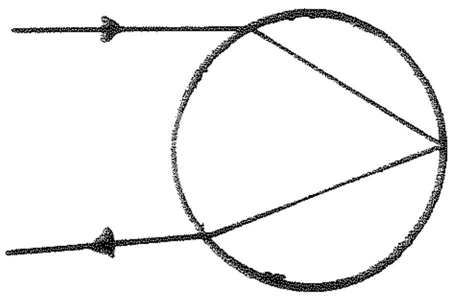
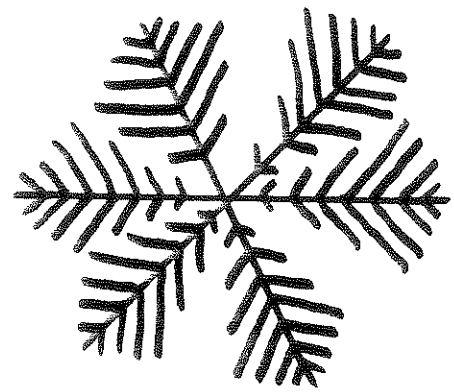
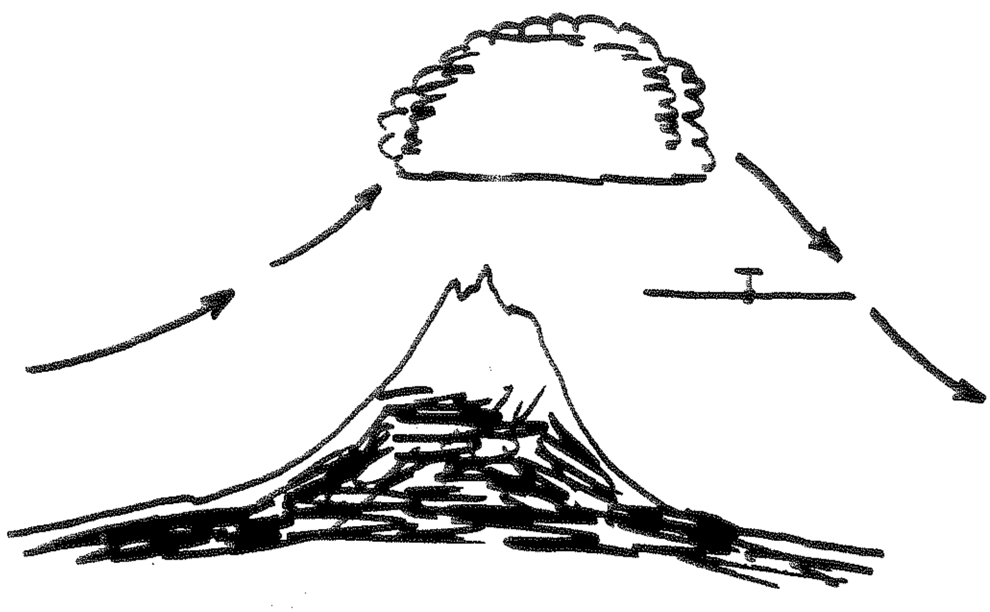
ATMOSPHERIC PHYSICS DEMONSTRATIONS







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Contents

References

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Concepts
1. diffraction
2. interference

THE CORONA

Introduction

The corona is an atmospheric phenomena observed in the atmosphere when looking at either the sun or moon when they are obscured by thin clouds. The corona appears as a series of colored rings surrounding the light source. The diameter of the outermost ring is normally equal to or less than ten degrees. The center of the corona is called the aureole and will generally have a bluish color which merges into a yellowish region which in turn becomes brownish on the outermost edge. Beyond the aureole will be a series of colored rings with the inner edges blue and the outer edges red.

Theory

The corona is formed by the diffraction of light by either water drops or ice crystals in the atmosphere. The light waves arrive at the water drops from the sun or moon as shown in Fig 1. The water droplet acts as an obstacle to the propagation of the waves and according to Huygen's principle, a series of "new" spherical wave fronts will be generated at either side of the water drop. The wave departing point A will arrive at O at the same time that the wave from B arrives at point O. However, because the wave from B had had to travel one half wavelength further, the two waves will be out of place and cancel each other out. This causes the dark region in the corona. The same argument allows us to observe a point P, where the two waves arrive in phase and constructive interference occurs. This results in the brightness observed in the corona rings. The color separation occurs because the wavelengths of the various color are different, and therefore the maximums of intensity for each color will occur at

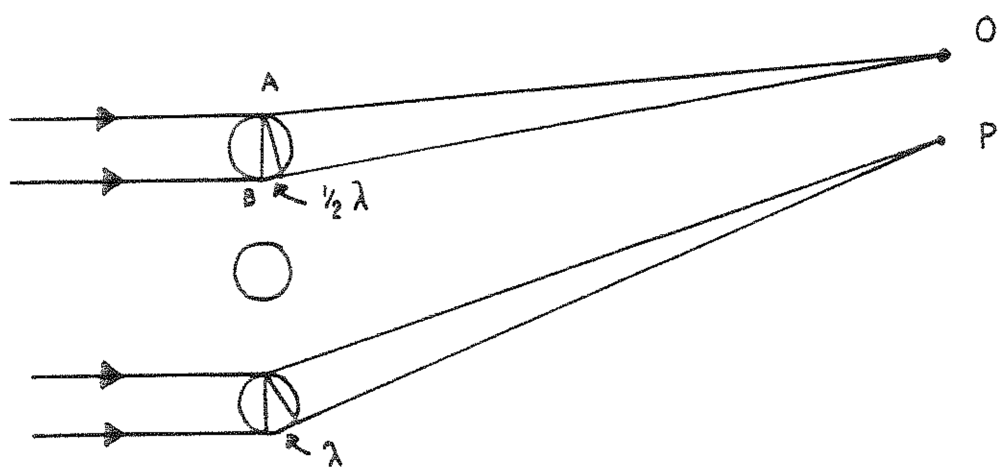


Fig 1. Diffraction by cloud droplets producing corona

different positions. An interesting correlation exists between the size of the corona rings and the cloud drops producing the interference patterns. This relationship is given by

$$\sin \phi = (n + 0.22) \frac{\lambda}{a}$$

where ϕ is the position of the nth minimum of light of wavelength λ. The diameter of the same cloud drop is a. This relationship, however, assumes a uniform distribution of drop size and monochromatic light. Therefore, it should only be used as an approximation in determining the size of the cloud drops producing the observed corona.

Apparatus

1. collimated light source

2. glass plate covered with lycopodium powder
   (this has been prepared and should be available from the technicians)
3. ring stands to hold glass plate and light source

Procedure

1. Set up the glass plate approximately 1 to 1½ meters from the light source. Orient the plate so that it is perpendicular to the incident light source and have the light strike the plate in the middle of the plate.

2. View the corona from a position 10-20 cm beyond the plate looking towards the light source.

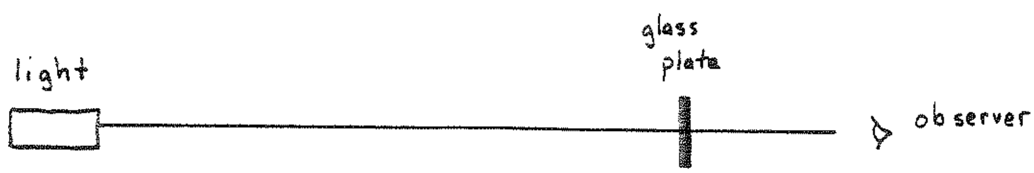


Fig 2. Apparatus arrangement for the corona

THE HALOE

Introduction

The haloe is an atmospheric optical phenomena that is observed as a bright ring around either the sun or the moon. The latter situation is perhaps more frequently observed, but only because the atmospheric conditions necessary for the formation of the haloe are better observed at night. The haloe is often times accompanied by mock suns, better known as "sun dogs" or technically as "prehelia." These occur at approximately 22° either side of and even with the sun.

Theory

The haloe is formed by the refraction of light passing through a thin cloud composing of ice crystals. This condition will usually prevail if the air temperature is below -20°C. The geometric optical explanation of the haloe phenomena makes three basic assumptions:

(1) The cloud is composed of ice crystals with a hexagonal cross section, and have all linear dimensions large compared to the wavelength of light.

(2) When falling through the atmosphere, the crystals align themselves with their longest axis parallel to the ground.

(3) The ice crystals are continuously spinning around their longest axis while falling.

When light from the sun or moon passes through the ice crystal its path will be deviated and it will be dispersed into separate wave lengths because of the difference in density between the air and the ice crystal. According to the theory of geometric optics there will be some angle of minimum deviation at which maximum light intensity will occur. It is at this angle of deviation that the haloe will be observed in the atmosphere. The angle of minimum deviation D is related to the prism angle of the crystal A and the index of refraction m by

$$\sin \frac{D+A}{2} = m \sin \frac{A}{2}$$

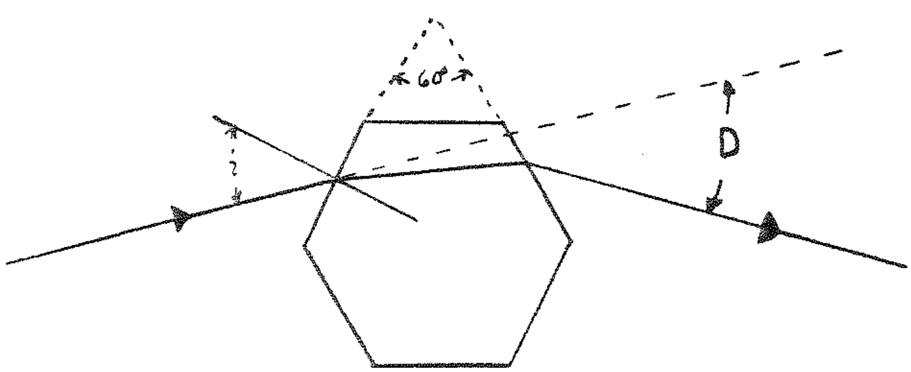


Fig 1. Deviation angle for 22° haloe.

For a crystal orientation of 60°, the haloe will occur at an angle of approximately 22° from the sun and for an orientation of 90°, the haloe is observed at an angle of about 46°. For the prism angle of 120° no real minimum deviation angle exists.

The hexagonal ice crystal will deviate blue light the most and red light the least. This will cause the observer to view red color nearest the sun and blue light further away. This is due the observer viewing a phenomena produced by many ice crystals. (The laboratory demo uses one crystal and will have the color scheme reversed). Fig 2 shows the two possible orientation of the hexagonal ice crystal in the atmosphere.

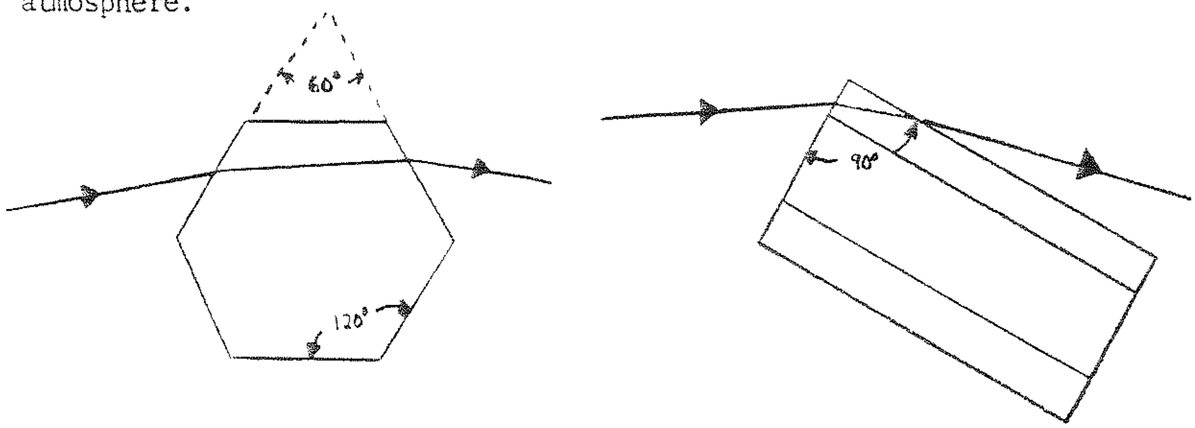


Fig 2. Possible crystal orientations for 22° and 46° haloes.

Fig 3 shows why the observer in the atmosphere observes red nearest the light source and blue on the outside of haloe.

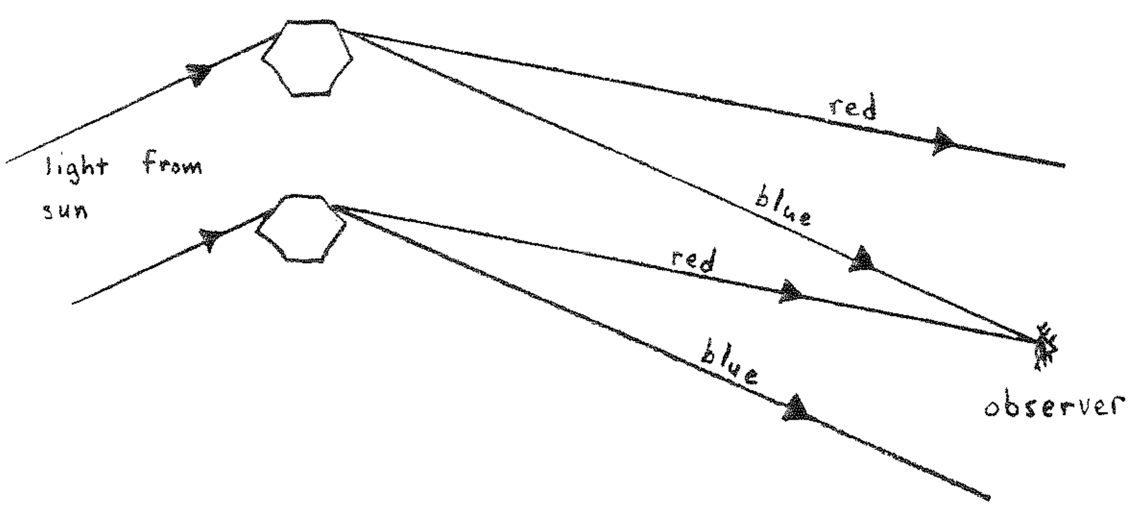


Fig 3. Observer's view of 22° haloe.

Apparatus

1. collimated light source

2. "plexiglass" ice crystals (available from technicians, one for $A = 60^{\circ}$ and one of $A = 90^{\circ}$).

3. translucent ground glass screen (onto which dispersed light is projected).

4. ring stand to hold ground glass.

5. jack stand to hold prism.

Procedure

1. Position the light source approximately one meter from the jack stand on which the prism is resting. Turn on the light source and adjust the position of the light beam so that it strikes the side of the crystal (see fig 4).

2. Position the ground glass screen approximately 1.0 meters behind the crystal (on the opposite side from the light source), and about 22° degrees off the center line of an imaginary line connecting the light source and the crystal.

3. Slowly rotate the crystal first clockwise and then counterclockwise until the greatest angle of deviation (away from the center line) occurs. This will be the point at which maximum intensity of light occurs.

4. Stand behind the ground glass screen and look toward the prism. The color of the haloe will be observed projected onto the screen. Note that the colors as observed on the screen are reversed from those observed in the atmosphere (as explained in the theory).

5. For the 46° degree haloe repeat the above steps only use the 90° prism and initially position the ground glass screen approximately 46° off the center line.

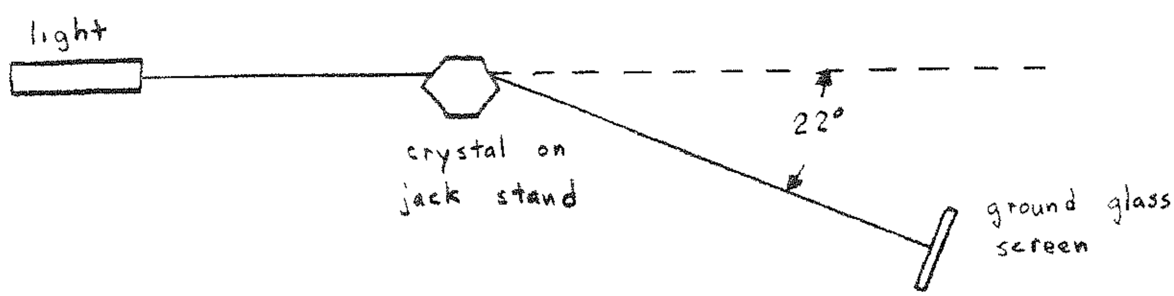


Fig 4. Apparatus arrangement for 22° haloe.

THE RAINBOW

Introduction

The most commonly observed and certainly most mythical of all atmospheric phenomena is the rainbow. The rainbow is most commonly observed when the sun is behind the observer and he is observing rain actually falling from a cloud. The bow appears as an arc of a circle, the center of which is the "anti-solar point," which lies on a line from the sun passing through the eye of the observer. The colors of the primary rainbow are observed in the following sequence, red on the outside and violet on the inside. Inside of the primary bow will on occasion appear a series of bows of fainter colors, known as supernummary bows. Almost as frequently observed is the secondary rainbow which appears outside of the primary bow. The sequence of color on the secondary bow is reversed with violet on the outside and red on the inside.

Theory

There are several different possible explanations to the formation of the various rainbow phenomena. The most commonly presented theory was developed by Descartes in 1637 and utilizes the concept of geometric optics. A more detailed analysis of the phenomena must also consider the wave nature of light. The theory outlined here will consider the geometric optics approach with only basic reference to the wave theory.

Consider a light ray from the sun entering a spherical rain drop which is falling through the atmosphere. Of all the possible angles of orientation for the above situation, there will occur a geometric combination of angles which produces, emergent from the rain drop, a light ray undergoing an angle of minimum deviation. This combination of events is what produces the greatest intensity of observable light, and therefore, is responsible for producing the commonly observed primary and secondary rainbows.

The primary rainbow is produced when the light ray enters the top of the raindrop and is initially refracted, then totally reflected internally off the back of the drop, and finally refracted a second time on emerging from the drop at the bottom. Fig 1 shows the path of the light ray through the drop. Because violet light is refracted more than red light, an observer

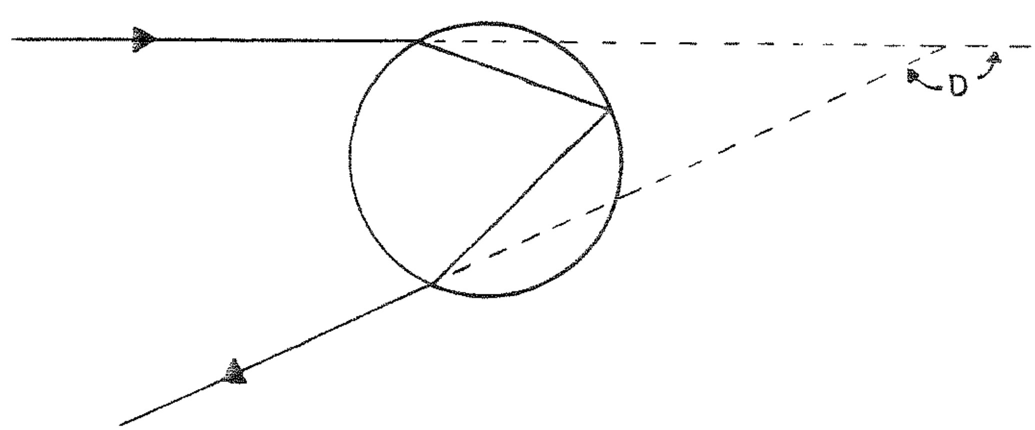


Fig 1. Primary bow ray trace

viewing a primary rainbow will see the red light coming from drops higher in the atmosphere than the drops producing the violet colors (see fig 2). In the laboratory demonstration, the observer will be viewing only one drop and will therefore see the colors reversed.

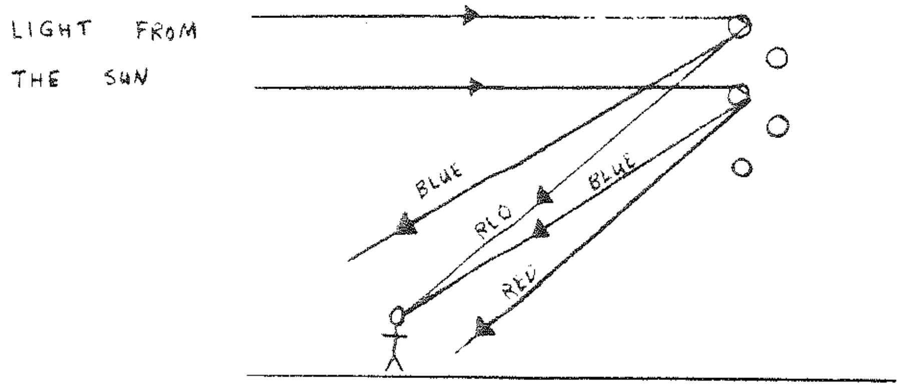


Fig 2. Observer's view of the primary rainbow.

The secondary rainbow is produced when the light ray enters a falling raindrop at the bottom. In this case the ray is refracted, than totally reflected twice inside the drop, before being refracted a second time upon leaving the drop. Once again because red light is refracted less than violet light, the observer on the ground will see the red on the inside of the secondary bow and the violet on the outside of the bow. In the laboratory demonstration, the observer will be viewing only one drop and will therefore see the colors reversed.

The tertiary bow occurs when a light ray is reflected three times inside the raindrop. This rainbow is seldom observed because the observer must look into the sun to see the bow.

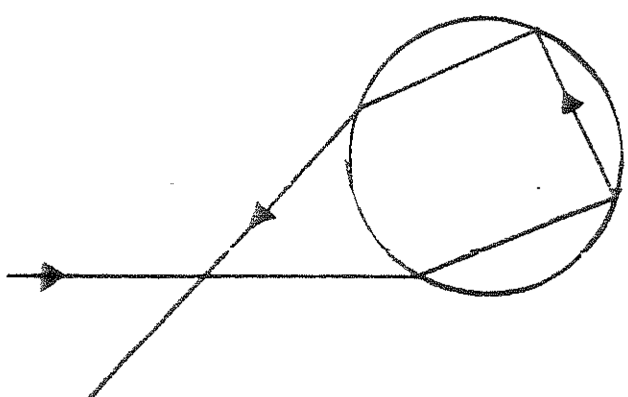


Fig 3. Secondary bow ray trace.

Often times inside of the primary bow will be observed a series of faint bows of various colors. These are called supernummary bows and are produced by the interference of light. As the light ray leaves the raindrop, according to Huygen's principle, it spreads out in a series of wave fronts. Because there are many raindrops, there will be many wave fronts. The result is that there will be lines of constructive and destructive interference produced. These will appear as bands of light inside of the primary bow.

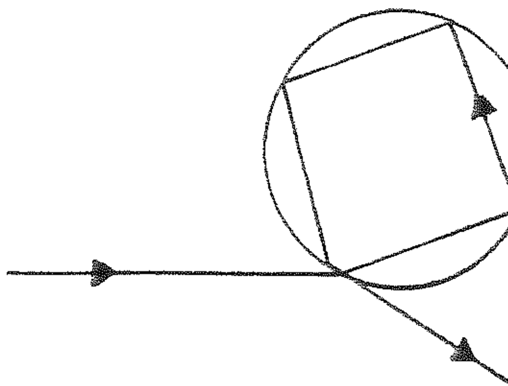


Fig 4. Tertiary bow ray trace.

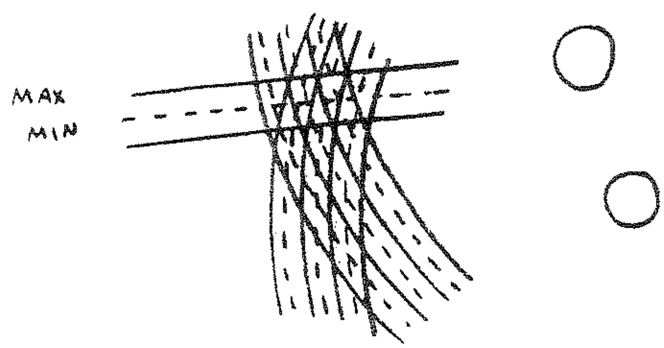


Fig 5. Supernummary bows

Apparatus

1. Two 1000 ml flasks with stoppers

2. Two light source

3. Two right stands to hold flasks

4. Two fork type clamps to hold flasks

5. Ground glass screen

Procedure (Primary bow)

1. Fill the flasks with water and reset the stoppers. Then fasten the fork clamps to the ring stands. Clamp the fork around the neck of the flasks and securely fasten. Be careful to position the clamp base and the flask so that the flask doesn't tip over.

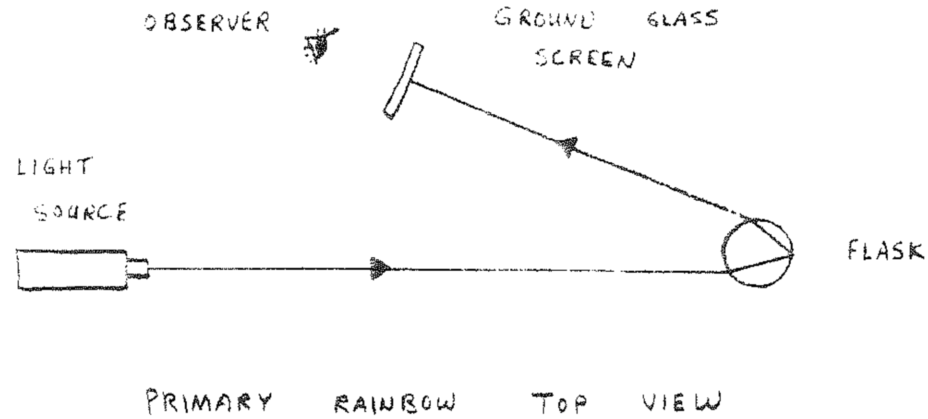
2. Take the light source and focus a narrow beam of light onto one side of the flask. Carefully move the flask and the light source so that the beam is refracted to the back of the flask. The beam will now be reflected off the back and will emerge on the opposite side of the flask as it entered. (See fig 6.)

3. Position the ground glass screen approximately one meter away from the drop in line with the emerging beam. The color of the rainbow will be observed on the screen. Note that the colors are reversed from those seen in a primary rainbow.

(Secondary bow)

1. Repeat step #1. (if not already accomplished).

2. This time you want to project the light beam on the opoosite side of the flask. The beam needs to enter at a very small angle. Adjust both the beam and the flask till you get two internal reflections before the beam emerges. (See fig. 6.)



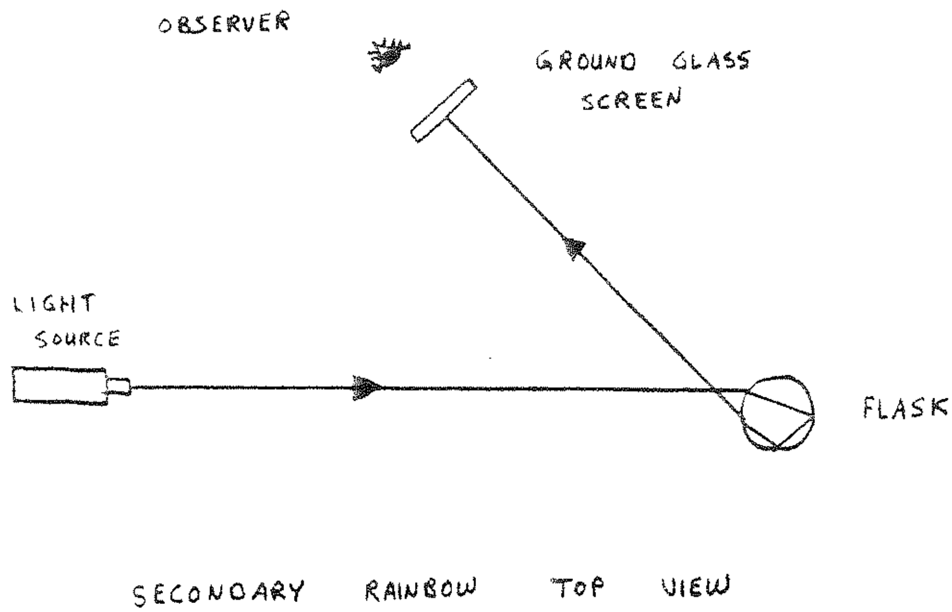


Fig 6. Apparatus arrangement for primary and secondary rainbow

Concepts
1. index of refraction
2. speed of light

THE INFERIOR MIRAGE

Introduction

The inferior mirage is an atmospheric optical phenomena most often observed in the desert or over a long straight stretch of highway. In the latter case, the roadway ahead of the observer appears to have "water" on it. As the observer gets closer to the "water" it always disappears. There are several different kinds of mirages that can occur in the atmosphere, but the inferior mirage is probably the most common. When viewing the inferior mirage of an object, the observer will see the object in one position on the horizon, and a second inverted image of the object below the horizon. The person who sees water on the highway is actually seeing an inverted image of the sky below the horixon. The blueish color of the sky accounts for the image appearing as water.

Theory

The inferior mirage occurs when a layer of air near the surface of the earth is heated by being in contact with a surface on the earth which has been heated by the sun (e.g. asphalt highway). The air in contact with the hot surface expands and becomes less dense. This reduces its index of refraction and in turn allows a light ray passing through it to travel from a device medium (cool air) to a less dense medium (warm air) refraction or bending of the light ray will occur. Consider the wave fronts leaving the object at point S in Fig 1. Ray 1 which passes above the warm air arrives at the observer at point A. The observer looking back along the ray perceives it as coming from S. Ray 2 leaves point S and is initially traveling away from the observer. It enters the less dense medium (or hot air) and its velocity increases and the light ray bends toward the observer. The wave front is therefore bent upward and the observer perceives the image of the object to come from S′. This bending upward explains why the inverted image appears below the horizon.

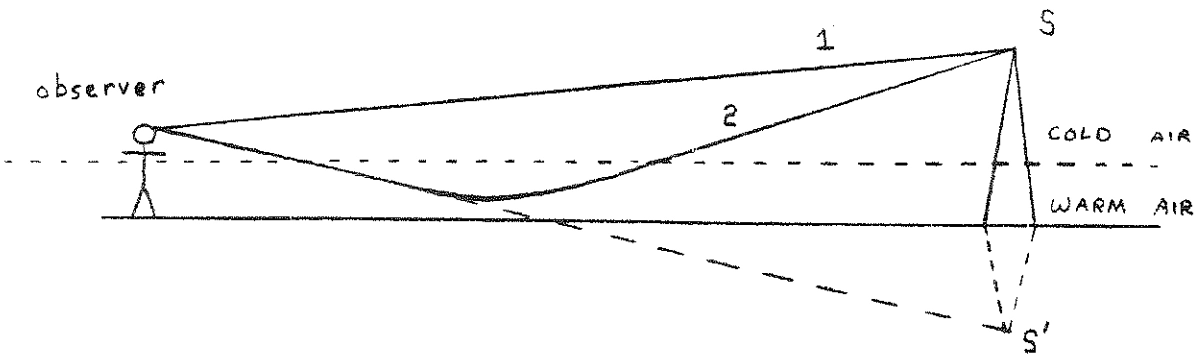


Fig. 1. Inferior mirage

Apparatus

1. slide projector to serve as light source
2. hot plate (available in 206) set on approximately 500
3. empty SPRITE bottle

Procedure

1. Plug in the hot plate, set it at approximately 500 and allow 5-10 minutes for warm up.

2. Position the slide projector one meter behind the hot plate pointer toward a screen or wall. Turn on the projector and adjust the focus (and zoom lens if it has one) so that a shadow of the hot plate appears on the wall. Allow enough projector light to pass above the hot plate so that you have an image as shown in Fig 2. After a few minutes you will begin to see a shimmering effect as the air above the hot plate warms up. This effect is often observed in the atmosphere as "heat waves."

3. Take the sprite bottle and holding it upright, slowly lower it into the path of the projector light between the projector and the hot plate. The sprite bottle will cause a colored shadow to appear on the wall above the shadow of the hot plate. This is shown in Fig 3.

4. Lower the sprite bottle slowly until you begin to see an inverted image of the sprite appear to be coming up out of the shadow of the hot plate. This image is the inferior mirage, and is caused by light rays being bent up toward the wall by the hot air above the hot plate. This situation is shown in Fig 4.

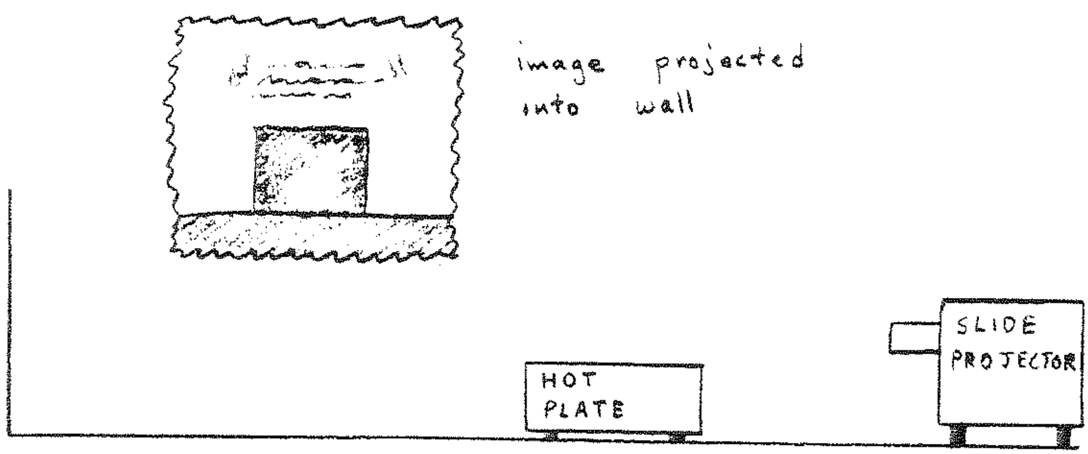


Fig. 2. Apparatus arrangement for inferior mirage

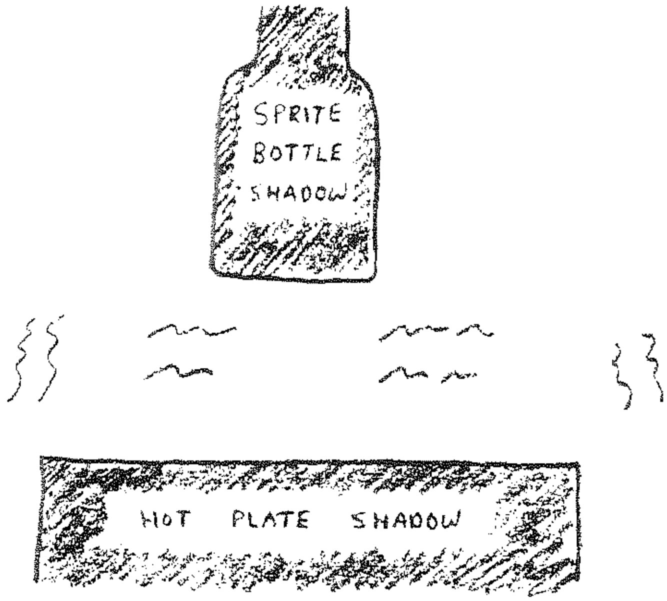


Fig. 3. Sprite bottle shadow.

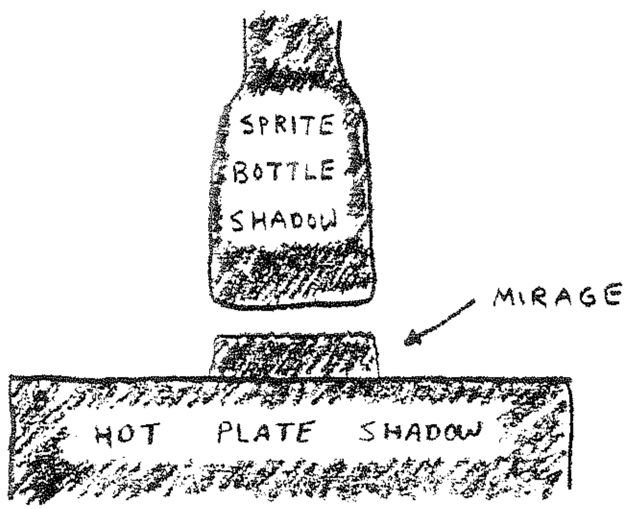


Fig. 4. Sprite bottle shadow with mirage image.

SETTING SUN

Concepts

1. Rayleigh scattering
2. Mie scattering

Introduction

Scattering is responsible for many of the events we commonly observe in the atmosphere. The blue color of the sky, the purplish haze of distant mountains, and the blue color of smoke are some of the common events due to scattering.

Theory

A complete discussion of scattering must consider in rigorous mathematical detail the wave value of light. However, a first approximation of the physics involved can be gained conceptually by examining two basic types of scattering, Rayleigh and Mie.

Rayleigh scattering occurs when the white light from the sun is scattered by particles in the atmosphere which are very much smaller than the wave lengths of light which are being scattered. Since the intensity of Rayleigh scattering is inversely proportional to the fourth power of the wavelength of light scattered ($I = 1/\lambda$), the shorter wavelength of light (blues) will be scattered more than will be the longer visible wavelength (reds). Fig 1 shows Rayleigh scattering occuring. The scattering will occur about equally in all directions.

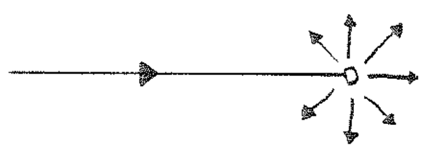


Fig 1. Rayleigh scattering

The blue color of the sky can be attributed to Rayleigh scattering of sun light by the air molecules in the atmosphere. Should larger particulate matter be present in the atmosphere, such as dust, smoke, etc., the large wavelength of light will be scattered and the apparent color of the atmosphere will change. The scattering of blue light by the atmospheric gasses also explain why mountains (or other objects) viewed at a distance appear to have a bluish haze. The air molecules between the observer and the object viewed, will scatter blue light in the direction of the observer. Fig 2 shows this effect.

Fig 2. Bluish haze of distant mountains

As the scattering particles become larger, all wavelength of light are scattered about equally, but now mostly at small angles. This is called Mie scattering and is shown in Fig 3.

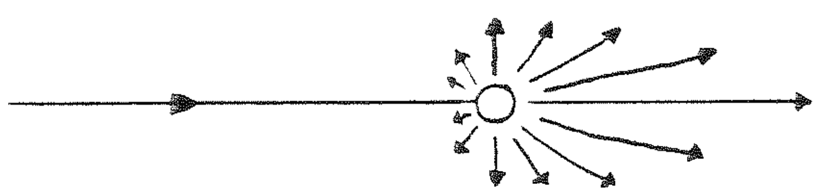


Fig 3. Mie scattering

The setting sun will often appear very red or orange if there is a large amount of particulate matter in the atmosphere. At sunset, the path length of the sun rays is much longer through the atmosphere than earlier in the day. The result is that much more light is scattered out and only the longer wavelengths (orange, red) reach the observer. In the winter time when the atmosphere is often times clear of large amounts of particulate matter, the setting (or rising sun) will appear very bright and almost white. This is because very little scattering occurs.

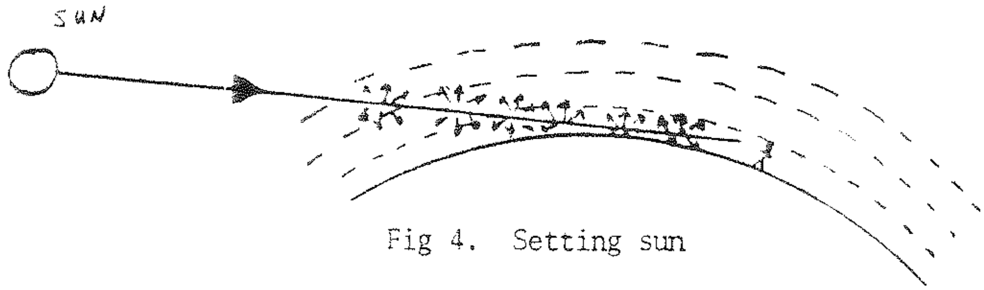


Fig 4. Setting sun

Apparatus

1. one rectangular aquarium, 2 gallon capacity.
2. light source
3. screen (can be white piece of cardboard or wall)
4. 12 oz of hypo solution (can be obtained from chemistry prep room) or 6 grams sodium thiosulfate.
5. 50 ml of concentrated sulfuric acid.

Procedure

1. Fill the aquarium with clear water.
2. Turn on the light source and project a beam through the aquarium and onto the screen. The color of the projected beam (simulating the sun) should be very light yellow to nearly white.
3. Pour into the tank approximately two grams of the sodium thiosulfate, (or 4 oz of hypo), and throughly mix the solution in the water. The water now simulates the day time sky when the sun is overhead. The projected light beam will be more yellowish, but there will be blue light scattered out the sides of the aquarium.
4. Add several drops of concentrated sulfuric acid and throughly mix the solution. After a minute or two, the sulfur will begin to precipitate out of solution, and the size of the particle will grow. Eventually the only light getting through the tank will be the longer wavelengths. This will cause a reddish orange image to be projected onto the screen. This is analogous to the setting sun light passing through many layers of dust, haze, smoke, etc., in the atmosphere, and all but the longest wavelength of light being scattered out.

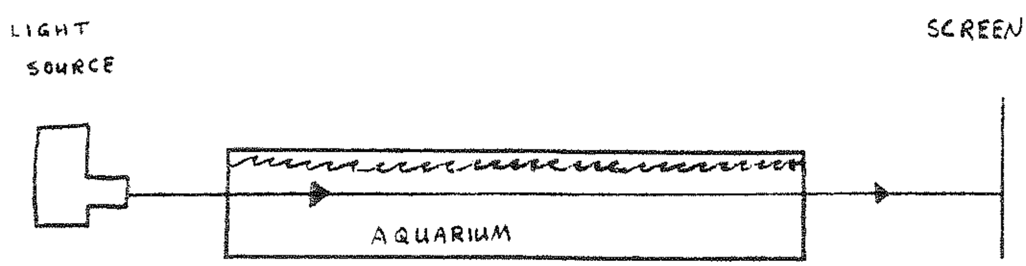


Fig 5. Apparatus arrangement for setting sun

SCATTERING

Concepts

1. Rayleigh scattering
2. Mie scattering

Introduction

One of the many physical processes light can undergo in the atmosphere is scattering. There are two basic types. Rayleigh and Mie. The basic differences between the two types can be demonstrated by using a cigar.

Theory

A basic discussion of scattering is given in the theory section of the "setting sun" demonstration, and therefore will not be repeated here.

Rayleigh scattering is done by very small particles, and will scatter the shorter wavelengths of visible light the most. The smoke coming off of a lighted cigar is composed of extremely small particles which will scatter the blue light waves the most. This is called Rayleigh scattering and explains why the smoke has a bluish color.

After the smoker inhales this cigar smoke, and then exhales the smoke, the color of the smoke has changed to a dull white. This is because the smoke particles, while in the smoker's mouth, picked up moisture and grew in size. The size of the exhaled smoke particles now approaches the size of the wavelength of the scattered light. This causes all wavelengths of light to be scattered approximately equally and therefore produces the dull white smoke. This type of scattering is known as Mie scattering.

Apparatus

1. cigar or cigarette
2. matches or cigarette lighter
3. one human smoker

Procedure

1. Light up the cigar (cigarette) and allow the smoke to rise up into the air. Observe the bluish color due to Rayleigh scattering.
2. Inhale the cigar smoke (carefully) and momentarily hold the smoke in your mouth.
3. Exhale the smoke and observe the dull white color of the smoke due to Mie scattering.
4. Extinguish the cigar (cigarette) when completed.

CONCEPTS

1. Work
2. Phase Change
3.

THE CLOUD CHAMBER

Introduction

Few things affect the activities of man more than does the weather. One of the things people always associate with the weather are the clouds. In fact the layman in observing the sky will most often judge the next day's weather by the appearance of the clouds in the sky. However, few people really understand how clouds are formed.

Theory

The formation of clouds can be explained by examining a unit volume of air, commonly called an air parcel. Consider that the parcel contains a certain amount of water in the vapor state. This vapor, at the same temperature as the air parcel, will exert a vapor pressure e, due to the thermal activity of the water molecules.

The first condition for the formation of a cloud is for the air parcel to be lifted upward in the atmosphere. This lifting is most often accomplished by one of three mechanism: (1) frontal activity, (2) thermal heating or (3) orographic lifting. Fig 7 shows the three lifting mechanisms in the atmosphere.

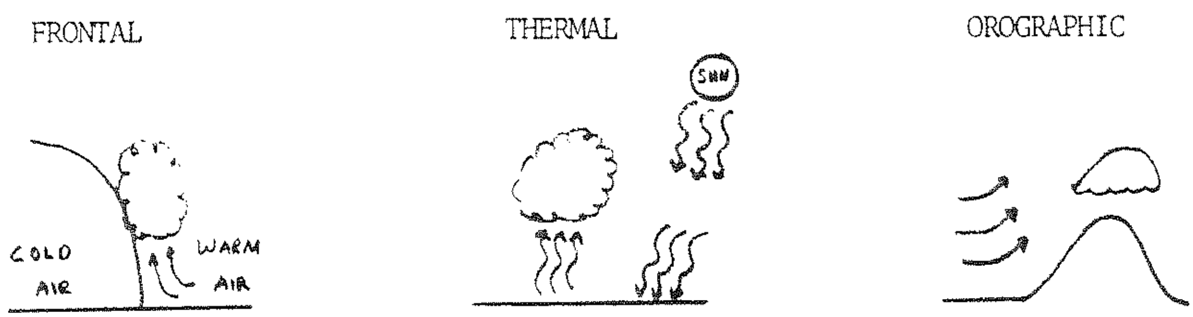


Fig 1. Atmospheric lifting mechanisms

The effect of all three kinds of lifting is basically the same. As the air parcel is lifted, the atmospheric pressure surrounding the parcel decreases and the air parcel expands. In order for the air panel to expand, it must do work. This work PdV (where P is pressure and V is volume) requires energy, which comes from the thermal energy of the air and water molecules inside the air parcel. ($1/2\ MV^2 = 3/2\ kT$). The net result is that the air parcel decreases in temperature as it rises in the atmosphere. Initially, this rate of temperature change, known as the lapse rate, is approximately 10^{o}C per kilometer. The process is basically adiabatic (no heat added to or taken away from the panel).

As the parcel continues to rise, expand and cool off, its ability to contain water in the vapor state decreases. Eventually, the parcel reaches an altitude at which the air parcel can not hold any more water in the vapor state. The air parcel is now saturated with water vapor, and the parcel is considered to be saturated. The vapor pressure, inside the parcel is known as the saturation vapor pressure, and the condition is also known as a relative humidity of 100%. This altitude is sometimes called the lifting condensation level and is observed to be the cloud base.

When the parcel reaches saturation, the water vapor will undergo a phase change if there are present in the air parcel small particles onto which the water vapor can condense. These tiny particles are called condensation nuclei, and range in size from approximately 10^{-9}m to 10^{-5}m. If the nuclei are present, when the air parcel becomes saturated, the phase change occurs and there will appear in the air parcel tiny cloud droplets of water in the liquid state. As the phase change occurs latent heat of condensation is released and the energy goes into the air parcel. The air parcel will slightly increase in temperature and therefore be slightly less dense than its environment. The result is that the air parcel is buoyant and will once again rise in the atmosphere. This causes the discussed processes of condensation and cooling to continue and the cloud continues to grow.

Apparatus

1. cloud chamber with hand air pump (this can be obtained from the technicians).

2. light source (can be slide projector or other similar strong light source).

Procedure

1. Arrange the chamber (with a small amount of water in it) and the light as shown in fig 2. It is best to have the len's between the chamber and the light parallel to the front of your audience.

2. Use the hand pump to increase the pressure inside the chamber.

3. Suddenly pull the cork out of the top of the chamber to generate a rapid decompression.

4. Observe the cloud that forms inside the chamber after the rapid decompression. The results can best be viewed with the lights in the room dimmed.

5. The demonstration can be repeated after a lightened match is first placed in the chamber before pumping up the pressure. The smoke from the match introduces a large concentration of condensation nuclei into the chamber, which in turn produces a larger concentration of cloud droplets.

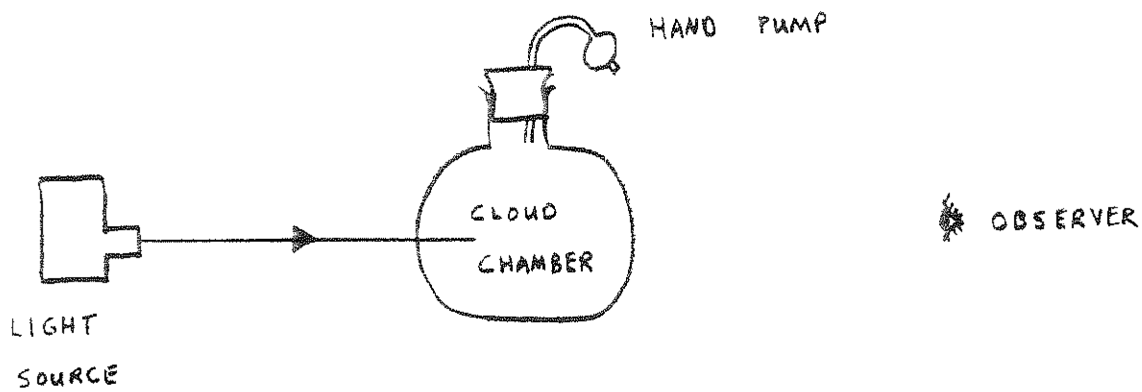


Fig 2. The cloud chamber

Concepts

1. conduction
2. convection
3. buoyant forces

THERMAL CONVECTION

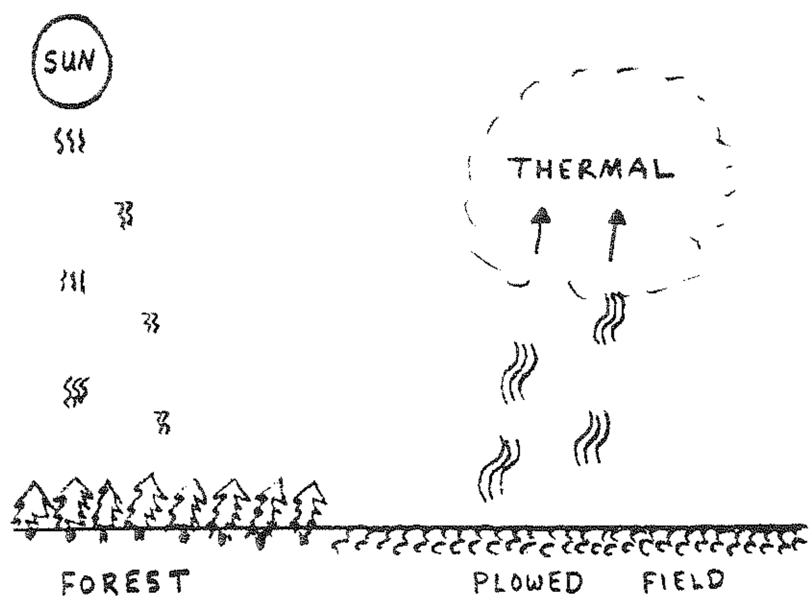
Introduction

One of the processes in the atmosphere which produces clouds is thermal convection. It is also the curse of air travelers who have experienced the unpleasant "air pockets" while flying. It is the same process which is the delight of soaring pilots who seek to capture the energy of these rising currents of air in order to remain aloft.

Theory

Most of the energy received from the sun is in the visible portion of the spectrum 0.1μ to 4.0μ in wavelength. Some of this radiant energy is absorbed by the earth's surface. The texture and composition of the earth's surface determines how good an absorber of solar energy it is. A plowed field for example will absorb considerable more energy than will a forest.

When the earth's surface absorbs the incident radiation, its temperature will increase because of the energy it has gained from the sun. Air which is in immediate contact with this warm surface (e.g. the plowed field) will gain some of the thermal energy from the ground by conduction. As the air increases in temperature it becomes less dense than its surrounding atmosphere and therefore becomes buoyant. Consequently it begins to rise upward in the atmosphere with some vertical velocity. This "pocket" of air is what is known as a thermal (see Fig 1.)



Apparatus

1. Thermal convection chamber (yellow box with plexiglass sides) available from technicians.

2. Smoke generator with package of cigarettes (generator and pack should be inside chamber).

3. Air supply (easiest to use from the instructors desk in one of the class rooms).

Procedure

1. Connect one end of the smoke generator to the air supply and the other end to the chamber. Connect the tubes so that the air leaving the supply will blow through the cigarette from the filter end. (see Fig 2)

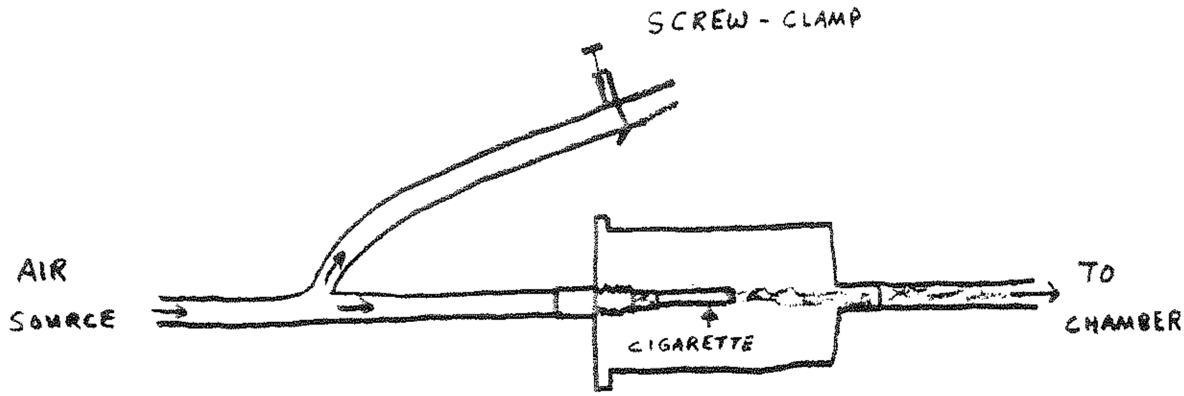


Fig 2. Smoke generator

2. Disassemble the smoke generator and light the cigarette. After the cigarette is burning evenly, reassemble the smoke generator and a steady stream of smoke will soon enter the chamber. The velocity of the smoke stream can be controlled by opening and closing the screw-clamp control valve on the air source side of the smoke generator.

3. The chamber has located on the bottom a hole covered with tinfoil. After the smoke collects in the hole, a lighted match can be held underneath it to generate a thermal. Other interesting effects can also be demonstrated using the styrofoam mountains (which should be inside the chamber). An advancing air mass, such as a warm or cold front, can be created if enough smoke is allowed to enter the chamber.

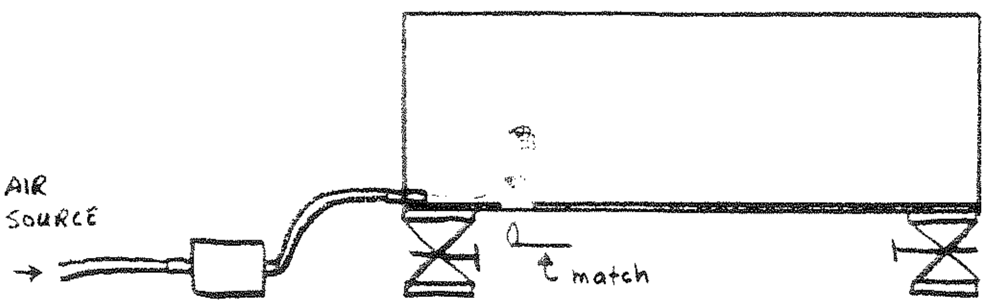


Fig. 3. Thermal chamber arrangement

THE DIFFUSION CHAMBER

Introduction

The formation of ice crystals in the atmosphere is one of the most important physical processes to occur in the atmosphere. In the winter time this process produces snow. Other times of the year, this process produces less common forms of precipitation such as graupel or frozen pellets. The process is highly temperature dependent, and therefore it is possible, to experience some form of ice precipitation throughout the year. This is of course very true of high altitude locations.

Theory

The presence of water in the atmosphere can be observed in all these physical states: solid-ice, liquid-cloud drops, and gas-water vapor. It is this latter phase water vapor, which contributed to the formation of ice crystals in the atmosphere. If there are present in a cloud, at a temperature below freezing, ice nuclei (a substance around which an ice crystal can grow), it is possible for the water vapor to directly sublime onto the ice nuclei and form ice crystals. This means the water goes from the vapor to the solid state without ever becoming a liquid. The amount of water vapor present in the atmosphere is determined by the temperature of the air. For each temperature there is a saturation level or maximum amount of vapor that the air can hold. However, it is possible, if there are few or no ice nuclei present (for the vapor to sublime onto) that the air can become "supersaturated." The more "supersaturated" a cloud is, the faster an ice crystal will grow if an ice nuclei is put into the cloud. Therefore, the rate of growth of the ice crystal is determined by the degree of supersaturation of the atmosphere surrounding the ice crystal.

An interesting feature of this ice crystal growth by sublimation process is that the shape or geometry of the ice crystal is determined strictly by the temperature of the atmosphere and the temperature of the crystal. The various possible crystal shapes and their related temperature are shown in Figure 1:

TEMP (°C)	NAME	SHAPE
0 to -3	thin hexagonal plates	
-3 to -5	needles	
-5 to -8	hollow hexagonal prisms	
-8 to -12	hexagonal plates	
-12 to -16	dendrite crystal	
-16 to -25	hexagonal plates	
-25 to -50	hollow hexagonal prisms	

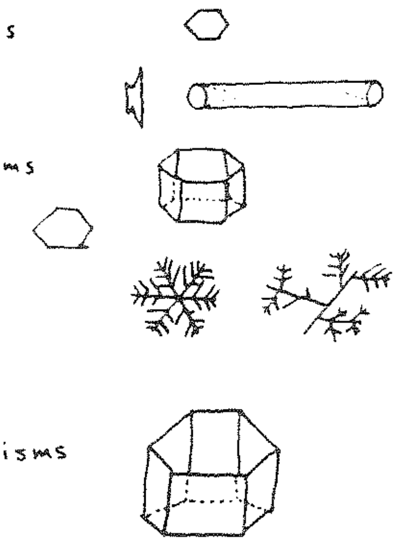


Fig 1. Ice crystal shapes and temperature

A valuable application of this phenomena is that it is possible to determine the temperature of the atmosphere by observing the shape of the ice crystal present.

Apparatus

1. diffusion chamber - available from technician.

2. 2-3 pounds of dry ice - available from Chemistry Department

3. Light Source

4. Camera with telephoto lens (Optional)

5. Tele-thermometer (with thermistor probe)

Procedure

1. Take the diffusion chamber and set it on a table or moveable cart, so that it can be left in one spot for three to four hours.

2. Remove the insulation from the bottom part of the chamber and open the door on the chamber. Inside you will find a spring and a board. Depress the spring and place a large piece of dry ice, about the size of a brick, on both sides of the center column. Replace the insulation around the bottom of the chamber. When the dry ice is in place, the inside of the chamber will appear as in Figure 2.

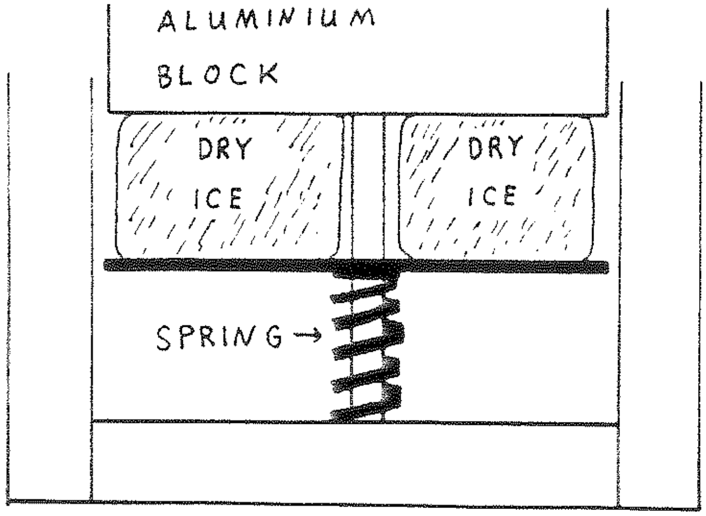


Fig 2. Chamber with dry ice installation

3. The dry ice will cool down the large aluminum block to a temperature below freezing. This process will take three to four hours and may require several repetitions of step 2 (because the dry ice will evaporate). This "cool down" time can be significantly reduced if the aluminum block is removed from the chamber and placed inside the department deep freeze. This will reduce to the cool down time to approximately one hour.

4. Carefully remove the glass rod suspended from the top of the chamber. Remove the top of the chamber and take out the cotton pad held by the screen. Soak the cotton in hot water, and then squeeze out just enough water so that the cotton pad doesn't drip. Replace the pad inside the screen holder and replace the top on the chamber. Be careful to replace the sponge pieces so that the chamber is tight on top. Replace the glass rod.

5. The chamber is now set up for the growth of ice crystals onto the glass rod. The temperature of the chamber can be monitored by inserting the thermostat probe (#_401_) through the top of the chamber and observing the temperature indicated on the telethermometer. The response time of the probe is about one minute.

6. The ice crystals will begin to grow as soon as the temperature of the chamber falls below $0^{o}C$. It may take several hours to obtain crystals large enough to be clearly visible. The growth process can be quickened by heating the top of the chamber with a bunsen burner or hair dryer). This causes more water vapor to enter the chamber and therefore increase the supersaturation of the air inside the chamber.

7. The ice crystals can be viewed by removing the insulation from one side of the chamber. A strong light can be used to illuminate the crystals. A camera with a telephoto lens and bellows attachment can also be used. The image viewed through the camera will then be enlarged.

8. The atmosphere inside the chamber will achieve a very stable condition, with temperature increasing from bottom to top and supersaturation increasing from top to bottom. The various ice crystal shapes will appear at the various temperatures.

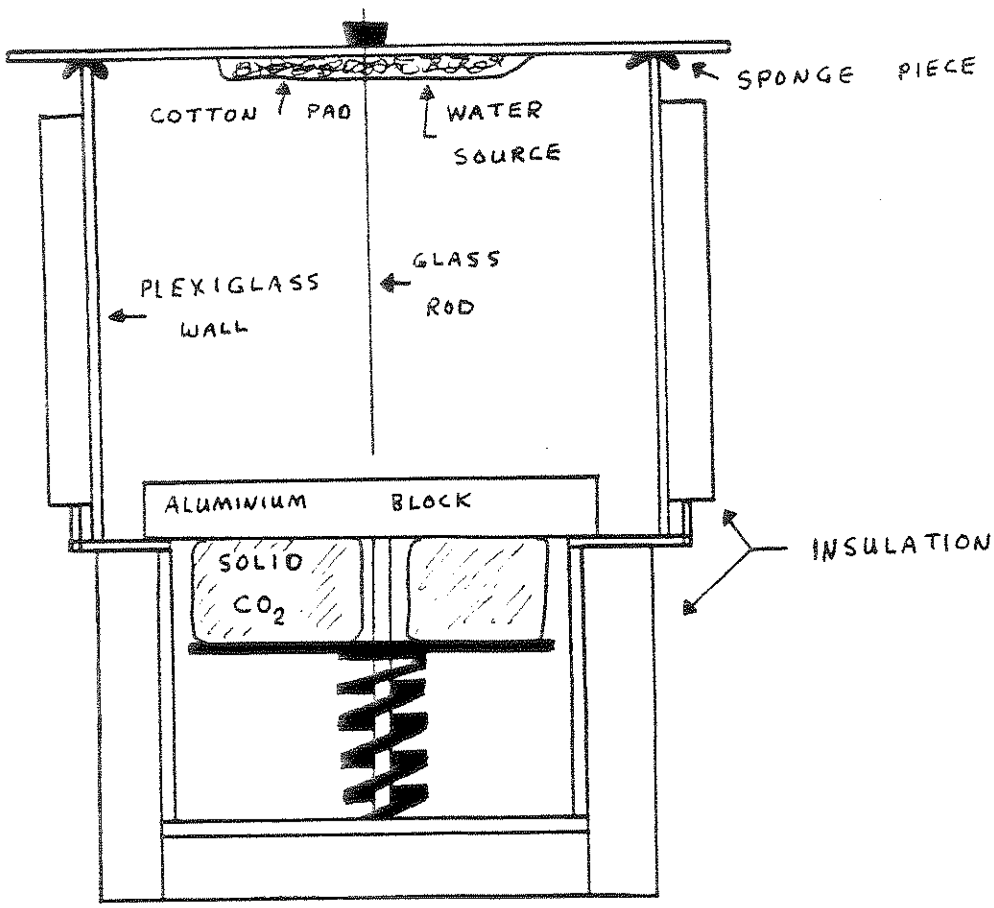


Fig 3. Diffusion Chamber

CLOUD SEEDING

Concepts

1. supercooling
2. supersaturation

Introduction

One of the most controversial issues of today is weather modification. The possibility of man controlling the weather has always been considered by writers, politicians, the military, and now the scientist. The earliest attempts at weather modification have been in area of rainmaking. This of course has brought to the attention of the public the concept of cloud seeding.

Theory

The basic approach to cloud seeding assumes that there are present in the atmosphere the conditions necessary to cause precipitation. These conditions are (1) moisture, (2) saturation or supersaturation, and (3) absense of the precipitation grow process (i.e. - no condensation is occuring). This means that although a cloud can be seeded and precipitation occurs, the cloud must, of its own accord, have brought itself to a condition of near precipitation.

A cloud must have moisture in order to develop the condensation and or sublimation process that produce precipitation. This moisture is generally in the form of water vapor, and if the temperature is cold enough, a condition of supersaturation can exist (relative humidity greater than 100%). This means that the water vapor is present in the clouds, but for some reason, lack of condensation or ice nuclei, it is not forming precipitation.

If some artificial condensation or ice nuclei are introduced into the cloud, the supersaturated air parcel will have its vapor condense or sublime onto the artificial nuclei and a precipitation formation mechanisim will develop. If there is sufficient moisture present in the atmosphere, the cloud droplet or ice crystal will continue to grow until its mass is large enough to cause it to fall out of the cloud.

Apparatus

1. deep freeze
2. dark clothes (can be obtained from technicians)
3. light
4. asbestos gloves (to handle CO_2)
5. dry ice
6. knife (or other sharp device to scrape with)

Procedure

1. Plug in the deep freeze and let it run for several hours. This will allow the temperature to drop to -10 to -20°.

2. Take the black clothes and line the sides and bottom of the freezer. The clothes provide a background to observe the ice crystals you will grow in the chamber. You can lay the ends of the cloth over the sides of the freezer to keep them from falling into the chamber. (See fig. 1.)

3. Open the lid and adjust the light so that a beam is projected into the chamber (See fig 1.)

4. Breath several times into the chamber. This will produce a super-saturated supercooled cloud, which will be visible inside the chamber.

5. Take the knife and holding the dry ice over the chamber, very gently scoop some small ice crystals (cloud seeding nuclei) off the piece of dry ice and into the chamber.

6. Observe the large snow flakes that will be growing inside the cloud and falling to the bottom of the chamber.

7. The above process can be repeated using different types of cloud seeding agents, e.g. water drops, metaldehyde.

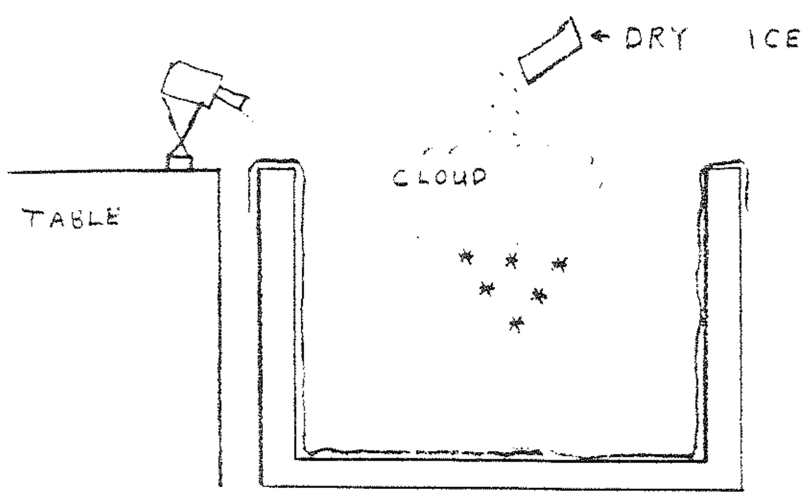


Fig 1. Cloud seeding apparatus

The Sling Psychrometer

Concepts
1. evaporation
2. saturation

Introduction

If a weather forecaster is to make a valid weather forecast, he must know the amount of water present in the atmosphere. This information is important because it tells him whether or not clouds will form, whether precipitation will occur and basically helps inform him about the physical state of the atmosphere. A convenient and widely used instrument for obtaining this information is the sling psychrometer.

Theory

The psychrometer consists of two thermometers placed along side each other and attached to a handle. (Fig. 1)

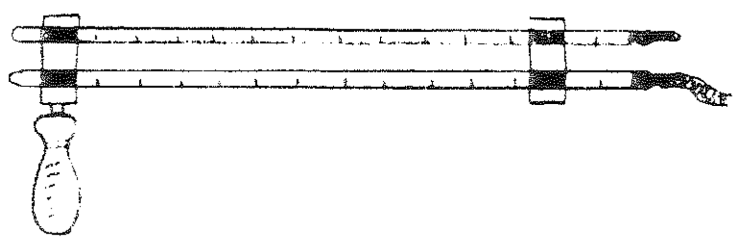


Figure 1. Sling psychrometer

The wet bulb is thoroughly soaked with water. The instrument is then rotated by the handle, through the air. The moving air past the wet bulb will cause some of the water, in the liquid phase to evaporate into the air. This causes a phase change which requires energy in the form of the lateral heat of vaporization. **This heat** has to be gotten from somewhere. The most convenient place for this energy to come from is from the heat contained by the mass of the wet bulb. This reduces the temperature of the wet bulb. From this idea, tables can be tabulated to calculate the amount of water vapor present in the air for the respective combination combination of wet and dry bulb temperature readings.
t

Apparatus

1. sling psychrometer
2. psychrometer calculator (a large round plaster slide-rule looking device)
3. water bottle (squeeze kind)
4. barometer

Procedure

1. Obtain the barometer pressure from the barometer in 2D13. You will need this information to use the psychrometer calculator.

2. Thoroughly wet the muslin surrounding the wet bulb.
3. Rotate the psychrometer about the handle. Obtain a rotation rate of from 2-3 revolutions per minute. Rotate for about one minute.
4. Record the temperatures of the wet and dry bulbs. Repeat step 3 until there is no significant difference in the temperatures from one attempt to the next.
5. Using the instruction printed on the psychrometer calculator, determine the relative himidity of the atmosphere.
6. This exercise can be repeated in different locations to observe the effects of temperature, ventilator, and location on the relative humidity of the atmosphere.

THE ROTATING DISHPAN

Concept
1. differential heating
2. conservation of angular momentum

Introduction

The atmospheric circulation pattern of the earth is a complex combination of many of the basic principles of physics. The primary driving force is the sun, which produces a vast heat engine in the atmosphere. The motion is affected by the distribution of the lands masses and the rotation of the earth, and the result is an interesting pattern of waves and circulation patterns which produce the physical events we call weather.

Theory

The general circulation patterns of the earth's atmosphere are the basic result of three factors. The differential heating of the earth's atmosphere by the sun. The rotation of the earth, and the uneven distribution of land and water on the earth's surface.

The sun supplies the energy to move the earth's atmosphere. Because the surface of the earth is curved, the equatorial region receives considerably more energy from the sun than do the polar regions. The result is a net gain of energy by the atmosphere above the equator and a net loss of energy by the polar regions of the atmosphere. This net loss of energy is due to energy being radiated out to space by the atmosphere. This situation is shown in Figure 1.

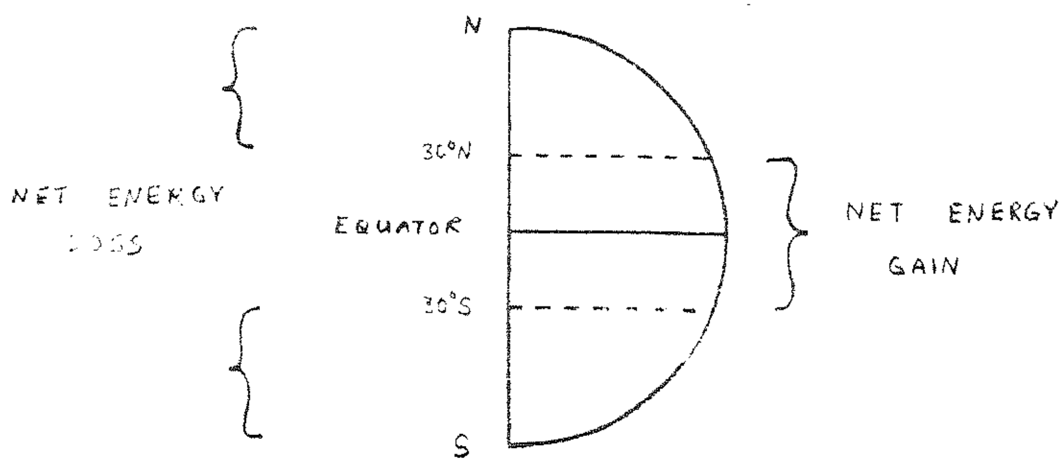


Figure 1. Differential heating of the earth's atmosphere

The differential heating causes the air at the equator to expand and therefore rise up higher in the atmosphere than the air at the poles. This causes a high pressure region at the equator and a low pressure region at the poles. The higher presure at the equator produces more potential energy in the atmosphere, and therefore the air has a pressure gradient force acting on it in the direction of the pole. This is shown in Fig. 2.

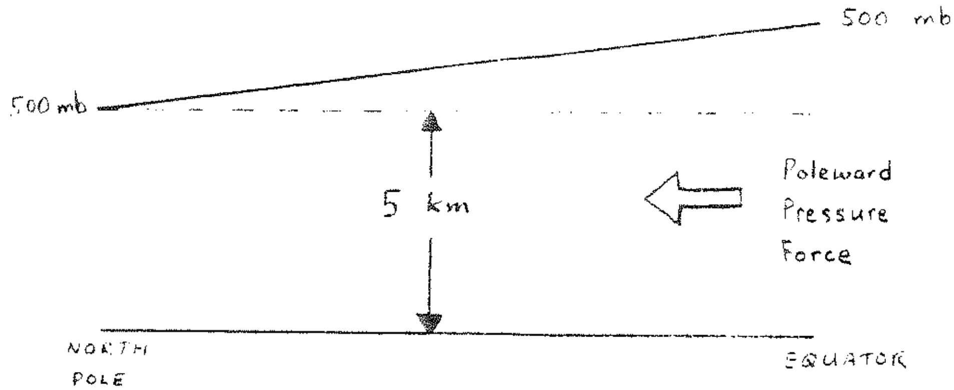


Figure 2. Poleward pressure gradient

This fact was recognized by Hadley who in 1735 proposed the first model of the earth's circulation (Fig. 3). His theory was partially supported by the observation of trade winds in the tropics. It is important to recognize at this point that no account has been made for the rotation of the earth.

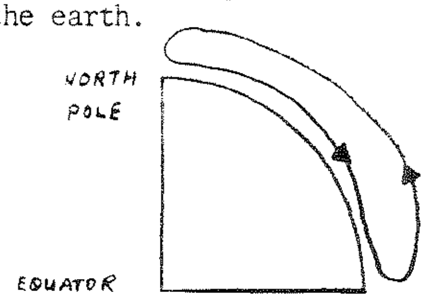


Figure 3. Hadley's circulation pattern

From these considerations, the atmosphere can be looked at as a giant heat engine (Fig 4). Energy from the sun is converted into potential energy, which in turn is converted into kinetic energy, some of which is lost through frictional dissipation.

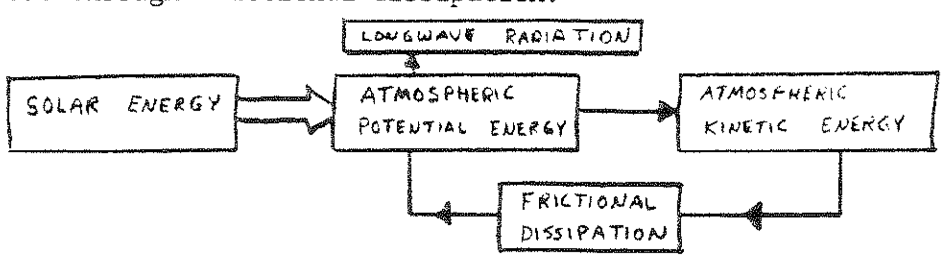


Figure 4. Atmospheric heat engine

The next factor to influence the earth's circulation is the rotation of the earth. The result of this rather complicated physical situation is that the air moving from the equator to the poles is deflected to the right in the northern hemisphere. This is the result of the earth rotating and the air experiencing an "apparent" acceleration when observed from the surface of the earth.

The inclusion of the earth's rotation into the atmospheric model was first done by Fenel in 1856, by Bergeron in 1928, and fully developed by Rossby in 1941. Rossby predicted that his three cell model would have east winds at altitude in the middle latitude and that there would be polar fronts between the upper two cells (Fig. 5).

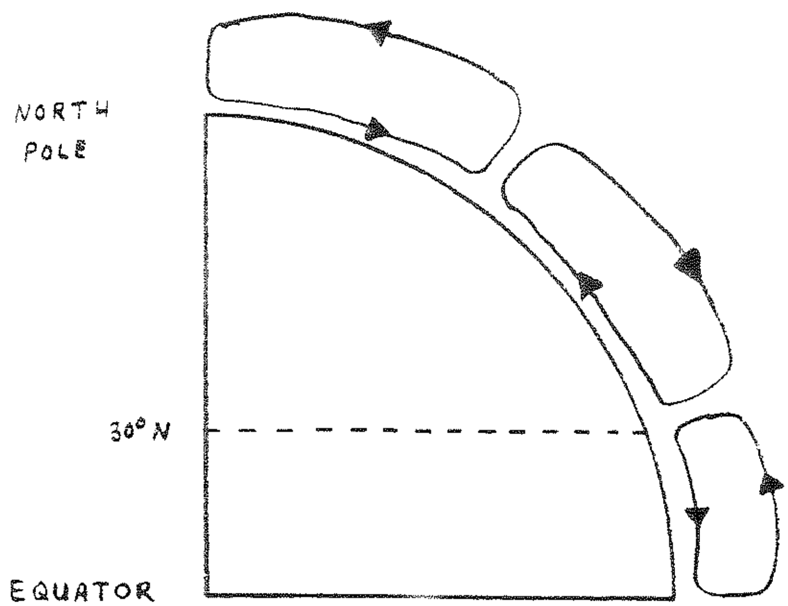


Figure 5. Rossby's three cell circulation model

Rossby's theory encountered problems when it was discovered by the long-range B-29's in World War II, that there were strong westerly winds at high altitudes in the mid-latitudes. It was these same aircraft that first encountered the strong jet stream while bombing Japan.

In 1951 Palmen proposed a new model which seems to basically fit todays observations. His theory proposed the existence of two jet stream systems in the upper atmosphere. His model shown in Fig. 6, predicts a high pressure region around the globe at 30° N and 30° S latitude. This would generally cause air to descend in these regions and therefore greatly reduce the formation of cloud system capable of producing precipitation. This concept is verified by the fact that all of the great deserts of the world lie in their region.

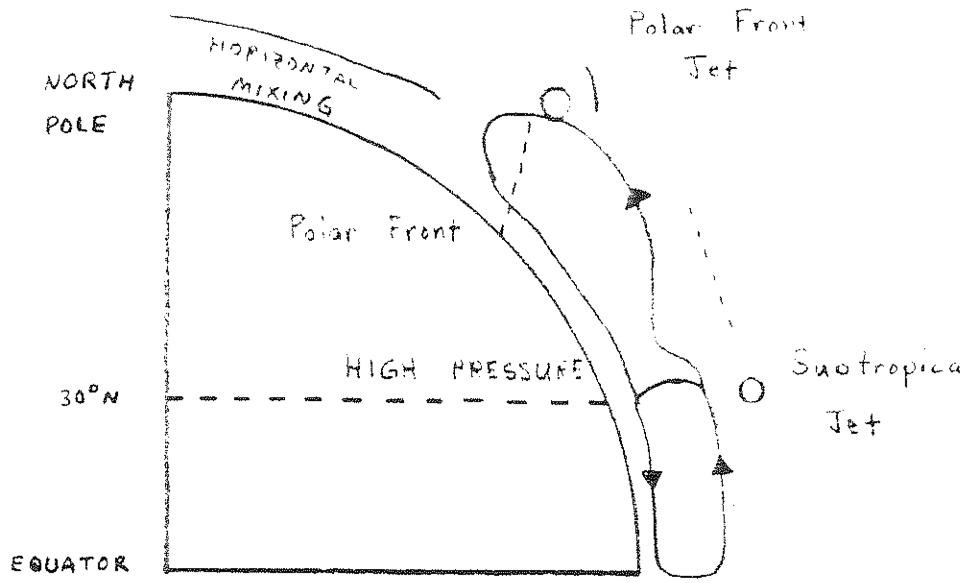


Figure 6. Palmen's model of atmospheric motion.

Palmen suggested that the jet streams are produced for the express purpose of conserving angular momentum. The angular momentum of an air parcel can be written as

$$G = \Omega mr^2$$

m = mass
r = radius of rotation
Ω = angular velocity

but $\Omega = \frac{v}{r}$ so that

$$G = mvr$$

For the earth than we have (see Fig 7)

$$r = R \cos \theta$$

$$G = mv\, R \cos \theta$$

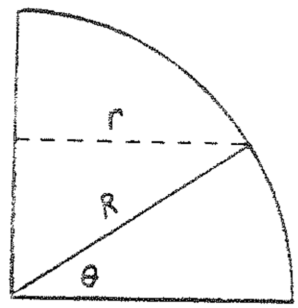


Figure 7. Angular momentum of air parcel in atmosphere

As the air parcel moves poleward, its radius of rotation r decreases and therefore its linear velocity v increases.

$$G = \text{constant} = m\, v\, R \cos \theta = m \underset{}{\overset{\text{increases}}{\overset{\uparrow}{v}}}\; \underset{\underset{\text{decreases}}{\downarrow}}{r}$$

This conservation of angular momentum in the atmosphere produces streams or narrow regions of air in the upper levels which greatly increases their speed to maintain this balance of angular momentum. These streams are the sub-tropical jet stream and the polar jet stream (see Fig. 6).

The net result of all these factors is a complicated interchange of momentum and energy in the mid latitudes. The situation here is never static, and as a result there are constantly changing patterns of circulation in the mid latitudes. Fig 8(a) shows the general west to east flow of air in the upper levels. The oscillation of the westerly winds (called Rossby waves) increases because of uneven heating, the earth's rotation and conservation of angular momentum (Fig 8b and 8c). Eventually to conserve momentum and transport energy poleward the waves break down into large circulation patterns. These circulation patterns, known as cyclones (low pressure) and anti-cyclones (high pressure) are the major circulation systems that produce the weather we all experience.

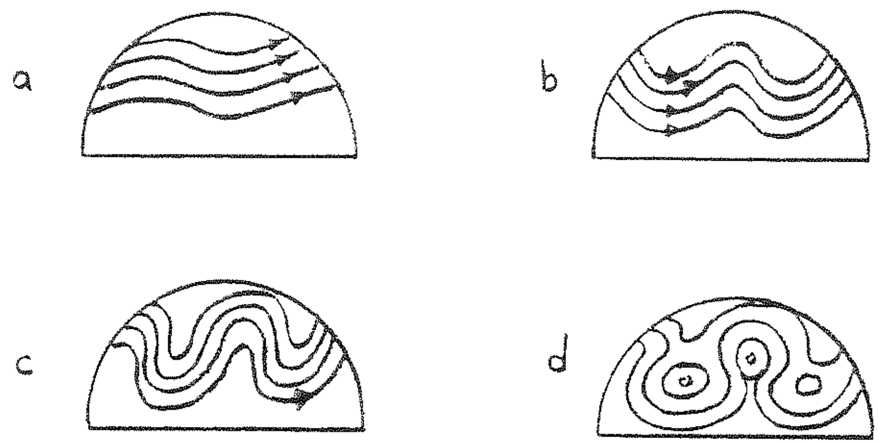


Figure 8. The index cycle of the atmosphere

The final factor to further complicate this already complex system is the earth's surface. The moving air masses are modified by the surface over which they flow. The result may be an increase in moisture content if over a warm sea mass or a decrease in temperature if over a cold land mass. The net result is that the situation shown in Fig. 8 is still farther complication.

APPARATUS

1. Rotating dish pan kit (this includes)

   (i) round pan
   (ii) 2 bunsen burners
   (iii) cast iron rotating platform
   (iv) electric driven rotater (variable speed)
   (v) colored dye
   (vi) lycopodium powder

2. Camera (polaroid)

PROCEDURE

1. Locate a table completely clear of all other objects. This is a rather large set-up and a clear working area is helpful.

2. Set the rotating platform on the table and adjust the rotater so that a good contact is made with the underside of the platform. Be careful not to place the rubber end of the variable speed rotater shaft too far under the rotating platform. Proper alignment will insure a constant rotation rate.

3. Place the dishpan in the center of the rotating platform. Fill up the outside area with about 3.5 - 4.0 cm of water. Next stir in a few drops of the colored dye. This darkens the water and will make more visible the lycopodium powder which will be sprinkled onto the surface of the water at a later time. Fill the inside part of the pan with ice. This will simulate the cold regions of the poles.

4. Set the variable speed control at a fast speed (rubber wheel at edge of motor shaft). Turn on the motor and make any minor adjustments necessary to insure smooth rotation. Turn down the variable speed control until a rotation rate of about 7-10 revolutions per minute is obtained.

5. Take the two bunsen burners and set them at opposite ends of the platform. Light both burners and set them up so they are heating the very outside edge of the dishpan. Be careful not to heat the outside edge of the rotating platform.

6. After an even rotation is obtained lightly sprinkle some lycopodium powder onto the top of the water. This makes it easier to observe the simulated atmospheric motion pattern.

7. It will take 8-10 minutes for the pattern to develop. Initially the water will streamline with the rotating pan. (see Fig 9a). Later on the Rossby waves will become visible (9b), and finally the circulation patterns with tiny jet streams occurring between the edges of the circulation patterns will develop (9c).

8. The entire process is rather difficult to observe because it is all rotating. A "snap shot" can be obtained of the flow patterns by standing above the apparatus and taking a picture (with one of the department polaroid cameras) looking straight down on top of the apparatus.

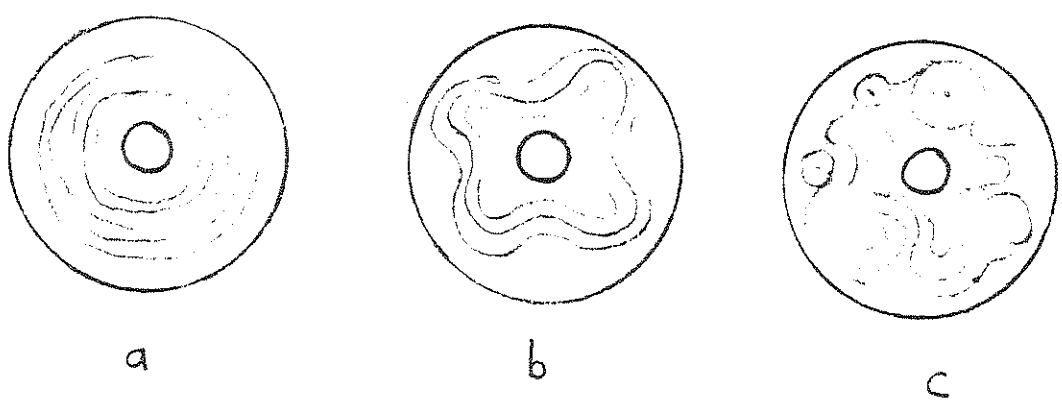


Figure 9. Rotating pan flow patterns

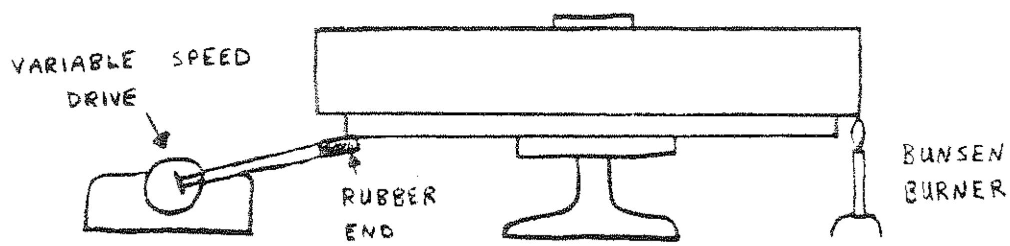


Figure 10. Rotating dishpan apparatus

The Nephoscope

Introduction

The motion and height of clouds is of interest to weather observers, because the information can be used for many different things. The height of the clouds and the size are of interest to the forecaster because it gives him information about the moisture content of the atmosphere. On the other hand, the height and motion (both speed and direction) are of interest to the aviator. A simple mirror nephoscope used with a sling psychiometer can be used to obtain the above information.

Theory

The theory of the mirror nephoscope uses basic geometry and the dry adiabatic lapse to calculate the height and speed of the wind. In Fig 2 let O be the center of the mirror and P the top of the pointer. As a cloud moves from A to B, its image will move from O to R on the mirror. If it is assumed the cloud moves horizontally, then AB is parallel to OR and the distance AB is related to OR by their respective height x and y by

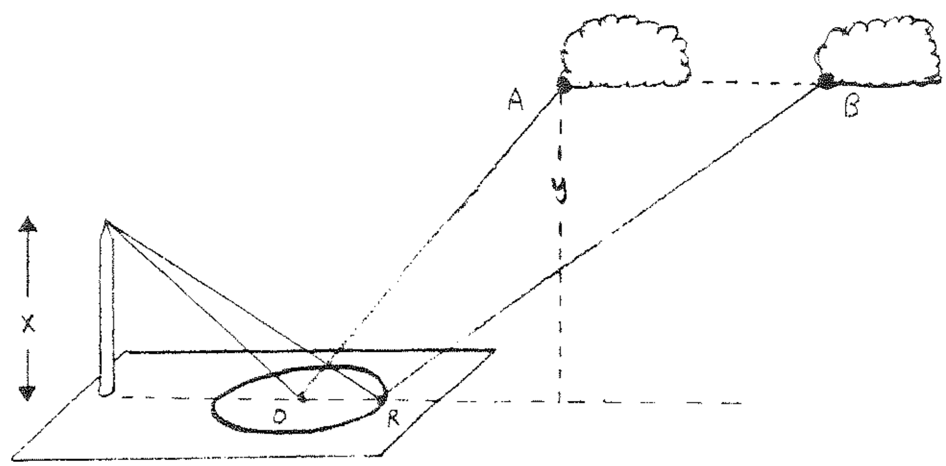


Fig 1. Theory of the nephoscope

$$\frac{AB}{y} = \frac{OR}{x}$$

If R lies on the edge of the mirror, then the cloud moves from O to R in t seconds. This gives the speed of the cloud to be

$$\frac{AB}{y}\left(\frac{1}{t}\right) = \frac{OR}{x}\left(\frac{1}{t}\right)$$

The speed of the cloud then becomes

(I) $$\frac{AB}{t} = \frac{OR\ y}{x(t)}$$

If a value can be obtained for y, the cloud height, then the velocity of the clouds, and therefore the winds at cloud base altitude, can be calculated.

The cloud base can be calculated using the knowledge that on days when there is thermal cumulus activity, the atmosphere is throughly mixed from the ground up to cloud base. Under these conditions the temperature of an air parcel rising in the atmosphere, decreases more rapidly than its dewpoint. The equation which relates the two rates of temperature change for a given altitude y (in meters) is

(II) $$y = 120.78\ (T - T_D)$$

where T is the temperature and T_D the dewpoint temperature can be obtained by using the sling psychrometer.

Once the altitude of the cloud base is calculated, the speed of the clouds, and hence the wind velocity can be measured.

Apparatus

1. mirror nephoscope
2. fair weather cumulus clouds.
3. sling psychrometer
4. psychrometer calculator (round plastic slide rule)
5. water squeez bottle
6. barometer

Procedure

1. Take the nephoscope and place it on a roll cart. Take the cart outside to an open area, such as the terrazzo. Before going outside get the barometric pressure from the barometer in 2D13.

2. Orient the instrument so that the south marker on the paper compass ring is pointing to magnetic north.

3. Locate a cloud image at the dot in the center of the mirror. Do this by sighting OVER the sighting pointer to the center dot. Continue to watch the cloud as it moves away from the center toward the edge of the mirror. At all times continue to sight OVER the sighting pointer. The angle at which the cloud moves over the edge of the mirror is the approximate direction of the wind.

4. To determine the cloud height you must use the sling psychometer. Take the water bottle and throughly soak the wick on the wet bulb thermometer. Now, grasp the handle of the psychometer and whirl the psychometer around in a circle. You need to make about 2-3 revolutions per minute.

5. Read and record the wet and dry bulb temperatures. Use the calculator and the atmospheric pressure you got earlier; determine the dewpoint temperature.

6. Use the dewpoint temperature to calculate the height of the clouds using equation II. Now calculate the speed of the clouds using equation I.

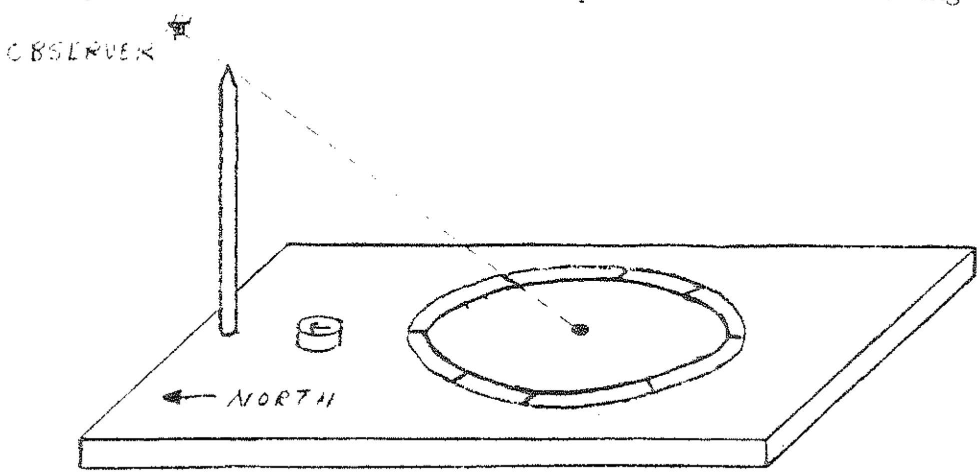


Fig 2. Nephoscope apparatus

Concepts

1. conservation of angular momentum
2. accelerating reference system

The Coriolis Effect

Introduction

To the student of meteorology, probably no single concept causes more confusion than the coriolis effect. This phenomena, resulting from the earth's rotation, plays an extremely important part in the formation of our daily weather.

Theory

When the motion of air parcels in the atmosphere is examined, it is convenient to use a reference system that is fixed on the surface of the earth. A world wide set of coordinates oftentimes used for this purpose is the set of longitude and latitude coordinates. Because the earth is rotating, this set of coordinates will also rotate. Therefore, any coordinate system on a rotating surface will be accelerating.

Consider a rotating plane, such as a turntable. Any point not at the center of the rotation, if it is to remain in circular motion, must experience a centripetal acceleration. When it is rotating, an object on the turntable will stay at one spot only if it is held there by a string (producing an inward tension), or some other centripetal acceleration producing a force. (Fig 2).

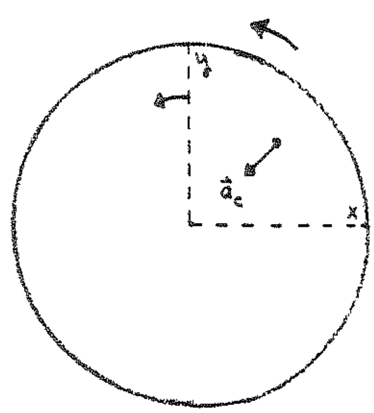


Fig 1. Rotation reference system

Consider a ball initially moving in a straight line, with respect to coordinate system fixed in space (not accelerating). According to Newton's First Law this mass will continue to move in a straight line until acted upon by an external force. Until such a force appears, the ball will continue to move straight ahead, as viewed by an observer not on the turntable (Fig 2).

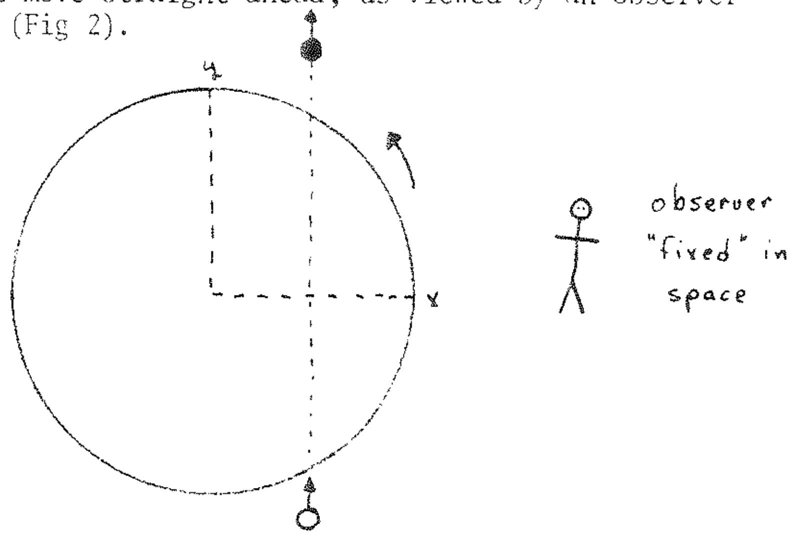


Fig 2. View of ball's motion from fixed reference system

Now consider what happens when the observer is resting on the turntable and therefore accelerating with the reference system. The observer would see that the ball moves to the right of its original direction if the rotation is counterclockwise as observed from above. The person on the turntable sees the ball change its direction of motion. To the observer this means that, according to Newton's Second Law, an acceleration must be present to produce a force on the mass of the ball causing it to change its direction of motion. To an observer fixed in space, there would not be any real acceleration or force present. However to the observer on the turntable the effect is very real and therefore can be thought of in the rotating system as a real acceleration. (Fig 3).

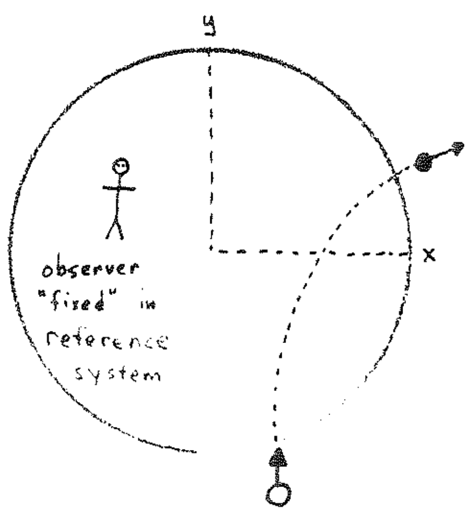


Fig 3. View of ball's motion from rotating reference system

In the atmosphere, this effect is observed in air masses moving through the rotating reference system. Consider an air mass at 30° N latitude. As it moves northward, its distance from the earth's axis of rotation decreases and therefore, because of the conservation of its momentum, it will continue in a straight line. At 30° N latitude, the speed of the earth's rotation is approximately 1450 km/hr. As the air mass moves north to 45° of latitude its rotation is now 1182 km/hr. The result is that the air mass will have moved earthward because it is traveling faster than the earth is rotating.

This phenomena causes low pressure system in the Northern Hemisphere to rotate counterclockwise while in the Southern Hemisphere they rotate clockwise.

A more rigorous mathematical treatment of the corioles effect can be found in Byer's General Meteorology. (See reference page).

Apparatus

1. coriolis turntable (available form technicians).
2. steel ball
3. contact sensitive paper.

Procedure

1. Set up the turntable on a large classroom demonstration table.

2. Place on the turntable some of the contact sensitive paper. When the steel ball rolls over the paper it will leave a visible mark of its tracks.

3. Rotate the table (in either direction) until a uniform rotation rate is achieved. About one rotation every 4-5 seconds is sufficient.

4. Take the metal track and aim it, with the end away from you down, toward the center of the table. Allow a steel ball to roll down the track and onto the table covered with the paper.

5. Observe the motion of the ball, within the rotating reference system. The direction of deflection depends upon the direction of rotation.

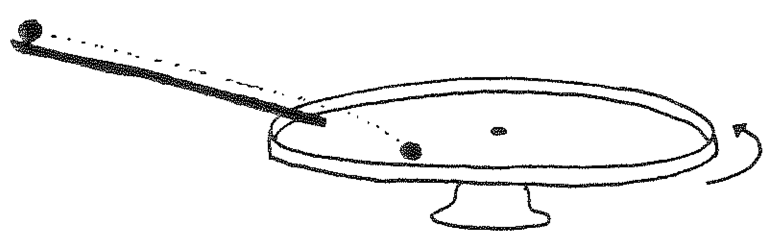


Fig 4. Coriolis effect apparatus

Concept

1. condensation
2. fluid flow

Wind Tunnel for Producing Standing Wave Clouds

Introduction

One of nature's most spectular aerial displays is the standing lenticular or wave cloud. Usually present in mountaineous regions, the wave cloud is both an item of beauty and an indicator of some of the physical conditions of the atmosphere. A simple wind tunnel using carbon dioxide vapor as a tracer, can be used to demonstrate the mechanisims which produce wave clouds.

Theory

The formation of wave clouds is similar in most respects to the formation of other clouds. The important difference is the lifting mechanism involved. The lifting occurs when a moving air mass, or wind, encounters a physical obstacle such as a mountain range. The air will be forced up over the mountain range as shown in Fig 1.

Fig 1. Air being lifted by mountain range

The lifting process will be felt at considerable heights in the atmosphere, often times much higher than the elevation of the obstacle.

As the air is lifted, it cools off and eventually condensation will occur, if there is enough water present in the air to form clouds. If there is not enough water present, no wave cloud will be seen, however, a standing wave (of air motion) will still exist. The wave cloud will have a very smooth layered or lens shape, hence the name lenticular cloud (Fig 2). As the air flow (or fluid flow) passes the obstacle, it will descend.

As it descends it will set up an oscillation pattern

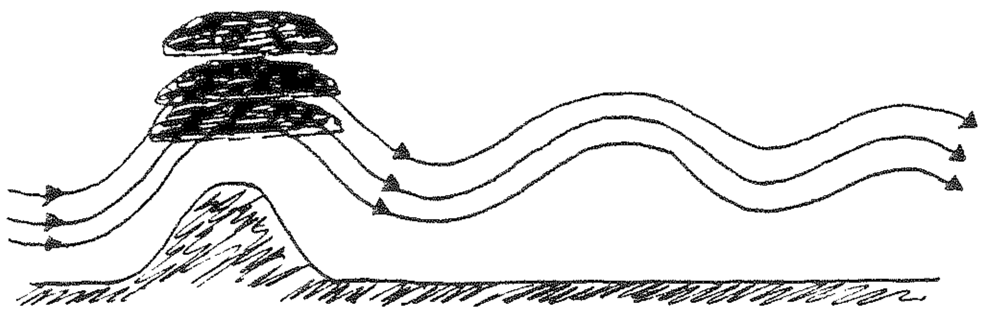


Fig 2. Wave motion with clouds present

and will undergo several more wave motions before its amplitude is dampened out (Fig 3). If there are other obstacles further down stream, such as another mountain range, the oscillation can be sustained or even increased.

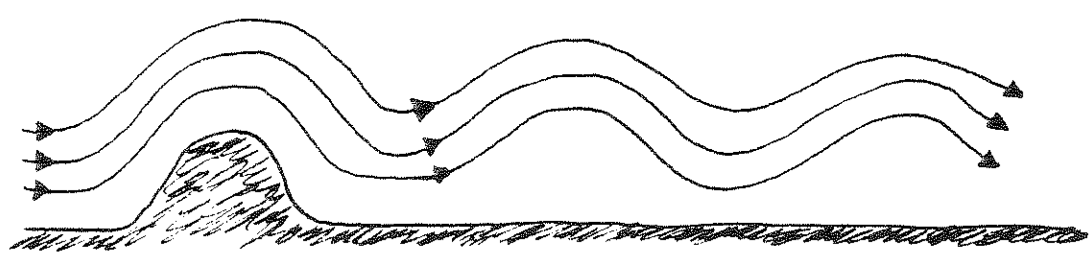


Fig 3. Standing wave motion

Underneath the smooth portion of the wave cloud and on the downwind of the obstacle will be a region of air turbulence. At this point the air flow is close enough to the ground that friction with the earth's surface will cause a rotation effect to occur. This can often times be a very turbulent region and if enough moisture is present in the air, a cloud will form This cloud has a ragged twisting appearance, and is often called a roll cloud (Fig 4).

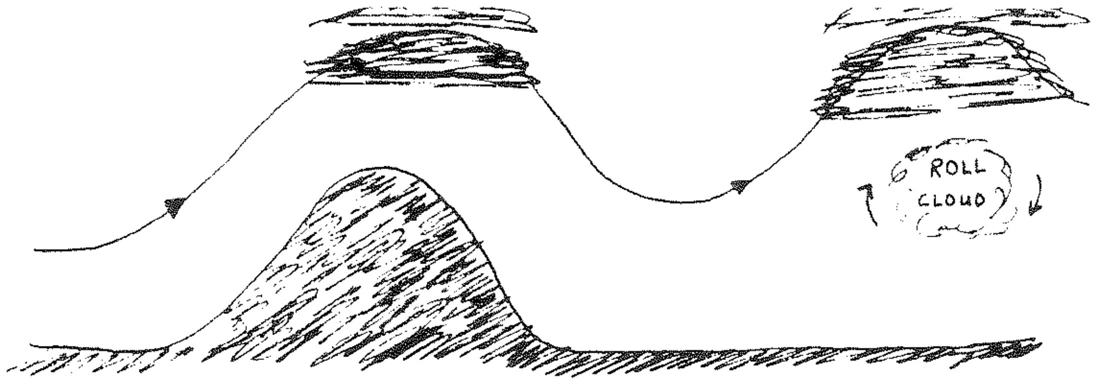


Fig 4. Roll Cloud

The air motion, or fluid flow, that produces standing waves in the atmosphere can occur whether or not there is moisture present in the atmosphere. The formation of wave clouds will occur only if there is enough moisture present to have condensation occur. This means that whenever wave clouds are visible there is present in the atmosphere the air flow which produces standing waves and its associated turbulence. When are no wave clouds present, it is still possible to have the standing waves and their turbulence present, but they will not be visible.

Apparatus

1. Wave cloud wind tunnel (available from technicians).
2. Dry ice vapor generator (available from technicians).
3. Dry ice (solid CO_2)(available from technicians).
4. variac
5. 2 jack stands

Procedure

1. Locate a large open table to set up the demonstrations.

2. Set up the wind tunnel as shown is Fig 5. Use two jack stands to adjust the height. Set into the upwind end of the tunnel (opposite the fan) the vapor generator.

3. Remove the lid from the vapor generator and place into the plastic basket several large pieces of dry ice. Lower the bucket into the generator. Pour into the generator enough water to cover the dry ice. This will cause the dry ice to vaporize and produce a visible cloud of vapor. Replace the lid on the generator.

4. Plug the fan into the variac and vary the voltage to obtain the desired fan speed. The fan will draw the vapor out of the generator and through the tunnel.

5. Open the lid of the tunnel and position the small "mountains" so that a standing wave pattern is set up. If the fan speed is properly set it is possible to observe several waves downstream from the mountain and also the rotor cloud may be visible immediately behind the obstacle.

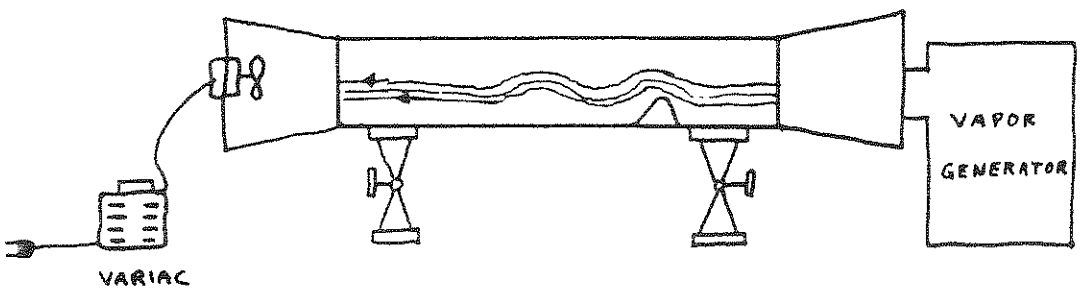


Fig 5. Wind tunnel apparatus