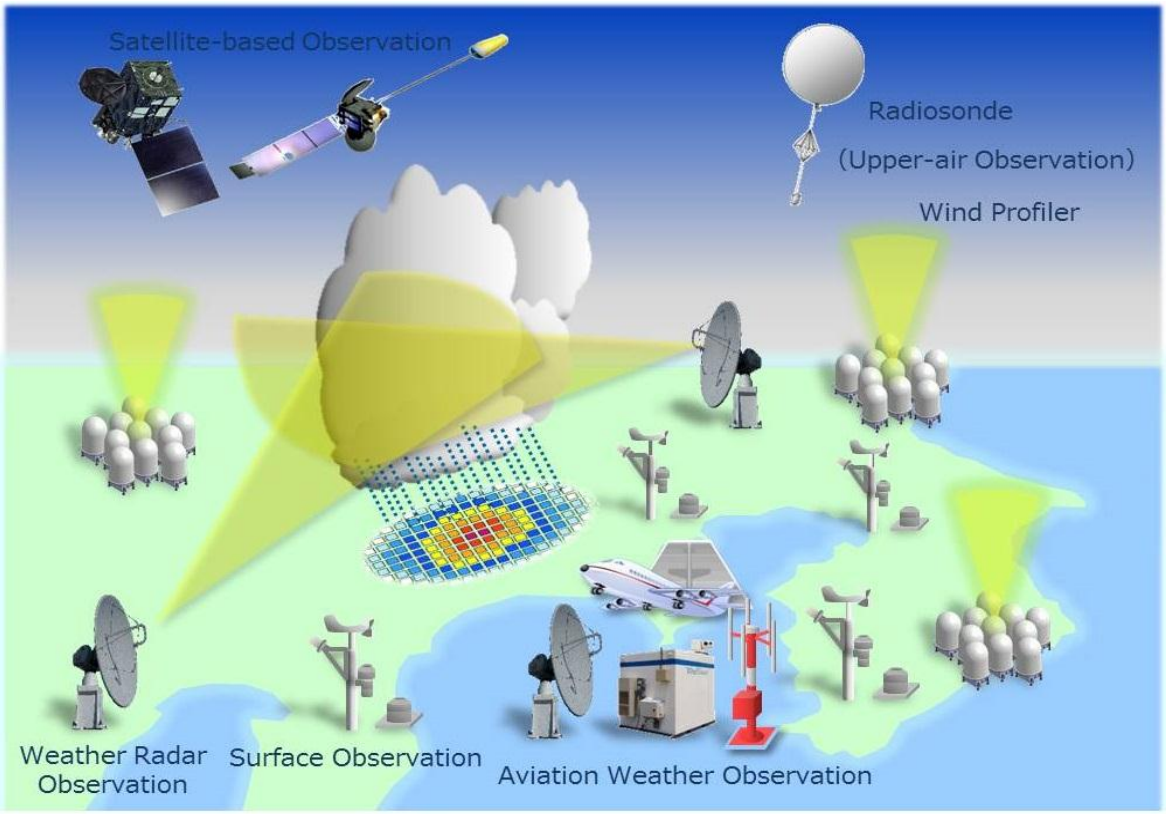
Weather Instruments and Observations



AL-MUSTANSIRIYAH UNIVERSITY
COLLEGE OF SCIENCES
ATMOSPHERIC SCIENCES DEPARTMENT

Dr. Sama Khalid Mohammed

SECOND CLASS

Introduction

Why do we make atmospheric observations?

- For current weather observation, now-casting, and forecasting
- For Climatologically purposes, and to measure climate variability
- Vital for atmospheric research, and process studies

The atmospheric variables we need to measure are the basic parameters that describe the surface & upper air properties. The Basic parameters are pressure, temperature, humidity, winds, clouds, precipitation, etc.

We can make these observations in two ways.

- First. in-situ (in the natural or original position) observation, basically you take measurements of the parameters right were you are. In-situ refers to measurements obtained through direct contact with the respective object. The in-situ observations can be surface based measurements, such as, those collected by surface meteorological stations, ships, or, buoys, but may also include those collected by rockets; balloons, and even aircrafts because they measure the parameters from where they are located at that moment.
- Second, remote sensing measurement. Remote sensing can be ether active or passive. Active remote sensing are those that send out radiation, hoping to get it back to analyze it (radiometers, radars, lidars, and profilers). Passive remote sensing are those that wait for radiation to come to them so that they can analyze the data (satellite visible/infrared measurements).

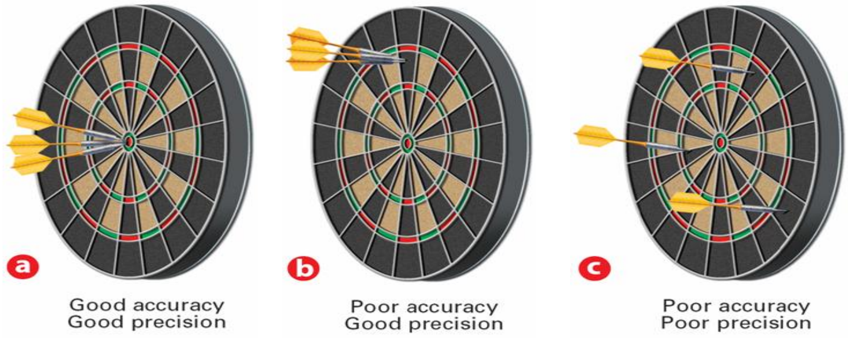
The steps needed to make measurements for a specific application are:

1. Define and research the problem (literature review may be needed and is advised). Determine what parameters are required and what must be measured. What is the frequency of the observations that will be required, how long will the observations be made and what level of error is acceptable?
2. Know and understand the instruments that will be used (consider cost, durability, and availability).
3. Apply instruments and data processing to the problem (consider deployment and data collection).
4. Analyze the data (apply computational tools, statistics, etc.).

General Concepts

- A measurement is a quantity that has both a number and a unit.
- Measurements are fundamental to the experimental sciences. For that reason, it is important to be able to MAKE measurements and to decide whether a measurement is CORRECT.
- However when we collect data, we should expect that there should be error in the data.

1. **Error**: is the difference between the actual value of a quantity and the value obtained in measurement.
2. **Actual value**: standard or reference of known value or a theoretical value.
3. **Accuracy**: refers to how close a measured value to is to an accepted (true) value.
4. **Precision (or resolution):** refers to how close together a series of measurements are to each other.
   A measurement could be very precise but not very accurate. For example, the real weight of a little piece of paper is 0.001 g, but a balance that reads 10.002, 10.001, and 10.001 for three weightings, which has a very good precision. But the real answer is only 0.001g.



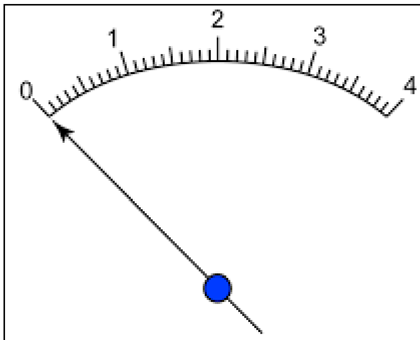
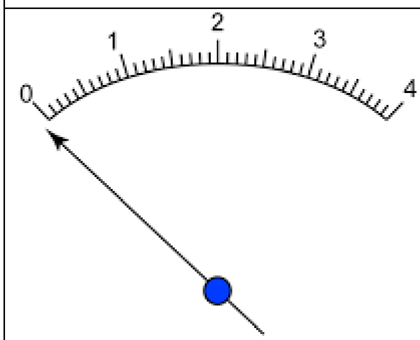
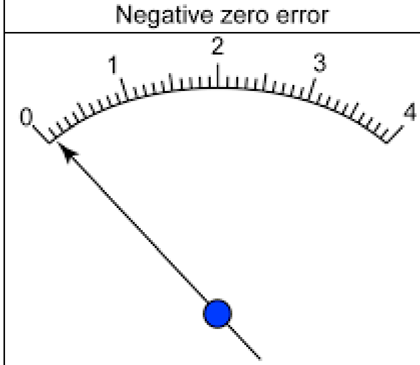
5. **Sensitivity:**
   - The sensitivity of an instrument is its ability to detect small changes in the quantity that is being measured.
   - Thus, a sensitive instrument can quickly detect a small change in measurement.
   - Measuring instruments that have smaller scale parts are more sensitive.
   - Sensitive instruments need not necessarily be accurate.

6. **Types of Errors:** There are two main types of error, systematic and random error

Systematic Error (bias)

1. Systematic errors are errors which tend to shift all measurements in a systematic way.
2. The mean of many separate measurements differs from the actual value of the measured attribute.
3. Systematic errors can be compensated if the errors are known
4. It cannot be removed by repeating measurements or averaging large numbers of results.
5. Examples of systematic errors are
   - ➢ Consistently improper use of equipment.
   - ➢ An incorrect calibration of the measuring instrument (***Constant):*** ex. The electronic balance has been calibrated 0.05g too high for all mass measurements, then all the measurements give reading plus +0.05g). Constant, they are simply due to incorrect zeroing of the instrument. Constant systematic errors are very difficult to deal with, because their effects are only observable if they can be removed.
   - ➢ ***Varying*** or the ***zero error*** (e.g. proportional or a percentage) caused by an incorrect position of the zero point.
     - o When they are not constant, they can change sign. For instance, if a thermometer is affected by a proportional systematic error equal to 2% of the actual temperature, and the actual temperature is 100°, 0°, or −100°, the measured temperature will be 102° (systematic error = +2°), 0° (null systematic error) or −102° (systematic error = −2°), respectively. Thus, the temperature will be overestimated when it will be above zero, and underestimated when it will be below zero.
     - o A zero error arises when the measuring instrument does not start from exactly zero. Zero errors are consistently present in every reading of a measurement. The zero error can be positive or negative.

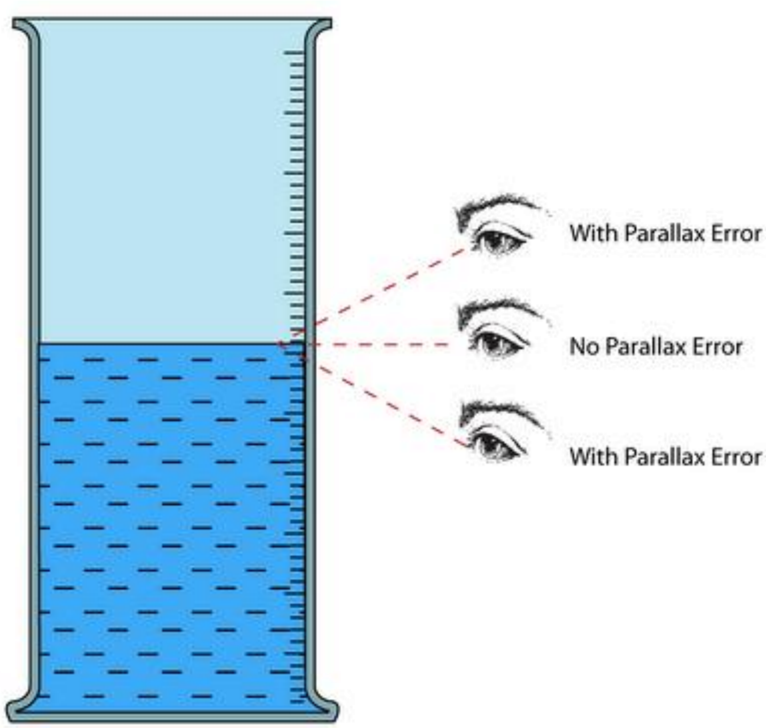
6. Systematic error can be reduced by :
   a) Calibration of the measurement instrument.
   b) Conducting the experiment with care.
   c) Repeating the experiment by using different instruments

 No zero error	(NO ZERO ERROR: The pointer of the ammeter place on zero when no current flow through it.)
 Negative zero error	(NEGATIVE ZERO ERROR: The pointer of the ammeter does not place on zero but a negative value when no current flow through it.)
 Positive zero error	(POSITIVE ZERO ERROR: The pointer of the ammeter does not place on zero but a negative value when no current flow through it.)

<u>Random errors</u>

1. Random error is the variation between measurements, also known as noise.
2. The word random indicates that they are inherently unpredictable, and have null expected value, namely, they are scattered about the true value, and tend to have null arithmetic mean when a measurement is repeated several times with the same instrument.

3. Random errors arise from unknown and unpredictable variations in condition.
4. It fluctuates from one measurement to the next.
5. Random errors are caused by factors that are beyond the control of the observers, but it can cause by personal errors such as
    - human limitations of sight and touch.
    - lack of sensitivity of the instrument: the instrument fail to respond to the small change.
    - natural errors such as changes in temperature or wind, while the experiment is in progress.
    - wrong technique of measurement.
6. Random error can be reduced by :
    - taking repeat readings
    - find the average value of the reading.
7. One example of random error is the parallax error: is an error in reading an instrument due to the eye of the observer and pointer are not in a line perpendicular to the plane of the scale.



Drift Error

1. If measurements changes (drifts) with time even though the input remains constant, we say there is a *Drift*. When the process of measurement takes place, there are some changes taking place in the environment such as changes in the temperature, pressure etc., such environmental changes affect the output of an instrument and this is termed as drift.
2. Drift is evident if a measurement of a constant quantity is repeated several times and the measurements drift one way during the experiment, for example if each measurement is higher than the previous measurement which could perhaps occur if an instrument becomes warmer during the experiment.
3. Drift error can often be seen in the zero reading, which may fluctuate randomly due to electrical noise and other random causes, or it can drift higher or lower (zero drift) due to nonrandom causes, such as a slow increase in air temperature in the room. Thus, drift error can be either random or systematic.
4. To detect a drift, there is three ways
    - By checking the zero reading during the experiment as well as at the start of the experiment (indeed, the zero reading is a measurement of a constant quantity).
    - By subtracting its (possibly time-varying) value from the readings, and by taking it into account in assessing the accuracy of the measurement.
    - Checking the measurements, either by measuring a known quantity or by comparing the readings with readings made using a different apparatus, known to be more accurate.

How to express errors:

- Absolute Error = |Measured Value- Actual Value |

  $\pm\Delta e$, e.g., $10^{o}C \pm 0.5^{o}C$

- Relative Error = Absolute Error / Actual Value

  $$\frac{\Delta e}{e}$$

- Percentage Errors = Relative Error x100%

  $$\frac{\Delta e}{e}(100\%)$$

Fundamentals Data processing concepts

a) Simple statistics

1. *Averaging*

$$\bar{x} = \frac{1}{n}[(x(1) + x(2) + ... + x(n)] = \frac{1}{n}\sum_{t=1}^{n} x(t) \qquad (1.1)$$

2. *Mean and perturbation quantities*

Let $$x(t) = \bar{x} + x'(t) \qquad (1.2)$$

Where x' is the deviation of x from the mean.

3. *Variance and standard deviation or standard error*

take the average of (1.2) and after a mathematical process

$$\overline{x(t)} = \bar{x} + \overline{x'(t)} \qquad \text{and} \qquad \overline{x'(t)} = 0$$

Thus, $\overline{x'(t)}$ is not a good quantity to measure the deviations of observations from the true value.

Classically, we use quantity $\overline{x'(t)^2}$ as a measure of variability of observations, Then

$$\overline{x^2} = \frac{1}{n}[x(1)^2 + ... + x(n)^2] = \frac{1}{n}\sum_{i=1}^{n} x(i)^2 \qquad \text{and} \qquad x^2 = \left(\bar{x} + x'\right)^2$$

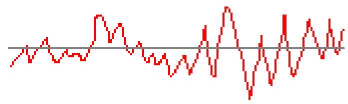
And after using mathematics and with $\overline{x'^2} \geq 0$ we get

$$\overline{x'^2} = \frac{1}{n}[x'(1)^2 + ... + x'(n)^2] = \frac{1}{n}\sum_{i=1}^{n} x'(i)^2 \qquad (1.3)$$

$\sigma_x^2 = \overline{x'^2}$ is called the variance

$\sigma_x = \sqrt{\overline{x'^2}}$ → standard deviation or standard error

Thus, for a time series of observations,

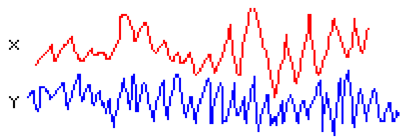


The mean value of observations are sometimes represented as
$\bar{x} \pm \sigma_x$

σ_x include both natural variability and random errors.

4. covariance

Now consider two variables that vary with time.



$x(t) = \bar{x} + x'(t)$
$y(t) = \bar{y} + y'(t)$

Then consider the product $\overline{xy}$

$\overline{xy} = \overline{(\bar{x} + x')(\bar{y} + y')}$

And after using mathematics

$$\overline{x'y'} = \frac{1}{n}[x'(1)y'(1) + ... + x'(n)y'(n)] = \frac{1}{n}\sum_{i=1}^{n} x'(i)y'(i) \qquad (1.4)$$

Eq.(1.4) is called covariance, which can be positive or negative or even 0

5. *Correlation coefficient*: how close it x correlated to y. The range of the correlation coefficient is [-1,1].

$$r = \frac{\overline{x'y'}}{\sigma_x \sigma_y} \qquad (1.5)$$

b) Significant figures

- The significant figures in a measurement include all of the digits that are known, plus a last digit that is estimated.

Significant Figures (Sig Figs) = Known + ESTIMATE

- Significant Figures relate to the certainty of a measurement – The PRECISION of the measurement

- There are rules (hints) to help you in determining the number of significant figures there are in a measurement:
  - Nonzero integers always count as significant figures (3456 has 4 sig figs).
  - Leading zeros do not count as significant figures (0.0486 has 3 sig figs).
  - Captive zeros (Zeros appearing anywhere between two non-zero digits) always count as significant figures (16.07 has 4 sig figs).
  - Trailing zeros are significant only if the number contains a decimal point (9.300 has 4 sig figs).
  - Every digit in scientific notation is Significant (4.73 x 101 = 3 sig figs, 6.00 x 10-2 = 3 sig figs)
  - Any number that is counted is an EXACT number and has UNLIMITED significant digits, There is no ESTIMATED number.
    (1 inch = 2.54 cm, exact unlimited sig figs)
    I have three cats = 3 Cats, Unlimited S.F

c) Rule of arithmetic computation:

- For multiplication and division, the result should have as many significant figures as the measured number with the smallest number of significant figures.
- **6.38 x 2.0 = 12.76 → 13 (2 sig figs)**

- For addition and subtraction, the result should have as many decimal places as the measured number with the smallest number of decimal places. Look at the decimal portion (i.e., to the right of the decimal point) of the numbers ONLY. Here is what to do:

1) Count the number of significant figures in the decimal portion of each number in the problem. (The digits to the left of the decimal place are not used to determine the number of decimal places in the final answer.)
2) Add or subtract in the normal fashion.
   3) Round the answer to the LEAST number of places in the decimal portion of any number in the problem. .

6.8 + 11.934 = 18.734 → 18.7 (3 sig figs)

Examples

SIG FIG PRACTICE #1

How many significant figures in each of the following?

1.0070 m → 5 sig figs

17.10 kg → 4 sig figs

100,890 L → 5 sig figs

3.29×10^3 s → 3 sig figs

0.0054 cm → 2 sig figs

3,200,000 → 2 sig figs

RULE-2: Every digit in scientific notation is Significant

47.3	4.73×10^1	= 3 S.F
0.0021	2.1×10^{-3}	= 2 S.F
1.200	1.200×10^0	= 4 S.F
36	3.6×10^1	= 2 S.F
2400	2.4×10^3	= 2 S.F
0.0600	6.00×10^{-2}	= 3 S.F
104,000	1.04×10^5	= 3 S.F

SIG FIG PRACTICE #2

Calculation	Calculator says:	Answer
3.24 m x 7.0 m	22.68 m^2	23 m^2
100.0 g ÷ 23.7 cm^3	4.219409283 g/cm^3	4.22 g/cm^3
0.02 cm x 2.371 cm	0.04742 cm^2	0.05 cm^2
710 m ÷ 3.0 s	236.6666667 m/s	240 m/s
1818.2 lb x 3.23 ft	5872.786 lb·ft	5870 lb·ft
1.030 g ÷ 2.87 mL	2.9561 g/mL	2.96 g/mL

SIG FIG PRACTICE #3

Calculation	Calculator says:	Answer
3.24 m + 7.0 m	10.24 m	10.2 m
100.0 g - 23.73 g	76.27 g	76.3 g
0.02 cm + 2.371 cm	2.391 cm	2.39 cm
713.1 L - 3.872 L	709.228 L	709.2 L
1818.2 lb + 3.37 lb	1821.57 lb	1821.6 lb
2.030 mL - 1.870 mL	0.16 mL	0.160 mL

Introduction

Temperature is one of the most fundamental measurements of meteorology. Not only is it a critical state parameter for all earth related systems; it is also used to characterize other state parameters like atmospheric moisture.

Air is a mixture of countless billions of atoms and molecules. Close to the earth's surface, each individual molecule would travel about a thousand times its diameter before colliding with another molecule. Moreover, we would see that all the atoms and molecules are not moving at the same speed, as some are moving faster than others. The energy associated with this motion is called kinetic energy, the energy of motion. The temperature of the air (or any substance) is a measure of its average kinetic energy. Simply stated, <u>temperature is a measure of the average speed of the atoms and molecules, where higher temperatures correspond to faster average speeds.</u>

Suppose we examine a volume of surface air about the size of a large flexible balloon:

- ► If we warm the air inside, the molecules would move faster, but they also would move slightly farther apart—the air becomes less dense.
- ► If we cool the air, the molecules would slow down, crowd closer together, and the air **would become more dense.**
- ► Suppose we continue to slowly cool the air. Its atoms and molecules would move slower and slower until the air reaches a temperature of –273°C (–459°F), which is the lowest temperature possible. At this temperature, **called absolute zero**, the atoms and molecules would possess a minimum amount of energy and theoretically no thermal motion. at absolute zero, we can begin a temperature scale called the absolute, or Kelvin scale

Heat, is energy in the process of being transferred from one object to another because of the temperature difference between them. In the atmosphere, heat is transferred by conduction, convection, and radiation.

After heat is transferred, it is stored as internal energy. The atmosphere contains internal energy, which is the total energy stored in its molecules.

Temperature Scales

► Let's take a temperature reading of boiling water and call it 100 degrees, and let us get a mixture of water and ice and call that measurement 0 degree. Then divide the scale into 100 partitions so that it will build the scale where each partition is one degree Celsius. (Celsius scale ^oC)

► Now let's take a temperature reading of boiling water and call it 212 degrees, and let us get a mixture of water and ice and call that measurement 32 degree. Then divide the scale into 180 partitions so that it will build the scale where each partition is one degree Fahrenheit. (Fahrenheit scale ^oF) One degree Fahrenheit is the difference in temperature in which our body can sense.

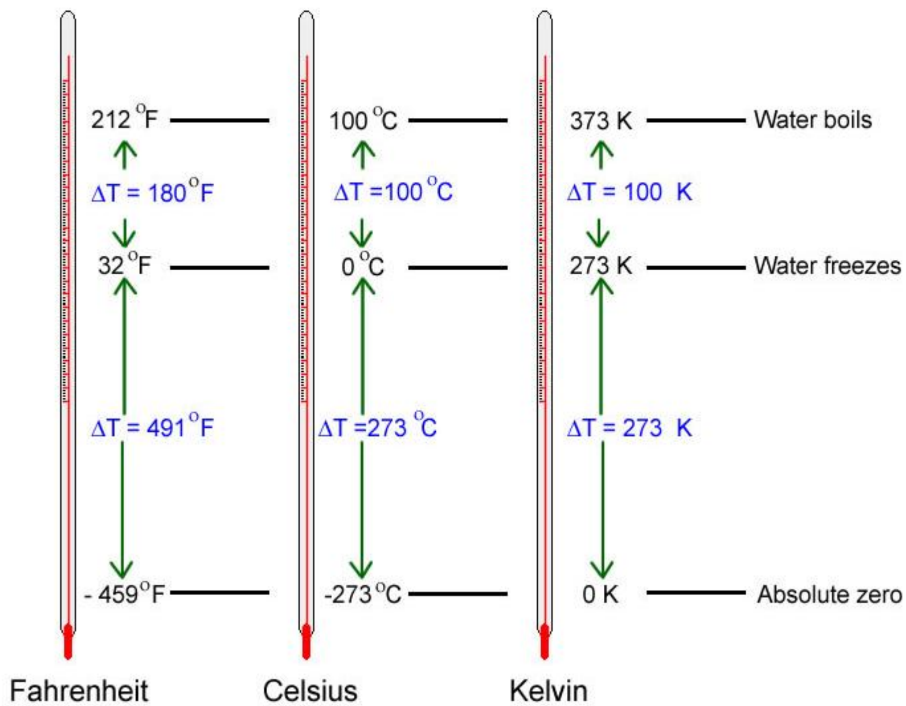


FIGURE 2.1: Comparison of Kelvin, Celsius, and Fahrenheit scales.

So to convert between each other:

$T_{^oF} = aT_{^oC} + b$

If $T_{^oC} = 0$ then $T_{^oF} = b = 32^oF$

When $T_{^oC}$ changes by 100^oC then $T_{^oC}$ changes by 180^oF

therefore $a = \frac{180^o}{100^o} = \frac{9}{5}$; finally

$$T_{^oF} = \tfrac{9}{5} T_{^oC} + 32^o F \qquad (2.1)$$

Another scale is the Absolute or Kelvin scale:

$$T_k = T_{^oC} + 273.15 \qquad (2.2)$$

Note: There is no degree sign in K

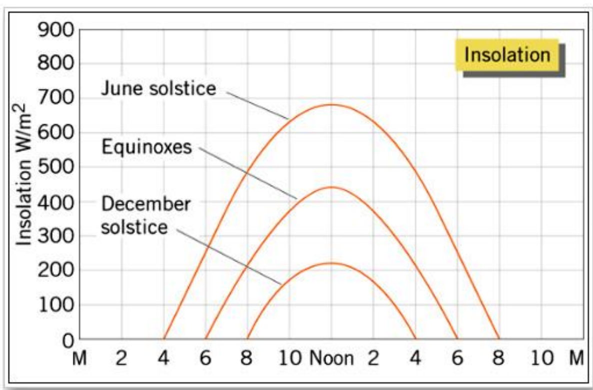
What determines the temperature of a place?

1. <u>Insolation</u>

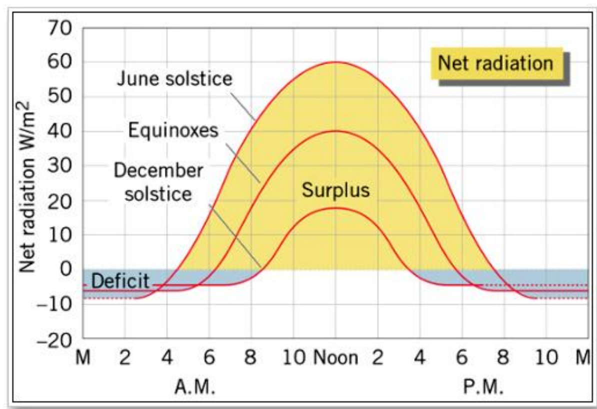
A. Changing angle of noon sun <u>throughout the year</u> changes temperature on a <u>seasonal</u> basis. Temperature difference between equinoxes is due to:

► Spring: at end of cold, short day period, thus more energy loss.

► Autumn: at end of warm, long day period, thus more energy gain.

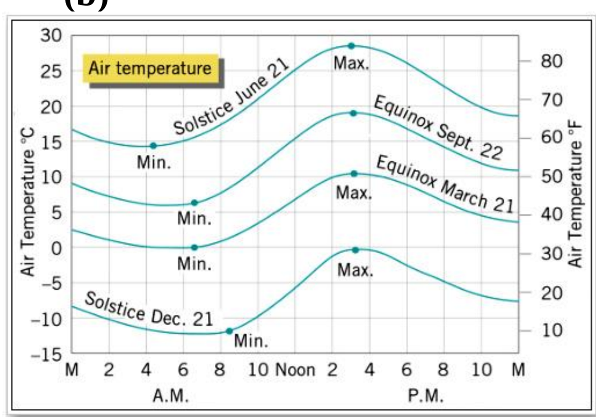


(a)



(b)

FIGURE 2.2: Daily cycles of insolation, net radiation, and air temperature. These three graphs show idealized cycles of insolation, net radiation, and air temperature for a mid-latitude station in the interior United States. Insolation (a) is a strong determiner of net radiation (b). Air temperatures (c) respond by generally increasing while net radiation is positive and decreasing when it is negative.



(c)

B. Changing angle of sun throughout the day changes temperature on a daily basis.

► lag between max insolation and max temperature because highest temp at time of max ABSORBED insolation

2. **Latitude**
   - ► Higher latitudes receive less insolation than lower latitudes
   - ▪ sun's rays are more oblique
   - ▪ day length is variable
   - ▪ Net energy surplus in tropics; net energy deficit in polar regions

3. **Urban/rural Surface**

- ► In rural areas, the land surface is normally covered with layer of vegetation. In the process of transpiration water is taken up by plants and moved to the leaves, where it evaporates. Since evaporation cools a surface by removing heat, <u>we would expect the rural surface to be cooler</u>
- ► In Urban areas, the surfaces are composed of asphalt, concrete, building stone, and similar materials. Sewers drain away rainwater, keeping urban surfaces dry, and they are highly absorbent (low albedo) surfaces in addition to the fuel consumption , all those factors are leading to <u>"Urban heat island"</u>

4. **Land and Water surfaces**

   Ocean temperatures vary less than land temperatures because water heats more slowly, absorbs energy throughout a surface layer, and can mix and evaporate freely. As a result, temperatures at maritime locations are less variable from day to night and from summer to winter when compared to continental locations.

5. **Altitude / Elevation**

- ► In the troposphere, temperatures decrease with increasing altitude. At high elevations we can expect temperatures to be colder than at sea level, as at these elevations the air is less dense and is more distant from the potential warming influence of the surface.
- ► When air temperature increases with altitude, an inversion is present. This can develop on clear nights when the surface loses long wave radiation to space.

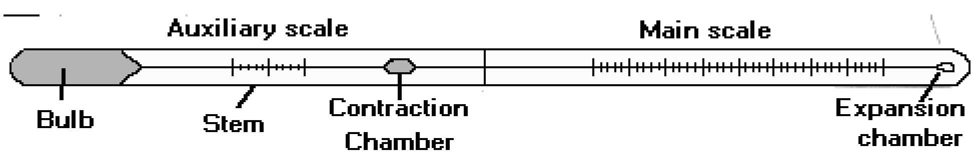
What is a Thermometer?

A thermometer is an instrument that measures the temperature of a system in a <u>quantitative</u> way. The easiest way to do this is to find a substance having a property that change in a regular way with its temperature. The most direct 'regular' way is a linear one:

t(x) = ax + b,

where t is the temperature of the substance and changes as the property x of the substance changes. The constants a and b depend on the substance used and may be evaluated by specifying two temperature points on the scale, such as 32° for the freezing point of water and 212° for its boiling point.

For example, the element mercury is liquid in the temperature range of -38.9° C to 356.7° C. As a liquid, mercury expands as it gets warmer; its expansion rate is linear and can be accurately calibrated.



The mercury-in-glass thermometer illustrated in the above figure contains a bulb filled with mercury that is allowed to expand into a capillary. Its rate of expansion is calibrated on the glass scale.

Thermometer Calibrations

There are three reference points; Extra care must be taken, in order to get a good ice point and boiling point values…

For a linear $T = ax + b$
Where x is some quantity that varies with temperature

	Ice	Triple Point	Steam
Kelvin	273.15	273.16	373.15
Celsius	0.00	0.01	100.00

Two calibration points will give you two equations for the two unknowns a and b as

$$T_1 = ax_1 + b$$
$$T_2 = ax_2 + b$$

That can be solved to give the calibration coefficients.

Types of Thermometers

Thermometers can be divided into two separate groups according to the level of knowledge about the physical basis of the underlying thermodynamic, namely, primary thermometers and secondary thermometers.

► For primary thermometers the measured property of matter is known so well that temperature can be calculated without any unknown quantities. Examples of these are thermometers based on the equation of state of a gas, on the velocity of sound in the atmosphere, and other mechanisms. Primary thermometers are relatively complex.

► Secondary thermometers are most widely used because of their convenience. Also, they are often much more sensitive than primary ones. For secondary thermometers knowledge of the measured property is not sufficient to allow direct calculation of temperature. They have to be calibrated against a primary thermometer at least at one temperature or at a number of fixed temperatures. Such fixed points, for example, triple points and boiling point.

1. <u>Gas thermometer</u>

Gas thermometers measure the temperature by **measuring the pressure changes** of an ideal gas enclosed. According to the ideal gas law:

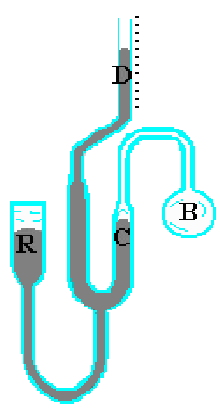
$$PV = mRT \qquad (1)$$

where T is the absolute pressure of the gas;
T is the temperature in Kelvin;
V is the volume of the gas;
m is mass of gas;
and R is the gas constant.
For constant volume gas thermometer, Eq.(1) can be written as

$$T = \frac{V_{const}}{mR} P$$

This relation is known as <u>Charles's Law</u>, which indicates that all we need is to measure pressure in order to calculate temperature. We can make a linear temperature scale in terms of pressure. This is because all gases have P = 0 at –273.15°C (i.e., T=0K). Note that all gases merge to the Absolute zero point, even though they have different slopes.

In a constant volume gas thermometer a large bulb B of gas, hydrogen for example, under a set pressure connects with a mercury-filled "manometer" by means of a tube of very small volume. (The Bulb B is the temperature-sensing portion and should contain almost all



Constant volume gas thermometer

of the hydrogen). The level of mercury at C may be adjusted by raising or lowering the mercury reservoir R. The pressure of the hydrogen gas, which is the "x" variable in the linear relation with temperature, is the difference between the levels D and C plus the pressure above D.

2. Liquid in glass thermometer

Liquid in glass thermometers measure the temperature **via volume expansion**,

$$\Delta V / V$$

The most common liquid in glass thermometer is the mercury-in-glass thermometer, invented by German physicist Daniel Gabriel Fahrenheit. Calibrated marks on the tube allow the temperature to be read by the length of the mercury within the tube, which varies according to the heat given to it. To increase the sensitivity, there is usually a bulb of mercury at the end of the thermometer which contains most of the mercury; expansion and contraction of this volume of mercury is then amplified in the much narrower bore of the tube. The space above the mercury may be filled with nitrogen or it may be a vacuum. Since the volume expansion of glass is about $1.2\text{-}2.7\times10^{-5}$ per $1.00^{o}C$, which is small compared to that of Hg (18×10^{-5} per $1.00^{o}C$), this type of measurement is very accurate. The mercury-in-glass thermometer can be calibrated using triple point.

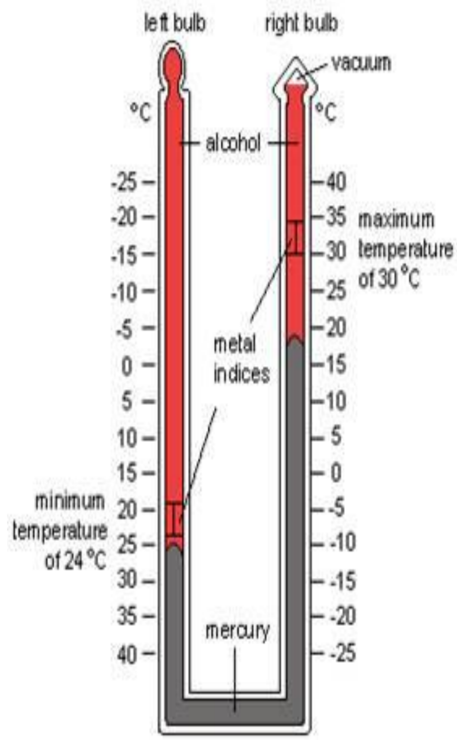
A. Maximum thermometer

Maximum thermometer works by having a constriction in the neck close to the bulb. As the temperature rises the mercury is pushed up through the constriction by the force of expansion. When the temperature falls the column of mercury breaks at the constriction and cannot return to the bulb thus remaining stationary in the tube. The observer can then read the maximum temperature over the set period of time. How does the constriction prevent the mercury from flowing back down the tube and into the bulb? It all has to do with pressure. The **pressure at the constriction is much higher** than the **pressure in the rest of the tube**. In order for the mercury to move into the bulb, it must overcome the pressure in the constriction. The free-flowing mercury does not have enough pressure to do this by itself and thus requires an outside force (your hand shaking the thermometer) to overcome the constriction. This is similar to the design of a medical thermometer.

B. Minimum thermometer

A minimum thermometer measures the lowest temperature during a given period of time. It is a liquid-in-glass thermometer that contains a barbell-shaped marker within the liquid. As the air temperature drops, the liquid and marker move down the thermometer tube. At minimum temperature, the liquid and the marker stop moving; as the temperature starts to rise, the liquid moves back up the tube, but the marker remains stationary. Thus the level of the marker represents the minimum temperature. The minimum thermometer must be held horizontally in order to work properly. To reset it, the thermometer is simply tipped upside down.

C. Six's thermometer



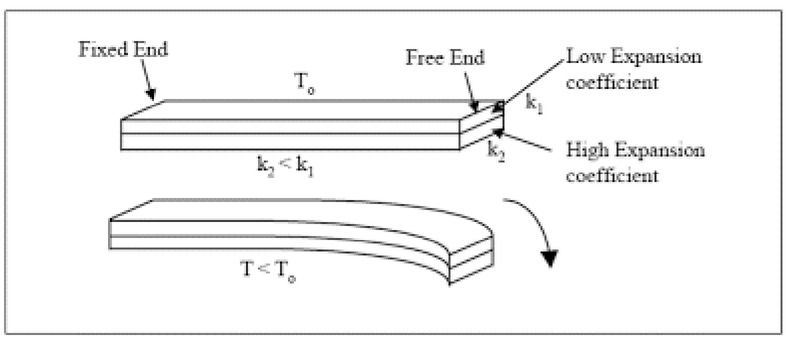
Six's thermometer is also known as a maximum-minimum thermometer, which can measure the maximum and minimum temperature during a given time. It was invented by James Six in 1782, and named after him. It consists of a U-shaped capillary tube with two separate temperature readings, one for the maximum temperature and one for the minimum temperature. There is a bulb at the top of the left arm (minimum reading scale) of the U-shaped tube that contains alcohol. A chamber at the top of the right arm contains a vacuum or low pressure alcohol vapor.

In the bend of the U tube is a section of mercury element, which is pushed around the tube by the expansion and contraction of the alcohol in the left arm bulb. At any given time the position of the mercury should be the same on both the maximum and minimum scales. If not then the instrument scales are not correctly positioned. In the left-hand bore, there is a minimum temperature index. A maximum temperature index is in the right-hand bore. As the mercury moves it pushes the two indexes. They record the furthest point reached by the mercury in each arm of the tube. When the temperature reverses and the mercury is moved in the opposite direction by the expansion or contraction of the alcohol, the sprung indexes remain in the tube at the furthest position they have been pushed by the mercury. They thus record the extremes of temperature experienced by the device since it was last reset.

Stevenson Screen: The Six's thermometers are placed in a white, wooden box called a Stevenson Screen. White wooden box to reflect heat Louvered sides to allow air to flow freely, Doubled layered roof to prevent direct heating from the sun ,Stand on stilts to prevent heat from the ground to be trapped

3. Bi-metallic strip

These thermometers use the following two principles:
1. All metals change in dimension, that is expand or contract when there is a change in temperature.
2. The rate at which this expansion or contraction takes place depends on the temperature co-efficient of expansion of the metal and this temperature coefficient of expansion is different for different metals. Hence the difference in thermal expansion rates is used to produce deflections which are proportional to temperature changes.

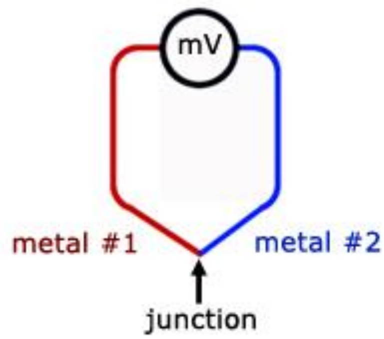


The bimetallic thermometer consists of a bimetallic strip. A bimetallic strip is made of two thin strips of metals which have different coefficients of expansion. The two metal strips are joined together so that the relative motion between them is arrested. An increase in temperature will result in the deflection of the free end of the strip as shown in diagram. This deflection is linear and can be related to temperature changes. The radius of the curvature of the bimetallic strip which was initially flat is determined using a mathematical relationship.

4. Electrical thermometers

Electrical thermometers are useful for many applications. There are three types: thermocouples, resistance, and thermistors.

Thermocouples: In 1821, the German–Estonian physicist Thomas Johann Seebeck discovered that when any conductor is subjected to a thermal gradient, it will generate a voltage. This is now known as the thermoelectric effect or Seebeck effect. So, using a dissimilar metal to complete the circuit creates a circuit in which the two legs generate different voltages, leaving a small difference in voltage available for measurement. That difference increases with temperature. A thermocouple uses two junctions made with two dissimilar metals



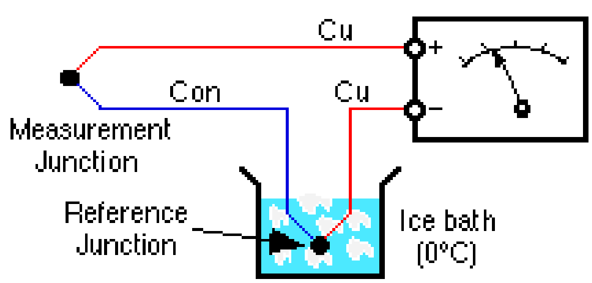
The electromagnetic field (Emf) output from a thermocouple is proportional to the temperature difference between the distances. By measuring the so-called “Seebeck Voltage” across the open circuit, the temperature can be determined by the equation:

$$\Delta e_{AB} = \alpha_{AB} T$$

where the proportionality constant, αAB, is the Seebeck coefficient for metals A and B ,and T is the absolute temperature.
The voltmeter reading is:

$$V = (V_1 - V_2) = \alpha(T_{J_1} - T_{J_2})$$

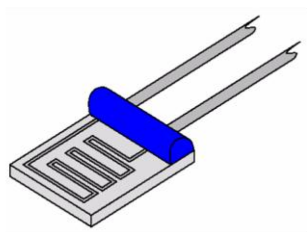
One way to determine the temperature of J2 is to physically put the junction into an ice bath, forcing its temperature to be 0 °C and establishing J2 as the Reference Junction.



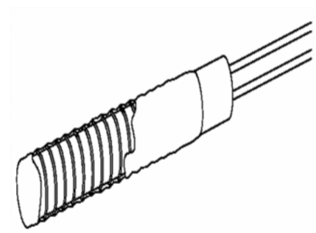
Traditional Thermocouple Measurement

5. **Resistance thermometer**:

- The property of metals that their resistance is temperature dependent makes them ideal as thermometers.
- The metal of choice is platinum as a result of its high melting point (1773^{o}C) and large resistance temperature coefficient.
- The resistance thermal sensor can be made with small wires to give fast response. The resistance of a wire increases with temperature. The finer the wire the faster the response time is.
- In practice resistance thermometers are either thin films of platinum on a substrate or platinum wire wound around a former.



Film



wire

6. **Thermistors:**

They are semiconductors, such as ceramic or polymer, sensitive to temperature. They usually have a large negative resistance (1^{o}C change gives about a 5% increase), and they can be made very small to give a very fast response.

7. **Radiation thermometers:**

- They are based on the principle that the radiation emitted from an object depends on its temperature. They are especially useful for remote sensing.
- The most common radiation thermometer is the infrared thermometer that measures temperature using blackbody radiation emitted from objects. They are, sometimes, called laser thermometers if a laser is used to help aim the thermometer, or non-contact thermometers to enhance the device's ability to measure temperature from a distance.

- By knowing the amount of infrared energy emitted by the object and its emissivity, the object's temperature can be determined.
- The most basic design consists of a lens to focus the infrared energy on to a detector, which converts the energy to an electrical signal that can be displayed in units of temperature after being compensated for ambient temperature variation.
- This configuration facilitates temperature measurement from a distance without contact with the object to be measured. As such, the infrared thermometer is useful for measuring temperature under circumstances where thermocouples or other probe type sensors cannot be used or do not produce accurate data for a variety of reasons.

Thermometer Response Time

The repose time of a thermometer is a very important parameter that determines the main characteristics of the sensor and can vary substantially.

If $\mathbf{T_o}$ is the initial equilibrium temperature of a thermometer, $\mathbf{T_a}$ is the final temperature, the response time, or we say time constant, is the time that sensor needs to change from T_o to T_a. Apparently, the smaller the time constant τ, the faster the thermometer's response time to a given temperature change.

► Factors that control the time constant:

The characteristics of the sensor and of the medium being sampled affect the time constant τ. The factors important in determining this coefficient are the heat capacity of the sensor and the heat transfer rate.

The constant τ will be proportional to the heat capacity and inversely proportional to heat transfer rate.

a) The heat capacity of the sensor may be represented as

$$C_s = c_s m \tag{2.1}$$

where m is the mass and c_s is the specific heat capacity. Since the mass can be represented as

$$m = \rho V$$

where ρ is the density and V is the volume of the sensor, so that

$$C_s = c_s \rho V \tag{2.2}$$

b) In air, the rate of energy loss from the sensor due to convective processes will be proportional to the area of the sensor A and the convective heat flux H_{conv} that depends on the ventilation of the sensor and sensor geometry. For temperature measurements in a liquid or solid, the relevant energy transfer will be associated with conductive properties of the medium. The total **heat transfer** from the sensor can then be written as AH_{conv}. With these expression for the heat capacity and transfer rates

$$\tau \propto \frac{\rho c_s V}{AH_{conv}} \approx \frac{\rho c_s d}{H_{conv}} \qquad (2.3)$$

where d is a size parameter whose relationship between V and A depends on the geometry of the sensor.

This expression shows that the smaller the sensor the higher the convective heat transfer rate, then the smaller the time constant. For some application, the sensor may be too fragile (weak), if the size is too small.

The heat transport is proportional to the ventilation rate of the sensor. Empirical studies indicate that τ can be related to the ventilation rate U as

$$\tau = aU^b \qquad (2.4)$$

where b is ~ -0.5. Thus, as ventilation increase, τ decreases.

Making temperature measurements in the air

1. Air is a poor conductor, thus, a good flow over the sensor should be maintained.
2. Sensor to be thermally insulated from the mounting to avoid conduction errors.
3. To prevent radiation, sensors can be polished or coated to reflect solar radiation and to reduce the absorption of infrared radiation. A shield can also be used to shelter the sensor, but it needs to be aspirated to ensure proper ventilation.
4. Heating by adiabatic compression may occur when a sensor is exposed to air moving at very high rates, e.g., aircraft measurements. Adiabatic heating is easily corrected using the air speed of the aircraft.
5. Wetting of a temperature sensor will lower the measured temperature due to evaporative cooling. Upper air measurements can be affected as a sensor goes through a cloud. A special device is needed to prevent sensor wetting. For surface measurements, the radiation shield should keep the sensor dry.

Sensor exposure

Exposure standards are necessary to define what is meant by **adequate exposure** for certain applications. For example,

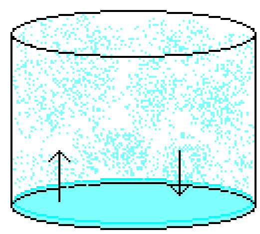
What is meant by surface temperature on synoptic scales?
Is it acceptable to mount the temperature sensor besides a building?
How about on the roof of a building?
For synoptic observations, we want the measurement to be representative of a large area. At what height above the ground should measurements be made?

World Meteorological Organization/Commission for Instruments and Methods of Observations (WMO/CIMO) has clear recommendations about siting and exposure of instruments.
The temperature sensor should be exposed in a radiation screen, with or without forced ventilation, at a height of 1.25 m to 2.00 m above the ground surface. The screen must be not shielded by or close to trees, buildings or other obstructions. The measurement site must not be on a steep slope or in a depression where thermal conditions might not be representative of the larger scale. Exposure on top of buildings is not recommended because of the vertical temperature structure in the atmosphere and the perturbation caused by buildings. Where snow is persistent, it is acceptable to maintain the sensor at a constant height above the snow surface.

Introduction

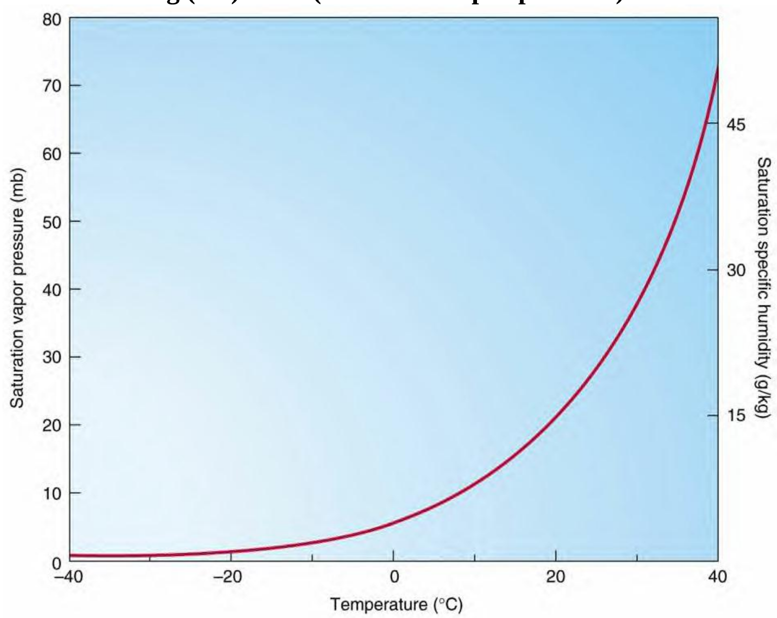
There are several variable used to characterize atmospheric water vapor. Different techniques for quantifying water vapor provide direct measurements of certain variables. Before discussing these techniques, it is useful to review the basic quantities used to quantify moisture and to show the interrelationship amount these variable.

Water vapor



Water vapor pressure is the partial pressure exerted by water vapor molecules in an atmospheric volume. To illustrate vapor pressure, the concept of equilibrium vapor pressure considers a closed container shown to the left. This picture illustrates a liquid water surface that is included in a container with a vacuum in the column above the water surface. As water vapor molecules evaporate from the surface the vapor pressure will increase. As this pressure increases, there will be condensation of water vapor molecules at the surface. The condensation rate will increase as the vapor pressure increases. At the point where the evaporation rate is equal to the condensation rate, we define the vapor pressure as the equilibrium or **saturation vapor pressure**. If now, the temperature of the system is increased, the evaporation rate will increase and the vapor pressure will increase again until a new equilibrium pressure will be obtained. Thus, as temperature increases the saturation vapor pressure increases. If one were to plot this relationship, shown would look like what is shown in the figure below.

Fig.(3-1): SVP (saturation vapor pressure) Curve



Thus saturation vapor pressure e_s is a function of temperature, such that $e_s(T)$. The vapor pressure e of an air parcel is the measure of the moisture content, while the saturation vapor pressure is a function of temperature. The ideal gas law provides the relationship between e, and water vapor density ρ_v as

$$e = \rho_v R_v T \qquad (3.1)$$

where R_v is the specific gas constant for water vapor (461 J K^{-1} kg^{-1}).
The relationship between saturation vapor pressure e_s and temperature is given by the Clausius-Clapeyron equation as

$$\frac{de_s}{dT} = \frac{\ell_v e_s}{R_v T^2} \qquad (3.2)$$

where ℓ_v is *the latent heat of vaporization or enthalpy of vaporization*(*is the heat that has to be given to a unit mass of material to convert it from the liquid to the vapor phase without a change in temperature)*. It decreases slowly with temperature and has a value of 2.5*106J kg^{-1} at 0^oC and a value of 2.25*106J kg^{-1} at 100^oC. At 0^oC e_s = 6.108mb and at 100^oC e_s=1013.25mb.

For small intervals of temperature around some reference temperature and e_s value, the **Clausius-Clapeyron** equation can be integrated assuming a constant value of ℓ_v. This gives us

$$\frac{e_s}{e_{so}} = \exp\left[\frac{\ell_v}{R_v}\left(\frac{1}{T_{Ko}} - \frac{1}{T_K}\right)\right] \qquad (3.3)$$

where in this expression temperature is in Kelvin and quantities subscripted with a $_o$ are reference values.

An empirical expression for e_s as a function of temperature that is valid for temperatures from -60°C to 40°C is given by Bolton (1980) as

$$e_{s\ of\ T} = 6.112mb\ \exp\left(\frac{17.67T}{T + 243.5}\right) \qquad (3.4)$$

where T in this expression is in °C, this expression can also be inverted to give

$$T = \frac{243.5\ln e_s - 440.8}{19.48 - \ln e_s} \qquad (3.5)$$

Other Humidity Variables

Dewpoint, T_D, is the temperature to which air would have to be cooled isobarically (with no change in air pressure or moisture content) to reach saturation. This process can be seen that

$$e = e_{s\ of\ T_D} = 6.112mb\ \exp\left(\frac{17.67T_D}{T_D + 243.5}\right) \qquad (3.6)$$

Similarly, this can be inverted to give an expression for T_D as a function of vapor pressure e as

$$T_D = \frac{243.5\ln e - 440.8}{19.48 - \ln e} \qquad (3.7)$$

Relative humidity, RH, is the ratio of the amount of water vapor actually in the air to the maximum amount of water vapor required for saturation at that particular temperature (and pressure).We can say, It is the ratio of the air's water vapor content (vapor pressure) to its capacity (saturation vapor pressure), thus is the ratio of the vapor pressure e to the saturation vapor pressure e_s(T), such that

$$RH = \frac{e}{e_s} * 100\% \qquad (3.8)$$

Where e is from the wet bulb temperature and e_s is from the regular temperature.

A change in relative humidity can be brought about in two primary ways:

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

Mixing ratio, r, is the ratio of the mass of the vapor m_v to the mass of the dry air m_d in a parcel such that

$$r = \frac{m_v}{m_d} = \frac{0.622e}{p - e} \qquad (3.9)$$

Specific humidity, q, is the ratio of the mass of the vapor to the total mass ($m_v + m_d$) or

$$q = \frac{m_v}{m_d + m_v} \qquad (3.10)$$

Using the definition for r and q it can be show that

$$q = \frac{1}{1+r}; \quad r = \frac{1}{1-q} \qquad (3.11)$$

Mixing ratio and specific humidity are conserved in the adiabatic descent for unsaturated air parcels. By the definition r and q are non-dimensional, although it is common to represent these in dimensional form as g/kg by multiplying the non-dimensional quantities by a factor of 1000. For example r = 10^{-2} = 10 g/kg. Saturation mixing ratio r_s and specific humidity q_s can be also defined as the values a parcel would have if it were saturated. Thus it follows that

$$r_s = \frac{0.622e_s}{p - e_s} \qquad (3.12)$$

From these definitions it follows that the RH is

$$RH \cong \frac{r}{r_s} * 100\% \qquad (3.13)$$

This expression for RH is in common use by the meteorology community

Enthalpy

The enthalpy may be defined as

$$H = C_p T = U + pV \qquad (3.14)$$

where U is the internal energy (in joules), p is the pressure of the system, (in pascals), and V is the volume, (in cubic meters).

H corresponds to the heat required to raise the temperature of a material from 0 to T K at constant pressure. For example, when a layer of air that is at rest and in hydrostatic balance is heated, for example, by radiative transfer, the weight of the overlying air pressing down on it remains constant. Hence, the heating is at constant pressure. The energy added to the air is realized in the form of an increase in enthalpy (or sensible heat, as atmospheric scientists commonly refer to it). The air within the layer expands as it warms, doing work on the overlying air by lifting it against the Earth's gravitational attraction.

The enthalpy is an arbitrary concept but the enthalpy change ΔH is more useful because it is equal to the change in the internal energy of the system, plus the work that the system has done on its surroundings. The change of enthalpy can be represented by

$$\delta H = \delta U + \delta pV + p\delta V \qquad (3.15)$$

The first law of thermodynamics can be written as

$$\delta U = \delta Q - \delta W \qquad (3.16)$$

where δQ represents the infinitesimal (very small) amount of energy attributed or added to the system, and δW represents the infinitesimal amount of energy acted out by the system on the surroundings. Combing (3.15) and (3.16) and representing δW as pδV, we have…

$$\delta H = \delta Q + V\delta p \qquad (3.16)$$

For isobaric process, δp=0. (3.16) can be represented as

$$C_p \delta T = \delta Q \qquad (3.17)$$

where specific heat at constant pressure.

<u>**Wet bulb temperature**</u>

Wet bulb temperature, T_w, is the coldest temperature that air can be cooled to by evaporation. An expression for T_w as a function of other humidity parameters can be derived using conservation of enthalpy in an isobaric, adiabatic process involving either evaporation or condensation of water mass. This conservation can be written as

$$c_p(T_i - T_f) = \ell_v(r_f - r_i) \qquad (3.18)$$

where the subscript i indicates an initial value, the subscript f indicates a final value, and c_p is the specific heat of moist air, which can be approximated in most applications as the value for dry air (1005 J kg^{-1} K^{-1}). If liquid water is evaporated in a parcel, the parcel will cool as the water vapor mixing ratio increases ($r=m_v/m_d$). <u>A good rule of thumb obtained from the equation (3.18) is that if 1gram of liquid water is evaporated or condensed isobarically in 1 kg of air, the air will cool (warm) by 1^{o}C as the mixing ratio increases (decreases) by 1 g/kg.</u>

For the determination of moisture using wet bulb temperature, the environmental temperature and mixing ratio (i.e., dry bulb) are designated as the ambient T and r, and the final wet bulb temperature is T_w while the final mixing ratio is r_s. Thus equation (3.18) becomes

$$r = r_{s\ of\ T_W} - \frac{c_p}{\ell_v}(T - T_w) \tag{3.19}$$

Since $r \approx \frac{0.622e}{p}$, equation (3.19) can be written as

$$e = e_{s\ of\ T_W} - \left[\frac{c_p p}{0.622\ell_v}\right](T - T_w) \tag{3.20}$$

where the quantity in the brackets has a value of 0.065mb K^{-1} at sea level and it is called the *psychometric constant* (although it is not really a constant since p can vary). Further, since $e = e_s(T_D)$ and $T \geq T_w$, it follows that $e \leq e_s(T_w)$ and that $T_D \leq T_w \leq T$ (for unsaturated air).

Humidity variables at T<0^{o}C

For temperature below freezing point, the equilibrium (or saturation) vapor pressure can be defined in two ways. One is for super-cooled water where the saturation vapor pressure is that given by the values discussed earlier for liquid water. The other is the saturation vapor pressure with respect to ice e_{si}.

To physically understand the difference between e_s and e_{si}, consider a container with a layer of water in the bottom as shown previously.

- If the water is super cooled and remains in liquid form at some temperature below freezing, the vapor pressure is that with respect to a pure water surface, and in equilibrium, the evaporation from the water surface will balance the condensation on the surface.
- If the liquid water is replaced with ice at the same temperature. Because of the increase molecular forces in the ice relative to those in the liquid, the evaporation rate will decrease, and the condensation rate will now exceed the evaporation rate and the vapor pressure will continue to decrease until the condensation rate decreases and again comes to equilibrium with the evaporation rate. Thus e_{si} will be less than e_s. The saturation vapor pressure with respect to ice can be quantified using the Clausius-Claperyon equation (3.2) where ℓ_v is replaced with the enthalpy (latent heat) of sublimation ℓ_s. Values for e_{si} can be calculate from equation (3.3) where ℓ_s replaces ℓ_v.

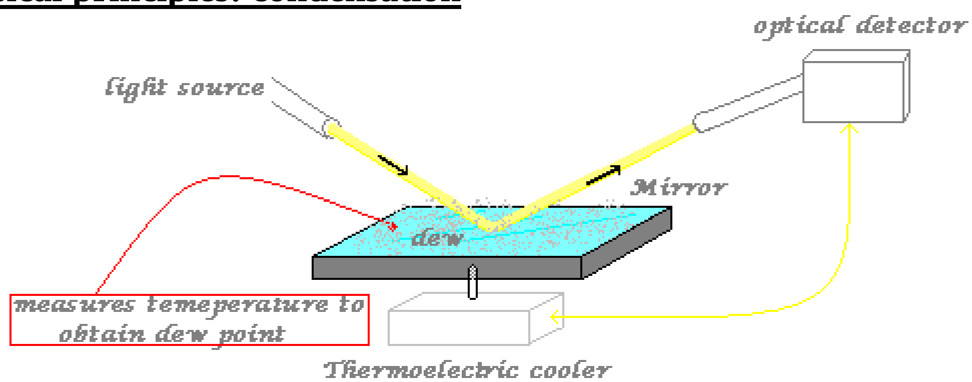
At temperatures < 0^{o}C, we can also define the relative humidity with respect to ice as

$$RH_i = \frac{e}{e_{si}} * 100\% \tag{3.21}$$

Thus it is possible to have condition that are unsaturated with respect to water but saturated with respect to ice since $RH_i > RH$. This result has important consequences for cloud physics at temperatures below freezing point.
Frost point temperature, T_F, can be defined as the temperature a parcel of air can be cooled isobarically to form frost. If the dew-point is greater than 0^oC, the frost point cannot be defined. But at temperature where the dewpoint is $<0^oC$, the frost point will be higher than the dewpoint. Thus, the general frost is not formed by dew freezing, since as air cooled below freezing the frost point will be reached before the dew point.

Humidity Measurements

- **Physical principles: condensation**



The above illustrates the measurement of humidity via a condensation principle. The thermoelectric cooler will cool the mirror to the point that dew will form, so that when a light source shines on the mirror, the optical detector would not pick it up. Then we may use a thermometer to measure the dew point. This process can be repeated until they get a precise measurement. The advantage is that it is capable of high accuracy; the disadvantage though is its slow repose (rest), because of the cooling of the mirror takes time.

- **Sling psychrometer**

It consists of two thermometers mounted in such a way that they can be ventilated by slinging. The bulb of one of the thermometers is covered by a muslin cloth that is wetted with distilled water. The two thermometers are then ventilated by slinging. The temperature of the wet bulb will lower as water from the wick is evaporated. The lower the humidity, the greater the difference between the wet and dry bulb temperatures. The lowest that can be reached by evaporative cooling is the wet bulb temperature. The vapor pressure at sea level is related to the wet and dry bulb temperature as

$$e = e_{s\ of\ T_w} - \left(0.65\frac{mb}{K}\right)(T - T_w) \qquad (3.22)$$

where T_w is the wet bulb temperature, T is the dry bulb temperature, and e_s is the saturation vapor pressure.

For accurate measurement of humidity by the wet-dry method; it is important to protect the thermometers from radiant heat and ensure a sufficiently high speed of airflow over the wet bulb. One of the most precise types of wet-dry bulb psychrometer was invented in the late 19th century by Adolph Richard Aßmann (1845-1918). In this device, each thermometer is suspended within a vertical tube of polished metal, and that tube is in turn suspended within a second metal tube of slightly larger diameter; these double tubes serve to isolate the thermometers from radiant heating. Air is drawn through the tubes with a fan that is driven by a clockwork mechanism to ensure a consistent speed (some modern versions use an electric fan with electronic speed control).

One difficulty for accurate humidity measurement is under the condition when the air temperature is below freezing. In this case, we can use a thermostatically-controlled electric heater to raise the temperature of outside air to above freezing.

1. A fan draws outside air past a thermometer to measure the ambient dry-bulb temperature,
2. A heating device.
3. A second thermometer to measure the dry-bulb temperature of the heated air.
4. A wet-bulb thermometer.

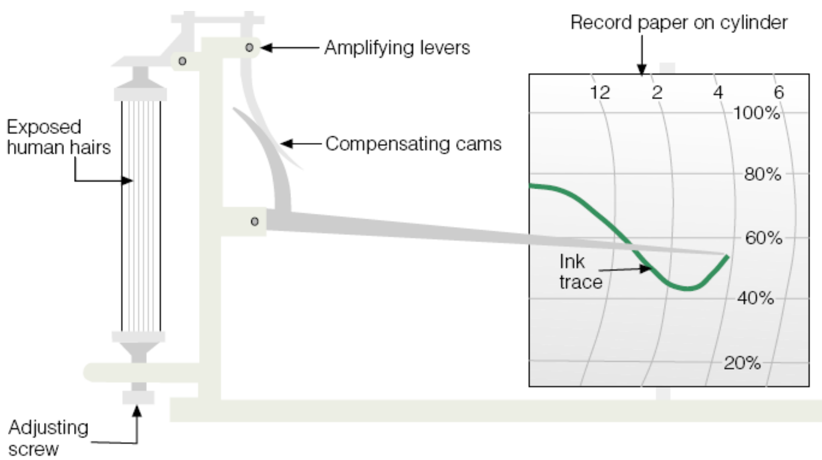
Humidity can be determined using three temperature measurements. According to the WMO Guide, "The principle of the heated psychrometer is that the water vapor content of an air mass does not change when it is heated. However, since the humidity of the ambient air is calculated indirectly from three temperature measurements, in such a device accurate thermometer calibration is even more important than for a two-bulb configuration. Humidity measurement is among the more difficult problems in basic meteorology. Hygrometers need regular recalibration.

Other hygrometers

Hygrometers can be made based on other mechanisms of using sensitivity of various physical processes with water vapor as a function of relative humidity. Like electric resistance, surface resistively, mechanical characteristics.

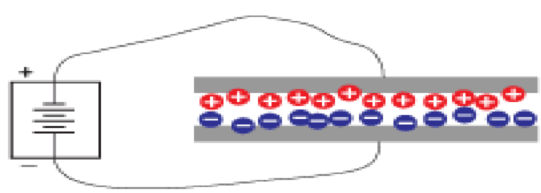
- **<u>Hair tension hygrometer</u>:**

It is constructed on the principle that, <u>as the relative humidity increases, the length of hair increases and, as the relative humidity decreases, so does the hair length</u>. A number of strands of hair (with oils removed) are attached to a system of levers. A small change in hair length is magnified by a linkage system and transmitted to a dial calibrated (Fig. 3-2) to show relative humidity, which can then be read directly or recorded on a chart. (Often, the chart is attached to a clock-driven rotating drum that gives a continuous record of relative humidity.) Because the hair hygrometer is not as accurate as the psychrometer (especially at very high and very low relative humidities), it requires frequent calibration, principally in areas that experience large daily variations in relative humidity.



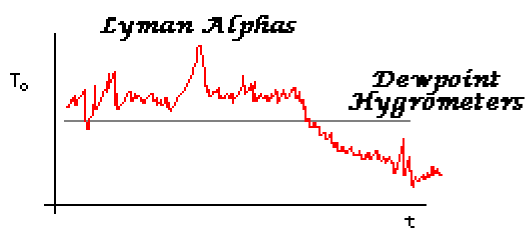
(Fig. 3.2)
Hair Hygrometer

- **<u>Electronic hygrometers:</u>** Modern instruments use electronic means of recording the information. The two most common electronic sensors are capacitive or resistive sensors.
- Capacitive sensor: Capacitance is the ability of a body to hold an electrical charge, or a measure of the amount of electric charge stored (or separated) for a given electric potential. A common form of charge storage device is a parallel-plate capacitor. The capacitive sensors sense water vapor by measuring the change in capacitance caused by the amount of water vapor present.



- Resistive sensor: It normally uses a thin film that changes conductivity according to absorbed water. This instrument is commonly used in the radiosonde, which gathers atmospheric data at various levels above the earth.
- **Extinction of light:** At certain wavelengths the absorption and scattering of light can be a strong function of water vapor density. The Lyman alpha hydrometer:

They have fast repose (rest) and are precise, but not very accurate, because of temperature and pressure sensitivity, plus salts may get in the way. Some times it is used in combination with slower but more accurate sensors.



Over the last several sections we saw that, as the air cools, the air temperature approaches the dew-point temperature and the relative humidity increases. When the air temperature reaches the dew point, the air is saturated with water vapor and the relative humidity is 100 percent. Continued cooling, however, causes some of the water vapor to condense into liquid water. The cooling may take place in a thick portion of the atmosphere, or it may occur near the earth's surface.

Introduction

Cloud: Is a collection of droplets of water floating in the air, found in the lower part of the atmosphere "troposphere". Some clouds are formed in the stratosphere, too

The shape and the position of the clouds tell the direction and speed of the wind in the sea, and clouds tells how much water vapor is in the air

Parameters measured for cloud (or ice) water content is called the liquid water mixing ratio represented by

$$w_l = \frac{mass\ \ liquid}{mass\ \ dry\ \ air}$$

The typical value of w_l is around 1 to 2 grams per kilogram. One may also define the liquid water density ρ_l of clouds as

$$\rho_l = \frac{mass\ \ liquid}{volume\ \ of\ \ dry\,air}$$

Therefore

$$\rho_l = w_l \rho_{air}$$

which is also typically 1 to 2 grams per cubic meter. A typical cumulous cloud is 1 cubic kilometer, and 1 kilogram is 2.2 pounds. So a cloud weights

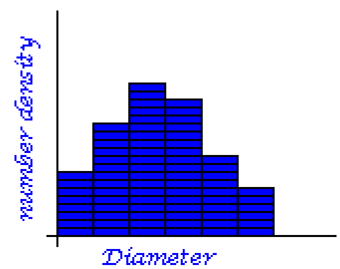
$$\frac{1g}{m^3}\left(\frac{1000m}{km}\right)^3 * 1km^3 = 1.0 * 10^9\, g$$

Cloud droplet distribution

Cloud droplets are not uniform and have a distribution in terms of sizes

Let N (D) be the number of droplets per nit volume (concentration) in an interval D + ΔD. N (D) is called number density. The volume of an individual droplet is $\frac{4}{3}\pi r^3 = \frac{\pi}{6} D^3$, so we get that the

$$mass\ \ of\ \ a\ \ droplet = \rho_l \tfrac{\pi}{6} D^3$$



The liquid water content is total mass per unit volume, thus

$$L = \tfrac{\pi}{6} \sum \rho_l N_i(\overline{D}_i) D_i^3$$

What are the main three cloud types?

- Cumulus
- Cirrus
- Stratus

Cloud classification

High level clouds at heights of 5-13 km

- Cirrus, Ci

Fibrous, threadlike, white feather clouds composed of ice of ice crystals, whose form resembles hair curls and predict fair to pleasant weather. the water vapor rises straight up high into the sky to form small lumps of clouds that look like feathers, they are formed when there is not much moisture in air

- Cirrocumulus, Cc

Fleecy cloud; Cloud banks of small, white flakes.

- Cirrostratus, Cs

Milky, translucent cloud veil of ice crystals, which sometimes causes halo appearances around moon
and sun.

Medium level clouds at heights of 2-7 km

- Altocumulus, Ac

Grey cloud bundles, sheds or rollers, compound like rough fleecy cloud, which are often arranged in banks.

- Altostratus, As

Dense, gray layer cloud, often evenly and opaquely, which lets the sun shine through only a little.

Low level clouds at heights of 0-2 km

- Stratocumulus, Sc

Cloud plaices, rollers or banks compound dark gray layer cloud.

- Stratus, St

Evenly grey, low layer cloud, which causes fog or fine precipitation, Often cover the entire sky, can be seen early in the morning or late in afternoon they are formed when the wind moves horizontally,

Clouds with large vertical extending at heights of 0-13 km

- Cumulus, Cu

Cumulus clouds are white, puffy clouds that look like pieces of floating cotton. Cumulus clouds are often called "fair-weather clouds". but when they become too big and grayish, they may bring bad weather characterized by lightning , thunder, and strong rain. The bottom of each cloud is flat and the top of each cloud has rounded towers. When the top of the cumulus clouds resemble the head of a cauliflower, it is called a towering cumulus. These clouds grow upward and they can develop into giant clouds, which are thunderstorm clouds.

- Cumulonimbus, Cb

In the middle or lower level developing thundercloud, which mostly up-rises into the upper level.

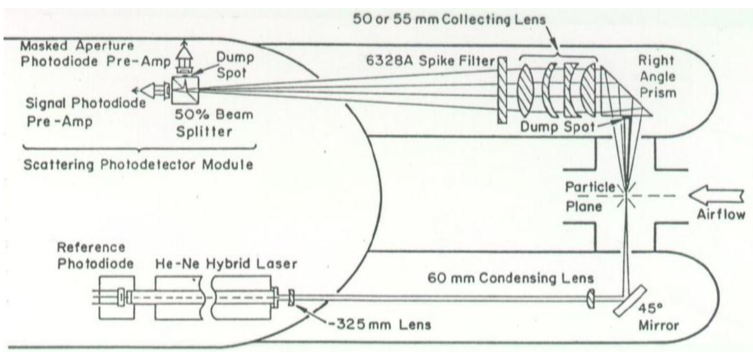
- Nimbostratus, Ns

Rain cloud. Grey, dark layer cloud, indistinct outlines.

FSSP (forward scattering spectrometer probe)

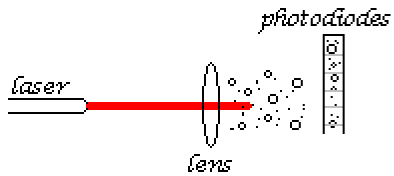
The Forward Scattering Spectrometer Probe (FSSP) is an instrument developed for the measurement of cloud droplet size distributions. The FSSP is of the general class of instruments called optical particle counters (OPCs) that detect single particles and size them by measuring the intensity of light that the particle scatters when passing through a light beam. The mechanism underlying the FSSP is that the forward scattered light by small droplets increases with size. Thus, measuring the forward scattering can tell us the droplet size distribution.

The schematic diagram shown below illustrates the optical path of this instrument. A Helium Neon laser is focused to a concentrated beam at the center of an inlet that faces into the oncoming airstream. This laser beam is blocked on the opposite side of the inlet with an optical stop, a "dump spot" to prevent the beam from entering the collection optics. Particles that encounter this beam scatter light in all directions and some of that scattered in the forward direction is directed by a right angle prism though a condensing lens and onto a Scattering Photodetector Module. The size of the particle is determined by measuring the light scattering intensity and using Mie scattering theory to relate this intensity to the particle size. The size is categorized into one of 15 channels and this information sent to the data system where the number of particles in each channel is accumulated over a preselected time period. Probes for liquid water measurements are usually made from aircraft and usually gives the number of droplets in a certain size bin.



Optical Array probe

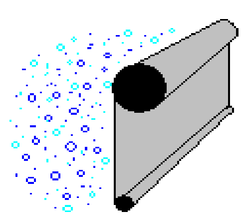
Optical Array probe is an instrument developed for the measurement of cloud droplet size distributions. It uses the same technique as the FSSP but instead of a detector they use an array of photodiodes. It measures the size of hydrometeors from the maximum width of their shadow as they pass through a focused He-Ne laser beam. The shadow is cast onto a linear diode array and the total number of occulted diodes during the airflow's passage represents the size of droplets. The size is categorized into one of 60 channels and this information is sent to the data system where the number of particles in each channel is accumulated over a preselected time period. The optical array probe is a particle sizing instrument, not a liquid water content probe. It detects any particles that cause the diode array to be occulted; however, the probe cannot differentiate shapes or particle orientation. If liquid water content information is desired, some fairly loose assumptions must be made with regard to the phase, habit, and density of the particles. These assumptions may lead to significant errors in derived liquid water content. The sample volume of this instrument is relatively small. This imposes a limitation on the minimum sampling time if a statistically significant measurement is to be made.



The figures above is a 2 dimensional optical array probe, the image to the right is to measure cloud drops and it is attached to a plane's wing, and the image on the left is use to measure precipitation.
Below is a photodiode of some ice crystals in a cloud, where it shows a typical output from one of these devices.

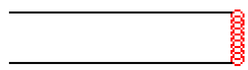
Older techniques

Use a slide with oil, such as vaseline, on it, expose it to air flow. The soft oil captures the water droplets. Then, one may take photos and read through a microscope to obtain the droplet size distribution.



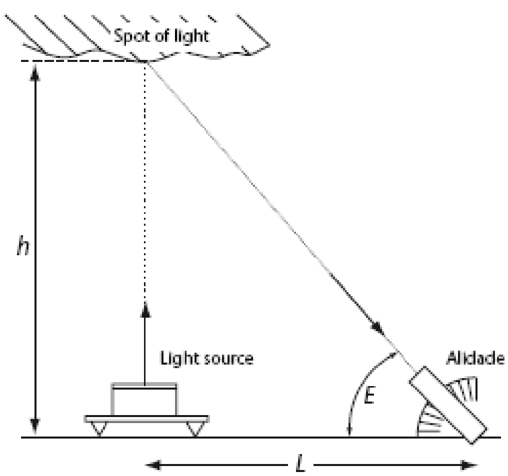
Other ways to measure liquid water content

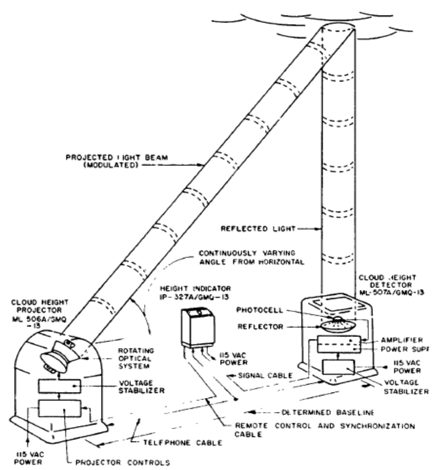
The hotwire probes, such as Johnson-Williams probe, also known as CSIRO and King probe can be used to measure liquid water content. The hotwire will cause the water droplet impinging on the wire to evaporate, which will cool the hot wire. To keep the probe at a constant temperature, an electric current must be applied that will be proportional to the liquid water content evaporated.



Ceilometer

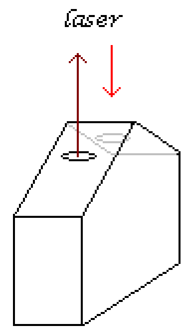
Ceilometer is an instrument for the measurement of cloud base. The device works day or night by shining an intense beam of light (often ultraviolet) at overhead clouds. Reflections of this light from the base of the clouds are detected by a photocell in the receiver of the ceilometer. The height can be determined using the emitted and received light. There are two basic types of ceilometers: the scanning receiver and the rotating transmitter.





The scanning-receiver ceilometer has its separate light transmitter fixed to direct its beam vertically. The receiver is stationed a known distance away. The parabolic collector of the receiver continuously scans up and down the vertical beam, searching for the point where the light intersects a cloud base (figure above to the left). When a reflection is detected, the ceilometer measures the vertical angle to the spot; a simple trigonometric calculation then yields the height of the cloud ceiling.

The rotating transmitter ceilometer consists of transmitter and receiver units separated by a determined baseline shown in figure above right. The transmitter rotates while the receiver is pointing vertically and coplanar with the rotating projector beam. Clouds encountered with the light beam produce a backscattered signal, which is detected by the receiver. Cloud height is then determined by triangulation.



Laser version: it has a transmitter and a receiver, and it measures the time of return from scattering of the laser off from the cloud; it's ideal because it can work during the day and night, but it only gives cloud observations from overhead.

Low power laser ceilometer: Laser could be harmful to people's eye. The low power laser ceilometer uses an eye-safe, low-power laser to transmit light pulses to the cloud base, up to 40,000 feet (13 km). Cloud height is measured by advanced signal processing of laser scatter as it propagates through clouds.

Measurement of cloud height using a balloon

Cloud height may be measured in daylight by determining the time taken by a small rubber balloon, inflated with hydrogen or helium, to rise from ground level to the base of the cloud.
The base of the cloud should be taken as the point at which the balloon appears to enter a misty layer before finally disappearing.
The rate of ascent of the balloon is determined mainly by the free lift of the balloon and can be adjusted by controlling the amount of the gas in the balloon.
The time of travel between the release of the balloon and its entry into the cloud is measured by means of a stop-watch. If the rate of ascent is n metres per minute and the time of travel is t minutes, the height of the cloud above ground is $n \cdot t$ metres, but this rule must not be strictly followed.
Eddies near the launch site may prevent the balloon from rising until sometime after it is released and this should be subtracted from the total time before determining the cloud height.

The rate of ascent in the lowest 600 m or so is very variable, although the height of the base of a cloud at middle altitude is sometimes obtained as a by-product of upper wind measurements taken by pilot balloons, the balloon method is mainly applicable to low clouds.
The measurement should not be attempted if the cloud base is judged to be higher than about 900 m, unless the wind is very light
In strong winds, the balloon may pass beyond the range of unaided vision before it enters the cloud.
Precipitation reduces the rate of ascent of a balloon and measurements of cloud height taken by a pilot balloon should not be attempted in other than light precipitation.
This method can be used at night by attaching an electric light to the balloon. For safety reasons, the use of candle lanterns is strongly discouraged.

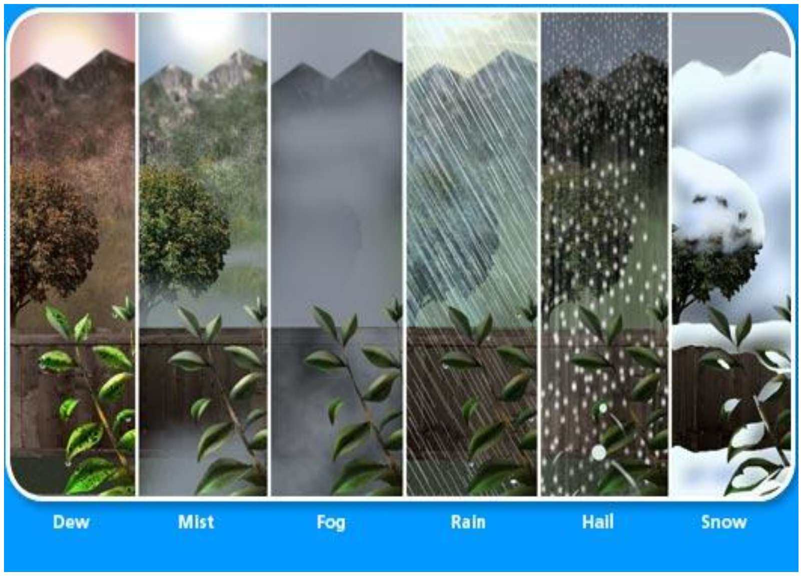
Precipitation

Introduction

In meteorology, precipitation is any product of the condensation of atmospheric water vapour that is deposited on the Earth's surface. The main forms of precipitation include rain, snow, ice pellets, and graupel. Precipitation intensity can be measured by precipitation rate (R), which is normally defined as the rain water falling on ground per unit area per unit time. Thus, the unit of R in SI system is $\frac{kg}{m^2 s}$, which is the same concept of mass flux. Since rain water has a nearly constant density of 1000 kg/m3, one may simply a kinematic precipitation rate as $\frac{R}{\rho_w}$, which has a unit of $\frac{m}{s}$. So, basically precipitation rate is measured by depth per unit time. $\frac{m}{s}$ is too large for precipitation measurement. In real practice, we usually use unit of mm/h.

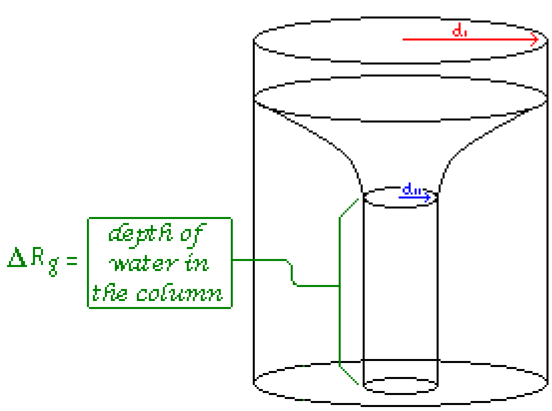
$$1\frac{m}{s} = 3.6\times10^6 \frac{mm}{h}$$

Forms of precipitation



Ordinary rain gauge

The most common rain gauge used today by official forecasters and airports was invented over 100 years ago. It consists of a large cylinder with a funnel and a smaller measuring tube inside of it. The official rain gauge has a 50 centimeter high cylinder with a 20 centimeter in diameter funnel that collects water into a measuring tube that has exactly one-tenth the cross sectional area of the top of the funnel. The reason for the smaller measuring tube is that more precise rainfall measurements can be made due to the exaggeration of the height of water in the tube. For example, one-tenth of an inch of rainfall would actually fill an inch of the measuring tube. A special measuring stick inserted into the measuring tube takes into account the vertical scale exaggeration. The standard rain gauge can measure up to two inches of rain.



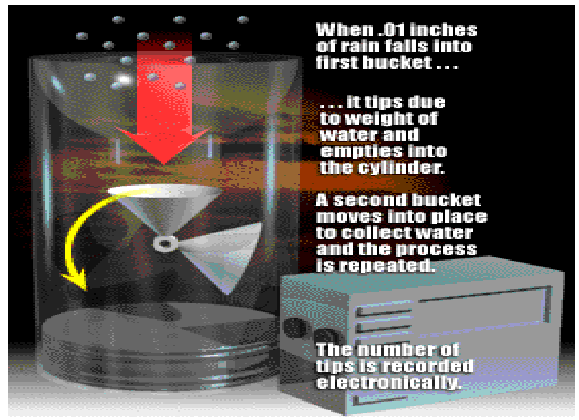
To make calibrations on this we would have to calculate the following

$$\Delta R\pi d_I^2 = \Delta Rg\pi d_{II}^2$$

$$\Delta Rg = \underbrace{\Delta R}_{rain\ fall\ rate}\frac{d_I^2}{d_{II}^2}$$

If rainfall exceeds two inches, water overflows into the cylinder surrounding the measuring tube. The observer takes the water in the cylinder and very carefully pours it into the measuring tube after emptying the tube. The observer then adds the measurement from the water in the cylinder to two inches in order to obtain the final rainfall amount. The rain gauge can be heated to measure the water equivalent of snow.

Tipping bucket rain gauge



The tipping bucket rain gauge is another alternative to the standard rain gauge for measuring rainfall. Two specially designed buckets tip when the weight of .01 inches of rain falls into them. When one bucket tips, the other bucket quickly moves into place to catch the rain. Each time a bucket tips, an electronic signal is sent to a recorder. To calculate the rainfall for a certain time period, simply multiply the number of marks on the recorder by .01 inches. The tipping bucket rain gauge is especially good at measuring drizzle and very light rainfall events. Counts the tips; and it can be automated. If the recorder is equipped with a clock, you can determine how much rain fell during certain time periods without actually being present at the station.
Disadvantages: due to its oscillations of buckets in high winds; evaporation, overflow with heavy rain. Thus, one weakness of the tipping bucket rain gauge is that it often underestimates rainfall during very heavy rain events, such as thunderstorms. In order to calibrate the tipping bucket rain gauge we would need to pour water into the tipping bucket rain gauge from a calibrated cylinder to give about 100 tips. Record the volume of water poured into the gauge. Calculate the equivalent input in millimeters by estimating the area of the rain gauge opening and converting the volume of water poured into the gauge to a depth (in millimeter) spread over this area.

$$d = \frac{Volume}{Area} = \frac{V_{H_2O}}{\pi r^2}$$

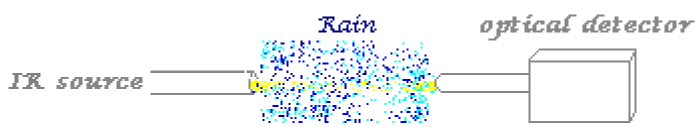
Since the total poured water is 100 tips, the resolution of the sensor is.

$$\frac{d}{100} = trial\ \ resolution$$

There is a calibration adjustment on the instrument. If the estimated error is greater than 5% attempt to adjust the gauge.

Optical rain gauge

Optical rain gauge (ORG) provides accurate measurement of rain rate. This ability makes the instrument more reliable than traditional tipping buckets or collection gauges which have problems with very light and heavy events. The ORG is not affected by overcapacity and not greatly influenced by wind effects as are mechanical methods. A ORG measures the scintillation in an optical beam produced by raindrops falling between a light source and an optical receiver. Scintillation is a generic term for rapid variations in brightness or color of a distant luminous object viewed through the atmosphere. The most common example of optical scintillation is the "twinkling" of stars observed through the atmosphere. Falling rain droplets cause intensity variations in the light (or infrared). By measuring the energy in selected frequency bands of the scintillation spectrum and comparing their ratios, the occurrence of precipitation, type of precipitation, and intensity of precipitation can be estimated as illustrated by the figure below.



Disdrometer

A disdrometer is an instrument used to measure the drop size distribution and velocity of falling hydrometeors. There are a few different types of distrometer designed based on different mechanisms.

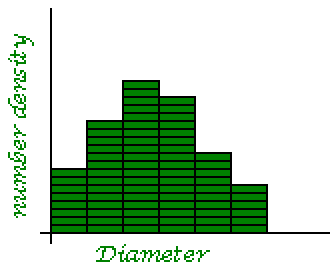
Rain intensity may be determined by measuring the falling speeds of rain droplets. It is found that the falling speed of a rain droplet is determined by its diameter

$$V \propto \tfrac{4}{3}\pi r^3 = \tfrac{4}{3}\pi\left(\tfrac{D}{2}\right)^3 = \tfrac{\pi}{6}D^3$$

The vertical momentum of an impacting raindrop can further be transformed into an electric pulse whose amplitude is a function of the drop diameter. The pulse height analysis will yield the size distribution of raindrops.

$$\int_0^\infty N(D)dD = N_o$$

Another type of disdrometers is basically a momentum video, which uses a video camera to count drops to give distribution of rain droplets N (D) or number density of the drops, so that rain droplets can be sized.



The disdrometers may also be designed based on acoustic signals. The sound of individual raindrops hitting the surface is different due to the intense compression wave is generated by the impact. The energy of this wave is proportional to the rain drop kinetic energy. Hydrophones may be used to measure the characteristics of individual drops and to distinguish cases where more than one drop arrives almost simultaneously.
Since the acoustic frequencies of individual raindrops hitting the surface is different. Disdrometers may be designed by analyzing the frequencies, so that the rain droplet distribution can be determined.

Liquid water content

The liquid water content of droplets with diameter Di is

$$L_i = \underbrace{\tfrac{\pi}{6} D_i^3}_{volume} \underbrace{\rho_l}_{density} N_i(D_i)$$

For droplets of all sizes, the liquid water content is:

$$L = \tfrac{\pi}{6} \rho_l \int_0^\infty N(D) D^3 dD \quad \text{or} \quad L = \tfrac{\pi}{6} \rho_l \sum N_i D_i^3$$

For drops of same size

$$L = \tfrac{\pi}{6} \rho_l D^3 N_O$$

The mass flux of rain fall can be computed as,

$$R = \tfrac{\pi}{6} \rho_l \sum N(D_i) D_i^3 V(D_i)$$

where V (Di) is the fall velocity of droplets, which depends on the size of the drop.

Diameter (mm)	Fall speed (m/s)	Diameter (mm)	Fall speed (m/s)
0.1 = 50μ =r	0.27	2.6	7.57
0.2	0.72	2.8	7.82
0.3	1.17	3.0	8.06
0.4	1.62	3.2	8.26
0.5	2.06	3.4	8.44
0.6	2.47	3.6	8.60
0.7	2.87	3.8	8.72
0.8	3.27	4.0	8.83
0.9	3.67	4.2	8.92
1.0	4.03	4.4	8.98
1.2	4.64	4.6	9.03
1.4	5.17	4.8	9.07
1.6	5.65	5.0	9.09
1.8	6.09	5.2	9.12
2.0	6.49	5.4	9.14
2.2	6.90	5.6	9.16
2.4	7.27	4.8	9.17

Precipitation radar

Weather radars are both transmitters and receivers. Weather radars transmit a microwave beam and then "listen" for echoes that bounce back from precipitation-sized particles (or "targets") within or falling from clouds. Since we know both the direction in which the radar transmitter is pointing and the speed at which microwaves travel (close to the speed of light), the direction and distance from the transmitter to the precipitation can be determined. (Distance to the precipitation echoes is calculated by dividing the travel time (outbound and inbound) in half and multiplying by the speed of light). This permits mapping of precipitation over the region surrounding the radar site. Precipitation intensity can be determined by measuring the strength of the echoes received by the radar antenna. The amount of energy reflected back to the radar is proportional to the precipitation intensity--the greater the energy reflected back to the radar, the greater the precipitation intensity. The relationship between the intensity echo and the size of rain droplets is represented by

$$Z = \sum N(D) D^3 V(D) \rightarrow \sum N(D) D^6$$

This gives us a Z-R relationship; unfortunately Z-R varies with type of rain. There were 69 Z-R relationships made on or before 1973, and the average Z-R relationship of all of them is

$$Z = 200R^{1.6}$$

Echo strength is measured in units of DBZ (decibels). In general, DBZ values greater than 15 indicate areas where the precipitation is reaching the ground; DBZ values less than 15 indicates very light precipitation which may be evaporating before it reaches the ground.

Doppler precipitation radar

Doppler radar is radar that makes use of the doppler effect. It does this by beaming a microwave signal towards a desired target and listening for its reflection, then analyzing how the original signal has been altered by the object(s) that reflected it. Variations in the frequency of the signal give direct and highly accurate measurements of a target's velocity relative to the radar source and the direction of the microwave beam.

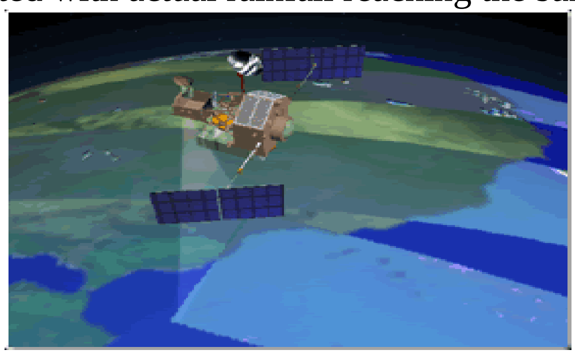
The Doppler effect (or Doppler shift), named after Austrian physicist Christian Doppler who proposed it in 1842, is the change in frequency of a wave for an observer moving relative to the source of the waves. It is commonly heard when a vehicle sounding a siren approaches, passes and recedes from an observer. The received frequency is increased (compared to the emitted frequency) during the approach, it is identical at the instant of passing by, and it is decreased during the recession.

The same effect takes place in the atmosphere as a pulse of energy from a radar strikes an object and is reflected back toward the radar. The radar measures the phase change of the reflected pulse of energy, which is then converted to the velocity of the object, either toward or from the radar.

Measuring precipitation from space

Tropical Rainfall Measuring Mission (TRMM) was launched by the National Aeronautics and Space Administration (NASA) and the National Space Development Agency of Japan (NASDA). TRMM was the first satellite dedicated to rainfall measurement, and is the only satellite that carries weather radar until recently launched CloudSat/CALIPSO (the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation). Rainfall

can be inferred from the temperature of cloud tops. Microwave radiation emitted by clouds can be used to discern rainfall intensity. And, in the case of TRMM, weather radar can transmit a beam of microwave energy downward inside clouds; the energy scattered back to the radar by raindrops provides information on rain intensity and its vertical distribution.
Though TRMM has exceeded expectations, the mission is still inherently limited for fully understanding the complete role of precipitation in the hydrologic cycle. TRMM has a limited view of the Earth, ranging from 36 N to 36 S, and samples rain relatively infrequently, passing over the same location about once a day. TRMM also cannot measure frozen precipitation and is insensitive to light rainfall. Also, cloud top temperatures are imperfectly correlated with actual rainfall reaching the surface.



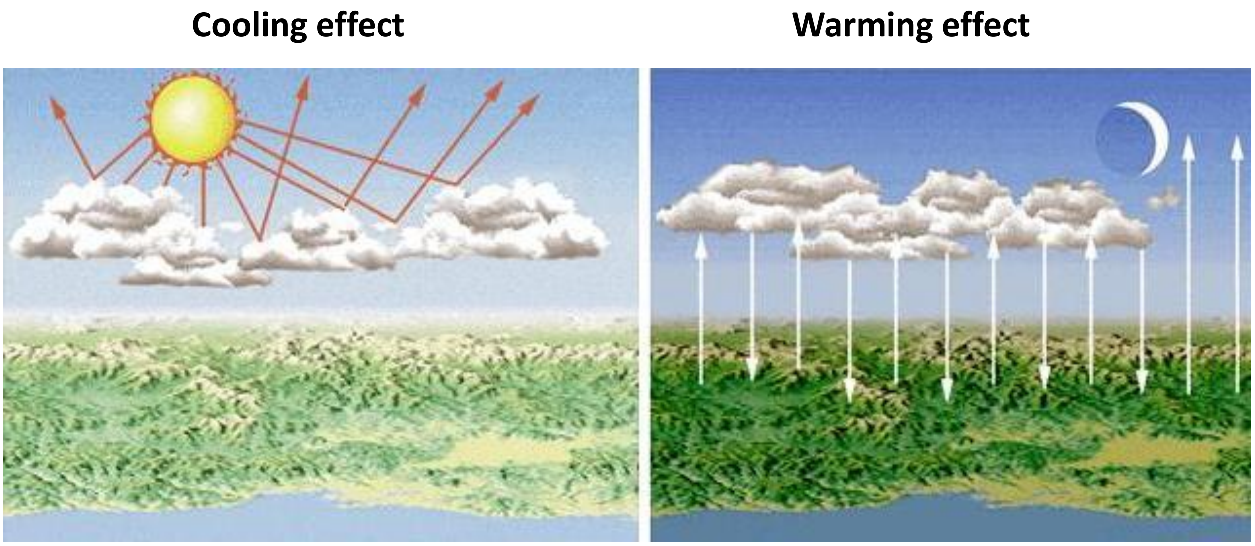
Radiative forcing or climate forcing

It defined as the difference of insolation (sunlight) absorbed by the Earth and energy radiated back to space. Radiative forcing is quantified at the tropopause in units of watts per square meter of the Earth's surface.
A positive forcing (more incoming energy) warms the system, while negative forcing (more outgoing energy) cools it. Causes of radiative forcing include changes in insolation and the concentrations of radiatively active gases, commonly known as greenhouse gases and aerosols.Forcing are external to the climate system

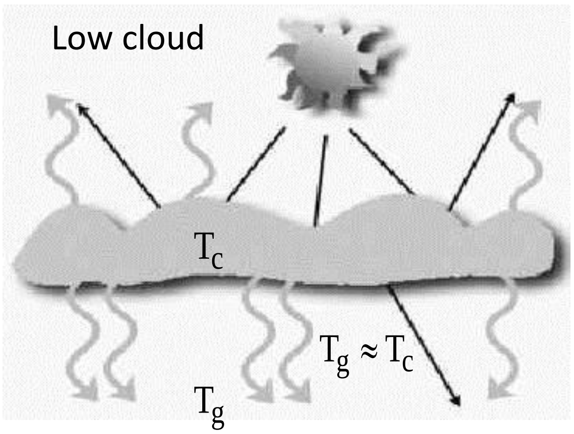
Climate change feedback
Important in the understanding of global warming because feedback processes may amplify or diminish the effect of each climate forcing, and so play an important part in determining the climate sensitivity and future climate state. Feedback in general is the process in which changing one quantity changes a second quantity, and the change in the second quantity in turn changes the first. Positive feedback amplifies the change in

the first quantity while negative feedback reduces it. Feedbacks represent the internal processes of the system.
The main positive feedback in global warming , warming leads to increase the amount of water vapour in the atmosphere which in turn leads to further warming.
The main negative feedback comes from the Stefan–Boltzmann law, the amount of heat radiated from the Earth into space changes with the fourth power of the temperature of Earth's surface and atmosphere.
Forcings, feedbacks and the dynamics of the climate system determine how much and how fast the climate changes.

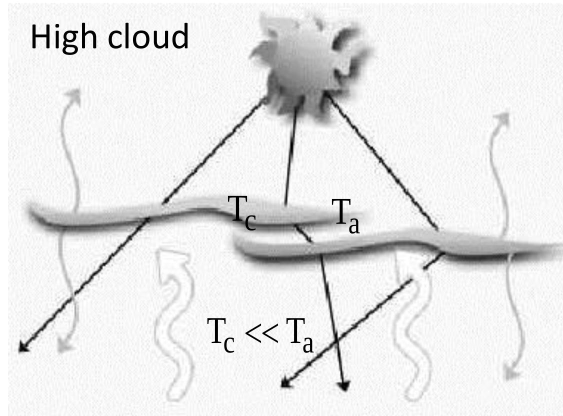
Cloud-Radiation-climate feedback



Clouds affect the Earth's radiation budget in a variety of ways:
On the one hand, High clouds tend to trap more heat and therefore have a positive feedback: their presence tends to reduce the long-wave emission from the Earth because their tops, thanks to their relatively high altitude, emit at a lower temperature than the surface.
On the other hand, low clouds normally reflect more sunlight so they have a negative feedback: clouds reflect a significant amount of the incoming solar radiation, resulting in a net decrease in the amount of solar radiation absorbed by the Earth.



SW cloud forcing dominates

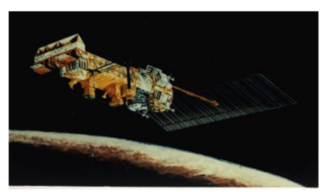


LW cloud forcing dominates

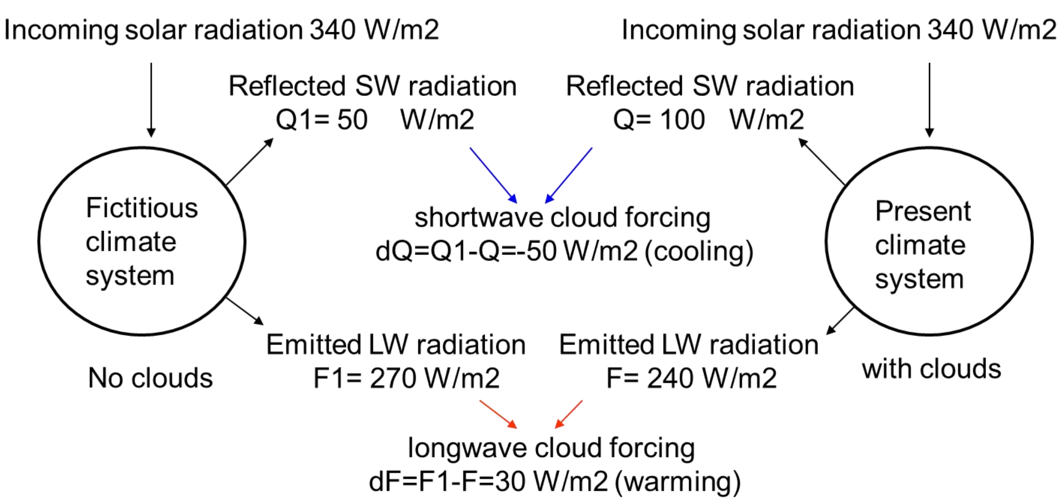
These details were poorly observed before the advent of satellite data and are difficult to represent in climate models.

NASA: The Earth Radiation Budget Experiment (ERBE)

It measures the energy budget at the top of the atmosphere.



Energy budget at the top of atmosphere (TOA)



SW cloud forcing = clear-sky SW radiation – full-sky SW radiation

LW cloud forcing = clear-sky LW radiation – full-sky LW radiation

Net cloud forcing (CRF) = SW cloud forcing + LW cloud forcing

Current climate: CRF = -20 W/m2 (cooling)

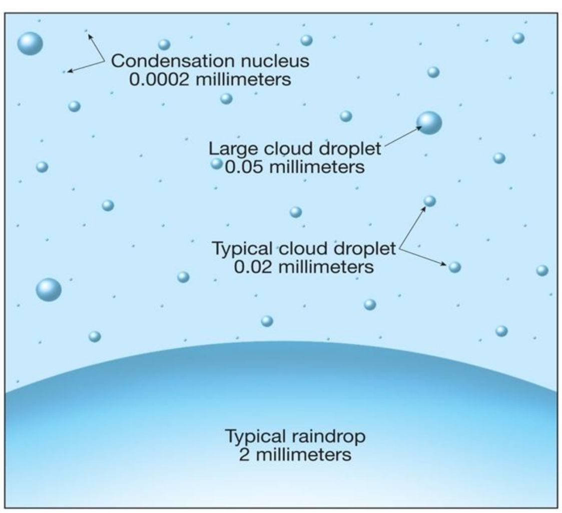
But this does not mean clouds will damp global warming! The impact of clouds on global warming depends on how the net cloud forcing changes as climate changes.

Cloud radiative effects depend on cloud distribution, height, and optical properties.

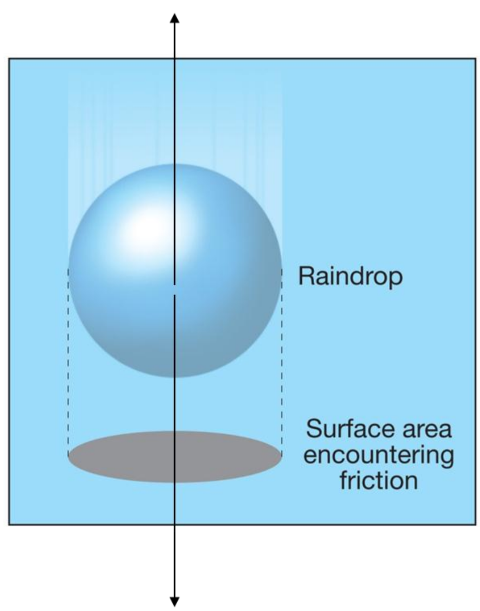
How precipitation forms

Frictional force = Gravitational force

Terminal velocity

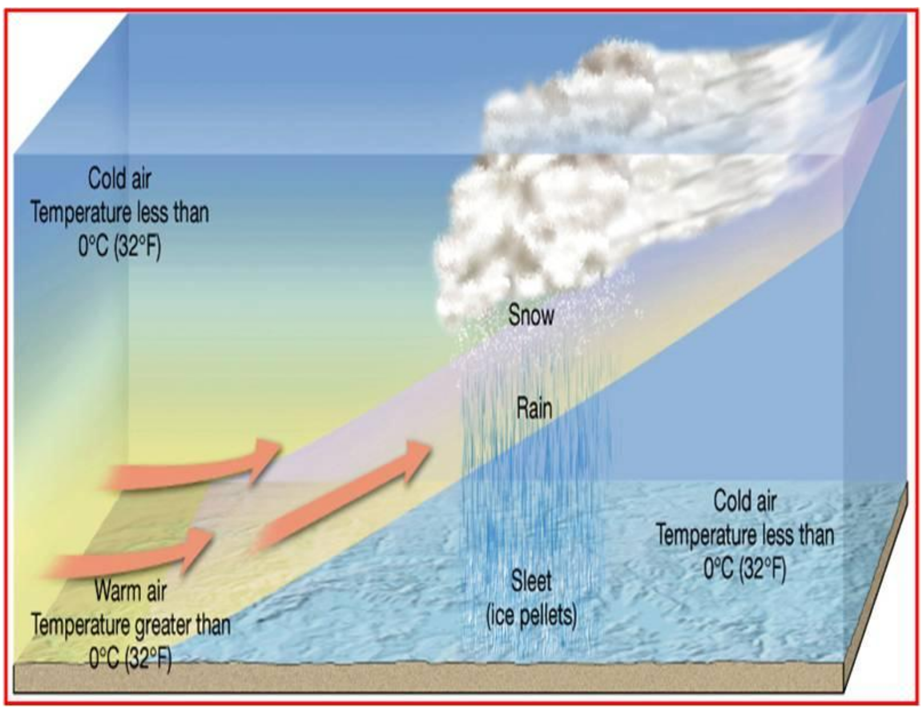


Frictional force



Gravitational force

- For precipitation to form, millions of cloud droplets must somehow coalesce into drops large enough to sustain themselves during their descent.
  The two mechanisms that have been proposed to explain this phenomenon are:
- the Bergeron process, which produces precipitation from cold clouds (or cold cloud tops) primarily in the middle latitudes, and
- The warm cloud process most associated with the tropics called the collision-coalescence process.
- The two most common and familiar forms of precipitation are:
  rain (drops of water that fall from a cloud and have a diameter of at least 0.5 millimeter) and
- Snow (precipitation in the form of ice crystals or, more often, aggregates of ice crystals).



Introduction

Pressure is defined as $p = \frac{F}{A}$ which would have the units of $\frac{kgm}{s^2 m^2}$.

A standard measure of pressure is a Pascal $Pa = 1 N/m^2$ where 100Pa = 1mb. We consider the follow conversions:

$$1\ atm = 1013.25mb = 760mm\ Hg = 29.92in\ Hg$$

Although pressure is an absolute quantity, everyday pressure measurements, such as for tire pressure, are usually made relative to ambient air pressure. In other cases measurements are made relative to a vacuum or to some other reference.
Measuring pressure can only be done when you compare it against another known pressure. This pressure is called the ***reference pressure***. Depending on what the reference pressure is, gives us three different categories:

Absolute pressure, gage pressure, and differential pressure

If a vessel were to be completely empty, containing no molecules, the pressure would be zero. When you are using this zero as the pressure reference point, the measurement mode is called ***absolute pressure*** because there is no lower pressure than the absence of all molecules. An example of something that is close to absolute zero pressure would be outer space, but even there, there are some molecules.

Note that it is impossible to go below zero when measuring in absolute pressure, so the concept of a negative absolute pressure is meaningless.

Absolute pressure: the absolute value of the force per-unit-area exerted on a surface by a fluid with respect to the absolute zero of pressure or a perfect vacuum

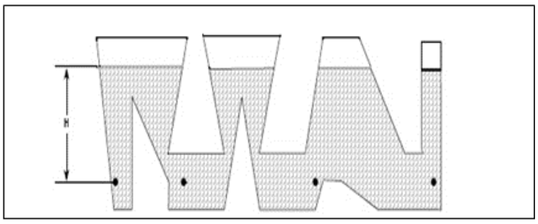
When using the atmospheric pressure as the reference point we call this mode ***gauge pressure***.

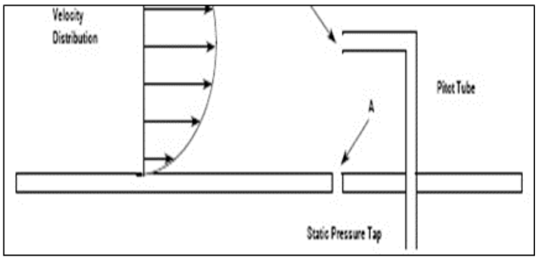
The classic example is a tire: on a typical tire the pressure is desired to be 30 psi (207 kPa) above atmospheric pressure. A gauge pressure of zero would mean a flat tire, even though there is technically still atmospheric air pressure in it (i.e.: a non-zero absolute pressure value). The difference between the absolute pressure and gauge pressure value is the variable value of atmospheric pressure:

gauge pressure = atmospheric pressure - Absolute pressure

Note that atmospheric pressure can vary depending on ambient temperature, altitude and local weather conditions.
In other applications, where knowledge of the pressure difference between two places or systems is needed, the reference pressure may not necessarily be either zero or atmospheric pressure but some other value. These are known as differential pressures.
For example, the flow of gas along a pipeline depends on the pressure difference between the ends of the pipe.
Differential pressure: the measurement of one unknown pressure with reference to another unknown pressure.

Two types of fluid systems	Static system: a system in which the fluid is at rest
	Dynamic system refers to the fluid that is moving





For a dynamic system:

- Steady-state systems are defined as no change in the system flow conditions: pressure, flow rate, etc.
- Transient systems are systems with changing conditions such as pressures, flow rates, etc.
- quasi-steady-state systems are systems in which the measure of the pressure has a faster response time than the rate of change in the system

STATIC PRESSURE SYSTEMS

- The pressure measured in a static system is static pressure.
- For a uniform static fluid, the pressure is the same at all points along the same horizontal plane in the fluid
- The pressure is dependent only on depth (increases with depth) and has nothing to do with the shape of the container. The increase in pressure at a deeper depth is essentially the effect of the weight of the fluid above that depth.

- In a static pressure system, the change of pressure with height can be described and computed by the hydrostatic balance.

Three different pressures in a dynamic system	**Static pressure:** Is the same as the static pressure that is measured in a static system, it is independent of the fluid movement or flow, and it acts equally in all directions.
	Dynamic pressure: This pressure term is associated with the velocity or the flow of the fluid.
	Total pressure: It is simply the static pressure plus the dynamic pressure.

Concepts about air pressure & Atmospheric pressure measurement

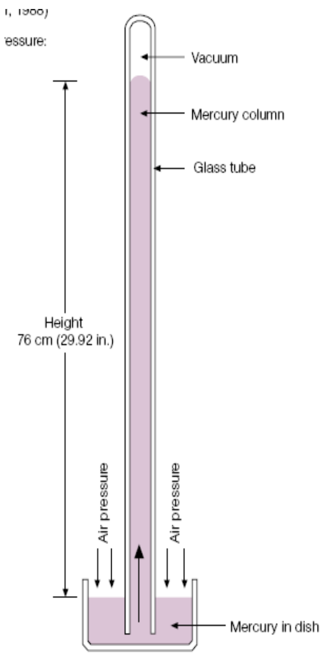
- Air pressure is simply the mass of air above a given level. Or as the force exerted by the air molecules over a given area.
- As we climb in elevation above the earth's surface, there are fewer air molecules above us; hence, atmospheric pressure always decreases with increasing height.
- The most of our atmosphere is crowded close to the earth's surface, which causes air pressure to decrease with height, rapidly at first, then more slowly at higher altitudes.
- But we should keep in mind some other important concepts, ex. air pressure, air density, and air temperature are all interrelated. If one of these variables changes, the other two usually change as well.
- The atmospheric pressure must be measured as absolute pressure,

$$1\ atm = 1013.25 mb = 760 mm\ Hg = 29.92 in\ Hg$$

- If the absolute pressure of a fluid stays constant, the gauge pressure of the same fluid will vary as atmospheric pressure changes.

Torricelli Barometer

- The mercury barometer was invented in 1643 by Torricolli (a student of Galileo's), and it was the first barometer.
- A glass tube enclosed at one side, and filled completely with mercury. Now all air was out of the tube. Locking the tube on the open side and turned the tube upside down in a reservoir filled with mercury. Now unlock the opening, a certain amount of mercury will still kept in the tube.
- This is caused by the air pressure on the surface of the mercury in the reservoir
- Pascal heard of this experiment, and his brother-in-law Fortin Prier and friends took a tube to a mountain top and found a decrease in pressure.
- Now we know that the change of pressure with height can be described by hydrostatic equation. So using



$$\frac{dp}{dz} = -\rho g \qquad\qquad P = \rho g h$$

- The hydrostatic balance can be applied to any fluids without motion.

Contra Barometer

- Developed in the late 1690's in Holland, using a u-shaped multiple tube to measure air pressure and used multiple types of liquids to display the air pressure.

- They were called "contra" as the mercury level, due to design, decreased in height with an increase in air pressure.

- It solved one of the major problems that the Toricelli barometer has: the degree of readability. It places a "multiplicator" onto the mercury tube. In the U-shaped instrument, colored alcohol was filled onto the mercury surface. All changes in the mercury column were transferred to the surface of the colored alcohol. The scale of the Toricelli became tenfold enlarged, and easy to read due to the colored fluid.

Fortin Barometer

Fortin barometers have been in use for over 100 years. Sometimes referred to as weather service barometers. They are probably the most accurate of all the barometer types. Fortin barometers have a zero setting device, which can be used to adjust the level of the mercury in the reservoir of the Fortin barometers. The main requirements of the place of exposure are uniform temperature, good light, solid and vertical mounting and protection against rough handling. Also great care should be taken when transporting a mercury barometer. All Fortin barometers are calibrated against standard instruments by complying with the recommendations of the WMO (World Meteorological Organization).

Eco-Celli Barometer

The Eco-celli contains no mercury. The U-shaped glass tube is filled with a red silicon-based fluid as well as a gas. The basic principle of Eco-Celli is based on the compressibility of gasses instead of the weight of liquid mercury. On the upper left-hand side of the barometer, one can see the gas reservoir above the red fluid tube. The gas provides a constant counter-pressure against the atmospheric pressure. Air pressure pushes down on the open side of the barometer tube onto the surface of the red fluid.

As atmospheric pressure increases, the gas in the barometer will be compressed and you will notice the red fluid level in the right hand portion of the barometer tube falling. When the air pressure decreases, the gas in the barometer will expand and the red fluid will rise in the right-hand portion of the barometer tube. A very important factor in measuring air pressure is the temperature.

High temperatures will cause fluids and gases to expand causing an error in the readout of the barometer scale. Eco-celli has solved this Problem by mounting a high precision thermometer parallel to the barometer tube. This thermometer has the same thermal expansion/compression rate as the barometer. With the help of a movable scale attached to both the barometer and thermometer tubes, you set the scale to the actual temperature (top of blue fluid level). The Eco-celli barometer is calibrated to sea level (0 feet).

Aneroid Barometer

An aneroid barometer uses a small, flexible metal box called an aneroid cell. This aneroid capsule (cell) is made from an alloy of beryllium and copper. The evacuated capsule (or usually more capsules) is prevented from collapsing by a strong spring. Small changes in external air pressure cause the cell to expand or contract. This expansion and contraction drives mechanical levers such that the tiny movements of the capsule are amplified and displayed on the face of the aneroid barometer. Many models include a manually set needle which is used to mark the current measurement so a change can be seen.

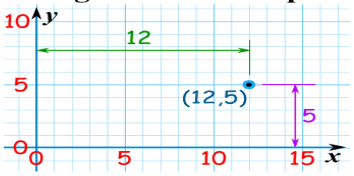
Barographs

A barograph, which records a graph of some atmospheric pressure, uses an aneroid barometer mechanism to move a needle on a smoked foil or to move a pen upon paper, both of which are attached to a drum moved by clockwork.

Introduction

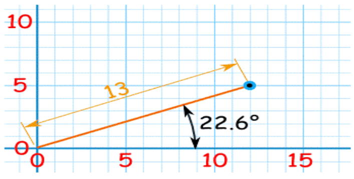
Cartesian Coordinates

Using Cartesian Coordinates we mark a point by **how far along** and **how far up** it is:



Polar Coordinates

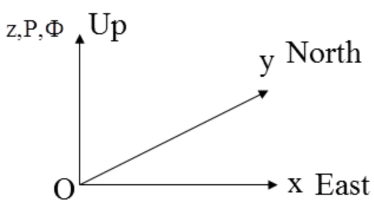
Using Polar Coordinates we mark a point by **how far away**, and **what angle** it is:

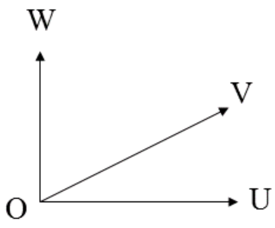


Wind Measurements

Wind measurements are usually taken in the *polar coordinate*, in which winds are written as two components: wind speed and direction.

Local right-hand Cartesian coordinate

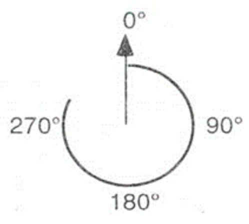




Polar coordinate

Winddirection α

Windspeed M



Conversion to speed and direction

$$M = (U^2 + V^2)^{1/2};$$

$$\alpha = 90^0 - \frac{360^0}{2\pi}\arctan(\frac{U}{V}), \qquad \text{if } V > 0.$$

$$\alpha = 90^0 - \frac{360^0}{2\pi}\arctan(\frac{U}{V}) + 180, \qquad \text{if } V < 0.$$

Conversion to U and V

$$U = M\cos(\alpha + 180)$$

$$V = M\sin(\alpha + 180)$$

Unites of wind speeds

m/s, mile/h, km/h, knot, …

$$1\frac{m}{s} = 1.943\ knot$$

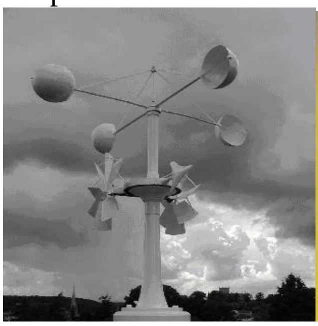
Wind sensors	1. dynamic force anemometers
Wind sensors have three classes of instruments:	2. pressure pulse frequency anemometers
	3. thermal anemometers

An instrument for measuring the wind speed is known as *anemometer*; the mechanical device turned by the wind to indicate the direction from which the wind is blowing is a *wind vane*.

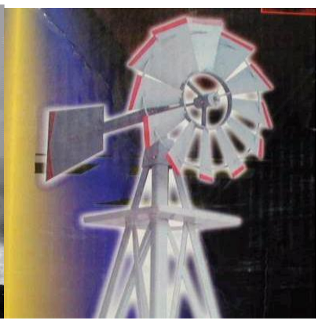
Dynamic force anemometers

The dynamic force anemometers consist of cup anemometers, vane windmill, and gill-type anemometers. The rotation rate is proportional to wind speed, which sometimes drives an electrical generator that gives voltage output which is proportional to the wind speed. The inertia of the sensor determines the threshold. Thus, the smaller and lighter of the sensor, the more sensitive it is.

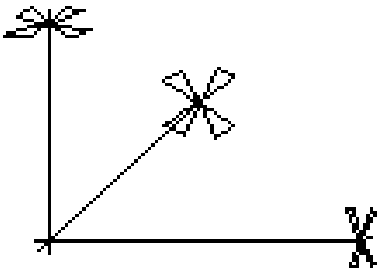
Cup anemometer



Vane windmill



Gill-type anemometer



Four Cup anemometer

It was invented (1846) by Dr. John Thomas Romney Robinson. It consisted of four hemispherical cups each mounted on one end of the four horizontal arms, which in turn were mounted at equal angles to each other on a vertical shaft. The air flow past the cups in any horizontal direction turned the cups in a manner that was proportional to the wind speed. Therefore, counting the turns of the cups over a set time period produced the average wind speed for a wide range of speeds.But he wrongly claimed that no matter how big the cups or how long the arms, the cups always move with one-third of the speed of the wind.

Anemometer factor :is the actual relationship between the speed of the wind and the speed of the cups. It depends on the dimensions of the cups and arms, and the relationship may vary for different anemometers.

Three Cup anemometer

Three cup anemometer was developed by the Canadian John Patterson in 1926, and subsequently improved by Brevoort & Joiner of the USA in 1935. Their work led to a cup wheel design. Patterson found that each cup produced maximum torque when it was at 45 degrees to the wind flow.
The three cup anemometer also has a more constant torque and responds more quickly to gusts than the four cup anemometer.

Wind direction:

- Australian Derek Weston added a tag to one cup, which causes the Cup wheel speed to increase and decrease as the tag moves alternately with and against the wind. Wind direction then can be calculated from these cyclical changes in cup wheel speed, while wind speed is as usual determined from the average cup wheel speed.
- The other way to determine wind direction for cup anemometer is to add a separate of wind vane for directional readings.

Windmill (propeller) anemometers

For windmill, the axis of rotation must be parallel to the direction of the wind and therefore horizontal compared to Robinson's anemometer.
Since the wind varies in direction and the axis has to follow its changes, a wind vane or some other device to fulfill the same purpose must be employed.
It combines a propeller and a tail on the same axis to obtain accurate and precise wind speed and direction.

Gill Propeller Anemometer

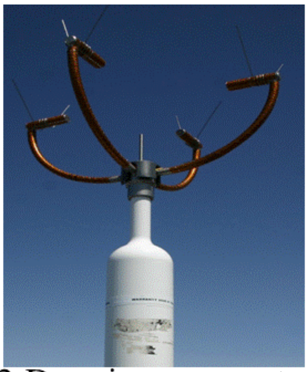
- Gill Propeller Anemometer utilizes a fast response helicoid propeller whose rotation is linearly proportional to air velocity.
- The propeller responds only to the component of the air flow which is parallel to its axis of rotation. For perpendicular air flow, the propeller does not rotate. Thus, using three parallels, one can measure 3-D winds.
- The standard expanded polystyrene(EPS) propeller offers maximum sensitivity at low wind speeds.
- Propeller response as a function of winds approximates the cosine curve, allowing true wind velocity and direction to be calculated.
- The propeller anemometer is especially suited for measuring the vertical wind component.

Pressure pulse frequency anemometers (sonic anemometer)

It measures the variation of speed of sound with wind. The device sends a synchronized sound pulse and measures the difference in time of sound.

$$\Delta t = \frac{2\ell u}{(c^2 - u^2)}$$

u is the velocity of the wind, is the distance, and c is the speed of sound.
The best way to get the wind direction is to measure the components in all three directions



2-D sonic anemometer

3-D sonic anemometer

- The spatial resolution is given by the path length between transducers, which is typically 10 to 20 cm
- Sonic anemometers can take measurements with very fine temporal resolution, 20 Hz or better, which make them well suited for turbulence measurements.

- The lack of moving parts makes them appropriate for long term use in exposed automated weather stations and weather buoys where the accuracy and reliability of traditional cup-and-vane anemometers is adversely affected by salty air or large amounts of dust.
- Their main disadvantage is the distortion of the flow itself by the structure supporting the transducers, which requires a correction based upon wind tunnel measurements to minimize the effect.
- 2-D (wind speed and wind direction) sonic anemometers are widely used in applications such as weather stations, ship navigation, wind turbines, aviation and weather buoys.
- Most sonic anemometer can also measure temperature.

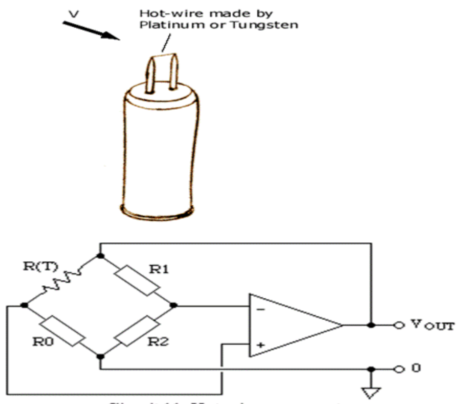
Thermal anemometers (hot wire anemometers)

- It uses a very fine wire (on the order of several micrometers) electrically heated up to some temperature above the ambient.
- Air flowing past the wire has a cooling effect on the wire. As the electrical resistance of most metals is dependent upon the temperature of the metal (tungsten is a popular choice for hot-wires), a relationship can be obtained between the resistance of the wire and the flow velocity.

Hot-wire devices can be classified as

1. CCA (Constant-Current Anemometer)
2. CVA (Constant-Voltage Anemometer)
3. CTA (Constant-Temperature Anemometer)

- The voltage output from these anemometers is thus the result of some sort of circuit within the device trying to maintain the specific variable constant (current, voltage or temperature)
- For example, in CTA mode, the current I through the sensor is related to the wind speed by King's law $I^2 = A + B\sqrt{V}$

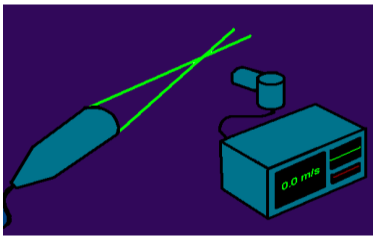


Circuit 11. Hot-wire anemometer

Hot-wire anemometers, while extremely delicate, have extremely high frequency-response and fine spatial resolution compared to other measurement methods, and as such are almost universally employed for the detailed study of turbulent flows, or any flow in which rapid velocity fluctuations are of interest.

Laser Doppler anemometers

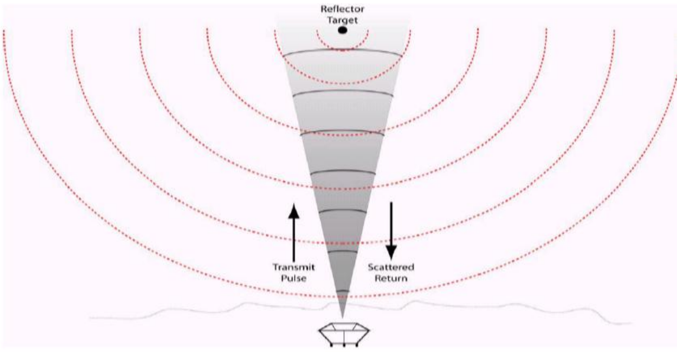
- Laser Doppler anemometers use a beam of light from a laser.
- Particulates flowing along with air molecules near where the beam exits reflect, or backscatter, the light back into a detector, where it is measured relative to the original laser beam.



- When the particles are in great motion, they produce a *Doppler shift* for measuring wind speed in the laser light, which is used to calculate the speed of the particles, and therefore the air around the anemometer.

Wind profilers

- A wind profiler is a type of sensitive Doppler radar that uses electromagnetic waves or sound waves (SODAR) to detect the wind speed and direction at various elevations above the ground, up to the troposphere (i.e., between 8 and 17 km above mean sea level).
- A wind profiler is designed to point (nearly) vertically and to respond to fluctuations of the refractive index of the (clear) air.
- The fluctuations of the refractive index are due to turbulence.
- They are so sensitive that they can translate the backscattered energy from these eddies into a vertical picture of wind speed and direction in a column of air.
- Wind Profilers detect minute fluctuations in atmospheric density, caused by the turbulent mixing of volumes of air with slightly different temperature and moisture content.



Scattering Mechanism

The emitted signal is also sensitive to:

- **Scattering from atmospheric targets:**

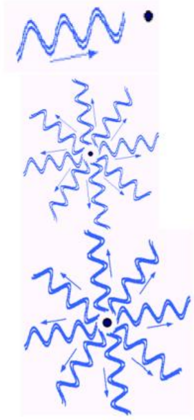
Irregularities in the refractive index of the air hydrometeors, particularly wet ones (rain, melting snow, water coated ice)

- **Scattering from Non-atmospheric targets:**

birds and insects (frequency dependent), smoke plumes

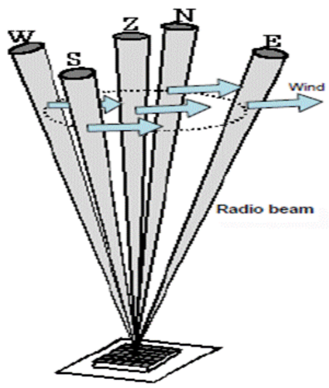
- **Interfering signals:**

Ground and sea clutter, Aircraft and migrating birds, RFI (depends on frequency band) [RFI: Radio Frequency Interference is generated from spikes/surges that usually come from - Lightning, man-made electrical equipment noise and various transmitting equipment].



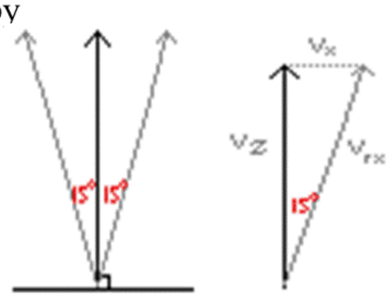
When a pulse encounters a target...It is scattered in all directions. Of interest is the signal component received back at the radar. This signal is typically much weaker than the original sent from the transmitter and is called the "return signal". The larger the target, the stronger the scattered signal.

The horizontal wind is measured by oblique beams in orthogonal directions (e.g. east and north). The beams are tilted 15 to 30 degrees from the zenith, and the Doppler shift of the echoes in each direction is compared to determine the wind speed and direction. This can be summarized as follows. A wind profiler operates on a simple 3 beam system: one pointing to the vertical, and two beams are tilted from the zenith, say 15 degree as illustrated by the figure below.



$$v_{rx} = v_x \sin(15^o) + v_z(\cos 15^o)$$

$$v_x = \frac{v_{rx} - v_z \cos(15^o)}{\sin(15^o)} \qquad v_y = \frac{v_{ry} - v_z \cos(15^o)}{\sin(15^o)}$$



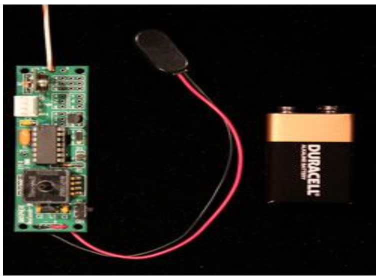
v_z, v_{rx}, *and* v_{ry} can be obtained from the vertical and tilted beams by determining the Doppler shift.

Introduction

A three-dimensional picture of temperature, pressure, relative humidity, and wind speed and direction in the atmosphere is essential for weather forecasting and meteorological research.

Radiosonde

- Radiosonde is a small, expendable instrument package that is suspended below a large balloon of natural or synthetic rubber filled with hydrogen or helium.
- It consists of sensors used to measure several meteorological parameters coupled to a radio transmitter and assembled in a lightweight box.
- The meteorological sensors sample the ambient temperature, relative humidity, and pressure of the air through which it rises.



- By tracking the position of the radiosonde, wind speed and direction aloft are also obtained, in which they are determined for each minute of the flight, generally 90 minutes.
- <u>The combined dynamic/thermodynamic observation is termed a rawinsonde observation.</u>
- The instrument package is attached to a parachute, and together, they are suspended from a balloon.
- It ascends at an approximate rate of 1000 feet/minute depending on weather conditions, amount of gas, and balloon size.

The ground-based Radiosonde Tracking System is housed in a fiberglass dome above the inflation shelter.

NWS Upper Air Inflation Building at Alabaster, AL

The altitude reached by **rawinsonde** varies for several reasons:

- ❖ bursting height of the balloon;

❖ faulty receiving equipment;
❖ atmospheric interference.

When the balloon reaches its elastic limit and bursts, the parachute slows the descent of the radiosonde, minimizing the danger to lives and properties. 600-gram balloon can rise approximately 90,000 feet. The bursting altitude for larger 1,200-gram balloon exceeds 100,000 feet. A flight is considered a failure and a second radiosonde is released if the balloon bursts before reaching the 400 mb level or if more than 6 minutes of data between surface and 400 mb are missing.

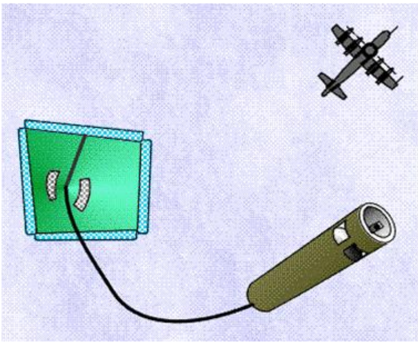
Worldwide, there are more than 900 upper-air observation stations using 15 major types of radiosondes. Most stations are located in the Northern Hemisphere and all observations are taken at the same times each day at 00:00 and 12:00 UTC, 365 days per year.

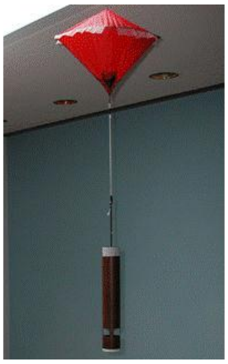
Importance of Radiosonde Data to Local Weather Prediction

Individual soundings help forecasters determine many local weather parameters including, atmospheric instability, freezing levels, wind shear, precipitate water, and icing potential. The following are examples of local weather phenomena that are predicted with the aid of sounding data:
Severe thunderstorms, Tornadoes, Microbursts, Flash floods, Ice storms, Aircraft icing conditions and turbulence, Cloud heights, Maximum temperature

GPS Dropsondes

Dropsonde is a weather reconnaissance device created by the National Center for Atmospheric Research (NCAR), designed to be dropped from an aircraft at altitude to accurately measure tropical storm conditions as the device falls to the ground. The dropsonde contains a GPS receiver, along with pressure, temperature, and humidity sensors to capture atmospheric profiles and thermodynamic data and winds.





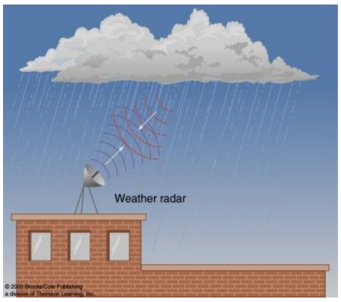
Driftsondes

It is a new type of observing system to track weather above hard-to-reach parts of the globe, as well as make soundings that will fill critical gaps in data coverage over oceanic and remote arctic and continental regions. These areas include (1) relatively void of in-situ measurements from radiosondes and commercial aircraft, such as the remote Pacific and Atlantic oceans, (2) covered with extensive cloud shields so that satellite measurements are limited. The across the ocean driftsonde flights will provide high resolution atmospheric profiles made by GPS dropsondes that would be difficult or impossible to obtain by deployment of aircraft alone.

Weather radar

Radar: RAdio Detection And Ranging. It was only in 1941 that radar was first used for intentionally looking at precipitation.

Radars in Meteorology



1. EM waves that fall into the microwave (1 mm < λ < 75 cm)
2. Active remote sensing technique.

What observations that a radar can give us?

- Precipitation measurements
- Wind measurements
  - Negative (heading towards the radar)
  - Positive (heading away from the radar)
- Turbulence and wind shear detection
- Severe storm nowcasting
- Hail detection
- Location of melting level in stratiform precipitation
- Mesocyclone detection
- Hurricane structure

Three fundamental properties of the emitted beam:

- pulse repetition frequency (PRF),
- transmission time,
- Beam width.
-

A radar usually emits a pulse for 0.000003 seconds then listen for 0.003 seconds (remember it goes through this transmit/receive cycle about 325 times every second!). So, 99.9% of the time, the radar is receiving, and 0.1% of the time, it's transmitting.

Attenuation

Particles will attenuate the energy in two ways: scattering and absorption, collectively known as *attenuation* Particles: raindrop, hail, snow, graupel, insects,…..

Attenuation may cause a void in reflectivity directly behind a heavy thunderstorm