Chapters 1 & 9 Atmospheric Basics and Weather Map Analaysis

Weather: A quick introduction

How does the atmosphere and weather impact our lives?

Weather: The state of the atmosphere at any particular time and place.

What defines the thermodynamic state of the atmosphere?

Air temperature: The degree of hotness or coldness of the air

Air pressure: The force of the air above an area

Air density: The mass per unit volume of air

What other properties define the state of the atmosphere?

Humidity: A measure of the amount of water vapor in the air

Clouds: A visible mass of tiny water droplets and/or ice crystals that are above the earth's surface

Precipitation: Any form of water, either liquid or solid (rain or snow) that falls from clouds and reaches the ground

Wind: Horizontal movement of air

Meteorology: The study of the atmosphere and its phenomena

What laws of physics do atmospheric scientists use to describe the behavior of the atmosphere?

The Earth is warmed by radiant energy from the sun. It is this radiant energy that drives the circulation and weather of the atmosphere.

The Earth's Atmosphere

Earth's atmosphere: A thin, gaseous layer that surrounds the Earth

NASA/JSC

Composition of the Atmosphere

TABLE 1.1 Composition of the Atmosphere near the Earth's Surface

PERMANENT GASES			VARIABLE GASES			
Gas	Symbol	Percent (by Volume) Dry Air	Gas (and Particles)	Symbol	Percent (by Volume)	Parts per Million (ppm)*
Nitrogen	N_2	78.08	Water vapor	H_2O	0 to 4	
Oxygen	O_2	20.95	Carbon dioxide	CO_2	0.039	395*
Argon	Ar	0.93	Methane	CH_4	0.00018	1.8
Neon	Ne	0.0018	Nitrous oxide	N_2O	0.00003	0.3
Helium	He	0.0005	Ozone	O_3	0.000004	0.04†
Hydrogen	H_2	0.00006	Particles (dust, soot, etc.)		0.000001	0.01–0.15
Xenon	Xe	0.000009	Chlorofluorocarbons (CFCs)		0.00000002	0.0002

*For CO_2, 395 parts per million means that out of every million air molecules, 395 are CO_2 molecules.

†Stratospheric values at altitudes between 11 km and 50 km are about 5 to 12 ppm.

Units

Scientists use Système International (SI) units when describing physical quantities.

The primary SI units are:
Length: meter (m)
Mass: kilogram (kg)
Temperature: Kelvin (K)
Time: second (s)

From these we derive additional units:
Speed: m s^{-1}
Acceleration: m s^{-2}
Force: Newton (N) = kg m s^{-2}
Pressure: Pascal (Pa) = N m^{-2} = kg m^{-1} s^{-2}
Energy: Joule (J) = kg m^2 s^{-2}
Power: Watt (W) = J s^{-1}

Remember, the units often used on weather maps or other weather data we will use are not in SI units, but when we need to do calculations we will usually need to use SI units.

Atmospheric Thermodynamic State

The thermodynamic state of the atmosphere is defined by the temperature, pressure, and density of the air at a given location.

Temperature (T) is a measure of the speed of random (microscopic) motion of molecules and also indicates the degree of hotness or coldness of an object.

For scientific calculations temperature should be in units of Kelvin.

Temperature Units

Temperature units are Kelvin (K), Celsius (°C), or Fahrenheit (°F)

Temperature interval
1°C = 1 K
1°C = 1.8°F

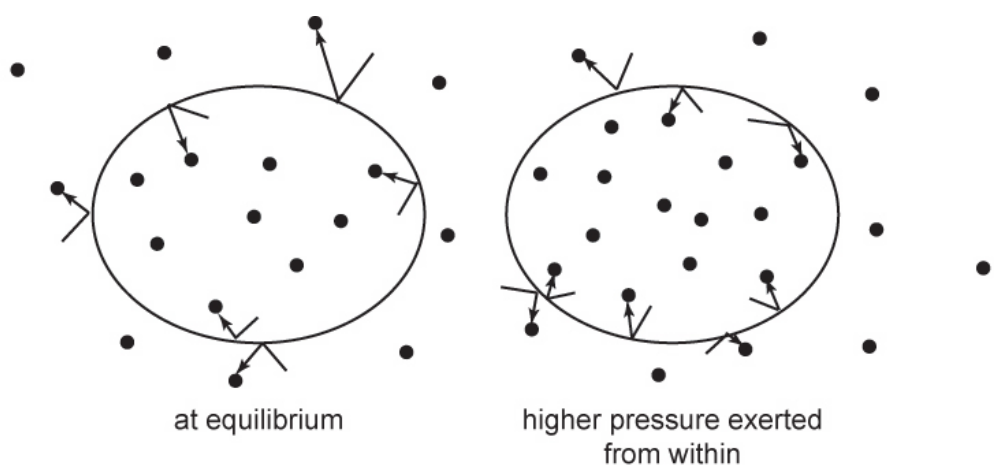
Temperature: Celsius degrees (°C)
$°C = K - 273.15$
$K = °C + 273.15$
$°C = (°F - 32°F) / (1.8\ °F\ °C^{-1})$

Temperature: Fahrenheit degrees (°F)
$°F = [°C \times (1.8\ °F\ °C^{-1})] + 32°F$

Pressure (P) is a force (F) acting perpendicular (normal) to a surface per unit area (A).

$P = F / A$

Air pressure is the force exerted by randomly moving air molecules as they bounce off of each other or off of surfaces they hit.



What is the air pressure in a vacuum?

Air pressure exerts an equal force in all directions (isotropic).

Units for Pressure

Force has units of Newtons ($N = kg\ m\ s^{-2}$)
Area has units of m^2
Pressure has units of $N\ m^{-2} = kg\ m^{-1}\ s^{-2}$.
A $N\ m^{-2}$ is also known as a Pascal (Pa).

Weather maps often report pressure in millibars (mb), but scientific calculations will usually use pressure with units of Pa.

1 mb = 100 Pa = 1 hPa = 0.1 kPa

At any height (z) in the atmosphere the pressure (P_z) is also equal to the weight per unit area of the air above that point.

Weight is the force acting on an object due to gravity.
Weight = mg (mass times the acceleration of gravity g)

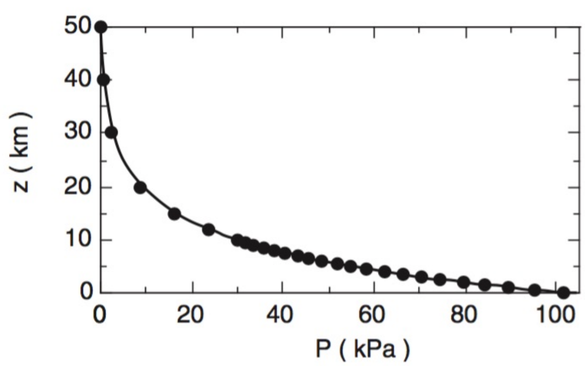
P_z = (weight of air above height z) / A = $(m_{above\ z})(g) / A$

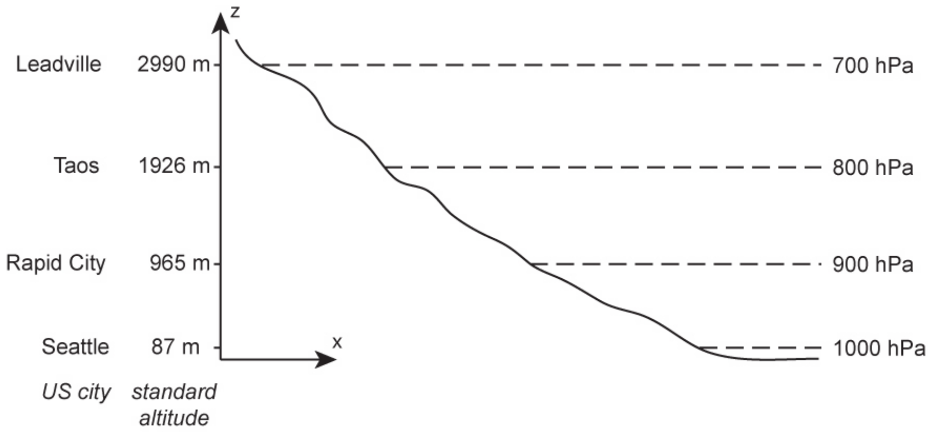
At sea level the weight of the air above 1 square inch is 14.7 lbs.

This normal sea level pressure is equivalent to:
14.7 lbs in^{-2} = 29.92 in Hg = 1013.25 mb = 1013.25 hPa = 101325 Pa = 101.325 kPa

How will air pressure change as you move up through the atmosphere?

Why does the air pressure change in this way?





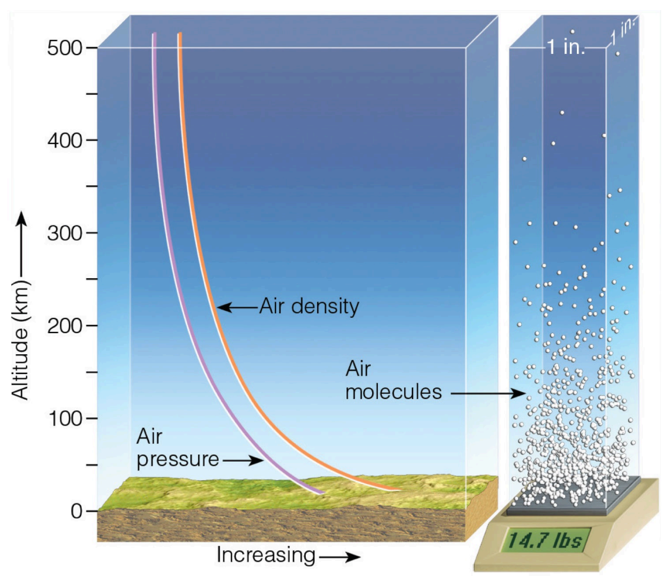
What is the approximate rate of decrease of pressure with height in the lower part of the atmosphere?

Estimate the pressure in Boulder, CO (elevation 1600 m)?

Since pressure always decreases with height in the atmosphere pressure can be used as an alternate measure of height in the atmosphere.

Density (ρ) is the mass (*m*) per unit volume (*Vol*) of a substance.

$\rho = m / Vol$ (units: kg m^{-3})



Air is a compressible fluid.

How does density change as we move up through the atmosphere?

What causes the density to change in this way?

What is the typical density of air at sea level?

How will the pressure change over a fixed depth (say 1 km) of the atmosphere as the density decreases?

Why does pressure change in this way?

The Ideal Gas Law

The equation of state is an equation that relates temperature (*T*), pressure (*p*), and density (ρ). Different fluids have different equations of state that depend on their molecular properties.

For the dry (no moisture) atmosphere the equation of state is known as the ideal gas law.

$P = \rho R_d T$ or $\rho = \frac{P}{R_d T}$, where R_d (= 287.053 J kg^{-1} K^{-1}) is the gas constant for dry air.

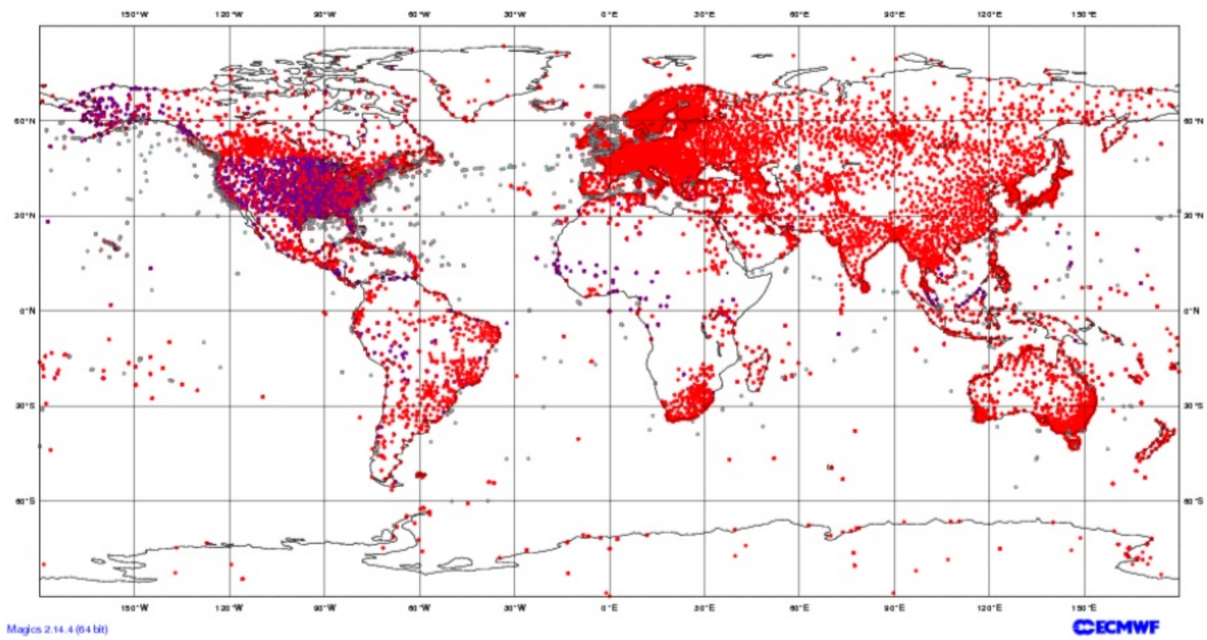
How will the density change as the pressure increases (decreases)?

How will the density change as the temperature increases (decreases)?

Why does density change in this way as pressure (temperature) changes?

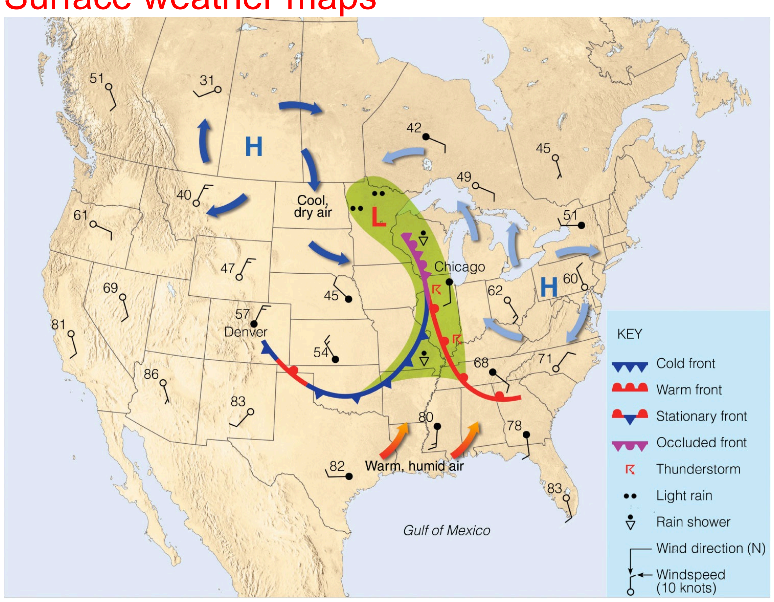
Weather Observations: Surface Weather

Weather stations located across the surface of the Earth make nearly continuous observations of the atmospheric state.



These weather observations are reported as METARs (Meteorological Aviation Reports) - see Chapter 9 for more details.

Surface weather maps



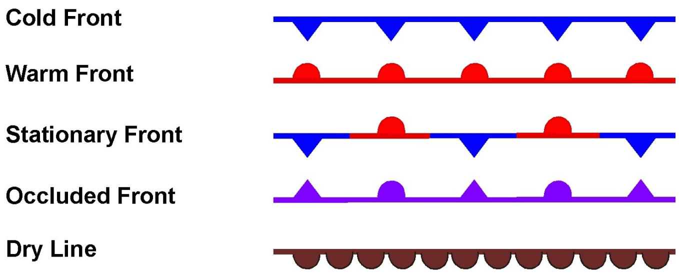
Low (cyclone): A region of low atmospheric pressure

High (anticyclone): A region of high atmospheric pressure

In what direction does the wind blow around a low (high) pressure center?

What is the typical weather near a low (high) pressure center?

Front: A boundary between air masses that have different temperature and/or humidity.



Cold front: An air mass boundary where cold air is advancing and replacing warm air.

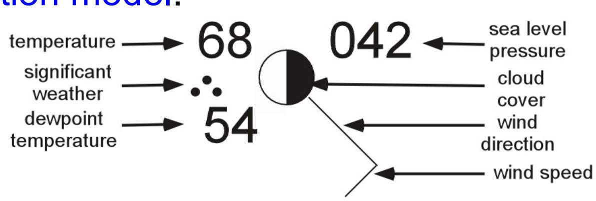
Warm front: An air mass boundary where warm air is advancing and replacing cold air.

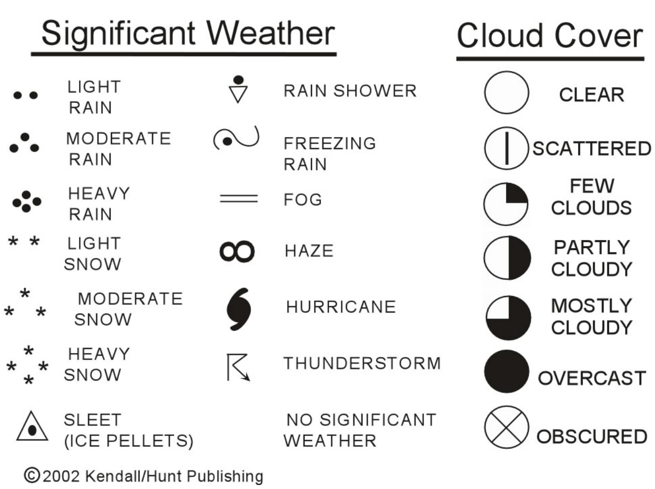
Occluded front: An air mass boundary where a cold front has caught up to a warm front and cold air is replacing slightly cooler air.

Dryline: An air mass boundary separating dry and humid air masses.

Reading surface weather maps

Weather observations are plotted on surface weather maps using a surface station model.





The surface station model shows:

- Temperature (°F)
- Dew point temperature (°F)
- Coded SLP
- Wind speed and direction
- Cloud cover
- Significant Weather

See Chapter 9 for additional details that can be plotted on a station model.

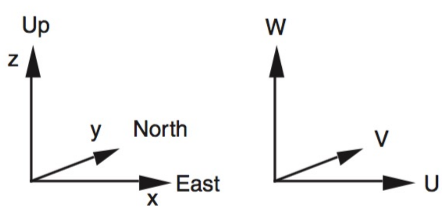
Decoding Sea Level Pressure Data

If coded SLP is greater than 500:
- Put a 9 in front of the 3 digit coded SLP
- Insert a decimal point between the last two digits
- Add units of mb
- Example: coded SLP = 956
- Decoded SLP = 995.6 mb

If coded SLP is less than 500:
- Put a 10 in front of the 3 digit coded SLP
- Insert a decimal point between the last two digits
- Add units of mb
- Example: coded SLP = 052
- Decoded SLP = 1005.2 mb

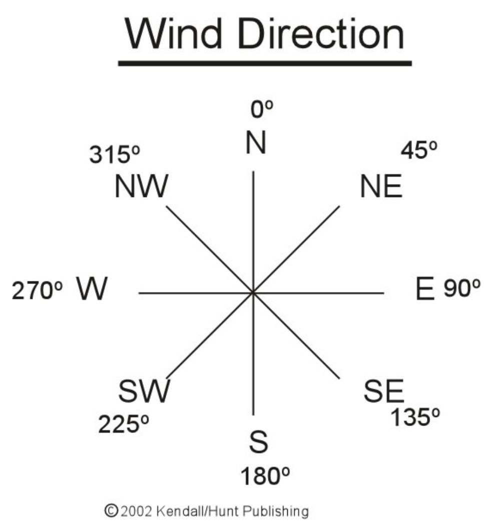
Reading Wind Speed and Direction

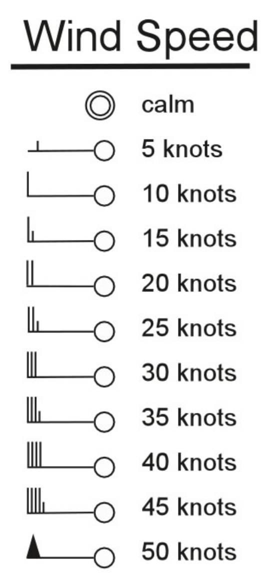
Meteorologists often use a coordinate system that is aligned with east/west and north/south directions.



The components of the three dimensional wind are given by *U, V*, and *W* (above).

Wind can also be reported as a wind speed and direction (at right).





Meteorologists want to know what direction the wind is coming from, so wind direction always indicates the direction that the wind is coming from.

Wind speed units conversion

Wind speed: knots (kts)
1 kt = 0.51 m s^{-1}

Wind speed: miles per hour (mph)
1 mph = 0.447 m s^{-1} 1 kt = 1.15 mph

Converting between wind speed and direction and wind components

U is the zonal component of the wind and is positive for a wind blowing from west to east (a west wind)

V is the meridional component of the wind and is positive for a wind blowing from south to north (a south wind).

W is the vertical component of the wind and is positive for a wind blowing upward.
For a horizontal wind the two horizontal wind components (*U* and *V*) can be converted into wind speed (*M*) and direction (α) using the following equations:

$$M = \left(U^2 + V^2\right)^{0.5}$$

$$\alpha = 90^\circ - \frac{360^\circ}{C}\arctan\left(\frac{V}{U}\right) + \alpha_0$$

α_0 = 180° for $U > 0$ and is zero otherwise
C = 360° or 2π radians (whether you use degrees or radians depends on your calculator)

Wind speed (*M*) and direction (α) can be converted into the horizontal wind components (*U, V*) using the following equations:

$$U = -M\sin(\alpha)$$

$$V = -M\cos(\alpha)$$

Meteorological observations and time

Meteorologists record the time of all weather observations using a universal time coordinate (UTC). This is sometimes referred to as Z or GMT.

Quick facts about Universal Time Coordinate (UTC)

UTC corresponds to the time at the prime (Greenwich) meridian.

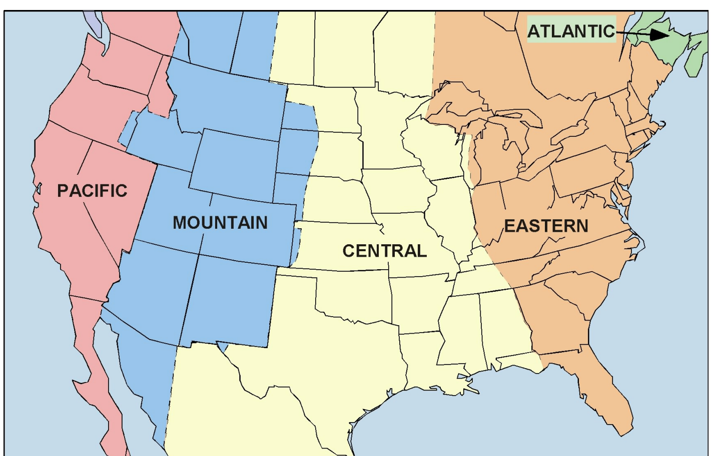
UTC is based on a 24 hour clock (so add 12 to any times after 12:59PM)

> 6AM UTC would be written as 06 UTC
> 12 noon UTC would be written as 12UTC
> 6PM UTC would be written as 18UTC

If UTC time is given as both hours and minutes it looks like this:

> 2:15AM UTC would be written as 0215 UTC
> 12:00 noon UTC would be written as 1200 UTC
> 10:20PM UTC would be written as 2220 UTC

UTC never switches from standard time to daylight savings time



		Pacific	Mountain	Central	Eastern	Atlantic
1200 UTC	STANDARD	4 a.m.	5 a.m.	6 a.m.	7 a.m.	8 a.m.
	DAYLIGHT	5 a.m.	6 a.m.	7 a.m.	8 a.m.	9 a.m.
0000 UTC	STANDARD	4 p.m.	5 p.m.	6 p.m.	7 p.m.	8 p.m.
	DAYLIGHT	5 p.m.	6 p.m.	7 p.m.	8 p.m.	9 p.m.

How do I convert from UTC to MST or MDT?

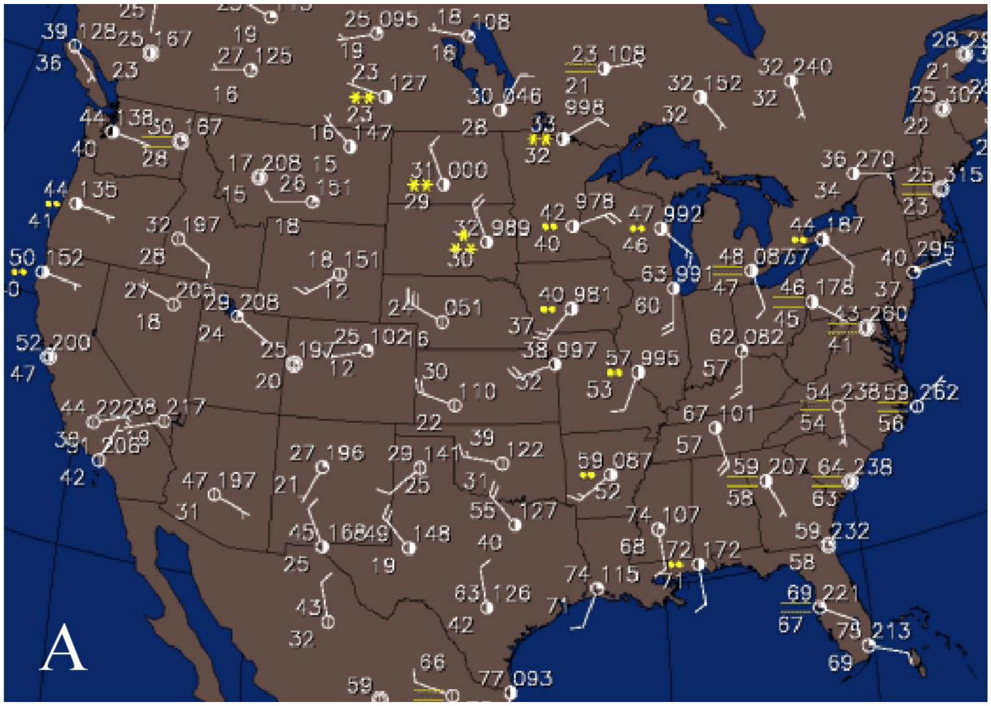
> MST = UTC - 7 hours
> MDT = UTC - 6 hours

How do I convert from MST or MDT to UTC?

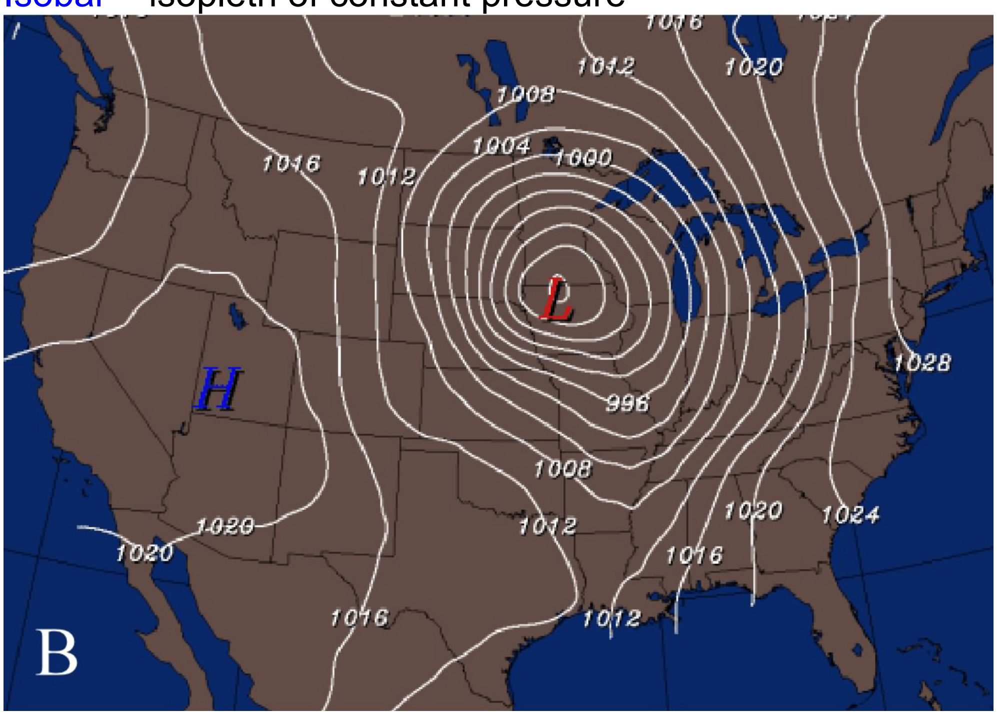
> UTC = MST + 7 hours
> UTC = MDT + 6 hours

Plotting weather data: Contour lines

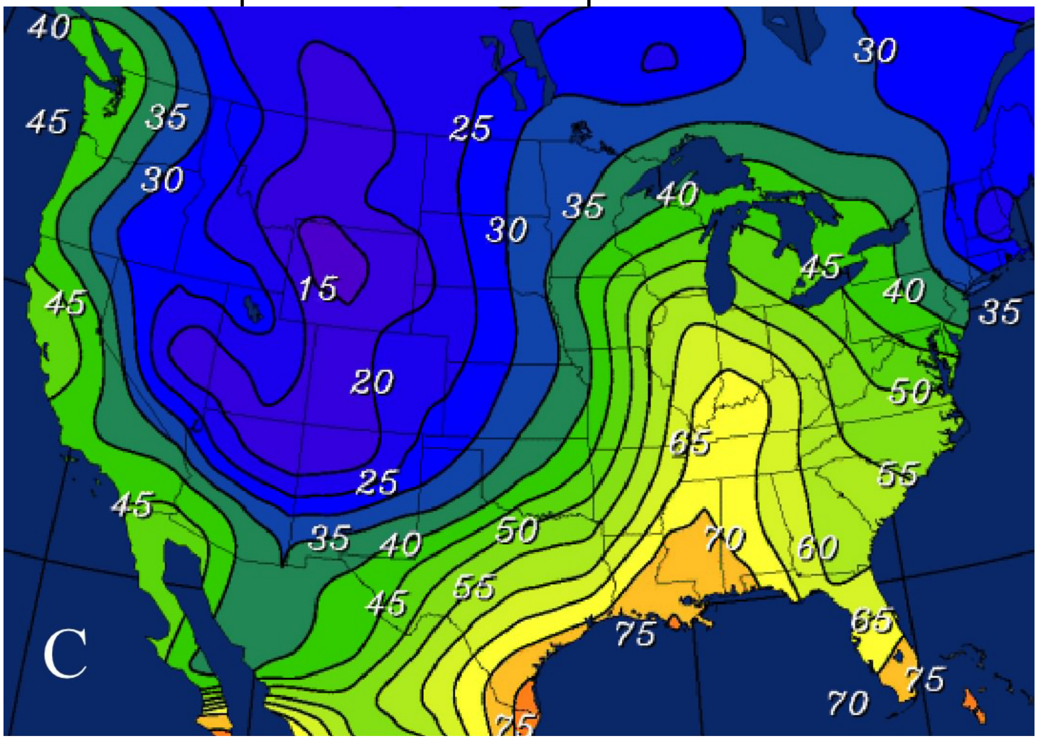
Contouring – drawing lines (isopleths) on a map that connect points with equal values



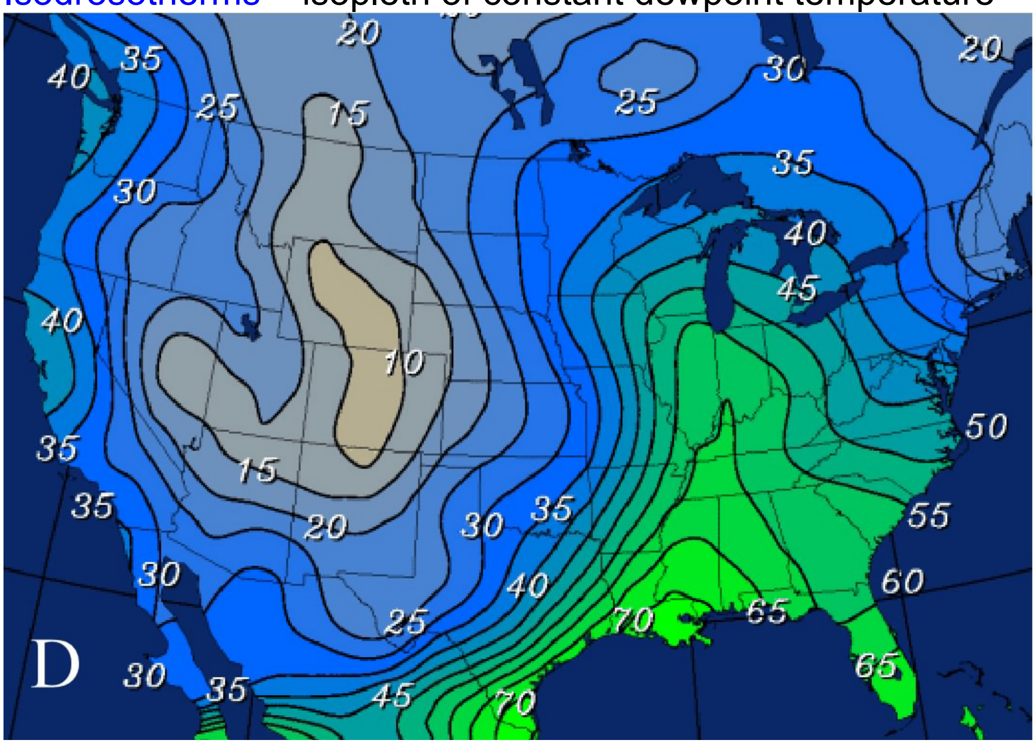
Isobar – isopleth of constant pressure



Isotherm – isopleth of constant temperature



Isodrosotherms – isopleth of constant dewpoint temperature



Rules for contouring data:

- Draw isopleths are regular intervals (this is the contour interval of the plot)
- Interpolate as needed between available observations
- Isopleths never cross isopleths of the same variable
- Label each isopleth

Table 1-6 lists the names of other constant variables / processes.

Table 1-6. Process names. (tendency = change with time)

Name	Constant or equal
adiabat	entropy (no heat exchange)
contour	height
isallobar	pressure tendency
isallohypse	height tendency
isallotherm	temperature tendency
isanabat	vertical wind speed
isanomal	weather anomaly
isentrope	entropy or potential temp.
isobar	pressure
isobath	water depth
isobathytherm	depth of constant temperature
isoceraunic	thunderstorm activity or freq.
isochrone	time
isodop	(Doppler) radial wind speed
isodrosotherm	dew-point temperature
isoecho	radar reflectivity intensity
isogon	wind direction
isogram	(generic, for any quantity)
isohel	sunshine
isohume	humidity
isohyet	precipitation accumulation
isohypse	height (similar to contour)
isoline	(generic, for any quantity)
isoneph	cloudiness
isopleth	(generic, for any quantity)
isopycnic	density
isoshear	wind shear
isostere	specific volume ($1/\rho$)
isotach	speed
isotherm	temperature

Vertical Structure of the Atmosphere

Geopotential and geopotential height

Geopotential (Φ): The work done against gravity to lift a unit mass (1 kg) from sea level to height *z*.

$$\Phi = g \cdot z$$

The acceleration of gravity (*g*) decreases as you move away from the center of the Earth.

At the surface of the Earth the acceleration of gravity is $g_0 = 9.8 \text{ m s}^{-2}$

Geopotential height (*H*) differs from the geometric height (*z*) in that it accounts for the change in gravitational acceleration as you move up through the atmosphere.

The Standard Atmosphere

How does the state of the atmosphere change in the vertical direction?

The standard atmosphere is an approximate representation of the atmospheric state as a function of height.

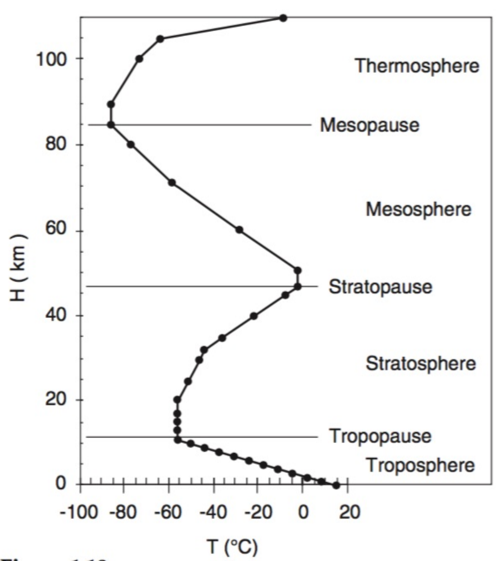


Figure 1.10

Standard Atmosphere Temperature

Equations 1.16 and 1.17 in the text can be used to calculate the temperature and pressure as a function of height in the standard atmosphere.

How can you identify if temperature is increasing, decreasing, or remaining constant with height on a graph of temperature versus height?

Layers of the atmosphere are defined by how the temperature changes with height.

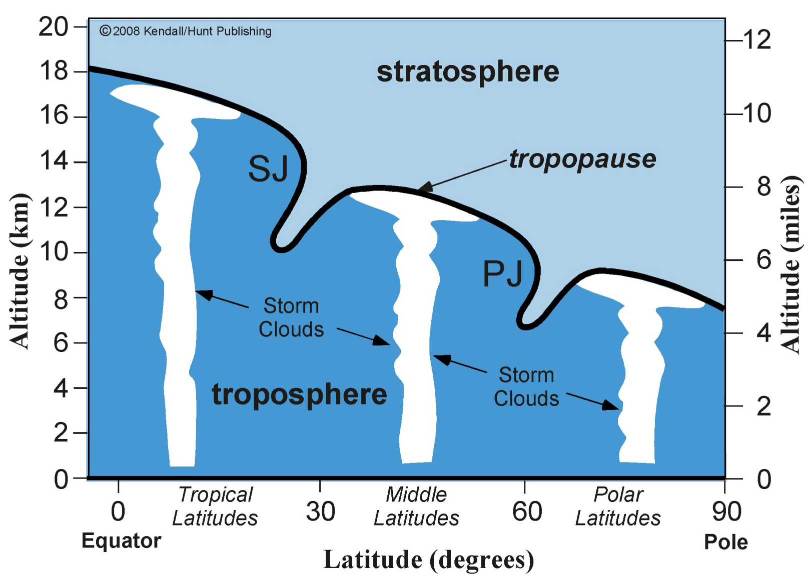
Inversion layer: A layer of the atmosphere where temperature increases with height.

What are the layers of the atmosphere and how does temperature change with height in each of these layers?

What causes the temperature maxima at the surface of the Earth, at the stratopause, and in the thermosphere?

Almost all clouds and weather occur in the troposphere.

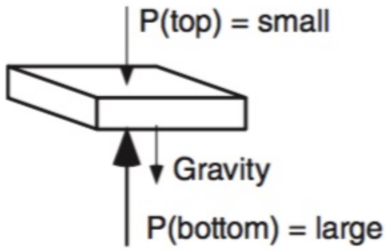
The tropopause is the boundary between the troposphere and stratosphere.



What is the average height of the tropopause in the mid-latitudes?

How does the height of the tropopause vary from the equator to the poles and seasonally?

Hydrostatic Equilibrium



What forces try to move air vertically in the atmosphere?

Hydrostatic equilibrium describes the balance between the effects of gravity (g) and the upward force $\Delta p/\Delta z$ caused by the decrease of pressure with height in the atmosphere.

$$\frac{\Delta p}{\Delta z} = -\rho g$$

This equation lets us calculate the rate at which pressure decreases with height if we know the density of air.

The density of air in the lower part of the troposphere is approximately 1 kg m^{-3}.

Based on this estimate the rate at which pressure decreases with height in this part of the atmosphere.

How does this compare with the value estimated from the graph of pressure versus height shown previously?

Hypsometric Equation

Combining the ideal gas law and hydrostatic equation gives the hypsometric equation, which relates changes in height (z) to changes in pressure (P) and the average temperature (T_v) in the layer of interest.

$$z_2 - z_1 = \frac{R_d T_v}{g} \ln\left(\frac{P_1}{P_2}\right) \quad \text{or} \quad z_2 = z_1 + \frac{R_d T_v}{g} \ln\left(\frac{P_1}{P_2}\right)$$

The form of the hypsometric equation on the left allows us to calculate the distance or thickness (z_2 - z_1) between two pressure levels (P_1 and P_2) in the atmosphere.

How will the thickness change as the temperature in the layer increases?

What is a physical explanation for this change in thickness?

We can also rearrange the hypsometric equation to allow us to calculate the pressure (P_2) at a given height (z_2) from a known pressure (P_1) at another height (z_1) in the atmosphere and the average temperature (T_v) between the two heights.

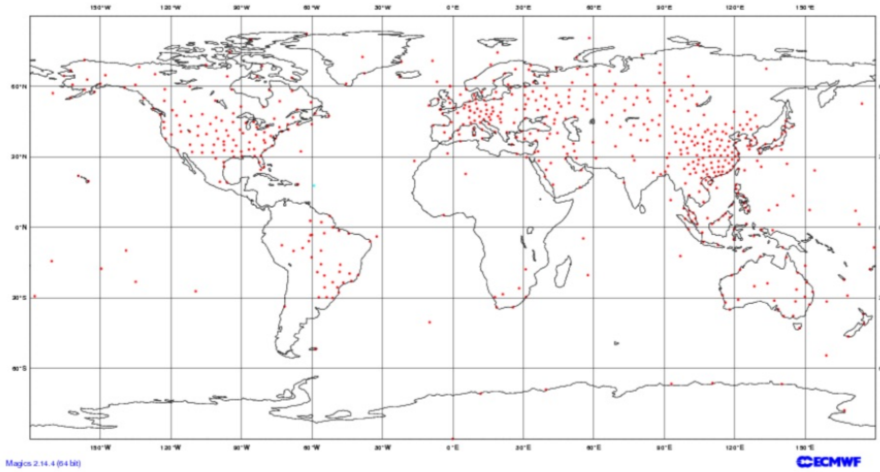
$$P_2 = P_1 \exp\left[\frac{-g(z_2 - z_1)}{R_d T_v}\right]$$

This equation can be used to calculate the sea level pressure from surface pressure observations made at elevations above (or below) sea level.

Why do meteorologists need to convert surface pressure (also called station pressure) to sea level pressure?

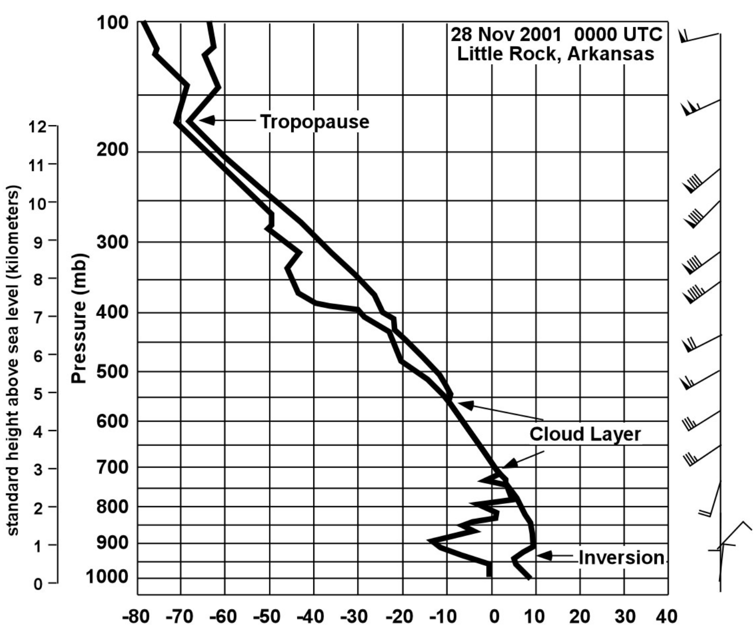
Weather Observations: Weather Above the Surface

The atmosphere is a three-dimensional fluid so we also need to know the atmospheric state above the surface of the Earth.



Radiosonde / rawinsonde: Weather instrument carried aloft by a helium balloon to measure the state of the atmosphere.

What properties of the atmosphere does a radiosonde measure?



Sounding: A plot of the vertical variation of atmospheric properties.