1940

METEOROLOGY FOR THE PILOT

by

C. L. Hosmer, 1st Lt., A. C. and D. H. Kennedy, 1st Lt., A. C.

Introduction

The single purpose of this thesis is to make available to the pilot, in his own terms, conclusions about weather phenomena that directly affect the airplane in flight. It is hoped that herein is provided basic information and guides which the pilot may use to help him determine flying procedure when confronted with weather conditions ranging from the best to the most ominous.

The writers do not intend that this treatment be considered anything but an extremely generalized condensation of meteorological information. All of the conclusions are qualitative rather than quantitive and their real benefit lies in giving the pilot the sense of the important weather factors and their effects rather than the exact magnitude of all the factors.

Of necessity, to treat any synoptic situation in detail, certain terms and processes must be introduced and used with which the average pilot has only a nodding acquaintance. The average pilot does not know what an equivalent potential temperature lapse rate is and does not care. He counts on the forecaster interpreting present weather conditions and future trends in a pilot's language. The interpreting of meteorological information about general conditions into terms and working tools already familiar to the pilot has been the aim of the writers. However, it was felt necessary to use the terms "stability" and "instability." Under the treatment, "Thunderstorms", these terms have been carefully illustrated at length. With this exception the writers have not devoted more than a line in explanation of any word or process but have restricted themselves to the very adequate words and phrases already in every-day use by the weather conscious pilot.

In the appendix a few words not used in the text but often encountered by the flier are simply defined. It is believed that every person concerned with the weather should know the meaning of these words in order to understand better weather phenomena as discussed by the meteorologist and treated in books. In the appendix is a temperature scale graduated in both degrees centigrade and fahrenheit. The simple formulae which the pilot may use to convert readings from one scale to the other is added for convenience.

Also in the appendix is a list of abbreviations of air mass symbols with the specific air masses they indicate. Of the several systems of air mass symbols in use, that introduced in its final form by Dr. Irving Krick is considered because the writers feel that those abbreviations are the most informative.

Determination of Winds Aloft by Cloud Forms

To the pilot knowledge of the wind direction and velocity at flying levels is highly desirable. To compensate for balloon run information, the pilot should be able to estimate the winds aloft from certain types of clouds. The variation of winds aloft is entirely relative; the information most important to the pilot is the location of the level of most favorable winds. The rules developed in this section have been found to be of real assistance in enabling pilots to make the most of variation in upper winds.

Cumuli clouds, from the fair weather cumulus to the cumulo-nimbus or thunderhead, are the best type indicators of the winds at cloud levels. The reasons for the superiority of the cumulus cloud are as follows: (1) It is confined to a relatively small horizontal area. (2) On the average over the earth's surface, it is the most commonly observed of all cloud types. In general, the cumulus cloud is a separate entity. Even in an area of many cumuli clouds the observer easily can identify the members within the group. This individual identity enables the pilot to make his observation in the minimum of time and to obtain the maximum of information by study of the cloud as a whole. There are three specific criteria which may be used. They are as follows: (1) travel of shadows cast by clouds, (2) variation of cloud shape, (3) circulation in the cloud boundary layer.

Cumulus cloud movement represents true wind at the cloud level. For practical purposes the clouds' shadow travel over level ground accurately indicates true wind. However, the pilot should take into account the type of terrain over which the shadow is moving. As shown in figure 1, the apparent shadow travel over steep slopes should be corrected for velocity error created by slant projection of the rays of the sun. The illustration has been simplified by neglecting the effects on the cloud of updraft and downdraft caused in the air by the ridge. In other words, the conclusions derived are true only for clouds moving at a level high above the ridge.

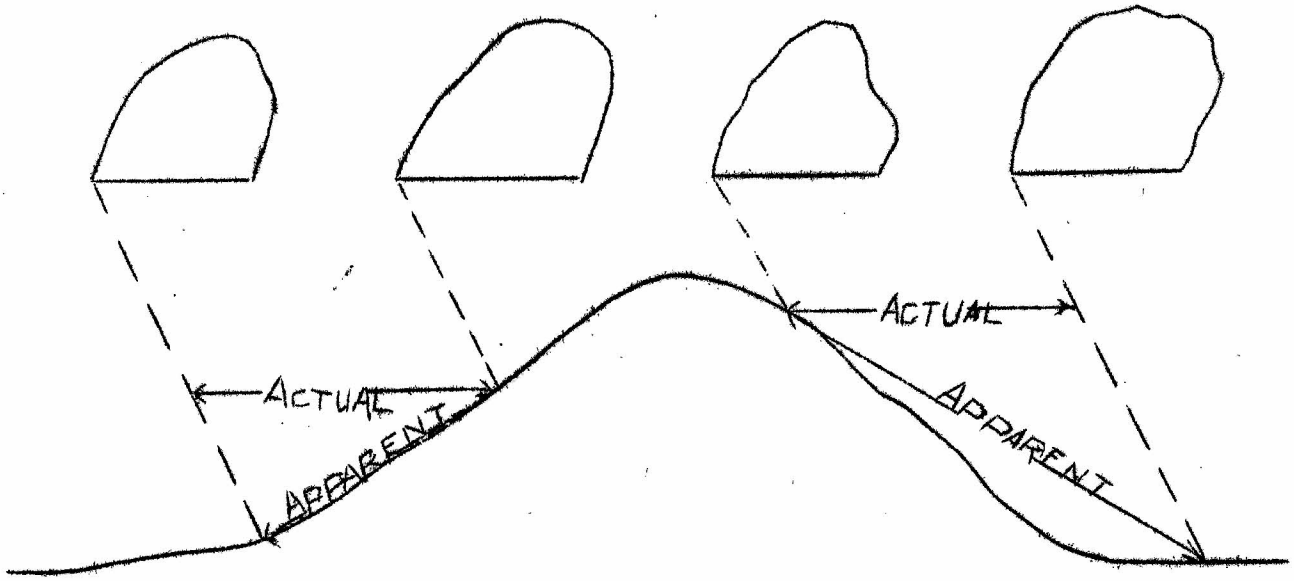


Figure 1

Note that for shadow travel upslope the resultant error is small and negative. The error caused by downslope movement is large and positive. With practice the pilot should be able to estimate the shadow movement within an accuracy of twenty per cent in velocity and ten degrees in direction.

As brought out in figure 2 the air within a cumulus cloud is ascending and the top is constantly changing. Hence, the rearmost boundary of the shadow is a better indication of the mean wind velocity then the forward edge of the shadow. The distance AB in the figure below, is a measure of the error caused by the building up of the top of the cloud during the observing interval.

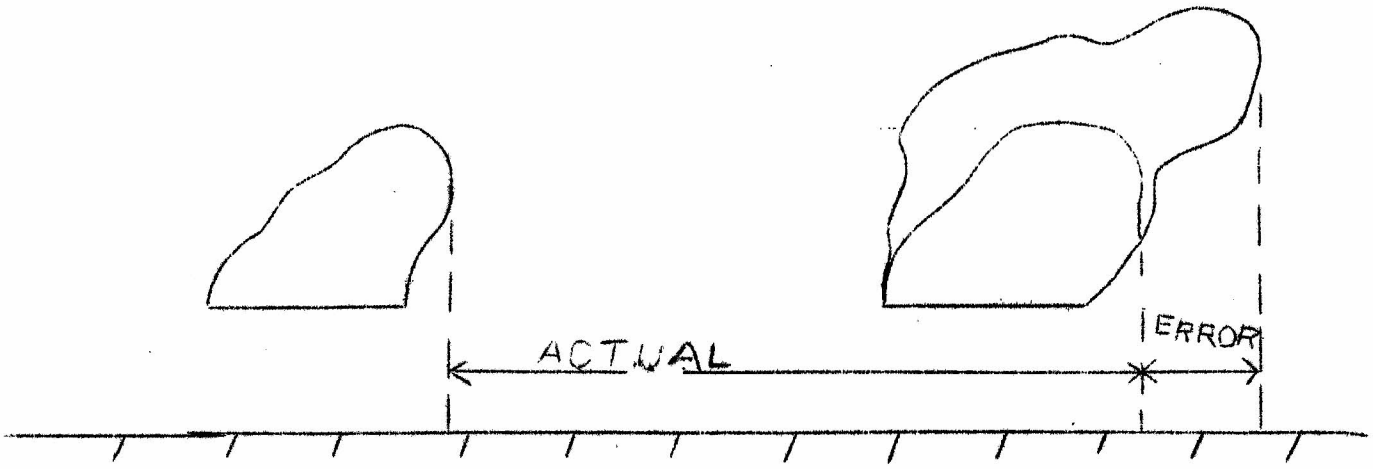


Figure 2

The second criterion by which the pilot may estimate the winds aloft is the variation in the shape of cumulus type clouds. Zimmerman's theory of the effect of the winds on cloud forms is based on the assumption that wind velocity increases with altitude through all flying levels up to the base of the stratosphere. This assumption may be in error in specific instances such as that shown below in figure 3. However, in general, it properly may be assumed that the velocity of the wind actually does increase with altitude, as illustrated in figure 4.

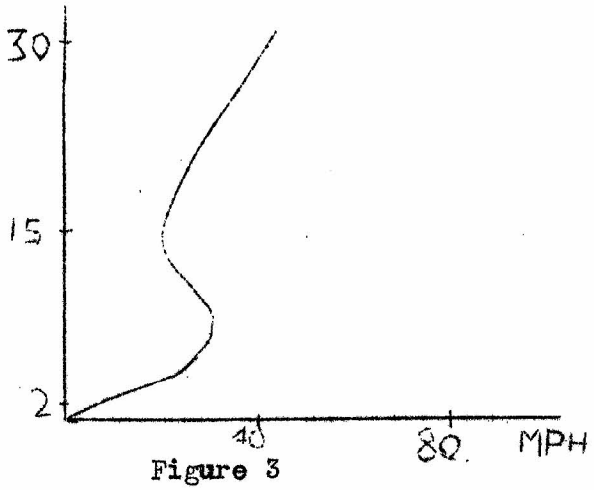


Figure 3

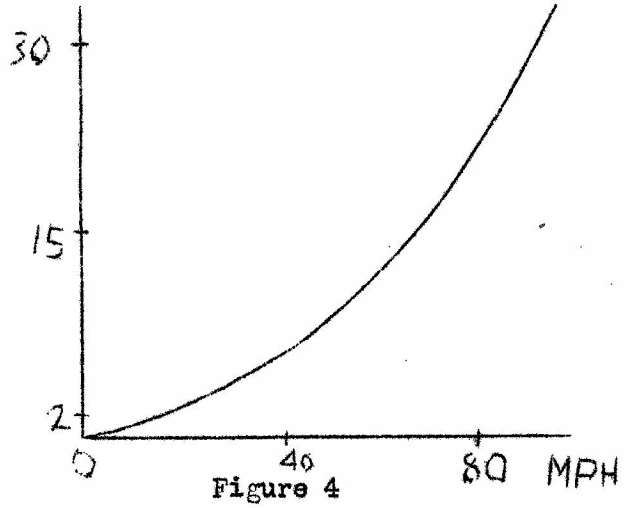


Figure 4

In figure 4 the greater rate of increase of wind velocity with altitude up to about two thousand feet, over the rate of increase from two thousand feet up to the base of the stratosphere, is a result of the effect of ground friction. This usually observed variation in the rate of increase of wind velocity with altitude is considered under "Air Roughness."

Nature has provided the pilot with multitudinous large scale ascending balloons in the family of cumuli clouds. This is true because these are convective type clouds and the air within them is moving upward as well as moving along with the horizontal component of the wind at each level. But a cumulus cloud is better than a balloon three feet in diameter in that the cloud shape presents a picture of the average horizontal path the air within the cloud is following for as thick a layer as the cloud is from bottom to top.

Assume a bubble of air is moving up through the wind pattern represented in figure 4, above. The resultant path of the bubble relative to the earth is a curve in the form of an arc, bent in the direction of the prevailing wind, as shown in figure 5 below. Considering the rising column of air that makes up the cumulus cloud as the bubble, the cloud itself should be built around the same type of curve as the arc. In figure 5 two cumuli clouds have been placed in an idealized wind flow pattern such as figure 4 represents.

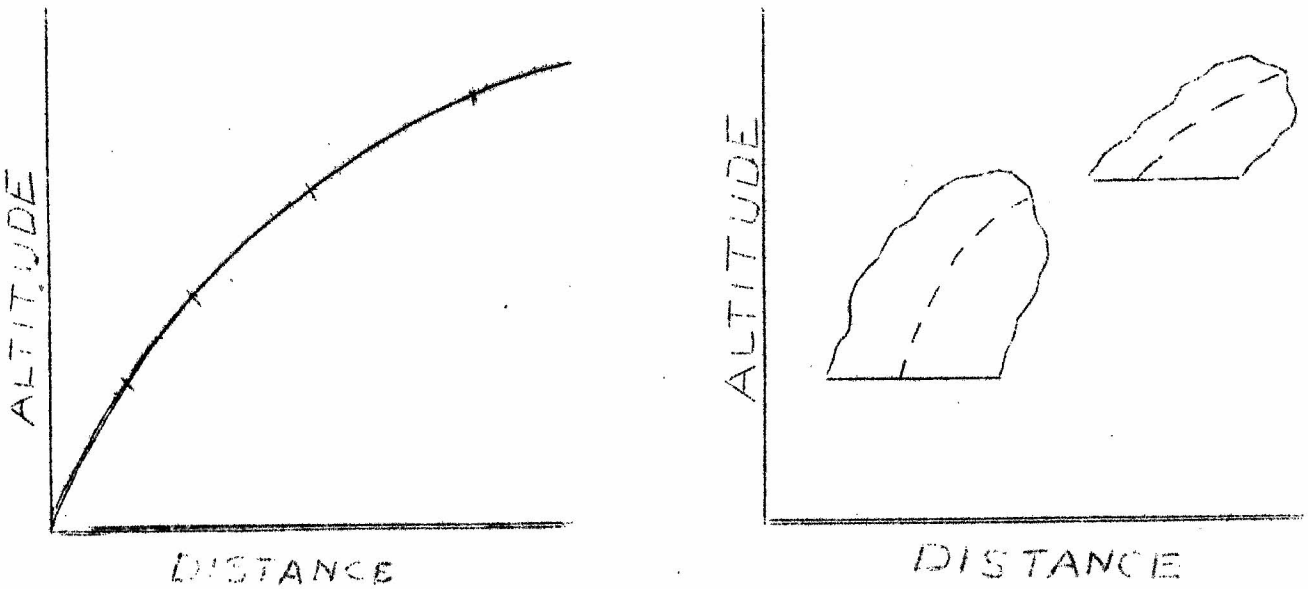


Figure 5

Note that no matter how high or low and no matter how thick or thin the cloud is, the same arcing configuration results. This head-up, tail-down shape is common to the cumulus cloud. The degree of arcing is dependent upon the difference in velocities at different levels. The individual cloud may

vary from one with a slight hunch to the other extreme--a cloud with a pressed, driven look. This difference in the degree of arcing indicates to the observer the actual differential between the low level velocities and the high level velocities. In order to be able to estimate the magnitudes of the high level velocities, the pilot if practicable, should obtain the low level velocity from the shadow travel of the rearmost portion of the cloud. The real value of this method of estimating the upper winds is in obtaining information for the pilot to use in making an accurate estimate of the level of most favorable winds for the purpose of his flight.

The second criterion, circulation in the cloud boundary layer, is another valuable indicator. The action of visible wisps in the boundary of the cloud gives corroboratory evidence of the winds at the cloud level. The effect of friction between layers of different velocities is to retard the faster moving air above and produce multitudinous intermittent arcing trajectories. The resultant whods of air act as "rollers" between layers of different speeds. The condensed moisture in the cloud boundary offers an excellent picture of these rollers. Although the sinking action in the lee side of the roller tends to evaporate the droplets and render the lee side invisible, the cloud droplets in the upper semicircle of the arc makes that part easy to observe. Because the wisps are small scale compared to the cloud, the cloud boundary contains many wisps as illustrated below in figure 6.

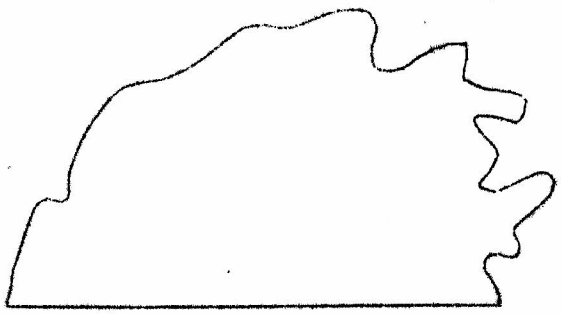


Figure 6

Note that the whorls along the rear side of the cloud are much less obvious than those at the top and forward side. This fact is of aid in estimating at a glance the wind direction. The frayed portion of the cloud is to the front and the relatively smooth surfaces are to the rear of the cloud.

All of the above discussion has been from the standpoint of cloud outline from the side view. It follows that, in outline, the cumulus cloud should present the least deviation from a symmetrical silhouette to the observer either upwind or downwind from the cloud. Therefore, after the pilot has determined the line along which a group of cumuli clouds most nearly conform to the idealized picture, line A, figure 7, he should make the additional check of determining the line along which the outlines of the clouds least conform to the idealized side view. This line is marked B in figure 7, below. Obviously, the two lines, A and B, will be perpendicular. The wind will be blowing parallel to line B and in the direction indicated by the shape of the cloud, the tops of the boundary wisps, and the shadow travel. The pilot should be careful to restrict his line of sight to a given level during any one observation of clouds in different directions.

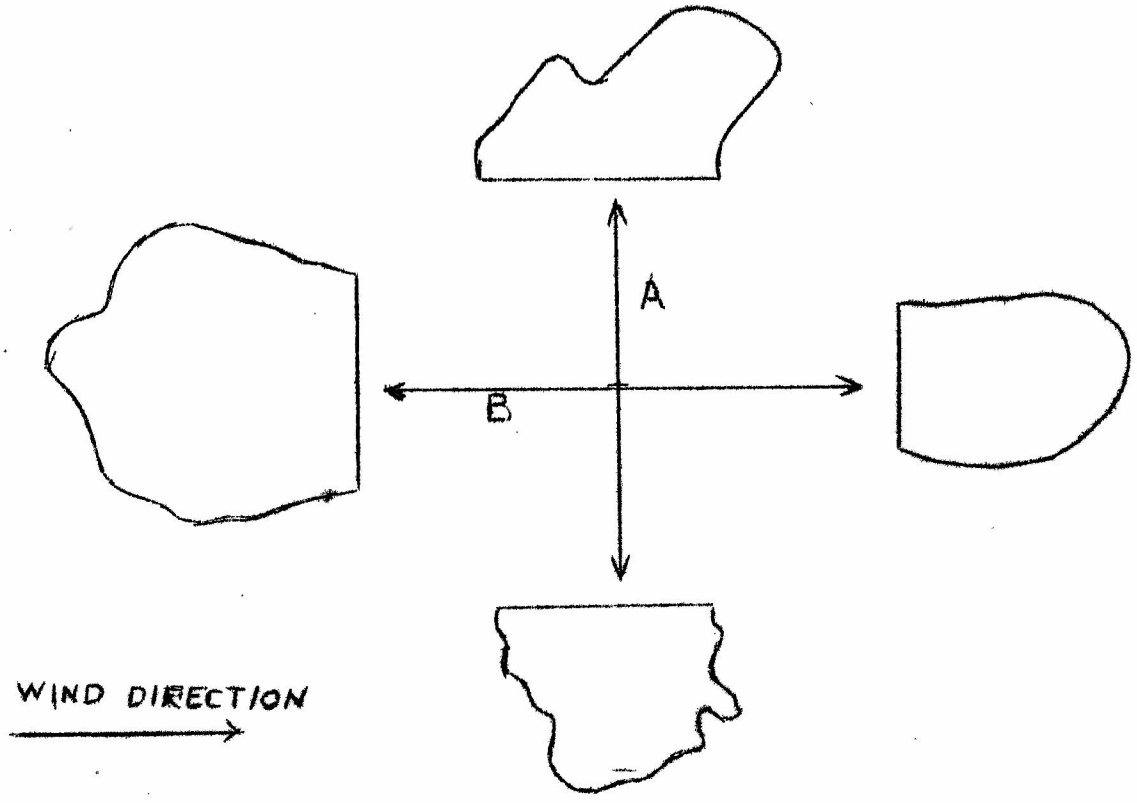


Figure 7

The result obtained in this manner then may be compared to results obtained by other series of observations of cloud shapes and boundary wisps at levels above or below the first considered in order to form a real basis for an estimate of the variation of wind direction with altitude.

There are other type clouds which should be discussed under this section. The most important point to be made is that the following cloud types offer to the pilot indications of the winds aloft not as reliable as indications already discussed offered by the cumulus cloud. The cumulus cloud moving in the general air stream without orographic restriction is the best winds aloft cloud indicator the pilot has. The restriction that the cloud move without orographic influence places even a special kind of the cumulus family (in the sense that it is convective) on the doubtful list. Two types clouds that may be unreliable in that they may not indicate both velocity and direction of the upper winds are the convective cloud that remains practically stationary above or to the lee of a mountain peak or ridge and, secondly, a layer of stratus clouds. The first of these may be called crest type clouds with special names determined by the location and appearance of the cloud with respect to the mountain, as illustrated in figure 8 below:

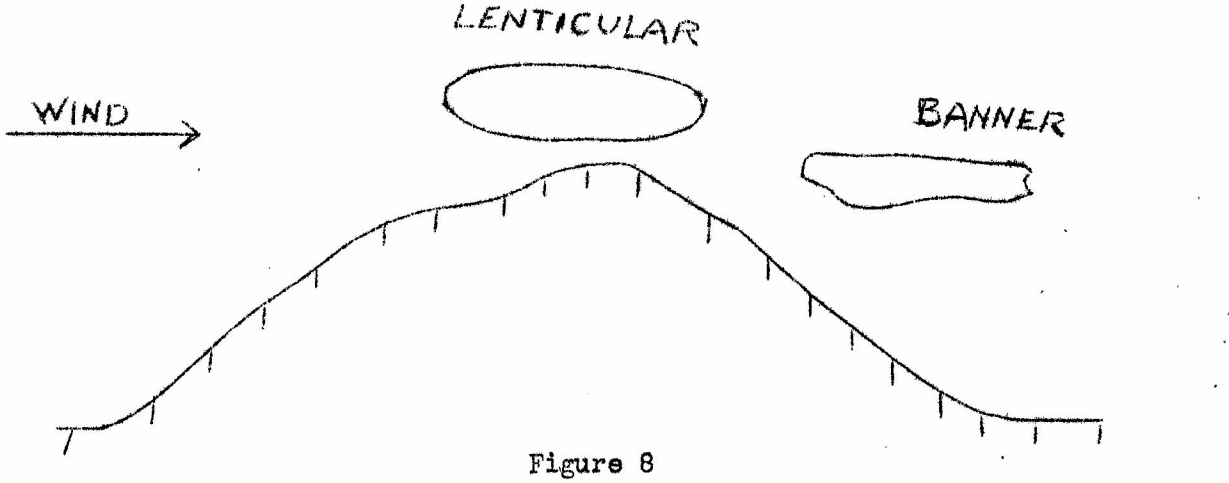


Figure 8

If the pilot remembers that the reason a cloud exists over the mountain in the first place is that the air has been cooled to its dew point by lift over the mountain, the difference between the lenticular and banner clouds becomes a difference in the velocities in the air moving over the mountain. The true lenticular cloud that is symmetrical with respect to the vertical lies in a smoothly flowing airstream. As discussed under "Roughness," air of even moderate velocity will be extremely turbulent over a mountain. Therefore, a true lenticular cloud will exist only in relatively slowly moving air. On the other hand, the banner cloud appears to be a flag flying from the mast of the mountain and sometimes is called a flag cloud.

In extreme cases, such as the banner cloud associated with Mount Everest the reduced pressure caused by the Bernoulli effect to the lee of the mountain has been credited with maintaining the cloud for its great length of six miles. That is, the pilot observes a crest cloud extending well beyond the region where the downdraft should have dissipated the cloud, he may rest assured that the wind velocity at the cloud level is great. Hence, the location relative to the mountain of the convective cloud that remains practically stationary is a good indication of the magnitude of the wind at that level. Of course, the wind direction for all but the true lenticular cloud is easy to determine. The wind is blowing from the mountain to that portion of the cloud fartherest from the mountain.

Stratus clouds are the least reliable of winds aloft indicators. In the first place, the upper winds associated with stratus clouds are usually of only light to moderate velocities. For our purposes, a layer of stratus cloud will include the solid and extensive stratus sheet and a secondary classification, the Helmholtz waves or long parallel bands of cloud with clear intervening spaces. The solid and extensive sheet is dismissed herewith as being totally unreliable. Even the shadow travel of the edge of the sheet may not represent the true wind. The minute whorls along the edges do indicate the relative winds through a thin layer, but the variability of the light winds may be associated with these cloud types invalidates general conclusions. However, some information may be derived from the kind of stratus that is formed in long narrow bands with clear intervening spaces or the Helmholtz waves. Here the most obvious criterion, shadow travel, is valueless. The bands of cloud in this type of formation are continuously being formed on the lifting side of the band and continuously being dissolved on the descending lee side. The wind is moving through the clouds and may not be moving them at all, as in figure 9.

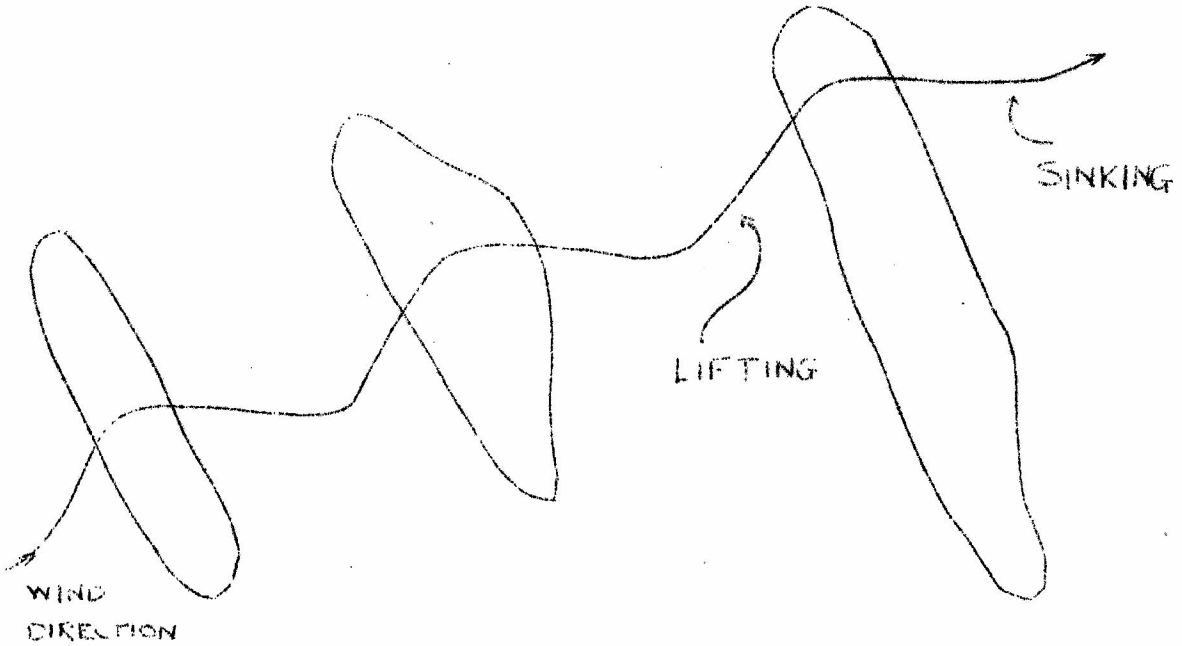


Figure 9

If this type of cloud is moving over the ground, the actual wind velocity may be considered to be greater than the speed of the cloud. Note that one conclusion that may be derived from the formation of these bands of clouds is that the wind is perpendicular to the long axes of the cloud bands or the crests and the troughs of movement. The pilot is cautioned not to confuse this wave arrangement of stratus bands with long columns of cumuli clouds observed, moving along with the wind. In coastal regions as in south Texas, the air flowing northward from the Gulf of Mexico often has set off within it series of cumuli clouds arranged in long columns whose axes are parallel to the wind direction. In this case, the pilot should determine the wind direction by using the criteria that apply to a cumulus cloud.

Finally, the pilot should keep in mind in making any estimate of the winds that in the highest flying levels over the United States the general air movement is westerly. It is only in association with the deepest and most intense synoptic cyclones that winds above twelve thousand feet become easterly.

In conclusion, aids a pilot may use in estimating the wind velocity and direction of the winds aloft are as follows:

I. Velocity and direction
   - A. Cumulus type clouds
     1) Shadow travel
     2) Variation in the shape of the cloud
     3) Circulation in the cloud boundary layer
   - B. Crest type clouds associated with a mountain
     1) Location with respect to the mountain (excluding true lenticular cloud)

II. Direction only
   - A. Helmholtz waves of alternating clear air and stratus bands.
     1) Orientation of axes
   - B. Winds above 12,000 feet are usually westerly

III. Velocity only
   - A. The convective cloud associated with a mountain
     1) The true lenticular cloud
   - B. Wind velocity usually increases with altitude

IV. Neither velocity nor direction
   - A. Solid stratus sheet

Air Roughness

Passenger comfort and even flight safety may be considered a function of the violence of air roughness. In order that a pilot may reduce to a minimum the effect of roughness in the free air, he should know what air roughness is, the different classifications of air roughness, and criteria that indicate violent air roughness. This phenomenon may be defined as the effect on the airplane of rapid changes in vertical motion of the air through which the airplane is flying. It is caused in either, or a combination of, two ways:

(1) convection in saturated air; and (2) the influence of the surface of the earth on air flowing over it. The first of these causes is discussed under thunderstorms. Air roughness, as discussed in this section, will be confined to that caused by the influence of the ground on the air stream above it, and for brevity, will be called orographic roughness.

Orographic roughness may be further subdivided into three types as follows:

1) Small scale turbulence associated with frictional effects between air layers of different velocities.

2) Small scale convection of unsaturated air over orographic hotspots.

3) Large scale turbulence associated with sudden displacement of air from its trajectory by large land obstructions.

The first type, turbulence from frictional effects, is here considered orographic because the greatest change in wind velocity usually takes place between the ground surface and the gradient wind level which is reached at approximately two thousand feet. The extensive mathematical theory developed for this phenomenon indicates that the roughness effect on the airplane in flight from this type of turbulence may become very great. This conclusion is well substantiated by experience of pilots who have had difficulty in landing in a "gusty" wind. The violence of the turbulence varies directly as the square of the mean or average velocity and inversely as the distance the level considered is from the ground. For the pilot then, this type of roughness may be expected to be a maximum near the ground at the time of highest wind ax indicated below in figure 10.

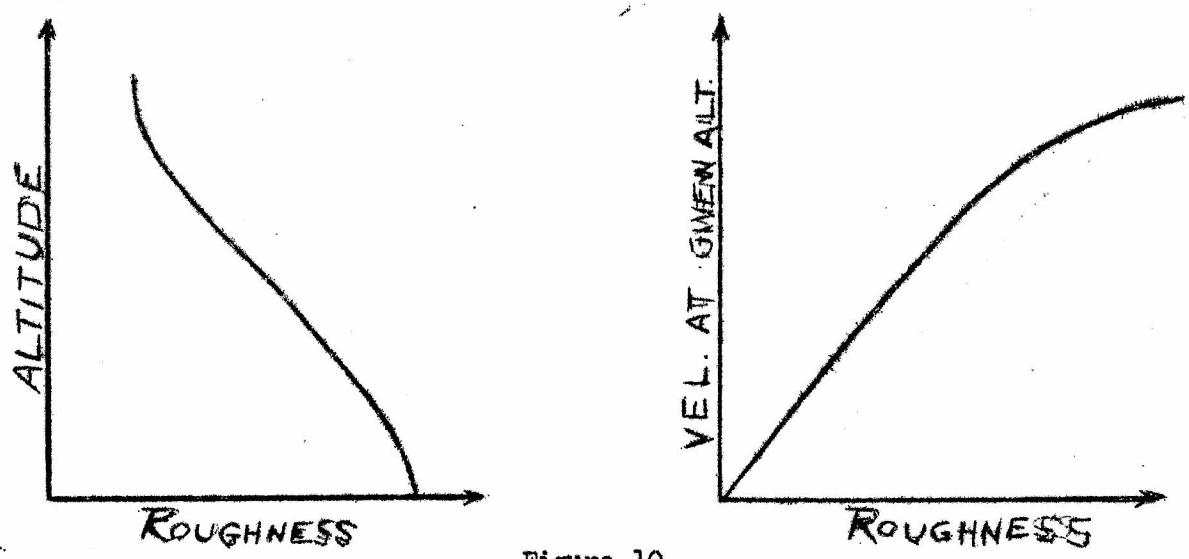


Figure 10

The rule for the pilot is, obviously, the higher the flying level chosen, the smoother the flight will be. A corollary admonition is to exercise caution in landings and take-offs.

The second type, the small scale convection over local orographic hot spots, is familiar to every pilot. It is this type of air flow that bewilders the unsuspecting pilot who seemingly cannot actually settle down to a landing on a runway on a hot afternoon. The high rate of insolation has heated the hard surface of the runway to an appreciably higher temperature than the adjacent ground. The air over the runway soon is hotter than the air at the same level over the grass. The air over the runway expands, rises, and is replaced by air moving in from the sides of the runway, causing a continuous supply of rising air. The same phenomenon causes the commonly observed bump after take-off from a grass field adjacent to plowed ground, and the sudden loss of lift just after crossing the downwind edge in landing at the same field. The side view of this type field is shown below with the airplane in the two critical locations.

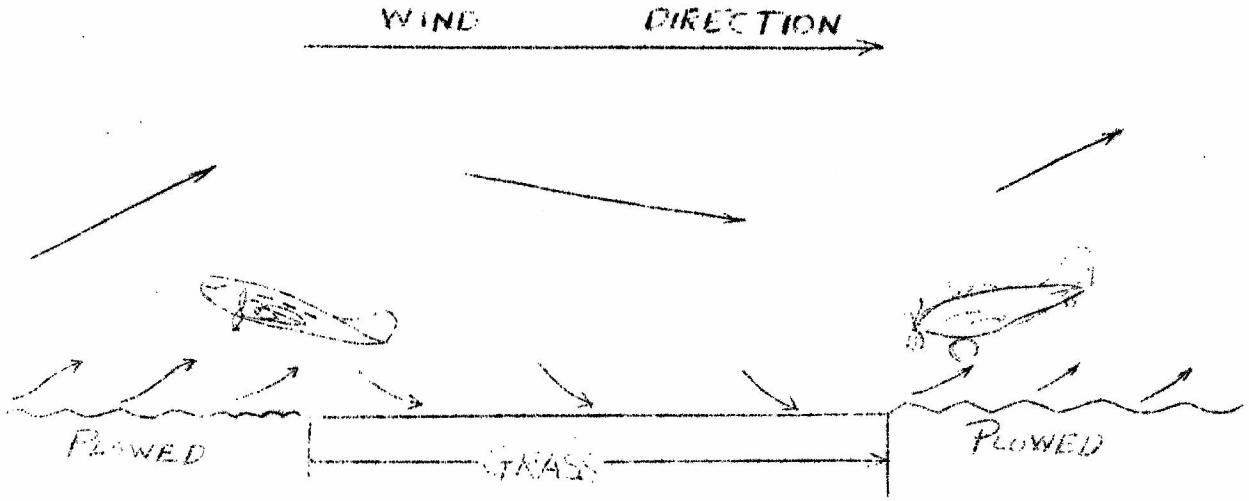


Figure 11

The third and most important type of orographic air roughness, that caused by the departure of air from a smooth approximately horizontal trajectory to a trajectory of vertical motion, is a result of the air stream being forced to conform to rough terrain. Even if no cloud forms are visible, as the pilot proceeds he should be able to visualize the flow of air over the rough country under him. With little practice the resultant flow picture will enable the pilot to avoid dangerous downdrafts and unnecessary discomfort due to roughness.

Beginning with the idealized case of air flow perpendicular to a long unbroken ridge, we will proceed to typical topographic situations. The number of possible solutions, of course, is infinite but conclusions derived from discussions of several typical situations will be useful in arriving at general rules for the use of the pilot in flying over rough country. Conformal flow over an unbroken ridge may be approximated by setting up a flow pattern as shown in figure 12.

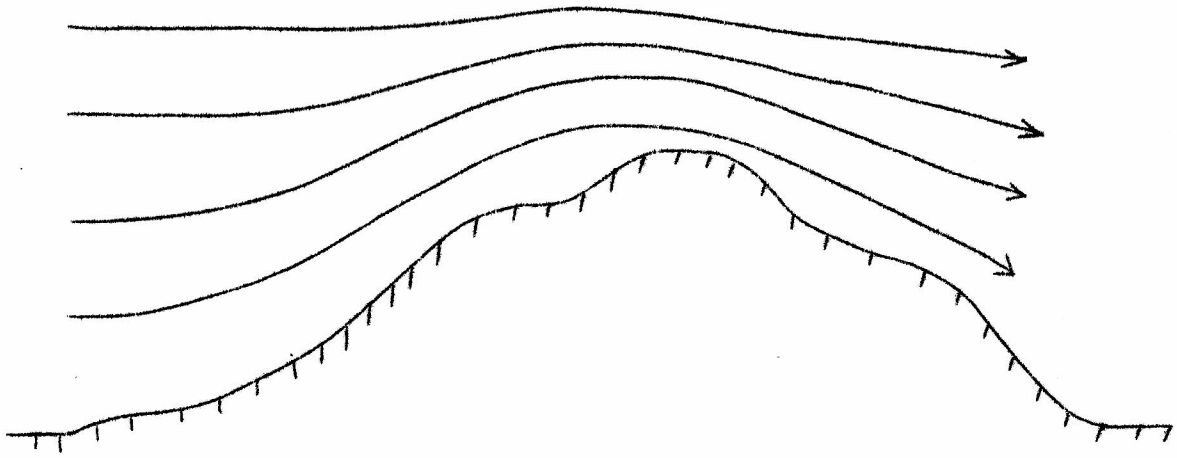


Figure 12

The maximum trajectory displacement takes place at the surface and the displacement is observed to be less and less in the air stream above the level of the crest of the ridge. The region of convergent flow, or crowding of air, directly above the ridge crest must have a materially increased velocity in accordance with Bernoulli's law. The maximum downdraft effect is on the lee side and close to the section of steepest slope. If the air below the level of the crest has a relative humidity close to a hundred percent, the cooling of the air in the rising section indicated may cause condensation but the subsequent rise in temperature in the descending current will quickly evaporate the droplets. However, as discussed under thunderstorms, if the air is initially conditionally unstable, the condensed portion of the air over the ridge crest will resist the expected sinking action. If the degree of convective instability is sufficient, the newly formed cloud will actually build up and subsequently move off with the upper air stream. Both of these cases are shown in side view, figure 13. Note the effect of the persistent cloud on the flow of air on the lee side of the ridge. The region of maximum downdraft is displaced well to the leeward.

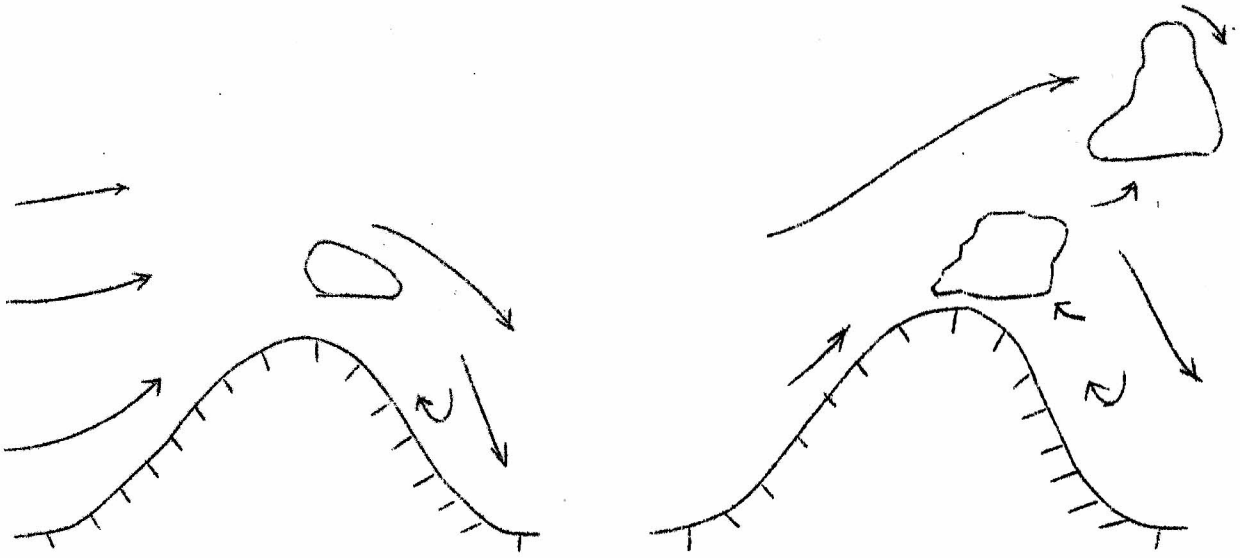


Figure 13

Returning to smooth flow without condensation over the ridge crest, another interesting result derived from theoretical investigations is that the first sinesoidal wave sets up subsequent but less pronounced waves of amplitudes and wave lengths determined by the intensity of the original wave. Illustrated below, figure 14, this conclusion is substantiated by the commonly observed riffles in water to the lee side of a dam or similar obstruction.

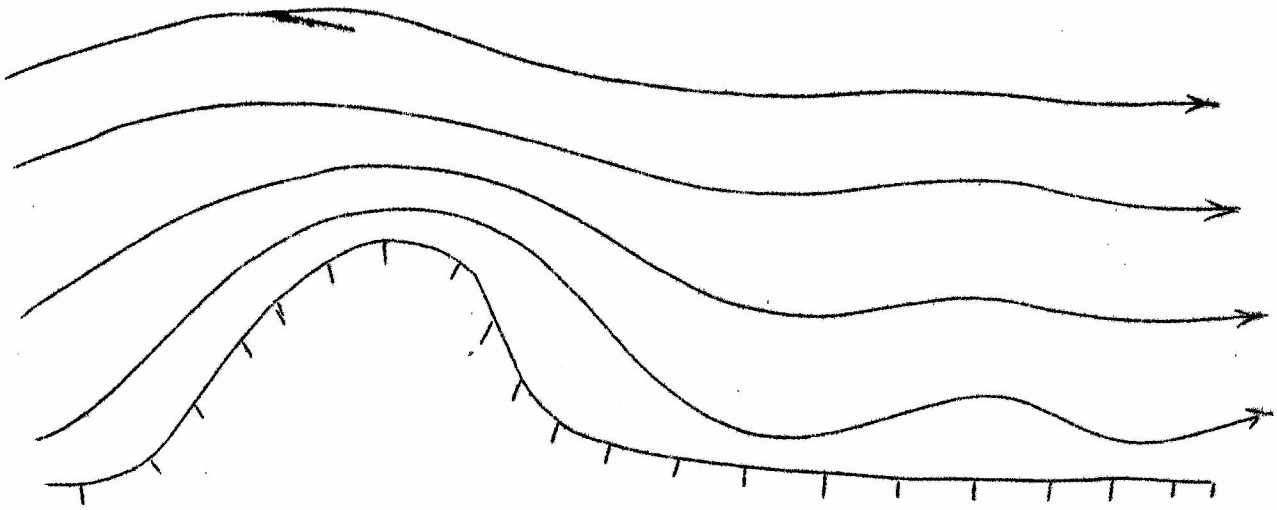


Figure 14

The visible effect of this riffle flow in air is to produce a stationary cloud over the crest and to the lee of the ridge, but only in the case illustrated in part in figure 13a, where the affected air originally was nearly saturated. These clouds are often observed in Scotland where the Peninne Mountains form an obstruction for the prevailing winds. On two occasions the same day, one of the writers definitely located one of the first waves to the lee of the Pelloncillo Mountains of southwestern New Mexico and to the lee of the Chiricahua Mountains of southeastern Arizona although there were no cloud forms in the extremely dry air.

There is a third classification to be discussed before we sum together the considered effects in order to obtain the idealized flow pattern perpendicular to an unbroken ridge. Air, just as any other moving matter, has inertia and resists a change of direction. After the air stream has been deflected upward in its trajectory by the upslopeland, it tends to continue moving in its new direction until other deflective forces overcome its directional inertia. As the air stream reaches the crest of the ridge, gravity tends to turn its trajectory toward the valley to the lee of the ridge. However, this turning action takes time and the result, illustrated in figure 15, below, is that a large back eddy tends to form to the lee of the ridge just as eddies form along the sides of the main current of a river.

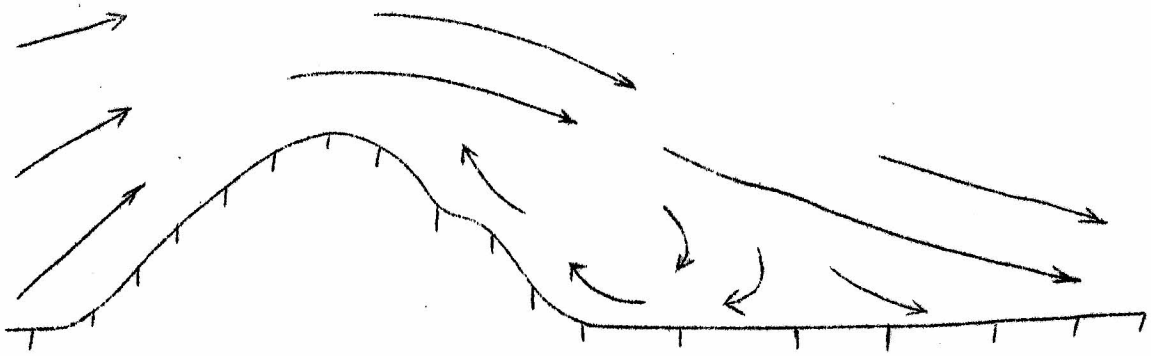


Figure 15

Now we are ready to combine all of the considered causes of orographical roughness (except the borderline case when air is initially near saturation as described in figure 13). The first figure below, figure 16, shows the flow during the afternoon of the day. The second figure, figure 17, shows the flow during the night.

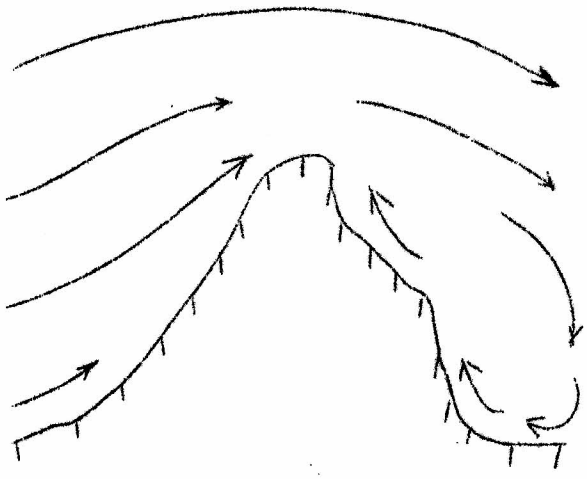


Figure 16

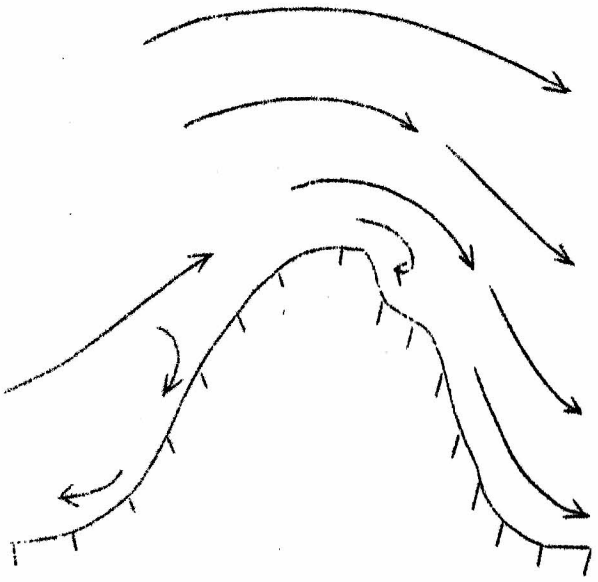


Figure 17

Note the effect of the influence of convection over hotspots. During the day the slopes of the ridge warm the adjacent air and accentuate the lifting of the air in passing up the windward side of the ridge. During the night, the slopes of the ridge cool the adjacent air and accentuate the downdraft to the lee of the ridge.

Because the conclusions illustrated above apply to an unbroken ridge which is found only occasionally in nature, it will be helpful to apply the general derivations to three typical orographic formations in order to approximate variations in the idealized flow pattern as actually found by the pilot in flight over: 1) A mountain pass, 2) a mountain peak, 3) the shoulder of a mountain ridge.

Considering a mountain pass as a definite break in the ideal ridge it is immediately apparent, from the assumption that air will flow as water, that the air stream will definitely converge into the pass from the windward side and diverge from the lee side. As illustrated below in figure 18b, this action of extreme convergence serves to accentuate the frictional component of roughness found in the ideal case.

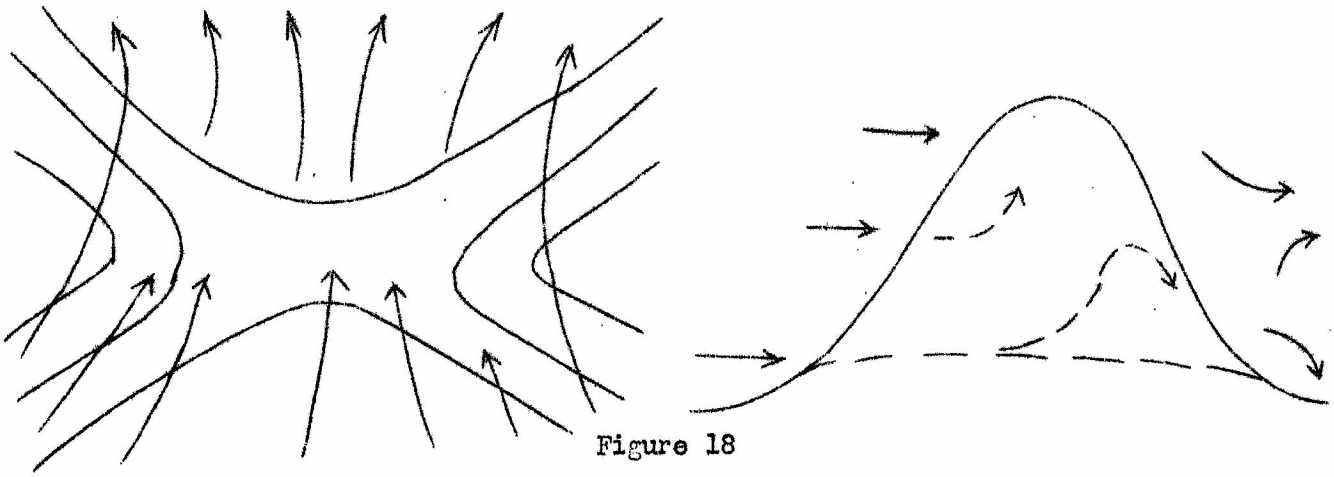
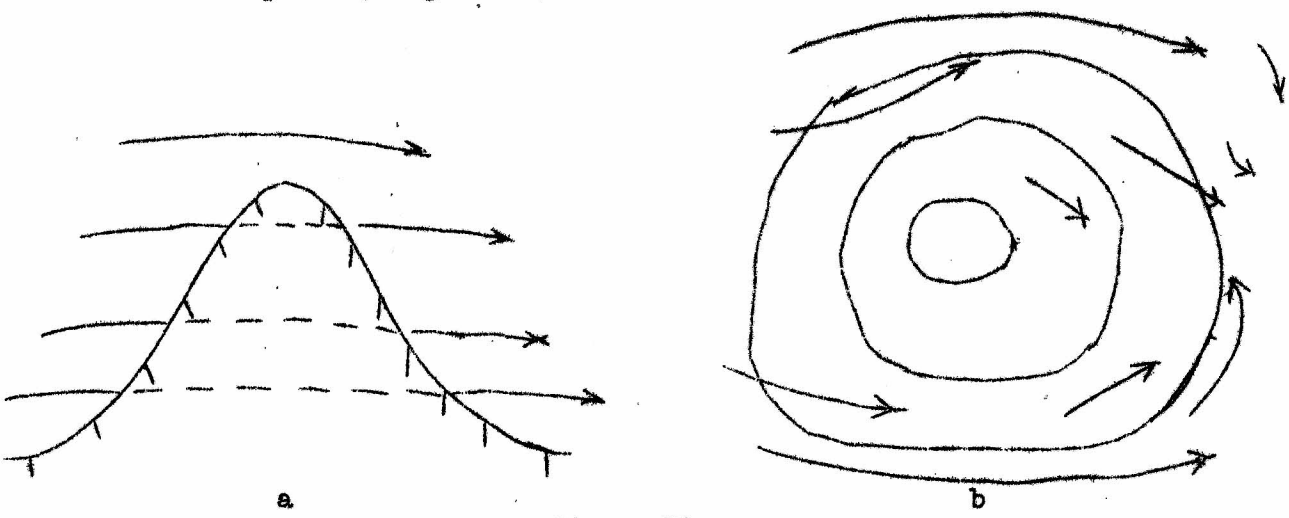


Figure 18

Note that the region of severe roughness extends even farther to the lee than it does in the unbroken ridge flow. This conclusion has been substantiated by reports from pilots stating that the region of roughness south of Cajon Pass between the San Gabriel Mountains and the San Bernardino Mountains extends almost to March Field (a distance of approximately 25 miles) even in moderate northerly winds. Furthermore, the downdrafts to the lee is much more severe than the lift to the windward because the air at low levels in the valley upwind from the pass does not take part in the mean flow to the extent that the air near the ground does on the downward side of the pass. In other words, the pilot should not judge the intensity of the downdraft to the lee of the pass by the lift felt to the windward.

The second of the typical orographic formations, the mountain peak, has the minimum relative effect on the airstream above and around it. The diversion of the airstream caused by the mountain peak is not as intense a process as the convergent flow through a mountain pass. In particular, the isolated and symmetrically sharp mountain peak causes the least deformation in the airstream for a given flat plate area exposed because the diverted air may transmit its deflection through a relatively unlimited horizontal extent of air, causing the crowding of air to be reduced very much in comparison to the case of the mountain pass. Therefore, as shown in figure 19 below, the pilot who might expect a violent downdraft to the lee of the mountain such as Sierra Blanca of Hudspeth County, Texas, actually would not experience as real a loss of lift as he would in the same flow of air perpendicular to a ridge of the same altitude. On the other hand, the same pilot flying fairly close to the shoulder of such a mountain will find himself in a relative side wind, as shown in top view, figure 19, below.

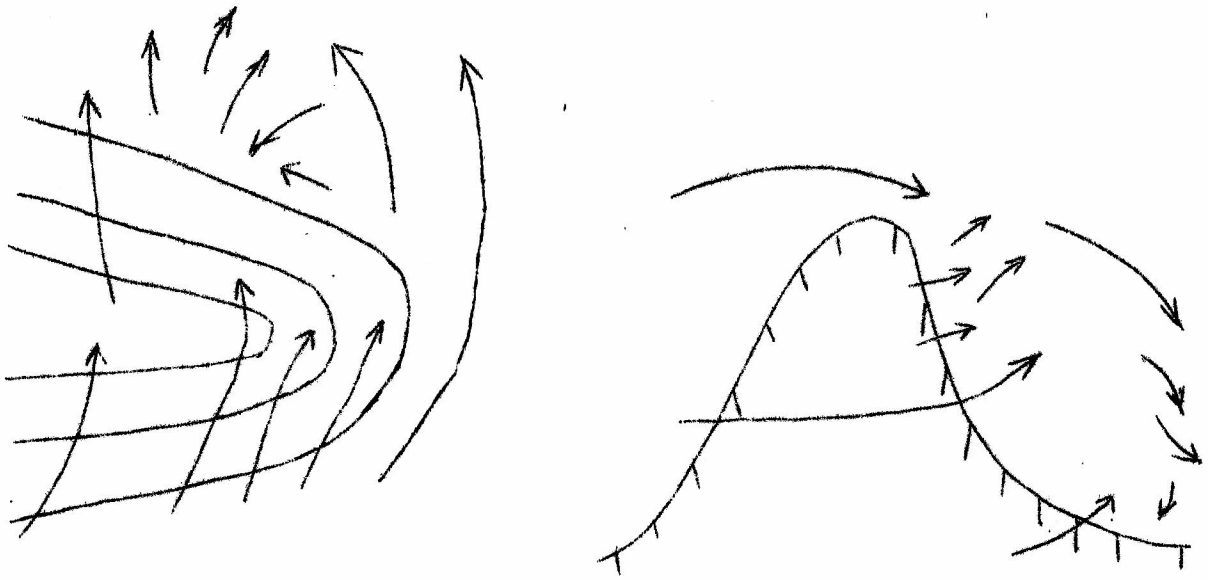


a b

Figure 19

It should be remembered, however, that if a symmetrical mountain peak is as large as Mt. Rainier, Washington, the fact that its effect on the air flow is less than a ridge of similar magnitude should not be used. A symmetrical mountain will cause turbulence no matter what direction the wind is blowing. One of the writers has experienced the extreme severity of turbulence to the lee of Mt. Rainier on occasion of strong winds.

The third of our typical formations, the shoulder of a mountainous ridge, is exemplified by El Capitan in Culberson County, Texas. The resultant air flow over and around this mountain in an east or west wind of even moderate velocities is approximately as illustrated in top view, figure 20a, and end view, figure 20b.



a b

Figure 20

Note the result is really a combination of the flow pattern over an unbroken ridge and an accentuation of the flow pattern around one side of a mountain peak. The side flow around the shoulder of a ridge is a maximum because all of the air approaching the shoulder must be forced up over the ridge or take the lower level, end route. The natural result is that the displacement of the air stream around the shoulder of the ridge is a maximum. As discussed under the section, "Ceilings and Visibilities", an inversion marks a stabilized layer of air which resists upward motion. If the pilot notices that the top of the layer of air containing smoke or other particles which reduce visibility is at the same level as the top of the ridge crest, he may count on the side flow around the shoulder being a maximum.

From the discussion above concerning the effects of orographic roughness, some factors may be listed which indicate information useful to the pilot. The time when downdrafts are at a maximum for a given situation is:

1. During the night hours.

Locations where downdrafts may be expected are:

1. To the lee side of orographic obstructions.
2. To the lee of the riffle wave set up by a major obstruction.
3. To the lee of a cloud at the top of, or moving away from, an obstruction.

Conditions necessary in order that downdrafts will be a maximum are:

1. Greatest wind velocities.
2. Wind direction perpendicular to the long axis of the obstruction.
3. Greatest slopes to the lee of the obstruction.

Time when roughness is at a maximum for a given situation is:

1. During the hours when the sun is highest.

In a given region of roughness the zone of maximum roughness is:

1. In a mountain pass.
2. In the lowest levels.

Conditions necessary in order that roughness will be a maximum are:

1. Greatest change of wind velocity with altitude.
2. Maximum orographic obstructions.
3. Greatest change of heating characteristics of the ground in adjacent areas.

Ceilings and Visibilities

If a way to formulate simple criteria to determine the future ceiling and visibility could be devised, the comprehensive weather forecasting services now extant could be replaced by each pilot making his own accurate flying forecast. The purpose of this section is to provide the pilot with a few simple aids to enable him to grasp more fully the picture presented by the meteorologist and to formulate an estimate of the weather tendency in the event he does not have recourse to a weather office and must make a decision based on the trend the weather will take. It is emphasized that none of the conclusions in this section should be used to nullify any part of the detailed airline forecast rendered by the meteorologist. The conclusions derived in this section are, of necessity, extremely general and cannot possibly conform in detail with any given synoptic situation as well as a specific airline forecast.

In general, ceilings may be considered a function of the lowest continuous level of condensed moisture. Usually the lowest level of condensed moisture will be in cloud form but may be in the form of rain drops in the case of heavy rain beneath the clouds, causing the effective ceiling to be less than the lowest level of cloud particles. Visibility, too, may be considered a function of the extreme case of the lowest level of continuous condensed moisture or fog. In addition, visibility is a function of haze and smoke.

There are three aids available to the pilot to help him determine the weather tendency or probable change in ceiling and visibility in any given situation. They are as follows:

1. The frontal disturbance.
2. The synoptic high pressure area.
3. Wind velocity and direction.

A front is a zone of demarkation and interaction between two large air masses, the temperature and water content of which usually differ considerably in magnitude. For our purpose, a frontal disturbance may be considered a concentration of weather phenomena associated with reduced ceilings and visibilities. There are two general types of frontal disturbances: (1) cold and (2) warm. The basic difference between them is simply the relative motion of the front over the ground.

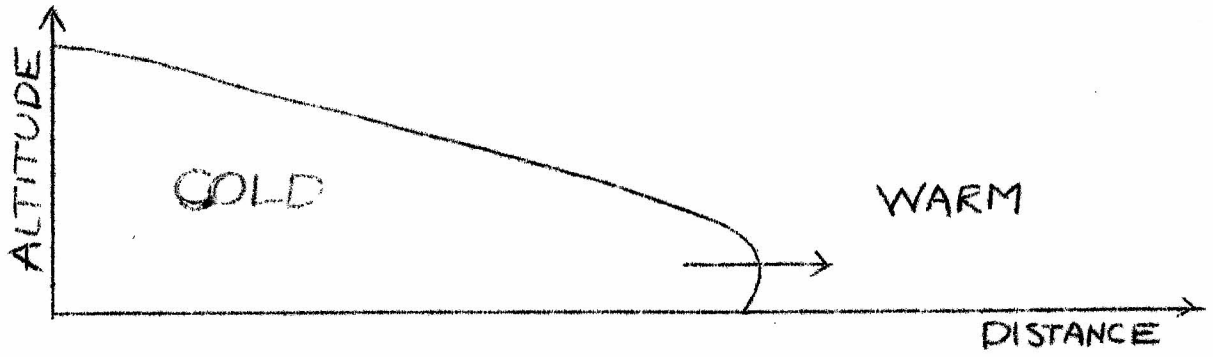


Figure 21

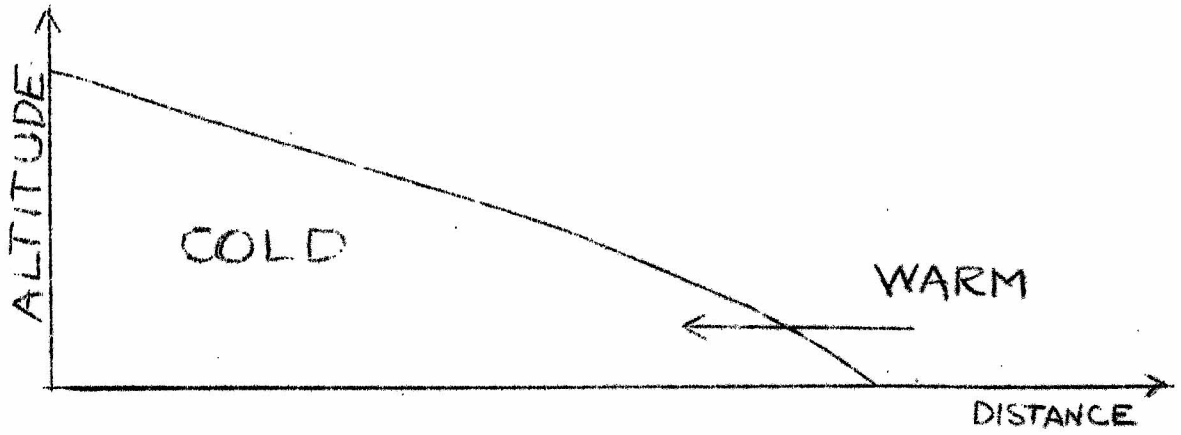


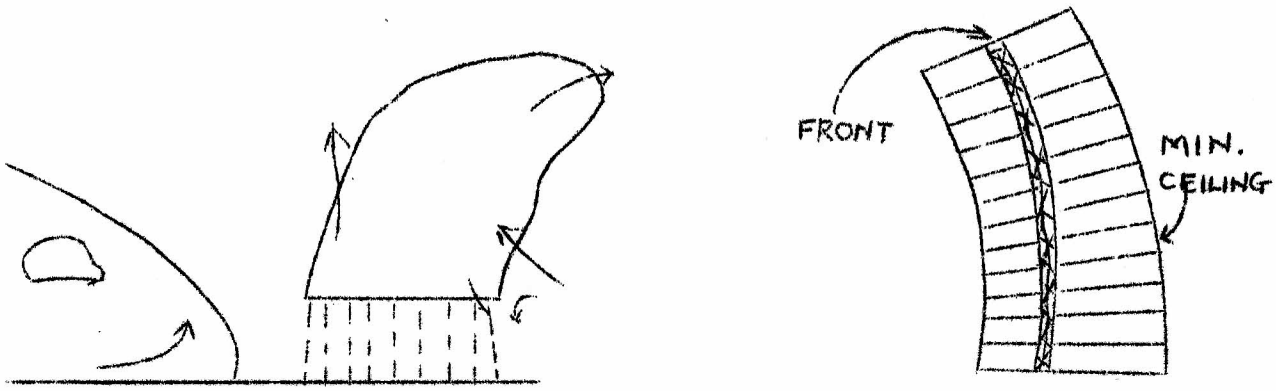
Figure 22

As illustrated above in figure 21, the intersection of the cold front with the ground is continuously displaced by the cold air. Similarly, the intersection of the warm front with the ground, figure 22, is continuously displaced by the warmer air. Note the effect of friction between the ground

and the moving air in changing the slope of the front near the ground. In particular, notice the extreme exaggeration of the vertical scale. The ground distance represented is equal to 100 miles and the vertical represents only one mile. There are several factors which contribute to the difference between the cloud systems normally associated with cold and warm fronts. Both the cloud systems cause ceilings and visibilities to be lower than in surrounding regions but there is considerable difference in:

1. Area affected.
2. Rate of change of conditions at a given point.

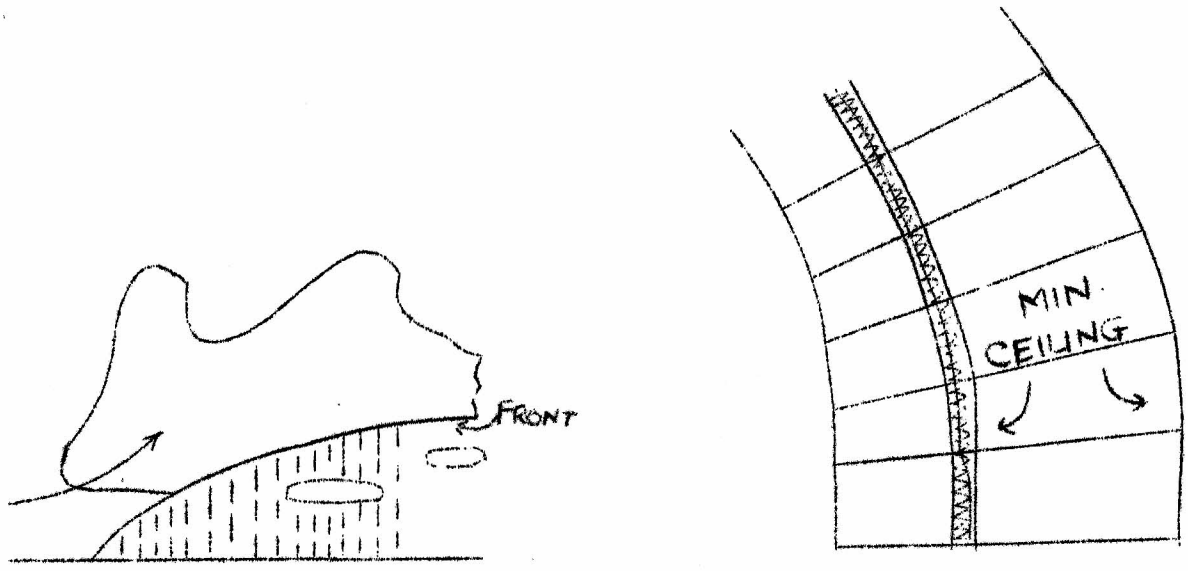
As illustrated below, in figure 23, the normal cloud pattern associated with a cold front is relatively narrow in cross section.



a b

Figure 23

The cold front usually is a faster moving front than the warm, which accentuates the rapidity of change of conditions at a point passed by the cold type disturbance. The fact that the intersection of the cold front with the ground is often called the squall line or "wind shift line" is a good indication of the turbulence and quickly changing conditions associated with the cold front. A typical cold front passage at a station may cause sky conditions to change from high scattered clouds to mid level overcast through zero - zero conditions with precipitations and back again to broken and then scattered clouds in a time interval of three hours or even less. On the other hand, as illustrated below in figure 24, the cloud system associated with a warm front is much more extensive.



a b

Figure 24

In contradistinction to the usual more rapid movement of the cold front, the cloud system associated with a warm front may take a day or more to pass a given point. The transition from the high scattered clouds through solid overcast with steady precipitation to gradually lifting ceilings after the front passage is generally slow and rather steady.

From the necessarily brief discussion above, several conclusions may be drawn to aid the pilot in visualizing the general aspects of the weather if he knows that a front of either type exists in a region close enough to affect the ceilings and visibilities along his flight line.

I. Ceilings
   A. Cold front
      (1) Sector of minimum ceiling narrow (25 - 75 miles)
      (2) Rate of movement of cloud system fast (15 - 40 m.p.h.)
   B. Warm front
      (1) Sector of minimums ceilings wide (75 - 300 miles)
      (2) Rate of movement of cloud system slow (5 - 20 m.p.h.)

Because visibility is a function of haze and smoke in addition to the extreme case of the lowest continuous level of condensed moisture or fog, fronts do not have as direct a relationship to visibilities as they do to ceilings. However, the pilot may consider the region of minimum ceiling associated with a front as a region of greatly reduced visibility and in that sense apply the above conclusions to the effect of frontal disturbances on visual reference near the ground.

The high pressure area in the synoptic or general sense may be considered a region of unlimited ceiling. There is an exception to this rule, however, important enough to consider. In the air to the east and southeast

of the center of a high pressure area, local squalls with or without precipitation may be caused by the instability (discussed under thunderstorms) induced by a rapid flow of cold air from the north over the warmer surface of the earth. This phenomenon is usually of a local character and the squalls may be avoided by the pilot. The effect of a high pressure area on visibility is not as favorable nor as easy to generalize. As a whole, the very fact that a high pressure area is stable and not conductive to cloud formation tends to make it an area conductive to lower visibility. Particularly, in thickly populated areas and coastal regions, the stability of the air tends to confine to the lower levels the smoke and haze found in these areas. The apparent top of the smoke and haze commonly observed by pilots marks the base of the stabilized layer. As the high pressure maintains, the stabilized layer becomes more and more pronounced and slowly settles to a lower level, although during the heat of the day it will tend to lift appreciably. If the pilot knows relatively high pressure exists in the region of his flight he may consider its effect on ceilings and visibilities as follows:

High pressure area
- A. Ceilings
  - (1) Unlimited except in possible local squalls
- B. Visibilities
  - (1) Generally ten miles or more
  - (2) In thickly populated areas
    - (a) May be reduced considerably by smoke below stabilized layer (1500-5000 ft.)
  - (3) In coastal areas
    - (a) May be reduced considerably by haze below stabilized layer (1500-5000 ft.)

Wind velocity and direction affect both ceilings and visibilities. Obviously, a moving air stream tends to carry with it any substance that is embodied in its mass or that exists along its boundaries. Consideration of the wind direction and velocity often is the only means the pilot has available to estimate the ceiling and visibility at a given location. Orographic modifications in the air stream both in trajectory and substances available to wind transport should be kept well in mind by the pilot in making his decision. The surface over which the air will move before reaching the location in question may entirely change conditions of ceiling and visibility within the air between the time of observation and the time the air arrives at the given location. Downslope or sinking movement will tend to dissipate clouds; upslope or lifting movement will tend to increase the thickness of pre-existent clouds. A trajectory over a dry land surface will not affect appreciably a pre-existent cloud layer; a trajectory over a water surface may accentuate cloudiness. In general, a strong wind will tend to keep the ceiling above a certain minimum, usually about three hundred feet. However, there are two exceptions to this rule: (1) if the wind is continuously upslope, the ceiling and visibility promptly reduce to zero - zero; and (2) if the air has a dew point appreciably higher than the surface over which it is being carried, the ceiling and visibility quickly will drop to zero - zero and will stay that way if the surface happens to be a good snow cover.

As has been well evidenced by the great dust storms of recent years, if the surface ground is dry and not protected by vegetation, wind of even moderate velocity will cause extreme reduction in the visibility.

In conclusion the pilot may consider that wind velocity and direction has the following effects on ceilings and visibilities:

I. Wind direction
   A. Ceiling
      (1) Downslope movement will dissipate cloud forms
      (2) Upslope movement will accentuate cloud forms
      (3) Trajectory over water may increase cloudiness
   B. Visibility
      (1) Upslope wind tends to induce zero conditions
      (2) Trajectory over a dust source will diminish visibility
      (3) Trajectory from a smoke source will diminish airport visibility

II. Wind velocity
   A. Ceiling
      (1) Strong wind tends to prevent zero conditions (300 ft.)
      (2) If continuously upslope, strong winds increase persistence of zero comditions
   B. Visibility
      (1) Strong winds tend to dissipate smoke
      (2) Strong winds over a dust source reduce visibility

Aircraft Icing

Ice is one of the most important hazards to modern aviation. It is dangerous because, to date, no completely satisfactory method has been developed for controlling ice after it has formed on the airplane. The danger lies neither in the ignorance of its potential existence, nor in the ignorance of the processes by which it is formed on the airplane. These processes are indeed quite simple.

The pilot who observes ice forming on his airplane is not necessarily in trouble. It is possible in specific instances that he could continue his course unaltered without mishap. He will, however, sooner or later, run into serious trouble if he does not have at least a rudimentary knowledge of the following factors:

(1) Type of ice forming together with its effect
(2) Why a certain type of ice is forming
(3) How to use the tools he has in determining the type of ice to be expected
(4) Procedure to minimize danger after the ice begins forming

There are two types of ice formation: (1) rime ice, and (2) clear ice. Rime is a white, opaque, granular substance composed of small, loosely bound ice particles; clear ice is generally a colorless, transparent, smooth

substance composed of amalgamated frozen drops of water. A modified type of clear ice is the type which has been impregnated with snow, or sleet, during its formation, rendering it opaque and less well knit than pure, clear ice.

The extreme tenacity of clear ice makes it highly resistant to cracking and removal by de-icing equipment. The modified type of clear ice is more easily removed, for the reason that its structure is somewhat weakened by air bubbles induced by the snow and sleet. On the other hand rime has so little adhesive power that in most instances the vibration of the airplane will break it off. Clear ice forms on the leading edge of the exposed surface in the shape of a mushroom, while rime builds forward in a streamline shape, figure 25.



Clear Ice Rime Ice

Figure 25

It is immediately evident that clear ice increases the wing loading and impairs the characteristic of the airfoil by increasing drag and decreasing lift, with the possibility of subsequent loss of control of the airplane. Rime has little adverse effect in these respects, although the weight effect may become appreciable. The snow impregnated type of clear ice, being more easily cracked and removed, produces effects less dangerous than pure clear ice, but is considerably more dangerous than rime. Therefore, it can be said that clear ice is by far the more dangerous of the two distinct types.

Both clear ice and rime ice form in either of two different ways: (1) when the temperature of water before coming into contact with the airplane is above freezing; and (2) when water has been subcooled to a temperature below freezing before striking the airplane. It will be noted that the terms "above freezing" and "below freezing" have been used. This has been done with the idea of incorporating into the discussion the possibility of icing at a free air temperature above 0°C. Icing under this condition is possible because of the effect of evaporation cooling at the surface of the airplane when the relative humidity is less than 100%. It frequently happens that the relative humidity within a cloud is less than 100% and this is generally true of the outer boundary layer of the cloud where evaporation is taking place. The difference between the free air temperature and the actual reduced temperature at the aircraft surface may be sufficient to cool below 0°C. water coming into contact with the surface. Investigation by McNeal shows that ice forms at temperatures as high as 2°C. but that ice which forms above 0°C. is not severe.

The low relative humidity in the thin boundary layer of the cloud accounts for pilots reporting that icing is heavier in this boundary region than it is toward the center of the cloud.

It has been found that cooling by the Bernoulli effect around the airfoil is offset by heat due to friction between the airfoil and the air flowing over it.

(1) Water whose temperature is above freezing coming into contact with an airplane surface whose temperature is below freezing. A type of situation in which this may occur is illustrated below in figure 26.

Raindrops, falling from a warm front, and striking an airplane flying in the colder air beneath the front, freeze upon the airplane, if its surface temperature is at the time, or becomes by evaporation cooling, zero degrees C. Icing also occurs when an airplane picks up water within a cloud where temperatures are above freezing, and then enters a region where the temperature is below freezing. As the airplane is cooled by the surrounding air to the icing range, the water accumulated on its surfaces freezes. Ordinarily it is said that icing occurs only where visible moisture is present. Provided that the airplane surface does not reach a temperature of zero degrees centigrade until after it emerges from the cloud, icing may occur outside the region of visible moisture. The latter case, which is relatively unimportant because of its borderline characteristic and the lack of a continuous supply of moisture, is the only exception to the rule that for ice formation water in the visible form must be present in the air.

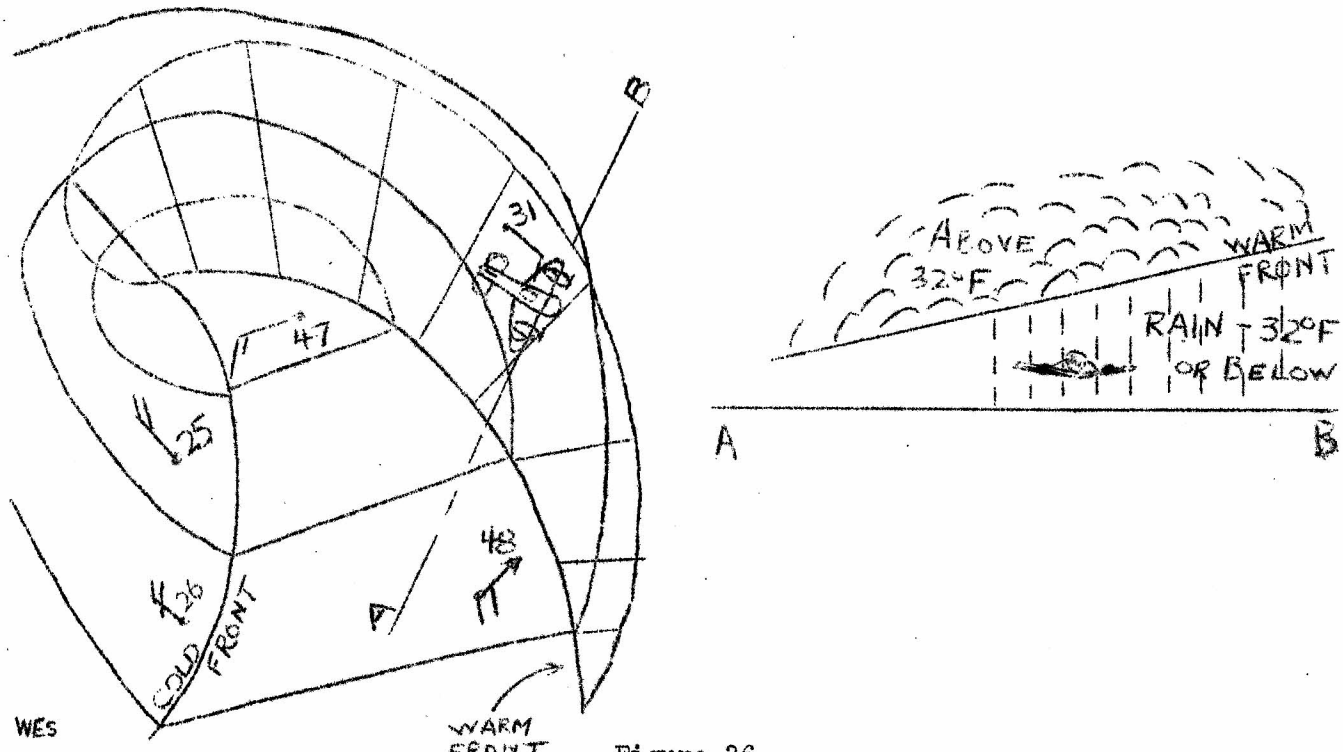


Figure 26

Impact with sub-cooled water droplets within a cloud or below a cloud from which they are falling. It is not within the scope of this paper to analyze the process of the sub-cooling of the water droplet. Water droplets may remain in the liquid state at temperatures as low as 40°C. Agitation starts the freezing process. Impact with the airplane supplies the necessary agitation.

Part of the droplet is frozen on impact; evaporation from the balance freezes a large portion of that balance. Table 1 and figure 27 show the remarkable effect of sub-cooling on the entire freezing process. The relations shown are independent of the original size of the droplet.

Subcooling °C	Frozen on Impact %(A)	Frozen by Evaporation %(B)	Lost in Process of Evaporation %	Portion of Original Droplet Frozen %(C)
0	0	86.7	13.3	86.7
-4	5	82.3	12.7	87.3
-8	10	78.0	12.0	88.0
-12	15	73.7	11.3	88.7
-16	20	69.3	10.7	89.3
-20	25	65.0	10.0	90.0
-24	30	60.7	9.3	90.7

Table 1

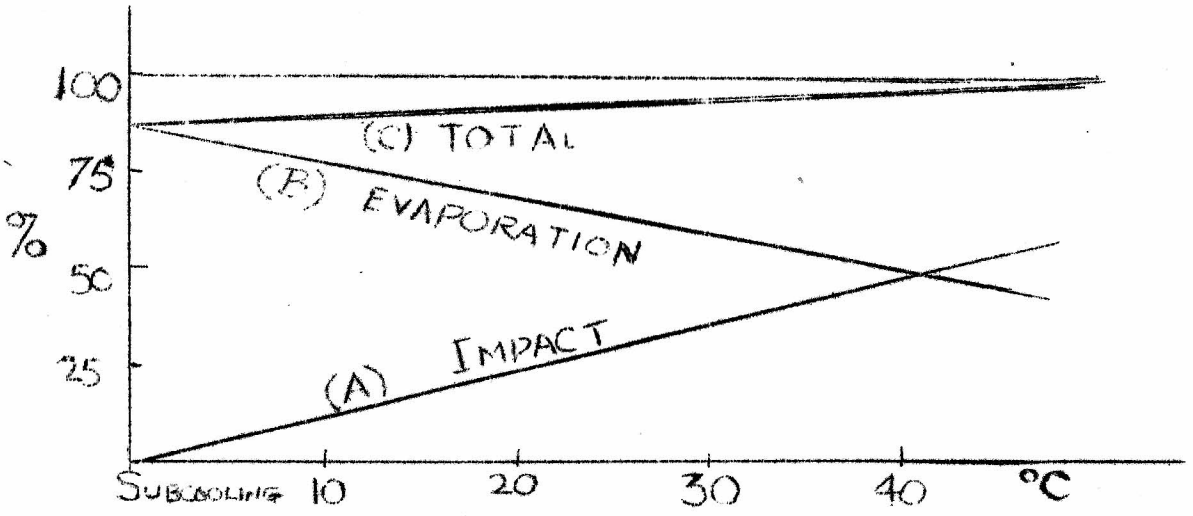


Figure 27

The following important results are brought out by Table 1 and figure 27:

(1) The percentage of the droplet frozen on impact, line A, is directly proportional to the degree of sub-cooling of the droplet.

(2) The percentage of the original droplet frozen by evaporation, line B, decreases linearly with the degree of sub-cooling.

(3) The total portion of a droplet frozen, line C, is virtually independent of the degree of subcooling (86.7 - 90.7% for range of 24°C.).

(4) The greater the percentage frozen at the instant of impact the smaller the percentage frozen by evaporation.

The differentiation between the effects of impact and evaporation freezing is significant. That part of the droplet frozen on impact is restricted to the point of impact. However, that portiom frozen by evaporation takes an appreciable time to solidify and during this time is spread out and back over the airplane surface. This spreading action during the freezing process is why clear ice has its well-knit, homogeneous structure and mushroom shape.

So far, we have analyzed the freezing process of the droplet from the quantitative standpoint. It has been pointed out that impact freezing is virtually instantaneous but no mention has been made of the rate of evaporation freezing.

No complete analysis of the rate of evaporation as related to aircraft icing has been made. But it is generally agreed among scientists that vapor pressure differential between the evaporation surface and the outside air, together with the velocity of air flow over the evaporation surface are the controlling factors. The vapor pressure differential is proportional to the degree of subcooling of a droplet before it strikes the airplane surface. Figure 28 below shows the effect of subcooling on the rate of evaporation.

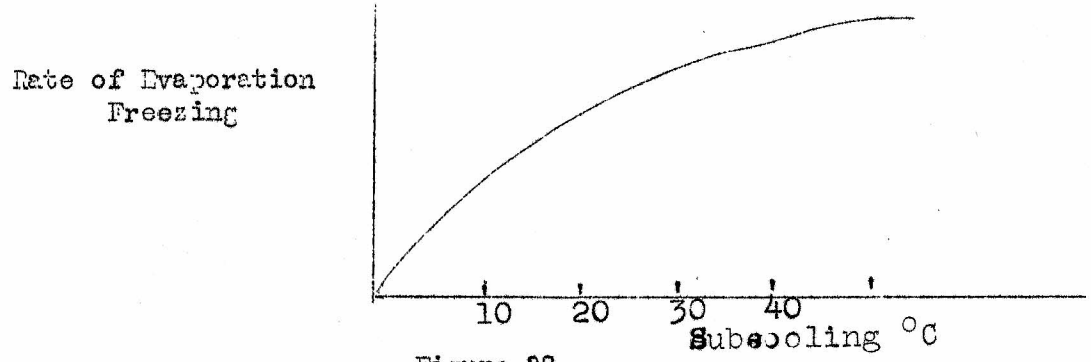


Figure 28

No data are available on the effect of velocity of air flow over the airfoil. Experiment along this line should be of great assistance in clarifying some unknown factors of aircraft icing. It is safe to assume that the greater the velocity of flow over the airfoil the faster the evaporation process becomes.

The amount of spreading of a particular droplet is limited to a certain extent by the rate of the evaporation freezing process. Therefore, a great degree of subcooling and high airspeed are factors which tend toward the less dangerous phenomenon, formation of rime ice.

In a given situation, a large droplet will spread over a greater area than a small one. In other words, the larger the subcooled droplet, the greater will be the tendency toward clear ice when it is struck by the airplane. As shown in the discussion of thunderstorms, the size of the water droplet is a function of the vertical velocity within a cloud. This is why J. K. Lacey (M.I.T. Thesis, 1936) has correlated severity of icing to the lapse rate which, of course, is the determining factor of instability, hence vertical velocity within a cloud.

The airplane pilot has several tools which he can use to great advantage in predicting the type of ice he will encounter. These are: (1) Outside air temperature, (2) Turbulence or roughness, (3) his vision.

Outside air temperature can be read directly from the free air temperature thermometer which is installed in the cockpit of almost every modern airplane. McNeal (Journal of Aeronautical Sciences, Vol. 4) has shown the following relations of outside air temperature to icing.

(1) Ice may be expected in any cloud where temperature is 2°C. or less. That occurring above 0°C. is relatively unimportant.

(2) On the average, clear ice prevails above -8°C; rime ice prevails below -8°C. Clear ice may form below -8°C.

(3) The lower the temperature the greater the tendency toward rime.

Turbulence or roughness is a measure of vertical velocities within the air, and as explained above, has a definite bearing upon the type of ice to be expected.

(1) If before entering a cloud from below, above, or from its side, the air outside the cloud is extremely rough, clear ice may be expected within the cloud if the temperature is below 2°C.

(2) If while flying within the smooth air of a cloud where rime ice is forming, roughness is encountered and increases, it is an indication that clear icing impends.

(3) Smooth air is indicative of rime icing.

What the pilot can see from his airplane may be used to great advantage as follows:

(1) Dangerous icing occurs only where visible moisture, i.e., some cloud form, is present in the air.

(2) Appearance of large raindrops beneath a cloud is sufficient evidence that clear icing will be encountered if the pilot enters the cloud or flies through the rain beneath the cloud in a region of icing temperature.

(3) Recognition of cloud forms is an advantage to the pilot. Clear icing is more likely to occur in the convective type clouds of the cumulus family; rime icing in stratus clouds.

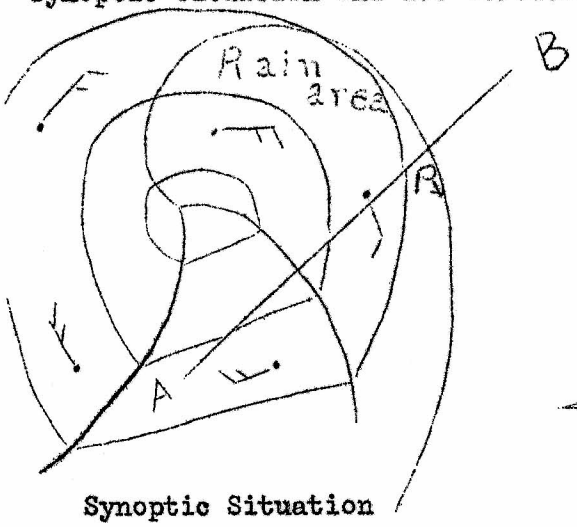
(4) Clear ice should be expected in frontal clouds where appropriate temperatures exist.

(5) Dry snow indicates a safe condition; wet snow indicates possibility of relatively dangerous clear icing, and climbing should decrease the danger.

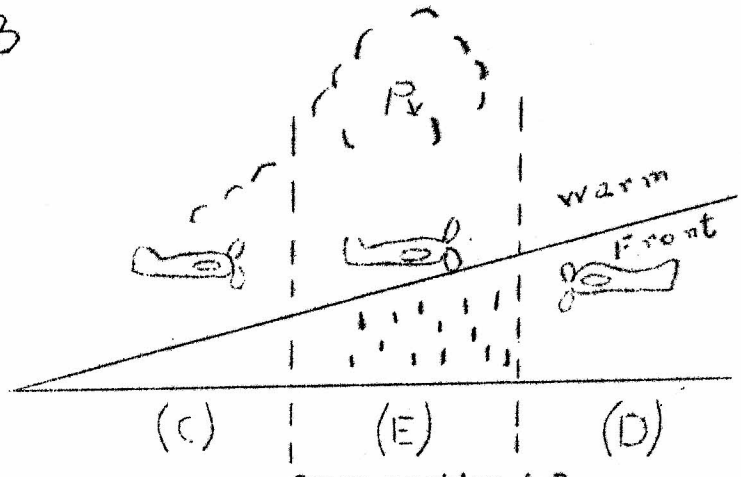
(6) Rime icing may be converted into clear icing when passing from regions of flat terrain to mountainous regions where lifting is accentuated by orographic influences.

Finally, the pilot should know what procedure to take to minimize danger after ice begins forming. A general plan is outlined below.

If rime ice is forming there is no immediate danger provided that the airplane is equipped with airfoil deicers. However, the pilot is warned in this connection that in one particular case, that of the warm front thunderstorm, he may suddenly run into severe icing conditions, after he has been picking up only light rime ice. The diagram below, figure 29, shows the synoptic situation and its vertical cross-section.



Synoptic Situation



Cross-section A-B

Figure 29

In regions (C) and (D) the air will be smooth and perhaps only light or moderate rime ice will be encountered. Suddenly and without warning the pilot finds himself in a thunderstorm region (E) where very severe icing is encountered. The pilot should be on the lookout for this situation, and at the first signs of severe turbulence he should turn back.

If clear ice is forming, the pilot should change his flight plans in order to avoid taking on a dangerous amount of clear ice. His decision is influenced by several factors; namely, (1) the altitude of the 2°C temperature level above the ground; (2) type of terrain below him; and (3) the height of the cloud base above the ground. In general, descent is to be preferred to climbing if the pilot is assured that descent is reasonably safe. It is obvious that the pilot must know the nature of the ground over which he anticipates descent. The height of the cloud base and 2°C. temperature level should be obtained from a nearby airways station. In mountainous areas in particular, and at other places, if possible, the descent should be planned so as to break through the cloud over the reporting airways station.

When clear ice begins forming, a good rule is to double back to the region where no clear ice was forming.

When clear ice is forming in rain in the cold air beneath a warm front, the pilot should descend below the 2°C. level or, if a field is available, land immediately. If this is impossible, and there is no indication of warm front thunderstorms (lightning or severe turbulence) climb as fast as possible for the top of the cloud system.

If rime ice is forming over flat terrain do not fly toward a mountainous region unless there is assurance that the cloud system is not continuous to and over the mountains. Rime icing, in fact, might be converted into clear icing over the mountain region.

Avoid climbing into cold front clouds to minimize icing conditions.

Never climb into a thunderhead to avoid ice.

It is by far easier to avoid severe icing than it is to escape it after it starts forming. Therefore, before takeoff the pilot should be sure that he has the best available icing information for the route which he is to fly. Too much emphasis cannot be placed upon the advantage of knowing the synoptic situation. If the weather conditions over the proposed route are known, the pilot will know where to expect ice and how to change his flight plans when severe icing is encountered. Always consult the weather specialist before take-off.

Frost Formation on Aircraft

Frost, which has been dismissed by Taylor (Aeronautical Meteorology, Revised Edition, 1940), by McNeal (Journal of Aeronautical Sciences, Vol. 4, Nov., 1936-Oct. 1937) as relatively unimportant considered from the icing

standpoint, may prove to be a hazard to the unsuspecting pilot. Dangerous frost may be divided into two classes: (1) Frost that forms on the airplane overnight, preventing take-off; and (2) frost that forms in flight just after take-off.

Conditions favorable for the formation of frost are as follows: (Napier Shaw, Manual of Meteorology).

(1) Good radiating surface
(2) Still air
(3) Clear sky
(4) Thermal insolation of radiating surface, i.e., not in contact with a surface from which it might receive heat by conduction.
(5) Falling temperature, temperature and dew point close together and just above 0°C or lower.

For the pilot the above conditions may be sifted down to a few simple rules. There must be insufficient solar insolation to heat the airplane surfaces and therefore frosting must be expected at night. Airplane surfaces are well insolated from outside sources of heat except the surrounding air. It is inconceivable that any effective heat could be gained or lost through tires and oleo struts. Regardless of the radiating capacity of the airplane surfaces, heat is readily lost by conduction to the surrounding air. Freedom of circulation around the surfaces affords transport of heat from their vicinity. It follows that the temperature of the airplane surfaces may be considered, for practical purposes, the same as that of the ground from which radiation is occurring.

For the pilot who might be required to leave his airplane out overnight preflight frost conditions are:

(1) No noticeable wind
(2) Clear sky
(3) Temperature falling and close to dew point
(4) Free air temperature just above 0°C or less.

When these conditions exist, the wings and control surfaces of the airplane which is to be left out over night should be covered. This precautionary measure is much easier than removing the frost deposit when the temperature is below freezing. The pilot who may be forced to stake out his airplane at night without facilities to cover the wings and control surfaces should not attempt to take off before removing the frost, however arduous the task may be. An attempt is dangerous.

In fact, once frost, even though very thin, has formed on the airfoils, take-off is practically impossible, due, it is believed, to disturbed flow over the airfoils caused by the frost. This important fact was verified by one of the writers. Frost varying in thickness from 1/32 to 1/8 inch had formed on the upper wing surfaces of a standard type army airplane which had been left out during the night. The weight of the deposit was calculated to be not in excess of 150 pounds and that weight was evenly distributed over the center of gravity. Three attempts to take off over a 5000 foot runway were unsuccessful. On the same morning two other airplanes could not take off for the same reason.

It is interesting to calculate from a theoretical point of view why heavy frost has been known to form on take-off from interior Alaskan airports. It should prove to be of some value as the Army will soon begin operations from Fairbanks, Alaska. In addition to warning the pilot that such a phenomenon does occur, he will be enabled to predict dangerous frosting conditions from a preliminary sounding.

Snow radiates with near black body efficiency. H. Wexler (Monthly Weather Review, Vol. 64, April, 1936) presents an interesting study of an air mass sounding over a snow cover at Fairbanks, Alaska, in December, 1932. It was found that a steep positive temperature lapse rate (marked increase of temperature with altitude) existed from the surface to 2500 feet. The sounding taken when the air was calm with a clear sky showed Polar Canadian air, trapped by the mountains in the lower levels, with overrunning Polar Pacific air above the top of the inversion. (See figure 30).

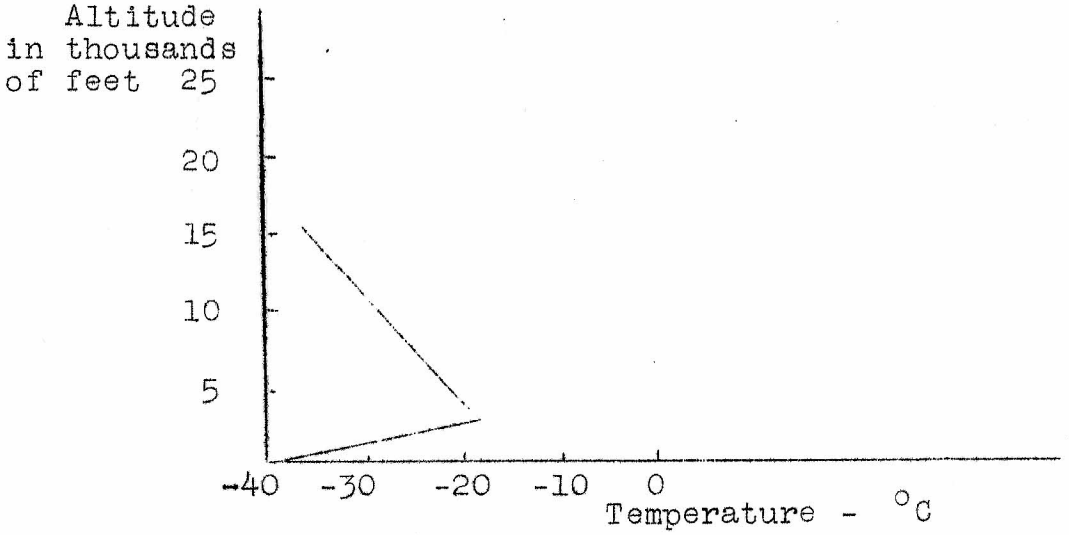


Figure 30

A study of Fairbanks soundings shows that this type situation occurs frequently in the winter. A Fairbanks sounding which typifies this condition is shown in figure 31.

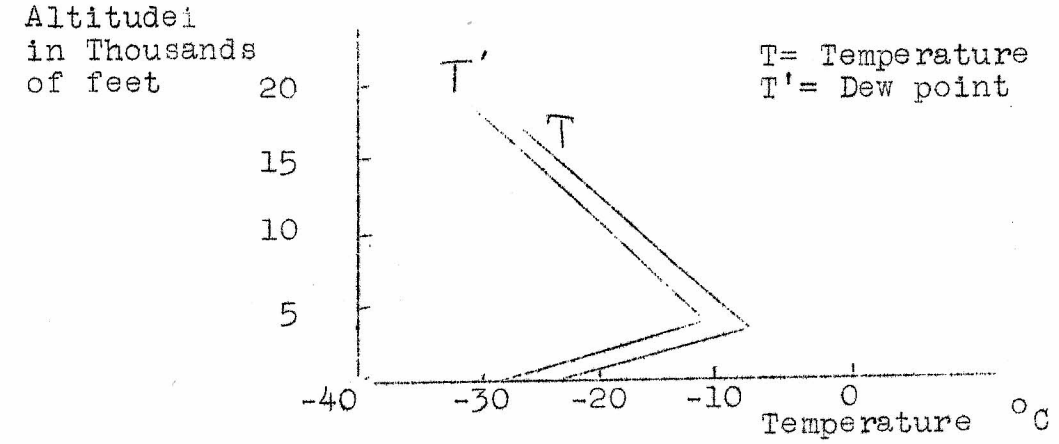


Figure 31

Sounding, February 6, 1940

Even though an airplane is kept in a heated hangar at night, it must be rolled out on the line for warm-up. As previously explained, its structure soon attains by conduction the temperature of the surrounding air. Upon take-off, ascent into the inversion places the airplane in air, the dew point of which is continuously higher than the temperature of the airplane. Only after piercing the inversion will the airplane cease picking up frost and start, by sublimation, to lose that frost already formed. (Figure 32.)

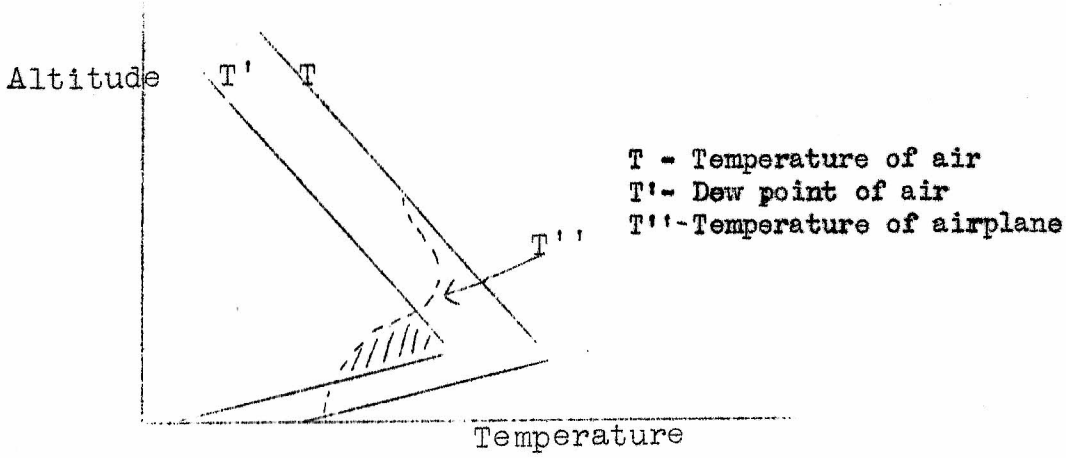


Figure 32

The airplane will be warmed by heat of vaporization and heat released by formation of frost and by conduction to relative warm air through which it climbs. Its temperature change is represented by the positive slope of T''. However, this warming has served its purpose in forming the frost, and although little is formed, the flight characteristic of the airplane is impaired.

Conditions from which the pilot may recognize the probability of frosting just after take-off.

(1) Marked decrease in temperature during the night with temperature far below freezing. Ordinarily a snow cover is required to give the necessary low temperatures.

(2) Calm air

(3) Clear sky

The pilot whose airplane begins to pick up frost on take-off should remain as low as possible. In so doing he will not penetrate the region where the dew point of the air is higher than the temperature of the airplane.

Thunderstorms

The thunderstorm, characterized by lightning and thunder is a gigantic exhibition of the potential power of the atmosphere. Electric potentials, thousands of times greater than man has ever been able to produce, are created within the thunderstorm. The release of this electrical potential in jagged bolts of lightning produces thunder. The sensational displays, lightning and thunder, are of minor importance to the airman. The forces which create them, together with other resulting phenomena, hail, turbulence, and icing are important.

The analysis of lightning has contributed valuable thunderstorm information. Simpson's theory of lightning is now almost universally accepted by meteorologists. His theory can be summarized briefly:

(1) The raindrop is composed of two electrical layers, the inner positive, the outer negative.

(2) No raindrops can fall through air whose vertical velocity exceeds 1575 feet per minute (8 meters/sec); the smaller drops are carried aloft, the larger ones ruptured by the force of the air upon them.

(3) Rupturing of the raindrops peels off the outer negative layer and carries it aloft in the form of spray. The positive nucleus maintains its form and being heavier, is displaced relatively a shorter distance upward, compared to the displacement of the negatively charged spray.

(4) Separation of opposite charges builds up an electrical potential.

(5) Lightning occurs when the electrical potential is strong enough to break down the dielectric air between the charges. Considering the potential of the earth, before the above process begins within the cloud, relatively the same as the air above the earth, it is evident that the above process establishes a difference in potential between the earth and the negative region of the cloud and also between the positive region of the cloud and the earth. Thus lightning flashes within the cloud and from cloud to earth are explained. A diagram, figure 33, according to Simpson, represents conditions stated above.

Lightning, in one respect, may be classified as an aid to the pilot. It serves as a warning that vertical velocities within a cloud exceed 1575 feet per minute. Indeed, they may be much greater. Humphries (Physics of the Air) states that in order to support hail one inch in diameter, vertical velocities of 5200 feet per minute must exist; to support the 3 inch hailstone, 10,200 feet per minute. Shaw (Manual of Meteorology) gives evidence that hailstones of greater diameter than 3 inches have fallen.

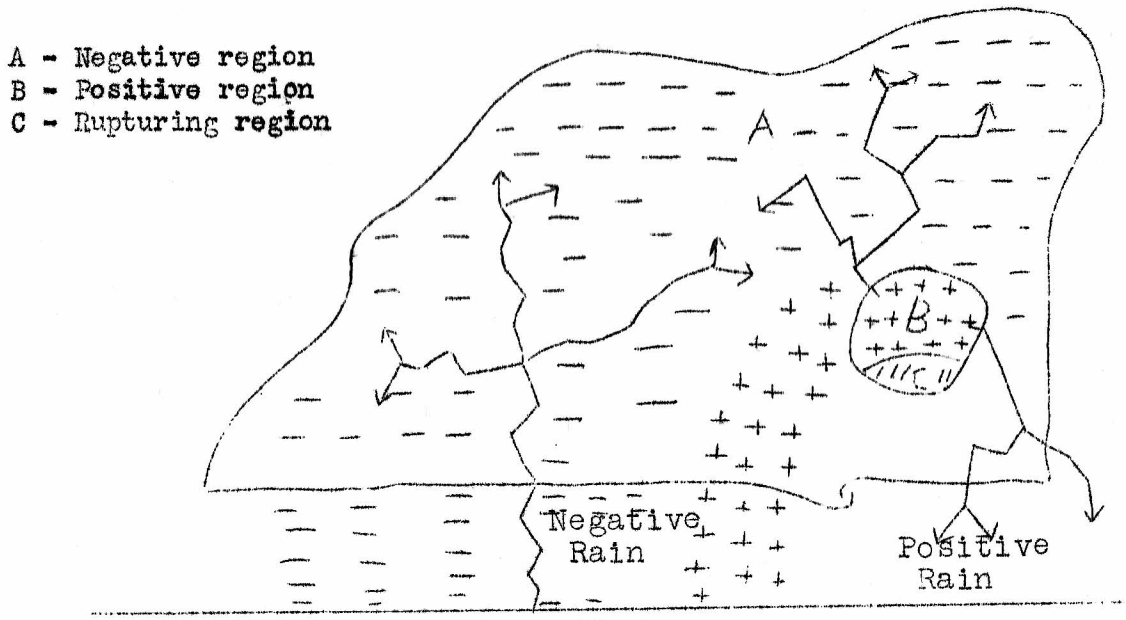


Figure 33

A short investigation will show what causes the great vertical velocities within the thunderhead. Consider two cloudless columns of air represented by (a) and (e), figure 34. Note that the only difference between column (a) and column (e) is the value of the temperature decrease with height; i.e., the lapse rates of the columns. Also assume that the dew point, the temperature at which condensation begins, is initially the same for air in the lowest level in both (a) and (e). It will be shown that (a) is stable air and that (e) is conditionally unstable air. Thunderstorms occur in air which is originally conditionally unstable and the difference between the two columns is therefore highly significant.

Now suppose that some force, F, which will be discussed later, is applied to a small volume, V, within column (a) as indicated by the arrow. V is forced upward, and, because of decrease of atmospheric pressure aloft, it expands, hence cools. Nature provides that the rate of cooling shall be approximately $3^{\circ}C$ per thousand feet of ascent-known as the adiabatic rate of cooling. The cooling within V as it is lifted is independent of the temperature of the air in the column surrounding V.

At some higher level, as indicated by (b) figure 34, the temperature of V has decreased to $19^{\circ}C$ which is colder than the surrounding air whose temperature is $25^{\circ}C$. V, being colder than the surrounding air, is heavier, and if the force, F, be removed, V will sink downward. If F continues to act on V up to some level indicated by (c) figure 34, the cooling process continues. When the temperature of V decreases to the dew point of V, which remains virtually constant during the ascent, condensation sets in. A cloud is formed.

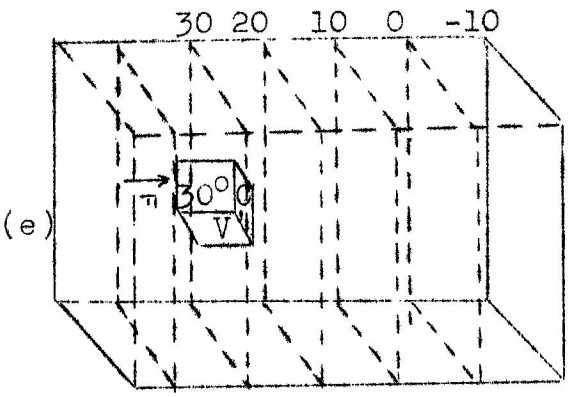
Condensation liberates heat just as evaporation cools. V is warmed by the heat which is liberated by the condensation process, but as indicated in (c), V is still colder than the surrounding air and tries to sink earthward. The cloud which has formed flattens out, as shown in (c) and becomes the commonly observed, stable stratus cloud. If now force, F, be removed, V will descend and the cloud will evaporate and disappear, as indicated in (d) figure 34. The conclusion is that, if at all levels V is colder than the surrounding air, the column itself is stable.

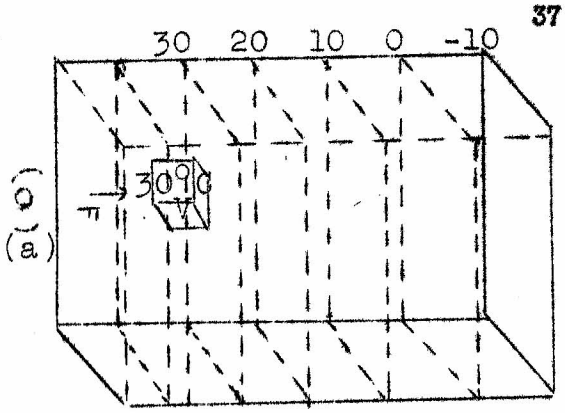
Now consider the column of air represented by (e) figure 34 and note that at the lowest level the small volume, V', is identical to the small volume, V, at its lowest level, as shown in (a) figure 34. Assume that V' is lifted by the same force, F, to some level as represented by (f), figure 34. At this altitude the temperature of V' is 19°C, and, level for level, the same as V as shown in (b) figure 34. The temperature of the air surrounding V' at this altitude is 20°C. Now if force, F, be removed, V', being colder by 1°C. and therefore heavier than the surrounding air, will sink. At this altitude it still exhibits the character of stable air.

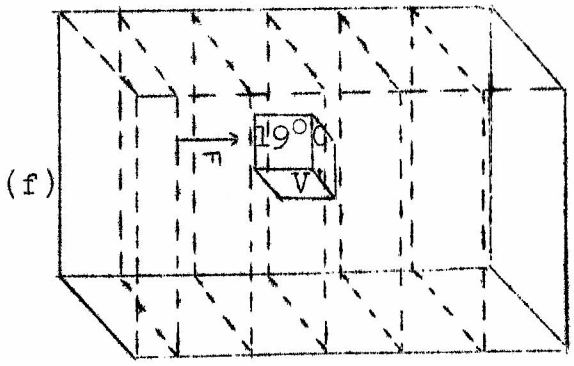
Let force, F, continue acting on V'. At a level represented by (g) figure 34, V' will be cooled to its dew point and condensation starts, forming a cloud. In this case the heat liberated by the condensation process is sufficient to raise the temperature of V' above the temperature of the surrounding air. This is possible because, as was shown above, there was only a slight difference of temperature, 1°C at the next lower level, before condensation started. Note that V' now has a temperature of 12°C. which is 2°C warmer than the surrounding air. Being warmer, V' is lighter and continues to rise of its own accord. A vertical force, F' has been created within V' itself, and at the same time the retarding opposition of stability has been removed.

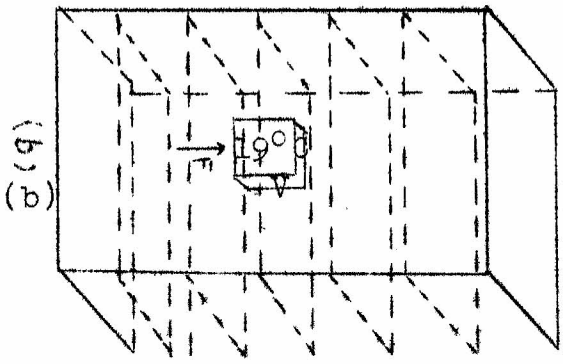
Neglecting friction, a force produces acceleration as long as the force acts. V', therefore, accelerates upward until the force, F', again becomes zero; i.e., until its temperature at some higher altitude again becomes equal to that of the surrounding air. It will suffice to say here that nature provides that at some higher altitude coincidence of temperature of V' and its surroumding air shall exist; that above this particular altitude V' shall become the colder. When the height of coincident temperature is passed the force, F', is reversed, but V' continues under its momentum somewhat higher, stops, and then starts downward. The above process has formed the familiar, towering cumulo-nimbus cloud, represented by (h) figure 34.

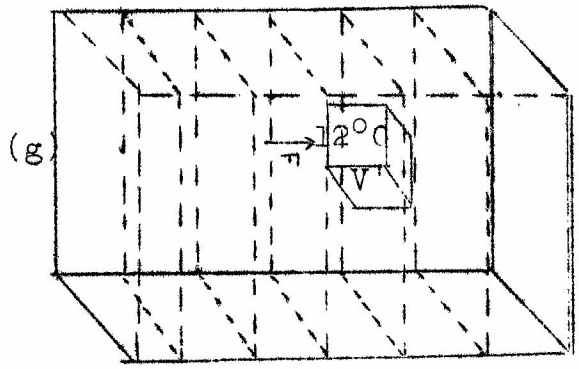
During the process the water droplet, minute at the condensation level, increases in size by amalgamation with other droplets and by further condensation upon its surface. If the force, F', is strong enough to accelerate V' to velocities exceeding 1575 feet per minute, the larger droplets as heretofore pointed out, will be ruptured and lightning and thunder ensue.

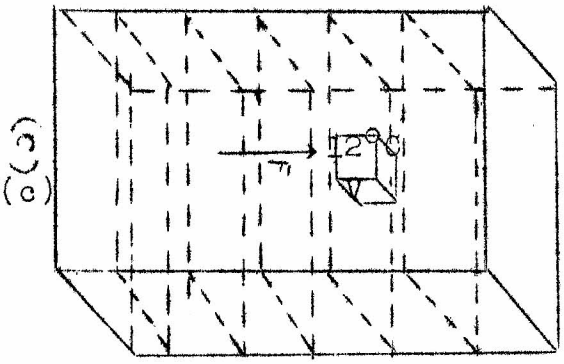

30 20 10 0 -10
(e)
30°C
V
F

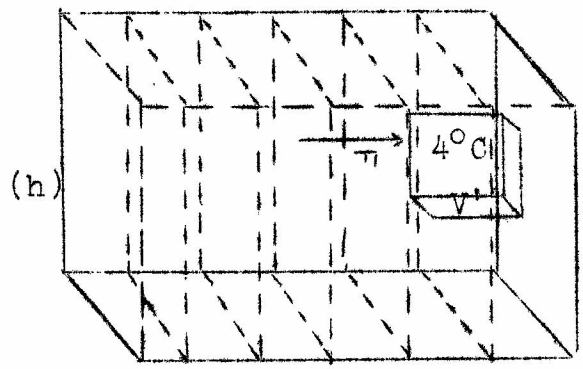

30 20 10 0 -10
(a)
30°C
V
F

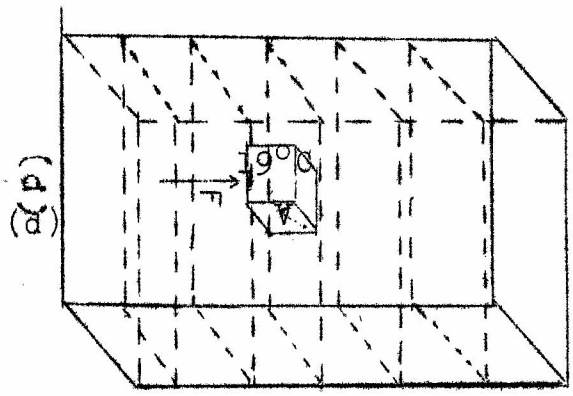

(f)
19°C
V
F


(b)
19°C
V
F


(g)
2°C
V
F


(c)
12°C
V
F


(h)
4°C
V
F


(d)
19°C
V
F

Since V' was transformed from a stable to an unstable state, we conclude that the column of air was originally conditionally unstable. We also note that the determining factor of stability or instability is the temperature change with respect to altitude, the lapse rate within the column.

Neither the lapse rate of the column of air nor the dew point of V' is a random coincidence. Both factors depend directly upon the past history of the air within the column. If the column of air has remained over relatively warm water for an appreciable time, the column is affected in two important ways: (1) the lower levels of the column are warmed by the water; and (2) the lower levels of the column pick up considerable moisture from the water.

Warming of the lower levels of the column establishes the conditionally unstable lapse rate, which, as shown above, is necessary to thunderstorm formation. Now the dew point of V' is determined by the amount of moisture at the lowest level within the air column, (e) figure 34. High moisture content means high dew point. The higher the dew point of V', the lower the altitude at which condensation occurs. It is obvious that the lower the condensation level, the greater the distance remaining above this level through which force, F', may act in accelerating V'. In short, therefore, thunderstorms of maximum intensity will occur in air which has maximum moisture content in the lower levels.

A study of air mass soundings shows that air which has remained over the Gulf of Mexico or the South Atlantic Ocean for four or five days during the spring, summer and fall, and air which moves out of interior Canada, Alaska or Siberia during spring, summer and fall and travels for six or more days over the Pacific Ocean develop characteristic thunderstorm lapse rates and moisture contents. These air masses are named, respectively, Tropical Gulf, Tropical Atlantic, and Polar Pacific. When entries on the synoptic chart indicate that such air exists over a region (see appendix for air mass symbols) thunderstorms may be expected provided that some force, F, is available to set them off.

The force, F, is supplied in either one, or a combination of two or more of four different ways:

(1) Convective lifting by radiation heating from the earth's surface. Figure 35.
(2) Lifting of warm air by the forward motion of the cold front. Figure 36.
(3) Upglide of warm air over a warm front. Figure 37.
(4) Mechanical lifting over mountain slopes. Figure 38.

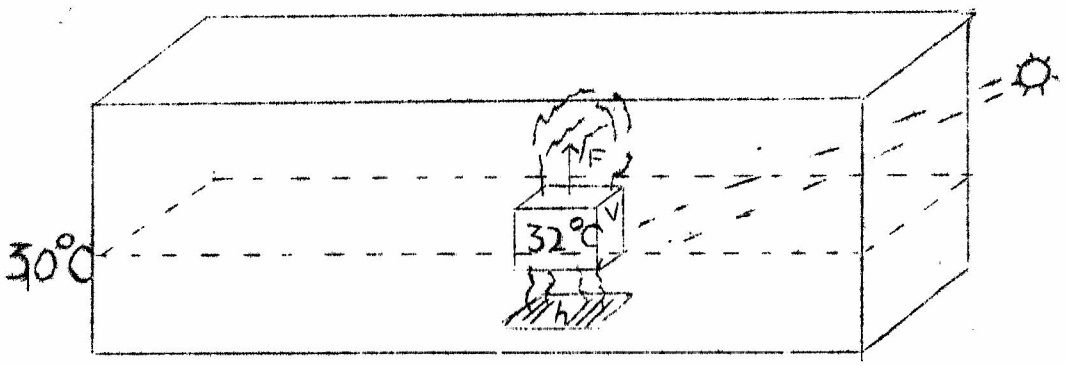


Figure 35

Orographic hotspot (h) reradiates heat received from the sun. V' is warmed, as shown, above the temperature of surrounding air, and being lighter (warmer) ascends. F caused by warming of V'.

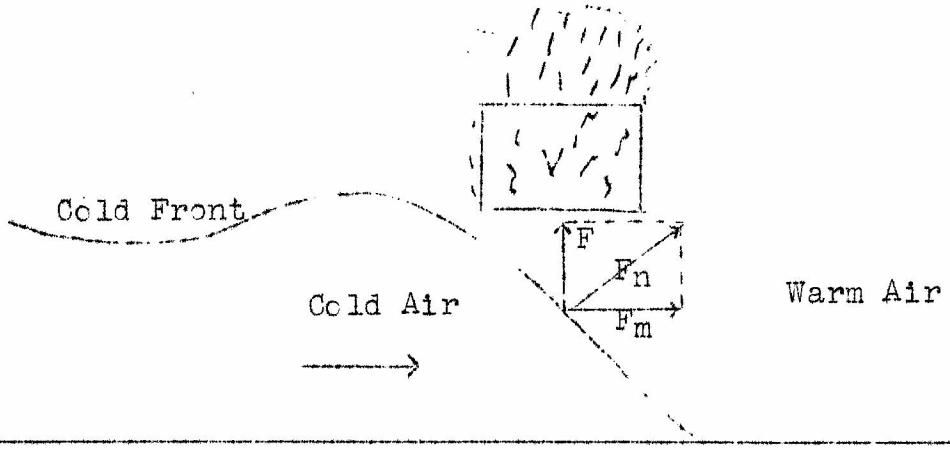


Figure 36

Forward movement, F_m, of cold front exerts normal force, F_n on warm air ahead of it. F_n has vertical component, F.

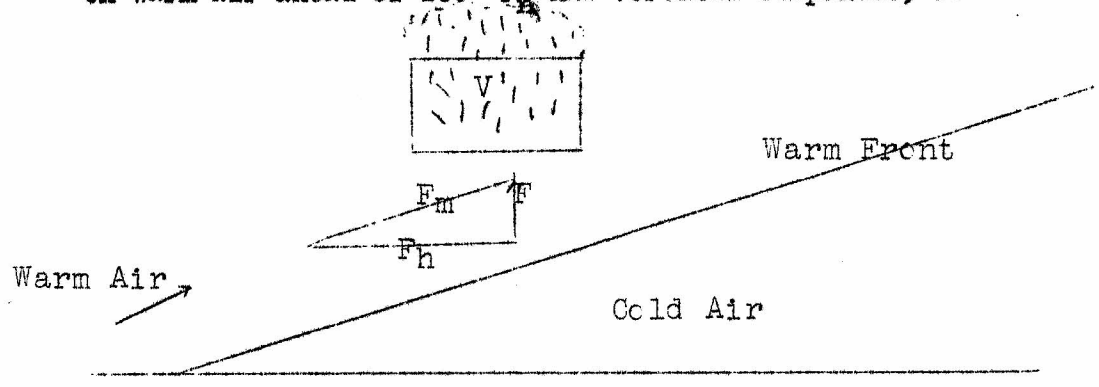


Figure 37

Forward movement, F_m, of warm air up warm front resolves into horizontal component, F_h, and vertical component, F.

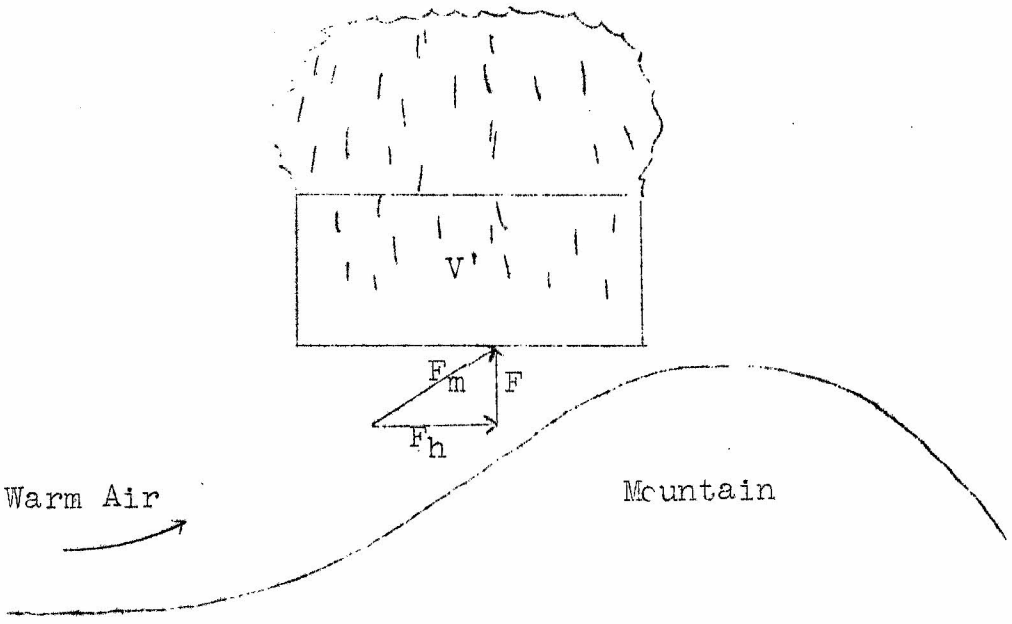


Figure 38

Forward movement, F_m, of warm air up the mountain slope, has horizontal component, F_h, and vertical component, F.

At night the upper boundary layer of a cloud is cooled by evaporation from the top of the cloud. Referring to figure 35, it is evident that cooling the top of V' has the same effect as warming it from below. This lifting force is not strong enough to set off a thunderstorm but it does account for the frequently observed increased intensity of the predeveloped thunderstorm in the early morning hours.

The altitude of the ice crystal level, the level of 0°C. temperature within the cloud, is an important factor. Refer to figure 39.

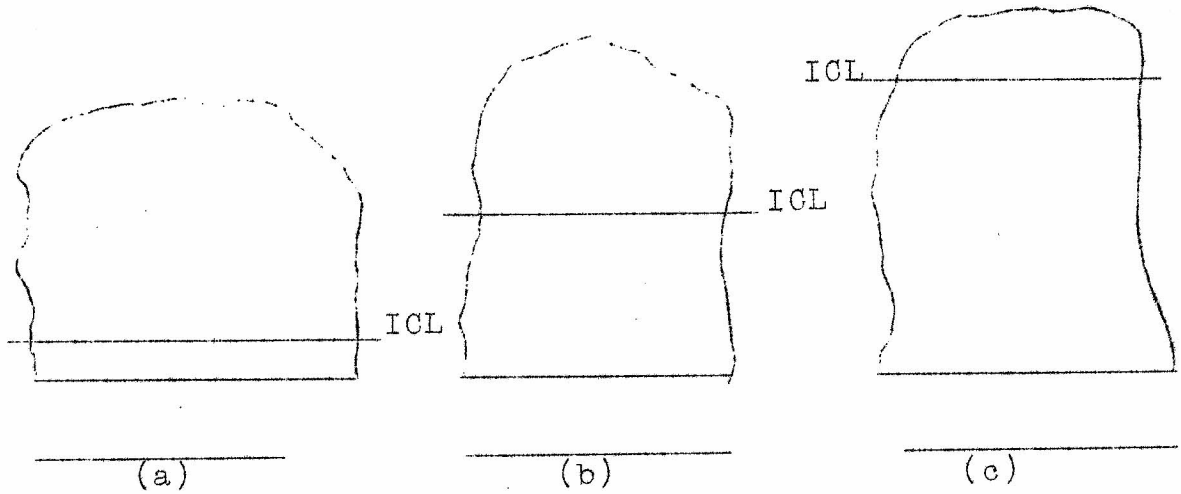


Figure 39

If the ice crystal level (I.C.L.) is below the base of the cloud or just within the cloud as represented in (a) figure 39, snow is formed and lightning rarely occurs although snow lightning is sometimes observed. If the ice crystal level is considerably higher within the cloud, as shown by (b) figure 39, lightning, thunder, rain, and hail may be expected. If the ice crystal level is near the top of the cloud, (c) figure 39, no hail will occur, but lightning, thunder and rain may be expected. It must be borne in mind that the intensity of the phenomena of each case above and also the turbulence within the cloud in each case is determined by the potential power within the air as heretofore discussed.

The convective type of thunderstorm and the mechanically lifted thunderstorm, both treated above, are generally classified as air mass thunderstorms. These types are usually isolated and are not dangerous to the pilot, because they may be circumnavigated. The warm front and cold front types, introduced above present special problems which we will now discuss. A cross-section of a warm front is reproduced below in Figure 40.

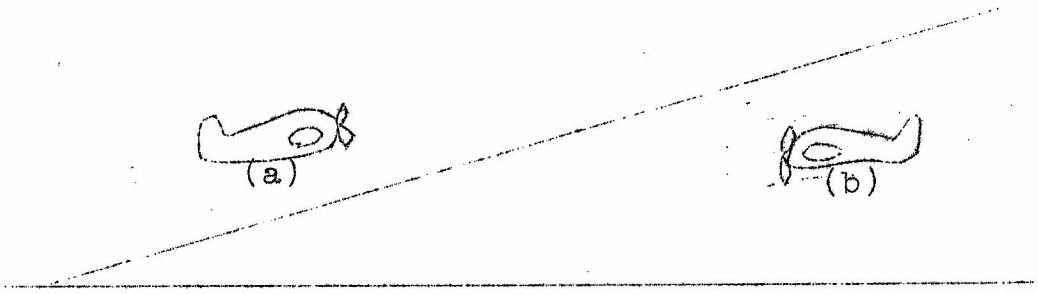


Figure 40

If the pilot is flying blind at a position (a) or (b) in the clouds above a warm front, he may suddenly run into a thunderstorm (c). The best way to avoid this situation is to fly above the cloud system. If this is done, the thunderstorm can be observed and circumnavigated.

Cold front thunderstorms present the greatest problem to the pilot. Along the cold front, thunderstorms are sometimes so close together that the pilot cannot circumnavigate the danger area. The pilot may,

however, be able to negotiate a line of cold front thunderstorms with a fair degree of comfort and safety, if he is familiar with the forces involved in and around the thunderstorms. An idealized thunderstorm pattern is shown in figure 41 on the following page.

The descending air, D, below the cloud is caused by the cooling effect of rain and hail falling through the cloud. The air in region C being cooled, is heavier than the surrounding and therefore descends. The forward motion of this downdraught is due to the forward motion of the whole system as indicated by the arrow to the righthand side of the figure. The large updraughts, A, in front of, and within the cloud, are the result of forces within the cloud as explained above. The scud or roll cloud, S, is a vortex at the base of the cloud between the ascending currents, A, and the descending currents, D. Vortices of less intensity than the scud cloud may be expected at positions above and below the scud cloud, as indicated by the dotted ellipses.

There must be a counter-settling outside of a thunderstorm to compensate for the tremendous upflow within the cloud. In the case of the isolated thunderstorm, this counter-settling may be quite ineffective, as it is spread out over a wide area. Close grouping of thunderstorms along a cold front may, however, convert this counter-settling into an intense down-draught, as shown in figure 42.

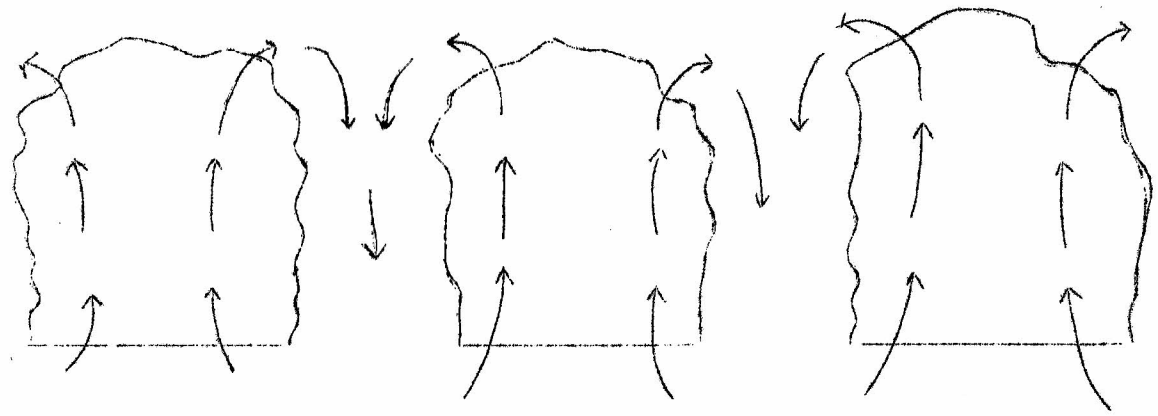


Figure 42

In this case, contrary to appearances, it is safer to fly beneath the thunderstorm; i.e., to fly through the dark rain area below the thunderstorm rather than the light space between individual thunderstorms. Flight should be made as far below the base of the cloud as the terrain permits. Flight through the scud cloud should never be attempted, as the turbulence in this region is prohibitive. The next best course is to fly through the

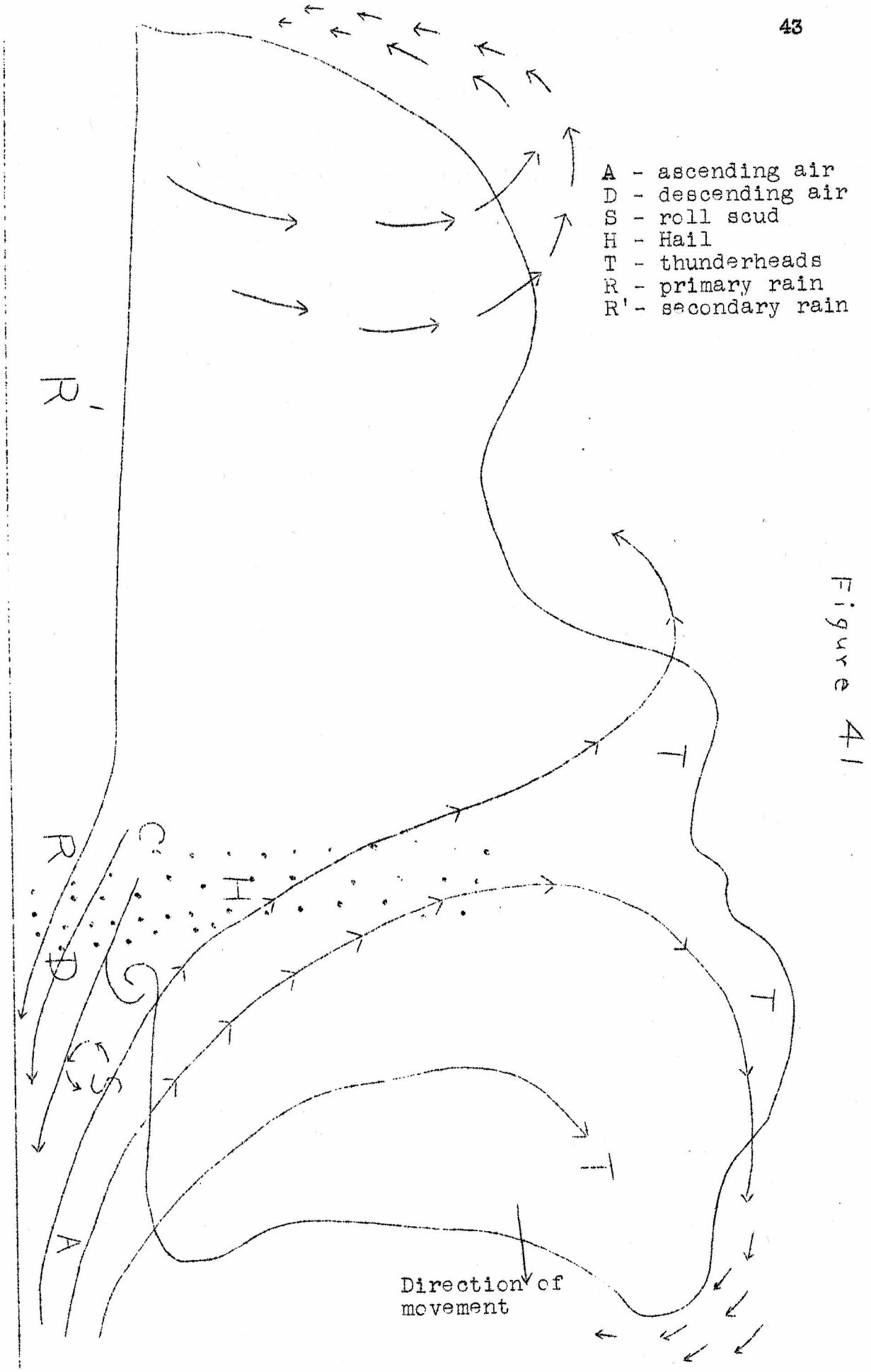

A - ascending air
D - descending air
S - roll scud
H - Hail
T - thunderheads
R - primary rain
R'- secondary rain
R
R'
S
H
T
A
Direction of movement

Figure 41

thundercloud just above the scud cloud. In no case should flight be attempted through the higher regions of the thunderstorm where destructive turbulence will probably be encountered. Thunderstorms extend generally parallel to the cold front, but they move with the upper air which is usually at an angle with the front as indicated in figure 43, below.

It is evident that in order to avoid running into a succession of thunderstorms, passage through the cold front should be made at the angle shown in figure 43.

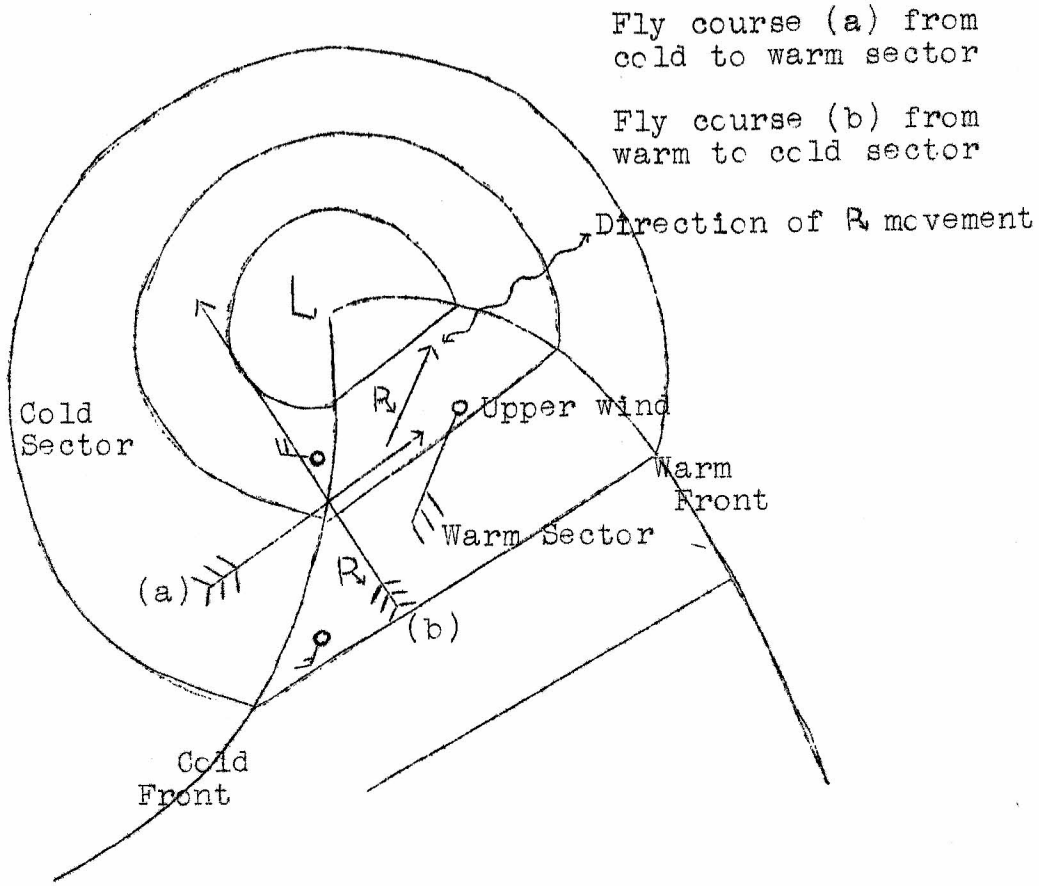


Figure 43

Conclusions:

(1) Lightning serves as a warning that vertical velocities in excess of 1575 feet per minute exist within the cloud. No case has yet been reported where lightning has seriously damaged the well-bonded, modern aircraft, although it may readily put the radio equipment out of order.

(2) The size of hail is a measure of the vertical velocities within the thunderstorm. It is known that vertical velocities in excess of 10,000 feet per minute have existed. Large hail may seriously damage the aircraft which it strikes.

(3) Icing, under favorable temperature conditions, discussed under icing, may be very severe in the thunderstorm and will be worst at or just above the ice crystal level.

(4) Isolated thunderstorms should always be circumnavigated.

(5) Blind flying in the clouds above a warm front should be avoided, if possible, if there is reason to believe that the air above the front has thunderstorm characteristics.

(6) Cold front thunderstorms may sometimes be negotiated but extreme caution must be exercised in doing so.

(7) Destructive turbulence may be encountered in any well-developed thunderstorm.

BIBLIOGRAPHY

Bowie, Edward H., "Weather and the Airplane."

Humphries, W. J., "Clouds and Fogs."

Humphries, W. J., "Physics of the Air."

Jordanoff, Assen, "Through the Overcast."

Kronfeld, Robert, "Kronfeld on Gliding and Soaring."

Lyon, T. C., (U.S. Dept. of Commerce) "Practical Air Navigation."

McNeal, Don, "Ice Formation in the Atmosphere."

Samuels, L. T., (N.A.C.A.) "Ice on Aircraft."

Schnell, I. I., "Differences Between Winds on the White Mountains and in the Free Air."

Schnell, I. I., "On the Diurnal Variations of Wind Velocity."

Schnell, I. I., "On Vertical Distribution of Wind Velocity over Mountain Summits."

Shaw, W. Napier, "Forecasting Weather."

Shaw, W. Napier, "Manual of Meteorology."

Taylor, George F., "Aeronautical Meteorology."

APPENDIX

For converting temperature readings from either of the standard scales to the other the approximate, simple formulae below will be found easy to use. By comparison with a scale graduated in both centigrade and fahrenheit, it is obvious that the pilot, by using the formulae will

obtain results sufficiently accurate for his purpose.

$C = 1/2 (F - 32)$. $\qquad\qquad$ $F = 2(C) - 32$.

- - - - - -

(Commonly used terms expressed, where possible, in a descriptive manner.)

An AIR MASS is any portion of the earth's atmosphere not less than five hundred miles wide, the temperature and water content of which at a given level is about the same.

A FRONT is the zone of demarkation and interaction between two dissimilar air masses.

FRONTOGENESIS is the process of creation and formation of a front.

FRONTOLYSIS is the process of dissipation or dying out of a front.

STABILITY is the characteristic of air which resists upward motion.

CONDITIONAL INSTABILITY (also potential or convective or thermodynamic instability) is the characteristic of air which resists upward motion, if unsaturated; but tends to rise if saturated.

ABSOLUTE INSTABILITY is the characteristic of air which tends to rise even if it is unsaturated.

MECHANICAL INSTABILITY is the characteristic of air which tends to overturn suddenly and completely because heavier air lies over a lighter layer.

An ISOBAR is a line joining points on the earth of a given air pressure.

An ISALLOBAR is a line joining points on the earth of a given change of air pressure.

An ISOTHERM is a line joining points on the earth of a given temperature.

PRESSURE GRADIENT is the rate of change of air pressure per unit of distance on the earth at a given time.

PRESSURE TENDENCY is the rate of change of air pressure per unit of time at a given point on the earth.

LAPSE RATE is the rate of decrease of temperature with altitude.

ADIABATIC LAPSE RATE is the lapse rate of unsaturated air in equilibrium.
(5 1/2 degrees F. per 1000 feet.
10 degrees C. per 1000 meters.
3 degrees C. per 1000 feet.)

SATURATED ADIABATIC LAPSE RATE is the lapse rate of saturated air in equilibrium.
(2 1/2 to 4 1/2 degrees F. per 1000 feet.
1 1/2 to 2 1/4 degrees C. per 1000 feet.)

DEW POINT is the temperature to which air must be reduced to cause saturation.

RELATIVE HUMIDITY is the percentage ratio of the amount of water in air to the amount of water the air could hold if saturated.

SPECIFIC HUMIDITY is the ratio of the weight of water to the weight of dry air in a sample of moist air.

ABSOLUTE HUMIDITY is the ratio of the weight of water to the volume of air in a sample of moist air.