Chapter 3 Thermodynamics

Chapter overview:

- Forms of energy
- Possession and transfer of energy
- The first law of thermodynamics
- Heat budget of air parcels
- Thermodynamic diagrams
- Heat budget at a fixed location
- Heat budget at the Earth's surface
- The Earth's annual energy budget
- Regional temperature variations
- Apparent temperature indices

Forms of Energy

Energy: The ability or capacity to do work on matter

Kinetic energy: Energy related to the motion of objects

Potential energy: Energy related to the attraction between objects

These forms of energy can be applied on the macro (large) or micro (molecular) scales.

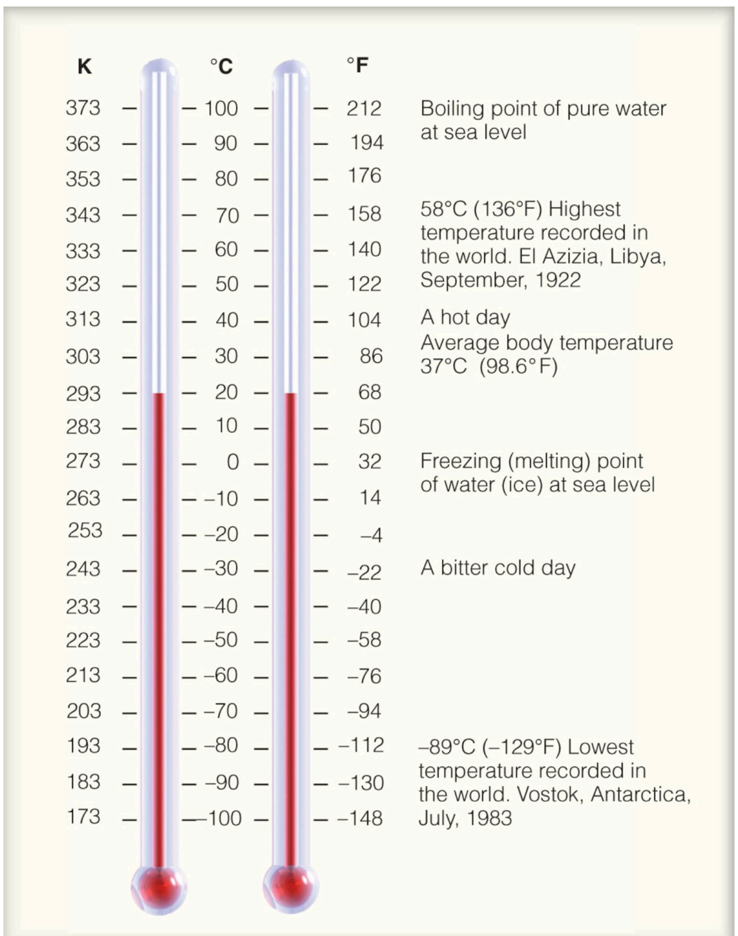
Energy can change forms (kinetic, potential, and other) and scale (micro or macro).

Thermodynamics is the study of energy conversion.

Internal Energy

Internal energy: The sum of the microscopic (molecular scale) kinetic and potential energy.

Temperature is a measure of the microscopic kinetic energy of an object.



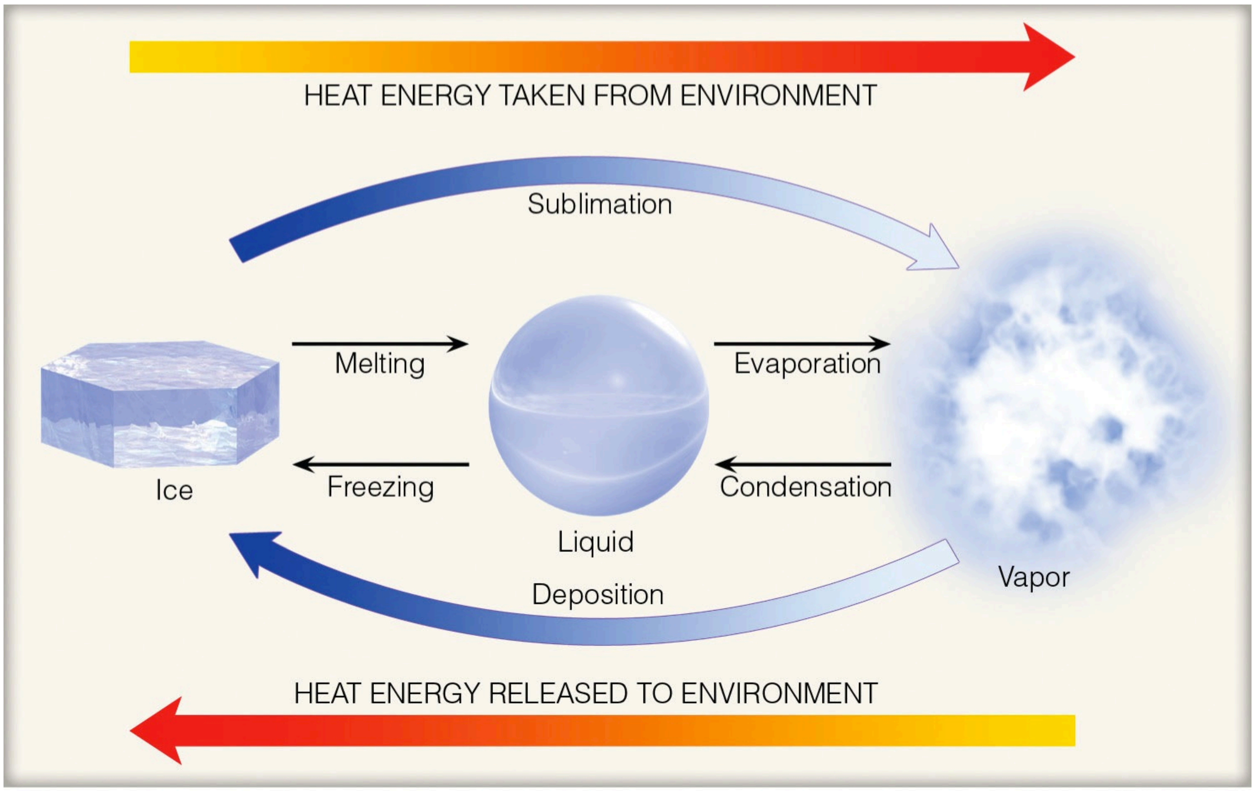
Absolute zero: The temperature at which there is no molecular motion

This temperature corresponds to 0 K, -273°C, or -459°F

Microscopic potential energy is related to the forces that bind sub-atomic, atomic, and molecular masses together.

Latent energy (Q_E): The microscopic potential energy due to bonds between molecules.

The latent energy associated with phase changes of water is critical for many atmospheric phenomena.



What are some examples of atmospheric phenomena that are impacted by latent heat?

Which phase changes shown above result in warming (cooling) of the atmosphere?

The change in latent energy (ΔQ_E) associated with a change in phase of a mass (Δm) of a material is given by:

$$\Delta Q_E = L \cdot \Delta m_{water}$$

L is the latent heat factor.

This indicates the amount of heat required to change the phase of 1 kg of an object. This varies with the material of the object and the phase change being considered.

Latent heat factors for water are shown at the right.

Table 3-1. Latent heat factors *L* for water (H_2O), for the phase-change processes indicated.

Process Name & Direction	L (J kg^{-1})	Process Name & Direction
	vapor	
evaporation ↑	$L_v = 2.5x10^6$	↓ condensation
	liquid	
melting ↑	$L_f = 3.34x10^5$	↓ freezing (fusion)
	solid	
	vapor	
sublimation ↑	$L_d = 2.83x10^6$	↓ deposition
	solid	
↑ requires transfer of thermal energy Δq TO water from the surrounding air.		↓ requires transfer of thermal energy Δq FROM water to the surrounding air.

Possession and Transfer of Energy

Energy can be transferred between objects and this energy transfer is critical to the study of weather and the atmosphere.

The transfer of thermal energy is referred to as the heat transferred or simply heat and is indicated with the symbol Δq (units of J kg^{-1})

The First Law of Thermodynamics

As energy (Δq) is added to a mass (m) of air this energy goes to warming the air (ΔT) and by causing the air to do work as its volume increases (ΔV). This is expressed as the first law of thermodynamics.

$$\Delta q = C_p \Delta T - \Delta P / \rho$$

C_p is the specific heat of air at constant pressure and represents the amount of energy that must be added to air to increase its temperature by 1 K while the pressure of the air remains constant.

▼ TABLE 2.1 Specific Heat of Various Substances

SUBSTANCE	SPECIFIC HEAT (Cal/g × °C)	J/(kg × °C)
Water (pure)	1.00	4186
Wet mud	0.60	2512
Ice (0°C)	0.50	2093
Sandy clay	0.33	1381
Dry air (sea level)	0.24	1005
Quartz sand	0.19	795
Granite	0.19	794

How does the specific heat of water compare to that of air or ground?

How will the rate of change of temperature of water differ from that of air or ground as heat is added or removed at a constant rate?

What impact will this have on the weather in areas with a lot of water nearby?

Lagrangian versus Eulerian Frameworks

Eulerian - a framework that is fixed in space.

Atmospheric properties in an Eulerian framework will change as wind blows air with different properties past the fixed location.

Lagrangian - a framework that follows air as it moves through the atmosphere.

Air parcel - a hypothetical “blob” of air that does not exchange properties with the surrounding air.

Heat Budget of an Unsaturated Air Parcel

Consider an air parcel in which no phase change of water occurs (although this air parcel may contain water vapor) and that has a pressure that is equal to that of the surrounding air.

The first law of thermodynamics and the hydrostatic equation can be combined to describe how the change in temperature, height, and heat for this air parcel are related.

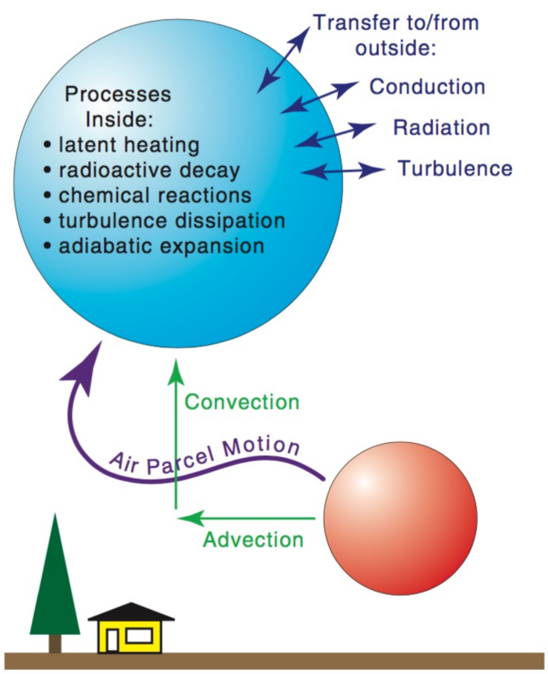
$$\Delta q = C_p \Delta T + \left(\frac{g}{C_p}\right)\Delta z$$

or

$$\Delta T = -\left(\frac{g}{C_p}\right)\Delta z + \frac{\Delta q}{C_p}$$

What does each term in this equation represent physically?

How can these equations be applied to studying the atmosphere?



What processes could cause the air parcel to gain or lose energy?

Lapse rate (Γ): The rate at which temperature decreases with altitude

$$\Gamma = \frac{T_2 - T_1}{z_2 - z_1} = -\frac{\Delta T}{\Delta z}$$

Process (parcel) lapse rate: The lapse rate of an air parcel experiencing a specific process (such as moving vertically through the atmosphere without any energy transfer).

Environmental lapse rate: The lapse rate of the air surrounding an air parcel (the parcel's environment).

Do the parcel and environmental lapse rates need to be the same?

How do meteorologists measure the environmental lapse rate?

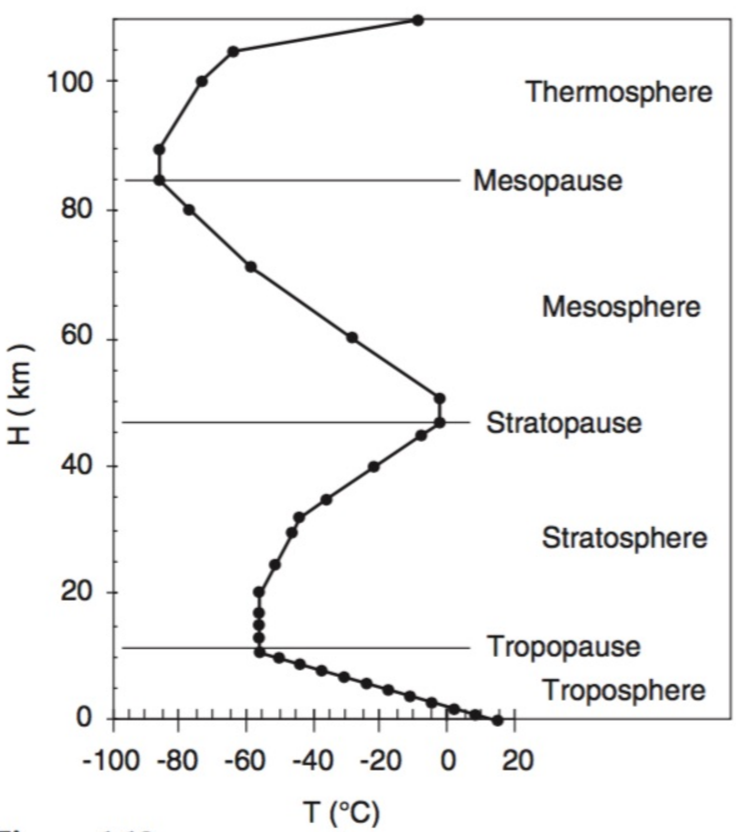


Figure 1.10

Sounding: a plot of environmental temperature vs. height.

A sounding is used to show the vertical temperature profile of the environment.

Example: Calculate the environmental lapse of the troposphere and stratosphere for the standard atmosphere temperature profile shown at the left.

Dry adiabatic lapse rate: An air parcel lapse rate when no heat (energy) enters or leaves the air parcel (Δq = 0)

For this dry adiabatic process the first law of thermodynamics reduces to:

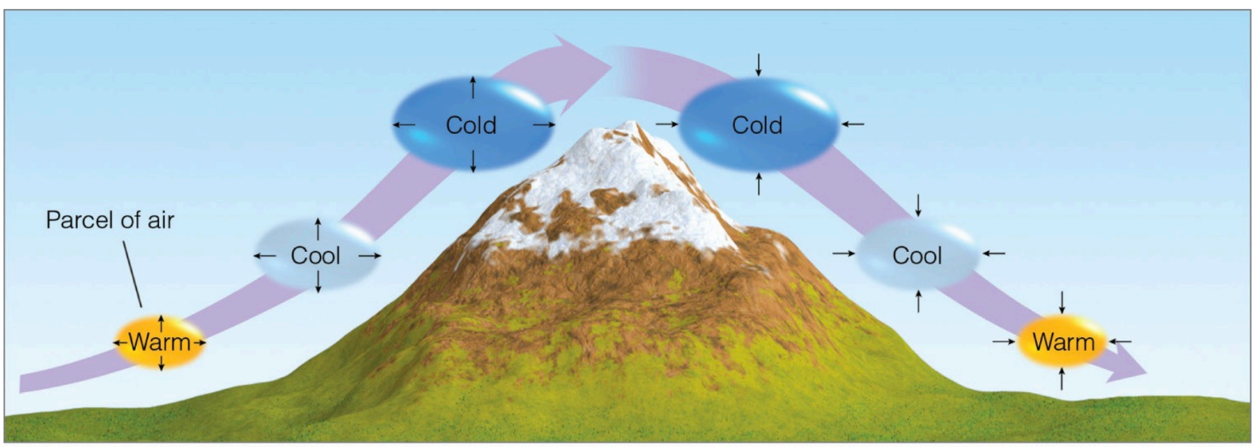
$$\Delta T = -\left(\frac{g}{C_p}\right)\Delta z \quad \text{or} \quad \Delta T = \frac{\alpha}{C_p}\Delta p$$

α is the specific volume (α = 1 / ρ)

As an air parcel rises how will its temperature and pressure change?

These equations tell us that as air rises it expands and cools and as air sinks it is compressed and warms even though no energy enters or leaves the air parcel (Δq = 0).

In a dry adiabatic process why does the air parcel temperature change even though no heat (energy) was added to or removed from the air parcel?



For a dry adiabatic process the dry adiabatic lapse rate is given by:

$$\Gamma_d = -\frac{\Delta T}{\Delta z} = \left(\frac{g}{C_p}\right) = 9.8 \text{ K km}^{-1}$$

Potential temperature (θ): The temperature an air parcel would have if moved dry adiabatically to a reference pressure (P_0) of 1000 mb (or a height of 0 m).

The potential temperature can be calculated using:

$$\theta = T(z) + \Gamma_d z \quad \text{or} \quad \theta = T\left(\frac{P_0}{p}\right)^{R_d/C_p}$$

How will the potential temperature change as an air parcel rises dry adiabatically through the atmosphere?

Introduction to Thermodynamic Diagrams

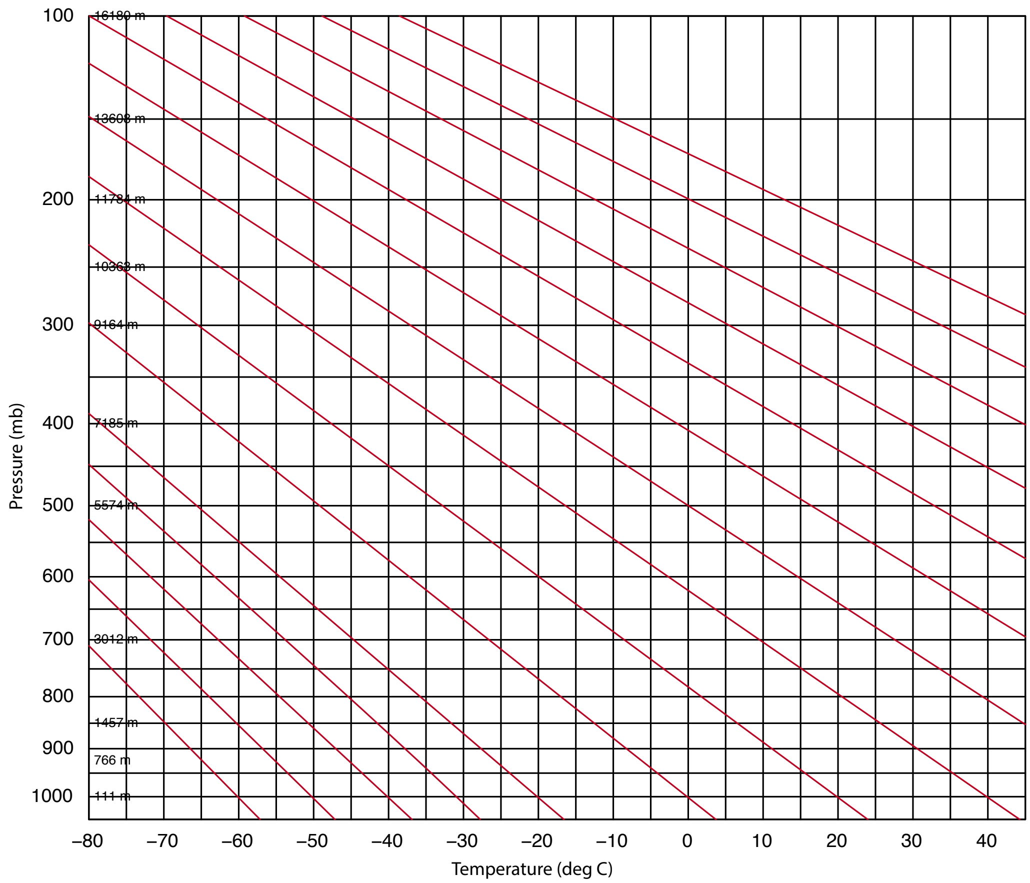
Convection: vertical air motion driven by differences in temperature

Air will rise convectively when an air parcel is warmer than its environment. Air will sink convectively when an air parcel is cooler than its environment

How can we determine if convection will take place in the atmosphere?

Need to compare an air parcel's temperature to the temperature of its environment.

We can do this by using a thermodynamic diagram.



A basic thermodynamic diagram shows pressure (on the vertical axis) and temperature (on the horizontal axis).

What are the lines of constant pressure and temperature on a thermodynamic diagram known as?

The equation relating temperature and pressure at different levels in the atmosphere for a dry adiabatic process can also be plotted on a thermodynamic diagram and are known as dry adiabats.

Heat Budget at a Fixed Location

Eulerian Form of the First Law of Thermodynamics

Consider a volume of air at a fixed location.

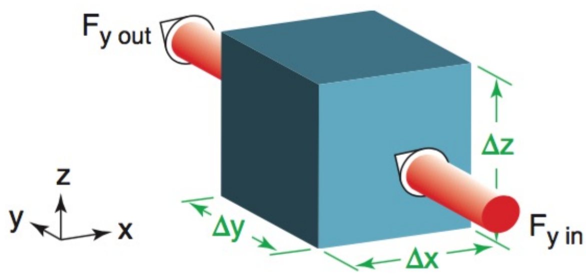
A forecast equation for temperature, based on the first law of thermodynamics for this volume of air, assuming that the pressure is not changing, is given by:

$$\frac{\Delta T}{\Delta t} = \frac{1}{C_p}\frac{\Delta q}{\Delta t}$$

What do the terms in this equation represent physically?

What processes can add or remove heat from an air parcel?

- Heat can be transported into or out of the box
- Heat can be released (or consumed) within the box



These processes can be represented as:

$$\frac{\Delta T}{\Delta t} = -\frac{1}{\rho C_p}\left[\frac{\Delta F_x}{\Delta x} + \frac{\Delta F_y}{\Delta y} + \frac{\Delta F_z}{\Delta z}\right] + \frac{\Delta S_0}{C_p \Delta t}$$

What do the terms in these equations represent physically?

What are the units for this equation?

The left hand side has units of K s^{-1}, so all of the terms must have the same units.

The heat fluxes (F) have units of J m^{-2} s^{-1} or W m^{-2}

$$-\frac{1}{\rho C_p}\frac{\Delta F_x}{\Delta x}[=]\frac{1}{\left(\text{kg m}^{-3}\right)\left(\text{J kg}^{-1}\ \text{K}^{-1}\right)}\frac{\text{J m}^{-2}\ \text{s}^{-1}}{\text{m}}[=]\frac{\text{K}}{\text{s}}$$

$$\frac{\Delta S_0}{C_p \Delta t}=\frac{\text{J kg}^{-1}}{\left(\text{J kg}^{-1}\ \text{K}^{-1}\right)(\text{s})}=\frac{\text{K}}{\text{s}}$$

Heat flux divergence represents the net heat transport into or out of the box.

How do you determine the sign of the heat flux divergence?

$$-\frac{\Delta F_x}{\Delta x}=\frac{F_{x\ \text{eastside}}-F_{x\ \text{westside}}}{x_{\text{eastside}}-x_{westside}}$$

Under what condition will the heat flux divergence term cause the temperature of the box to increase (decrease)?

What are some processes that can result in heat being transported into or out of the box?

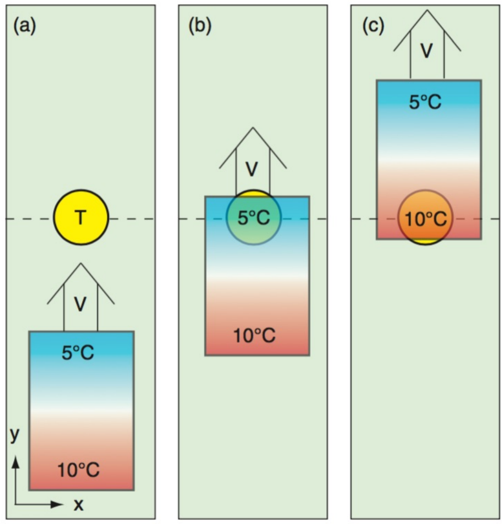
$$\frac{\Delta F_x}{\Delta x}=\left.\frac{\Delta F_x}{\Delta x}\right|_{adv}+\left.\frac{\Delta F_x}{\Delta x}\right|_{cond}+\left.\frac{\Delta F_x}{\Delta x}\right|_{turb}+\left.\frac{\Delta F_x}{\Delta x}\right|_{rad}$$

What are examples of internal sources (or sinks) of heat (ΔS_0) within the box?

Next, we will consider the different heat flux divergence and internal source terms in the first law of thermodynamics.

Advection of Heat

Advection: The transport of an atmospheric property by the movement of air (wind)



Temperature advection: The transport of heat by the wind

How will the temperature at a fixed weather station change if a south wind is blowing and it is warmer to the south than the north?

The advective heat flux divergence in the first term on the right hand side of the first law of thermodynamics can be calculated as:

$$\frac{\Delta F_{x\ adv}}{\Delta x} = U\frac{T_{east} - T_{west}}{x_{east} - x_{west}} = U\frac{\Delta T}{\Delta x}$$

$$\frac{\Delta F_{y\ adv}}{\Delta y} = V\frac{T_{north} - T_{south}}{y_{north} - y_{south}} = V\frac{\Delta T}{\Delta y}$$

The vertical temperature advection needs to account for the fact that air adiabatically warms or cools as it sinks or rises.

$$\frac{\Delta F_{z\ adv}}{\Delta z} = W\left[\frac{T_{top} - T_{bottom}}{z_{top} - z_{bottom}} + \Gamma_d\right] = W\left[\frac{\Delta T}{\Delta z} + \Gamma_d\right]$$

Molecular Conduction and Surface Fluxes

How is this energy transferred from the ground to the air and up through the atmosphere?

Molecular heat conduction occurs as molecules with different temperatures (molecular kinetic energy) transfer their energy to adjacent molecules.

Is the conductive heat flux important in the atmosphere? Why or why not?

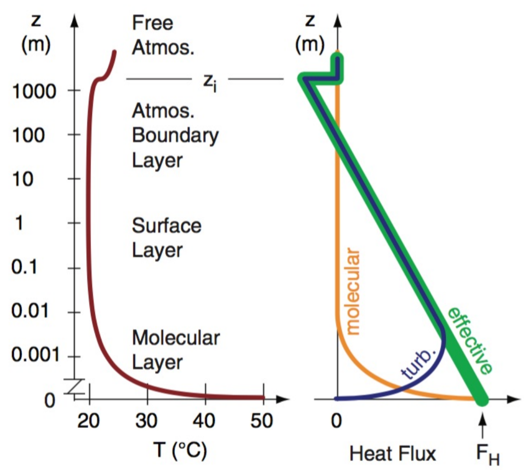
Atmospheric boundary layer (ABL): The lower portion of the atmosphere that feels the influence of the underlying surface.

The effects of the Earth's surface on the ABL include diurnal heating and cooling and slowing of the wind due to surface drag.

How deep is the boundary layer?

A defining characteristic of the boundary layer is that it is turbulent.

How would we recognize a turbulent portion of the atmosphere?



How is heat transferred from the ground to the atmosphere?

The effective surface turbulent heat flux (F_H) combines the conductive and turbulent heat fluxes

$$\left(\frac{\Delta F_z}{\Delta z}\bigg|_{cond} + \frac{\Delta F_z}{\Delta z}\bigg|_{turb} \right).$$

The effective surface turbulent heat flux can be estimated as:

$$F_H = C_H \cdot M \cdot \left(T_{sfc} - T_{air}\right) = C_H \cdot M \cdot \left(\theta_{sfc} - \theta_{air}\right)$$

where, *sfc* and *air* subscripts refer to the Earth's surface and the air temperature at 2 m above the ground.

M is the wind speed at 10 m above the ground.

C_H is a bulk transfer coefficient that represents the effectiveness of turbulence at transporting heat and ranges from 2 x 10^{-3} over a smooth surface (calm lake) to 2 x 10^{-2} over a rough surface (forest).

Turbulence can also transport other properties between the surface and the atmosphere including moisture and pollutants.

Solar and Infrared Radiation

The radiative heat flux divergence $\left(\left. \frac{\Delta F_z}{\Delta z} \right|_{rad} \right)$ must be estimated when using the first law of thermodynamics to calculate the rate of change of temperature in the atmosphere.

How will the amount of solar and infrared radiation absorbed and emitted by the atmosphere vary spatially?

In the troposphere, away from clouds, the radiative heat flux divergence due to infrared radiation results in cooling rates of 0.1 to 0.2 K h^{-1} and is near 0 K h^{-1} for solar radiation.

Internal Sources of Heat

The heat fluxes discussed above represent energy being transferred across an air parcel boundary.

What are some examples of internal sources of heat (ΔS_0) within an air parcel?

If water changes phase within an air parcel the latent heat associated with that phase change needs to be accounted for.

$$\frac{\Delta S_0}{C_p \Delta t} = \frac{L_v}{C_p} \frac{\Delta m_{water}}{m_{air} \Delta t}$$

Δm_{water} is the mass of water that has changed phase. This will be positive if water vapor is condensing and negative if liquid water is evaporating.

m_{air} is the mass of air in which the water is changing phase.

L_v is the latent heat of vaporization (2.5×10^6 J kg^{-1})
See the latent heat factor table (Table 3-1) for latent heat values to use for melting, freezing, sublimation, or deposition.

C_p is the specific heat of air at constant pressure (1004 J kg^{-1} K^{-1})

Example: Estimate the heating rate for a rainfall rate of 4 mm h^{-1}.

Simplified Eulerian Heat Budget

We can use the various heat budget terms from above to write an Eulerian heat budget equation.

For this we will assume that the following processes are negligible:
- vertical temperature advection by the mean wind
- horizontal turbulent heat transport
- molecular conduction
- shortwave heating of the air
- IR cooling of the air

This gives:

$$\left.\frac{\Delta T}{\Delta t}\right|_{x,y,z} = -\left[U\frac{\Delta T}{\Delta x} + V\frac{\Delta T}{\Delta y}\right] - \frac{\Delta F_{z\ turb}}{\Delta z} + \frac{L_v}{C_p}\frac{\Delta m_{water}}{\Delta m_{air}\Delta t}$$

What does each term in this equation represent?

How can this equation be used?

Heat Budget at the Earth's Surface

How can we represent the heat budget of the surface of the Earth?

The heat budget equation at the surface of the Earth is given by:

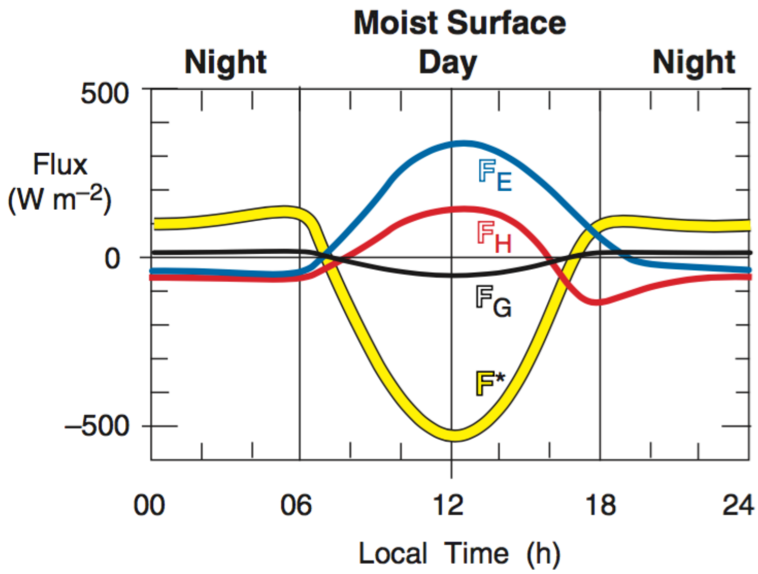
$$0 = F^* + F_H + F_E - F_G$$

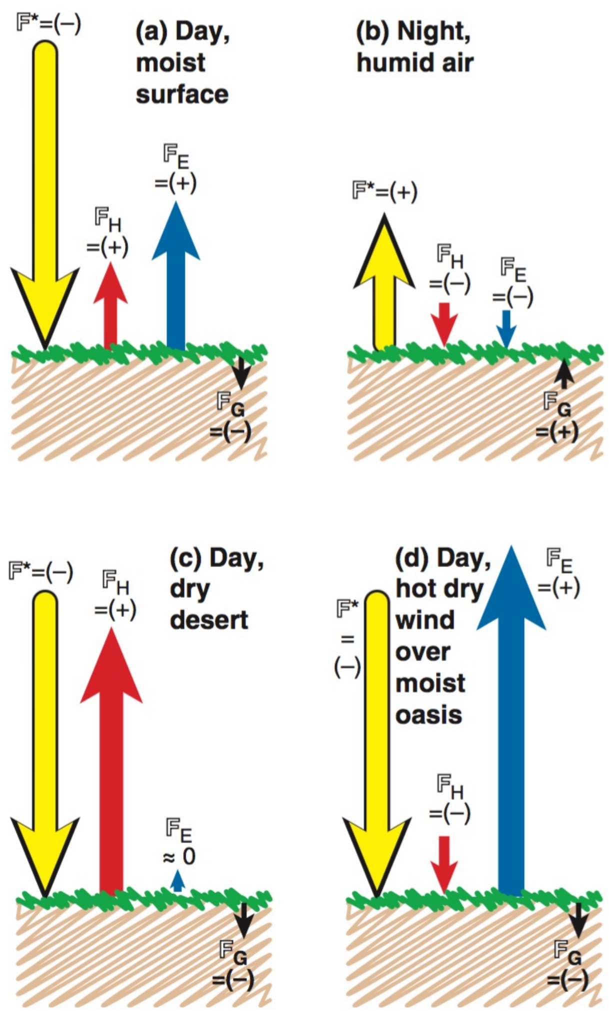
F^* - net radiation between the surface and atmosphere
F_H - effective surface turbulent heat flux
F_E - effective surface latent heat flux
F_G - molecular heat conduction

These terms are positive if directed upward towards the atmosphere.

Why is there a negative sign in front of the F_G term?

How do the terms in the surface heat budget vary from day to night?





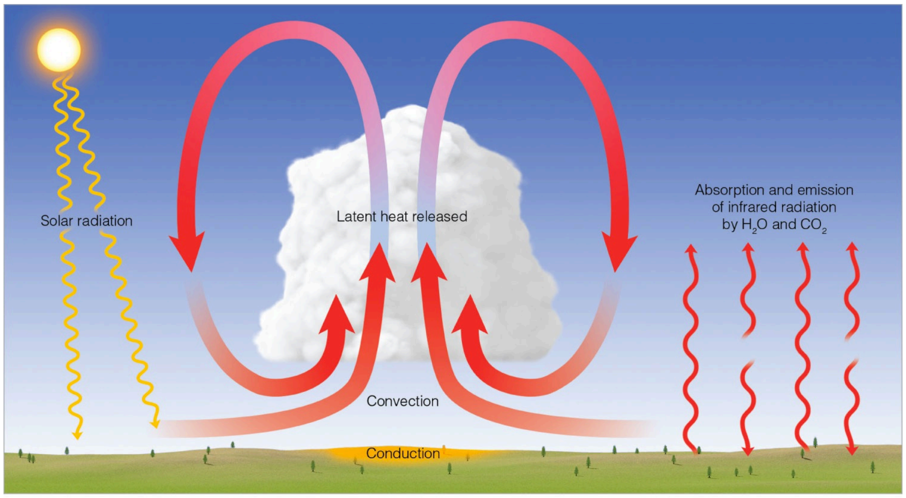
By what mechanisms do the air and ground warm during the day?

By what mechanisms do the air and the ground cool at night?

Radiational cooling: A process in which the ground and the air lose energy by radiating infrared energy.

How do the surface energy budget terms vary if the surface is moist or dry?

How is the atmosphere heated on a clear, sunny day?



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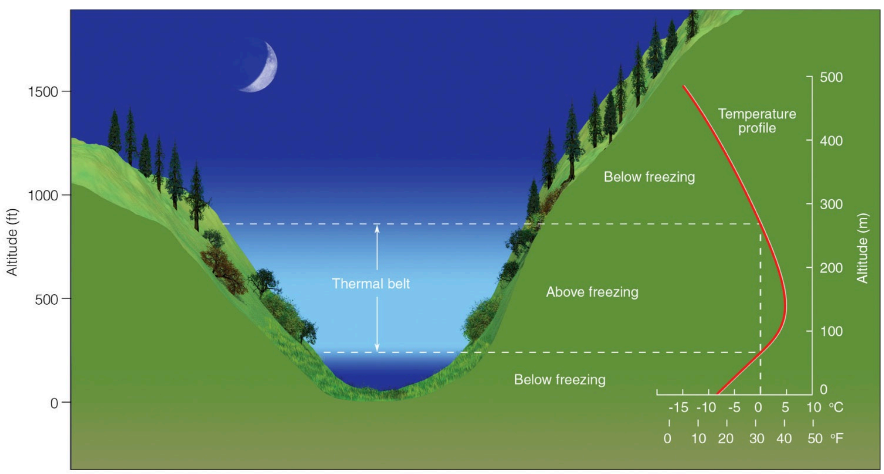
Radiation (or nocturnal) inversion: An increase in temperature away from the surface due to radiational cooling of the ground.



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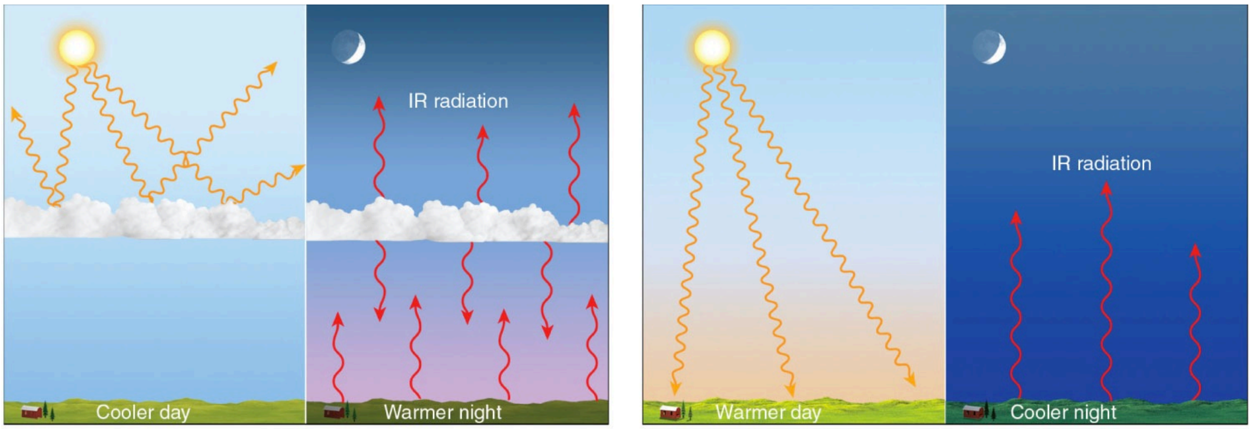
Why is temperature observed to increase as you move up away from the ground at night?

Why is the coldest air at night often found in valley bottoms?

Daily Temperature Variations

Diurnal temperature range: The difference between the daily maximum and minimum temperature

Factors that control the diurnal temperature range



(a) Small daily temperature range

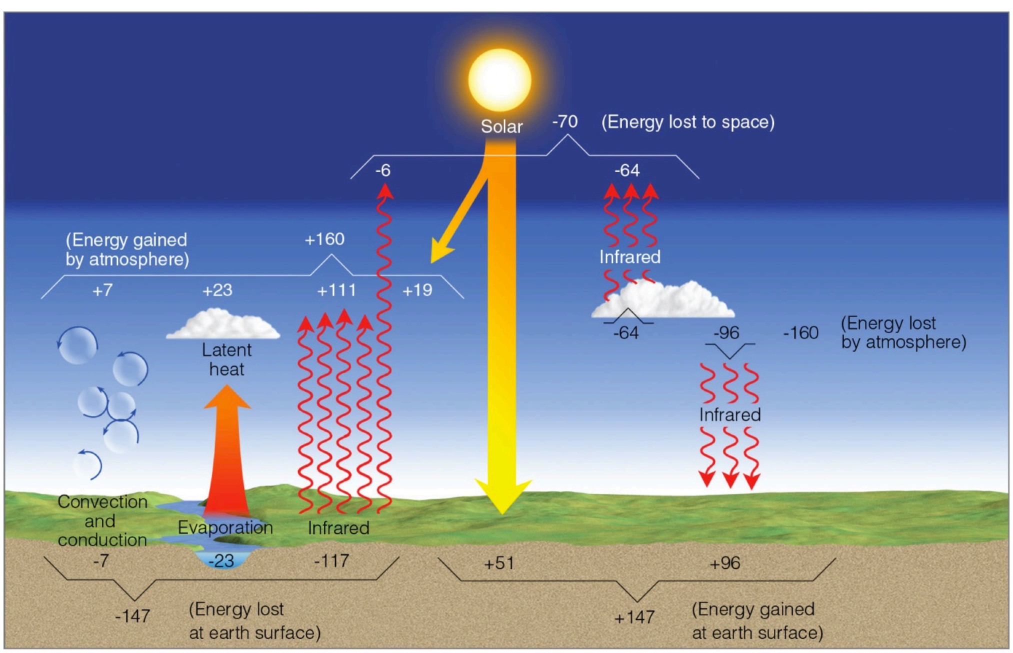
(b) Large daily temperature range

What factors control how warm it can become during the day?

What factors favor the coldest nighttime temperatures and strongest nocturnal inversions?

The Earth's Annual Energy Budget

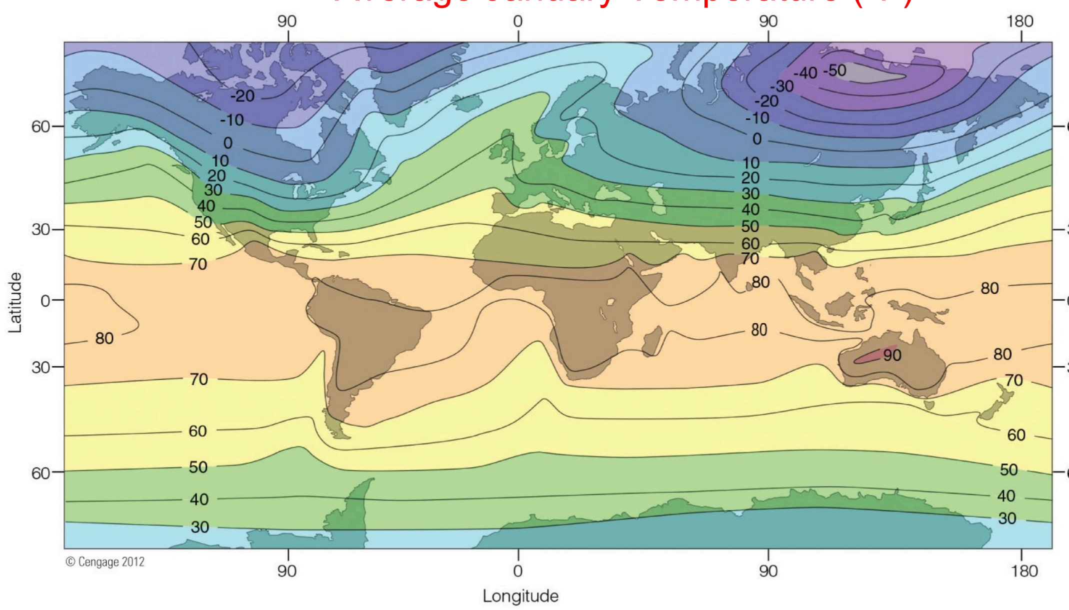
On an annual basis the earth and atmosphere have a balance between energy gained and lost.



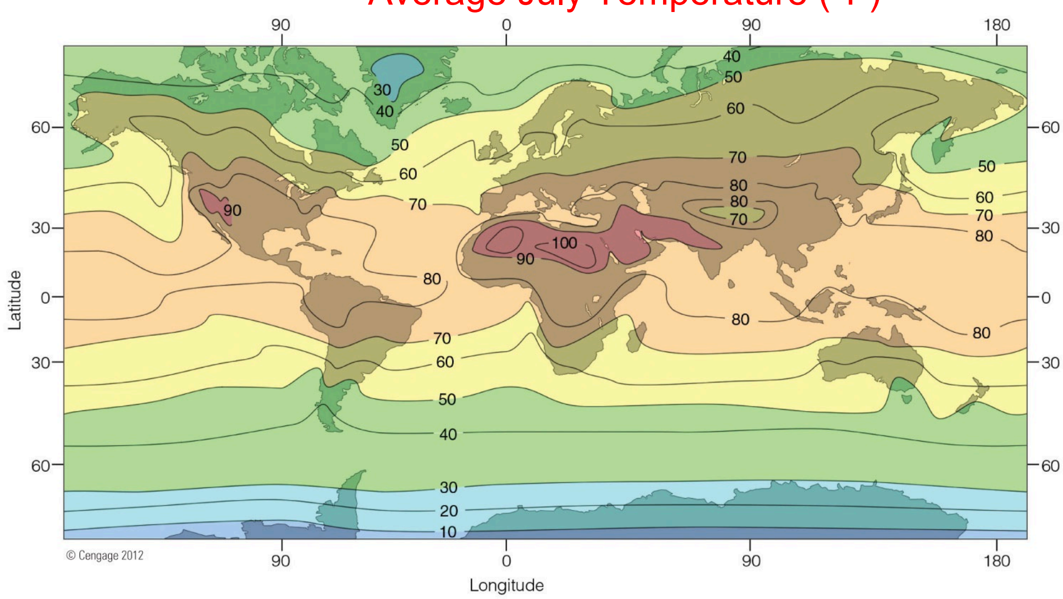
Regional Temperature Variations

Isotherm: A line on a map that connects locations with the same temperature.

Average January Temperature (°F)



Average July Temperature (°F)



What are the four main factors that control how temperature varies from one location to another?

How does the distribution of temperature differ between the summer and winter hemispheres?

Where is the warmest air found in January (July)?

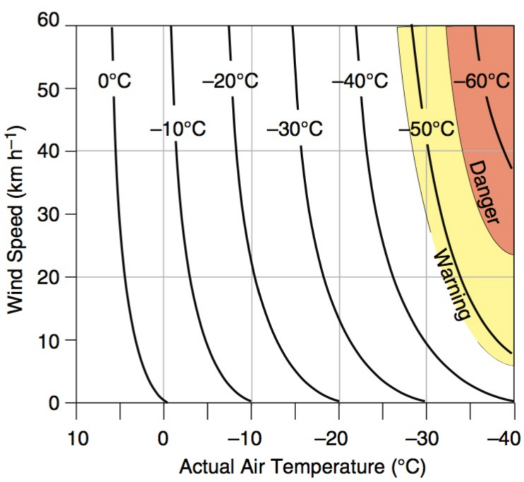
Why does the temperature over the ocean vary less between January and July than it does over land at similar latitudes?

Apparent Temperature Indices

How hot or cold we feel depends on more than just the air temperature.

By what mechanisms does the human body transfer energy to and from its environment?

The wind chill and heat indices attempt to account for how exposed skin "feels" under windy or humid conditions compared to reference conditions of light winds and moderate humidity.



Wind Chill Index

Besides temperature and wind what other factors impact how cold we feel?

Frostbite: Freezing of the skin.

Hypothermia: A lowering of the body's core temperature below its normal range.

The heat index accounts for the role of humidity in making you feel warmer (or cooler) than the actual air temperature.

Why does humidity alter how you perceive the temperature?