin exposed to it makes us warm and may even burn. Is that all the same stuff, that which our eyes sense, that which makes us feel warm, and that which burns our skin? Where does it come from?

Consider two examples, the sun (a ball of hot gas) and an electric light bulb. Similarities exist between the sun and the bulb. If you could look inside the sun or at the wire in the electric light bulb, you would see many rapidly moving molecules which appear as a bright glow. The glow represents molecular movement; things that are moving expel energy. We call this glow "hot." If you touch something hot, those hot molecules will make the molecules of your skin move very fast and your skin will then feel hot. If molecules are dangerously hot, they will move your skin so fast that it is injured—burned. But neither the sun nor the wire inside the light bulb are touching anything. They do not have an object to transfer their motion to by conduction, that is, by touching. So they get rid of their motion by sending it away. They send that motion away by express mail if you will, which we call **radiation**. One physical view is that they send that motion out in little packets of energy called **photons**. Another way of looking at it is that energy is sent off in **waves**.

Electromagnetic Spectrum

Energy travels in waves forming the **electromagnetic spectrum**. These radiant energy waves come in different lengths (measured from trough to trough or peak to peak), and each wavelength from gamma rays to radio waves carries a different amount of energy (Figure 21). The shorter the wavelength, the more energy it carries.

Different instruments can be constructed to detect each type of wave. The instrument that we are most familiar with is the human eye. The eye is capable of detecting wavelengths in the range we call visible light (0.4 to 0.7 μ). These are the waves that form the colors of the rainbow. We also feel infrared rays (0.7 to 4 μ) as heat on our skin, and ultraviolet rays (0.32 to 0.42 μ) tan our skin or cause sunburn and snowblindness (0.29 to 0.32 μ). Special antennas detect microwaves, television, and radio waves.

Different portions of the electromagnetic wave spectrum are known by different names. The portion up to 4 μ is generated mostly by the sun; these waves are known as **solar radiation** or the short wavelengths. The long wavelengths, starting at 4 μ, are referred to as **terrestrial radiation**. Solar radiation also is known as **shortwave radiation** and terrestrial radiation as **longwave radiation**. The earth radiates energy as does the sun. The earth and the sun exchange radiation. To see how this occurs it is easiest to consider radiation as photons.

Measuring Energy

Consider **photons**, those little packets of energy "seeking" something to move. The photons originate as radiation from hot molecules at the sun's surface. As a photon enters the earth's atmosphere, one of three things may happen. A photon may strike a molecule in the atmosphere. If so, it can transfer its energy by increasing the motion of the atmospheric molecule. The increased motion in the atmospheric molecule we would detect as an increase in temperature. This is how the heat of the sun is transported the tremendous distance to become heat of our own atmosphere. The photons from the sun interact with the molecules of our atmosphere and cause them to increase their activity, in essence causing the molecules to wiggle more, which we detect as increased temperature.

A second possibility is that when a photon strikes a molecule in the atmosphere, they are incompatible. For some reason the energy of the photon cannot be transferred to the molecule. The photon is bounced or reflected away and proceeds through the universe looking for something else to move. About 30 percent of the sun's radiation is reflected by the earth, its atmosphere, and clouds back into space.

Third, a photon may reach the earth's surface without colliding with a molecule in the atmosphere. The photon may also reach the surface after having been reflected by atmospheric molecules. At the earth's surface, the photon may be absorbed or it may be reflected. If it is absorbed, it will increase the movement or wiggling of the surface molecule that it hits, which we would note as an increase in its thermal

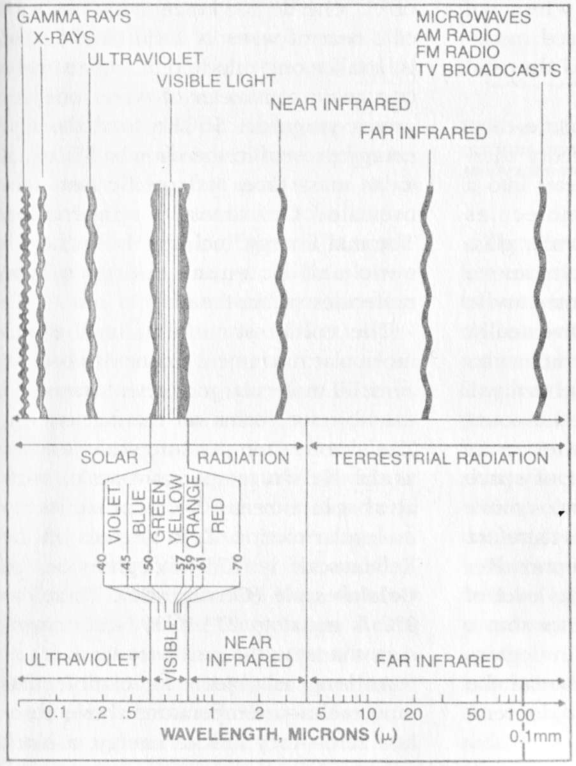

Figure 21. *The electromagnetic wave spectrum. Wavelengths are measured in microns (μ), which equal one millionth of a meter or 0.000001 m (0.00003937 in).*

energy. The photon would release its energy into the molecule of what it hits, whether it is an atmospheric molecule or a molecule in a rock, a plant, or an animal. This is what happens to us when we sit in the sun. The radiation striking our skin is changed into thermal energy.

Humans are good sensors of thermal energy. We have very sensitive sensors in our skin that detect heat, the increased vibrational movement of our molecules. If we touch something, we can tell how rapidly its molecules are moving. The more movement in the surface, the hotter it feels to us; the less movement, the cooler it feels. When we talk about movement here, we are speaking of the movement of individual molecules, not movement that we can see with our eyes. We sense that movement by noticing what the effect is on our temperature sensors when we touch an object. This increased movement and increased warmth is **thermal energy.**

Another way that we measure thermal energy is to use a mercury thermometer. Stick the thermometer into a snowbank. As the snow molecules come in contact with the warmer glass of the thermometer, the thermometer transfers its energy from the mercury to the glass and into the snow. Eventually, the snow and the mercury molecules will have the same motion and that will be reflected by the decreased amount of space that mercury requires in its tube. The decreased amount of space results because colder molecules move slower, exerting less pressure therefore requiring less space. The thermometer is marked on the side and the level of the mercury in the thermometer shows the temperature of the snow in degrees centigrade or Fahrenheit. We read the lowered mercury level as a colder temperature.

Temperature relates directly to thermal energy. Even a snowball has thermal energy. If a snowball has a temperature of -6°C. we can ask how much thermal energy is in the snowball. To answer this question completely, we need to know how big the snowball is. In effect, we are asking how many molecules are there in the snowball. We also need to know when a molecule of snow has a certain temperature, how much energy it contains. A molecule of snow vibrating at a certain rate has a different amount of energy than a molecule of mercury vibrating at the same rate or frequency. This property is called the **specific heat** of a substance and represents the heat-holding capacity of the substance. The specific heat of the substance is usually represented by the amount of energy needed to raise the temperature of the object one degree centigrade. The specific heat of water is 1 cal/cm^3/°C; that is, it takes one calorie of energy to raise one cubic centimeter of water one degree centigrade. So the total thermal energy present in the snowball is equal to its mass times its specific heat (abbreviated **Cp**) times its temperature. Thermal energy includes both the kinetic and potential energy of the molecules within the object.

The colder something is, the less molecular movement exists. At absolute zero, all molecular movement stops and the object contains no thermal energy. The absolute temperature scale, known as the **Kelvin** temperature scale, starts at absolute zero: 0°K represents no molecular motion. Zero degrees on the Kelvin scale is -273.16 degrees on the **Celsius** scale (**Centigrade**). Therefore 0°C is equal to 273.16°K (see conversion charts on the inside front cover).

As long as objects have molecular movement—a temperature above absolute zero—they radiate energy; a black

hole may be an exception to this rule. The book you are holding is now radiating energy at you, and you in turn, are radiating energy back to this book. The higher the absolute temperature (°K), the shorter the wavelengths radiated and the more energy per wavelength.

The Sun's Energy: Shortwave Radiation

Sunlight is made up of many wavelengths. For example, the things that we sense as different colors, the reds through the deep blues to the violets, are due to our perception of different wavelengths within the visible light. How do different wavelengths arise and what is their significance in terms of understanding winter?

The surface of the sun has a temperature of approximately 6,000°K (5,727°C or 10,341°F). That does not mean that every molecule in the sun and on its surface is moving with an energy equivalent to 6,000°K. As in any group of people you observe, there are some who move very fast and some who move slowly. If you watch over time, those that are moving fast will at some point most likely move a little slower and some of those who are moving slowly may start to move faster, especially as they are bumped by one of those who is moving very fast. This is also true of the sun's molecules. Some molecules are moving extremely fast, most are moving at a more moderate speed and a few are moving very slowly. A plot of the percentage of molecules that are moving fast, moderately, and slowly is a bell-shaped curve (Figure 22). As the temperature heats up, that plot will shift to the warmer end so that the peak shifts to a faster speed. As it cools off, the peak moves down to a slower speed.

Since the motion of the molecules on the sun's surface or on the surface of any object is not uniform, the wavelengths or the photon energies that are sent off are not uniform. Therefore, the radiant energy of the sun also assumes a distribution like a bell-shaped curve. A molecule which is moving very fast will send off a short wave that has lots of energy, that is, it is a very short distance from trough to trough or peak to peak (Figure 21). Or it will send off a photon that has potential for lots of motion in it. In other words, a molecule that is moving very slowly will send off a much more gentle, longer wave or a photon that is not as highly energized.

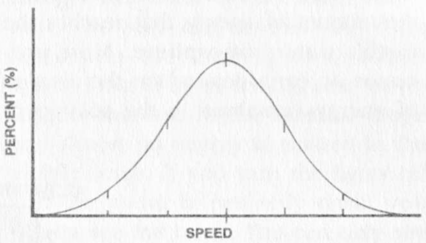

Figure 22. *The distribution of the sun's radiant energy shown as the percentage of molecules moving at different speeds.*

The distribution of wavelengths that leave a surface will be exactly that distribution of the motion of the molecules. The higher the absolute temperature (°K), the shorter the wavelengths radiated and the more energy per wavelength. Hotter surfaces will have more of the wavelengths in the shortwave region and cooler surfaces will have more of the wavelengths in the longwave region.

The energy emitted by a surface can then be calculated by knowing the temperature of its surface. For theoretical work, we consider objects as true **black bodies**, that is they absorb all the energy falling on them and in turn radiate out energy in direct proportion to the fourth power of their absolute temperature (°K). Slight changes in temperature, therefore, can make dramatic differences in radiative energy (see *Energy and Mass Balance*).

The amount of energy given off by the sun (E) is calculated according to the **Stefan-Boltzmann law**: E = $\sigma T4$, where σ is the Stefan-Boltzmann constant (5.7×10^{-8} W/m²/K4) and W stands for watts of energy. The sun, with a temperature of 6,000°K, gives off 8.4×10^7 W/m² at its surface. By the time it travels 148,800,300 km (93,000,000 mi) to earth's atmosphere it has spread out, reducing the energy to 1,360 W/m². This is the **solar constant** which remains relatively stable over time and is the amount of energy that reaches the earth's outer atmosphere. Most processes on earth depend on the amount of energy contained in the solar constant. So we will look in greater detail at this 1,360 w/m² of energy and at it components.

$=\sigma T^4$

Radiation from the sun (6,000°K) is emitted over a broad range of wavelengths with a peak intensity at a short wavelength of 0.5 μ (Figure 23). Photons traveling at a wavelength of about 0.5 μ have their energy stored at the frequency of green light. But to our eyes, the sun appears yellow because it emits wavelengths almost as strongly in the broader range we see as yellow. The planet earth, on the other hand, has a surface temperature of about 283°K and radiates at a peak energy of about 10 μ, a frequency too long for our eyes to sense as a color. We see the earth's surface as the colors of reflected sunlight, not in its own radiation (except for molten lava).

A few of the sun's molecules have a much higher energy or a shorter wavelength, between 0.29 and 0.32 μ. These are the ultraviolet wavelengths that can burn our skin. Those between 0.32 and 0.7 μ may stimulate tanning but they do not cause as much injury as those wavelengths between 0.29 and 0.32 μ. On the other end of the spectrum, we get into the region we call infrared, consisting of wavelengths that are longer and have lower energy content. Other names for these longer wavelengths are **thermal wavelengths**, or **thermal radiation**. These wavelengths are felt by our skin as heat.

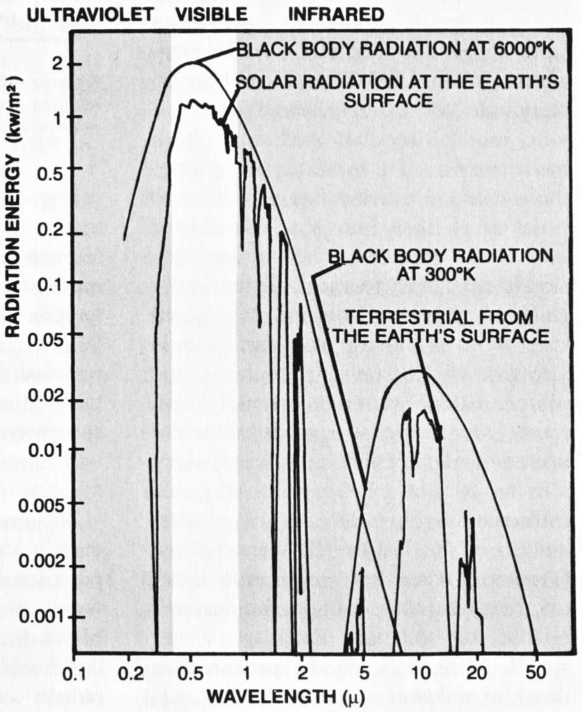

Figure 23. *Radiation spectra for black bodies with the temperature of the sun (6,000°K) and a temperature near that of planet earth (300°K). The actual radiation spectra given off by earth differs from the theoretical value because of interference from water vapor and atmospheric gases.*

The various wavelengths or photons have different effects because of the way they interact when they collide with objects. The green wavelengths are small enough to enter a molecule inside the human eye and stimulate its chemical bonds in such a way as to cause a reaction which we interpret as green. An infrared wavelength or photon is too large to get into the tiny little space and interact inside the vision molecule. Instead, it shakes the entire molecule in a gross sort of way. The photon increases the vibration in the molecule it strikes. That vibration is felt as heat or thermal energy, rather than affecting the chemical nature of the eye.

The very short wavelengths are of such small size, and such intense energy, that they can actually break chemical bonds in molecules, causing injury to the organism. For example, certain chemical bonds maintain the elastin molecules in our skin. Damage to these bonds produces the skin injury called wrinkling. Some photons will collide with DNA, the genetic material of our cells, causing little nicks in the DNA. If those nicks are not repaired by the body, skin cancer may result. In our eyes, radiation can injure the muscle of the iris, burn the conjunctiva, or penetrate and injure the retina. The combination of these injuries is called **snow-blindness** since it usually occurs in the brightness of reflected sunlight from a snowy world.

The Earth's Energy: Thermal or Longwave Radiation

The sun is not the only object that emits radiation; any object that has molecular movement, a temperature above absolute zero, emits energy. This book, as mentioned before, is radiating. And again, just like the sun, the book emits photons in proportion to the energy of the molecule that is emitting the energy. This book is very much cooler than the sun and almost all of its molecules are moving at a slower speed. Most of its molecules emit wavelengths that are in the thermal range and almost no energy is emitted in the visible range. If you turn the lights off and the room is perfectly dark, you cannot see the book. You can only see the book because of reflected energy from a light source such as the sun or a light bulb.

Of course, the electrified wire inside a light bulb is at a much higher temperature, and it does emit wavelengths or photons with visible wavelengths so that we can see the light bulb even at night when the sun is not shining. Most objects on the earth's surface have temperatures somewhere between about minus 80°C to 100°C and most objects on the earth's surface emit radiation in the longwave or thermal band. Conversely most objects on the earth's surface emit very little radiation in the visible wavelengths and certainly very, very little in the ultraviolet range. We see objects not because of their own energy emissions, but because they reflect energy from an external source.

In nature, the external source is the

sun; the lack of the sun makes it dark at night since the earth does not emit in the visible color range. However, the earth's objects are emitting thermal radiation of substantial amounts, and we certainly can sense that with our skin. The important point is that all objects are emitting radiation; they are changing the thermal energy of their molecules into radiant energy at their surface and sending it elsewhere. Unless objects receive an equal or greater amount of energy from other sources in return, they will naturally cool off. At night, when we lose the input of the sunlight, we cool off at a much greater rate because we are radiating energy out under the night sky and not getting much radiation in return. If you are sitting in a warm room in front of a window on a cold winter night, you can feel your thermal energy take off for the stars.

From Solar Energy to the Winter Skier

Energy from the sun can pass into plants where it is transformed into a form of chemical energy that can be used by other organisms. The remarkable journey begins as the photon from the sun makes it through the atmosphere, through the surface of a green plant, and into a chloroplast and where it collides with a molecule of chlorophyll, the green pigment in the plant. A chlorophyll molecule is a very large molecule which acts as a workbench. It has a special **shape** which allows it to hold much smaller molecules of **carbon dioxide** and simple **sugars** in such a way that the photon can impart some of its energy to the rotation of an electron between the carbon of the carbon dioxide molecule and a carbon of the longer sugar molecule. Energy trapped in such a fashion we call **chemical energy**. The energy stored between carbon atoms has the potential to make something happen—to do work or to make heat. Chemical energy can be released and can be felt as thermal energy. We get warm when we digest our food or when we burn wood. Chemical energy in the body is used to contract a muscle or to run **ion pumps** in our cells. It is the energy that makes our heart beat, and our brain function.

Chemical energy is stored whenever molecules are held close together. The amount of energy stored between two, three, or more atoms cooperating in this storage depends on the type of **bond** and the type of molecule involved. Physical chemists quantify the amount of chemical energy by measuring the amount of thermal energy that is released when a certain type of bond is broken. If we want to know the amount of chemical energy stored in a Snickers bar, for example, we need to know how much it weighs, how much of it is protein, fat, or sugar, and how many calories are in each food type. On a rather crude level, protein has about 3.1 **kilocalories** (kilocalories [kcal] are a measure of thermal energy) of energy in each gram, and fat has about 9.0 kcal per gram. Carbohydrates, including starches and sugars, have around 3.8 kcal per gram. Thus the chemical energy in the Snickers bar equals the weight of the bar times the food type (type of molecule) times the kilocalories (type of bond). This energy, which started out from the sun, can finally be converted into a snack for a human. The photon has completed its journey from the sun into a chemical form used by a winter skier.

Energy Transfers

We traced the transfer of energy from the sun to a winter skier. Now let's con-

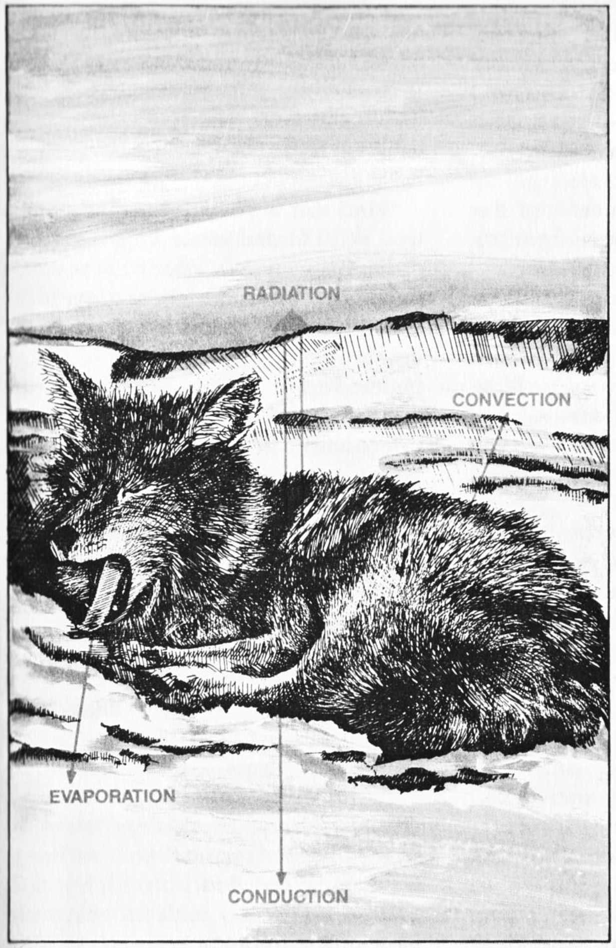

Figure 24. *Energy is transferred away from the coyote by four mechanisms: radiation, conduction, convection, and evaporation.*

sider energy transfers in general. Energy transfers occur by four different modes: radiation, conduction, convection, and evaporation (Figure 24). **Radiation** is the movement of energy through a medium without influencing the medium. For example, sunlight travels as radiation through the window without heating the glass. If you hold your hand near the window it will feel warmer due to radiative heating by the sun.

Conduction is the transfer of energy by molecule-to-molecule contact. When you touch the glass, it feels cool. The sensation of cold is due to the transfer of energy from your hand to the window glass. Molecules in the window glass are closely packed, and many molecules are available to accept energy. The contact of your hand thus quickly conducts energy to the glass.

Convection is the transfer of energy by movement of the medium surrounding an object. Blow across the back of your hand. The cool feeling is due to the movement of air away from your hand; the warm air molecules near the surface of your hand are convected away by the slight wind. The energy lost is that of **sensible heat**, that energy stored in the molecules of the air. Movement of large air masses (cold weather fronts for example) is a special type of convection known as **advection**.

Evaporation is the transfer of energy by the change in phase from liquid water to vapor in the air. Evaporation removes energy because additional energy is needed to complete the phase change. Wet the back of your hand with your tongue and blow on it. Blow on your other hand for comparison. The colder feeling on the wet hand is due to the additional energy loss by evaporation. Considerable energy is required to change the water in the skin to vapor in the air. This property of water is known as the **latent heat of vaporization**. Additional energy loss occurs as the sensible heat in the water molecules is wafted away. Evaporation losses are often hidden. As you breathe out on cold, dry winter days, the air circulating over the surface in your lungs causes considerable evaporative loss from your body. Both energy and water are lost during this process. Coping with water loss can often be critical to survival during the winter.

Since energy moves by warmer or active molecules transferring their motion to the slower moving cold molecules, the direction of energy transfer is always from hot to cold.

Insulation is the property of a material which slows or impedes the transfer of heat energy by conduction. **Dead air space** is the most effective way to stop conduction. To be considered a dead air space, the space must be small enough that effective convection currents are not set up within the space. In a down coat, the air trapped in the dead air space between the feathers is a good insulator. Many other materials are effective thermal insulators during the winter because they trap dead air. These include feathers, fur, dacron, PolarGuard, wooden walls, and fiberglass. Also, snow is an effective insulator because it traps large amounts of air in small spaces.

Wind that is powerful enough to get into material and cause convection reduces the material's effectiveness as an insulator. Windproof outer layers of clothing are very important in maintaining the insulating value of clothing during the winter.

Space blankets (a very thin mylar or plastic sheet coated with a highly reflective silver-colored material) are often mistakenly thought to increase insulation. Space blankets themselves have no trapped air and add very little insulation! This is particularly important if the space blanket is used between a person and the ground. Conduction loss to the ground will still be effectively as high with the blanket as without. Since space blankets are windproof, they can prevent convective and evaporative loss, thereby maintaining the effectiveness of existing insulators. Space blankets may reflect some longwave radiation, but only highly polished (brand new) surfaces effectively stop much longwave radiation. The blanket may reduce radiant loss by the same mechanism as other layers. Space blankets are effective reflectors of shortwave radiation from the sun and can serve as solar collectors or signal mirrors.

Under different situations during the winter, any one of these four processes, (conduction, convection, radiation, or evaporation) may dominate the **energy balance** of an organism. When sleeping, conductive loss to the snow may be most important, but during the day evaporative loss might dominate. Convective loss to the wind can easily exceed evaporative loss but might be off-

set by solar radiation. It is the net balance of these four energy transfers that is important to each organism. In fact, the proper energy balance for the earth as a whole is essential for the existence of life on earth.

Energy Balance for Earth

Life on earth has evolved to live in a relatively narrow temperature range and were that temperature range to vary much, life would cease to exist. This narrow range of temperatures is maintained by the **energy balance** between the amount of energy earth receives from the sun and the amount of energy that earth radiates back to space. Each day earth receives and radiates energy, but over the course of the year, incoming and outgoing radiation are nearly equal. The yearly net **energy budget** of the earth is nearly zero; it can be neither negative nor positive for long or the earth would get colder and colder or hotter and hotter.

Seasonal energy budgets for a region, however, are either positive or negative. The winter energy budget is negative in the hemisphere where winter is occurring (Table 2). That negative balance is the driving force behind cold fronts, snow, and wind. In other words, a negative energy balance is what causes winter!

Energy budgets can be constructed for any item, and later in the book we will look at energy budgets for both plants and animals. Life on earth is just like your financial budget—your checkbook cannot exist in a negative state for long without trouble developing. Neither can earth nor organisms living on it exist for long with a negative energy balance. Animals with negative energy balances starve before the winter is out. Over the long run, energy budgets must equal zero for the earth and be zero or positive for organisms. A positive balance shows as growth or reproduction, a negative balance as weight loss, illness, or eventual death.

Differences or changes in energy budgets are responsible for many of the processes that we observe in winter ecology. We will now look at one process in which changes in the energy budget can create a **temperature inversion** during the winter, resulting in extreme cold. Temperature inversions may develop in several ways, including inversions driven by radiative cooling.

A temperature inversion may be ob-

Table 2. The average energy budget for Teton Science School (northeast Wyoming) during December (presentation patterned after Reifsnyder and Lull, 1965) (units are cal/cm²). Radiation expressed in different wavelengths.

Direction	Shortwave Radiation	Longwave Radiation	Radiation, all wavelengths
Downward from space (direct solar beam)	+12	——	——
Downward from the atmosphere (solar waves scattered by particles and reradiated by particles in the air)	+39	+582	+623
Upward from the earth's surface	-18 *	-621 **	-639
Totals	+33	39	-6

* = reflected from surface, ** = emitted from surface

served on a still, cold day when smoke, instead of rising from the warm air to colder air above as it usually does, stretches out, sometimes almost horizontally, as if trapped under a low ceiling. In fact, it is trapped under a ceiling of warmer air. Normally, air at higher elevations becomes successively colder, creating a gradient colder towards the top. With a temperature inversion, starting at some elevation, the normal relationship is reversed, and air is successively warmer at higher elevations. Smoke will not rise into warmer air, so it flattens out where the air begins to become warmer. The development of this temperature inversion by radiative cooling can be thought of as a four-step process (Figure 25).

In the first step, a normal, reclining temperature gradient occurs above the surface of the earth; temperatures taken at higher elevations are successively colder. During a clear winter day, insolation is high and the earth heats up. The earth emits longwave radiation, but the net energy balance is positive with insolation exceeding longwave radiation loss.

In step two, the sun sets and insolation is cut to essentially zero. The radiative loss from earth now becomes the dominant force in the energy budget and the energy balance becomes highly negative.

The ground becomes cooler because of excessive radiative loss in step three. The air is, however, slightly warmer than the ground. So the warmer air starts to transfer energy to the ground primarily by conduction. As the air loses energy, it continues to cool. The cooling is from the base of the air column, and energy is transferred from high in the relatively warm column toward the bottom, where it in turn is transferred to earth. The earth then radiates the energy to space. The cooling of the air column is shown in the temperature gradient where the bottom of the curve starts reversing itself. This draining of energy is cumulative, and the longer the period of radiative cooling, the greater the development of the temperature inversion. The temperature inversion is that portion of the temperature curve where temperature warms with increased elevation. The clearer

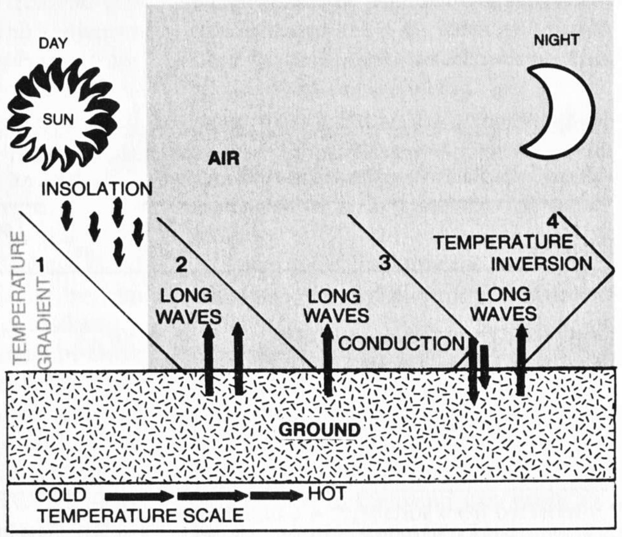

Figure 25. *The development of a temperature inversion due to radiation cooling. See text for explanation.*

and the colder the night, the greater the development of the temperature inversion due to the greater loss of longwave radiation.

In step four, we see a well-developed temperature inversion. It is characterized by the appearance of a breaking point to a regular temperature gradient located high in the air column. Smoke normally rises up an air column from warmer temperatures to colder ones. However, in the temperature inversion, warmer temperatures are found at higher levels and the smoke cannot rise—it is trapped below the breaking point. We can see the presence of the temperature inversion in low-lying levels of trapped smoke.

It should be noted that air flow is not part of this mechanism forming the temperature inversion. Indeed, air flow would serve to disrupt the inversion. The radiative temperature inversion is common in mountain valleys and areas where extremely cold clear nights with no winds occur frequently. These temperature inversions cause bad pollution conditions by trapping polluted air, including wood and industrial smoke, close to the ground. This condition may last for days on end.

When the new day arrives, insolation heats the earth and starts to break up the inversion. However, since the energy budget is negative during the winter, the cooling effect at night exceeds the warming effect during the day. The net negative energy balance is cumulative during the cold winter season and each day's warming cannot catch up. The inversion then continues to strengthen until the arrival of a new front or windstorm to disrupt it.

Temperature inversions have a significant impact on life in the valley bottoms because they may trap extremely cold air down where the animals are wintering. It is not unusual to have air temperatures at the bottom of the inversion of -40°C (-40°F), while only a short vertical distance above, the temperature may be near freezing. The trapped cold air drives the animal's energy balance into a negative state, which requires the animal to use up valuable fat reserves. If conditions are too cold for too long, the animal will not live until spring.

Energy, or rather the lack of energy depicted in low energy balances, drives the factors controlling winter. Reduced radiation leads to colder temperatures, increased winds, and winter snows—in short, reduced energy input causes **winter weather**.

Winter Weather

Many of the factors that make winter *winter* have already been discussed, and each of us is familiar with the cold, the wind, and the snow that characterize winter. These weather factors result from the yearly change in global weather patterns as the energy balance becomes negative in the northern hemisphere. Reduced solar radiation in the fall drives the cooling of polar air masses over the arctic basin. As temperatures drop in the north, the winds of the jet stream transport cold air south, and winter temperatures and storms take hold of the continents. During the winter, the Canadian Arctic weather front shifts south towards the equator and cold weather sets in.

Snow is perhaps the single weather factor that most signifies the arrival of winter. As snow blankets the earth, its effects are observed in many ways: slick roads, sidewalks that need shoveling, camouflage for winter's white animals, insulation for the plants, and a radiation reflector to space. Snow is an incredibly complex material characterized by many different physical properties that affect winter and all life. Because of the intricacies and complexity of snow, we will consider snow in its various forms in detail in the next section.

SUGGESTED READING

Reifsnyder, W.E., and H.W. Lull. 1965. Radiant energy in relation to forests. U.S.D.A. Forest Service, Tech. Bull. No. 1344. 111 pp.

SNOW

People, especially northern natives, have long recognized not only the importance of snow, but the many different types of snow. Although we can characterize snow by density measurements, numbers do not tell the whole story. Skiers recognize many types of snow, but have few words for describing them: powder, packed powder, corn snow, etc., but more detailed conversations rely to a large extent on numbers. Native peoples long ago developed vocabularies which described many types of snow (Table 3). They didn't use numbers, but their rich vocabularies allowed them to describe conditions that were critical to their way of life. Northern peoples knew and named different types of snow, such as snow on the ground and snow that collects on trees.

Snow Language

Languages of northern peoples, the **Inuit** and the **Chipewyan** Indians, described the snow conditions they knew. Those living in different areas where certain types of snow did not occur, did not have words for those snow conditions. Modern winter ecologists have found it useful to incorporate many of these terms into their vocabulary to provide concise definitions for types of snow that would otherwise require many words to describe. For example, **qali** quickly and efficiently describes falling snow that collects on tree branches (Figure 4). Winter ecologists use other foreign terms, such as the Russian term **sastrugi**, to aid in describing the winter environment.

Even with the Inuit vocabulary, it is still necessary for modern snow scientists and winter ecologists to have **classifications of snow**. These classifications provide a standardized basis by which we can communicate. Through the years, many different systems have been proposed and used. We will discuss those in common usage.

Snow Classification

Strictly speaking, snow consists of ice crystals in the atmosphere which grow large and heavy enough to fall to the ground. However, in common language, the term "snow" often includes surface-generated ice features which are of great importance to ecologists. Practically we can define three general types of snow: falling snow (precipitation), snow on the ground (unmetamorphosed and metamorphosed), and surface-generated ice features (Table 4).

Falling Snow

Snowflakes that fall from the sky are composed of one or more ice crystals. **Crystals** form when water **vapor** freezes around a particle known as a **nucleating agent**. The resulting ice crystal grows when water molecules are transferred from water droplets in the air. Crystal type is determined by the temperature and available vapor supply during formation (Figure 26).

Table 3. Inuit and Indian terminology for different types of snow.

English	Inuit Kobuk Valley Alaska	Dindye Fort Yukon Alaska
Falling snow	Annui	Za
Snow that collects on trees	Qali	De-za
Snow on the ground	Api	Non-kot-za
Depth hoar	Pukak	Zai-ya
Wind-beaten snow	Upsik	Seth(ch)
Fluffy taiga snow	Theh-ni-zee	
Drifting snow (smoky snow)	Siqoq	Za-he-ah-tree
Smooth snow surface of very fine particles	Saluma roaq	
Rough snow surface of large particles	Natatgonaq	
Sun crust	Siqoqtaoq	Za-es-(ch)a
Drift	Kimoaqruk	Za-ke-an-e-hae
Space formed between drift and obstruction causing it	Anmana	
Sharply etched wind-eroded snow surface (**sastrugi**)	Kaioglaq	
Irregular surface caused by differential erosion of hard and soft layers	Tumarinyiq	
Bowl-shaped depression in snow around the base of trees	Qamaniq	(zh)e-guin-zee
Snow deep enough to need snowshoes	Det-thlo(k)	
Spot blown bare of snow	Si(ch)	

How to pronounce Inuit (Eskimo) words

a = ah as in saw	u = oo as in tool
e = ey as in prey	au = ow as in now
i = i as in stick	ai = i as in hide
o = o as in bone	q = like a "k" gutturalized far back in the throat

Derived from works by Pruitt (1960, 1973), and Williams and Major (1984)

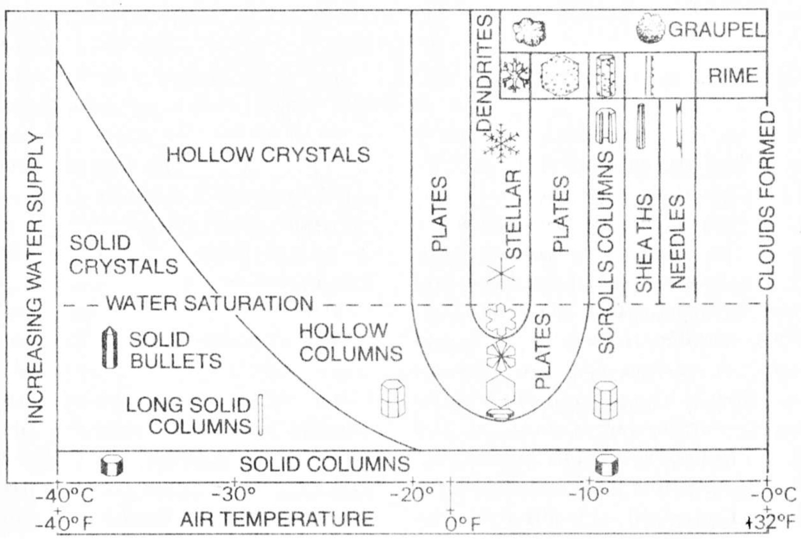

Figure 26. *Snow crystal type is determined by temperature and vapor supply (after Perla and Martinelli, 1976, and Magono and Lee, 1966).*

Table 4. Outline of types of snow and ice features and classification systems in use today.

I. Falling Snow (precipitation)
  A. Classification systems
    1. International Snow Classification
    2. Magono-Lee
  B. Types of snow

II. Snow on the ground (unmetamorphosed and metamorphosed)
  A. Classification systems
    1. Sommerfeld and LaChapelle
    2. Colbeck
  B. Types
    1. Dry snow
    2. Wet snow

III. Surface-generated ice features
  A. Classification systems
  B. Types
    1. Rime
    2. Hoar
    3. Needle ice
    4. Water ice
    5. Melt-freeze layers
    6. Ice layers
    7. Crusts
      a. Wind crust
      b. Sun crust
      c. Freezing-rain crust
    8. Runoff channels

One of the earliest and still very useful classifications of falling snow is known as the **International Snow Classification System** (Figure 27). This system divides precipitation into ten categories. The first six types are known as plates, stellar crystals, columns, needles, spatial dendrites, and capped columns. **Columns** are hollow crystals, **needles** are solid crystals, and **spatial dendrites** are three-dimensional crystals. The seventh category, irregular crystals, serves as a catchall unit. All too often, crystals are lumped into this category because they have not been carefully classified. Efforts should be made to avoid identifying too many crystals as irregular.

Ice crystals in the air may grow by another process called **rimming**, in which supercooled droplets of water collide with the crystal and freeze to it. When little rimming has occurred and the crystal retains its initial shape, it is referred to as a rimmed snowflake. However, when the rimming process is extensive, the crystal loses its identifiable shape, and is referred to as **graupel**.

Two other processes may form ice crystals. Water droplets which freeze on the outside are known as sleet. Those which have a solid core and grow by layering as they pass up and down through the clouds are known as hail.

Snow scientists may use a more detailed classification system developed by Magono and Lee (1966). This system has the advantage of providing more categories, making it easier to identify crystals without resorting to the irregular crystal category (Figure 28). However, this system does include a miscellaneous category. Several other useful distinctions can be made in this system, including the degree of rimming, the division of needles into subcategories, the addition of sideplanes as subdivisions of the irregular crystal category, the addition of a **germ** category for crystals in the first stage of formation, and the categories for broken branches.

At the current stage in the evolution of winter ecology, scientists have only begun to understand some relationships between falling snow and living organisms. We know, for example, that spatial dendrites form **qali** (snow resting on tree branches) more readily than other crystals, that snow composed of needles may easily avalanche, and that rimming may overload tree branches (causing breakage) or coat animals with ice (causing their death). For the most part, our knowledge is barely adequate to utilize the few categories of the International Snow Classification System and we are not yet able to use the finely divided Magono and Lee system. The future awaits our ability to learn to interpret the biological importance of the categories provided by Magono and Lee.

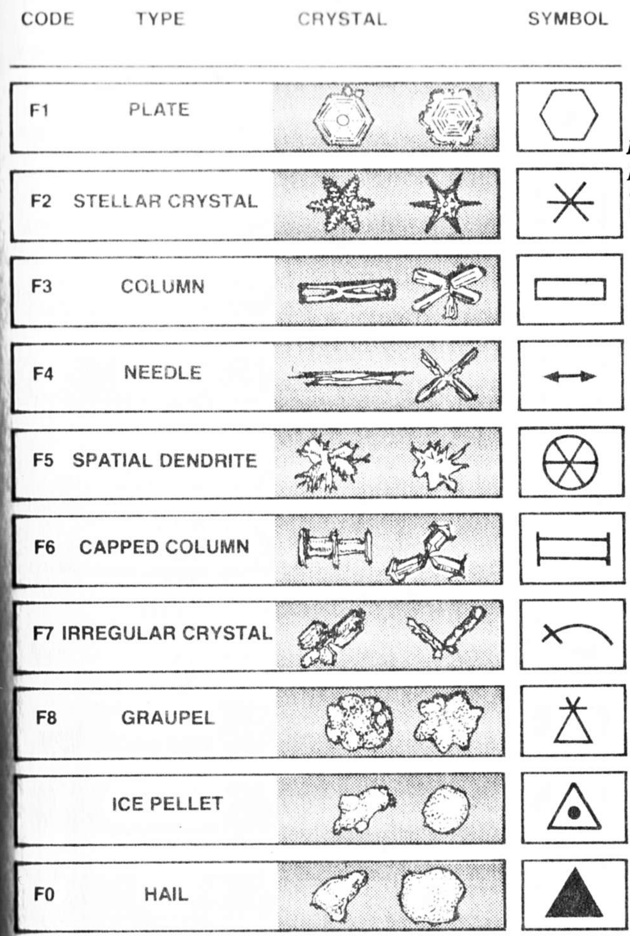

Figure 27. *Falling precipitation as classified by the International Snow Classification System.*

Snow on the Ground

Snow on the ground can remain unchanged for a period of time, but generally only a short period. Colder temperatures tend to promote the preservation of the original precipitation shape, and at temperatures below -40°C (-40°F), crystals change only very slowly. Wind can, however, mechanically change the crystals even at low temperatures. The falling-snow classifications can be used for crystals which have not been changed by the wind or through time.

Usually snow on the ground quickly starts to change (**metamorphose**) as water molecules move from the crystal points to the valleys between the crystal branches. Crystals in the snowpack can also grow as water vapor moves within the pack. A round shape results when the **surface free energy** is re-

Figure 28. *Classification of snow crystals according to Magono and Lee (1966).*

duced to its lowest point at any given temperature and water supply. Faceted crystals occur with rapid growth. Different metamorphic processes act to reach the equilibrium, and kinetic states and classifications have been developed which emphasize processes over morphological classifications of shape. The best-known classification system based on processes was proposed by Sommerfeld and LaChapelle and is shown in Figure 29.

The Sommerfeld and LaChapelle system recognizes four major categories of snow on the ground: unmetamorphosed, equitemperature, temperature-gradient, and firnification. In this system, wind-blown and fragmented snowflakes are classified in the unmetamorphosed category.

The first process changing snow crystals is known as **equitemperature (ET)** or **destructive metamorphism** because the newly fallen crystals are changed to form rounded ice grains. Under the idealized conditions of ET metamorphism, water vapor diffuses (evaporates and redeposits as a solid) from the sharp points of the crystals to new positions, creating rounded ice crystals in an equilibrium state. Grain size decreases because of water loss from crystals. During this process, the snowpack shrinks, resulting in a reduction of depth. ET metamorphism slows at lower temperatures and essentially stops at -40°C (-40°F).

In reality the temperature gradient in the snowpack is never equitemperature, and ET metamorphism actually occurs when the temperature gradient in the snowpack is relatively low. Under most conditions ET metamorphism will occur if the temperature gradient within the snowpack does not exceed 0.1°C/cm (also written as 10°C/m). This figure is only an approximate guide, however, and will vary slightly with the absolute temperature and the vapor pressure within the snowpack. ET metamorphism was originally known as **destructive** metamorphism because individual crystals are broken down.

Temperature-gradient (**TG**) or **constructive metamorphism** occurs when the temperature gradient in the snowpack exceeds 0.1°C/cm. Water vapor moves by a "hand-to-hand" process from warmer snow (higher **vapor pressure**) to colder snow (lower vapor pressure). Water molecules are transferred along the crystal branches, from crystal to crystal, and through the air between crystals. As the water **sublimates** (changes from ice to vapor or vapor to ice without going through a water stage), it moves to new crystals causing those crystals to grow in layers, ultimately forming large, cup-shaped crystals known as **depth hoar**. The process is known as **constructive** metamorphism because snow crystals grow in size.

Larger crystals form with larger temperature gradients and greater vapor pressure gradients. Greater vapor pressure gradients occur at higher temperatures that are found at the base of the snowpack. The largest crystals are therefore found at the base of the pack. Crystal growth often occurs just above ice layers in the snowpack, however, when the ice layer blocks water transport.

The mechanical strength of the snowpack is dramatically reduced since the crystals are only weakly bonded together and can easily collapse. A weak layer of TG crystals at the base of the snowpack is a potential release layer for avalanches. TG crystals are also important to those animals that live beneath the snow. Once the depth hoar layer forms each year, mammals easily burrow throughout the snowpack. This layer is often called **sugar snow**.

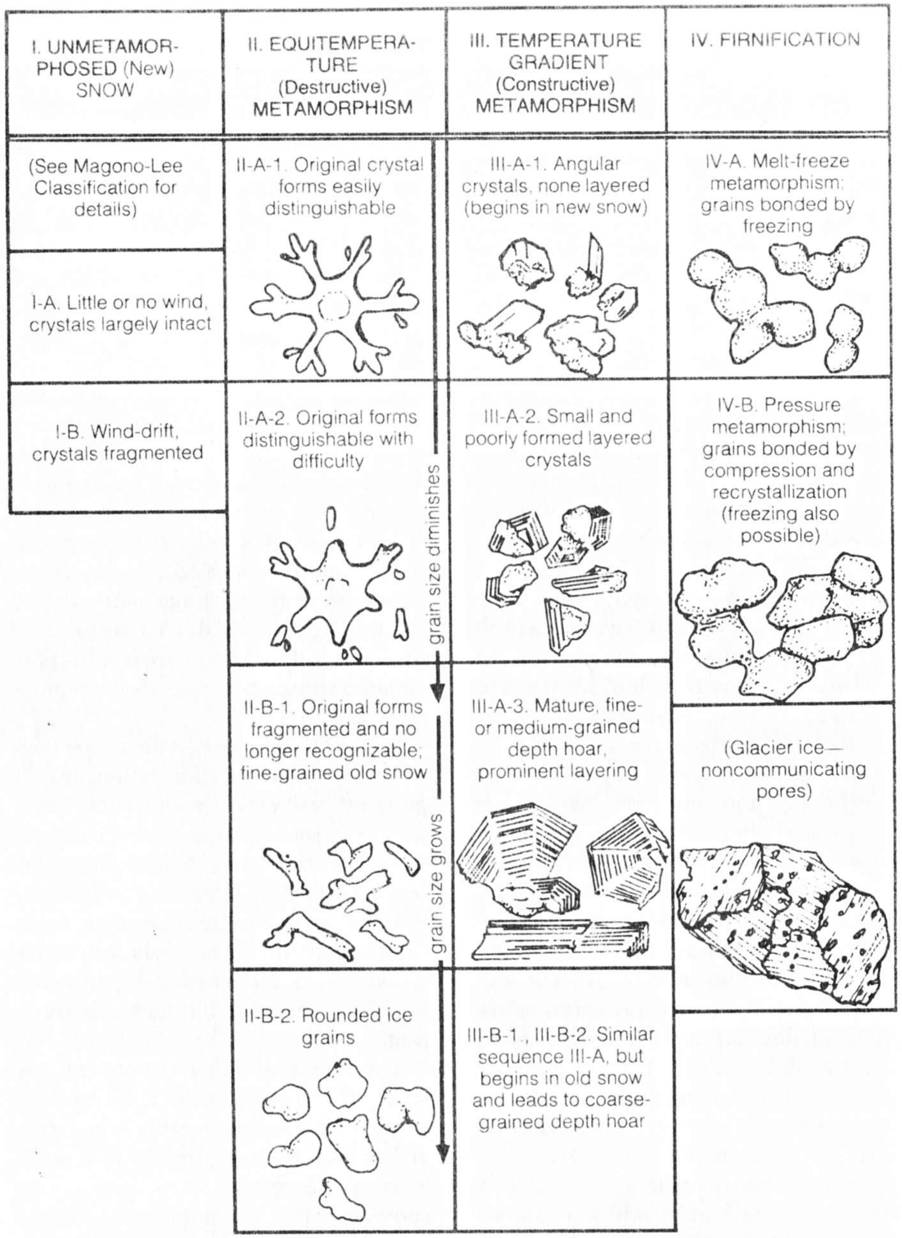

Figure 29. *Classification of snow on the ground (LaChapelle, 1969, Sommerfeld and LaChapelle, 1970).*

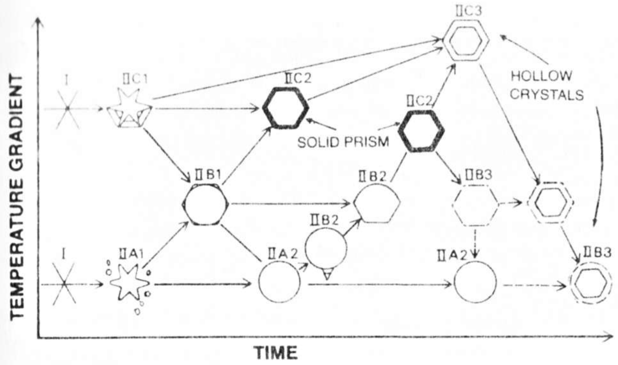

Figure 30. *A generalized configuration of dry snow formation showing the effects of temperature gradient and time (after Colbeck, 1986).*

Depth hoar formation occurs in cold regions where winter temperatures set up large gradients across relatively shallow snowpacks, such as in the Rocky Mountains of Wyoming and Colorado. Considerable depth hoar formation may occur early in the fall if air temperatures are unusually cold or if the snowpack is unusually shallow.

The final category, **firnification**, includes two processes: **melt-freeze** and **pressure metamorphism**. When melting occurs, water moves between crystals. Later freezing **sinters** (bonds) the crystals, increasing the strength and density of the snowpack. The weight of the snowpack can also force the crystals closer together, causing bonding by compression and recrystallization.

Problems exist with the Sommerfeld and LaChapelle system. First, there is a problem with terminology. Crystal growth is really controlled by temperature gradients whether or not the resultant form is identified as an ET or TG product. According to Colbeck (1986), "The equilibrium form (usually rounded) and the **kinetic** growth form (usually faceted) both appear in snow covers subjected to temperature gradients." The distinction between ET and TG metamorphism is thus an artificial one which does not exist in reality.

The Sommerfeld and LaChapelle system does not allow for the classification of snow containing liquid water—**wet snow**. In wet snow, crystals can grow without going through melt-freeze processes. Pressure can push crystals together but the effect of pressure contributes relatively little to crystal growth. In wet snow, it is the curvature of the crystal and not the pressure, that effectively sets the melting temperature. Because of these problems, Colbeck (1986) proposed a new classification system (Table 5).

The Colbeck classification of dry snow is best understood by referring to Figure 30, which shows one possible configuration that snow metamorphism might follow. Other configurations are possible depending on how the temperature gradient varies with time. At a low temperature gradient, newly fallen snow begins to round off (IIA1) and with time the crystal becomes well-rounded (IIA2). At medium temperature gradients (intermediate growth rates) crystals remain rounded but continue to grow (IIB1). As the temperature gradient increases, faceted crystals begin to form (IIB2). This may start with **spicules** (protrusions of ice) hanging down from the crystal and progress to crystals faceted on the growing or bottom half. The sublimating or top half is still rounded in shape. As the temperature gradient begins to decrease (warmer temperatures or additional

Table 5. Snow classification system.

I. Precipitation
II. Dry Snow
  A. Equilibrium (rounded) form
    1. Initial rounding of precipitate
    2. Fully rounded (may be faceted at low temperatures)
  B. Mixed rounded and faceted
    1. Intermediate growth rate
    2. Transitional as temperature gradient increases
    3. Transitional as temperature gradient decreases
  C. Kinetic growth (faceted) form
    1. Faceted growth on precipitate
    2. Solid crystals, usually hexagonal prisms
    3. Hollow crystals called depth hoar
III. Wet Snow
  A. Pure grain clusters
  B. Melt-freeze particles
  C. Slush
IV. Surface-generated features.

falling snow), faceted crystals begin to round off (IIB3). Fast growth occurs at large temperature gradients and results in the **kinetic** form of the crystal. Layering may occur on the newly fallen snow crystal (IIC1) but quickly progresses to solid crystals with hexagonal prisms (IIC2). Hollow crystals (**depth hoar**) form (IIC3) the "climax" crystal in this category. Note that reductions in the temperature gradient cause crystals to round off to the IIB3 form.

The Colbeck classification requires some knowledge of the history of the snow metamorphism. Several crystal types may be arrived at through different paths, but by knowing the history of crystal formation, important information is added to our knowledge of the snowpack. The requirement of additional knowledge before classification should not be considered a drawback but rather a chance to further our knowledge of the snowpack. The important lesson is to learn how to interpret the classified snow in ecologically meaningful terms.

Surface-Generated Features

Surface-generated ice features occur through many different processes and no one has thoroughly addressed the classification of all features. Both the Sommerfeld-LaChapelle and Colbeck systems consider surface features, but only in a cursory way. Surface-generated features are very important to living organisms and we are suggesting a slightly expanded classification that has direct implications for organisms. The classification suggested here considers the shape of features first and secondarily the processes by which these features are formed. The types of surface-generated features are:

Rime frost
Hoar frost
Needle ice
Water ice
Melt-freeze layers
Crusts
  a. Wind crust
  b. Sun crust
  c. Freezing-rain crust
Runoff channels

Rime frost forms when **supercooled** water droplets (water below 0°C, or 32°F, but not frozen) contact an object and freeze in place. The water droplets are often in the form of a low-hanging cloud or fog. Rime accretions grow into the prevailing wind and the size of the formation is directly proportional to wind speed. Formations may look hummocky, feathery, or like slender needle-like spikes, but close examination will reveal a fine-grain granular structure lacking crystalline detail. The deposit may become very thick, threatening to break trees and shrubs where it accumulates. Rime accumulations mat down the fur of large mammals, reducing the insulation provided by the fur. The resulting exposure can cause death.

Hoar frost forms when water vapor **sublimates** onto a surface. It is the frozen equivalent of dew. Hoar frost shows a well-developed crystalline structure with considerable **layering** on the upper ends of the crystals (Figure 29). Crystals grow from small bases expanding to broad but flat feathers at the tips. Conditions leading to hoar frost formation include the movement of vapor within the snowpack, the presence of **supersaturated** air in crevasses, ice caves, and animal burrows, and the occurrence of clear evenings with high levels of outgoing longwave radiation. Vapor movement in the snowpack causes **depth hoar**, while hoar that forms in crevasses, caves, and on snow surfaces is known as **crevasse hoar**, **cave hoar**, and **surface hoar**, respectively.

Hoar crystals are the most spectacular of the surface-generated features. Ecologically, they are important for several reasons. The formation of surface hoar indicates extremely cold night temperatures and heavy loss of terrestrial radiation. Active rodent burrows and beaver lodges can be identified by the formation of hoar frost at the entrances or in the cracks between the logs in beaver lodges. Is it possible that predators can cue in on these small clues? A buried surface hoar frost in a snowpack can also serve as a weak zone on which avalanches may slide. Incidentally, when first buried the crystals would be classified as Colbeck IIB3 and eventually as IIA2.

Needle ice forms in soil with very high water content (Figure 31). The formation is due to repeated freeze-thaw cycles and occurs more often in the fall and spring before constant cold conditions have set in. At high latitudes and altitudes, needle ice formation is associated with **permafrost** (permanently frozen ground). Most often needle ice formation occurs where the ground is not covered by snow. Freezing initially occurs at the surface with subsequent freezing and accretion of additional ice occurring at the base of the needle ice. This stepped process pushes the needle ice from the ground. Smaller objects on top of the ice are lifted or torn from the ground. Each main melt-freeze cycle (not necessarily **diurnal**, day to night, cycles) defines a visible boundary or layer within the ice grain and cycles of formation can be easily counted.

Roots of plants and burrows of animals are destroyed by the cutting ice. In cold regions, buildings are torn from their foundations and concrete is broken as the ground heaves 30 cm (12 in) or more. Needle ice is extremely powerful. If the ground is denuded of vegetation by other processes, needle ice formation can keep it exposed to erosional processes. Plant recolonization is very slow.

Water ice or **verglas** is formed when water flows over a surface and freezes. Verglas surfaces on rocks are treacherous to mountain animals. The most common formation of water ice in the winter, however, is in stream bottoms. Since the earth is warm, water often flows in a stream below the snow

Figure 31. *Nancy Einarsen holds a well-developed example of needle ice from the Firehole River basin, Yellowstone National Park.*

during the winter. When a cold spell causes the ice to freeze to the bottom in spots, it forms dams. Water reaching these dams eventually increases in level until it finds a way out from under the ice and snowpack. Successive layers of water ice are then built up in the channel. When blocked, the water may find alternate ways around the existing channel, causing considerable damage to wildlife and surrounding land. Water ice dams, which do not form every year, also delay the spring meltoff.

Melt-freeze layers occur when the surface melt percolates down through the snowpack. This water is trapped by fine-grained layers of snow, where it freezes and increases the density of the layer. The layer is not a complete ice layer because it maintains some permeability. However, the layer can be strong enough to impede or stop the movement of small mammals within the snowpack. These layers are often called **lenses** where they do not cover large areas but are restricted to areas a few meters (yards) across.

Ice layers usually form at the ground-snow interface as the result of melting because of the warmer ground

layer heat from the center of the earth. These layers can be nearly pure water ice and may restrict small mammal movement; they may also stop animals from grazing on the grass.

Crusts are generated in three ways. **Wind crusts** are the product of mechanical breakage of snow crystals. The resulting fragments are densely packed and **sintered** (frozen) together. Wind crusts can be very strong; when working above treeline on Niwot Ridge in Colorado we often need picks to dig snow pits to examine the snow.

Sun crusts (or **melt-freeze crusts**) form due to solar melting and refreezing. A specific type of crust called **firnspiegel** or **firn mirror** causes the rare but spectacular reflection referred to as **glacier fire**. The mirror surface is transparent and often acts as a greenhouse. Liquid and warmed water is present under the surface. **Snow algae** that live and grow in the snow thrive under the protective surface of the mirror. In Colorado, slopes with a southerly aspect at midelevations may be covered entirely with a sun crust. **Freezing rain** also forms a similar crust.

All crusts, when buried, become important potential sliding surfaces capable of causing avalanches.

Runoff channels form during warm spells or in the spring as meltoff begins. The general slumping of snow is probably a random but down-slope directed process. The snow surface develops shallow, somewhat parallel troughs aligned above surface water percolation. Melt water also percolates down through the snowpack drenching all creatures living below the surface. Wet animals can die of hypothermia or can simply drown during extreme warm spells.

Winter ecologists need to make better use of snow classification systems. The challenge for the next decade is to try to improve our level of ecological interpretation to match the precision of existing classifications. Currently, the International Snow Classification System of falling snow is adequate for use by most ecologists. The Sommerfeld and LaChapelle classification system for snow on the ground is in widest use because of its popularity within the community of skiers and avalanche workers. As ecologists our efforts might be well served by increasing the use of the Colbeck system and learning to interpret the additional and corrected information that it contains. We hope that our classification of surface-generated features may spark additional research concerning their effects on organisms.

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Snow Properties

Our fascination with snow, for its beauty and its uniqueness, is encompassed in its classification. However, snow is a substance that bends like warm tar, absorbs heat, reflects radiation, and insulates from temperature change. To understand the ecological role of snow, we must understand these inherent properties and many more. We must also understand how the properties of snow may interact with various organisms. We will now review the different physical and mechanical properties of snow.

Density

The snowpack on the ground is made up largely of air. Only a small portion of the snowpack actually consists of water in the form of snow. Glacial ice, in contrast, is mostly water and very little air. The **water content** of snow or ice is the measure of the amount of water it contains. We may refer to the water content by percentage, with an imaginary block of water being pure water or 100 percent water. We may also define the water content of the block by its **density**, the weight of the water in the block divided by its volume. Different researchers speak of density in different units, but these units all relate to each other and to the percentage of water content (see Table 6). We will use grams per cubic centimeter (g/cm^3) to refer to the density of snow.

Age

Colloquially we speak of snow in terms of age. If you read directions on a tube of cross-country ski wax, it will recommend usage for new snow or for old snow. These terms refer to the amount of metamorphism that the snow has undergone. A crude correlation can be made between the type of snow and the density of the snow as it metamorphoses. In general, density increases with time on the ground (not true with depth hoar formation), correlating density with age. Newly fallen snow varies from 0.07 to 0.15 g/cc and old snow may vary from 0.20 to 0.45 g/cc. This is just a shorthand method of referring to snow and lacks accuracy. The terminology is useful, however, when we wish to speak generally.

Plasticity

Snow, though frozen, often behaves like water in slow motion. A snowpack moves and deforms under the pressure of gravity and the weight of the upper layers of snow. Snow is capable of flowing around objects without breaking. We refer to this movement and deformation without breaking as **plastic** (or **viscous**) **behavior**. The results of plastic movement are observed where the snow slowly curls under the edge of a roof (Figure 32). As the snow slides down the roof, the snowpack

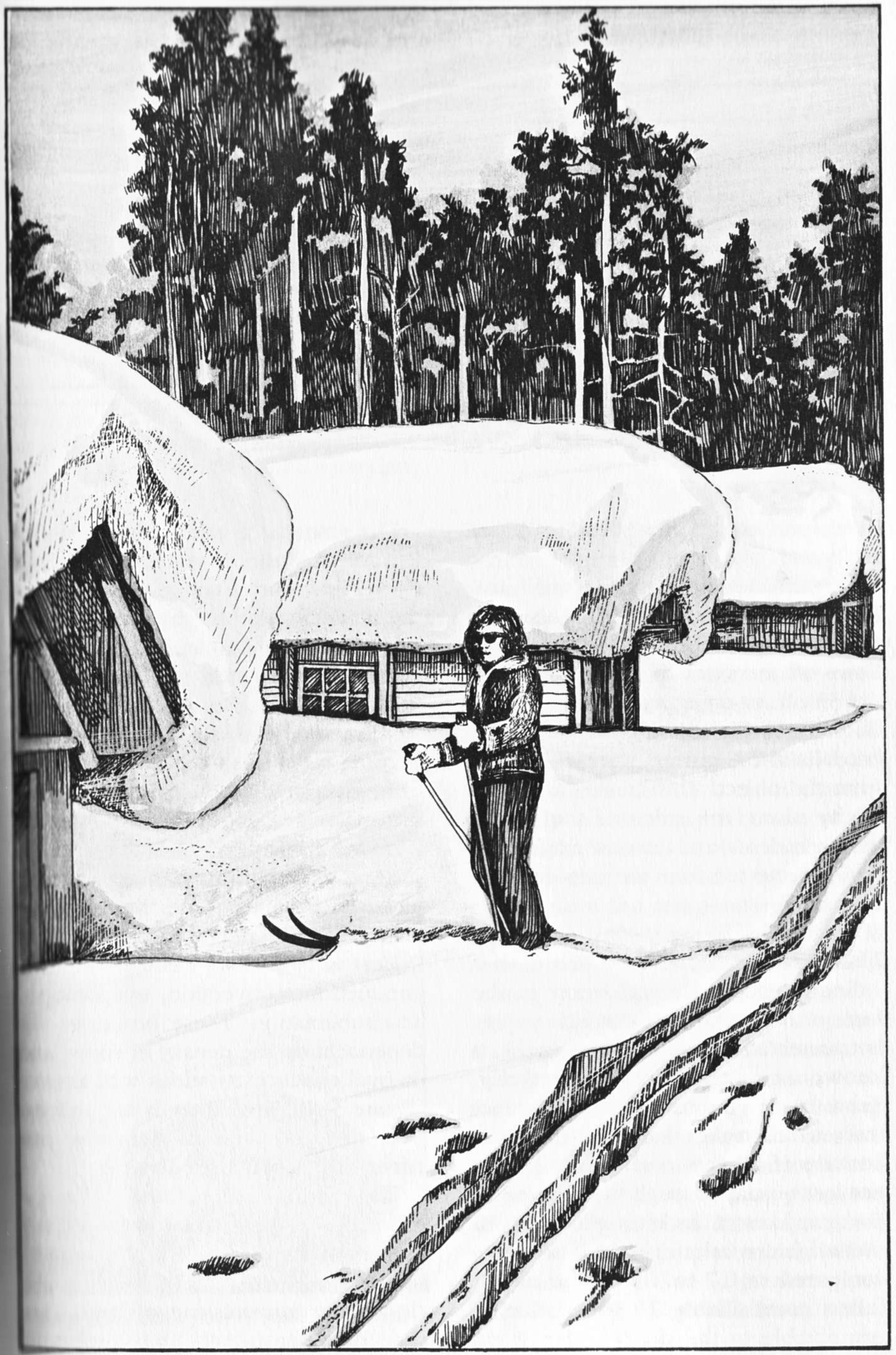

Figure 32. *Robin Ritger observes the plasticity of snow that has slid off a roof in Yellowstone National Park.*

Table 6. Measurement of the water content of snow. Examples are of specific instances and will vary with different conditions.

	Water Content		
Example	Percent	g/cm^3	kg/m^2
Fluffy new fallen snow	8	0.08	80
Slightly metamorphosed snow	15	0.15	150
Depth hoar	20	0.20	200
Settled snow	30	0.30	300
Ice lens in snowpack	45	0.45	450
New glacial ice	70	0.70	700
Old glacial ice	90	0.90	900
Pure water	100	1.00	1000

g = gram, cm^3 = cubic centimeter, kg = kilogram (2.2 lbs), m^2 = square meter

bends and curves around the eaves of the house.

Plasticity is important for small animals living under the snow. The snow that settles on a rock or a log gradually flows off the sides to the ground (Figure 33). In so doing, the snow does not fill the area directly next to the object, but falls to the ground a short distance from the object. This creates a hollow cavity along the sides of the object where rodents and insects may travel easily, protected from the outside environment.

Thermal Conductivity

Energy moves through snow in the form of heat. The rate at which energy is transmitted through the snowpack is known as its **thermal conductivity**. Snow has a very low thermal conductivity which makes it a good insulator; because of the low conductivity heat is not lost quickly through the snowpack. For comparison, rocks conduct 200 to 400 cal (cal = calorie) of heat per hour compared to 0.7 to 1.3 cal for newly fallen snow (Table 7). This value is comparable to the dry wooden walls (0.7 to 1.8 cal) which insulate our homes.

The amount of water that is present in a material affects its thermal conductivity. Wet material transmits heat about ten times faster than dry material. For example, wet sand transmits 7 to 21 cal, whereas dry sand conducts only 1.4 to 2.5 cal. The increased conductivity of wet material helps explain why our feet become so cold as our socks get wet from perspiration during winter outings. Older or denser snow also contains more water, which reduces its insulating value because dense snow may transmit about ten times more energy than newer or lighter snow.

Heat is transferred through snow by conduction, convection, evaporation, and sublimation. These processes are dependent on the density of snow, and thermal conductivity varies with density (Figure 34). Conductivity is not uniform over the full range of densities, but curves slightly at lower densities.

The transmission of heat through a material takes time. The lower the thermal conductivity (which is the same as saying the better the insulator) the slower the transmission of heat. This time delay results in two important phenomena in the snowpack: temperature gradients and thermal memory.

Table 7. Comparison of thermal conductivity in several materials (calories/hour/cm^2/ for a thickness of one cm and a difference of 1°C)

Material	Thermal Conductivity	
Rock	193.3 – 416.3	
Glass	74.3 – 89.2	
Plastic	29.7 – 74.3	
Wet sand	7.2 – 21.6	
Ice	3.2 – 9.8	density 0.4 – 6.5
Wind-packed snow	1.3 – 3.1	density 0.2 – 0.35
Masonite	4.9	
Felt (thermafelt)	4.2	
Dry sand	1.4 – 2.5	
Newly fallen snow	0.7 – 1.3	density 0.1 – 0.2
Dry wood	0.7 – 1.8	

Note that thermal conductivity is shown here based on the energy conducted per hour rather than per second. This was done to award extremely small values and provide a more intuitive feel for the data.

The **temperature gradient** may be observed in a **snow pit** dug for the purpose of examining the snowpack (see Experiencing Winter). Once a pit has been dug, temperatures are taken in the side of the pit wall from the top to the bottom. These temperatures are graphed out to provide a **snow temperature profile** (Figure 35).

Generally snow profiles are warmest at the bottom. Excess energy from the sun is stored during the summer when

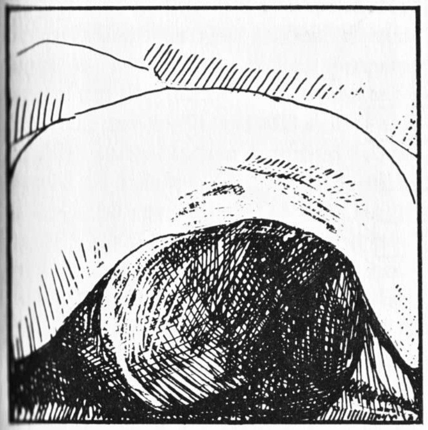

Figure 33. Plastic flow of snow off a boulder. Tunnels around objects are formed by snow slowly flowing off the boulders and creating spaces. Animals move freely within these spaces.

the flow (**heat flux**) into the ground is positive. During the winter, heat flux from the stored energy is from the ground to the air at about 20 to 30 $cal/cm^2/d$. The contribution to heat flow from the warm center of the earth is minor, amounting to about 0.1 $cal/cm^2/d$. Only in thermal areas, such as **Yellowstone National Park** would heat flow from the earth contribute significantly to warming the bottom of the snowpack. Since all snow (which is really ice) must be melted in the snowpack before the temperature can rise above 0°C, the bottom of the snowpack surface will seldom be above freezing during the winter. However, the soil temperature may rise several degrees above the freezing point. Contrary to common beliefs, the ground-snow interface is not necessarily at freezing (0°C). The temperature at the interface may in fact drop many degrees below freezing and freezing may progress deep into the ground. In cold regions, it is necessary to bury plumbing below the annual frost line to protect pipes from freezing. In **permafrost** areas, soil remains frozen all year; only the surface of the frozen ground melts each summer. In warmer regions, the

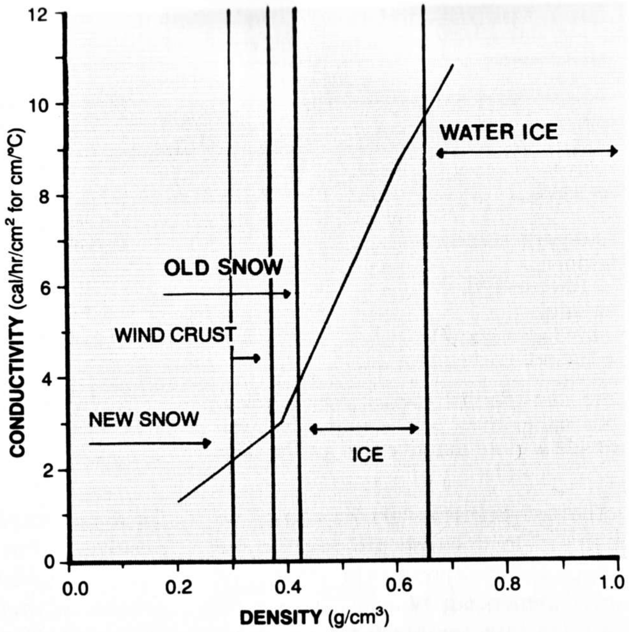

***Figure 34.** Thermal conductivity of snow in relation to snow density (after Langham, 1981). Arrows indicate the general regions referred to by common names for snow.*

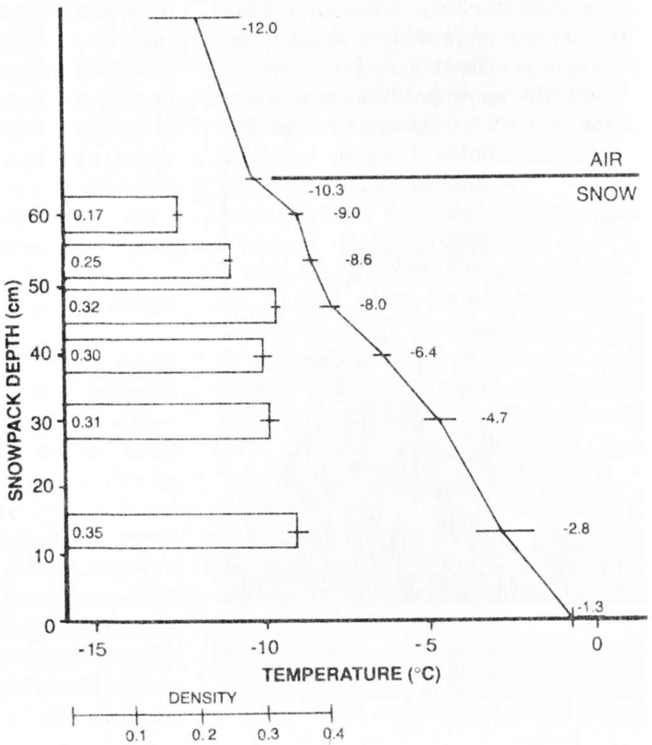

***Figure 35.** Snow temperature profile from Teton Science School, January 9, 1984. Data gathered by Marsha Benning and Leslie Appling.*

ground-snow interface may be near freezing all winter. In any case, plants and animals living at the ground-snow interface, with a relatively constant temperature around freezing, may find it more conducive to survival than the harshness associated with life on top of the snowpack.

As long as the air temperature is cold, the snow temperature gradient may be very large. The greater the gradient of the profile, the faster the snow metamorphism is acting to produce **depth hoar** crystals. Shallow snowpacks and cold temperatures produce the greatest gradients through the snowpack.

The temperature profile can change dramatically during the day, especially with larger ranges of air temperatures during a 24-hour period. A large diurnal fluctuation in air temperature will start to cool the snowpack from the top, as energy is transported from the snow surface to the colder air. However, this transfer takes time. One January, students at Teton Science School followed the cooling wave down through the 53 cm (20.9 in) snowpack (Figure 36). The coldest air temperature occurred at midnight; the snow surface temperature was also coldest at midnight. By 1:00 AM, the coldest temperature of the day reached down another 2 cm (0.8) in) to 51 cm (20.1 in). The coldest temperature reached lower depths as follows: 46 cm (18.1 in) at 4:00 AM, 36 cm (14.2 in) at 8:00 AM, 18 cm (7.1 in) at 7:00 PM, and ground level at 8:00 PM. The passage of the cold pulse down the 53 cm (20.9 in) snowpack took 21 hours. The amount of temperature change (0.07°C) that reached the ground-snow interface was greatly reduced from the diurnal range of air temperatures (9.9°C).

The cooling or warming effect of diurnal changes often does not reach completely down to the bottom of the snowpack. For example, a long cold spell will lower the temperatures in the snowpack and will produce a reclining temperature profile (a in Figure 37). Then a warm day will increase the temperature near the snow surface (b in Figure 37). Although the air temperature may be above freezing, the snow temperature might still be far below freezing. This **thermal memory** results in a cold, lower layer that may cause a skier to suffer frostbitten feet on a day when the temperature is above freezing. In very cold regions, such as the Yellowstone Plateau, we have experienced daytime air temperatures above freezing when the middle of a one-meter snowpack was still -20°C (-4°F) or colder.

Each spring the warm weather begins to melt the snowpack from the top. Increasingly warmer temperatures from above and the warm earth impart energy to the snowpack, warming the snow (steps 1, 2, 3, and 4 in Figure 38). The temperature curve tends to flatten out and approach 0°C. As long as there is a snow-ice mixture, the temperature of the snowpack cannot go above freezing. Eventually the whole snowpack reaches the 0°C point, called the **isothermal** point (step 5 in Figure 38); this is the point where all the snow is just at freezing. At this temperature, liquid water is present throughout the snowpack. The isothermal period is a very important time for small animals, since they may die of hypothermia or even drown as gravity pulls the water down through the snow into their nests. Once reached, the isothermal condition of the snowpack begins to break down **depth hoar**, and the snowpack is temporarily stabilized against avalanches. With continued warming, the free water lubricates the snow and wet avalanches become a potential danger.

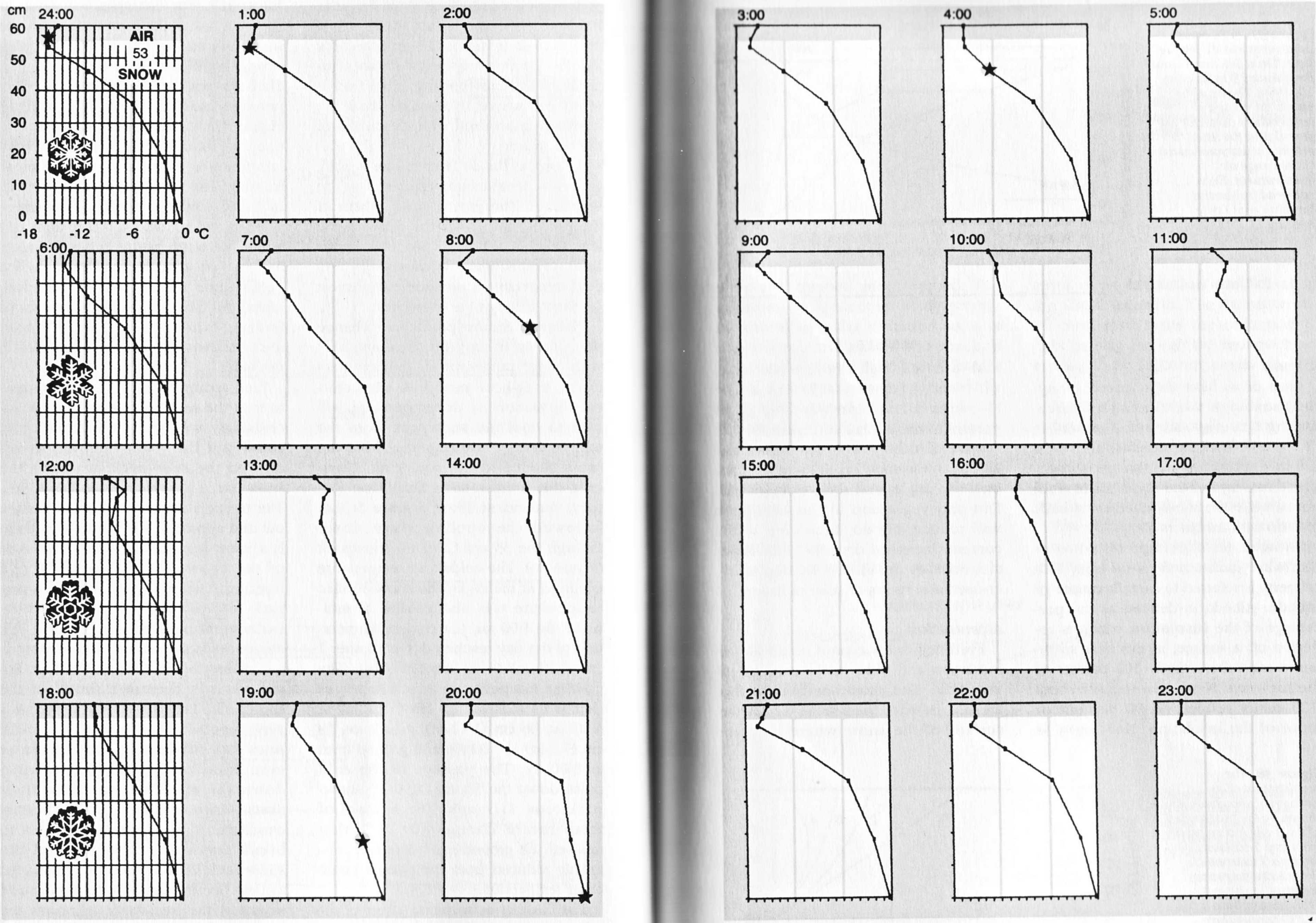

Figure 36. *A 24-hour series of snow temperature profiles showing the movement of the coldest temperature down the snowpack. Profiles were obtained by Marsha Benning and Leslie Appling on January 9 and 10, 1984. The coldest temperature in the snowpack starts at the time of the coldest air temperature about midnight.*

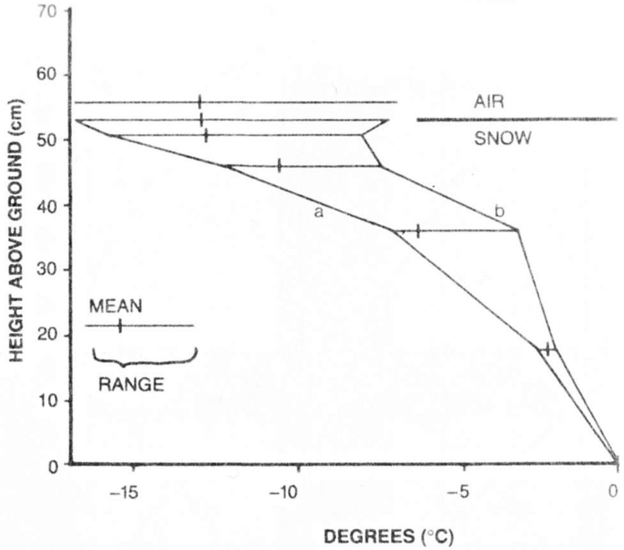

Figure 37. A 24-hour snow temperature profile from Teton Science School for January 9 to January 10, 1984. The letter "a" marks the coldest temperature curve for the period and the letter "b" marks the warmest curve of the range in temperatures. Data gathered by Marsha Benning and Leslie Appling.

Albedo

Most of us have experienced springtime sunburns while skiing in March. During those episodes, the underside of the eye sockets, nostrils, and even the roof of the mouth can get burned. The direct rays of the sun burn us from above while the snow reflects rays back to burn us from below.

Snow is an excellent reflector of shortwave radiation from the sun. This property is referred to as **reflectance** or **albedo**. Albedo is defined as the percentage of the **insolation** which is reflected off a surface, in this case snow. Snow can reflect nearly 100 percent of the sun's rays. New snow (density about 0.1) easily reflects 85-90 percent or more of the insolation. New snow is said to have a high albedo while older, dirty snow (density 0.5) has a low albedo and may reflect as little as 40 percent of the insolation (Figure 39).

Several other variables affect the albedo of the snow, such as snow grain size, sun angle, and surface roughness. Dirt and vegetation in the snowpack will reduce albedo. Increased water content (increased density) in the snow also reduces the albedo leading to increased absorption of solar radiation.

Attenuation

Even new snow cannot reflect all the insolation and older snow may reflect very little. The short wavelengths that are not reflected **penetrate** below the surface of the snow where they are eventually trapped and absorbed. The **attenuation** (reduction of detectable radiation) of solar radiation as it is transmitted through the snowpack is very rapid. Below 30 to 50 cm (12 to 20 in) of low-density snow, most of the light is attenuated (Figure 40). Below this depth, a dark environment exists for plants and animals. Later in the spring season light will penetrate deeper into the dirtier and denser snowpack.

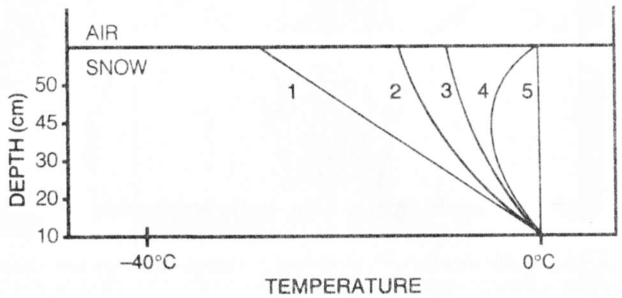

Figure 38. The development of an isothermal snowpack is shown by the progression of the temperature profile from step 1 (coldest) through 5 (warmest). Progressive warming eventually causes the snowpack to have a 0°C (32°F) temperature throughout (indicated by line 5).

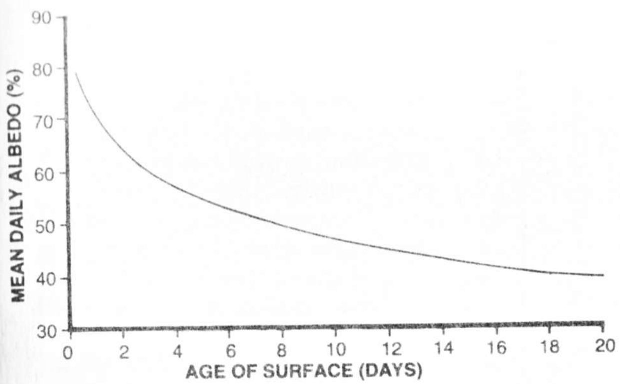

Figure 39. Reduction of albedo as the snowpack ages.

Transmission

Light **transmission** is measured in terms of an **extinction coefficient**, ν, the Greek letter Nu. The extinction coefficient represents the reduction in light passing through the snowpack according to the following equation:

$$I = Io\,(e)^{-z}$$

Io represents the intensity of original radiation passing through a snowpack, e is a constant (2.718), and I is the remaining radiation. The larger the extinction coefficient, the less light that is transmitted through the snowpack.

The efficiency of light **transmission** through snow is primarily dependent on three factors: the grain size of snow,

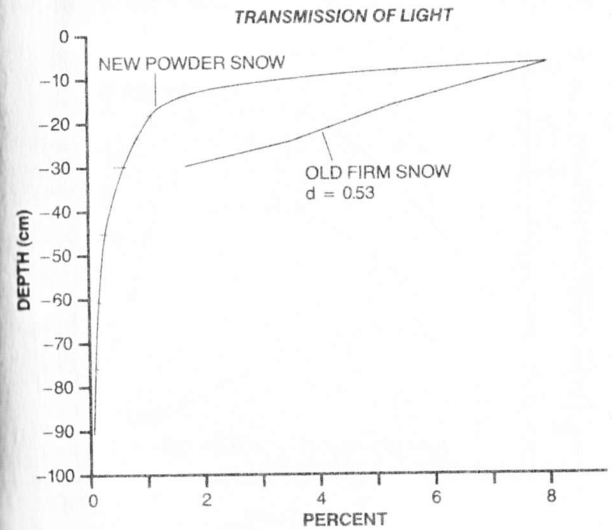

Figure 40. Attenuation of light that penetrates below the surface of the snowpack (Curl et al., 1972).

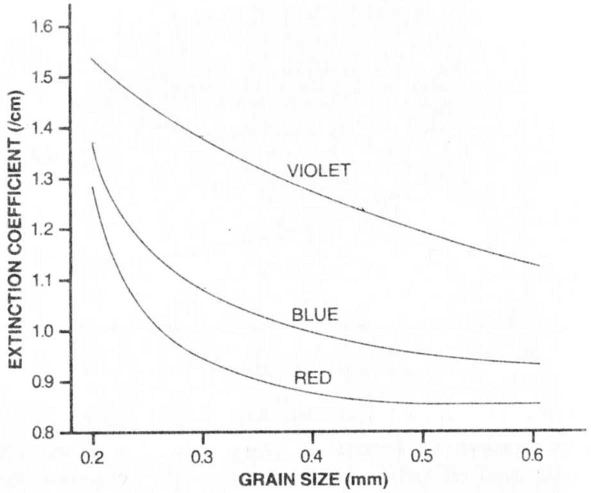

***Figure 41.** Reduction in visible light transmission as a function of snow grain size (d = 0.45 g/cm^3). The extinction coefficient indicates reduction of light that penetrates the surface of the snow and is usually reported in units/cm (after Mellor, 1965).*

the density of snow, and the wavelength of light. Extinction is inversely related to **grain size** and is dependent on the **color** of light (**wavelength**) (Figure 41). At small grain sizes (about 0.5 mm), extinction of all colors tends to converge and reach a maximum. At a grain size of about 2.0 mm extinction values again converge, indicating that larger grains transmit considerably more light. Shorter wavelengths (violet and blue) are more strongly affected than longer wavelengths (red).

The relationship of light transmission to **density** is more complex (Figure 42). Snow with a low or high density passes more light than does snow in the middle density range of about 0.5 to 0.56 g/cm^3. The extinction coefficient is also dependent on the **color** of light, with shorter wavelengths (violet and blues) being more strongly affected than longer wavelengths (red). Light transmission is more sensitive to snow grain size than it is to density.

Two processes affect the extinction

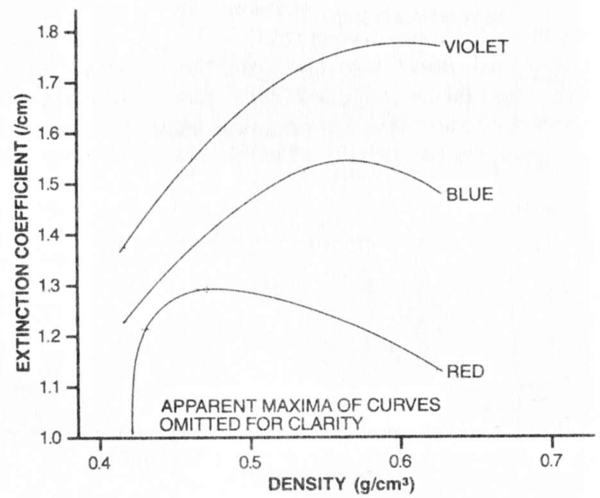

***Figure 42.** Change in visible light transmission as a function of snow density (grain size = 0.2 mm) (after Mellor, 1965).*

of light as it passes through the snowpack: **scattering** and **absorption** of light. Scattering is most important in fine-grained snow and the extinction coefficient is lower at longer wavelengths. Absorption is more important in coarse-grained older or wetter snow. Absorption becomes stronger at the longer wavelengths removing more blues than reds. When density is considered, the transition from scattering attenuation to absorption occurs at about 0.50 to 0.56 g/cm^3 for refrozen or wet medium-sized grains the transition may occur as low as 0.4 g/cm^3. A density of 0.50 g/cm^3 is considered the **critical density** in snowpack formation. Further densification can no longer occur from compaction, but must result from freeze processes. Sintering of grains and refreezing of melt water provides clear avenues for light transmission. Above 0.50 g/cm^3, increased light transmission probably results from reduced pore space within the snowpack. Snow grain size increases by bonding between ice particles. Bonding reduces pore size, but develops continuous paths for light transmission within snow grains. Light then is transmitted not only between crystals but within crystals. As density and grain size increase in the spring when the snowpack starts to melt, light is also transmitted deeper into the snowpack.

Different **colors** of light react differently to grain size and density and absorption is strongest in the long (red) wavelengths. The net effect is that the red color disappears and light passing through snow appears blue. As an experiment, stick a pipe into the snowpack during the day and look down into it at the snow. The pipe will cut out scattered light and only that light reflected back up the pipe will be visible. The snow will appear blue. The **visual spectrum** is strongly selected by the snowpack. Absorption reduces the intensity of light below the snowpack and **spectral selection** reduces the longer wavelengths (Figure 43).

The scientific literature is full of contradictory statements about transmission of light through snow. Some have suggested that transmission increases with increased snow density, while others have suggested that transmission decreases with increased density. Results

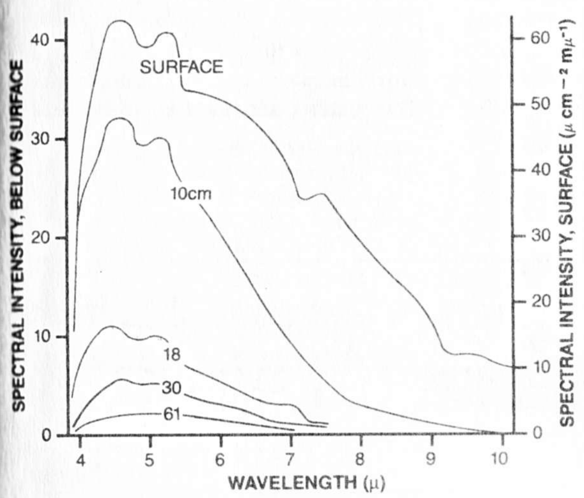

***Figure 43.** Spectral selection reduces not only the total amount of light beneath the snowpack but the color (wavelength) of light (μW/cm²/mμ). Blues are the most prominent color visible within the snowpack.*

of scientific experiments often vary by several fold. Much of the contradictory evidence originates from equipment limitations, weak experimental procedures, simply different techniques, as well as from not accounting for density or grain size differences. Ecologists, in general, need to be more aware of the research of the physical scientists. The picture painted here appears to represent the current view by leading researchers. Several references are listed at the end of this section for those with more interest in this subject.

Absorption

While snow reflects nearly all of solar shortwave radiation that reaches its surface, snow acts like a **black box** (a theoretical object which absorbs all radiation) to terrestrial or longwave radiation and absorbs most of it. The differences in the manner in which snow reacts to shortwave and longwave radiation cause many interesting phenomena; three examples follow. In the springtime, as the snowpack starts to thin out and the sun climbs to a higher angle in the sky, shortwave radiation that is not reflected passes through the snowpack to dark objects below the snowpack. The shortwave radiation starts to heat up rocks and tree trunks. As temperatures increase within in these objects, they emit more longwave radiation. Remember, longwave radiation is proportional to the fourth power of the temperature of the object. Therefore a small increase in surface temperature will result in a large increase in longwave radiation. The object then radiates longwave radiation back into the snowpack where it is readily absorbed by the snow. Warming of the snowpack close to the objects makes the snow soft and starts the melting process. The soft spots that occur around rocks in the high mountains are often called **elephant traps** by the hikers who fall into them.

In Antarctica, there are several lakes which are warmed by this process. The lakes, including Lake Vanda, have permanent ice on the surface. During the warm part of the summer the ice melts on the edge leaving a floating raft of ice still covering most of the lake. Shortwave radiation passes through the clear ice into the water below. Due to the greater density of the water compared to the ice, the shortwave radiation is readily absorbed. As the temperature of the water increases, energy is transferred to nearby water by conduction and longwave radiation. This warms a lens of water deep in the lake. This lens may be as warm as 21°C (70°F) even though the average yearly air temperature may be below freezing. The water does not turn over causing the lens of warm water to circulate, because of layering caused by different density salt solutions.

A similar process leads to the formation of water on ice surfaces of lakes (Figure 44). This process is dependent on the presence of a snowpack on top of the ice. Shortwave radiation passes through the snow to the ice surface. Since the water content in the ice is higher than in the snow, the ice absorbs more of the radiation. When the temperature of the ice begins to increase, it emits longwave radiation back to the snow surface. The snow readily absorbs the longwave radiation and eventually the snow at the ice-snow interface begins to melt forming a puddle under the snow. These puddles may form when the air temperature is far below zero. We have experienced them on the lakes in Yellowstone National Park at daytime temperatures of -30°C (-20°F). This is not the only mechanism that forms puddles under the ice; puddles can also be formed by cracking of the ice which allows lake water to flow out on top.

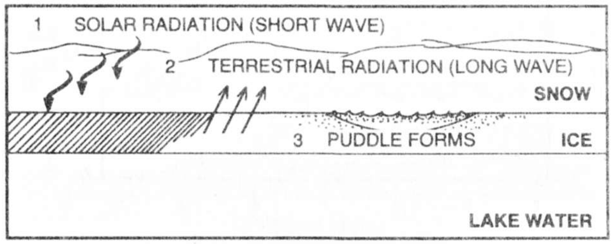

Figure 44. *The formation of a puddle of water on lake ice during the winter. Shortwave radiation passes through the snow and is absorbed by the ice. The warmed ice radiates longwave radiation back to the snow, where it is absorbed. This causes the snow and ice below it to melt, forming a puddle. This process is dependent on having a covering of snow.*

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