NIGHT RADIATIVE COOLING

The effect of clouds and relative humidity

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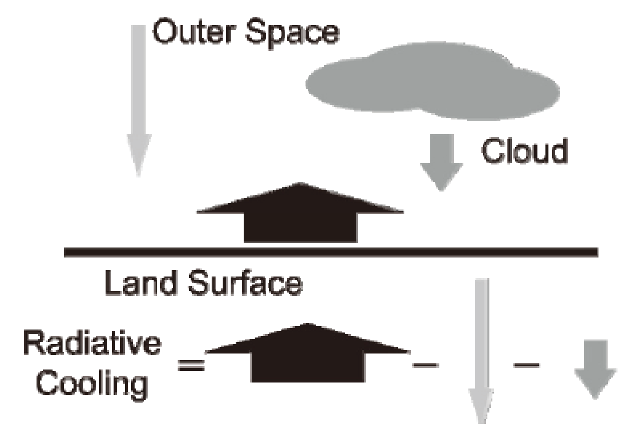

Figure 1. Simple Radiative Cooling Illustration
See references for source

We've all experienced that chilly feeling after sunset on a clear calm night. It seems unusually cold, and, in the winter as well as spring or fall, we might find frost on our windshields. This is usually due to radiative cooling. On the other hand, temperature drops on cloudy nights are more temperate. This cooling effect is illustrated by Figure 1, which shows that radiative cooling is the sum of the three sources of radiation: outgoing radiation from objects versus incoming sky and cloud radiation. It's obvious that on those clear nights, the lack of downwelling cloud radiation results in greater radiative cooling.

Nighttime radiation cooling is very dependent on atmospheric water vapor conditions from cloud cover and ambient relative humidity. Low humidity areas like desserts and high elevation locations can generate large temperature drops: "… temperature differences as large as 40^0C have been measured for thermally insulated approximate black bodies in the Altacama dessert in Chile" (Eriksson and Granqvist). However, even mild winds can overwhelm the cooling effects of radiation. Many radiation cooling studies have been carried out by the agriculture industry. Fruit crops and certain types of seedlings are vulnerable to this phenomenon, making it advantageous to study avoidance strategies like using protective coverings, wind machines, fog generators, etc.

STEFAN-BOLTZMANN LAW

To determine outgoing radiation, we can utilize the Stefan-Boltzmann Law:

$$P = A\varepsilon\sigma T^4$$

Where P (watts) is the radiated power from a body of area A (m^2) at temperature T (K).

ε is emissivity, a dimensionless number between 0 and 1 that determines the efficiency of a body to radiate and absorb energy. A black body has an emissivity of 1. Soil, asphalt and human skin have emissivity of about 0.95. The emissivity of the night sky is approximately 0.74.

σ is the Stefan-Boltzmann constant, $5.67x10^{-8}\ Wm^{-2}T^{-4}$

T is the body temperature in Kelvin. All bodies with temperature greater than absolute zero (-273.15 ^{0}C) radiate power.

We can estimate radiation amounts from a naked human body with the radiation law. The average human has a skin area of about 2.2 m^2 with an average skin temperature of 33 ^{0}C (91 ^{0}F). The emissivity of skin is about 0.95. Therefore the outgoing radiated power *of* that body would be about

$$(2.2)(0.95)(5.67x10^{-8})(273+33)^4 = 1039\,W\ .$$

In other words, a human body radiates power close to that of a toaster, with a peak wavelength of about 9.5 μm. However, in normal temperatures of 22 ^{0}C (72 ^{0}F), a room radiates about 897 watts back to the body. The net radiation loss at this skin temperature would be about 142 W. This is why a naked person feels chilly at room temperature. With time, as skin temperature settles toward room temperature, net body radiation loss ceases.

RADIATION COOLING

On calm nights, objects radiate power as illustrated above in Figure 1. The radiation law permits an exact way to determine outgoing radiation. However, atmospheric and cloud complexities do not permit an exact method of calculating incoming downward sky radiation. Field measurements collecting such data have been made to develop quite accurate downwelling sky radiation empirical formulas. That is how a determination of night sky emissivity was made. Although it's slightly dependent on water vapor content, a sky emissivity value of 0.74 is a good approximation. Water vapor in the atmosphere from relative humidity and clouds creates a source of radiation through greenhouse effects which can be quantified by a radiative temperature. Carbon dioxide and ozone have a lesser greenhouse effect. A modified Swinbank model of night time downward thermal radiation has been developed (Goforth et al):

$$P_{thermal} = (1+KC^2)\ x\ 8.78\ E-13\ x\ T^{5.852} x\ RH^{0.07195}$$

Where $P_{thermal}$ is the down-going thermal night sky radiation, W/m^2

K = 0.34 for cloud height $\prec$ 2 km, 0.18 for 2km $\prec$ height $\succ$ 5 km, and 0.06 for height $\succ$ 5km

C = cloud cover (0.0 for clear sky through 1.0 for totally overcast)

T is the temperature in Kelvin, K

RH is the relative humidity percentage

CLEAR NIGHT EXAMPLE

Assume a clear sky, temperature 10 ^{0}C (50 ^{0}F) with a relative humidity of 25%.

At 10 ^{0}C, from the Stefan Boltzmann Law, a body of emissivity 0.95 radiates

$$0.95\ x\ 5.67E-8\ x\ (273+10)^4 = 345.5\,W/m^2$$

The downwelling thermal radiation via the Swinbank formula is

$$(1+K(0)^2)(8.78E-13)(273+10)^{5.852}(25)^{0.07195} = 246.6\,W/m^2$$

The net outgoing radiation is 345.5 – 246.6 = 98.9 W/m^2

We can also determine the radiative clear night sky temperature as follows:

$$T = (\frac{P}{\varepsilon\sigma})^{0.25} = (\frac{246.6}{0.74x5.67E-8})^{0.25} = 276.9\,K = 3.9\ ^0\text{C}$$

OVERCAST NIGHT EXAMPLE

Same temperature and relative humidity as above, with 100% cloud cover below 2 km height. At 10 ^{0}C, from the Stefan Boltzmann Law, a body of emissivity 0.95 radiates

$$0.95x5.67E-8x(273+10)^4 = 345.5\,W/m^2$$

The downwelling thermal radiation via the Swinbank formula is

$$(1+0.34(1.0)^2)(8.78E-13)(273+10)^{5.852}(25)^{0.07195} = 330.4\,W/m^2$$

The net outgoing radiation is 345.5 – 330.4 = 15.1 W/m^2

We can also determine the radiative overcast night sky temperature as follows:

$$T = (\frac{P}{\varepsilon\sigma})^{0.25} = (\frac{330.4}{0.74x5.67E-8})^{0.25} = 397.9\,K = 24.9\ ^0\text{C}$$

RADIATION COOLING TIME

Note that in these examples, there was a 34% increase in downwelling sky radiation between an overcast (330.4 W/m^2) and clear sky (246.6 W/m^2). As a result, the net radiation loss on the ground was 98.9 W/m^2 for clear skies and 15.1 W/m^2 for overcast skies. Therefore, greater surface radiation losses on clear nights result in greater and faster temperature drops than on cloudy nights. Note also the difference in the radiative sky temperatures between clear and overcast skies, 21.0 ^{0}C. In the example above, a temperature of 10 ^{0}C and RH of 25% implies a dew point of -9.1 ^{0}C. At this temperature, water vapor in the atmosphere leaves the gaseous state, condenses as frost, and may deposit on cold objects.

Radiation cooling time for an object with outgoing radiation can be theoretically calculated as follows (HyperPhysics):

$$t_{cooling} = \frac{mN_A k}{2M\varepsilon\sigma A}[\frac{1}{T_{final}^3} - \frac{1}{T_{initial}^3}]$$

Where $t_{cooling}$ cooling time, s m object's mass, kg N_A Avogadro's number, $6.02E23$
k Boltzmann constant, $1.38E-23\,m^2kgs^{-2}T^{-1}$ M molar mass, kg
ε emissivity, 0.0 – 1.0 σ Stefan-Boltzmann constant, $5.67x10^{-8}\ Wm^{-2}T^{-4}$
A object radiating area, m^2 T temperature, K

Note that increased cooling times correlate positively with increases in object's mass and its "initial – final" temperature range, and correlate negatively with increases in molecular weight, emissivity and body area.

Assume we have an aluminum dish (emissivity = 0.02, density = $2700\,kg/m^3$, atomic weight = 27), 30 cm diameter and 3 mm thick and *insulated from the ambient environment* *except for its zenith facing area*. It's a cloudless night, temperature 10 C, relative humidity 25%. How long will it take for the temperature of the dish to reach 0 C?

The dish mass, m = $2700\pi(0.15)^2(0.003) = 0.573\,kg$

The dish zenith facing area, A = $\pi(0.15)^2 = 0.0707\,m^2$

Molar mass, M = 0.027 kg for atomic weight of 27

$t_{cooling} = \frac{(0.573)(6.02E23)(1.38E-23)}{2(0.027)(0.02)(5.67E-8)(0.0707)}[\frac{1}{(273+0)^3} - \frac{1}{(273+10)^3}]$ = 5,529 s or 92.1 minutes

However, this calculation assumes an outgoing radiation of 345.5 W/m^2 without downwelling sky radiation. The actual net outgoing radiation was 98.9 W/m^2. Therefore, we should increase the calculated cooling time by a factor of $345.5/98.9 = 3.49$. So the true cooling time for clear nights is 321.7 minutes or about 5.4 hours. For a totally overcast night, the net outgoing radiation is 15.1 W/m^2. The true cooling time would be $345.5/15.1\,(92.1) = 2{,}107$ minutes or 35.1 hours, 6.5 times longer than for a clear night. The graph below (Figure 2) illustrates temperature profiles for the two sky conditions. Clear night cooling occurs at about 1.9 ^{0}C per hour, and overcast night cooling about 0.3 ^{0}C per hour.

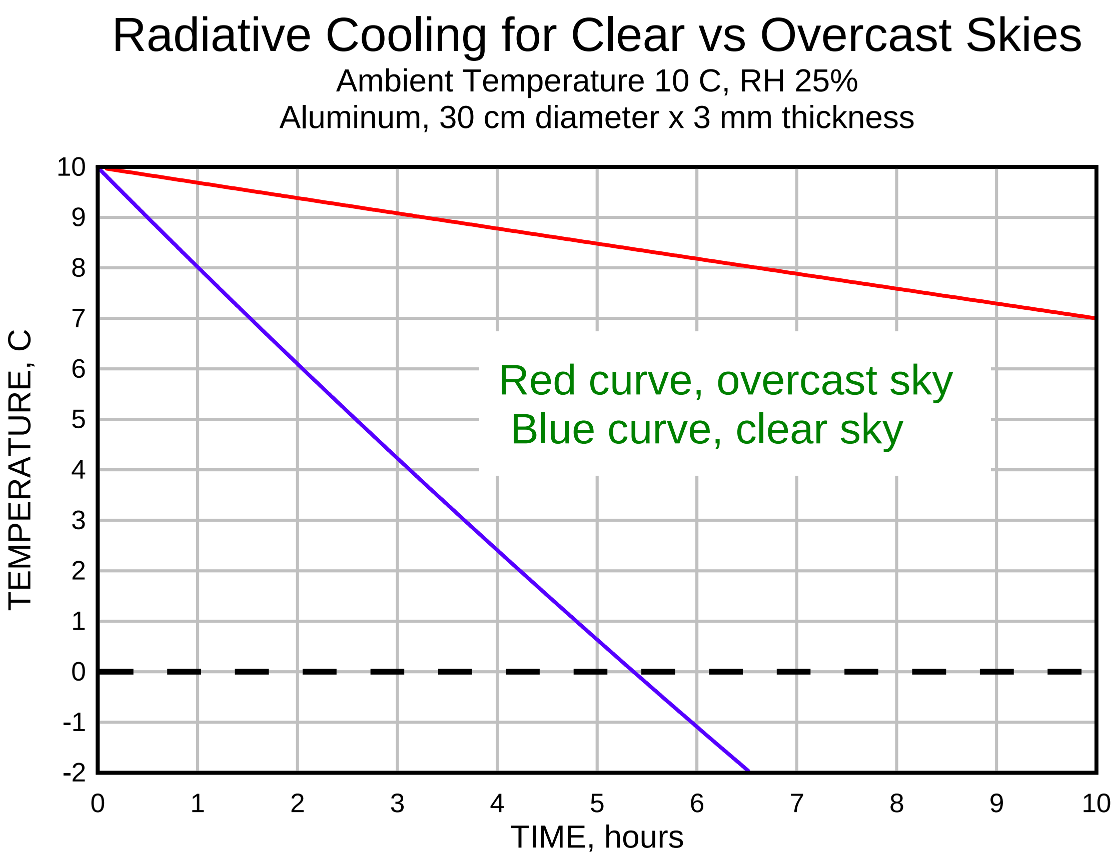

Figure 2. Night Radiation Loss Temperature Profiles

Since these hypothetical examples are based on a dish insulated from its environment, it's important to point out that in practice, temperature cooling would likely occur at slower rates than shown in the graph.

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Figure 1 source:

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