Series of Weather Forecasting Articles

Below is the first of a series of articles developed as an ordered study for learning weather forecasting. Doing so using the WWW is eventually emphasized, though many preliminaries must be discussed. Please read the first article as an introduction of their purpose. The end of the year is past, so that is one perhaps ambitious goal I did not accomplish; but I'll keep doing this when I can. For now, I am placing the articles I have here in their original form, and go from there. Many links are no longer valid - some because you must register - pay - or whatever to see them.

Regarding reading the articles, hot references in these are directed to a new window(s). Those for graphics at my site should open a new window for each. Those for another WWW site should open only one new window for all of such pages. This is done so that you can continue reading the article while browsing. Though displays using different PC's, systems, and browsers vary, these pages should appear best using 800×600 pixels and a base font size of 11 or perhaps 12.

Electromagnetic Theory & Related Topics - 10/19/1997
Basic concepts regarding electromagnetics and relative motion.

Weather & Space - 10/29/1997
What weather is and its basic relation with outer space.

Electromagnetic Radiation & Our Sun - part 1 - 11/08/1997
Brief summary of electromagnetic radiation and its relation with solar composition.

Electromagnetic Radiation & Our Sun - part 2 - 11/18/1997
Sunspots and other solar features, and Earth's orbital effects regarding climate.

Energy Collection, and Atmospheric Composition and Layers - 11/29/1997
Discussion of these basics, with illustrations.

Global Atmospheric Circulations - 12/10/1997
A brief discussion of basic global atmospheric circulations.

Home Page

Mission Possible

More than 2 years ago, I began a mission for internet users interested regarding weather - particularly forecasting. A combination of the enthusiasm & surprising display of knowledge I see from many people and the great availability of internet weather data suggest the emergence of a phenomenon. Much more so than previously, people with an interest have the tools and capability of being a proficient meteorologist - or more. As with any pursuit, this depends with the amount of effort a person wishes making and inherent ability; though some methods of learning are much more proficient than others. If you study meteorology at a college, much of the information you are taught is irrelevant for the task above. I offer a simpler way - and hopefully more fun.

This is not meant to be structured, per se. You obviously have no obligation to anything, and can read any articles you wish when you wish. Yet my study of weather during 2 decades with emphasis regarding the aspects of education & forecasting made clear to me a preferable order of study.

Fundamental Study Topics

Clicking on the above heading opens a new window with a list of topics for meterological study and an explanation (mentioned for those not very familiar with browsing the internet). Though seemingly quite complicated & exhaustive, the topics in the order shown inculde the great majority of those relevant for learning weather forecasting. Many people want to explain to you a few things about radar and satellite images and model forecasts, and convince you that you are then a weather forecaster. Nothing can be further from the truth. Weather is the consequence of processes which constantly evolve in our atmosphere, understanding of which is the foundation of effective prediction. Yet as mentioned above, this neither requires a college cirriculum; though that is suggested if you want to pursue the many other aspects of meteorology - research, modeling, theory, etc. A weather forecaster must sometimes be a little of some of those. Here we opportunistically pick & choose things only helpful for our purpose 😉

Official Information...

should be heeded. Your tax dollars pay for this information (in most places); and unless you are a severe weather specialist, your guess probably won't be as good as thier educated one or forecast. I am not suggesting this mission as an alternative to the warnings provided for your safety (though they can sometimes be a bit 'lame' 😉).

Weatherwise

Ben Franklin, the first American meteorologist (perhaps anywhere) said so - that "some people are weatherwise, but most are otherwise". Thus more so (than what is not suggested above), this mission intends to reverse that statement. If you look at another forecast, it is not necessarily made with your purposes in mind. Each person has a specific agenda, and ideally wishes a weather forecast tailored to it. The Farmer makes 60 % of his forecasts wrong, but insists that they are better for the purposes intended (& you won't change his mind with facts ☺). The broadcaster finishes her 'song & dance', then 20 minutes later feels the weather will do something else. Even though Joseph gives away his free gifts, I mean forecasts and articles ☺, niether does he know what's important to you. What can a person do ? If this is important to you, I suggest learning to forecast to for your purposes when desired. I understand that many people do this - each with a degree of proficiency. This mission is about improving that proficiency, and I illustrate what's most effective. (Every person is actually a weather forecaster to some extent - whether that means exclusively or simply adjusting another's forecast for a locale.)

Inherent Skills

Though not implied as being necessary, good physics understanding and sense, mathematical skills, and sense of proportions and rates are very helpful. E.g., if a storm is moving 50 mph toward you, but dissipating in drier air, when should you expect it to reach you, and what other factors might affect its movement (e.g., 'Coriolis' deflection) and development (e.g., evaporation and subsidence) ? Such mental calculations, not necessarily numerical but perhaps instinctive, are often used.

Topics

Below I briefly discuss aspects of and reasoning for topics from the list above, which should be studied as ordered. Not strictly so, but this idea should be kept in mind.

Weather

This should naturally be studied first. These are the main ingredients of weather, and are what basically concern you when forecasting. For study, they are discussed many ways and at many WWW sites - I provide my thoughts.

'**Getting Your Bearings**'

If you have a road map, you'll likely find a location of interest. If you have a weather map, you'll likely know what weather will occur. Each provides a sense of position relative others (i.e., cities or weather regimes), for reference. Because weather occurs in physical space, being aware of positioning of all relevant factors is helpful.

Sun & Earth

Our sun provides essentially all energy to Earth, and its interaction with our atmosphere is responsible for atmospheric layers often referred to - troposphere, stratosphere, mesosphere, thermosphere, and exosphere. After understanding relevant positioning, we can better understand basic consequences of it.

Description of our Atmosphere

Basic physical laws cause weather we experience. Interaction of solar energy and our atmosphere and consequential weather developments must occur a specific way. More exist than I include. This section is quite important. E.g., the most common problem with meteorology learned form other sources than colleges, and why such instruction often fails, is a lack of appreciation for things which must occur. Unless you know these things, **you might expect things which are impossible** (like making an accurate weather forecast with insufficient data). Note that the same basic philosophy of the entire study guide is contained in this section. I.e., radiative transfer is first studied (Sun-Earth interaction), how temperature and other thermodynamic quantities which you can feel are affected at all altitudes, dynamics which occur within our atmosphere, and consequential motions.

Atmospheric Boundary Layer

We live near the ground, so processes ocurring in it are of particular importance to us.

Weather Forecast Models

These final 3 headings are not so much about the atmosphere as its analysis and interpretation. I include this topic before the last, not because such is logical (logically this would be last, being the only topic not directly involving the atmosphere), but because it is typically used for topics included with the next heading, which is our goal (and thus should be included last if possible).

Weather Analysis and Forecasting

Methods for achieving our goal of accurate weather prognosis.

Instrumentation

Including our goal as last was not possible. This heading is like an appendix, though a very important one. You should be aware of the extent atmospheric measurements portray real conditions.

Purposeful Sequence

Note that the succession of topics begins & ends with description and observation of weather.

Series of Articles

Now that my purpose is explained, I next place a series of articles on this site intended to accomplish it. More articles should be here soon, and hopefully it can be finished before the end of the year. The first several will likely be boring, but they mention important aspects of the prerequisites in the first portion of the list of topics. Knowledge of them is not absolutely necessary for progress later, but quite helpful.

Home Page

Prerequisites - Geometry

This was suggested prior to my list of topics for understanding weather. Here is the reason why : When you read or study something, your understanding is perfect (whether you agree, disagree, or neither !) until a word or concept encountered is misunderstood. That may *seem* obvious, but this idea can reveal interesting things. If you think of times during study when your understanding decreased or perhaps ceased, this was likely the reason. That can be your fault and / or the presenter's. If you had ability and resources (i.e., a dictionary) adequate for resolving the misunderstanding, it's your fault. If something was presented which required ideas or concepts not previously mentioned or defined, it is the presenter's fault; whether that 'presenter' was a person, a group of TV program directors, a school, etc. Our mission does not focus on the past though, but the present and future - things we can certainly do something about. If you accomplish our mission, your rewards will be great !

Unfortunately, the prerequisites are a little too extensive to mention most aspects here, and your familiarity with each depends with your previous study. Ideally, that's what high school and college degrees are for. Thus, I mention concepts particularly relevant for our mission. If you do not understand these, you won't understand parts of the rest. If you have questions, please send me a message. If any of your inquiries are more than I can answer, I'll attempt suggesting the best reference.

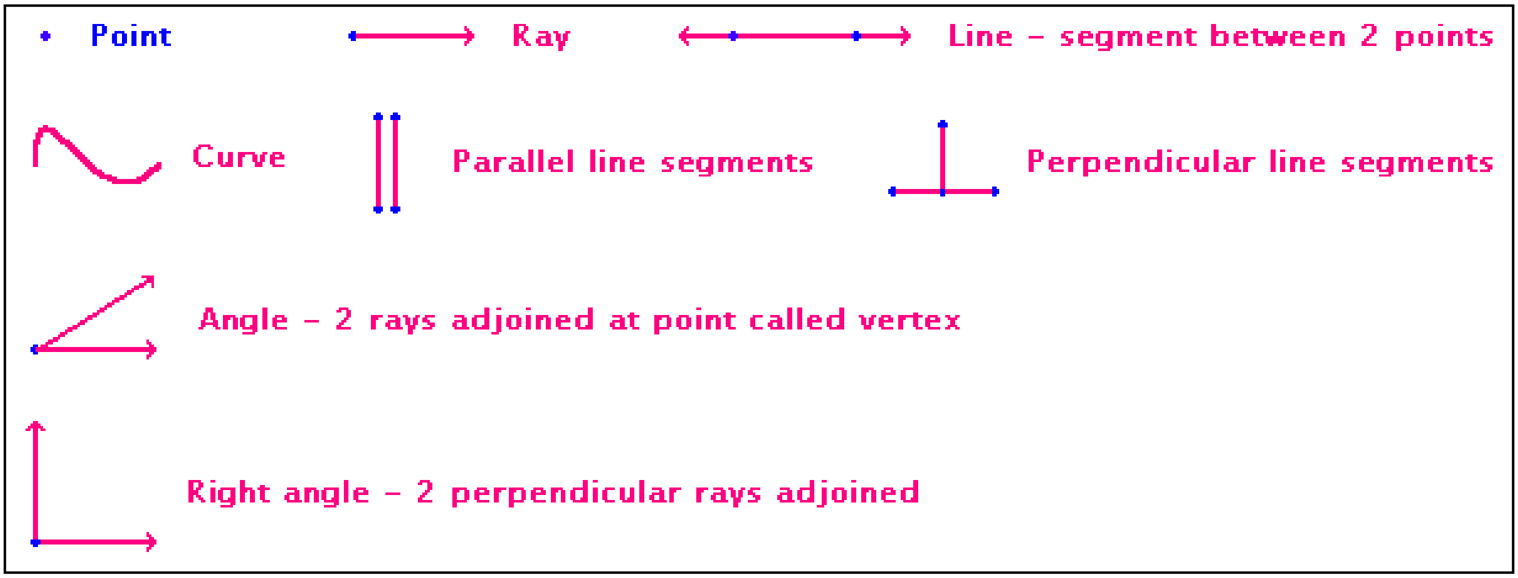
Geometry

You can study geometry for years, ranging between elementary school to doctoral study and beyond. It is quite relevant because meteorology greatly involves descriptions of weather systems & variables in 3-dimensional space, most often depicted on 2-dimensional maps. Though you may understand these topics well, you should be aware that I strictly refer to them as they are defined. I.e., if I write **line**, I mean exactly that - not curve or arc.

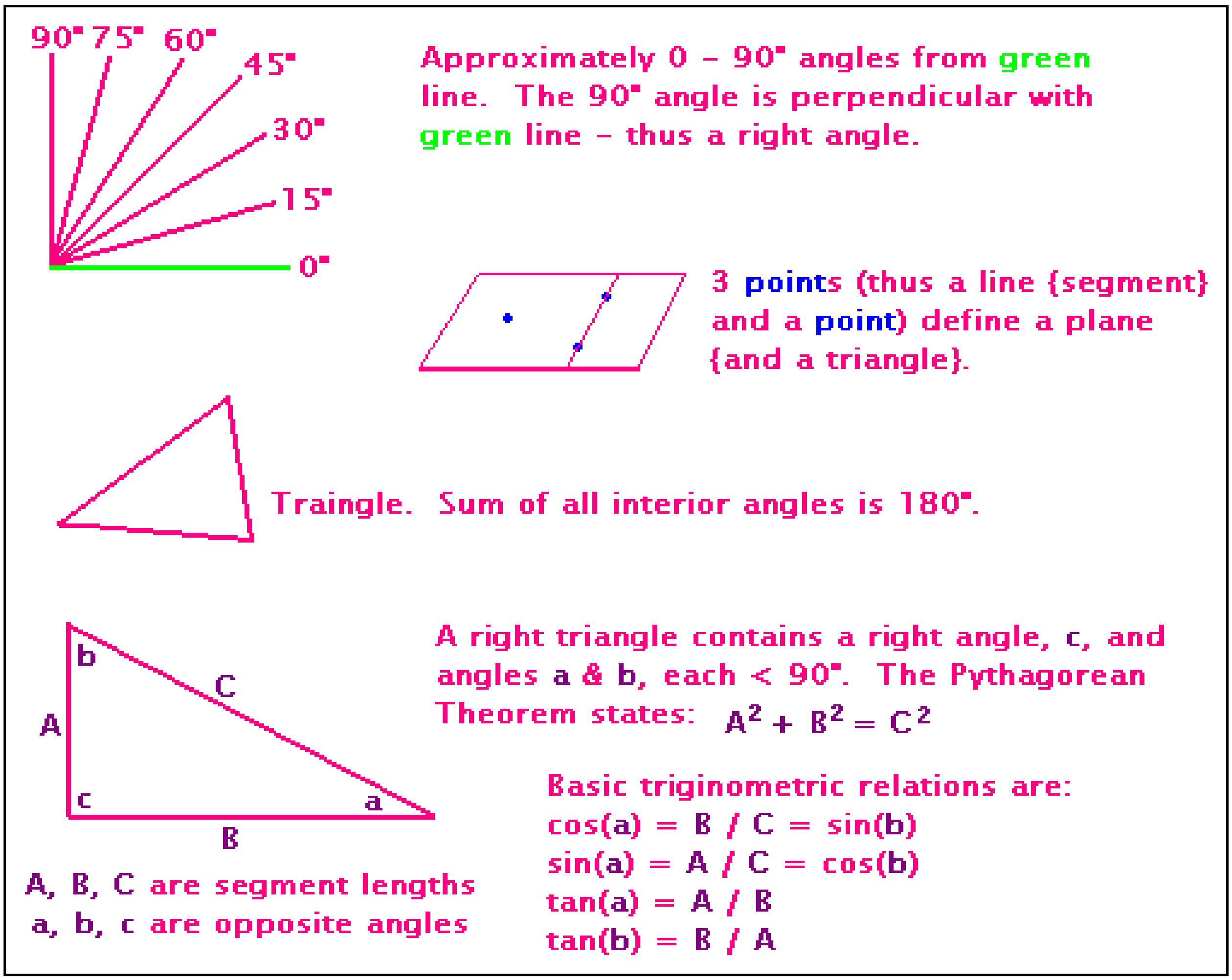
I do not prove nor derive anything, nor discuss topics with much detail here. Among the more useful WWW resources for this are the following sites : Elementary Geometry Tutorial & Geometry Formulas and Facts, though they also are not comprehensive - a geometry textbook ideally being required. Even so, proofs & derivations are little help for our purposes - more so are calculations using concepts important to us (which are proven or derived).

Below are concepts I'll most often use :

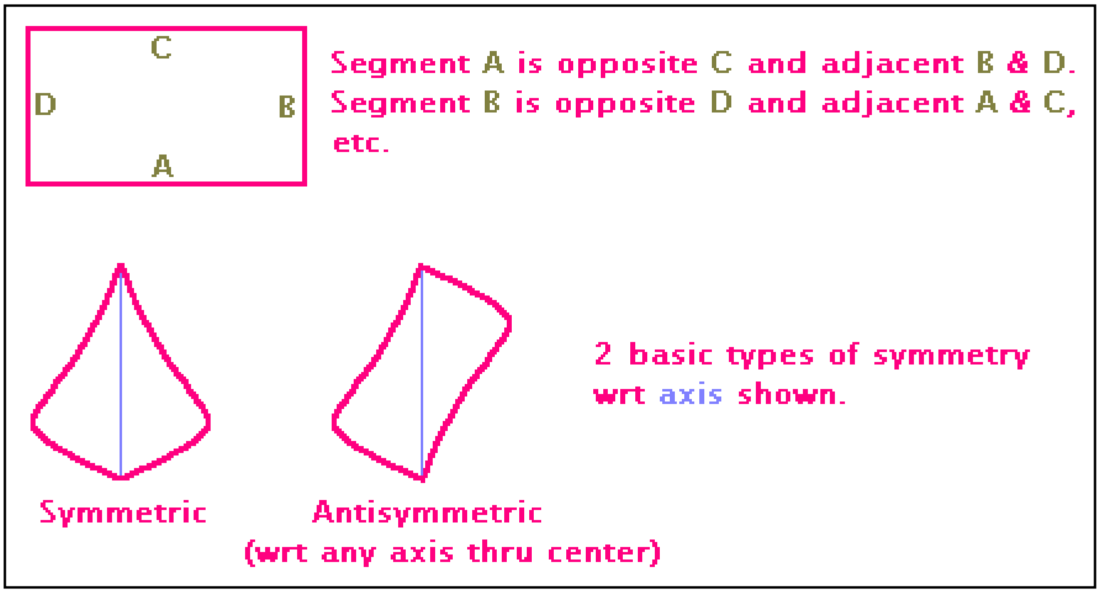
Point, ray, line, curve, parallel, perpendicular, angle, right angle :



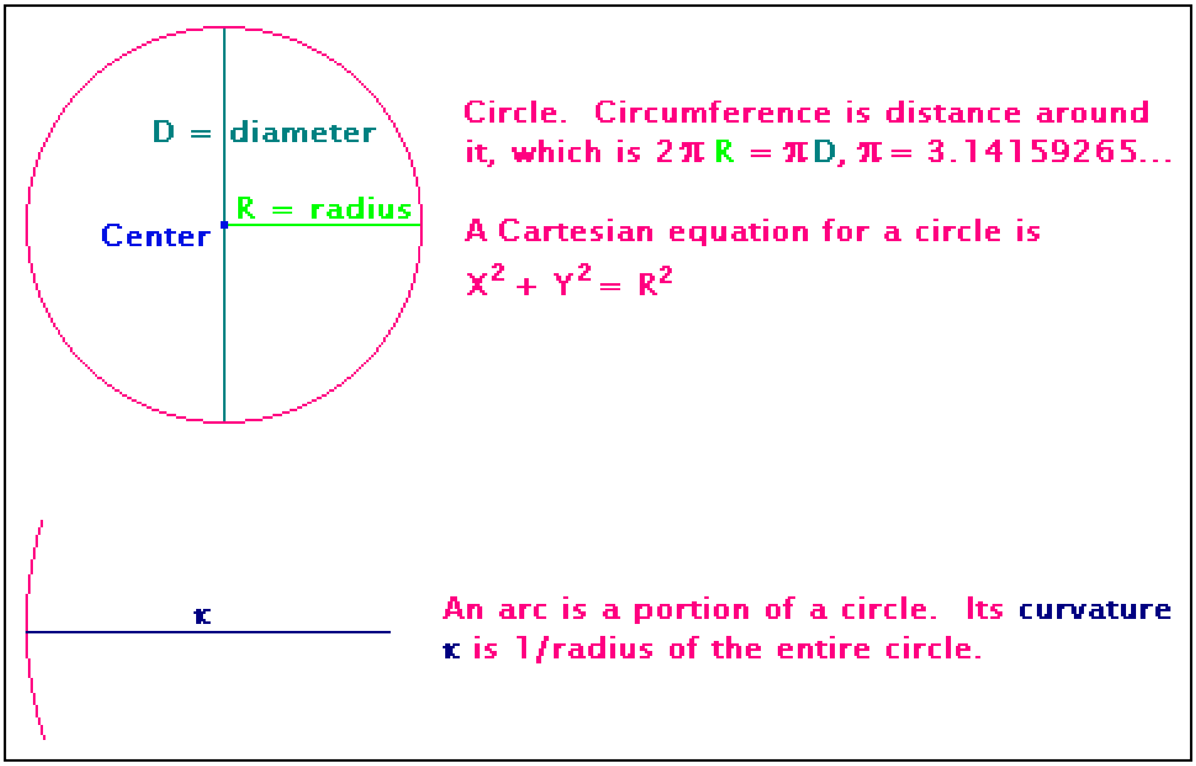
Plane, triangle, right triangle, trigonometric functions :



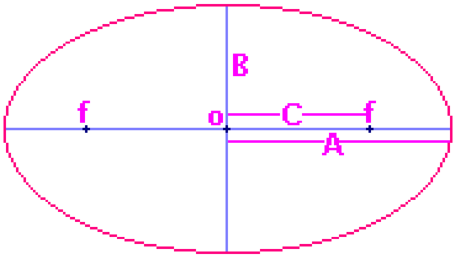
Adjacent, opposite, symmetry, axis (wrt means "with respect to") :



Center, circle, circumference, radius, diameter, arc, curvature :



Ellipse, ellipsoid (not shown) :

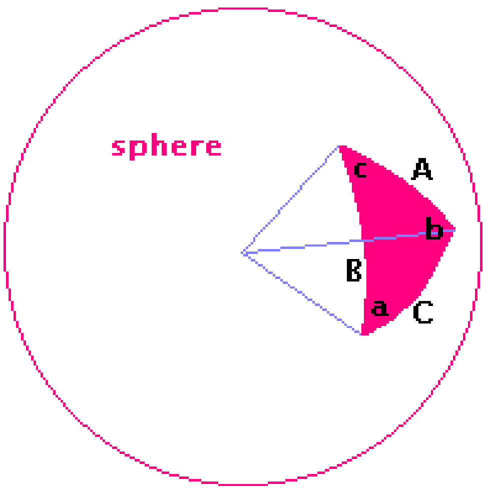


Cartesian coordinate equation:

$$X^2 / A^2 + Y^2 / B^2 = 1$$

Ellipse is symmetric about major (long) and minor (short) axes shown. o is its center, and f foci. Eccentricity is E = C / A. You may notice 0 <= E < 1. If f & o are same, C = 0 & E = 0, which is a circle.

Sphere, and great circle arc, angle, & triangle :



A spherical triangle consists of Great Circle Arcs, extending from the sphere's center, forming Great Circle Angles. Relations among arcs and angles are:

$$\cos(A) = \cos(B)\cos(C) + \sin(B)\sin(C)\cos(a)$$

$$\cos(a) = -\cos(b)\cos(c) + \sin(b)\sin(c)\cos(A)$$

$$\sin(A)/\sin(a) = \sin(B)/\sin(b) = \sin(C)/\sin(c)$$

Similarly, for other arcs and angles.

Some equations in diagrams refer to coordinate systems described below.

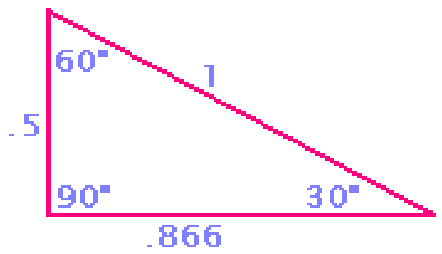
Among most relevant applications are :

Plane : With no elevation change, ground can locally be considered as approximately a horizontal plane :

Approximation of ground on our large, curved Earth as a horizontal plane is reasonable locally (left), and sloped terrain can be approximated using an inclined plane (right).

Though it contains a slight curvature, such is of little consequence regarding most weather phenomena (but very significant regarding large scale weather systems such as Highs and Lows seen on a weather map). Mountain slopes can be approximated as planes tilted various angles wrt horizontal.

Trigonometric Relations : Many are relevant, but most so are sine functions and the Pythagorean Theorem. A consequence of these is that perpendicular components of a right triangle are greater than their opposite angles indicate, greatest difference for 45° angle.



Considering a 30-60-90 triangle, you may notice that although the 30° angle is only 1/3 toward vertical, its opposite distance is half the hypotenuse of 1. Similarly, the 60° angle is 2/3 toward horizontal, but .866 of the hypotenuse distance. $.5^2 + .866^2 = 1$. You can image the vertical and horizontal distances as northerly and westerly wind components, with the hypotenuse distance representing total wind speed.

Circle : If you consider regular polygons (figures with each side equal, such as a 'perfect square, hexagon', etc.), increasing the number of sides to infinity produces a circle. Each place on a circle is same distance from its center.

Sphere : Rotating a circle in any direction except in its plane produces a sphere.

Ellipse : An ellipse is symmetric wrt 2 axes. A circle is an ellipse with eccentricity 0. Planet and Moon orbits are very nearly elliptical. Kepler's Laws describe the basic character of orbits, though the details can become much more complicated. Earth's orbit is very nearly circular, with eccentricity presently .0167.

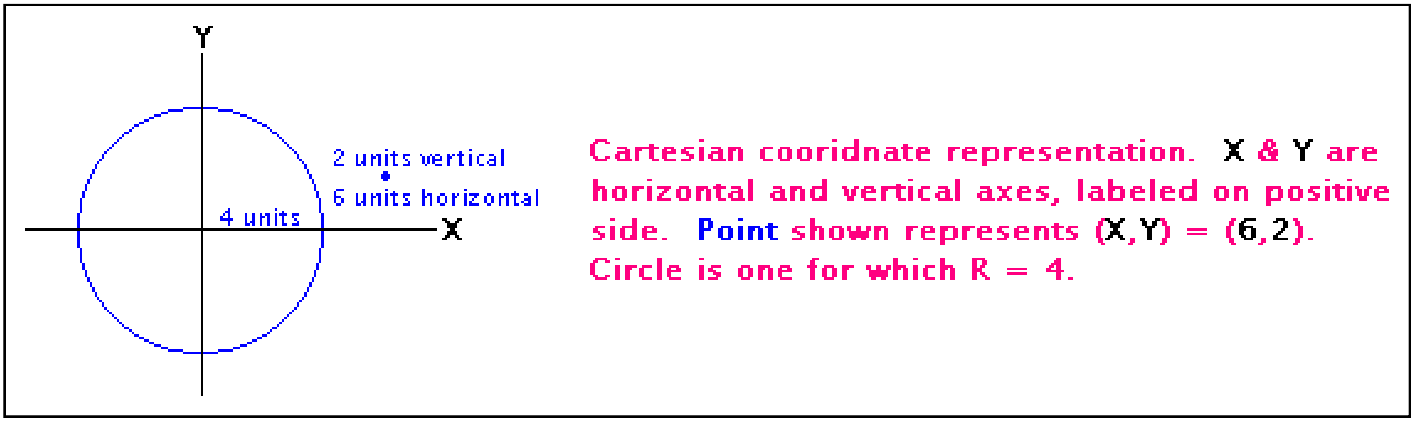
Ellipsoid : An ellipsoid is an ellipse rotated around one of its axes. Earth is nearly an ellipsoid, which is often an adequate approximation for basic astronomical calculations. Properly, Earth is an oblate spheroid.

Great Circles : Great circle arc, angle, and triangle refer to those on a spherical surface. This is relevant because distance between any 2 points on earth can be estimated using relations shown if their angular locations are known (i.e., latitude and longitude). Assuming Earth is a sphere is fine for many meteorological calculations, introducing less error than other factors involved.

Coordinate Systems

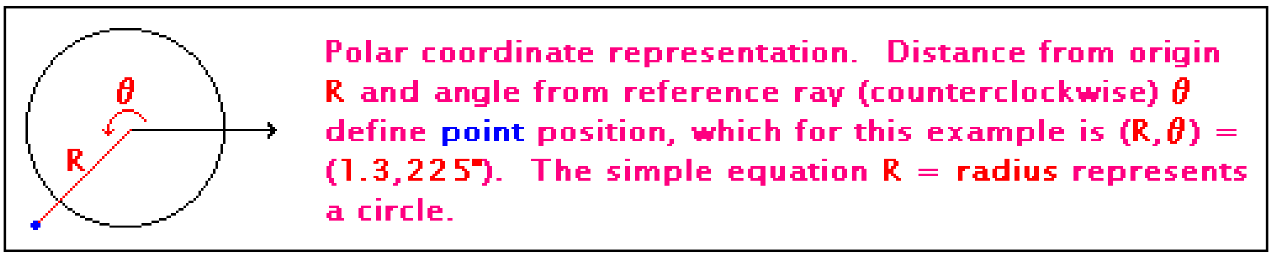
These are abstract ways of defining locations of objects. Notice that I mentioned geometry first, avoiding reference to these as much as possible; because curves, shapes, angles, distances, etc. are most relevant, rather than position specification. Such is necessary though. I mention 3 systems most relevant :

Cartesian Coordinates : These are defined according to perpendicular axes, the abscissa and ordinate, typically labeled X & Y, respectively :



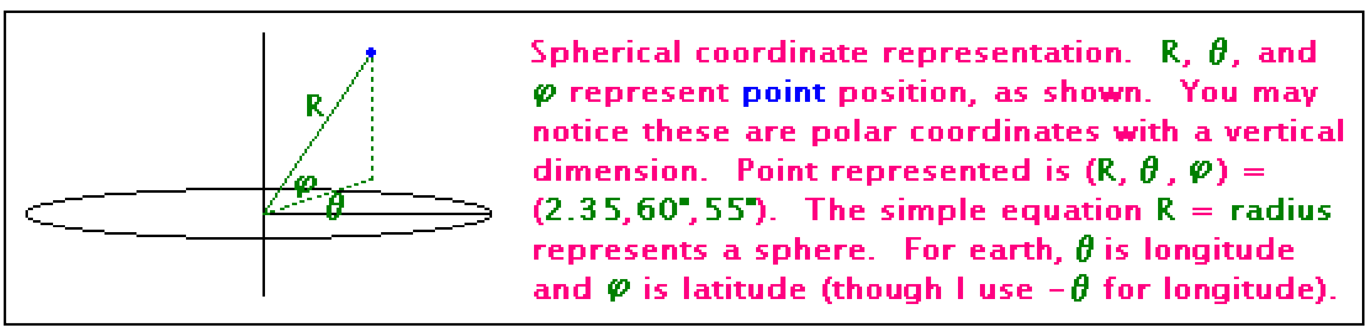
Location of objects are specified similarly as the point's shown. Equations previously shown represent such objects on Cartesian coordinate axes. Such is often used as reference for meteorological data - U & V analogous with X & Y, representing west-to-east and south-to-north directions. I.e., a wind with positive U & V components is from a direction generally W & S.

Polar Coordinates : These are defined according to distance from the origin of coordinate axes, and arc from a reference ray :



Radar images and hodographs are among common meteorological uses of polar coordinates - storms' distance and direction from a base radar are specified.

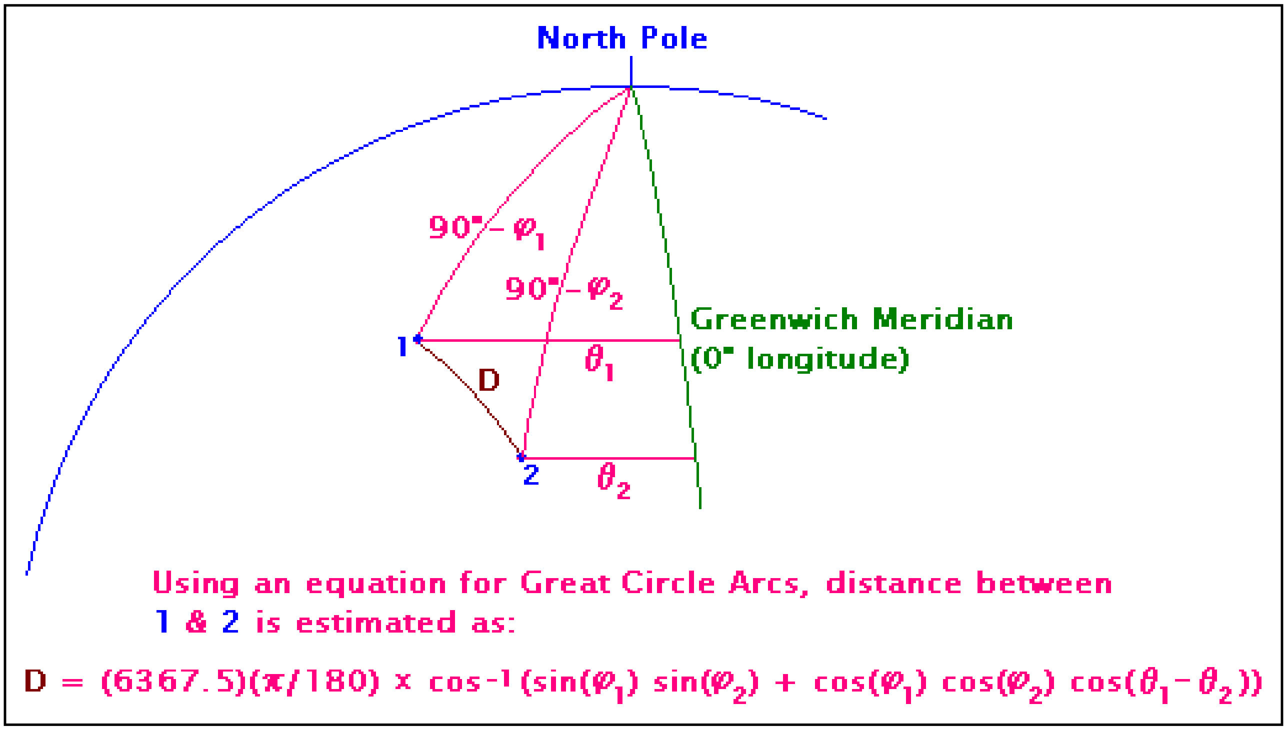
Spherical Coordinates : These are often used for earth, being a good approximation of a sphere. They are defined according to distance from origin and (spherical) longitude and latitude angles :



If you imagine a polar coordinate system flat (as on a table), longitude is polar arc angle (from reference ray) and latitude is elevation angle above horizontal (table), as shown. Thus for Earth, the equator is in the polar coordinate plane, its North and South Poles along the axis perpendicular to that plane. Because Earth is not spherical, radial distance is not same everywhere on its surface, but is nearly so.

A Few Applications

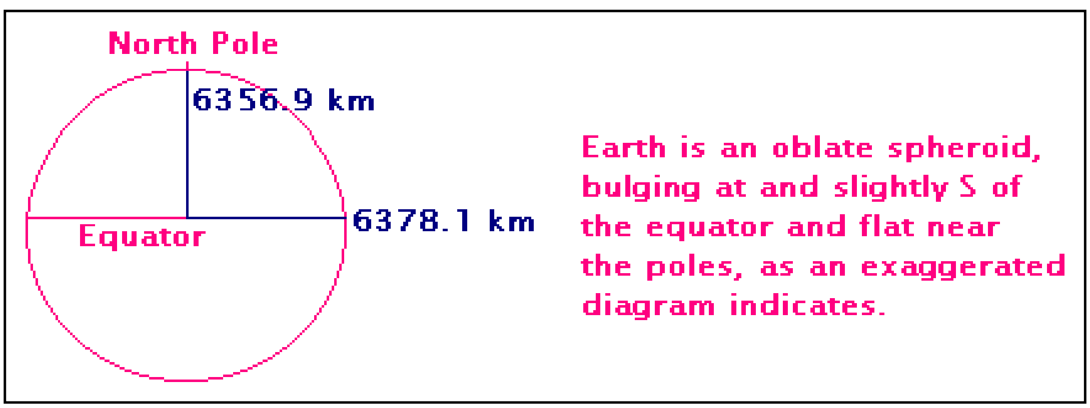
Distance Between 2 Points on Earth : Using the formulas for Great Circle Triangles above, distance between any 2 points on a sphere's surface can be simply estimated :



Considering average Earth radius of 6367.5 km, such can be estimated for Earth locations. Such includes the reference ray contains the Greenwich Meridian, 0° longitude. I define longitude as 0-360°, positive to W, and latitude -90° to 90°, S to N. Such is a natural reference, because our Earth rotates approximately 360° each day such that our sun rises E and sets W. North Pole is a common reference (i.e., Polaris, the North Star), thus is chosen as positive. Note that meteorologists often refer to longitude negative west of the Greenwich Meridian and positive east of it - opposite as I define. As an example, distance between New York City and Edmonton, Alberta :

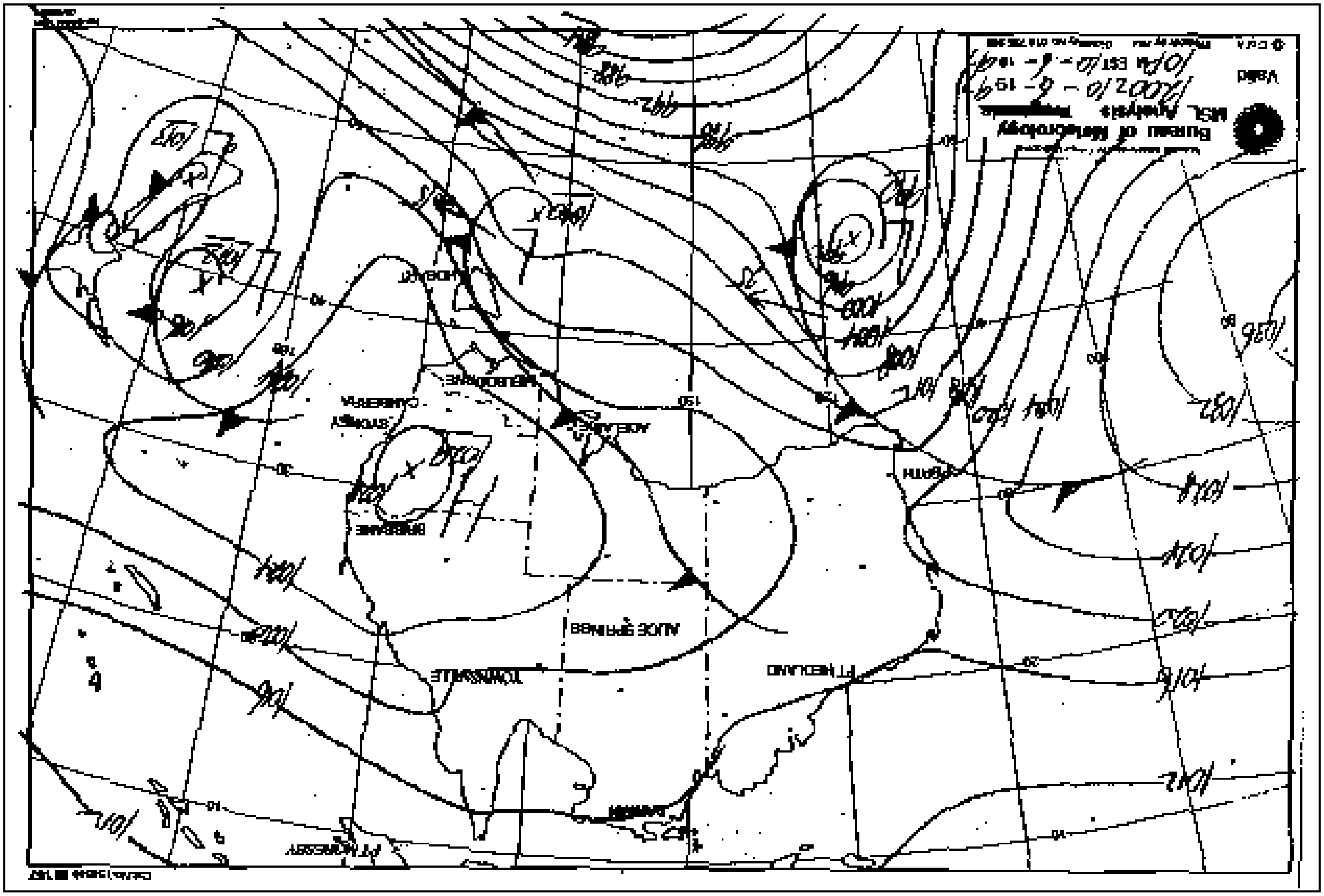
$$D = (6367.5)(3.14159 / 180) \cos^{-1}((\sin(40.8°)\sin(53.6°) + \cos(40.8°)\cos(53.6°)\cos(73.9°-113.6°)) = 3262.8 \text{ km}$$

As mentioned above, Earth is not a sphere, but an oblate spheroid :

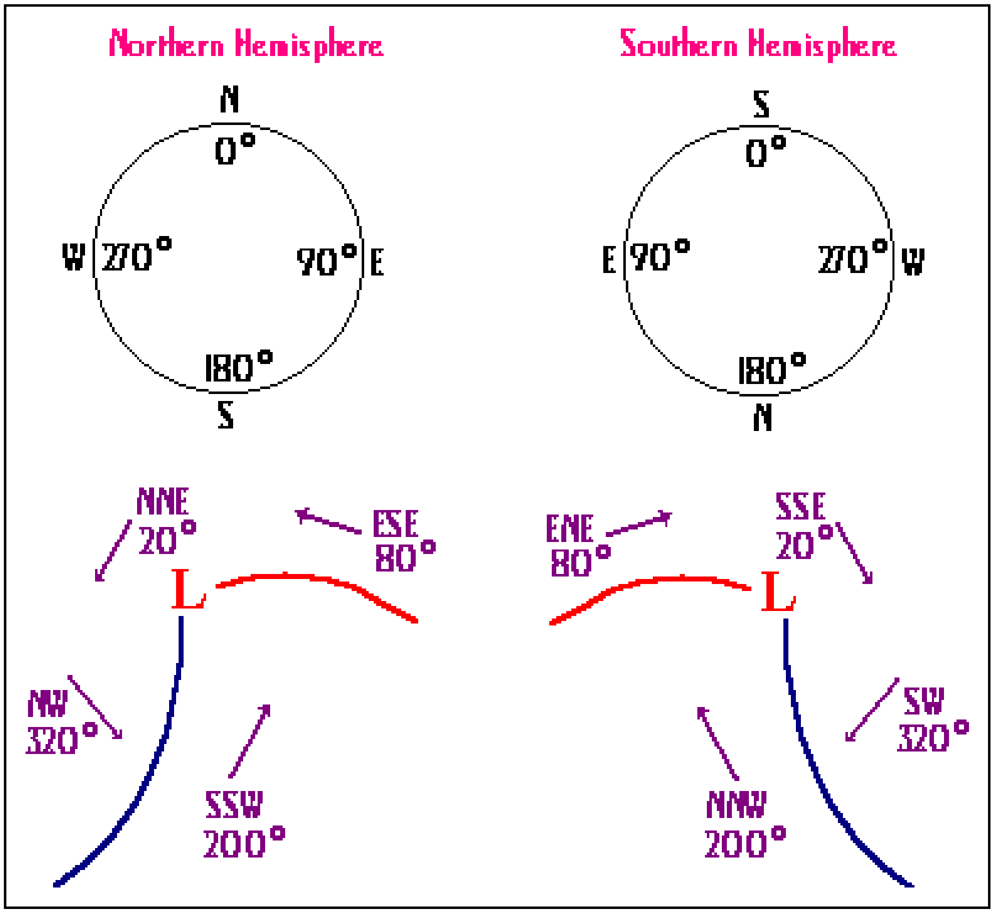


though differences are not great.

Wind Direction : Among the most commonly misinterpreted meteorological parameters is wind direction. People don't often have trouble understanding that wind speed is 32 mph (especially if it's blowing in their face), but if you ask them if such a wind is called a northeast or southwest wind, many are unsure. I'm gonna seemingly add more confusion - define winds differently for each hemisphere ! Because weather systems tend to circulate W to E around the poles, placing the pole on top of a map for either hemisphere is a natural representation. This idea became evident for me while forecasting for the World Solar Challenge in Australia. If I turned Australian weather maps up-side-down :

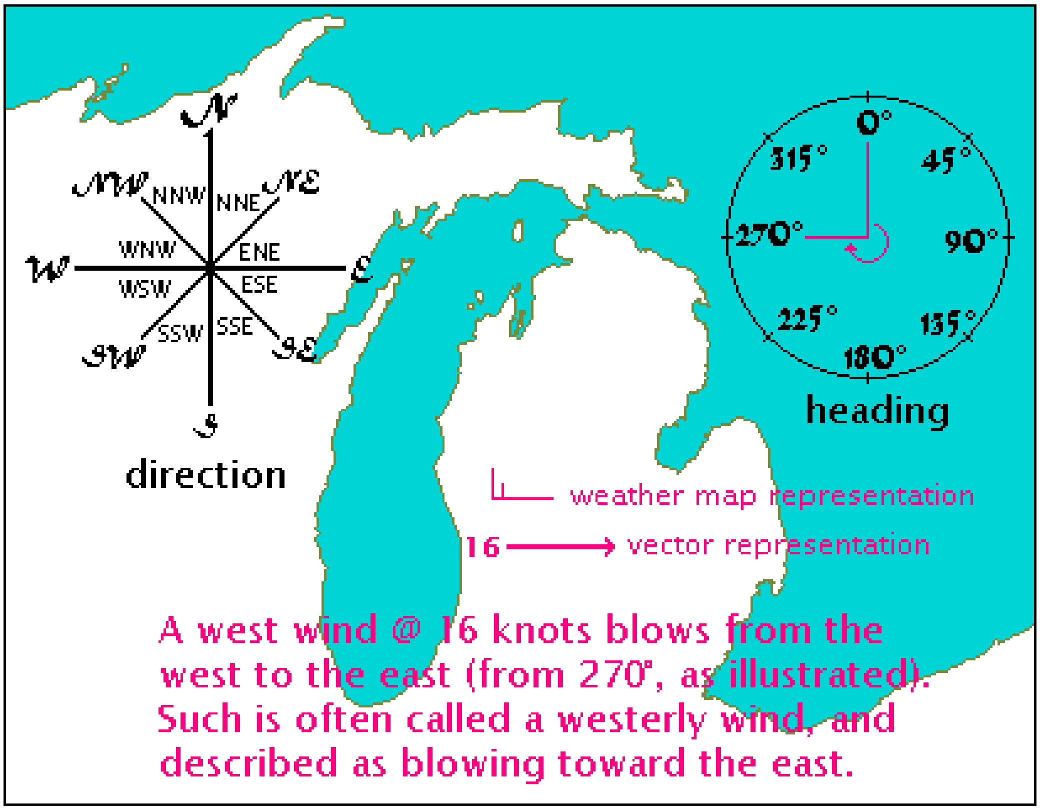


things were exactly as in the Northern Hemisphere, except that circulating from W to E meant right to left instead of left to right. The days when all analyses are accurately portrayed on 3-D images which can be viewed from any perspective are likely long from now, so this idea is currently relevant. I won't change directions we are familiar with (i.e., the North Magnetic Pole's location remains so anywhere on the globe), but headings. I understand that such is perhaps not recommended for many other applications, mainly because it requires a reversal from one side of the Equator to the other (which programming in atmospheric models is not extremely difficult). As can be seen, using such specification allows *similar meteorological significance for similar wind headings*.



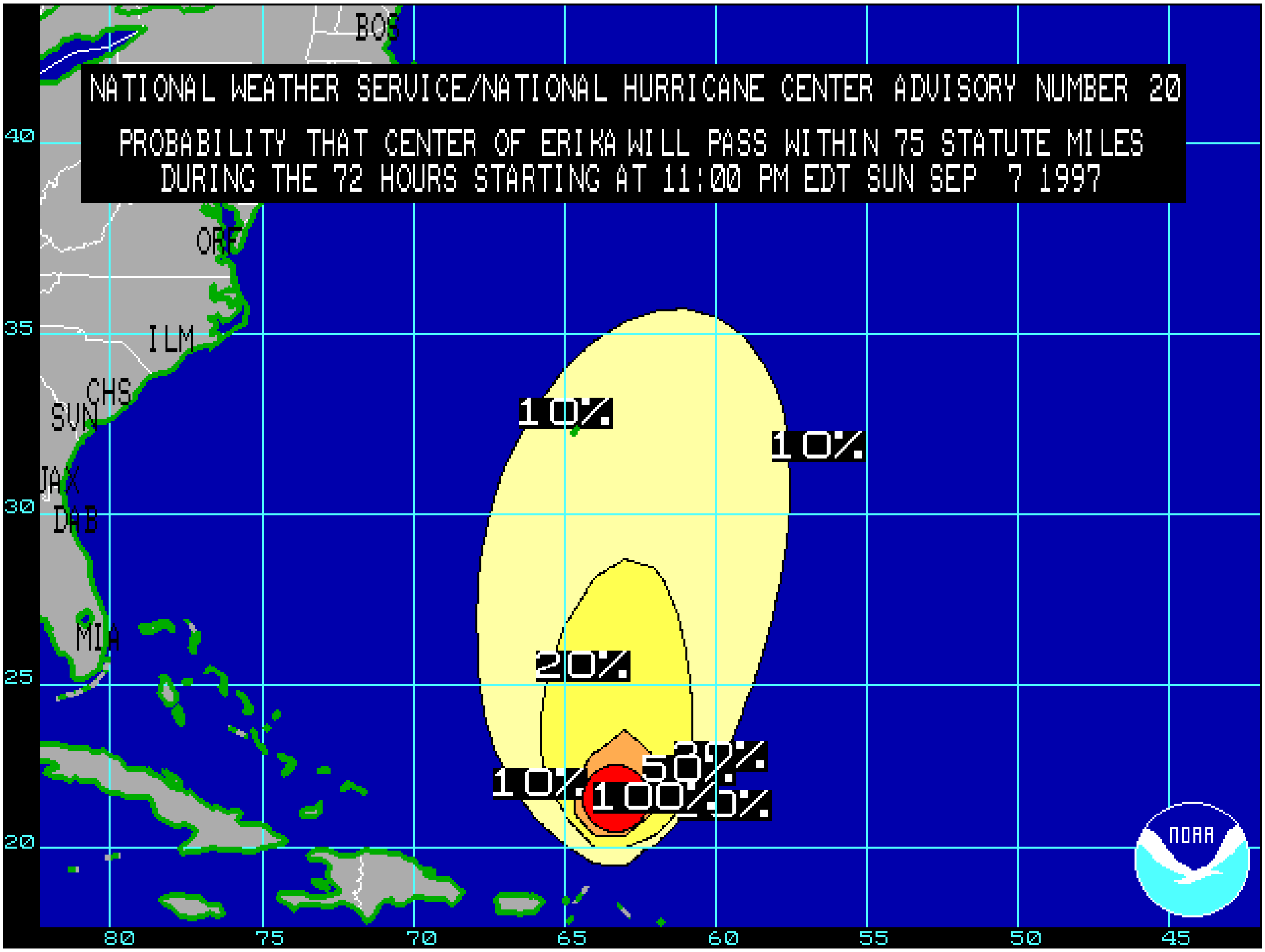
My suggested convention is irrelevant regarding the following definitions :

- When a wind direction is mentioned with **no modification**, such is assumed direction wind is blowing **from**. I.e., if reported wind is SSW @ 4 knots, such is **from the SSW** (southsouthwest).
- When a wind is called easterly, northerly, etc., such also implies direction wind is blowing from.
- When modifiers **to**, **toward**, or **blowing** are used prior direction specification, such is direction winds are blowing toward (opposite direction as from). You may notice that this is one of the surprisingly few times when usage of the word **to** is truly correct.



E.g., a ***wind*** *called W (west) @ 16 knots blows* ***from W to E*** *(east) with speed 16 knots. Such is also commonly called a* ***westerly wind****, which* ***blows (to the) east***. Modified base map above was obtained from Tiger Mapping Service. I apologize if this is obvious, but I've seen many misinterpretations. Note that **wind velocity** means (both) **direction and speed**. Quite often, the term *velocity* is used when *speed* (only) is meant.

Storm Movement : This typically means **direction storms move to or toward**. Consider for example, a hurricane warning and strike probability map :



The warning mentions **direction the storm is moving to -** N, or 360°. 16 compass points are used (as illustrated above), so the nearest is chosen.

Next I plan to briefly finish discussion of prerequisites, then begin a brief discussion of topics listed.

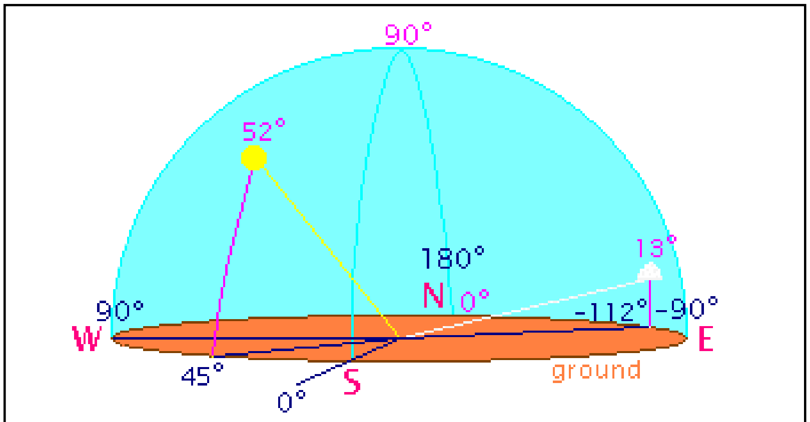
Home Page

Prerequisites - Geometry & Math

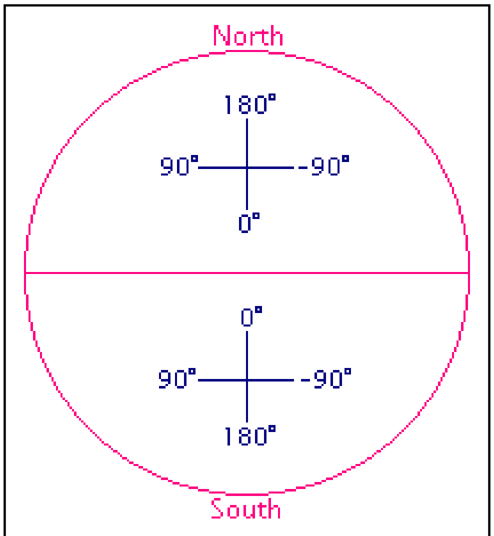
These beginning articles may seem quite simplistic, though most readers are probably unaware of some subtle details of these simplistic topics. Because I desire a series of articles which progress from A to Ω, as it were, the simple foundations of our endeavor must first be discussed.

Sky Hemisphere

This is something you perhaps did not see before. As for specifying locations on Earth's surface, spherical coordinates are useful for specifying sky locations. E.g., as direction and distance using polar coordinates indicate location of a storm in the horizontal plane, direction and elevation do so in the imaginary sky hemisphere :

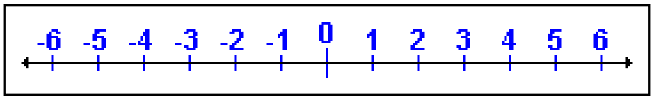


Sky Hemisphere. From a location (center of ground area), elevation and azimuth angles are defined. Positions of sun during afternoon and a cloud near the ENE horizon are illustrated.



Azimuth angles for Northern & Southern Hemispheres

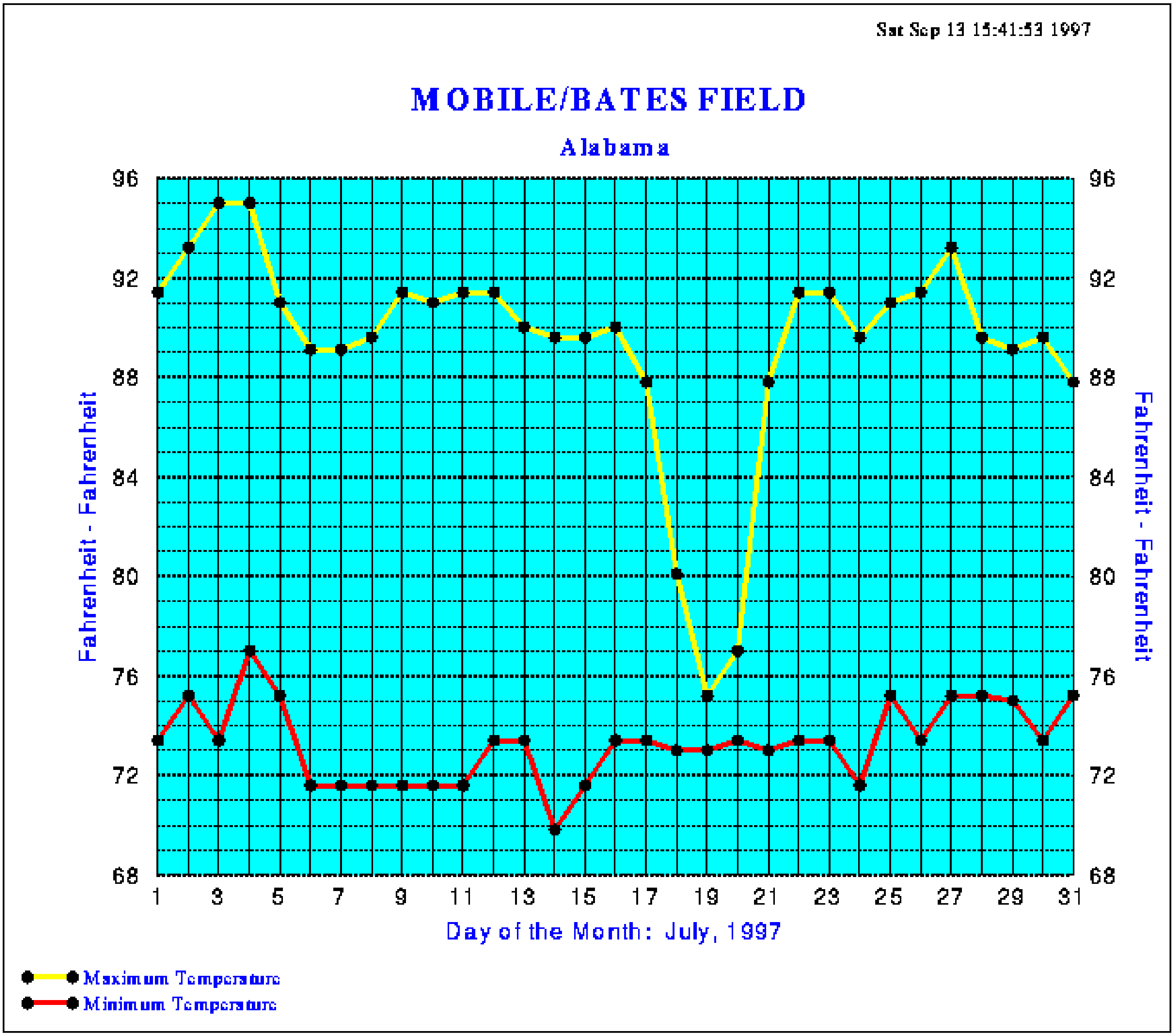
Elevation angle is angle above the local horizontal plane (related with distance of objects *in* our atmosphere), and azimuth angle is direction. Please notice that **my specification differs from the standard of 0° being North at any location**. My primary reason for this is not confusing people **-** rather that time is determined using solar noon as a reference, which is the time the solar disc crosses the local meridian, which **should be considered 0** similarly as 0 separates positive & negative numbers on the number line :



Solar transit of the local meridian is most often directly equatorward at any location not at it, which is 0° azimuth in the illustrations above.

Data Plotting

A few simple examples of plotting points in coordinate systems are presented here for illustration. July 1997 maximum and minimum temperatures for Mobile, AL are plotted in a Cartesian coordinate system :



Day of month is chosen as the abscissa and temperature as the ordinate. Though such is arbitrary, it is more appealing as shown. Data was obtained from NCDC's CLIMVIS. A polar coordinate example is the hodograph (upper left section) from an atmospheric sounding for Topeka, KS, from UCAR's Realtime Weather Data site. The reference axis is North, and wind direction during balloon ascent is indicated as its angle from it, positive clockwise (standardly-defined azimuth). Distance from the origin represents wind speed. 3-dimensional plots using spherical coordinates or 3-dimensional Cartesian coordinates can be made, though representation in 2 dimensions is difficult. Such plots can be extended for representing physical systems, e.g., ocean surface oscillations, from NOAA-CIRES CLimate Diagnostics Center. Plots and mathematics for coordinate systems greater than 3 dimensions are made, some with practical applications. Time can be considered a 4th dimension, though not a physical dimension.

Waves

Many definitions exist for this, but each regarding motion implies behavior varying between extremes (high then low then high, warm then cold, etc.). Note that if sine (& co*sine*) functions are plotted in Cartesian coordinates and extended past 0-360°, representation is a **periodic wave**. Most things we call waves, such as those on ocean surfaces and in our atmosphere (e.g., gravity waves - true waves, or upper air trof / ridge patterns represented on weather charts - a product of cold and warm regions of our atmosphere which have wave characteristics), are not periodic. Any wave or function can be described as a sum of periodic waves though, as this Java applet for 2 periodic waves illustrates. Though often called "interference", these actually augment as often as they cancel each other; so that is a sort of negative interpretation 😉

Algebra

Rational and irrational numbers comprise all real numbers. Imaginary numbers exist, which are related with some real representations (e.g., sine functions). As mentioned, I cannot explain all of such topics here. An important thing to notice though, is the word ratio in rational number. All rational numbers can be expressed as a ratio of whole numbers (integers). E.g.,

```
.625 = 625/1000 = 5/8,  6 = 6/1, etc.
```

Calculations are only exact when such ratios are retained. E.g., suppose you wish calculating :

```
(5/7)(3/26 + 17/9)
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(A product and sum of rational numbers). You can write approximate decimal numbers as :

```
5/7 = .71429,  3/26 = .11538,  17/9 = 1.88889
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Thus :

```
(.71429)(.11538 + 1.88889) = (.71429)(2.00421) = 1.4315871609
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But retaining rational numbers, you must use the least common denominator of added terms, which is 26 × 9 = 234. Thus :

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(5/7)((27 + 442)/234)) = (5/7)(469/234) = 2345/1638
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which is the (only) correct answer. Expressed as decimals, this is :

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1.4316239316239...
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... indicating that the sequence continues (rather than its usual indication of a smart-alecky comment 😉). Notice that the sequence 316239 continues repeating. The decimal sequence representing any rational number either ends or repeats. The sequence of an irrational number such as π = 3.14159265**...** (circumference of a circle with diameter 1) does neither. A great majority of real numbers are actually irrational - if points of the number line above were white if rational & black if irrational, it would appear almost same as above - only a very slight shade of grey. Perhaps the term **real numbers** is a misnomer though, because irrational numbers may describe few if any **real objects**. I.e., even if you think something is circular *and* a physical law implies it should be, close examination would likely reveal a collection of objects comprising it in positions which only tend toward circularity. But even so, the law and consequential tendency would be real !

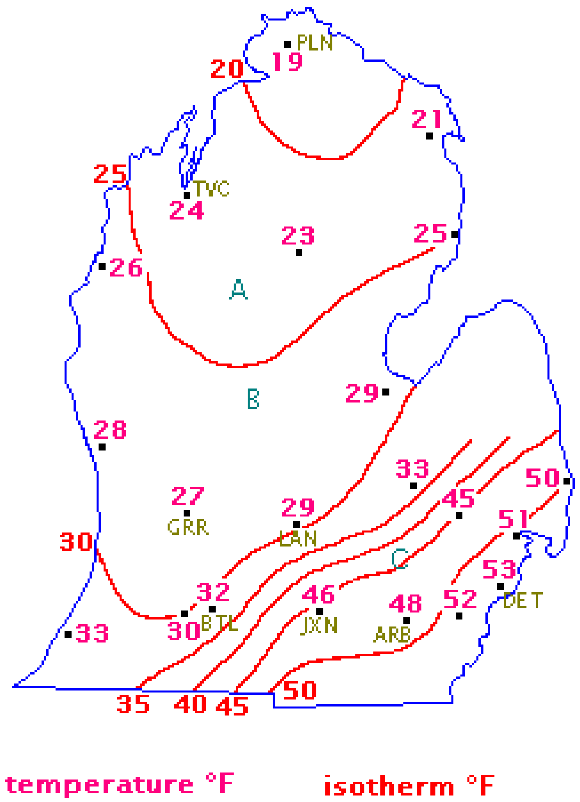
Notice that the approximate answer above only agrees with the exact rational answer (if you round it) for the least number of approximating digits used (5), which is typical.

Among the worst mistakes that people as a group ever made was deciding to represent numbers with our decimal system. That's an exaggeration, but with a point (perhaps also words with multiple meanings, such as *point*). Most things have a binary character. E.g., either a branch is attached to a tree or separated, either you catch a fish or don't, a musical scale consists of repeating octaves (though the number of notes in such is arbitrary), either you like a someone or hate him ☺, etc. Thus things are best represented with some form of binary numbers - base 2, 4, 8, 16, 32, etc. Computers use binary number representations for calculation, storage (bytes & bits), etc., because such are most efficient. For a computer, converting among binary and decimal number representations is an extra task which slightly decreases efficiency. If people have 10 fingers & 10 toes though, counting to 20 is natural I suppose ☺

Whichever number system is used, it represents counting. Joseph means *he shall add* - so I know about this. I'm not sure regarding accuracy or significance of such meanings, but some people worked determining those I suppose. Thus, you should not disregard alternative methods of forecasting events (e.g., psychic powers, premonitions, dreams, etc.), even if that event is weather. Previous societies probably did not consider such things so much because short-term weather did not affect them nearly so much as us (e.g., aviation), though long-term weather (e.g., drought) did more so. Another Joseph is recorded as effectively dealing with a future drought (I am the probably "other" one actually - being named after him - quite literally). A main problem with such things is false prophets though, which exist regarding most any endeavor. People will claim that a person "has salvation", etc., when they are really unsure. If a situation occurs such as the drought mentioned above, the person who knowledge has been revealed to is perhaps as certain of it as you are that when you drop a ball it will fall to the ground. That is a slight digression.

Addition is the only computational operation. Every other - subtraction, division, derivatives, etc. - are (some quite complicated) combinations of addition. An integral is analogous with multiplication (a different form of it), and a derivative analogous with division; which are all consequences of addition.

Because of analogies mentioned, I include *basic* calculus as part of algebra in my list of topics. For theoretical and thorough meteorological studies, a thorough knowledge of calculus basics is necessary; but as I've previously mentioned, not for accomplishing the mission here. Now I mention the concept **gradient**, being quite important for us. If you examine almost any weather map, you'll see gradients with various magnitude. Because large gradients are locations of greatest change, such are often locations of weather which most interests us - especially regarding temperature :



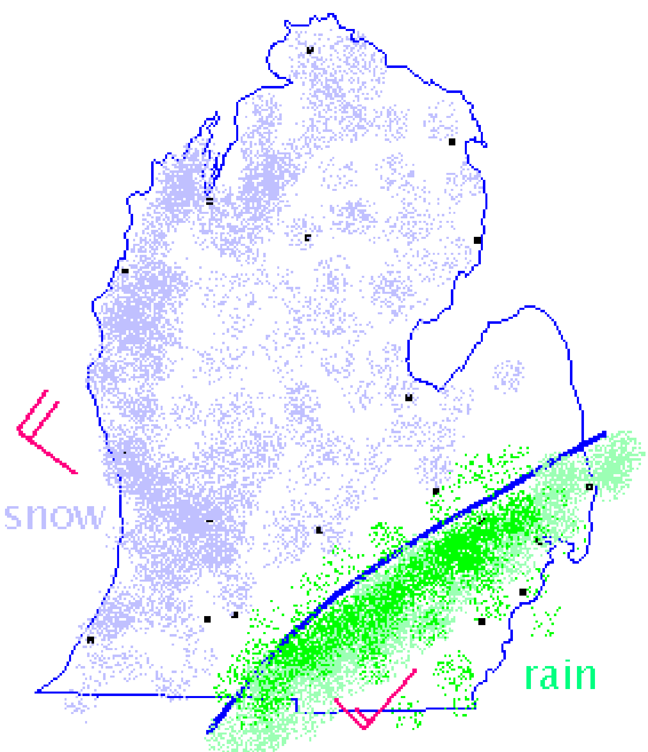
Gradient is :

change of magnitude of a parameter / distance change

Thus large gradients are locations such as that where isotherms are closest together on the map shown (cold front).

The simplest type of interpolation is linear, for which gradient is assumed constant between interpolation points. E.g., suppose linear interpolation between Grand Rapids (GRR) & Pellston (PLN). Temperature at point A would be 23 - not a bad approximation. If Jackson (JXN) & Traverse City (TVC) are chosen though, temperature at point B would be 35 - a poor estimate. Similalrly, between Ann Arbor (ARB) & Battle Creek (BTL) would be 40, which is near Jackson. Between Detroit (DET) & Lansing (LAN), 41 is estimated for point C - not bad because they are basically directly on either side of the strongest gradient. Often maps only indicate 2 or 3 temperatures for a region such as this, which this illustration hopefully shows can often be misleading.

You may notice that I basically used linear interpolation between points shown. The real temperature gradient for such a map might be slightly greater than illustrated.



A cold front (solid blue line) is a transition zone between cold and warm air masses as illustrated above. Heaviest precipitation tends to be near the front (but upper air flow greatly influences this also), and winds are often disorganized in this zone separating generally southerly and westerly winds from generally westerly and northerly winds.

Fronts are regions of large temperature gradient - strongest being those with largest temperature gradient. A front is not a border between warm and cold air, but a transition zone between generally cold and warm air masses, where most active weather often occurs. I plan discussion of this much more later.

Related with gradients is interpolation. This refers to estimating magnitude of a parameter at a location between those at which the value is known or measured. Simple linear interpolation (assuming the values vary @ a constant rate between points) is often used, but regarding map analysis, can be quite incorrect in regions where large gradients exist.

Probability and Statistics

I obviously cannot discuss this completely here, nor even close. Basics of these topics should be known also. A good example of probability is a 6-sided dice. If obtaining each number is as likely as any other, then the probability of obtaining each is 1/6 - 6 possibilities, only 1 of which satisfies each of them. Notice that this is the reciprocal of 6/1, mentioned above - both rational numbers. For reasons I mentioned, rational numbers should be retained when possible while doing statistical calculations involving them.

Clearly, the dice example involves rational numbers. What about meteorological variables though ? If you read a thermometer as 48.1 °F, that is quite approximate. No matter how accurate your thermometer and how careful your reading (if not digital), the actual temperature may differ. Thus I would not consider this a rational number, per se; even if the physical system determining temperature actually is (temperature is the root-mean-square kinetic energy of molecules in an ideal substance, which I plan discussion of later). Thus using 48.1 with other decimal numbers if computing monthly averages (for example) is preferable than using 48 1/10 with rational numbers. Precipitation likelihood is often expressed as a probability. Among other interpretations, it is an expression of a forecaster's uncertainty. Similar as the dice example, if (measurable) precipitation occurred approximately 4 of 10 times a weather forecaster previously felt as confident of its likelihood as a current situation, (s)he may express this as "a 40 % chance of (measurable) precipitation". I.e., 10 events, during 4 of which (measurable) precipitation occurred. Probability obviously becomes much more complicated, including conditional probabilities, combinations and permutations, functional distributions, and many other analysis techniques. Try understanding binomial trials and related distributions (particularly normal) if you can - many applications use them (perhaps I'll offer explanations later).

Statistics is closely related with probability, also much too complicated for complete discussion (if I could provide it). Ideas most commonly used for meteorology are average, mean, median, extremes (maximum & minimum), and variance (e.g., standard deviation). Standard deviation is an indicator of variance - how much values of a statistical sample vary, but assumes a normal distribution. Though many things can be approximated with statistical distributions, I'm not sure if any can be exactly described using such. Note that the idea of climate normals likely derives from the normal distribution.

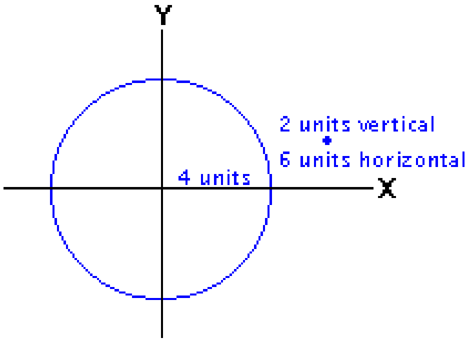
Epilogue

Though only describing some prerequisite concepts of geometry applications & math, I mention above some of the more interesting aspects of them; which hopefully makes the reader aware of how I think.

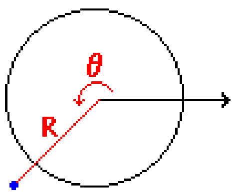
Home Page

Vectors & Gradient

Consider if you wish, 2-dimensional coordinate axes corresponding previously discussed :

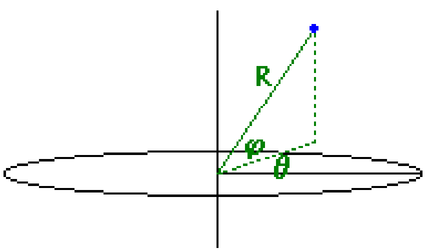


Cartesian cooridnate representation. X & Y are horizontal and vertical axes, labeled on positive side. Point shown represents (X,Y) = (6,2). Circle is one for which R = 4.

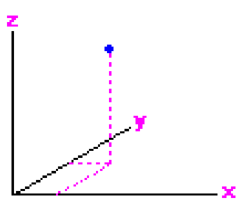


Polar coordinate representation. Distance from origin R and angle from reference ray (counterclockwise) θ define point position, which for this example is (R,θ) = (1.3,225°). The simple equation R = radius represents a circle.

Similarly, for 3-dimensional coordinate axes :



Spherical coordinate representation. R, θ, and φ represent point position, as shown. You may notice these are polar coordinates with a vertical dimension. Point represented is (R, θ, φ) = (2.35,60°,55°). The simple equation R = radius represents a sphere. For earth, θ is longitude and φ is latitude (though I use −θ for longitude).



Cartesian coordinate representation of the same point. Point represented is (x, y, z) = (.67, 1.17, 1.93).

Relations among representations of points are :

Polar Coordinates

$x = R\cos\theta$ $\quad R = \mathrm{SQRT}(x^2 + y^2)$

$y = R\sin\theta$ $\quad \theta = \arctan(y/x)$

Spherical Coordinates

$x = R\cos\phi\cos\theta$ $\quad R = \mathrm{SQRT}(x^2 + y^2 + z^2)$

$y = R\cos\phi\sin\theta$ $\quad \theta = \arctan(y/x)$

$x = R\sin\phi$ $\quad \phi = \arcsin(z/(\mathrm{SQRT}(x^2 + y^2 + z^2))$

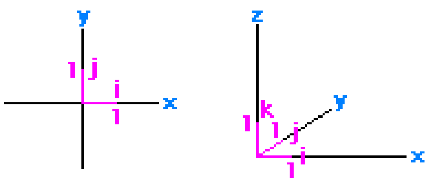
ϕ is typically defined oppositely as I do, as angle from vertical axis rather than horizontal plane which corresponds with latitude. Thus in my equations, sines and cosines are switched for ϕ compared with the standard definition.

Thus, if position of a point for either system is known, it can be determined for the other. These are the 4 main coordinate systems meteorologists use, often with modifications. E.g., for atmospheric modeling, points are often described using 3-dimensional Cartesian coordinate system with the origin at some place on Earth's surface; such that equations for motion must be modified to account for the fact that the x-y "plane" is curved, etc.

As an example, consider the spherical coordinate point shown above. For Cartesian coordinates, we can calculate :

$$x = 2.35 \cos(55°) \cos(60°) = .67$$
$$y = 2.35 \cos(55°) \sin(60°) = 1.17$$
$$z = 2.35 \sin(55°) = 1.93$$

For the Cartesian coordinate systems shown above, unit vectors can be defined - vectors parallel with each axis with length 1 :



Unit vectors using 2 & 3-dimensional Cartesian coordinate axes. The 2-dimensional x-y axes could be same as those for 3-dimensions, but tilted for better view in screen.

Forces, velocities, etc. can be described using unit vectors. E.g., suppose the point described above represents a 2.35 N (Newton) force. X, Y, and Z components of this force are :

$F_x = .67$ N $\quad F_y = 1.17$ N $\quad F_z = 1.93$ N

Thus, you can see that :

$$\mathbf{F} = \mathbf{i}\ F_x + \mathbf{j}\ F_y + \mathbf{k}\ F_z$$

bold letters indicating vector quantities. Thus, a vector quantity can be described as a sum of the product of unit vectors and scalar components.

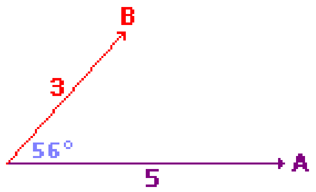
2 operations often used for meteorology are scalar and cross products. Scalar product of 2 vectors is :

$$\mathbf{A} \cdot \mathbf{B} = A_x B_x + A_y B_y + A_z B_z = |A||B| \cos(a)$$

for which | | represents absolute value - positive value of the quantity contained (magnitude of the vector), and "a" angle between the vectors. Note that scalar product is an expression of how parallel vectors are. It is expressed as a number relative with the product of magnitudes of the vectors. Cross product of 2 vectors is :

$$\mathbf{A} \times \mathbf{B} = \mathbf{i}\ (A_y B_z - A_z B_y) + \mathbf{j}\ (A_z B_x - A_x B_z) + \mathbf{k}\ (A_x B_y - A_y B_x) = |A||B| \sin(a)$$

It is a vector (magnitude and direction), direction determined using the "right-hand rule" (described below). Thus, 2 vectors for a cross product must be written in the proper order. I.e., **A** × **B** points in the opposite direction of **B** × **A**. As an example, suppose 2 vectors **A** & **B** (these may be forces, etc.) :



Scalar product of vectors **A** & **B** is :

A·**B** = **A** **B** cos(56°) = 8.39

Cross product of vectors **A** & **B** is :

A X **B** = **A** **B** sin(56°) = 12.44

to a direction according to the right-hand rule (toward you for this diagram)

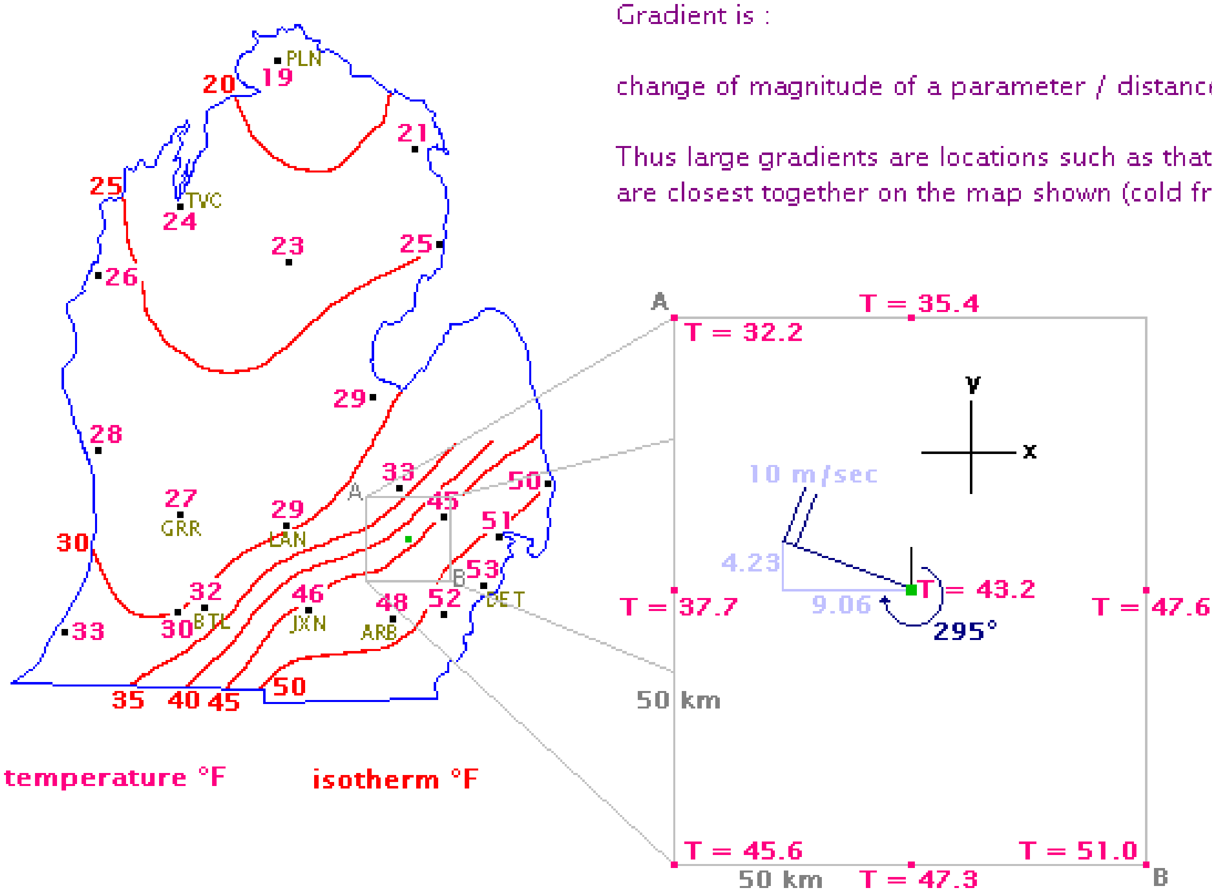
Direction for the cross product is determined using the 'right-hand rule'. I.e., open your right palm & curl your fingers in the plane of **A** & **B** from **A** toward **B**, closing your hand. Point your thumb up also ☺ The direction your thumb points is the direction of **A** × **B** (toward you for this example).

Why mention these things ? Because meteorological analysis requires such specifications. Consider the temperature example of gradient I previously showed :

Gradient is :

change of magnitude of a parameter / distance change

Thus large gradients are locations such as that where isotherms are closest together on the map shown (cold front).



Distance from A to B is the square root of $50^2 + 50^2$, which = 70.711 km = 70711 m.

Temperature changes are -13.4°F for y-direction, 5.4°F for x-direction, and 18.8°F from A to B.

Temperature differences centered at location are 9.9°F for x-direction and -11.9°F for y-direction.

Wind is from 295° @ 10 m/sec, such that the y-component is -4.23 m/sec and the x-component is 9.06 m/sec.

On this diagram I now suppose a cold front just passed the location indicated. I include a wind velocity, specified as both magnitude and direction, and temperature change components at a location. I previously mentioned that cold fronts are regions with a large temperature gradient, where storms often occur. If you are unfamiliar with calculus, this may not be so meaningful to you; but even so, you can probably see what I describe. A **gradient** can be mathematically expressed using the del operator ∇ :

$$\nabla = \mathbf{i}\ d/dx + \mathbf{j}\ d/dy + \mathbf{k}\ d/dz$$

d representing 'change'. Ideally, this is an infinitesimal change at the point of interest, but approximating it with finite changes (finite differences) is okay. Because our map is 2-dimensional, only the **i** & **j** (x & y) components concern us. (If it did, calculation of the **k** (z) component would also be included). **Temperature gradient** ∇T (temperature change ÷ distance change) **is** :

$$\nabla T = \mathbf{i}\ dT/dx + \mathbf{j}\ dT/dy$$

How much does temperature change in the x & y directions ? On our map, we see that temperature change from A to B is 18.8 °F, which occurs over a distance of 70711 m. Thus, temperature gradient is

$$\nabla T = 18.8\ °F \div 70711m = .0002659\ °F/m = .2659\ °F/km$$

about ¼ °F / km. Expressed as components, this is :

$$\nabla T = \mathbf{i}\ (5.4°F)/(50000\ m) + \mathbf{j}\ (-13.4°F)/(50000\ m)$$

Note that I am labeling units now because I am not using strictly MKS units.

Advection is a meteorological term used for transport of a property from one location to another. Mathematically, for temperature it is :

$$T\ advection = -\ \mathbf{V} \cdot \nabla T = -\ V_x\ dT/dx\ -\ V_y\ dT/dy$$

For this, we consider the teperature differences centered at the location shown (i.e., across the point along x & y directions). If wind velocity **V** is as shown, temperature advection is :

$$\begin{aligned} T\ advection &= -\ (9.06\ m/sec)(9.9°F)/(50000\ m) - (-4.23\ m/sec)(-11.4°F)/(50000\ m) \\ &= -.002758\ °F/sec = -9.93\ °F/hr \end{aligned}$$

Temperature at the point indicated is decreasing .002758 °F / sec or because 3600 sec are an hour, 9.93 °F / hr (assuming conditions remained same). That is only because of advection. Other factors influence temperature also - radiative cooling, turbulence, etc., but would be a realistic estimate for temperature decrease during the next hour. Hopefully this illustrates usefulness of vector representations.

For reference, the Cartesian representation of gradient using polar coordinates is :

$$\nabla = \mathbf{i}\ d/dr + (1/r)\ \mathbf{j}\ d/d\theta$$

and using spherical coordinates is :

$$\nabla = (1/(r\ \cos(\varphi))\ \mathbf{i}\ d/d\theta + (1/r)\ \mathbf{j}\ d/d\varphi + \mathbf{k}\ d/dr$$

Home Page

Notation, Symbols, and Physical Quantities

Though this can perhaps be boring, familiarity with standard ways of describing the physical attributes of the atmosphere is necessary for accomplishing our goal.

Notation

This is the way we express concepts & quantities numerically. Because all commonly available data is described using decimal numbers, the rest of this discussion is.

Scientific Notation

As hinted previously, many numbers are much too large or small for reasonable expression. E.g., Avagadro's number - number of atoms in a mole of matter :

602213670000000000000000

This can be expressed :

6.0221367×10^{23}

Note that :

10^{23} = 100000000000000000000000 (23 0's)

Thus,

```
  6.0221367
× 100000000000000000000000
  ------------------------
  602213670000000000000000
```

An interesting WWW page related with this.

Similarly for very small numbers. E.g., peak wavelength of solar energy emission :

.0000047 m = 4.7×10^{-6} m = 4.7 µm

Note again that :

```
10-6 = 1/1000000 = .000001
```

Thus,

```
  4.7
× .000001
  ------------------------
  .0000047
```

Note that 10^{-6} is easily determined (as is 4.7×10^{-6}) moving the decimal point 6 places left from 1.0 or 4.7, respectively; adding 0's where necessary, similarly as they were added for 10^{23} above.

Introduced above (as most readers are aware) is notation for distance - meters (m) & micrometers (µm), mentioned below. Most common scientific notation prefixes are :

Prefix	**Symbol**	**Magnitude**
Giga	G	10^9
Mega	M	10^6
kilo	k	10^3
hecto	h	10^2
deka	da	10^1
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	u *or* µ	10^{-6}
nano	n	10^{-9}

Many others exist, but these should be memorized. Common terms evolve from such prefixes (or vice versa). E.g., a cent (¢), which is 10^{-2} \$. Note that capital letters are used for prefixes Mega & larger, small letters for others. Logically, capitals should be used for all multipliers (prefixes > 1) and small letters for all divisors (prefixes < 1). E.g., D could represent deka & d deci (and why use k for one and c for another ?). Several reasons exist for not doing so - especially conflicts with other symbols (e.g., K for carat). Because the English alphabet includes only 26 letters, some conflicts are inevitable. Else, you can eat sushi & watch sumo wrestling. Just kidding - a little humor can be entertaining ☺ The [National Institute of Standards and Technology]() was designed partly for solving this problem, participating with [international]()

efforts for creating consistent standards.

Physical Quantities

Any common object or process can be expressed as combinations of 4 fundamental properties - Mass, Distance, Time, and Electric Current. Standard measures for each are :

Property	Standard measure	Symbol
Mass	kilogram	kg
Distance	meter	m
Time	second	sec *or* s
Electric Current[1]	ampere	A

Such are called MKS units (meter-kilogram-second), a subset of the Metric System. This concept is very useful because when doing complicated calculations, if you know your equations are correct and you express all quantities as MKS units, your answer must be MKS units. Such a calculation is efficient, and a final conversion to desired units is seldom more difficult than required conversions would otherwise be.

Square brackets are often used for dimensional analysis. I.e., Mass [M], Distance [L], Time [T], and Electric Current [E]. L is used for distance, standard term for which is "Length". I do not like that, because length is typically associated with width and height of specific objects. Distance is a more general term. I am not sure if [E] is the correct letter used for dimensional analysis - please correct me if you know this is wrong. Nobody is perfect - part of the process of becoming a good scientist is following a logical course of action until you discover a better one.

Example : **Energy** = Force × Distance = Mass × Acceleration × Distance = Mass × (Distance / Time^2) × Distance = **Mass × Distance^2 / Time^2**. Thus, Energy's dimensions are expressed as **$[M][L^2][T^{-2}]$**.

3 other basis units for the International System of Units (SI) (1) (2) are :

Property	Standard measure	Symbol
Temperature	Degree Kelvin	°K
Luminous intensity	candela	cd
Substance Amount	mole	mol

I include these in a separate list because using all 7 is redundant. (Please be aware that some people who are funded to go to France and argue in English about these things think they have good reasons for including them together.) Temperature is related with internal energy of a substance, which can be expressed as a combination of M, L, and T, as illustrated. Heat capacity must be known though, which is determined from experimentation (i.e., temperature change), so if you say this should be included in the list above, I won't argue. If luminosity interests you, it is related with photon frequency and optics - expressible with very complicated combinations of M, L, T, and E. Substance amount is as simple as counting, previously discussed - though counting to Avagadro's number is impossible for a person & simple for a computer. A mole is a fundamental physical constant, as many others which are required for physical analysis; but not a fundamental property more so than mass, which mole's definition describes.

Units can be expressed many ways - distance can be expressed as feet, miles, furlongs, etc., each with their specific purposes. For our purpose, the following are most useful :

Mass This is seldom expressed other than as kg or g. Using table above, you should be able to see that 1 kg = 10^{-3} g. This is often confused with weight.

Distance This is commonly expressed as m, cm, km, dam, µm, inch, foot, yard, and mile (statue & nautical). You should know conversion factors among these - which this page from Micro-Images provides. Exact values are perhaps not as important as being able to recognize (i.e., when viewing a weather map) things such as 50 miles being approximately 80 km, which is 80000 m, and a cloud with 5600 m altitude being about 18000 feet (high alto or low cirro type). A useful way for me of thinking of this when doing rough calculations is approximately 8 km for every 5 mi & a little more than 3 feet for every meter. I.e., I add a little to the 5600 to make it an even 6000, then multiply with 3. That's generally as accurate as changing cloud heights are estimated. Each person thinks differently, so make you own which serve you well.

Time Second, minute, hour, day, week, month, year, decade, century, and millennium are all commonly discussed. You should memorize that 3600 sec are in an hour, and 86400 sec in a day. Quite often hourly and / or daily meteorological observations must be converted to MKS units, which requires sec for time. Coordinated Universal Time is the standard time reference, which I obtain from the U.S. Naval Observatory. For common purposes is same as Greenwich Mean Time (GMT). Its relation with local standard time for all locations which interest you should be memorized. I suggest keeping *standard time* on your meteorological clock, because :

- UTC / GMT is printed on nearly all weather maps, for consistent reference from any Earth location - conversion to local standard time never changing.
- Such is the best representation of a consistent local time reference if time zones are well-chosen.

Adding 1 hour to standard time during daylight savings time is easy, for confirmation with commonly-used time.

Electric Current[1] Ampere (Amp) is the only common expression I am aware of. This is some ways rather important in our atmosphere - perhaps ways not realized as well as the obvious charge separation required for lightning. Little knowledge of electricity is required for effective weather forecasting though.

[1] Perhaps **electric charge** instead of current (which includes redundancy with time) should be a fundamental property. Such is expressed as Coulombs (C), fundamental charge quantity being that of an electron, $1.60217733 \times 10^{-19}$ C.

Epilogue

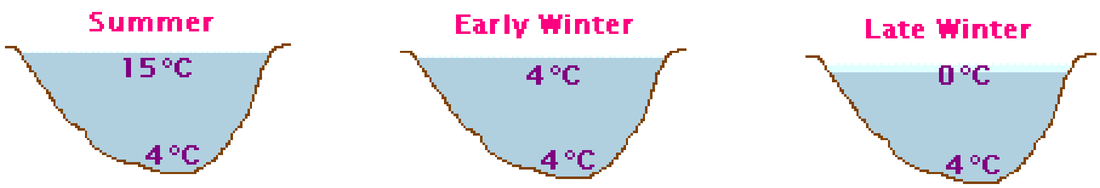
The purpose of this article is not teaching this material per se, but mentioning the notation and representations used most for our purpose.

Home Page

Temperature and Kinematic and Dynamic Quantities

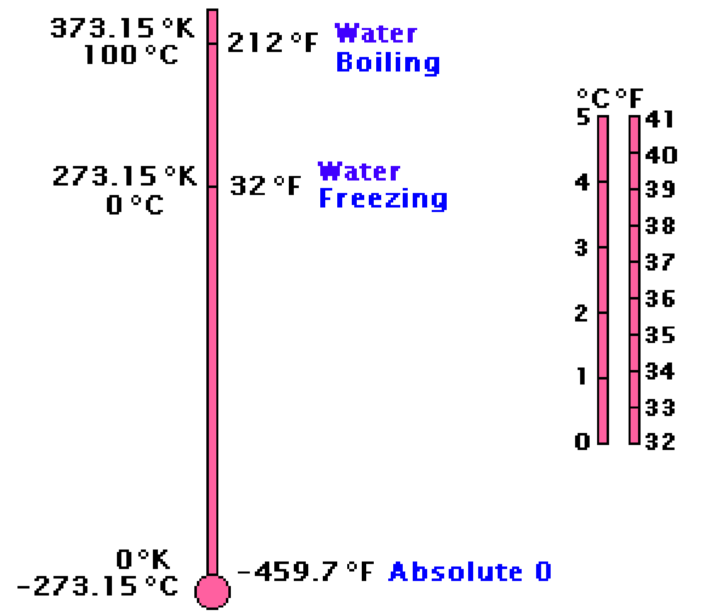
Now that fundamental quantities are discussed, I mention specifics and ways combinations of such are used for describing physical phenomena.

Temperature is a fundamental weather-related quantity, likely most important. It is proportional with energy (please see below) of molecules in a substance, rotational / vibrational energy of solid and liquid molecules, and translational energy of gas molecules. When a substance acquires heat, such typically (i.e., for almost all substances) causes expansion because increased motion separates molecules, though



A consequence of water being most dense with temperature 4°C is that an entire lake must become approximately 4°C before surface freezing occurs. During late summer and autumn, water which cools at lake surface sinks until 4°C is ahieved. More cooling allows surface freezing because such water is less dense than that near bottom, where temperature of a deep lake may not vary significantly.

water is a common exception. This principle makes thermometers effective for temperature measurement, heating causing experimentally-determined expansion rates. Thus, temperature is 0 if all molecular motion ceases. Such is called absolute 0, and is represented as 0 °K. °K refers to Kelvin temperature scale (° symbol is not standard for this) which absolute 0 and the freezing and boiling temperatures of water with standard atmospheric pressure define. Kelvin scale is a centigrade scale - cent meaning hundredths. 100 centigrade ° are included between freezing and boiling temperatures. Thus, "the Centigrade scale" is very similar with the Kelvin scale, except using 0 °C & 100 °C for freezing and boiling temperatures, respectively. °C actually more commonly refers to the Celsius scale, which differs very slightly from Centigrade. The Fahrenheit scale is commonly used, 32 °F and 212 °F chosen for freezing and boiling temperatures. Thus, a ° K & C represent the same temperature difference, which equals 1.8 °F. Mentioning these seemingly obvious things is parctically useful - e.g., for surface maps with °F and upper air charts with °C, being able to quickly judge how much warmer 25 °C is than 46 °F and realizing that 80 °F is not twice as warm as 40 °F, nor 30 °C 3 × as warm as 10 °C, but 300 °K is 20 % warmer than 250 °K, etc. Some temperatures should be memorized for reference :



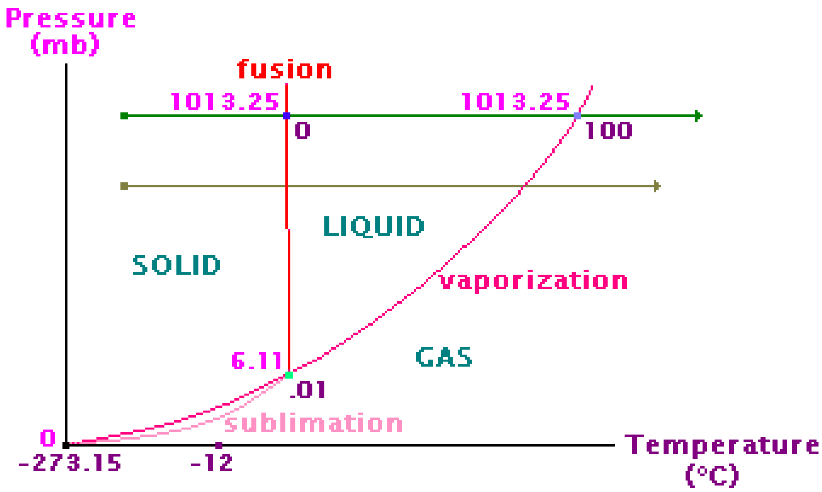
Perhaps you've seen this before - illustration of Kelvin (°K), Centigrade (°C), and Fahrentheit (°F) temperature scales. Each 5 °C (or °K) change = 9 °F change. The following temperature conversions are evident :

$$°K = °C + 273.15$$

$$°F = (9/5)\,°C + 32$$

$$°C = (5/9)(°F - 32)$$

- Freezing and boiling water temperatures with standard atmospheric pressure.
- Triple point of water is .01 °C = 273.16 °K = 32.02 °F, temperature at which gas, liquid, and solid phases exist in equilibrium (with pressure of 6.11 mb - 166 × less than standard)



Phase diagram for water. Curves indicate phase changes : fusion (freezing/melting), vaporization (condensation/evaporation), and sublimation / deposition. The green line indicates processes which occur as temperatures changes for standard atmospheric pressure 1013.25 mb. When water is heated to 0 °C, melting occurs, and to 100 °C, boiling occurs. Freezing temperature remains very close to 0 °C, but for small atmospheric pressures (e.g., high elevations), boiling temperature greatly decreases, as the olive line indicates. A specific amount of vapor pressure always exists above water - the value along the vaporization curve. This is called saturation vapor pressure, which depends only with temperature. It is 0 for absolute 0, increasing to 6.11 mb at .01 °C, and to 1013.25 mb at 100 °C. Pressures for which sublimation (ice to vapor) and vaporization occur differ for temperatures < 0 °C. This difference is largest near -12 °C, as indicated. The vaporization curve is extended for temperatures < 0 °C because supercooled water can exist, though rarely observed for temperatures < -40 °C. The triple point is that for which all 3 phases of water exist at equilibrium - pressure 6.11 mb (166 X less than standard) & temperature .01 °C.

- All equivalent °F temperatures for each 5 °C for [-40 °C, 50 °C], especially middle values
- Average Earth surface temperature is about 15 °C = 288.15 °K = 59 °F
- Maximum recorded Earth surface shelter temperature was 70 °C = 158 °F (for 2 minutes) in Portugal, or 58.0 °C = 136.4 °F at Azizia, Lybia (sustained)
- Minimum recorded Earth surface shelter temperature is approximately -88 °C = -127 °F at Vostok, Antarctica
- Diurnal temperature range of about 11 °C or 20 °F is common at midlatitudes, record temperatures often being about that same amount greater / less than normal temperatures

Fundamental kinematic and dynamic quantities and their units are now presented, for reference regarding topics discussed below :

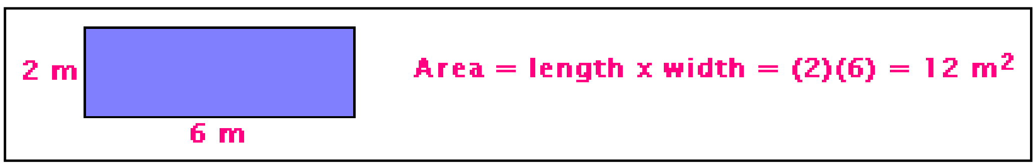
Quantity	**Units**
Area	m^2
Volume	m^3
Density	kg/m^3
Speed	m/sec
Acceleration	m/sec^2

Force	kg m/sec^2 = N
Pressure	kg/(m sec^2) = N/m^2 = Pa
Energy	kg m^2/sec^2 = J
Power	kg m^2/sec^3 = J/sec = W

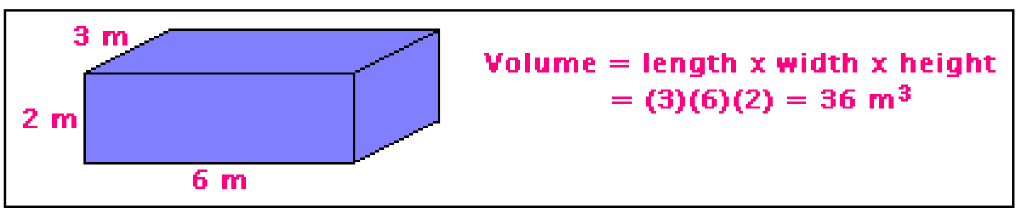
Note that all are combinations of [M], [L], and [T], fundamental quantities previously discussed, and units measured for a phenomenon determine its characteristics (i.e., whether it is a speed, a power, an energy, etc.). Names for new units shown are : N : Newton, Pa : Pascal, J : Joule, W : Watt.

Below some concepts regarding motion and statics are mentioned. These are obviously not intended as comprehensive, but are a good introduction, meant for illustrating most relevant concepts. I cannot emphasize too much how useful study of basic (physics) mechanics is regarding weather study. Being thoroughly aware of physics involved with atmospheric motion, you'll understand why you observe what you do and develop a 'feel' for it, which is helpful for deciding how fast a storm may develop, how much snow may occur, etc.

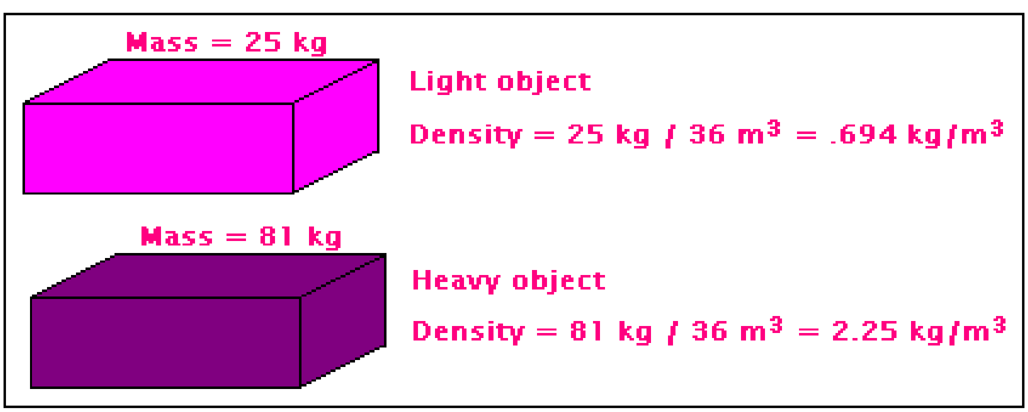
Area = Distance^2. This involves 2 dimensions, length and width :



Volume = Distance^3. This involves 3 dimensions, length, width and height.

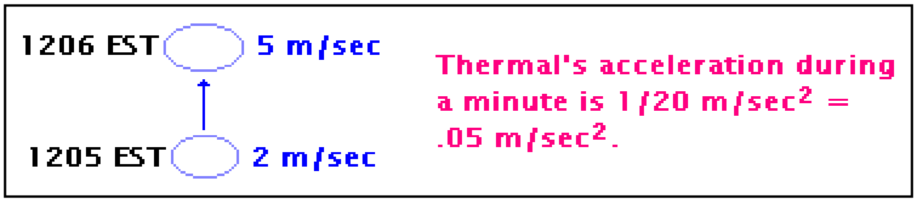


Density = Mass ÷ Volume. This describes how much matter is contained in a volume, which is very relevant regarding atmospheric thermodynamics, for which air densities are of great consequence. A dense object feels 'heavy', while one not dense 'feels light'.



Speed = Distance ÷ Time. E.g., if air travels 20 miles during 2 hours, its average speed is 10 miles / hour. This **differs from velocity**, which is a vector quantity - speed and direction.

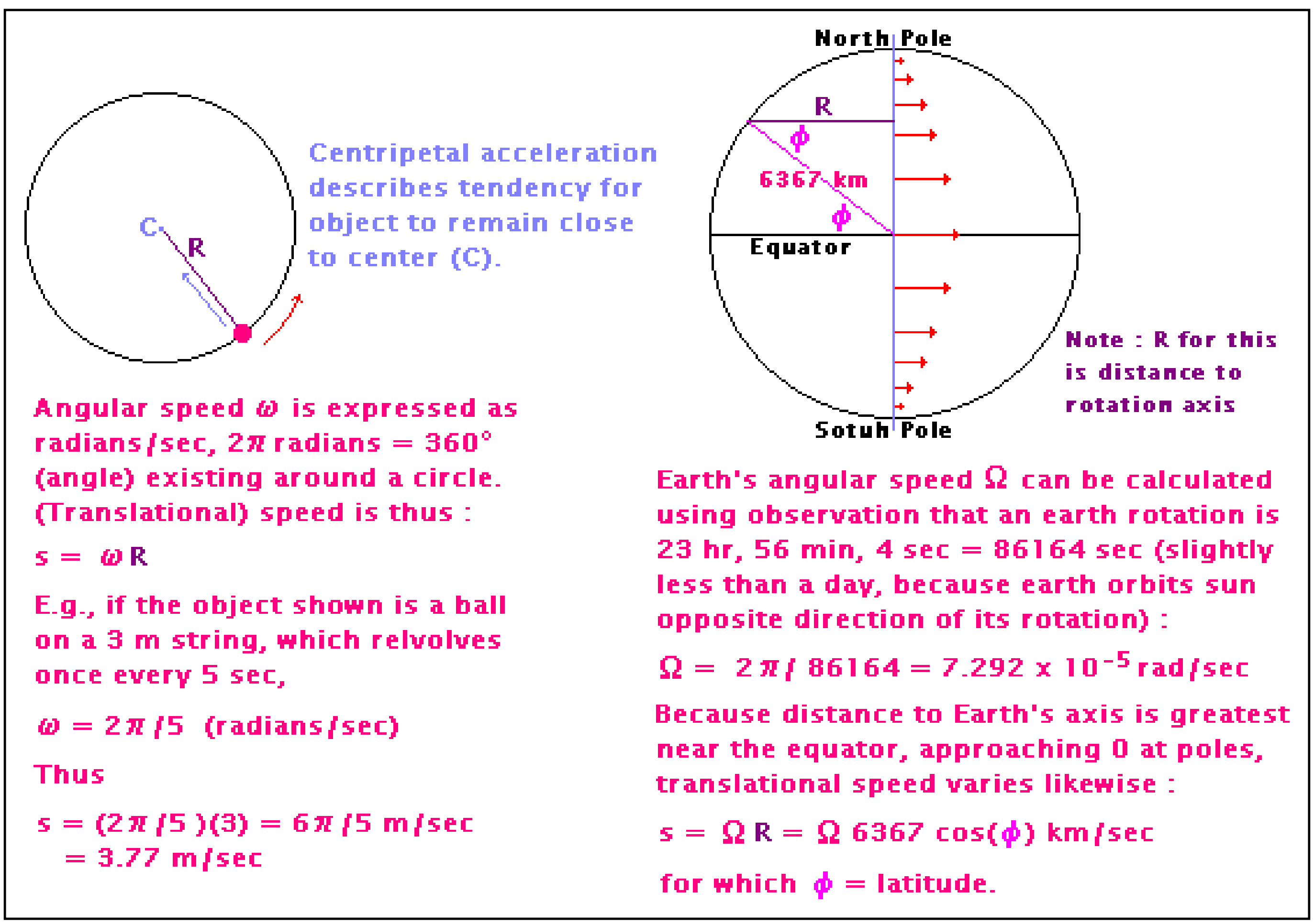
Acceleration = Speed change ÷ Time. Thus, it specifies speed rate of change to a specific direction. E.g., if a rising thermal with speed 2 m / sec accelerates, speed a minute later becoming 5 m / sec, its acceleration is 3 m / sec ÷ 60 sec = 1 / 20 m / sec^2 = .05 m / sec^2 :



Note that an accelration can occur with constant speed - if curving as in the example below.

Description of motion as above is called kinematics. "Air" and "thermal" above are treated as objects (technically, particles), though they consist of many objects (molecules). Such a treatment is often sufficient for analysis though, especially regarding solid objects.

The above describe linear motion. Because we live on a rotating planet, and because rotating weather systems are so common, rotational kinematics should be studied also, which include the concepts of angular speed and centripetal acceleration :



Now Newton's 3 Laws of Motion should be mentioned :

- Every body persists in its state of rest or uniform motion in a (straight) line unless it is compelled to change that state by forces impressed on it.
- Acceleration of an object is a consequence of the sum of all forces acting on it, related as : F = m a ; F = Total force acting on mass m, a = acceleration.
- To every action there is an opposed and equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

The 1st and 3rd Laws are basically the original descriptions (interpreted & simplified), the 2nd later interpretation of the general idea. These are very important regarding atmospheric phenomena (perhaps the foundation of such), and should not only be memorized, but become part of the way you view events if not already so - especially the 1st & 2nd Laws. I am not so sure regarding the 3rd Law - I suppose it depends how you interpret it; though if nothing else, it can help analysis.

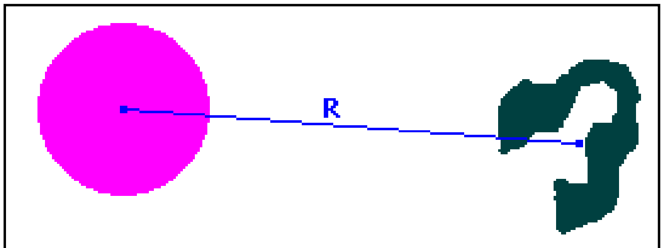
If you study Physics very much, you will / did discover that such laws are not perfect, but are such a good description that they are sufficient for predicting planetary motions (e.g., eclipses, transits, etc.) using the Universal Law of Gravitation. Now dynamics, which involves description of forces responsible for observed motions, can be discussed :

Force = Mass × Acceleration. Acceleration of an object (i.e., a mass, because all objects have mass) is a consequence of all forces acting on it. This is the 2nd Law, used as a foundation for atmospheric theory and modeling. Note how the 1st and 2nd Laws compliment each other. Any object with uniform motion (i.e., constant velocity) is considered being at rest (resting). This is so because all motion is relative, so a reference frame can be defined which coincides with any object. For planetary studies, our sun is a natural reference, and for atmospheric studies, earth's rotational axis, which are resting with velocity 0 when used as references. If a force acts on any such resting object, an acceleration occurs, inversely proportional with mass of the object. I.e., great force is needed for moving a very massive object, which experience indicates.

Simple example of relative motion. Though object A appears to move toward object B with speed 10 m/sec (observed as illustrated), you can correctly say that B is moving 10 m/sec towrad A, and you (observer) are moving with B.

Gravity is a force inherent with any object, proportional with its mass, which the Universal Law of Gravitation describes :

$F = G\, m_1\, m_2 \;/\; r^2$



G : Universal gravitation constant = $6.6720 \times 10^{-11}\ m^3\ kg^{-1}\ sec^{-2}$
m_1 : mass of object 1
m_2 : mass of object 2
r : radial distance between 1 & 2

It acts in a direction between centers of mass of the objects.

Gravitation is thus a quite weak force (considering how little you feel the force keeping you on the huge earth). Note that though seemingly implied, it is not necessarily an attraction - abscence of a repelling force from all directions because one object blocks it from another can produce the same effect. Considering mass and radius of Earth (original determination of which was difficult !), a gravity force (F_g) at Earth's surface can be considered :

$F_g = G\, m_e\, m \;/\; r_e^2$

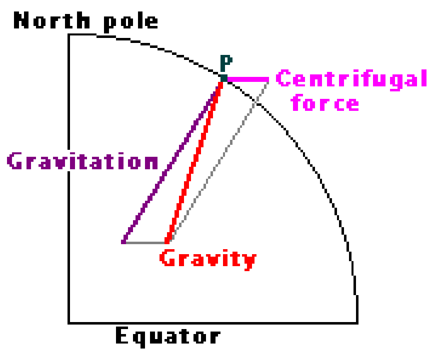
m_e : Earth mass = 5.98×10^{24} kg
r_e : Earth radius = 6367000 m

Thus,

$F_g \;/\; m = (6.67 \times 10^{-11})(5.98 \times 10^{24}) \;/\; 6367000^2 = 9.84\ m/s^2 = g$

g : gravitational acceleration on Earth

g is the symbol customarily used for representing Earth gravity. This situation is more complicated because we live on a rotating, nonuniform planet. Thus, what we consider "gravity" is a sum of contributions of all masses which Earth consists of (rock, iron ore, nickel, oil, etc.) and a centrifugal force - an imaginary force because of our natural reference as Earth's rotational axis chosen :



Gravity as we experience it is the sum of gravitations among Earth and an object and a centrifugal force (because we accelerate wrt Earth's rotation axis, used as reference). Diagram is from Atmospheric Thermodynamics by Iribarne & Godson. Scale of diagram is greatly exaggerated - maximum centrifugal acceleration is .00086 m/sec^2 at the equator, compared with typical graviational acceleration 9.81 m/sec^2.

The consequence of all of such considerations is the geoid. Because a fluid such as water achieves equilibrium with gravity, the geoid defines sea level, which is not any perfect shape because of mass inconsistencies below. Each time people or other creatures drill, tunnel or redistibute earth mass, they alter gravity and thus the geoid slightly (even rain showers redistributing water among lakes). Gravity is constantly measured, changes or discrepancies noted. This is relevant because concepts such as geopotential height use gravity as a basis. A first order approximation for gravitational acceleration around Earth is :

$g = (9.80616)(1 - 2.59 \times 10^{-3} \cos\{2(Lat)\})(1 - 3.14 \times 10^{-7} Z)$ m / s^2

Lat : latitude
Z : altitude above sea level

9.80616 m / s^2 being the standard value for gravitational acceleration at Lat = 45° and sea level.

Pressure = Force / Area. Because weight is a force, a fine description for atmospheric pressure is "weight of air above a location". On Earth,

$W = m\ g$

W : weight

is an expression of weight - product of mass and gravity. Because of such, it decreases as altitude in our atmosphere increases (unless vertical air accelerations are very large). It is often measured using depth of a column of mercury which it can support. Because average atmospheric pressure at Earth's surface is very nearly 100000 = 10^5 Pa, this value was called a **bar** (b) (perhaps referring the column of mercury supported). Meteorologists most often use millibars for atmospheric pressure, 1002 mb being easier for dealing with than 1.002 b. You may notice that a millibar is also a hectopascal, another term commonly-used. Standard atmospheric pressure (1 (standard) atmosphere) at sea level is 1013.25 mb, though I believe the global average is more like 1011 mb. Inches of mercury (column supported) is another commonly-used measure, standard value being 29.92 inches. Thus, the **weight** mentioned above is equivalent with about that of a 30 inch mercury column, which is same weight as about 31.6 feet of water (mercury is a dense substance !). Among common pressure conversions are :

1 atmosphere = 1013.25 mb = 29.92 inches mercury
1 mb = 1 hPa = 2.95 hundredths of an inch of mercury
1 inch of mercury = 33.865 mb

Energy = Force × Distance. This acquires many forms, translational energy, heat energy, electromagnetic energy, etc., and includes anything which can be described using units of energy. 2 common descriptions for mechanics are kinetic energy (KE) and potential energy (PE). **Kinetic energy** describes energy associated with translational motion :

$KE = 1 / 2\ m\ s^2$

m : mass
s : speed

Thus, a force applied along a distance equivalent with kinetic energy can be responsible for causing such motion. Notice that if an object is resting (i.e., moving with constant velocity), its kinetic energy does not change, specification of which depends with reference frame; and any further force applied changes kinetic energy, which can be an opposing force decreasing it or an additional force increasing it. According to kinetic theory, temperature of a gas (e.g., air) is proportional with root-mean-square speed of its molecules :

$$1/2\ m\ s_{rms}^2 = 3/2\ k\ T$$

m : mass of gas molecule
s_{rms}^2 : root-mean-square speed of gas molecules
k : Boltzmann constant
T : absolute temperature

I plan discussion of this later regarding thermodynamics, root-mean square speed (sort of average speed of molecules), etc..

Potential energy describes distribution of masses wrt (with respect to) a reference datum :

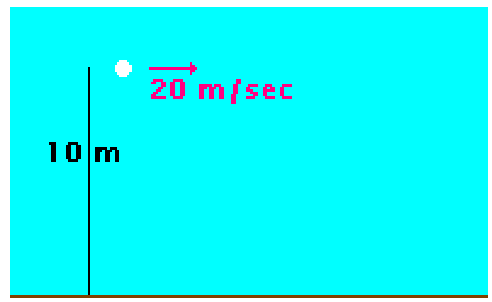
$$PE = m\ g\ d$$

d : distance above datum

Total mechanical energy (ME) can be described as a sum of kinetic energy & potential energy :

$$ME = KE + PE$$

Note that the reference frame and datum determine such specification, natural ones for Earth atmospheric studies being Earth's rotational axis and mean sea level, though the ground is often used as reference as in this diagram.



Suppose a 1/5 kg ball travels 20 m/sec at 10 m altitude. Its kinetic energy is :

$KE = (1/2)(1/5)(20^2) = 40$ J

Its potential energy wrt ground is :

$PE = (1/5)(9.81)(10) = 19.62$ J

Thus, total energy expended between this time and time it becomes stationary is :

$ME = 40 + 19.62 = 59.62$ J

which is mainly lost as friction, slightly heating air & ground.

Power = Energy change ÷ Time, or Energy change = Power × Time. E.g., suppose 10 100 Watt (power) light bulbs shine for an hour :

$$(10)(100\ W) \times (1\ hour) = 1\ kW\text{-}hour$$

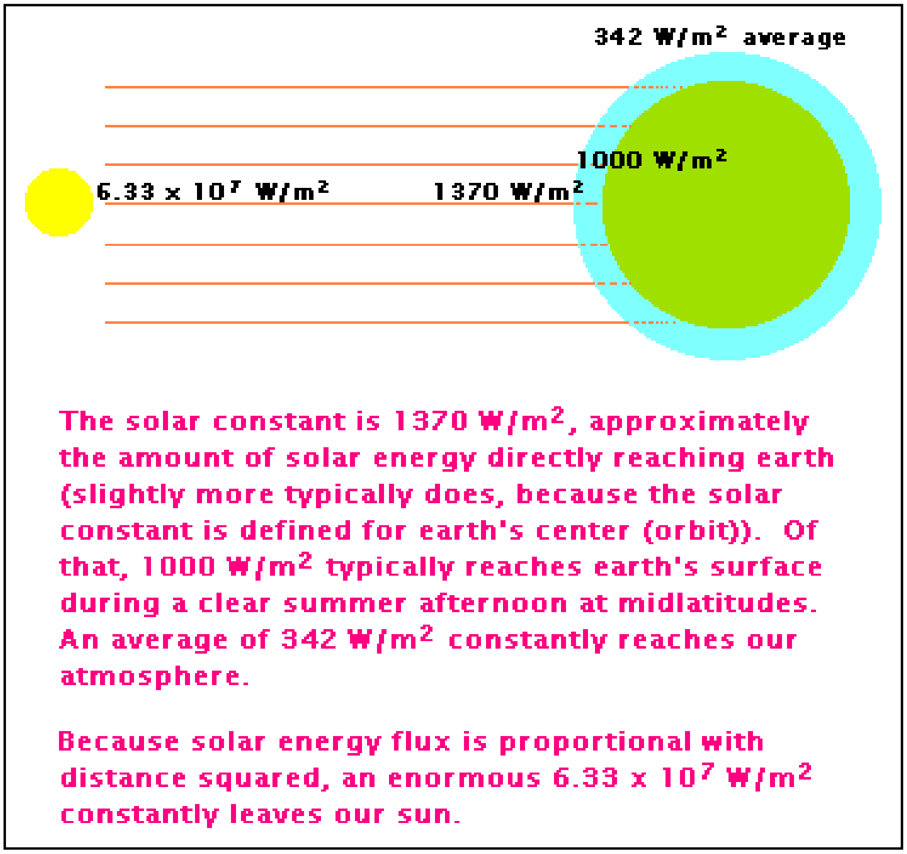
or

$$(10)(100\ W) \times (3600\ sec) = (1000\ J/sec)(3600\ sec) = 3600000\ J = 3.6\ MJ.$$

The conversion :

1 kW-hour = 3.6 MJ

is very useful, because energy is often expressed using W-hour or KW-hour, not only regarding electrical power, but also solar power. J is preferable, which should only be used regarding solar energy (i.e., earth heating). Because global solar energy at Earth's surface during a clear summer day near noon at midlatitudes is about 1000 W / m^2, a square meter (horizontal) surface on ground receives about 3.6 MJ energy during an hour of those conditions (but does not absorb all of it). The solar constant is 1370 W / m^2, such that average solar energy reaching earth is about 342 W / m^2. This is the fundamental source of energy for earth, driving weather.



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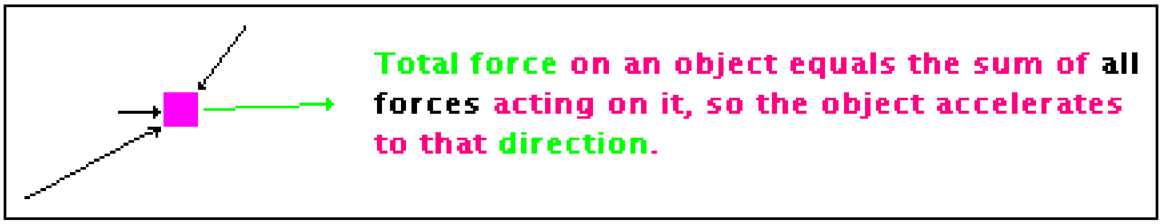
A few more Math, Physics & Related Topics

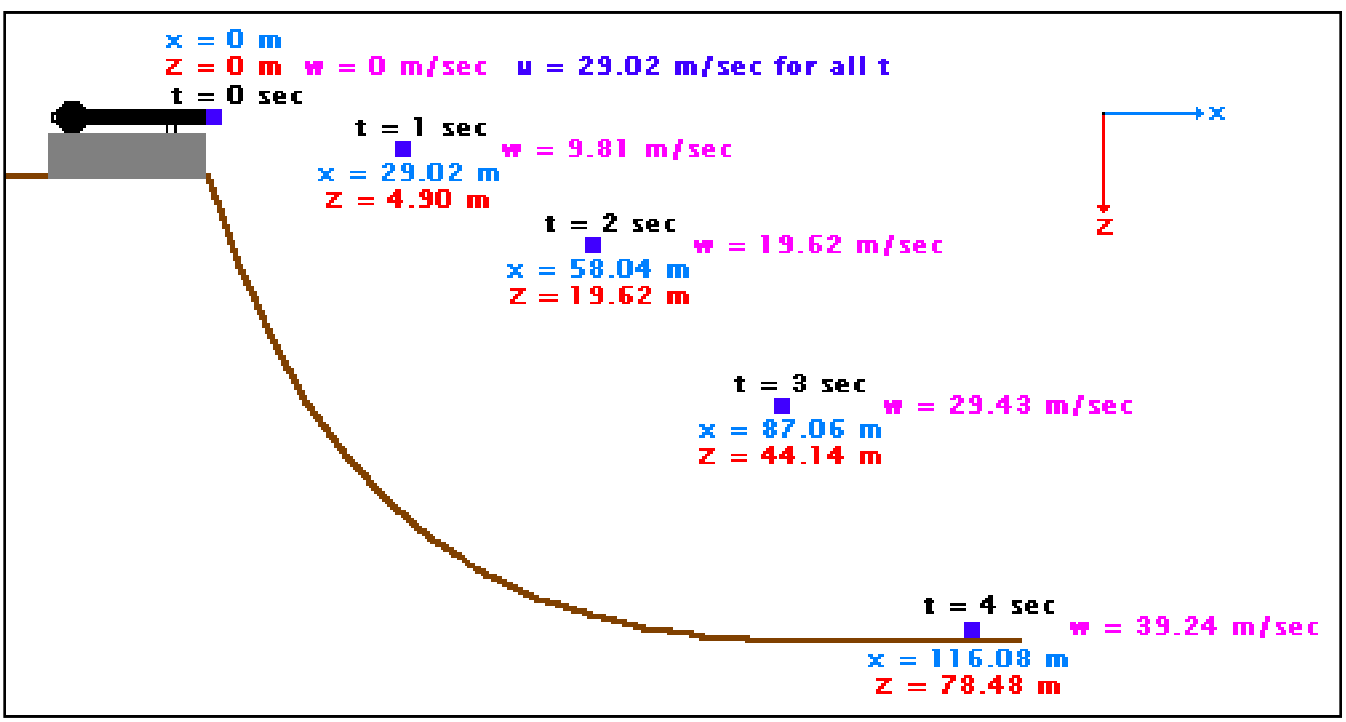
This feature and the next are required before I begin discussion of topics relating more specifically with weather; and even then, some fundamental physics & chemistry concepts must be mentioned.

Force balance should be described with more detail, being the basis of much of what we observe in the physical world. When previously discussing Earth's gravitational acceleration, it was presented as a sum of vectors. Newton's Second Law of motion can be written **F** = m **a**, meaning that acceleration occurs to the specific direction a force is applied, which can be a sum of several forces :



Though objects considered "particles" such as crudely depicted above do not often interest us, these forces apply at each point in the primarily gaseous atmosphere. Here is another interesting discussion regarding Newton's Laws.

Projectile motion is relevant because some objects in our atmosphere either are or can be treated as projectiles. E.g., falling hailstones, raindrops, or even clouds droplets.



Applying Netwon's Laws, equations describing this are found from simple integration. Neglecting air friction for simplicity, Netwon's 1st Law implies horizontal speed ($u = dx / dt$) won't change (i.e., no horizontal forces applied). Vertical acceleration of the object is simply that because of gravity, which is approximately 9.81 m / sec^2 as indicated above. From simple integration, equations describing vertical motion of the projectile are :

Acceleration : $a = g = 9.81$ m / sec^2
Speed : $w = a\ t = 9.81\ t$ m / sec
Position : $z = \frac{1}{2}\ a\ t^2 = 4.905\ t^2$ m

I conveniently chose my coordinate axes such that (x,z) = (0,0) at the point of release (thus integration constants are 0 above), the positive z-axis pointing down to simplify calculation (thus gravitational acceleration is to the positive z direction), and mks units are used. Please be aware that almost everything subsequently written will use z as positive to the vertical - upward in our atmosphere. I think this illustration is relevant because it illustrates a technique of simplifying a problem - a very useful skill for practical application of things learned !

Quite often only an additional consideration of air drag is sufficient for analyzing forces on such an object. Though this is not extremely necessary for accomplishing the mission discussed, such analyses improve a person's perceptions of forces influencing weather they observe.

Chemical Elements : Matter consists of combinations of chemical elements. E.g., water's chemical formula is H_2O, meaning a each water **molecule** consists of 2 hydrogen (H) and 1 oxygen (O) **atom**. Protons, neutrons, and electrons are the fundamental components of matter, masses of which are :

- Proton : 1.67265×10^{-27} kg
- Neutron : 1.67495×10^{-27} kg
- Electron : 9.10953×10^{-31} kg

As the name implies, electrons have a (electronic) charge. This has been chosen as being a negative (-) charge. Protons have an opposite (positive (+)) charge, and as the name implies, neutrons no (neutral) charge. Elements are often displayed in a periodic table, which among other things indicates :

- Atomic number - Number of protons, which characterizes a distinct element. Number of neutrons in an element can vary (isotopes), but adding or eliminating a proton changes element type. E.g., 6 protons are in each carbon atom, 7 in Nitrogen.
- Atomic mass - Mass of a mole of atoms of an element, with a standard distribution of isotopes assumed.

Organization of the table, isotopes, ions, etc. can be topics of very lengthy discussion. Many of these features are shown & explained at the site linked to. Thus, I don't mention any more, though a weather forecaster should know basic atomic theory. Chemical reactions are not very meteorologically important, unless environmental issues concern you, but phase changes are - particularly for water. This link is from HyperPhysics, an excellent online resource !

Phases of Matter Matter exists in 4 basic phases with which we are all familiar - solid, liquid, gas, and plasma - the first 3 of which are common on Earth. Substances can acquire each of the phases, which depends on temperature and pressure. A phase diagram can be determined for each substance, as I illustrated for water. At the **triple point** for water, all 3 phases (ice, liquid, and gas) co-exist in **equilibrium** (meaning that some ice molecules become liquid, some liquid molecules freeze, etc., but total number of each type remains same). Note that such occurs at a ridiculously small pressure of 6.11 mb though, something we don't see in our ~ 1000 mb atmosphere. Similarly, a **critical point** exists for which liquid water and gas cannot be distinguished - with temperature > 647 K and pressure > 2.22×10^7 Pa (219 × standard sea level pressure). The phase diagram is very relevant for meteorology though, because it indicates how much water vapor air can exist at specific temperatures, and evaporation / condensation, melting / freezing, and sublimation / deposition processes which are important regarding cloud and frost formation, cooling via evaporation, and other things.

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Electromagnetic Theory & Related Topics

This is the last of the articles before topics more directly related with weather are discussed. Here I briefly mention and provide equations for fundamentals of topics as titled. Though thorough knowledge of these is not vital for weather forecasting, you should be aware that these physical properties are inherent in our atmosphere, which is a physical system. Much of this information is found in Fundamentals of Physics, and an excellent online source is HyperPhysics, which I linked to last article. Rather than try redescribing the topics below, I suggest you read the appropriate topics at that site (electric charge, magnetism, etc.).

The speed of light is very relevant because as I mentioned several times, our sun is the ultimate source for almost all energy on earth (which drives our atmosphere). If you peek at our sun, it is not at the location you see it, but ahead of it (toward the west, unless you are near a polar region). The location you see our sun is where it was more than 8 minutes ago - that is how long light from our sun requires to get here. Light speed is thought to be a universal speed limit of sorts - as fast as anything can go, and that's only thru empty space. Place anything between a light source & you, and light travels slightly slower, but not significantly so thru our atmosphere.

Electric Charge What is responsible for the speed of light ? A complete explanation (which I cannot provide) would require many of these articles. Beginning of such discussion involves electric charge, hinted at in last week's feature. As mentioned previously, charge of an electron (1.602×10^{-19} Coul) can be considered the fundamental unit of electric charge, which is equal and opposite as proton charge. Charge of an electron is chosen as negative (-), and that of a proton positive (+), and like charges repel and opposites attract. Similarly with gravity, electric force (F_e) between 2 objects is proportional with the charges and inversely proportional with square of distance separating them :

$$F_e = (1 \ / \ (4 \pi e_0))(q_1 q_2 \ / \ R^2)$$

q_1, q_2 electric charges
$e_0 = 8.854 \times 10^{-12}$ Coul / (N m)

Thus just as gravity creates a gravitational field, electricity creates an electric field. This similarity is probably related to a universal Law relating such attractive and repelling forces, which may not be presently understood. I can continue such discussion, which I don't presently believe is very relevant here. I state it that way because perhaps the universal Law I mention (if such exists) would be very relevant regarding basic causes of weather. Presently, the greatest relevance of atmospheric electricity is lightning, which I believe is the #1 killer from thunderstorms. Many other electronics-related topics can be mentioned - voltage, resistance, capacitance, direct and alternating current, etc., which are very important if you want to build a weather station...but if not, let's blissfully ignore them & proceed ☺

Magnetism You are probably familiar with attractive & repelling forces of magnets. Similarly with electric charges, magnetic forces are defined; one side of a magnet arbitrarily called north (N), the other south (S). Magnetic field strength can be measured using electric charge, suggesting a relation among them. If a fundamental charge q_0 moves thru a magnetic field with strength **B** with velocity **V**, a force (F_B) acts on the charge :

$$\mathbf{F}_B = q_0 \, \mathbf{V} \times \mathbf{B}$$

Unlike electric charges though, isolated magnetic poles evidently do not exist. If a magnetic N pole exists, an associated S pole does also, which together are called a dipole. Lines of force connect the dipole, arbitrarily from S to N, similarly as electric current flowing from - to + charges. If such a dipole (e.g., a compass needle) is placed in an external magnetic field (e.g., Earth's), a torque (**T**) acts on the dipole so that its N pole faces the external S pole (opposites attract, likes repel), and vice-versa :

$$\mathbf{T} = \boldsymbol{\mu} \times \mathbf{B}$$

$\boldsymbol{\mu}$: magnetic dipole moment

Magnetic dipole moment is a vector a similar way electric current is. A group of electrons can combine to make a total charge many, many times the fundamental charge, and flow as a current, direction of flow defining direction of the electric field vector. Similarly, a magnetic vector is defined, strength of the dipole (moment) similar with charge strength. Earth's magnetic field is relatively weak at any location, but strong considering how far we are from the poles (which I think originate from rotation of molten metals of Earth's interior - geology is not my specialty). It is $\mu_{Earth} = 8.0 \times 10^{-22}$ J/T. T (Tesla) is a symbol for units of magnetic flux density, equivalent MKS base units being kg/(Coul sec). Presently, Earth's magnetic N pole is located in Greenland and the S pole in Antarctica. I.e., these do not correspond exactly with North and South poles as Earth's rotation axis define, such that an adjustment should be made when using a compass, depending with your location.

The Maxwell Equations James Clerk Maxwell is attributed with unification of electric and magnetic theories and observations as a set of equations known as the Maxwell Equations. They are :

Gauss' Law for Electricity

Governing equation

$\S\ \mathbf{E} \cdot d\mathbf{S} = q\ e_0$

E : electric field
S : surface normal vector
§ denotes line integral

This describes relation of charges with electric fields. The critical experiments supporting this are 1) Opposite charges attract and like repel, inversely proportional with separation distance 2) A charge on an insulated electrical conductor moves to its outer surface (as the dot product with the surface vector describes).

Gauss' Law for Magnetism

$\S\ \mathbf{B} \cdot d\mathbf{S} = 0$

This describes behavior of magnetic fields. A closed magnetic dipole (line integral = 0) must be present. A magnetic monopole has not been observed.

Faraday's Law of Induction

$\S\ \mathbf{E} \cdot d\boldsymbol{l} = -\ d\Phi_B / dt$

l : current loop vector
Φ_B : magnetic field strength
t : time

This describes the electrical effect of changing a magnetic field. The critical experiment supporting this is the observation that a bar magnet thrust thru a conducting wire loop produces an electric current in the loop.

Ampere's Law (Maxwell's extension)

$\S\ \mathbf{B} \cdot d\boldsymbol{l} = \mu_0\ e_0\ d\Phi_E / dt + \mu_0\ i$

Φ_E : electric field strength
μ_0 : permeability constant = $4\ PI \times 10^{-7}$ T m / A
i : conduction current

This describes the magnetic effect of changing an electric field or current. The critical experiments supporting this are 1) a current flowing in a wire loop creates a magnetic field 2)

The speed of light can be measured from purely electromagnetic measurements.

Among the most relevant consequences of this is that Earth's magnetic field protects us from harmful charged particles flowing from our sun, diverting them around Earth. These set of equations describe electromagnetic theory. **Energy is often transported as alternating electric and magnetic waves - electromagnetic radiation**. All bodies radiate according to their temperature and emissivity (which I hope to discuss later). Maxwell showed that speed of such waves is determined as :

$c = 1 \ / \ (\mu_0 \, e_0)^{1/2}$

c : light speed = 3.00×10^8 m / sec

Energy of such waves is determined as:

$\mathbf{S} = (1 \ / \ \mu_0) \, \mathbf{E} \times \mathbf{B}$

S : Poynting vector (different than **S** above)

The Poynting vector specifies magnitude (energy flux, e.g., W / m^2) and direction of electromagnetic wave propagation.

Equation for Relative Speed If object A moves 30 m / sec to one direction (relative with an observer) and object B moves 10 m / sec to the opposite direction, what is their speed relative with each other? You may say 40 m / sec, stating that 10 m / sec + 30 m / sec = 40 m / sec. What if object A's speed is 2.7×10^8 m / sec & object B's 1.8×10^8 m / sec ? Is relative speed 4.5×10^8 m / sec ? Can relative speed be greater than light speed? Experience indicates that velocities are additive, but relativity theory states that such indication is deceiving, a consequence of nearly all human experience occurring with speeds much less than light speed. The equation for relative 'linear' speed (SP) of objects A & B is :

$SP = (SP_A - SP_B) \ / \ (1 - (SP_A \, SP_B) \ / \ c^2)$

Now what is the answer to the questions above? For the first situation (MKS units used) :

$SP_A = 30$ (arbitrarily positive direction)
$SP_B = -10$

$SP = (30 - (-10)) \ / \ (1 - (30)(-10) \ / \ (3.00 \times 10^8)^2) = 39.999999999999867$ m / sec

For the second situation:

$SP_A = 2.7 \times 10^8$
$SP_B = -1.8 \times 10^8$

$SP = (2.7 \times 10^8 - (-1.8 \times 10^8)) \ / \ (1 - (2.7 \times 10^8)(-1.8 \times 10^8) \ / \ (3.00 \times 10^8)^2) = 2.922 \times 10^8$ m / sec

I.e., for small speeds such that we are accustomed to, the experience of additive speeds very nearly agrees with relativity theory, but approaching light speeds, such is evidently quite incorrect. For comparison, a polar orbiting Earth satellite typically travels about 7000 m / sec, .000023 × light speed! I mention this not because it corrupts wind speed etc. calculations so much as so you are aware (if you weren't) of the presumed character of speed.

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Weather & Space

Before mentioning many of the mysteries of weather, first we should decide what **weather** is. Customarily with literature, "we" is the author, though I tend to avoid that nonsense. Unless you tell me what you think though, *we* can't change *our* definition ☺ Anyway, here's *my* definition (for Earth) :

Weather : Natural occurrences in and motion of the gaseous atmosphere above the Earth, particles not artificially suspended in it, and direct physical consequences of these.

Considering that definition, weather includes sunshine, clouds, rain, snow, hail, tornadoes, wind, hurricanes, lightning, dust devils, duststorms, sea and land breezes, dew, frost, air pollution, volcanic ash, sea spray, condensation nuclei, terrestrial radiation, ionization of upper atmospheric gases, ozone formation and destruction, neutrinos passing thru our atmosphere, etc. and any direct physical affects they may cause such as wind breaking branches off a tree or freezing rain making the ground icy. Further affects such as someone slipping on this ice (after it is formed) is not considered a direct physical consequence. Weather does not include particulate matter artificially propelled thru or suspended in our atmosphere such as frisbees, airships, weather balloons or monitoring instruments, nor natural objects transiently passing thru the atmosphere such as an acorn falling from a tree.

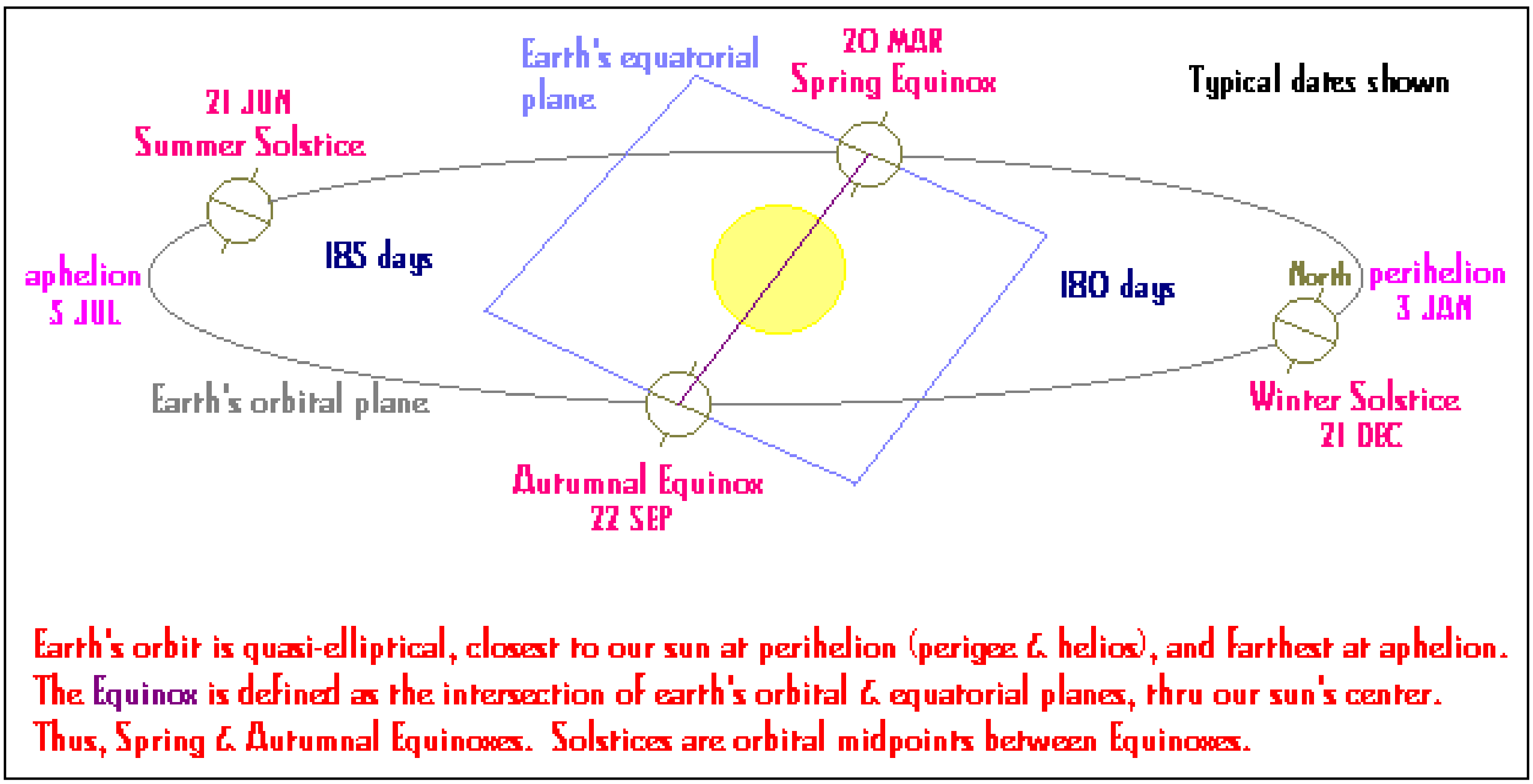
The above discussion is not meant to be confusing - it is simply established so any specific phenomenon can clearly be considered as being part of weather or not being so. For example, I consider air pollution a part of weather, being gases, liquids, or particles suspended in the atmosphere. Though they might've been artificially propelled into the atmosphere, they are not artificially suspended in it as a dirigible is. You may argue that the dirigible affects weather when suspended, and it does; but so do towers, buildings, etc. which are attached to the Earth (and thus considered as being part of the Earth). If the dirigible or tower are struck by lightning, the lightning and its direct damage are part of weather. I include the damage (direct physical affect) because the **weather phenomenon** is responsible for **altering the previous state of the object**. Once its state is altered, any further affect is not part of weather.

Weather *variables* are often considered as being *weather* - temperature, humidity, wind speed, etc. Similarly as wind speed describes magnitude of wind motion, temperature describes magnitude of molecular air motion. Though they help a person's perception of the weather, they are not among the occurrences which comprise weather.

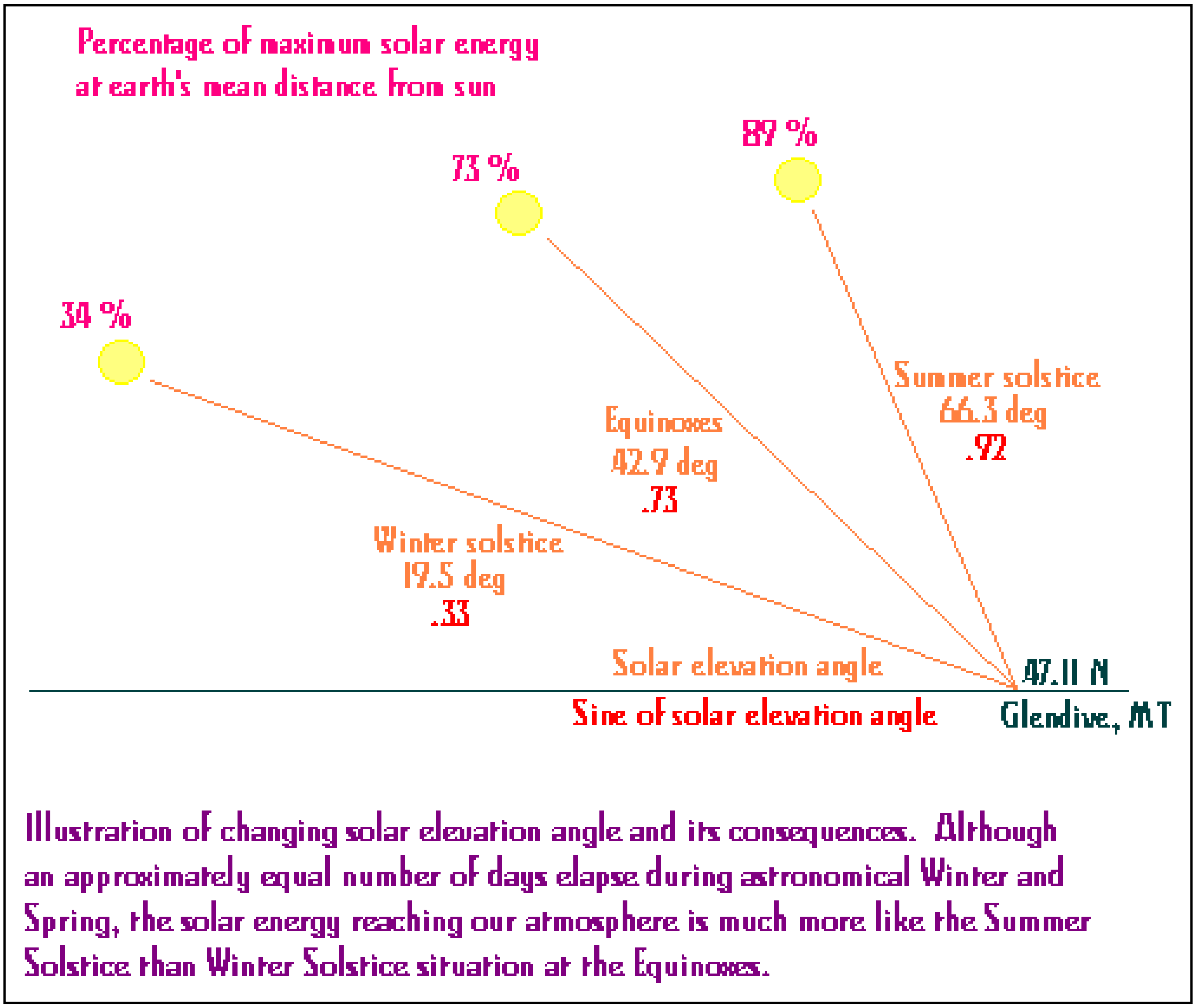
Weather includes only terrestrial occurrences - within significant influence of Earth's atmosphere. Anything outside is considered as being in **outer space**, or extraterrestrial. Such a boundary does not truly exist. I.e., at an altitude of about 31 km, atmospheric pressure is only about 1 % (.01) as at the surface, quickly decreasing as altitude increases. At altitudes of several hundred km and above, amounts of matter largely depend on the solar wind, particles left from previous comets, and meteors. Just enough atmosphere exists at the these typical altitudes of polar orbiting satellites such that drag forces very gradually alter their orbits. Concentrated at about 80-400 km altitudes, X-ray and ultraviolet solar energy ionizes some molecular air components, causing D, E, and F ionospheric layers. Interaction of solar plasma (charged particles) with Earth's magnetic field often causes brilliant aurorae around polar magnetic field cusps. There and above, a diffuse part of the solar "atmosphere" interacts with both Earth's magnetic field and Earth's atmosphere, creating among other things radiation belts - regions of large proton and electron concentrations - often named for James Van Allen, discoverer and a researcher of these. Note the shape of such belts and their occurrence at altitudes greater than previously mentioned. At about 400 km altitude, little atmosphere exists and radioactivity is evidently just weak enough such that it is not extremely detrimental for terrestrial life. Considering these things, 400 km is perhaps a good choice for the boundary.

Common Weather Occurrences

A brief mention of this is helpful for maintaining focus regarding and clarifying our goal. Perhaps I am biased regarding clouds, being my first topic of detailed study, but their influence regarding weather most relevant for us is great enough such that some people have suggested methods of forecasting weather primarily using cloud observations. Other than earth's orbital characteristics :



and its consequences :



they most significantly influence solar energy. Solar energy (radiation) and terrestrial energy cause the diurnal (day / night) cycle. Most everyone is aware that solar heating occurs during daytime, mainly near ground, but Earth & its surroundings constantly radiate heat to space, during day and night. When solar heating is absent, cooling occurs. A theory exists that because heat is eventually equally distributed among hot and cold objects, a universal temperature of about 3 °K will exist. Among the diurnal cycle's many consequences include maximum and minimum temperatures, daytime and nocturnal boundary layers, convection, low-level jet streams, sea / land breezes, and local cloudiness characteristics. When studying weather, a person should keep in mind weather characteristics most relevant regarding her / his main interests and how phenomena studied may influence them.

When measurements of atmospheric pressure, temperature, humidity, wind, cloudiness, and precipitation became abundant enough, synoptic weather charts were drawn, on which weather characteristics at various places at a specific time (or relatively closely) were included. Because mass-communication did not exist, such charts could only be drawn forensically, but included a synopsis of weather info previously unavailable. Some researchers previously noticed correlation of low atmospheric pressure with inclement weather (and vice-versa), but among the most relevant things synoptic charts revealed was existence of **cyclones** and **anticyclones** - large areas of minimum and maximum air pressure around which winds circulate counterclockwise and clockwise (in the

Northern Hemisphere), respectively. As observing and communication techniques improved (e.g., telegraph), near-current info regarding such pressure systems, temperatures, weather became available. Even today, with sophisticated electronic and satellite measurements of weather parameters and communications, data availability remains a problem for some locations and situations. During the early 1900's a frontal theory was developed at the Bergen school of meteorology, associating cyclones with observed fronts and their characteristics. The theory is good enough such that not many adjustments and improvements regarding the basic theory are necessary.

Universe

Our universe is supposed as created with a "big bang" billions of years ago (how many, 4-20 ? is debatable, though some people are very confident of their ideas). From this, elementary atomic and subatomic particles supposedly formed, later becoming more sophisticated (greater atomic number), many molecules forming also. Frequency shifts of objects sensed in space indicate general movement away from the location where such a bang possibly occurred. In our skies, we can see some of the hundreds of billions of galaxies, many arranged in clusters, one of which is our Milky Way galaxy (the word galaxy is from the Greek word gala, meaning milk). The 2 basic galaxy types are X and spiral galaxies, the latter of which ours is. Similarity among its shape and that of hurricanes is interesting, with spiral arms (ala rain bands) around a more massive nucleus (ala eye & eyewall), though I think eyes are rather unique for hurricanes and some strong extratropical cyclones. In each, a force causes the bands to spiral toward the center - for the galaxy, it is gravity; for the hurricane, it is low pressure causing air convergence there. Our solar system is estimated as being in one of Milky Way's spiral arms, about 2/3 from the center. If you live at a rural location, you can see evidence of the Milky Way galaxy's shape - concentration of stars in a band - which is sort of like looking at a frisbee from its side.

Solar System

Our solar system contains everything our sun's gravity retains as orbiting bodies. Our sun is at its center, and at least 9 planets and their moons, asteroids, comets, and meteors. Each orbit our sun or planets, though our sun and planets capture some (and portions thereof) with insufficient escape or orbital speed. Perhaps you are unaware that spacing of the inner planets is rather organized, suggesting that the asteroid belt between Mars & Jupiter either was once a planet, or one which never formed. The universal law of gravitation describes all of such motion very well. This is more so observation than theoretically-based. I do not think any person presently knows exact causes of gravity, but we know its affects, which is often sufficient for effective problem-solving. This description is not perfect, because it includes only Newtonian physical considerations, not relativistic ones. Not so significant regarding magnitudes - e.g., solar eclipses can be accurately forecast using the Law of Gravitation - but perhaps regarding a basic understanding of how all objects relate with each other, which can be an important consideration for forecasting events, as I've previously mentioned. As an astrologer once stated "To be a good astrologer, you must be a good mathematician".

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Electromagnetic Radiation & Our Sun - part 1

Though much more can be said regarding our universe, galaxy, and solar system, not much more is necessary for acquiring correct physical sense of factors affecting our weather. Regardless of which way Earth acquired its atmosphere, our sun provides nearly all energy for maintaining its present state. Though probing the solar interior is very difficult, knowledge of physics and chemistry acquired here on Earth allows development of many plausible theories. Before these are discussed though, electromagnetic radiation should be explained. Characteristics of electromagnetic waves include frequency and wavelength. Because their propagation occurs with light speed, these are related, as expressions show. You can see that because wave speed is constant, large frequency (number of wave crests passing a point during a specific time period - i.e., how *frequently*) corresponds with small wavelength, and vice-versa. Waves of all possible characteristics comprise the electromagnetic spectrum, which varies between those with very large frequency (also very large energy) such as gamma rays, and those of very small frequency (very small energy) such as radio waves. The most relevant portion of the spectrum for us is visible light, which we see as colors between violet (large frequency) and red (small frequency). Thus, light from the sun is electromagnetic waves of this form.

Spectral Lines

Studying colors of light from our sun during 1802, Wollaston (a physicist) discovered that it does not form a continuous spectrum, but includes dark lines. Separating colors of sunlight using a prism during 1814, Johann von Fraunhofer rediscovered the lines, which he labeled with letters of the alphabet. With further study, Fraunhofer found 574 of such lines. Thus, the name Fraunhofer Lines is used for these. During 1859, Kirchoff and Bunsen discovered that although a hot solid object emits a continuous light spectrum, hot gases emit light of specific frequencies, corresponding with the spectral lines. Considering this, a connection was made among lines in the sunlight spectrum those emitted from heated gases, especially for Na (Sodium), which causes very pronounced sunlight spectral lines at .5890 µm & .5896 µm. The idea that dark spectral lines were the cause of a cancellation among light emerging from the hot sun (solar electromagnetic spectrum) and cooler gases of elements above the solar 'surface' was conceived. Further experimentation revealed that position of each element's spectral lines is unique, similarly as a person's fingerprint is considered so. Thus, a method for identifying elements in the sun (spectroscopy) was discovered, which led to great possibilities regarding solar theories.

Electron Energy States

Spectroscopy revealed that our sun consists mainly of H (Hydrogen) and He (Helium). During these original experiments, the .5876 µm spectral line for Helium matched no known element -

it was then an element only known on the sun. Only later was it found on Earth. Thus, Helium is so named because of the Greek word Helios, meaning sun. Many strong spectral lines were found for H, which were labeled using Greek letters, i.e., H-alpha, H-beta, H-gamma..., for decreasing wavelengths. During 1885 Balmer discovered a mathematical relationship (using the good ol' trial & error method) among wavelengths for the H series lines. This became known as the Balmer series, and the limit as N approaches infinity the Balmer limit (.3646 µm). Hydrogen, with atomic number 1, is the simplest of all atoms; containing 1 proton and 1 electron. During 1913, a relation was found among energy of an electron orbiting the 'Bohr H atom' and H series spectral line frequency. Energy was imagined as being quantized - occurring with discrete amounts. Thus, an electron change from a higher to lower energy state causes emission of a photon. Similarly, absorption of a photon causes an electron change from lower to higher energy state. You may notice that N = 3 is the lowest possible value (called N = 1 in the energy diagram shown), called *ground state,* with wavelength .6563 µm; and N = infinity is the Balmer limit - highest energy state. The energy diagram for a H atoms is quite simple - ones for other elements are much more complicated (and cannot always be graphically represented well).

Solar Composition

Continuing the story of solar composition, H and He abundance means that the most logical cause of energy production in the solar interior is thermonuclear H to He fusion reactions in the solar core. The molecular mass of H is 1.008, and that of He is 4.003. Thus, when 4 H atoms fuse as 1 He atom, 4.032 mass units of H become 4.003 mass units of He + **energy**. This is related with the $E = m c^2$ often cited as 'Einstein's equation'. The extra .029 mass units of each reaction is transformed as energy, causing the enormous heat amounts our sun emits. This process is not so simple as described. It requires several intermediate processes, which require an *average* of about 14 billion years!, a product of which are positrons and neutrinos (which travel from the sun and generally thru your body, earth, and most everything else). Such fusion reactions require a temperature of at least 10000000 °K, and the solar core's temperature is typically estimated as 15000000 °K. The the distance from the core at which temperature is not hot enough for initiating fusion, a radiation zone exists, and above that, a convection zone, where the sun becomes cooler. Some people believe that convection also occurs in the radiation zone. At the top of the convection zone is the photosphere - the solar 'surface'. This is the portion of the sun which we see, which has temperature of about 5800 °K. The solar surface rotates, left to right as we face it, with period of about 25 days at its equator increasing to 37 days at its poles. An interesting thing to notice is that almost all rotation and orbiting is counterclockwise (as viewed from top or with our North Pole on top) - cyclones, Earth's rotation, Earth's orbit, Sun's rotation, and I think even rotation of stars in our Galaxy.

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Electromagnetic Radiation & Our Sun - part 2

Continuing from last time, I discuss our sun with greater detail and then briefly mention radiation exchange, which is largely a consequence of that and electromagnetic radiation previously discussed, and largely determines earth and atmospheric temperature.

Solar interior to surface

Solar composition was previously mentioned, regarding abundance of elements in our sun. Additionally, the solar interior consists of many free particles - some products of nuclear fusion, some a consequence of molecular collisions in a high temperature environment. A mixture of charged particles is called a plasma, which exists inside and outside the sun (assuming a boundary is specified).

Sunspots

The solar surface more clearly affects weather. Perhaps the most well-known solar features are sunspots, dark magnetic regions in the solar photosphere. If a person guessed that sunspots are dark because they are cool, they'd be correct - sort of. Their typical temperature being about 4000-5000 °K, they are hot, and would appear quite bright if they could be isolated in space; but because of contrast, are quite dark in the 5800 °K photosphere. If you are very picky regarding words like me, you may be thinking '*in* the photosphere...?' - yes. These relatively cool areas are dense, and thus form a depression in the photosphere (which can be seen on the solar limb); lowest area being a dark umbra, which a less dark penumbra surrounds. Why don't hotter photospheric gases fill the depression? Sunspots' magnetic fields evidently prevent such a flow, shielding its base & periphery. Hot gases are forced around them, perhaps causing the bright faculae there (though faculae are also isolated and rather abundant near the solar poles, where sunspots seldom occur). Sunspots are greatly magnetized regions, a magnetic couplet occurring with each sunspot. The situation is opposite for each solar hemisphere; - magnetic regions (dark) often associated with sunspots or those forming) leading + magnetic regions (bright) in one hemisphere, + magnetic regions leading - in the other. You may be familiar with the sunspot cycle - that number of sunspots varies quite significantly with an approximately 11 year period, as illustrated. An extended period occurred (~ 1645-1715) though, during which almost no sunspots were observed, known as the Maunder Minimum. That was not long after Galileo's original observation of sunspots during 1610 and those which followed. Why did that happen? I know of 2 possibilities - the reasonable one being existence of a much longer cycle of several hundred or perhaps 1000 years; the paranoid one being that once extraterrestrials knew we knew about sunspots, they decided to play a little game with us, making them disappear for several decades ☺ No matter what reason exists, energy emitted from our sun evidently increases during times of large sunspot activity, as correspondence of recent satellite measurements of the solar constant (definition) and annual number of sunspots indicates. This is mainly because of many other bright areas such as faculae during active solar periods. Solar energy flux does decrease slightly when large sunspot groups pass near the sun's center. You can see that the sunspot cycle has been very consistent during the past few centuries. A magnetic dynamo because of Sun's differential rotation is thought as being responsible for the sunspot cycle, causing sunspot formation at greatest solar latitudes at the beginning of a new cycle (which can be seen on current solar images), developing toward the solar equator at the end of a sunspot cycle, as a butterfly diagram indicates. The dynamo causes a magnetic pole reversal in the sun, such that the next cycle occurs with polarity reversed (+ & - regions mentioned above reversed). Thus, many people consider the sunspot cycle a 22 year cycle.

Solar atmosphere

Above the photosphere are the chromosphere and the corona, often considered the solar atmosphere (particularly the chromosphere). The chromosphere is an eventful area, with hot gases often above sunspots, and magnetic loops and prominences. Solar flares are often ejected from the solar surface, becoming part of its atmosphere. The solar corona is perhaps the most brilliant solar feature, a diffuse portion of the outer solar atmosphere with temperatures of as much as 2000000 °K from which X-rays are emitted. For much time it was only observable during solar eclipses because the intense solar beam & great scattering near the solar disc mask it. Invention of the coronagraph, which blocks the solar disc and eliminates stray light near it using 2 lenses, enabled study of the corona. Now very sophisticated coronagraphs are flow on satellites, for more detailed observation. Coronal mass ejections (called the hurricanes of solar weather) occur, though processes causing them are not extremely well-known.

Solar wind & magnetosphere

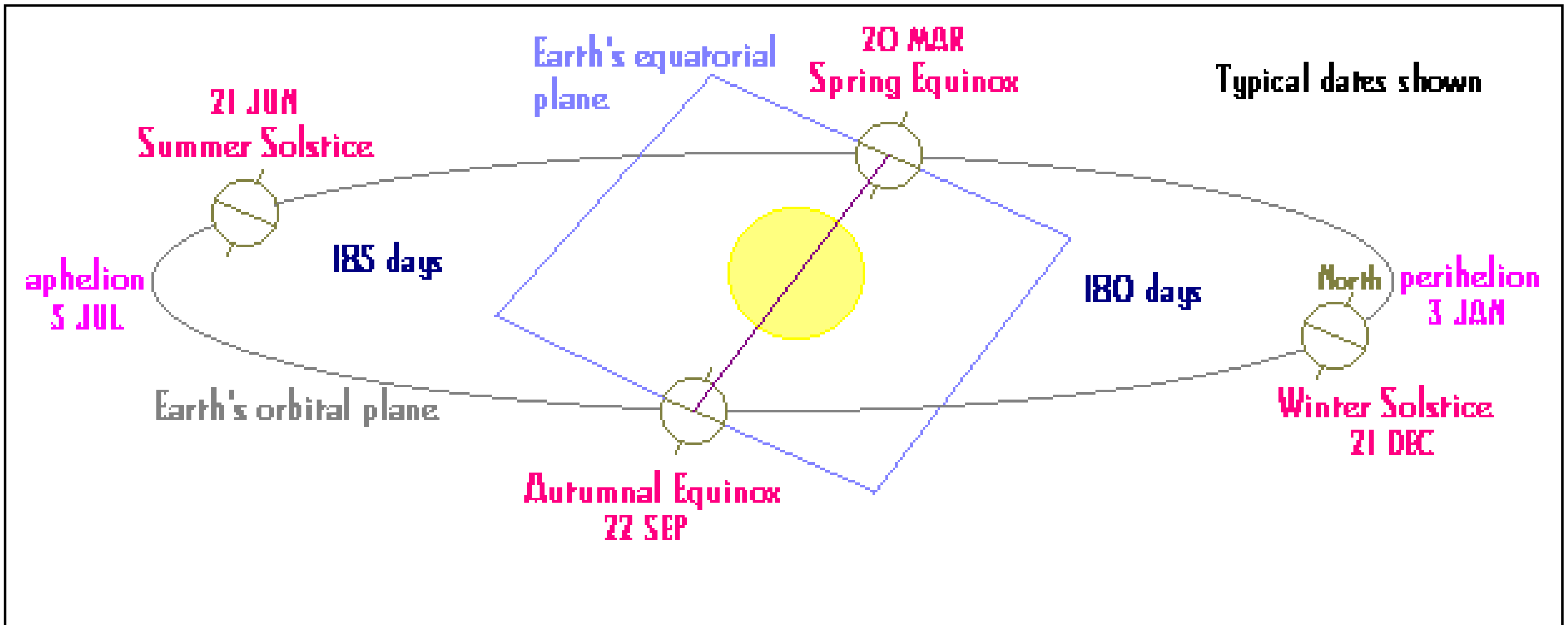
A constant flow of plasma is emitted from our sun, called the solar wind. It travels toward earth and all other directions with speeds of several hundred km / sec, extending to the outer extent of our solar system is currently measured using satellites. Its interaction with comets (image description), dirty iceballs, causes the familiar tail, which points directly from the sun whichever direction the comet travels. Interaction of the solar wind with Earth's magnetic field causes radiation belts, ring currents, and other features in and below the magnetosphere. Strong solar flare events and other solar magnetic disturbances greatly augment the solar wind, with affects including aurorae and modification of earth's magnetic field in the upper atmosphere near Earth's polar regions, where magnetic field cusps exist. Some geomagnetic storms are sufficiently strong to cause electric currents to flow across satellites, power lines, and other electrical objects on or near Earth, damaging some and disabling others. Space weather forecasts (main site) are often issued for aiding preparation for such events.

Radiation exchange at Earth

Though geomagnetic storms are a major concern, our sun obviously affects Earth more so because it provides heat for it and its atmosphere. Quite often the term 'radiation balance' is used, though such a term implies equal amounts entering and leaving, which is not necessarily so. Thus, I like the term **radiation exchange** - regarding solar electromagnetic (EM) radiation and terrestrial EM radiation. EM radiation emission increases as temperature does (proportional with its 4^{th} power for a theoretical blackbody), thus solar EM radiation (solar energy) is mainly ultraviolet, visible, and infrared and terrestrial EM radiation (terrestrial energy) is mainly infrared. An equilibrium temperature can be supposed, a consequence of solar and terrestrial energy balance. I plan to provide such calculations later, but at this point recognition that increasing solar energy increases such an equilibrium temperature is sufficient (more solar energy implies warmer Earth).

Long-term climate & glaciations

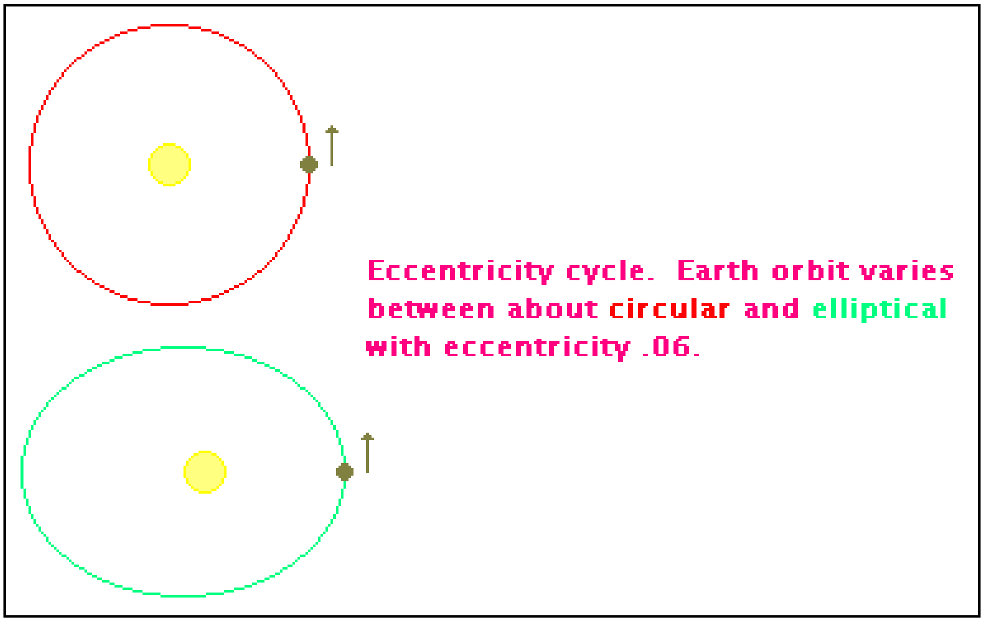
I obviously cannot completely discuss these topics here, but mention the very basics, at least for now. Because of radiation exchange, possible connection among climate and solar parameters is often considered. Geology and paleoclimatology has revealed likelihood of many abnormally warm and cold periods during Earth's existence, corresponding with long and short term glacial (ice age) and interglacial periods. What causes such changes? Many theories exist, but considering long-term changes, solar heating changes because of orbital changes are often considered most relevant; and geologic data supports such a theory. Johannes Kepler calculated that planetary orbits (around Sun) are elliptical, a consequence of 3 Laws governing orbital motion. This idea was quite controversial during his days - a time when religion ruled and the creation of God was commonly considered perfect and unblemished. Even the idea of spots on a supposedly perfect sun was ridiculed. Now we live during a different time, rather opposite, when a scientific explanation is required if practically any theory regarding physical occurrences is taken seriously. Another troublemaker, Issac Newton, used Kepler's discoveries for development of the Universal Law of Gravitation, which adequately described all particle motion. Because of Earth's elliptical orbit :



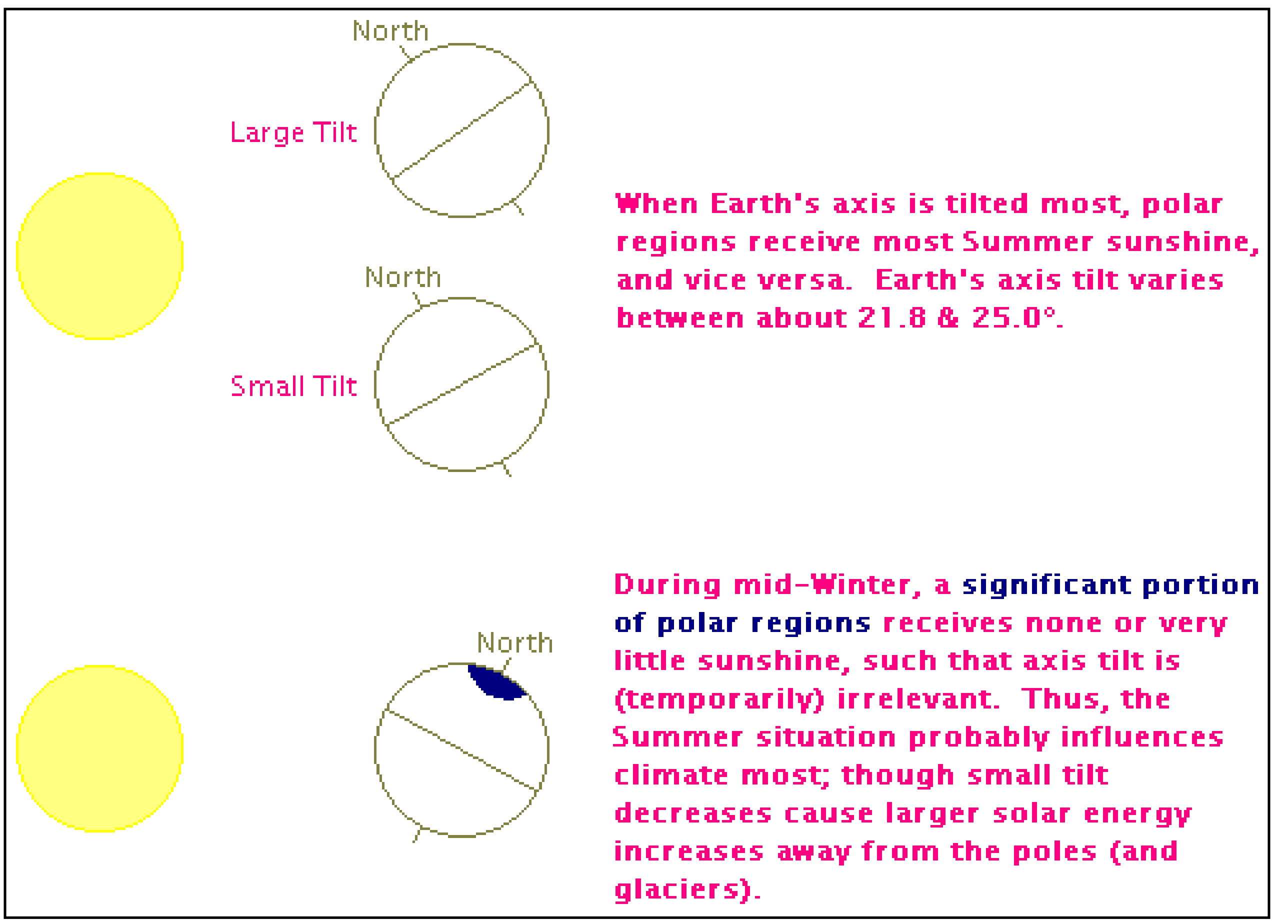
Earth's orbit is quasi-elliptical, closest to our sun at perihelion (perigee & helios), and farthest at aphelion. The Equinox is defined as the intersection of earth's orbital & equatorial planes, thru our sun's center. Thus, Spring & Autumnal Equinoxes. Solstices are orbital midpoints between Equinoxes.

most solar energy reaches Earth when closest to Sun, presently about 3 January.

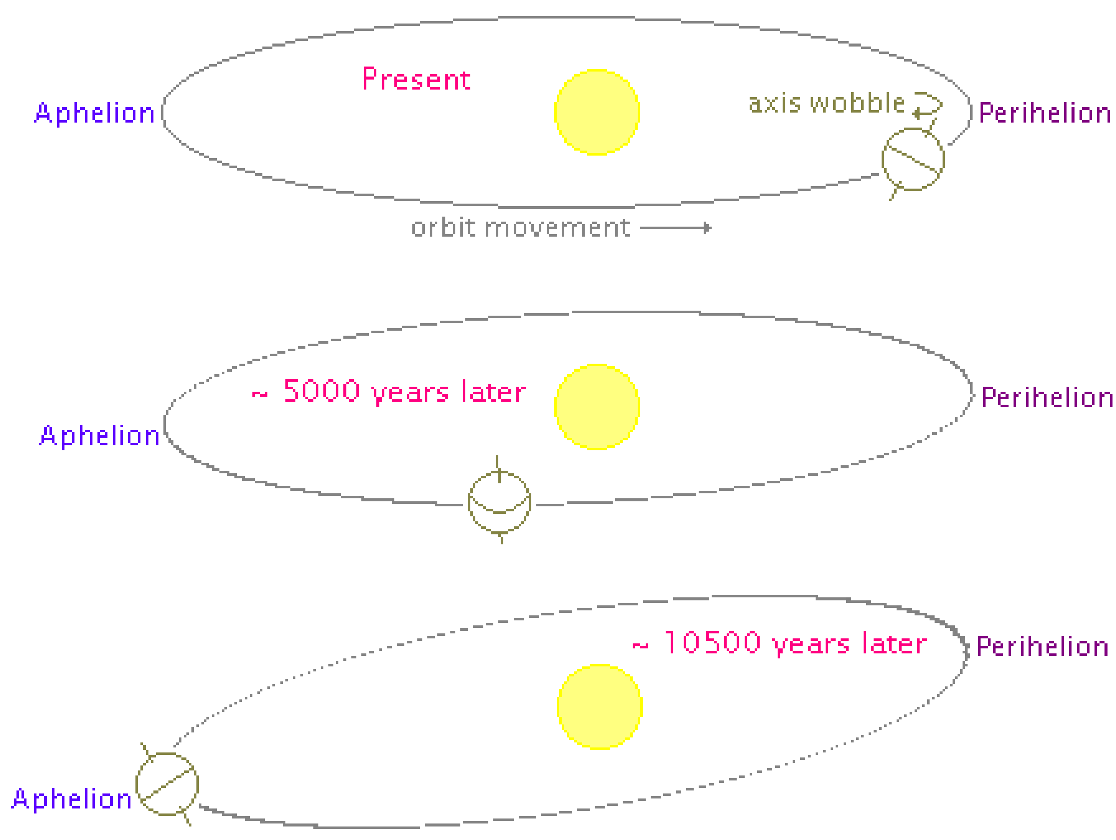
During the early 1900's, Militun Milankovitch worked many years developing a mathematical theory relating Earth motion with geologic evidence of past glaciations, emphasizing Earth's solar energy collection. Detailed astronomical measurements indicate basic changes of 3 aspects of Earth motion (and other very small ones - some chaotic!) - eccentricity :



tilt :



and equinoctial precession:



Equinoctical precession. Earth's axis wobbles, similarly as a top; each rotation thought to take about 25800 years. Earth's orbital plane moves also though, such that a complete precession period requires about 22000 years. Thus, Winter Solstice (Earth positions shown, with North Pole pointing directly away from Sun) which presently occurs near **perihelion** is expected to occur at mean distance from Sun about 5000 years from now, and at **aphelion** about 10500 years from now.

The primary eccentricity cycle (main site) is about **100000 years**, and tilt cycle about **41000 years**. Precession is a combination of 2 factors - wobbling of earth's rotation axis (like a top), and movement of earth's orbit (itself), which combine for about a **22000 year** cycle (i.e., an *extremely slow* top!). How do these factors affect climate and thus glaciations? A question for that question is how do glaciers form and advance equatorward and recede poleward? Many possibilities exist, but seasonal growth and melting is considered the primary reason. If orbit changes so that Earth receives a more consistent solar energy amount during a year (especially near poles where glaciers are), summertime glacier melting is less effective, and winter weather not as cold (which probably increases snow amounts and thus glacier advancement). Using that as a basic premise, I consider influence of each of the orbital affects mentioned. If **eccentricity** became very large, such that perihelion (orbital point closest to sun) corresponded with Mercury's position, much if not all ice would melt during summer. That exaggerated example illustrates a circular orbit is most favorable for glaciations. According to Milankovitch theory, earth's orbit during the past several hundred thousand years has varied between near circular and about .06 eccentricity. Correspondence of the eccentricity cycle and supposed major glaciations is very good, though some researchers question whether such is because of near coincidence, other factors being responsible. Orbital eccentricity is presently .0167 and decreasing, favoring development of an ice age many thousands of years from now. If **Earth's axis** were tilted perpendicular with its orbital plane, polar regions would receive little sunlight and remain cold year-round, such that glaciers would probably extend much further south than presently. Earth's axis tilt varies between about 21.8° & 25.0°. It is presently 23.44°, and decreasing. According to theory, this also favors development of an ice age several thousands of years from now. **Precession's** affect is less certain, but a glance at our globe reveals that most land is in the Northern Hemisphere and most ocean in the Southern Hemisphere. Particularly, a large ocean expanse surrounds Antarctica, preventing great glacier movement there. Thus, glacier advancement is mainly a Northern Hemisphere phenomenon. Presently, Earth aphelion corresponds nearly with Summer Solstice, and perihelion nearly with Winter Solstice. Theory indicates that Summer Solstice is approaching perihelion, reaching it about 10000 years from now - least favorable for glacial conditions (most heating variation among seasons). We're not experiencing an ice age now though, only about 840 years after the most favorable situation. Rather than considering these factors separately, Milankovitch calculated combined effects regarding solar energy collection, and was confident that such changes corresponded with major glaciations.

Other factors are more relevant regarding our climate situation - a possible greenhouse effect, etc.

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Energy Collection, and Atmospheric Composition and Layers

Perhaps our sun has been discussed too much recently, so I promise this will be the last time for awhile, though mentioning it is necessary regarding future topics. I finish the introductory material with a brief discussion of major factors influencing observed weather characteristics, which includes affects of earth's orbit regarding solar energy collection, atmospheric composition, atmospheric layers, and basic global atmospheric and ocean circulations.

Earth's Orbit and Solar Energy Collection

Atmospheric Composition

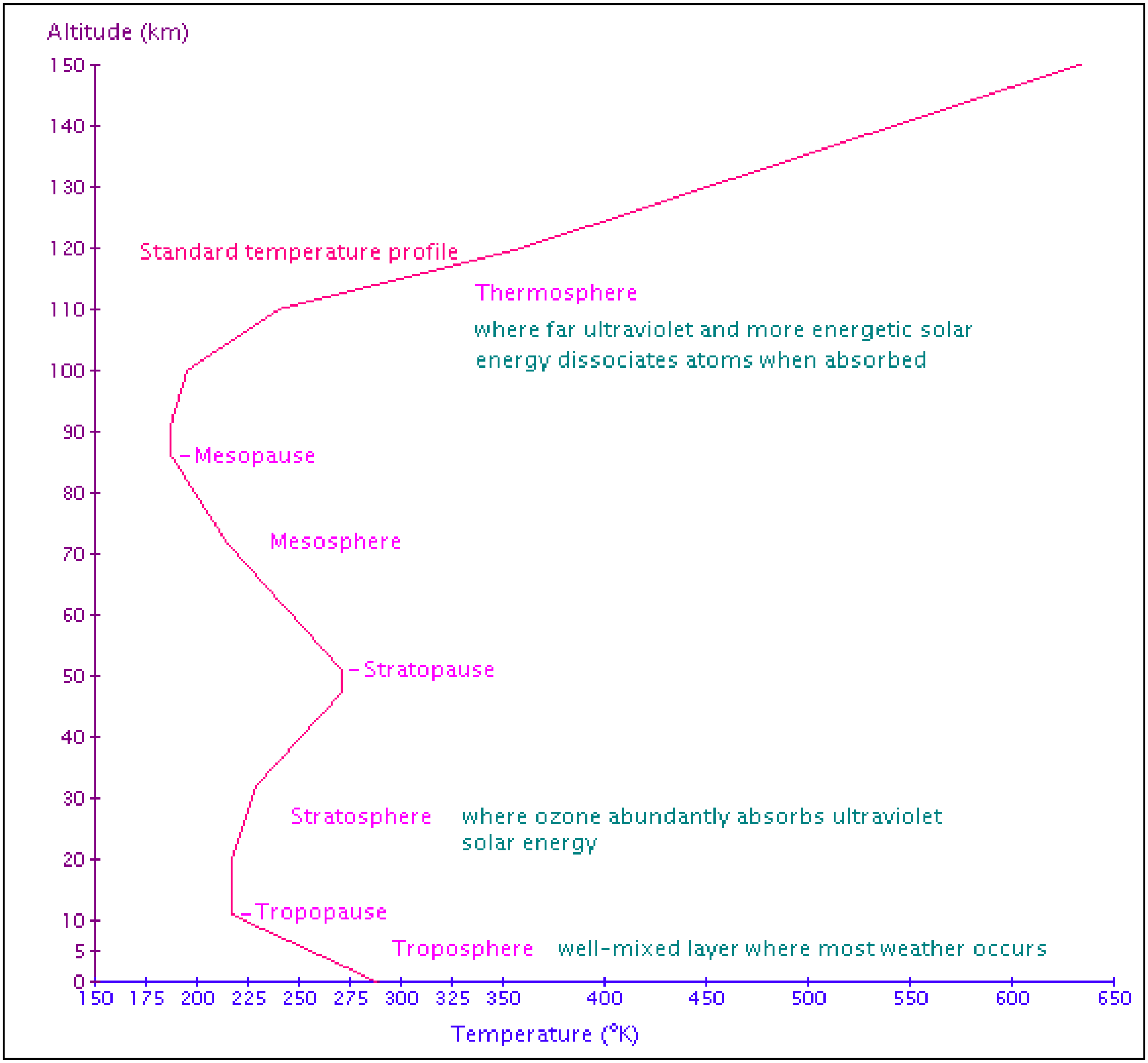
Our atmosphere is comprised mainly of diatomic nitrogen and oxygen, and is quite homogeneous in the lowest 80 km, with standard proportions of main constituents as follows :

Constituent	Symbol	Volumetric Fraction
Nitrogen	N_2	.78084
Oxygen	O_2	.20946
Argon	A	.00934
Carbon Dioxide	CO_2	.00034
Neon	Ne	.0000182
Helium	He	.00000524
Methane	CH_4	.0000015
Krypton	Kr	.00000114
Hydrogen	H_2	.0000005

Among very significant properties of the 2 primary gases are their chemical stability (they don't react with most natural substances - nitrogen much more so than oxygen, which does react well with some) and their thermal inactivity. Perhaps a good 'catch phrase' for them would be 'nonreactive and thermally inactive'. Physical objects such as plants, ground, and metals are very thermally active. Air is a poor medium for absorbing and emitting far infrared (terrestrial) radiation. Thus, air can remain rather mild during a 15-hour night, after frost quickly forms on surfaces. Air is nearly transparent to visible, near infrared, and very near ultraviolet radiation also. Water vapor is a variable component, and people often speak of air as consisting of dry air (less variable standard components) and water vapor. Many of less abundant constituents significantly affect Earth's energy exchange, and perhaps weather, more subtly. Ozone amount is variable, but less than hydrogen. You are probably aware of the greenhouse affect and its possible consequences regarding climate.

Atmospheric Layers

Atmospheric soundings reveal vertical regions with specific temperature characteristics :



Hydrostatic balance (which I plan discussion of later) requires that air density remain constant or decrease vertically. This does not imply warmest air aloft though, because vertically decreasing pressure allows densest surface air when a relatively small vertical temperature decrease is present. A quasi-limit for such is the dry adiabatic lapse rate, about 9.8 °C / km, more than which would violate hydrostatic balance.

Because of air's thermal inactivity, solar heating most efficiently occurs near ground, air mainly heated via conduction and then rising in convection currents. Thus, a positive temperature lapse rate (vertical decrease) is typical, especially during daytime. Such occurs in the lowest portion of our atmosphere, the **troposphere**, and would likely continue to outer space if not for thermal activity of atmospheric gases at greater altitudes. One of such gases is ozone (O_3), concentrated at 12-40 km altitudes. It very effectively absorbs high energy ultraviolet radiation, causing heating. Thus, temperature begins increasing vertically, becoming maximum near the top of the ozone region. Because such a temperature inversion greatly restricts vertical air motions, this layer is called the **stratosphere** (stratification sphere), and most weather is confined to the layer below called the troposphere (turning sphere). The hypothetical point where those layers meet is called the **tropopause**. As you may imagine, such is highest at equatorial regions where great convective vertical mixing occurs.

Above the ozone layer, temperature begins vertically decreasing in a region known as the **mesosphere** (middle sphere), the hypothetical point between it and the stratosphere called the stratopause. Noctilucent clouds sometimes occur in this region near arctic regions near Summer Solstice, sustained solar heating perhaps contributing to convection there, depositing trace amounts of water vapor. At altitudes about 80 km and above, atmospheric gases including diatomic nitrogen and oxygen absorb very energetic ultraviolet, X-ray, and gamma-ray solar energy, causing heating. Similar with the stratosphere, temperature vertically increases, but much more so, often becoming 600 °K or more during active solar periods. This layer called the **thermosphere** (thermal sphere) contains ionized atoms and aurorae previously mentioned. As you may guess, the mesopause is where the mesosphere and thermosphere meet. Above the thermosphere and (of course) thermopause is the **exosphere** (exit sphere) - a region at several hundred km altitude where earth's gravity no longer retains high energy absorbing atoms, which escape to outer space. This is the hypothetical top of the atmosphere, near the upper boundary I previously mentioned.

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Global Atmospheric Circulations

As mentioned previously, solar heating drives atmospheric circulation. Thus, if earth were a uniform substance constantly tilted perpendicular with its orbital plane (and perhaps another requirement being that Earth rotated sufficiently slow such that the 'Coriolis force' were much smaller than presently), a **thermal circulation** would be expected (also called a *direct circulation*) as a simple diagram (referenced site) (main site) indicates. This is similar with other types of thermal circulations, e.g., sea and land breezes. We don't live on such a planet though, as previously mentioned regarding Earth orbit. The Northern Hemisphere contains the majority of land, and the Southern Hemisphere is primarily water. It also rotates quite quickly - a rotation per day meaning a speed of 1038 mph at the equator, decreasing to about 732 mph at 45° latitude, 518 mph at 60° latitude, to 0 at the poles. Each of these factors alter global air circulation from the idealized situation previously mentioned.

Observational studies suggested that several basic wind regimes exist, which correspond with atmospheric pressure observations, the thermal circulation being one. Average global air circulations indicate that such a thermal circulation may exist in tropical regions, called Hadley cells. The supposed Hadley circulation extends to the mid-latitudes. Low pressure tends to be near the equator (the monsoon trof or Intertropical Convergence Zone), and high pressure where the topics and mid-latitudes meet, so the observation of surface flow from high to low pressure conveniently fits this theory. Air convergence at equatorial regions requires a poleward return flow aloft as illustrated. The Coriolis force is supposed responsible for its termination, where subsidence occurs. Poleward of the Hadley cell is supposed a Ferrel cell - an 'indirect' circulation (reverse sense of a thermal circulation) - a consequence of subsidence at its equatorward end and ascent at its poleward end because of similar coriolis turning and supposed convergence. North of the Ferrel cell, a Polar cell is supposed, which completes the 3-cell idealized global circulation shown. Why is the coriolis force assumed responsible for the transitions occurring at approximately 30° and 60° latitude when it is sin(60°) = .866 the maximum polar value at 60° latitude and sin(30°) = .5 that value at 30° latitude, instead of 42° latitude and 19½° latitude which would equally spilt the coriolis difference ? That's a good question which I can't answer, not being a global circulation specialist; which an analysis of the atmospheric equations of motion may answer. I have perhaps a better explanation for the observed circulation below.

Before I mention that though, what *is* the observed average global circulation ? I.e., how well does the 3-cell theory mentioned above describe observations ? Let's look at some. First, I display average January and July temperatures for each hemisphere. These plots are 5-day averages for 1979-1995 centered about the day shown each year (85 total days) obtained from the Climate Diagnostics Center's Atmospheric Variables Plotting Page. I include these first for 2 main reasons : 1) So users unfamiliar with polar stereographic data plots can gain perspective using an intuitive concept such as temperature (latitude varies on the plot from the equator at the edge to the pole at the center, and continents are shown), 2) So you can imagine how a consequential thermal circulation might appear during warmest and coldest times of year. Perhaps the first things you notice viewing these plots (you can save them for later viewing using your right mouse button) are that temperature gradients are much greater during the cold than the warm season in each hemisphere, and the maximum temperature gradient during the cold season occurs at poleward locations of mid-latitudes. Thus, a purely thermal circulation would perhaps be over mid-latitudes rather than tropical regions - temperature gradients are not so large there.

So if a thermal circulation is perhaps imagined, then what type of circulation does exist ? To help answer that, we can examine plots of average surface pressure and wind. A necessary concept regarding this is **zonal wind** and **meridional wind**. Zonal wind refers to a west-to-east direction as positive, meridional wind refers to a south-to-north wind as positive (unfortunately, no matter which hemisphere). The zonal wind is called its **u**-component and the meridional wind its **v**-component. Let's consider surface pressure (corrected to sea level) plots. Among most notable features are regions of average high pressure at subtropical oceanic regions, particularly eastern portions of large oceans. You can also see semi-permanent Lows near arctic oceanic regions, particularly during winter - an Aleutian Low south of Alaska and an Icelandic Low near that continent. These semi-permanent features follow the subsolar point to some extent. Comparing Northern & Southern Hemisphere plots, you can also see a much more uniform pressure distribution over the Southern than Northern Hemisphere, because it is much more similar to the idealized situation I previously mentioned. The monsoon trof near the equator is evident, though admittedly difficult to see on these plots which end there. The corresponding near-surface wind distributions are interesting. Because the plotted wind vectors are almost impossible to see, I plotted zonal and meridional components previously mentioned. First examining zonal winds, you can see evidence of the 3 regimes previously mentioned. Easterly winds (negative values) dominate equatorial regions, and westerlies (positive values) at mid-latitudes. The polar easterlies are not so evident. They are in the Antarctic, where high pressure resides over a cold mass of ice encircled by warmer ocean and air - most likely a consequence of those factors more than rotational dynamics (though I am prepared to be proven wrong regarding that). Let's peek at the meridional circulation. Peek is about all we're doing. You can probably surmise that these average characteristics are a sum of the many greatly variable conditions which occur. These might be surprising after staring at them for awhile. The Intertropical Convergence Zone, though evident, does not seem like that which may be imagined. In quite a few locations, equatorial easterlies exist, but not necessarily *trade winds*. You can see a tendency for poleward flow at mid-latitudes, especially during summer, an 'indirect' circulation, considering the temperature gradient previously seen. Again, equatorward (northerly) flow from the frigid South Pole (positive values) is seen, but not so well-organized from the North Pole, if existent. An interesting plot is that for April in the Northern Hemisphere. The meridional flow is primarily poleward over the continents. A possible reason is a temporary thermal circulation caused as rapid surface heating occurs as the subsolar point quickly moves northward (24 hour days occur at many Arctic locations then).

What about the flow aloft ? First I show zonal wind plots for 500 mb (approximately halfway into the atmosphere according to weight - Southern Hemisphere is similar). These indicate westerly winds at all locations, ranging from near 0 at equatorial regions and the poles to as much as 35 m / sec (average !) at mid-latitudes to arctic locations. The poleward movement of maximum winds is evident during summer, and equatorward movement during winter, with stronger winds associated with the larger temperature gradient. Meridional winds are comparatively small and not particularly organized (though many reasons exist for each maximum and minimum). I'll leave it as an exercise for the reader to obtain those plots ☺

One more series of plots is quite helpful - meridional plots of winds further aloft - near ther tropopause. Any well-organized Hadley circulation would require a return poleward flow aloft corresponding with the supposed trade wind convergence (regarding which I showed some contrary evidence also). I chose 2 levels for these plots - 250 mb & 150 mb - corresponding approximately with the subtropical and equatorial tropopause. The lack of such a return flow during July might be disappointing to a believer of the 3-cell theory, but you should keep in mind that this is only a few plots at a few levels. If trade wind convergence was absent for some locations, perhaps return flow should also be (though the trade winds are more absent for the Northern Hemisphere and the return flow for the Southern Hemisphere). The maps for October are similar, thought the maps for April similar with January's, indicating return flow.

A much greater examination of detailed mass flux calculations are required to rigorously critique Hadley circulations, determine global wind characteristics, etc., but we have examined some of the basic flows. What is a good explanation for the observed atmospheric circulation ? Perhaps the most noticeable aspect of daily weather are the westerly-traveling cyclones and anticyclones people from the subtropics to arctic regions often experience. Theory provides a reason why such are not often experienced near the equator nor the poles (Coriolis force approaches 0 at the equator, thus no large scale circulations), though some quite intense tropical storms can be very near the equator (Typhoon Paka is at about 7° N as I type this, with estimated sustained 85 knot winds !) and easterly waves are common easterly-traveling tropical disturbances. Tropical cyclones do not often form because of baroclinic instability though, and require other processes to become hurricanes. Baroclinic cyclones cause air at mid-latitudes to preferentially rise while moving poleward and sink while moving equatorward. The same is true regarding anticyclones, around which cold air tends to subside from poleward regions and rise from equatorward regions. Winds with cyclones are the primary contributors to wind, anticyclones being much more tranquil. Thus, a combined Hadley cell and mid-latitude cyclone regime is imagined, with a less organized polar regime.

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