The Elements of Weather

I. Energy, Heat & Temperature
  - Adiabatic Heating & Cooling
  - Latent Heat

II. Temperature

III. Humidity

IV. Air Pressure

V. Winds

Image: NOAA

Science Partnership

NSF

California Science Project

CALIFORNIA STATE UNIVERSITY EAST BAY

ALAMEDA COUNTY OFFICE OF EDUCATION

NGSS Performance Expectation
Collect data to provide evidence for how the motions and complex interactions of air masses results in changes in weather conditions. MS-ESS2-5
Clarification Statement: Emphasis is on how air masses flow from regions of high pressure to low pressure, causing weather (defined by temperature, pressure, humidity, precipitation, and wind) at a fixed location to change over time, and how sudden changes in weather can result when different air masses collide. Emphasis is on how weather can be predicted within probabilistic ranges. Examples of data can be provided to students (such as weather maps, diagrams, and visualizations) or obtained through laboratory experiments (such as with condensation).
Assessment Boundary: Assessment does not include recalling the names of cloud types or weather symbols used on weather maps or the reported diagrams from weather stations.

NGSS Disciplinary Core Ideas
Weather and climate are influenced by interactions involving sunlight, the ocean, the atmosphere, ice, landforms, and living things. These interactions vary with latitude, altitude, and local and regional geography, all of which can affect oceanic and atmospheric flow patterns. MS-ESS2-6

NGSS Cross-cutting Concepts
2. Cause and Effect
Events have causes, sometimes simple, sometimes multifaceted. Deciphering causal relationships, and the mechanisms by which they are mediated, is a major activity of science and engineering.
5. Energy and Matter
Tracking energy and matter flows, into, out of, and within systems helps one understand their system's behavior.

The study of weather is expressed in terms of *elements* that are quantities or properties that can be measured regularly in the atmosphere:

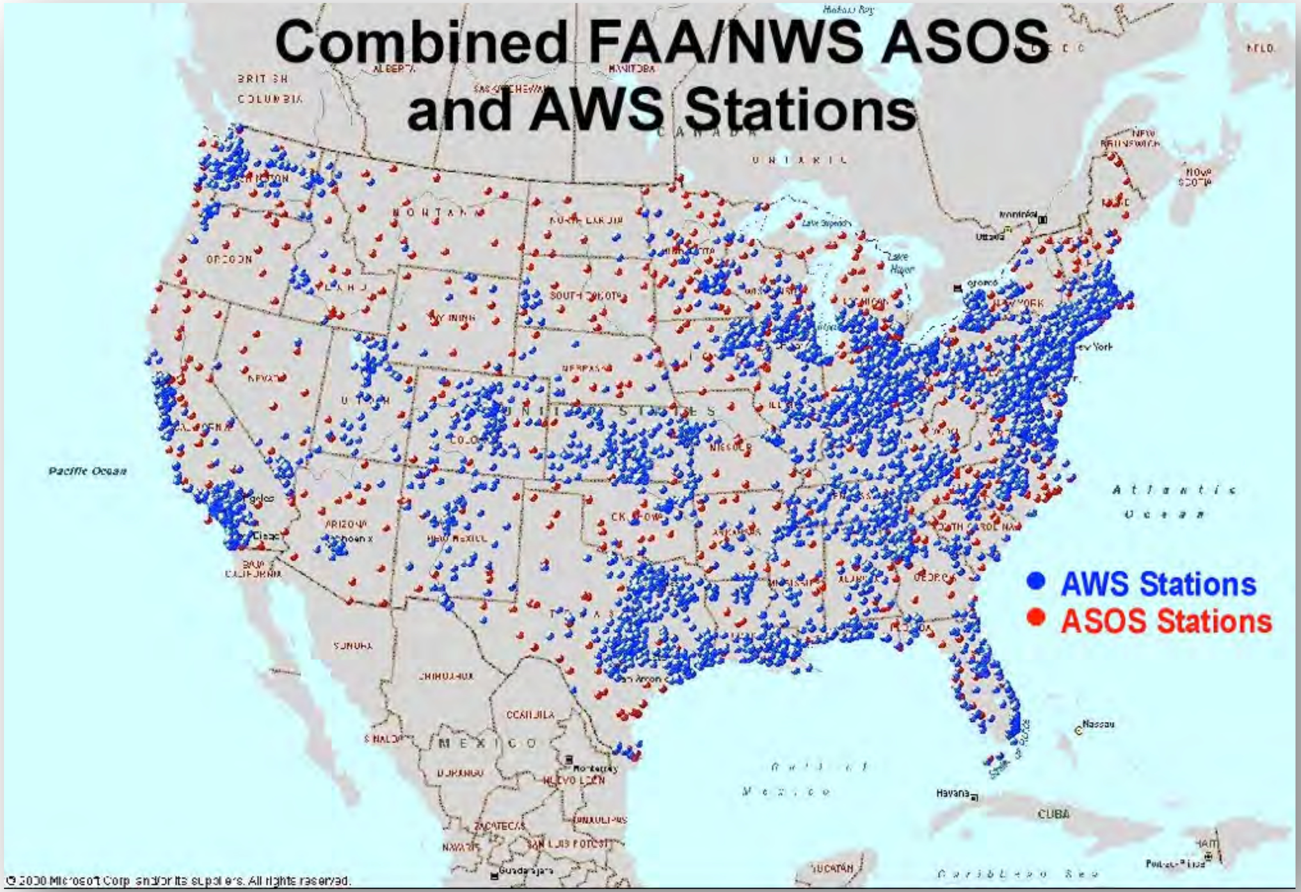
- Air temperature
- Humidity
- Air pressure
- Type and amount of cloudiness
- Type and amount of precipitation
- Wind speed and direction

We consider the weather *elements* separately, but they are interrelated - a change in one often results in a change in others.

NOAA

The elements of weather are constantly measured and the observations are used for monitoring weather events and forecasts.

The map shows the distribution of weather stations operated by the National Weather Service (NWS) and Federal Aviation Administration (FAA).



ASOS = Automated Surface Observing Station
AWS = Automated Weather Station

I. Energy, Heat, and Temperature

Temperature is the quantity that tells us how hot or cold an object is - relative to some other object or standard.

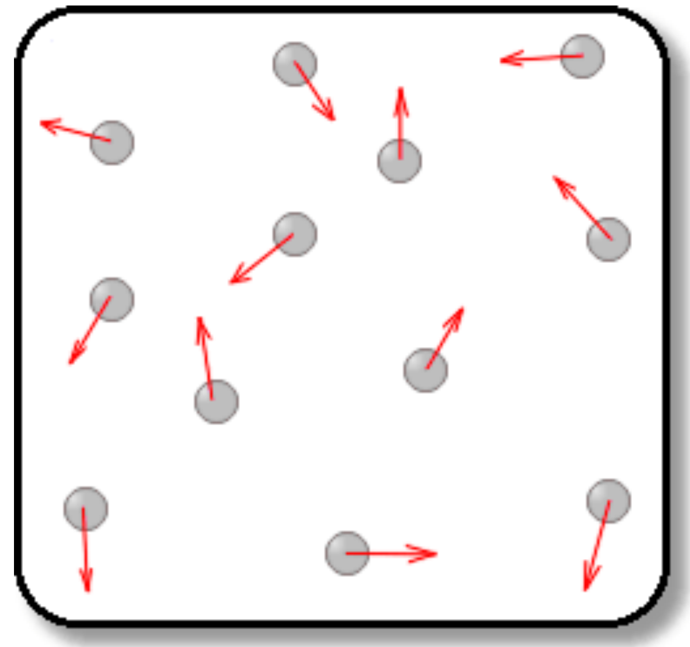
Remember that objects expand as they heat and contract as they cool - in meteorology that implies that warm air is less dense and cool air is more dense.

Heat is energy in the process of being transferred from one object to another because of a temperature difference.

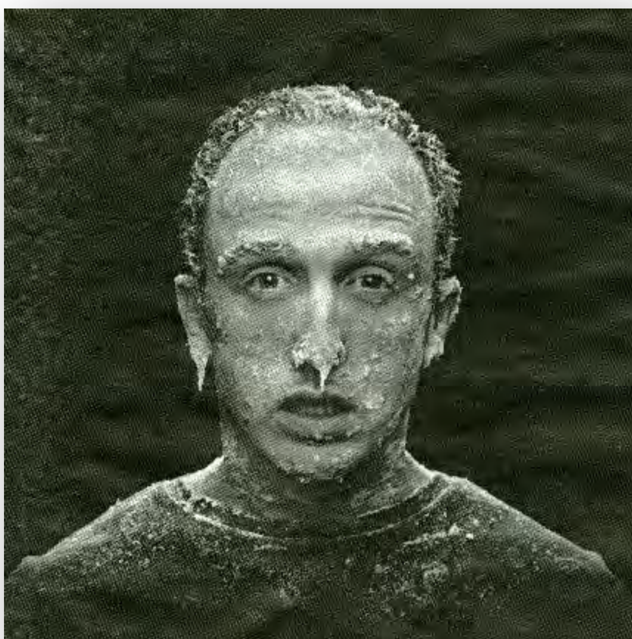
NOAA

Emirates Engineering

A more precise way to look at temperature (as a measurable quantity) is as a measure of the average *kinetic energy* of atoms and molecules.



Molecular motion increases with an increase in energy (heat) — the molecules have a higher *kinetic energy*. Thus, higher temperatures correspond to higher *kinetic energy* or faster molecular motion.



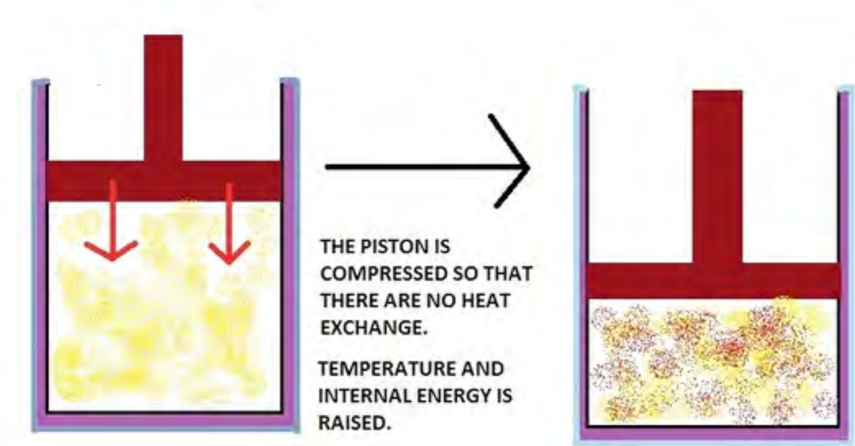
It is an important concept to understand the relationship between heat (temperature) and molecular motion.

The concept of absolute zero implies that molecular motion and vibration are at the slowest that they can be.

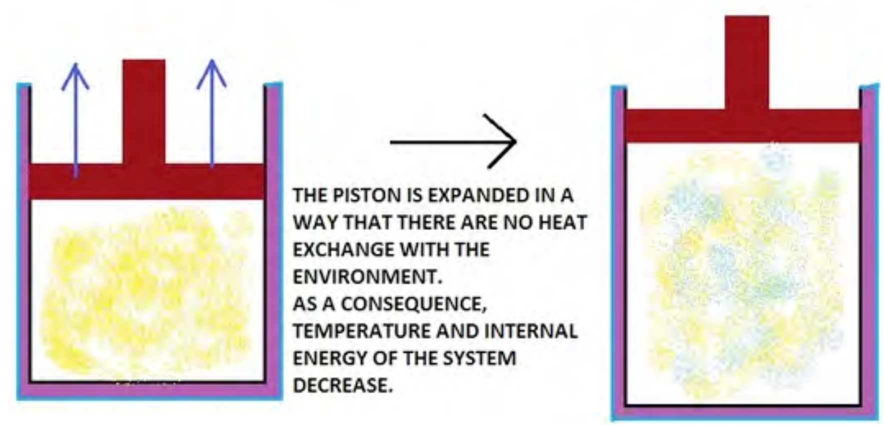
Adiabatic Heating and Cooling

An *adiabatic process* is a process that occurs without the transfer of heat or matter between a system and its surroundings. Adiabatic changes in temperature (heating and cooling) occur due to changes in gas pressure. Adiabatic heating and cooling (from compression or decompression of gas) is a function of the “work” done on a system.

Increase in gas pressure results in an increase in temperature.



Decrease in gas pressure results in a decrease in temperature.

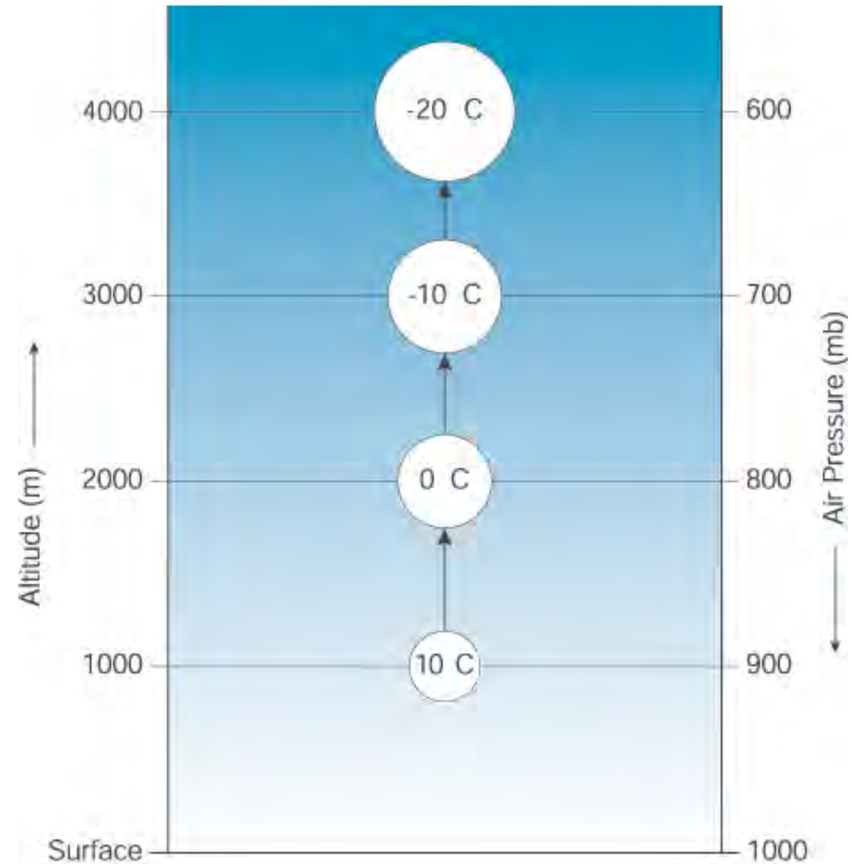


Chemistry LibreTexts

As an *air parcel* rises in the atmosphere, the parcel will increase in volume due to the decrease in pressure.

An *air parcel* is an imaginary body of air that is permitted to change its volume but not exchange heat with its surroundings.

The expansion of the air parcel is an adiabatic process results in decompression of the gas and a decrease in temperature.



Latent Heat

Latent heat is the heat energy that is exchanged when a substance is changed from one *state* (or *phase*) to another.

What are the common *states* of matter on Earth?

- Vapor
- Liquid
- Solid

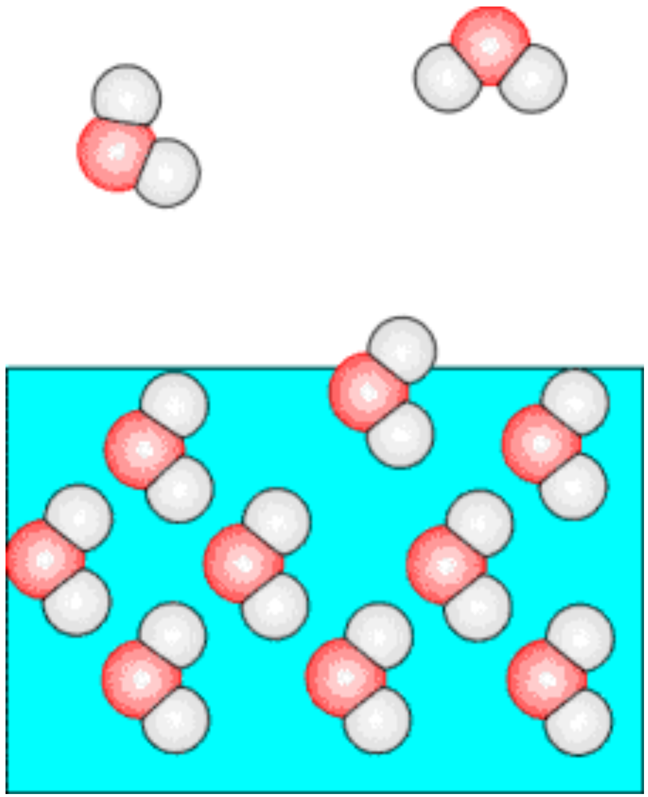
Water exists as three phases on Earth: water vapor in the air, liquid water, and ice.

When water changes from one state to another, we say that it undergoes a change of state or phase.

Name some of the processes that represent a change of state for water.

Latent Heat

One simple (intuitive) way of thinking about how heat is exchanged during a phase change is to consider a beaker of water; each molecule has a different amount of kinetic energy.



The faster molecules have more energy and can more easily escape from the liquid to the vapor. This represents evaporation (liquid → vapor).

As each of these high-energy molecules leaves the liquid, it leaves behind slower molecules (less kinetic energy) in the liquid and thus the temperature of the remaining water decreases.

Thus, *evaporation* is a cooling process.

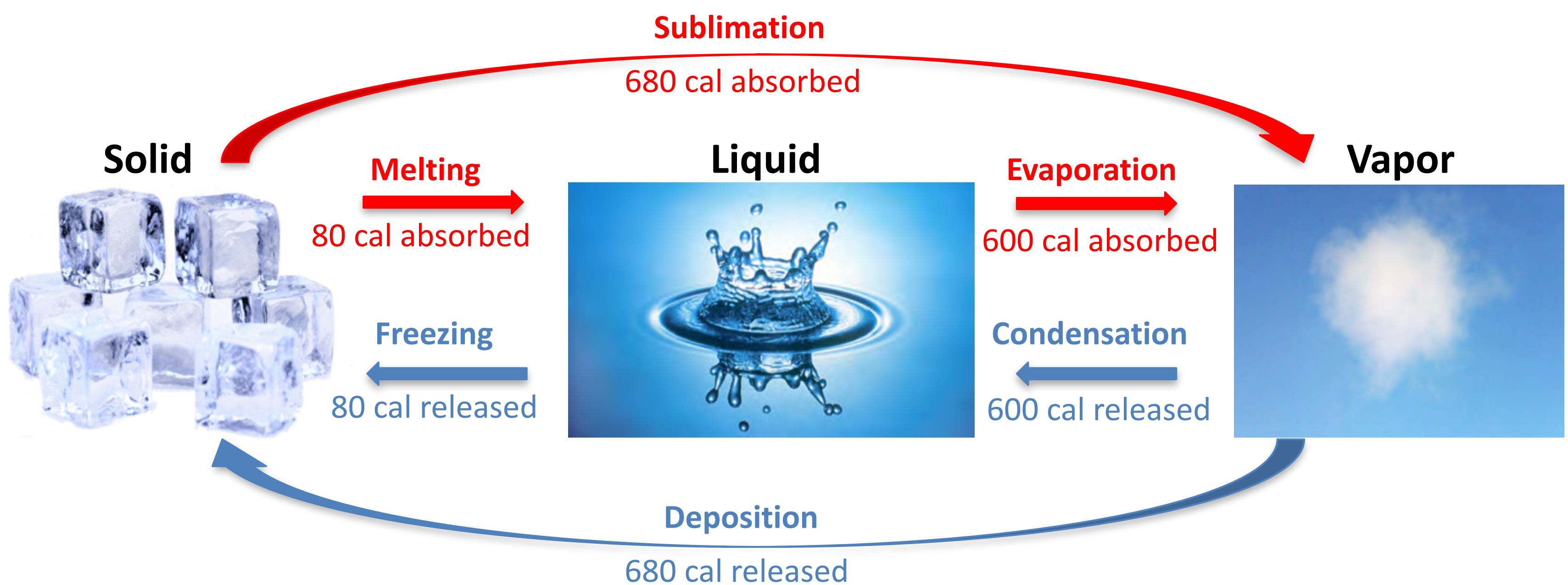
Condensation is the opposite of *evaporation* and releases heat to the environment (warming process).

It takes ~600 calories of heat energy to evaporate a single gram of water - this is known as the *latent heat of evaporation* (vaporization).

When a gram of water condenses, it releases the same amount of heat energy known as the *latent heat of condensation*.

Processes involving a change to a more disordered state usually results in a cooling process - energy is required and removed by the less "ordered" state.

Processes where you have a change to a more ordered state usually results in a warming process - the energy of the disordered state is released when it becomes more ordered.

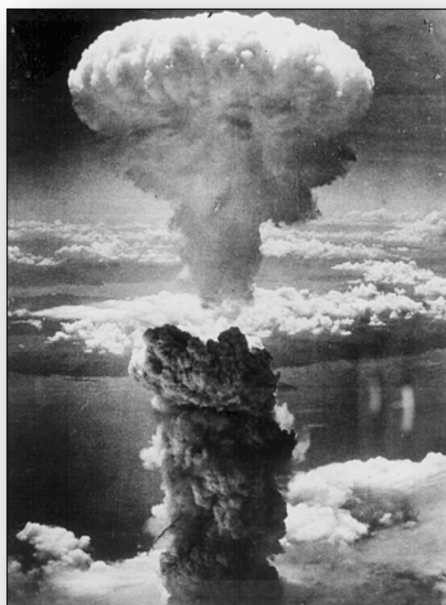


Latent heat is an important source of energy in the atmosphere and is responsible for the transfer of energy in the environment.

As a cloud forms, water vapor condenses to form tiny water droplets - releasing the latent heat of condensation. This heats the air in the cloud causing it to move upward (buoyancy).

During a thunderstorm, as equivalent to a small nuclear explosion is released into the environment.

Thunderstorm



Nagasaki

Physical Science Disciplinary Core Ideas: Matter & Chemical Reactions

Grade 2

PS1.A: Structure and Properties of Matter Different kinds of matter exist and many of them can be either solid or liquid, depending on temperature. Matter can be described and classified by its observable properties. (2-PS1-1)

PS1.B: Chemical Reactions Heating or cooling a substance may cause changes that can be observed. Sometimes these changes are reversible, and sometimes they are not.

Middle School

PS1.A: Structure and Properties of Matter The changes of state that occur with variations in temperature or pressure can be described and predicted using these models of matter. (MS-PS1-4)

PS1.B: Chemical Reactions Some chemical reactions release energy, others store energy. (MS-PS1-6)

Physical Science Disciplinary Core Ideas: Temperature and Heat

Grade 4

PS3.B: Conservation of Energy and Energy Transfer Energy is present whenever there are moving objects, sound, light, or heat. When objects collide, energy can be transferred from one object to another, thereby changing their motion. In such collisions, some energy is typically also transferred to the surrounding air; as a result, the air gets heated and sound is produced. (4-PS3-2), (4-PS3-3)

Middle School

PS3.A: Definitions of Energy The term "heat" as used in everyday language refers both to thermal energy (the motion of atoms or molecules within a substance) and the transfer of that thermal energy from one object to another. In science, heat is used only for this second meaning; it refers to the energy transferred due to the temperature difference between two objects. (secondary to MS-PS1-4)

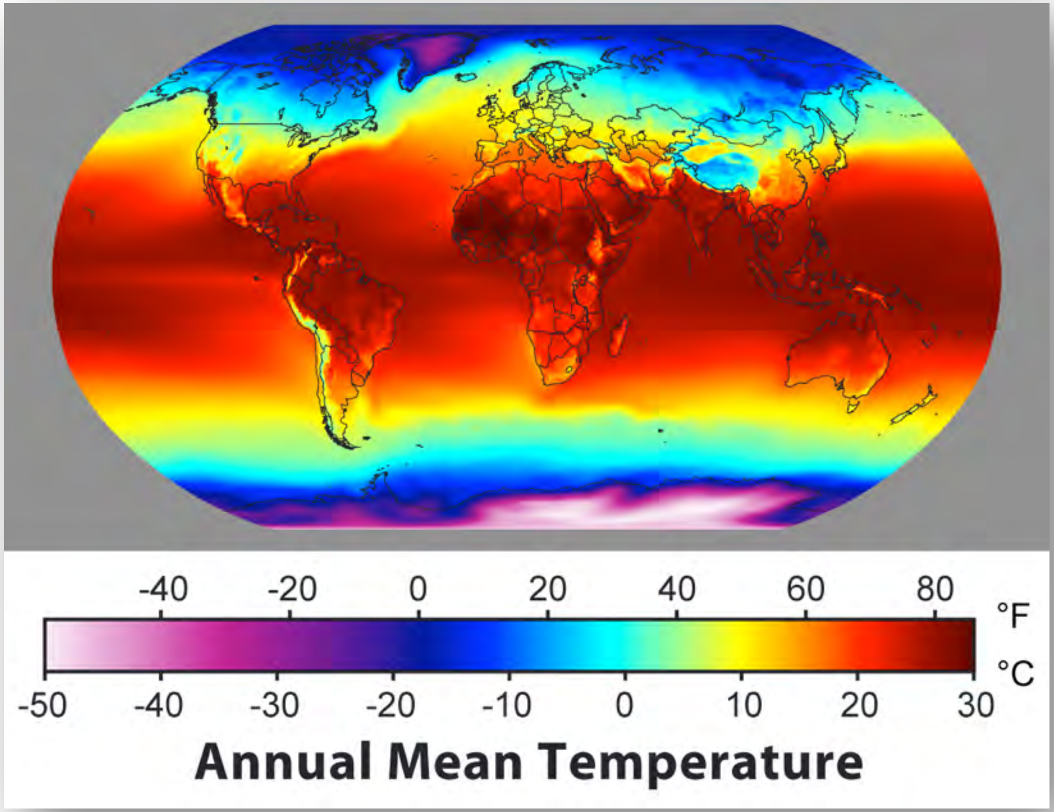
The temperature of a system is proportional to the average internal kinetic energy and potential energy per atom or molecule (whichever is the appropriate building block for the system's material). The details of that relationship depend on the type of atom or molecule and the interactions among the atoms in the material. Temperature is not a direct measure of a system's total thermal energy. The total thermal energy (sometimes called the total internal energy) of a system depends jointly on the temperature, the total number of atoms in the system, and the state of the material. (secondary to MS-PS1-4)

PS3.B: Conservation of Energy and Energy Transfer Energy is spontaneously transferred out of hotter regions or objects and into colder ones. (MS-PS3-3)

II. Temperature

Temperature is a primary measurement used in studying the atmosphere.

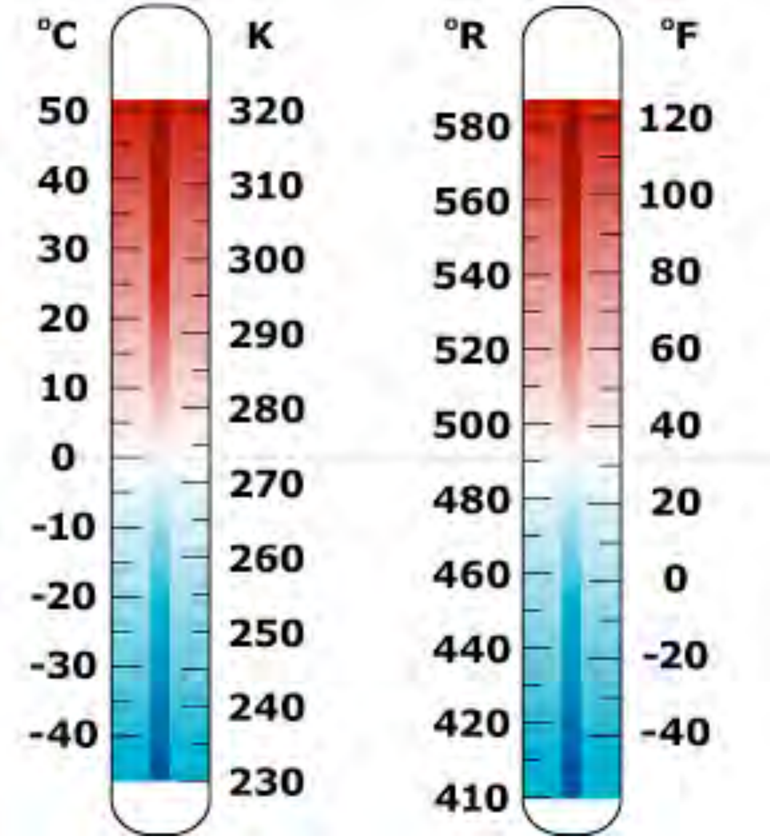
Temperature is a numerical measure of hot and cold and is usually measured by the kinetic (translational and vibrational) energy or electromagnetic energy emitted by a substance.



Temperature is important in studying the atmosphere because temperature affects physical properties (density, vapor pressure, etc.) and the rate of chemical reactions (generally the rate increases with temperature).

Temperature scales

Celsius (aka centigrade) is the standard scale where 0°C is the freezing point of water and 100°C is the boiling point of water (traditionally).



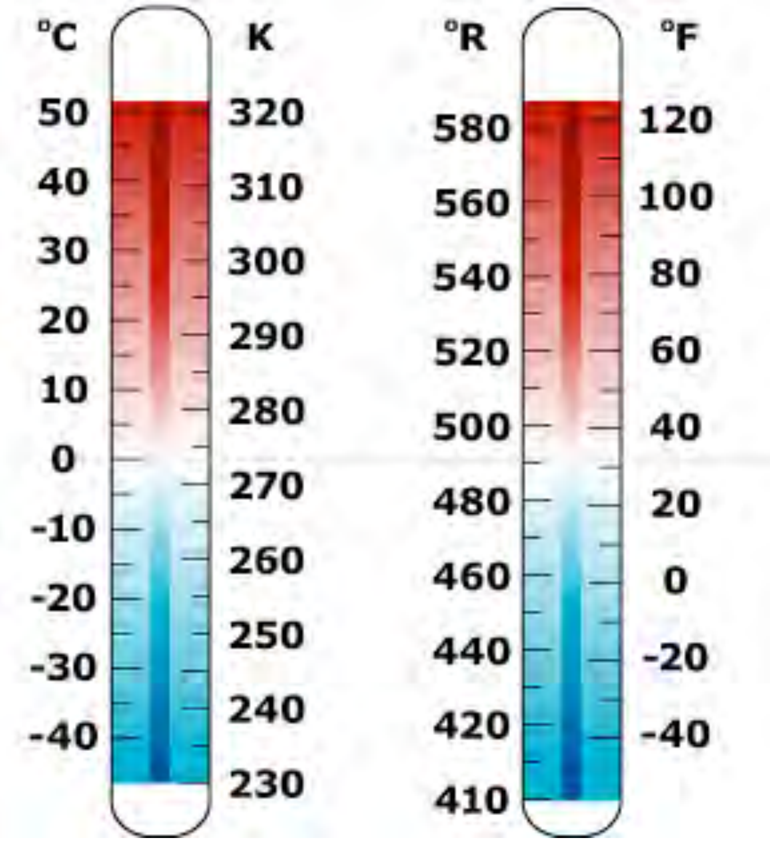
The Celsius and Kelvin scales are related and often used in combination in science and engineering.

The Kelvin scale is an absolute temperature scale where 0 K is absolute zero. Note the absence of the degree symbol (°).

The United States is the only industrialized nation that has not adopted the Celsius scale.

The Fahrenheit scale (proposed in 1724) was based on arbitrary anchor points

- 0 °F was the coldest that a brine solution could be cooled
- 100 °F was thought to be the human core temperature



Water freezes and boils at 32 °F and 212 °F, respectively.

The Rankine scale is an absolute temperature scale that is based on Fahrenheit where 0 °R is absolute zero.

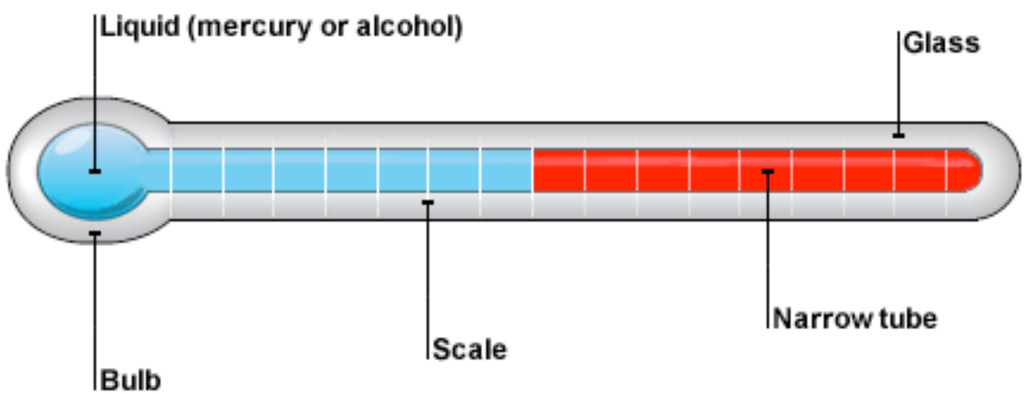
Absolute zero: -273.15 °C = 0 K = -459.57 °F = 0 °R

Freezing of water: 0 °C = 273.15 K = 32 °F = 491.67 °R

Boiling of water: 100 °C = 373.15 K = 212 °F = 671.64 °R

A *thermometer* is a device that is used to measure temperature. A thermometer works due to a physical change in a material as a function of temperature and a means of converting the physical change into a temperature.

A *bulb thermometer* contains a reservoir of a liquid material (commonly mercury or alcohol) at the probe end that expands/contracts as a function of temperature. With increasing temperature, the fluid expands into an evacuated and calibrated tube.



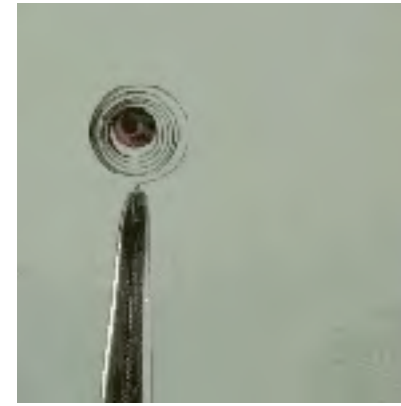
BBC

At 20 °C, the volume of mercury expands 0.02% per degree.

Alcohol expands 0.07% per degree.

Water has a thermal expansion of of 0.02% per degree that would make it a good thermometer. Why is it not commonly used in thermometers?

A *bimetal thermometer* consists of two strips of different metals that are layered and wrapped into a coil. Since the metals will expand/contract at different rates as the temperature changes, the coil will wind or unwind as a function of temperature. An indicator needle is attached to the coil and calibrated for temperature.



Wikimedia User:Hustvedt

A variety of electronic *digital thermometers* have been developed that are based on changes in electrical properties of materials (resistance, voltage, etc.) at in the temperature probe.

III. Humidity

Humidity is a general term that refers to a number of ways of talking about the moisture content of air. Humidity is an important parameter in the atmosphere because it indicates the likelihood for precipitation and fog. The humidity also affects the evaporation of sweat and thus the cooling of the body.

When air is saturated with water vapor, it is holding as much water as it can at a particular temperature. Not all air is saturated and we need a way to express the water content in air.

We will look at three common ways of representing the water-content of air:

- Absolute humidity
- Relative humidity
- Dew point temperature

Absolute humidity is the total amount of water vapor in a volume of air. At 30°C, the absolute humidity may range from nearly 0 to >30 g/m^3.
The table shows the absolute humidity of air at saturation as a function of air temperature. Clearly, warm air may hold more water vapor than cold air.

Temperature (°C)	Abs. Humidity (g/m^3)
0	4.8
10	9.4
20	17.3
30	30.4
40	51.1

Relative humidity (RH) is the ratio of the air's water vapor content compared to the maximum amount of water the air could hold at the same temperature.

A change in *relative humidity* can be brought about by

1. changing the air's water vapor content
2. changing the air temperature

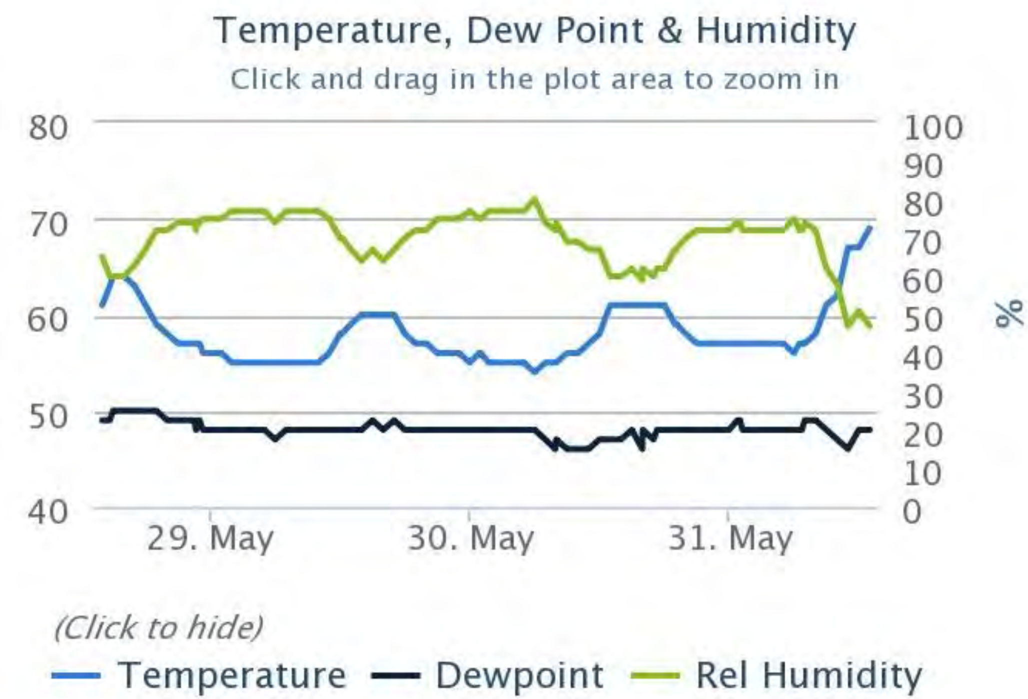
Wikimedia: Brocken Inaglory

Look up the current weather data for Hayward, CA.

- What relationships do you see?
- Explain.

Hayward Weather Data

Hayward, CA Weather Data



NWS

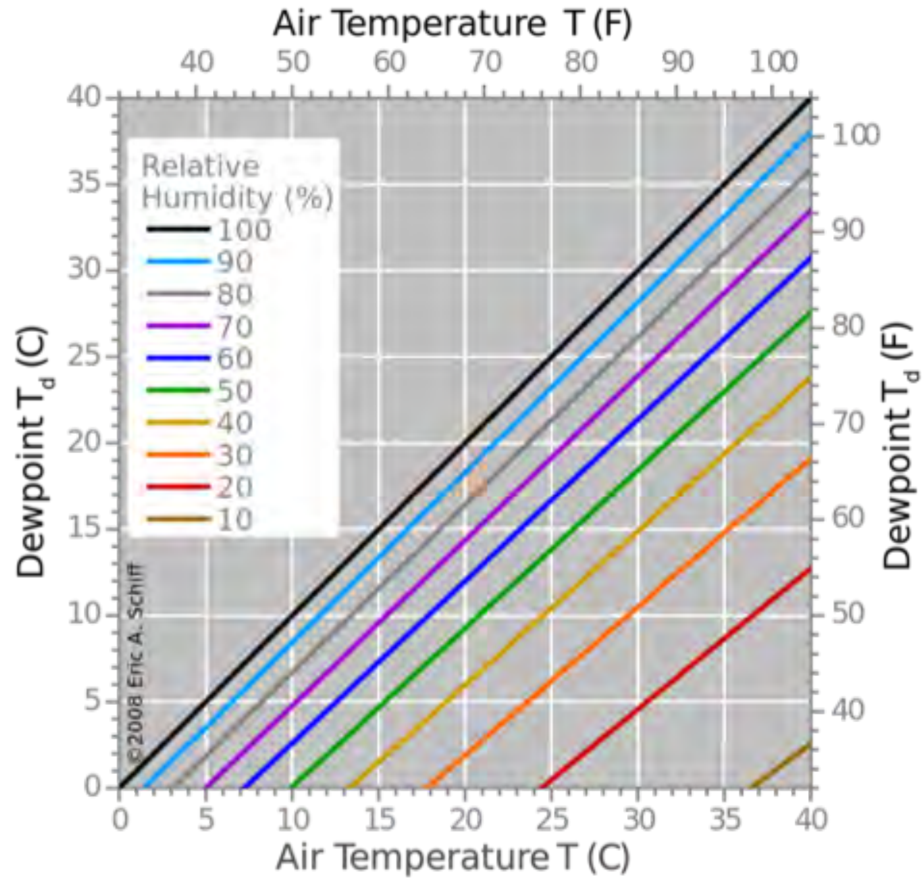
If the amount of water in the atmosphere is constant, daily changes in temperature change the *relative humidity* of the air.

A *decrease* in temperature results in an *increase* in *relative humidity*.

An *increase* in temperature results in a *decrease* in *relative humidity*.

The *dew-point temperature* is the temperature that air would have to be cooled (with no change in air pressure or moisture content) for water saturation to occur.

The *dew point temperature* is a good indicator of the air's actual water content.



Wikimedia User Easchiff

- When the *dew-point temperature* and air temperature are very different, the *relative humidity* is low.
- When the *dew-point temperature* is very close to the air temperature, the *relative humidity* is high.

If the *dew-point temperature* is equal to the air temperature then RH = 100%

Measuring Humidity

A *hygrometer* is a device for measuring the moisture content of the atmosphere. A *sling psychrometer* is a type of *hygrometer*.

Fisher Scientific

- *wet bulb* is a thermometer with a wet material wrapped around the bulb and measures the lowest temperature that can be reached by evaporating water
- *dry bulb* measures the air temp
- *wet bulb depression* is the temperature difference between the *wet* and *dry bulb*

The sling psychrometer is swung to enhance evaporation of water on the wet bulb.
A *sling psychrometer* operates based on the latent heat of water - the cooling of the wet bulb due to the evaporation of water.

If the air temperature (dry bulb) is 22°C and the difference between the wet bulb and dry bulb (wet bulb depression) is 4°C, The relative humidity is 68%.

Relative Humidity (%)

Dry-Bulb Tempera-ture (°C)	Difference Between Wet-Bulb and Dry-Bulb Temperatures (°C)															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
–20	100	28														
–18	100	40														
–16	100	48														
–14	100	55	11													
–12	100	61	23													
–10	100	66	33													
–8	100	71	41	13												
–6	100	73	48	20												
–4	100	77	54	32	11											
–2	100	79	58	37	20	1										
0	100	81	63	45	28	11										
2	100	83	67	51	36	20	6									
4	100	85	70	56	42	27	14									
6	100	86	72	59	46	35	22	10								
8	100	87	74	62	51	39	28	17	6							
10	100	88	76	65	54	43	33	24	13	4						
12	100	88	78	67	57	48	38	28	19	10	2					
14	100	89	79	69	60	50	41	33	25	16	8	1				
16	100	90	80	71	62	54	45	37	29	21	14	7	1			
18	100	91	81	72	64	56	48	40	33	26	19	12	6			
20	100	91	82	74	66	58	51	44	36	30	23	17	11	5		
22	100	92	83	75	68	60	53	46	40	33	27	21	15	10	4	
24	100	92	84	76	69	62	55	49	42	36	30	25	20	14	9	4
26	100	92	85	77	70	64	57	51	45	39	34	28	23	18	13	9
28	100	93	86	78	71	65	59	53	47	42	36	31	26	21	17	12
30	100	93	86	79	72	66	61	55	49	44	39	34	29	25	20	16

A *sling psychrometer* can also be used to determine the *dew point temperature*.

Using the previous example:

Dry bulb = 22 °C

Wet bulb depression = 4 °C

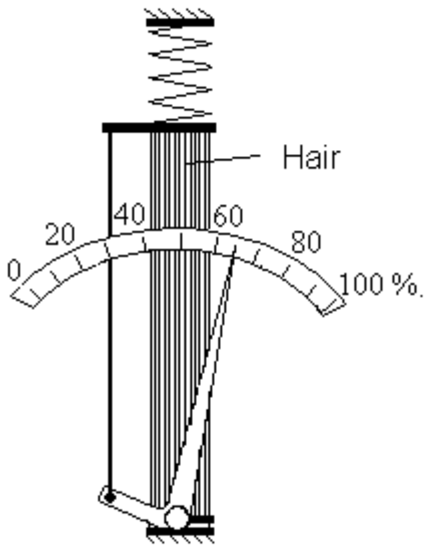
Then, the dew point temperature is 16°C.

Dew-point Temperatures (°C)

Dry-Bulb Temperature (°C)	Difference Between Wet-Bulb and Dry-Bulb Temperatures (°C)															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
–20	–20	–33														
–18	–18	–28														
–16	–16	–24														
–14	–14	–21	–36													
–12	–12	–18	–28													
–10	–10	–14	–22													
–8	–8	–12	–18	–29												
–6	–6	–10	–14	–22												
–4	–4	–7	–12	–17	–29											
–2	–2	–5	–8	–13	–20											
0	0	–3	–6	–9	–15	–24										
2	2	–1	–3	–6	–11	–17										
4	4	1	–1	–4	–7	–11	–19									
6	6	4	1	–1	–4	–7	–13	–21								
8	8	6	3	1	–2	–5	–9	–14								
10	10	8	6	4	1	–2	–5	–9	–14	–28						
12	12	10	8	6	4	1	–2	–5	–9	–16						
14	14	12	11	9	6	4	1	–2	–5	–10	–17					
16	16	14	13	11	9	7	4	1	–1	–6	–10	–17				
18	18	16	15	13	11	9	7	4	2	–2	–5	–10	–19			
20	20	19	17	15	14	12	10	7	4	2	–2	–5	–10	–19		
22	22	21	19	17	16	14	12	10	8	5	3	–1	–5	–10	–19	
24	24	23	21	20	18	16	14	12	10	8	6	2	–1	–5	–10	–18
26	26	25	23	22	20	18	17	15	13	11	9	6	3	0	–4	–9
28	28	27	25	24	22	21	19	17	16	14	11	9	7	4	1	–3
30	30	29	27	26	24	23	21	19	18	16	14	12	10	8	5	1

Other Types of Hygrometers

Metal-paper coil hygrometer. Consists of a coil of salt impregnated paper layer with a thin metal layer shaped into a coil. As water is absorbed by the salt, the shape of the coil changes. The humidity is indicated by a needle connected to the coil on a dial.



Hair hygrometer. Human and animal hair changes its length as a function of humidity. A hair hygrometer is a mechanical device that magnifies the change in the hair and is indicated by a dial.

Digital hygrometers. Some modern hygrometers measure the changes in the electrical properties (capacitance, resistance) of a material (polymer, salts, oxides).

Heat Index

Humans regulate body temperature by perspiration – evaporation removes body heat. When the relative humidity (RH) is high, the evaporation rate is much lower. The Heat Index is a parameter that combines temperature and humidity. It is an attempt to develop a scale of "how it feels."

NWS Heat Index — Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

Caution | Extreme Caution | Danger | Extreme Danger

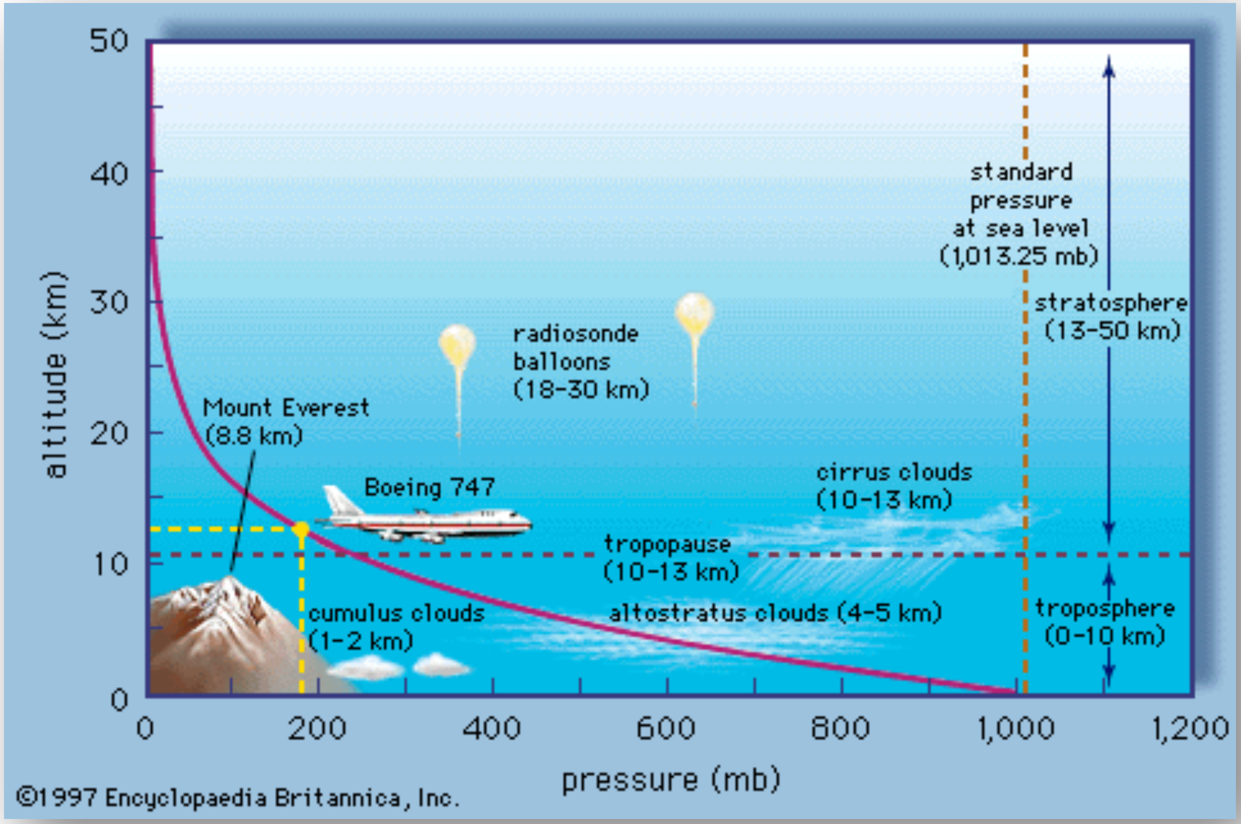
IV. Air Pressure

Atmospheric (Barometric) Pressure is the force exerted over a surface area by the weight of overlying air molecules.

Air pressure decreases with increasing altitude.

A 1-inch column of air would weigh ~14.7 pounds — thus air pressure at sea level is ~14.7 pounds per square inch.

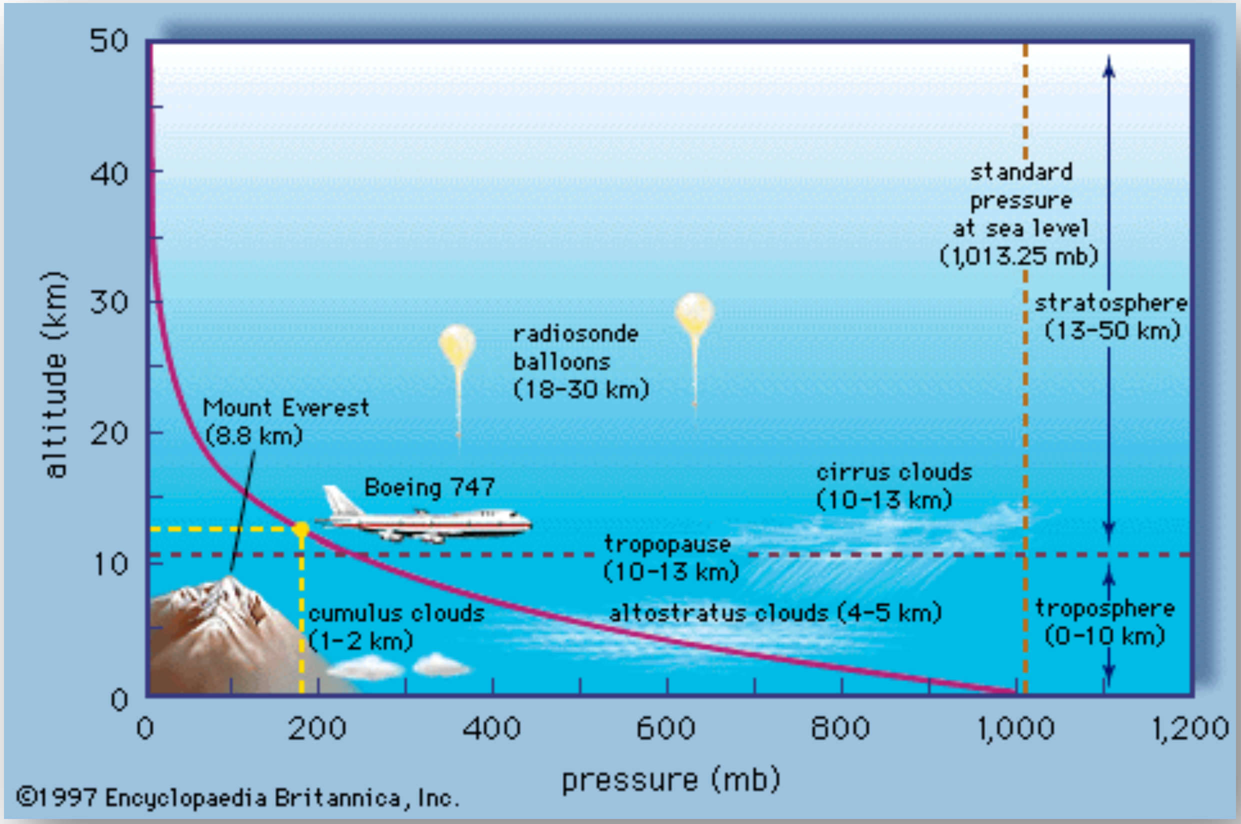
The weight of the air is ~1 kg per each cm^2 — at sea level, the atmospheric pressure is slightly more than 1000 millibars (mbar).



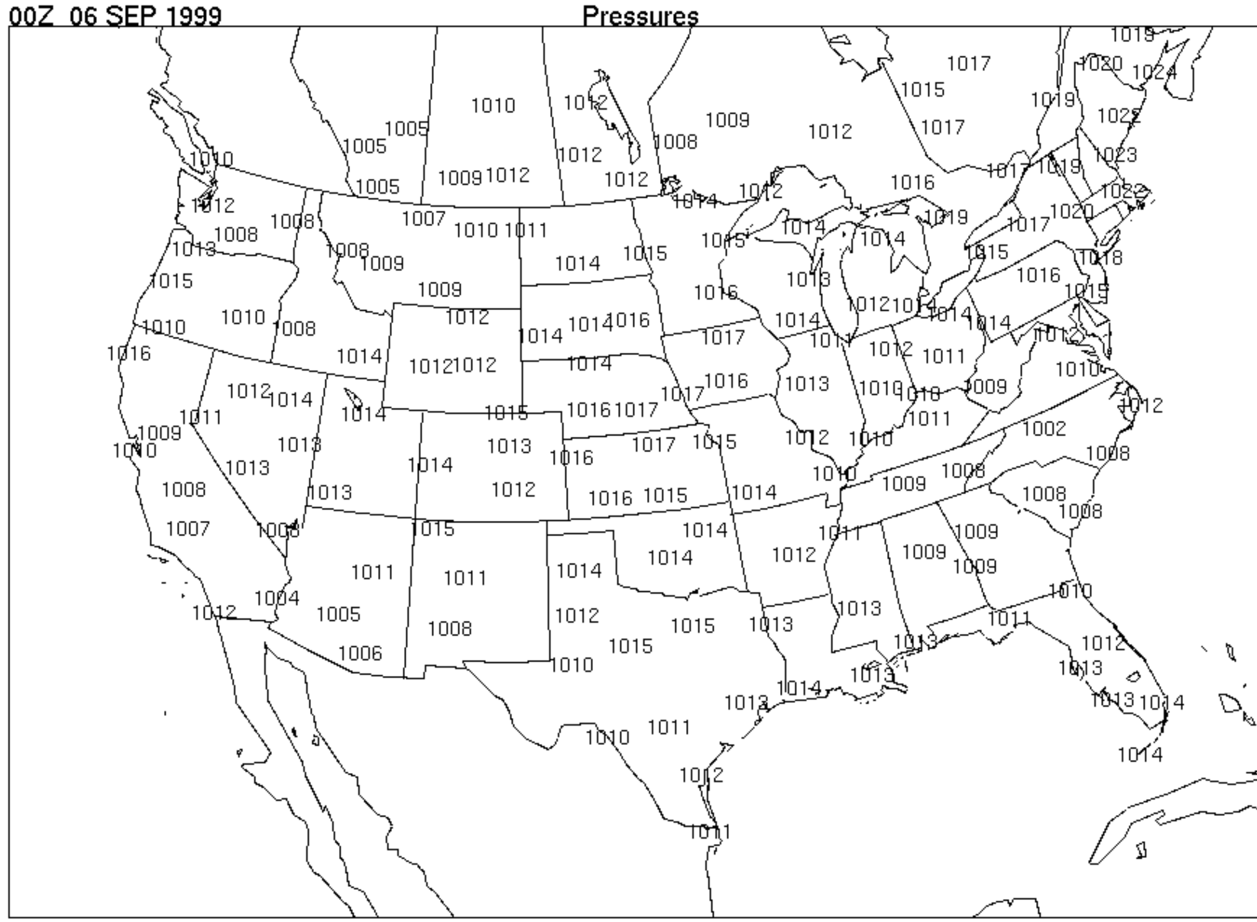
1 atmosphere = 14.7 psi = 1.013 bar = 1013 mbar

At an altitude of only ~5.6 km, the air pressure is less than half of what it is at sea level (~500 mb).

The atmosphere extends up for hundreds of kilometers gradually merging into empty space.



Since barometric pressure is a sensitive function of elevation, pressure is usually compensated for elevation to what the pressure would be the sea level. Otherwise, cities at high elevation (ex. Denver) would always to appear to be in a region of low pressure.



NWS

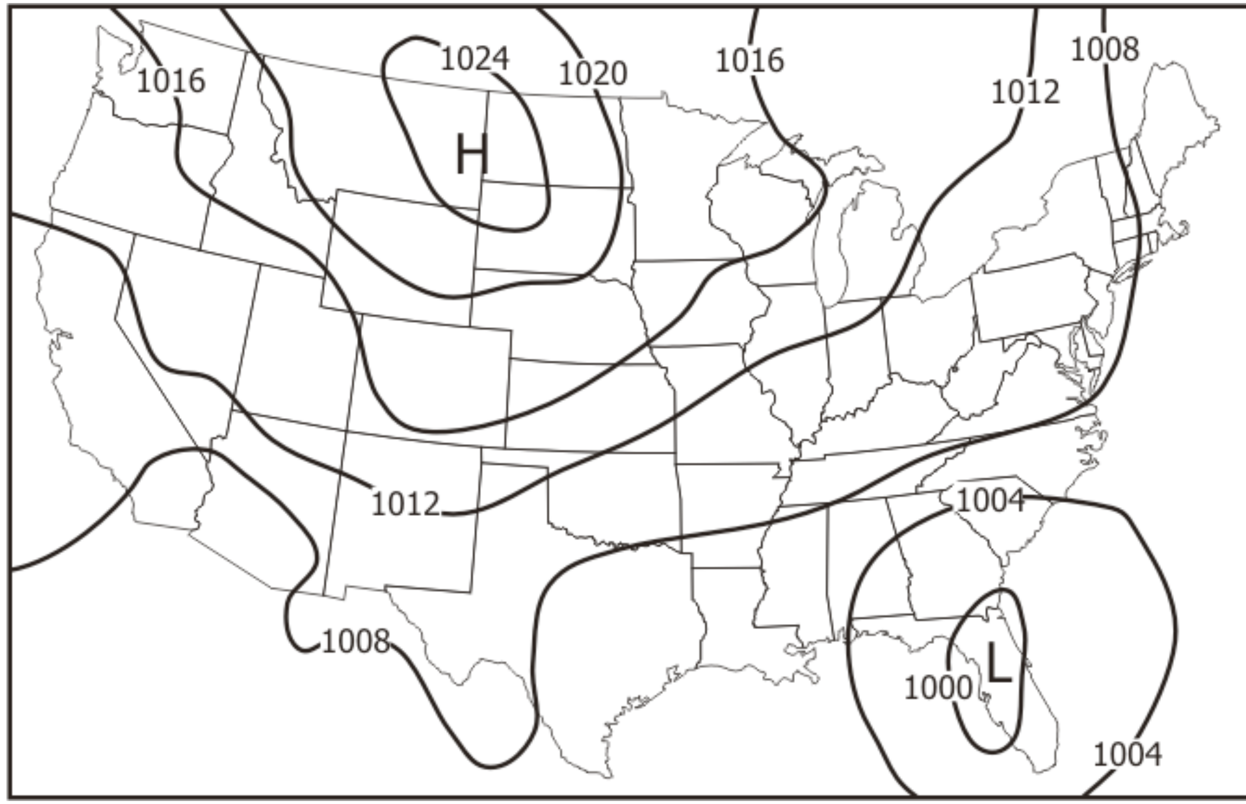
The map shows the barometric pressure as reported by a number of weather stations (in millibars).

[Hayward current conditions]()

[Sacramento current conditions]()

Barometric pressure is generally shown on weather maps as *isobars* that are lines that connect places of equal pressure.

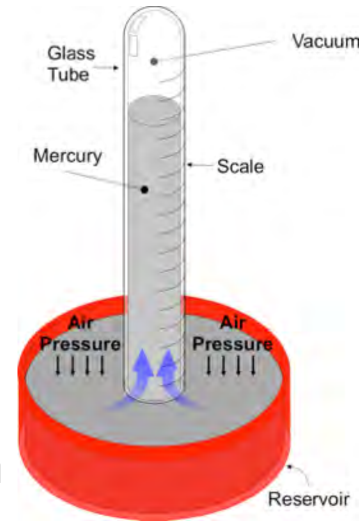
Winds blow from regions of high pressure (H) to regions of low pressure (L).



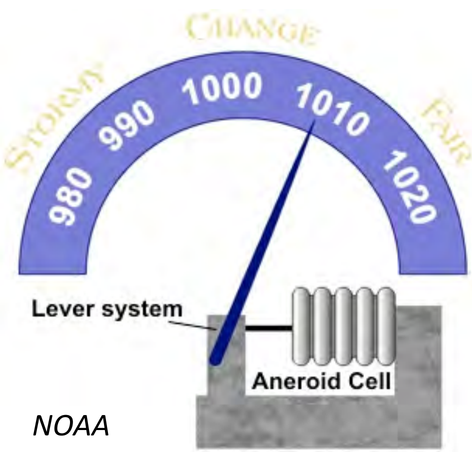
Isobaric maps are useful since they indicate the *pressure gradient* in a region.

A *barometer* is a device that measures air pressure.

Fluid-based barometers measure the height that a fluid is forced up a tube by atmospheric pressure. High pressure forces the liquid up the tube. The mercury barometer measures the height of mercury in a column. At sea level, atmospheric pressure is 1013 mbar = 29.9 in Hg.



weatherhut.com



NOAA

An aneroid barometer uses a flexible metal box that expands or contracts as a function of atmospheric pressure. The expansion and contraction of the aneroid is coupled to mechanical lever so that the barometric pressure can be read from a dial.

Wikimedia User: Jean-Jacques MILAN

Build your own barometer

How much pressure is on your body?

At sea level, the average barometric pressure is 1,014 mbar. This is equivalent to

= 14.7 pounds/in^2

= 10,340 kg/m^2

The body surface area (BSA) is used in medicine for proper dosage of some specialized drugs:

$$BSA = \sqrt{W \times Ht}/600$$

Where BSA is in m^2, weight (W) is in kg and height (Ht) is in cm.

BSA online calculator

	Ave. BSA (in^2)	Ave. BSA (m^2)
12-13 year old child	2061	1.33
Ave. man	2945	1.9
Ave. woman	2480	1.6

	Ave. BSA (in^2)	Ave. BSA (m^2)
12-13 year old child	2061	1.33
Ave. man	2945	1.9
Ave. woman	2480	1.6

For a the average middle school student:

$$1.33\ m^2 \times 10{,}340\ kg/m^2 = 13{,}752\ kg$$

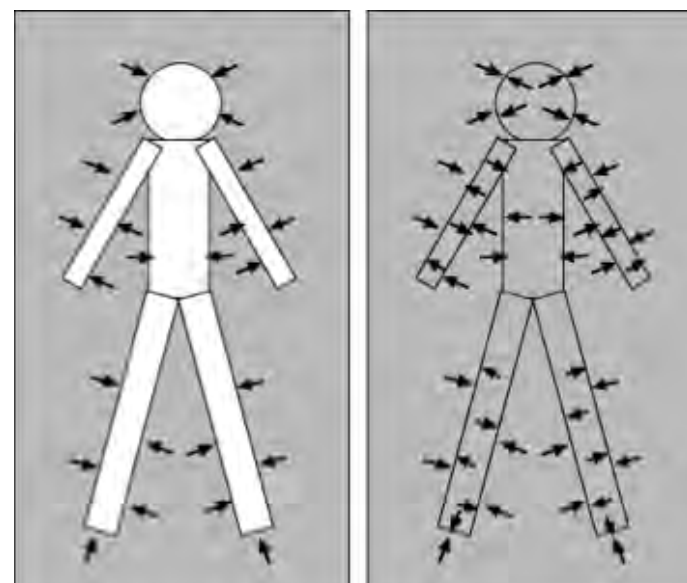
$$2{,}061.5\ in^2 \times 14.7\ lb/in^2 = 30{,}304\ lb$$

Steve Spangler

In the can crush experiment, the barometric pressure outside the can is much greater than the pressure inside the can. The can is crushed (changes its volume) to equalize the external and internal pressure.

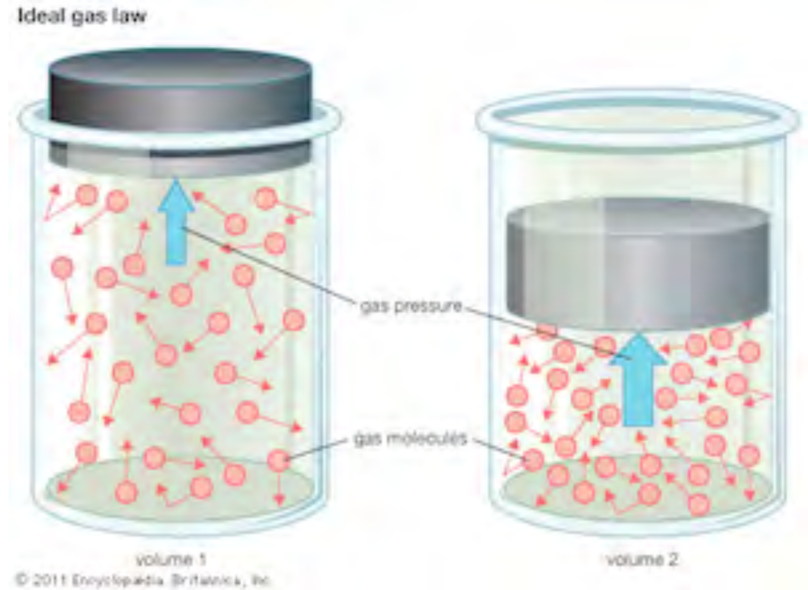
Why is the human body not crushed by the weight of the atmosphere?

The internal body pressure pushes outward. Also, the air inside the body balances out the pressure on the outside of the body.



astronomynotes.com

The ideal gas law describes the relationships between volume (V), pressure (P) and temperature (T) in an ideal gas.



$$PV=nRT$$

Where n is the amount of gas (in moles) and R is *ideal gas constant* that accounts for the units by relating the energy scale in physics to the temperature scale.

The value of R depends on the units used in the equation but a common value is

$$R = 0.0821 \text{ liter}\cdot\text{atm/mol}\cdot\text{K}$$

The ideal gas law assumes that there are no molecular interactions between gas molecules. Gases approach ideal behavior at low pressure and/or high temperature and can be used to approximate the relations in the Earth’s atmosphere.

Rewriting the ideal gas law:

$$\text{density} = n/V = P/RT$$

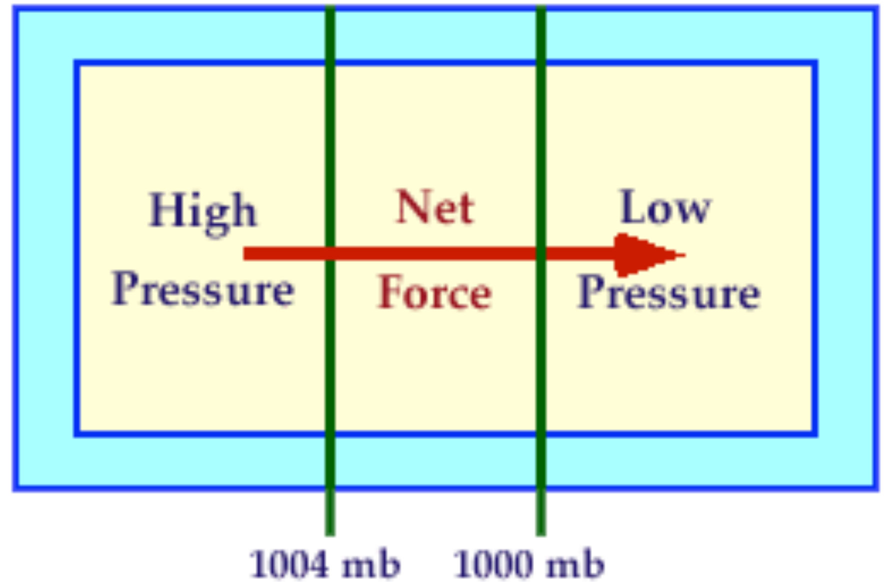
If the temperature of a liquid or gas increases and it expands, the density (mass/volume) decreases.

Thus warm air (or water) rises buoyantly because it is less dense.

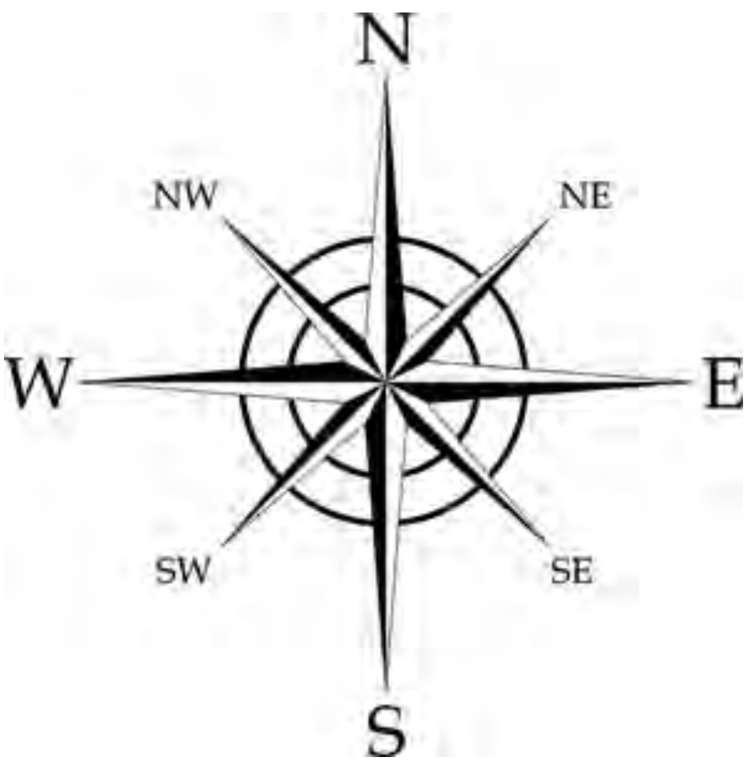
Conversely, if air or water is cooled, the density increases and it will sink.

V. Winds

Air moves in response to horizontal differences in pressure — *wind* blows in an attempt to equalize imbalances in air pressure.



WW2010 Univ. of IL

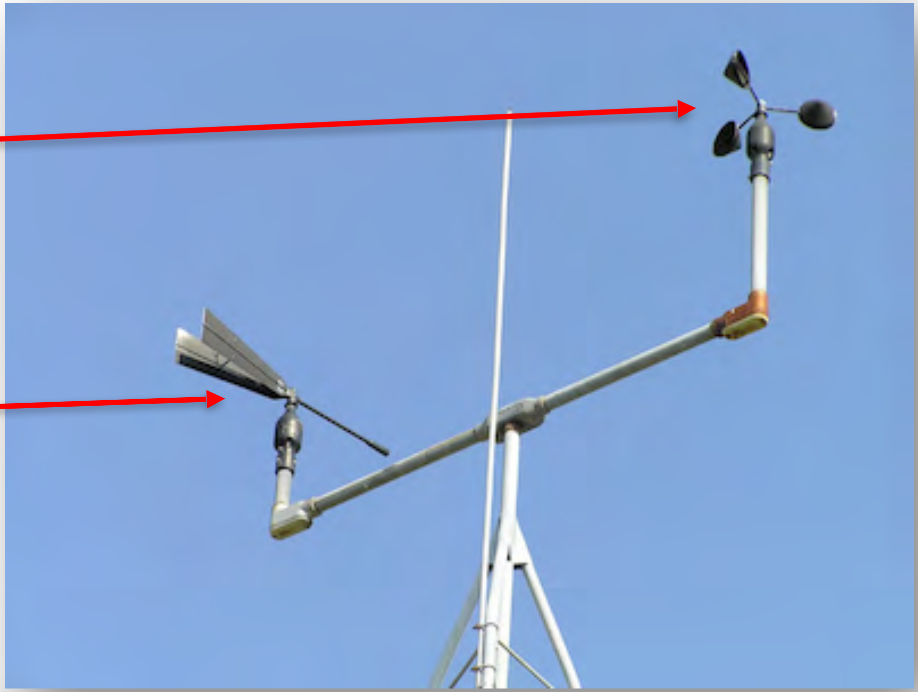


Wind is characterized by its direction, speed, and gustiness.

The direction of the wind is the direction from which it is blowing. For example, a north wind blows from the north to the south (this is opposite for ocean currents).

An *anemometer* measures wind speed.

A *wind vain* points into the direction that the wind is coming from.



NOAA

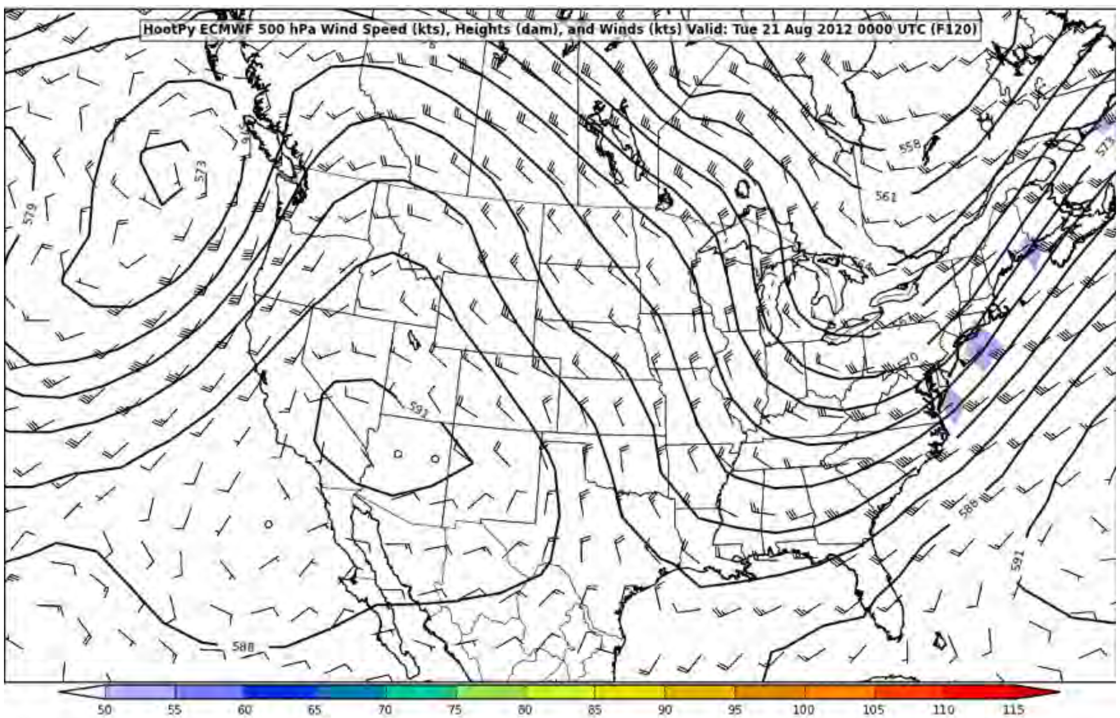
NOAA

An *aerovane* can simultaneously measure wind direction and speed.

Symbols on weather maps (known as wind barbs) indicate the wind direction and wind speed. Wind barbs point in the direction from which the wind is blowing.

Wind Speeds

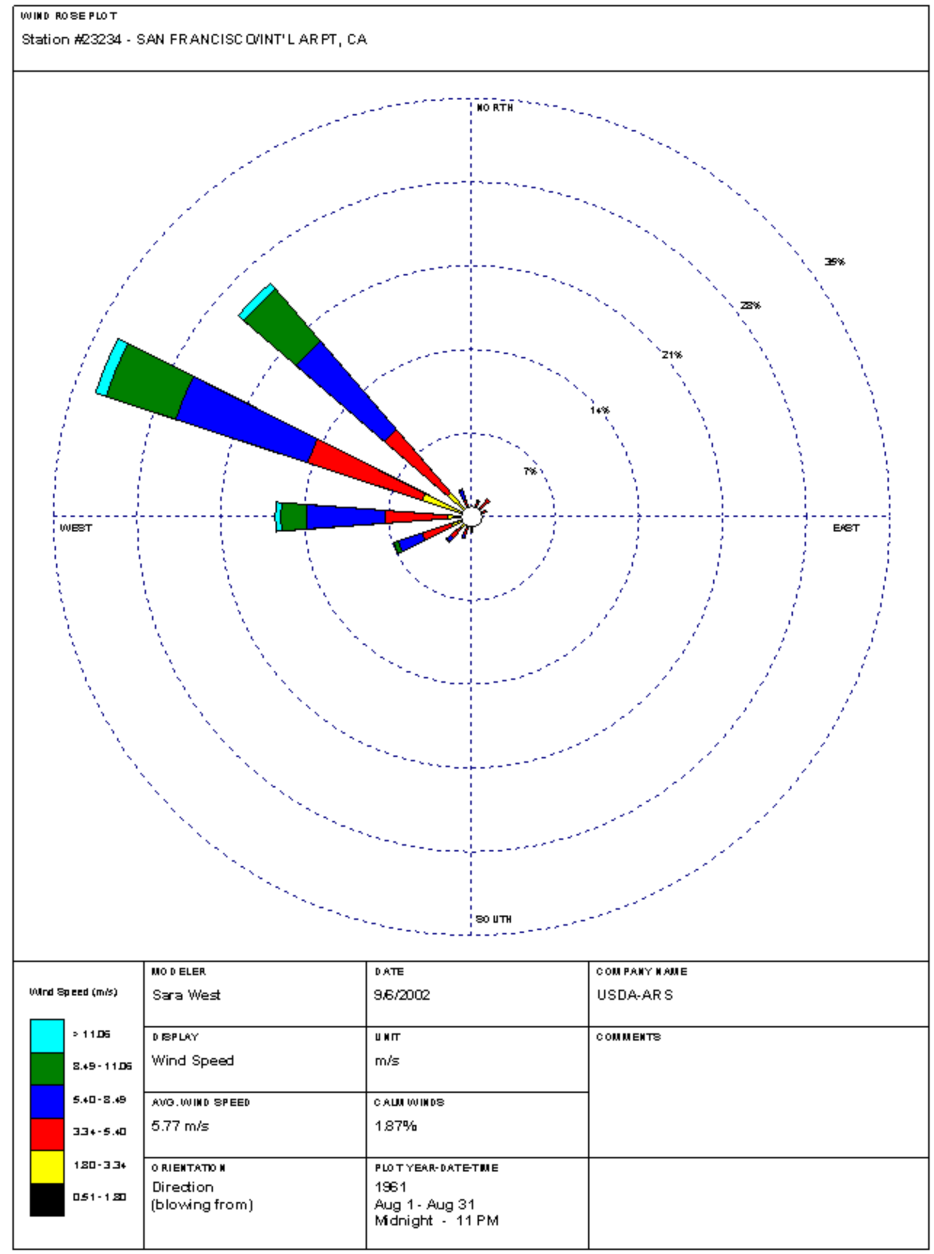
Symbol	Knots	Miles/hr.	Symbol	Knots	Miles/hr.
	Calm	Calm		38-42	44-49
	1-2	1-2		43-47	50-54
	3-7	3-8		48-52	55-60
	8-12	9-14		53-57	61-66
	13-17	15-20		58-62	67-71
	18-22	21-25		63-67	72-77
	23-27	26-31		68-72	78-83
	28-32	32-37		73-77	84-89
	33-37	38-43		103-107	119-123



A *wind rose* is a graphical tool used to portray wind direction and speed for a particular location over a specific period of time.

The wind rose is for San Francisco International Airport during the month of August 1961 and shows that the dominant wind direction is from the west-northwest (blowing to the east).

windhistory.com provides wind data for the U.S.



USDA