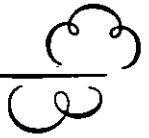


Aircraft Icing



Aircraft icing is one of the major weather hazards to aviation. It affects an aircraft both externally and internally. In general, external icing (including what is called airframe and propeller icing) is defined as the accumulation of ice on the exposed surfaces of aircraft when flown through supercooled water drops (cloud or precipitation). Structural (external) ice reduces aerodynamic efficiency; in severe instances this efficiency is reduced to the point where an aircraft will no longer fly. Internal ice (intake, carburetor, or engine icing) literally reduces the breathing of the engine, which results in a loss of power.

The total effect of aircraft icing is:

- Loss of aerodynamic efficiency.
- Loss of engine power.
- Loss of proper operation of control surfaces, brakes, and landing gear.
- Loss of aircrews' outside vision.
- False flight instrument indications.
- Loss of radio communication.

In wind tunnel experiments it has been found that an ice deposit of $\frac{1}{2}$ -inch on the leading edge of some airfoils reduces the lifting power of the airfoil as much as 50% and increases the drag by an equal amount. Ice can form on an aircraft very rapidly, and there are recorded cases where two to three inches of ice have accumulated in a matter of minutes.

The facts indicate the importance of knowing pertinent information about aircraft icing. This chapter is intended to familiarize the aircrew member with the types of icing, weather

conditions favorable to the formation of ice, hazards of aircraft icing, methods of preventing or reducing icing, and how to combat it after it has formed on or in the aircraft.

STRUCTURAL ICING

Conditions Contributing to Structural Icing

Two atmospheric conditions necessary for the formation of structural icing (except frost) are: (1) presence of visible liquid moisture; and, (2) free-air temperature at or below freezing. Also, the aircraft-surface temperature must be colder than 0° C (32° F).

The temperature range in which ice and water coexist in clouds is generally from 0°C to -20°C. In the atmosphere, supercooled liquid water droplets are normally not in contact with ice and they continue to exist in a supercooled state at temperatures well below the freezing point of water. In fact, supercooled water droplets have been found at temperatures colder than -40°C and at altitudes above 40,000 feet. Supercooled water droplets in the atmosphere are in a relatively unnatural state, even though they are frequently encountered. Any slight jar or contact with a surface will cause immediate freezing.

Air flow around aircraft surfaces will decrease the free air temperature in some cases as much as 2°C. This is of little consequence to the over-all icing problem but it will explain why there will be times when icing will take

place when the outside free-air temperature gage indicates temperatures are slightly above freezing.

The dynamic (compression and friction) heating effect on airframes at high airspeeds will also affect icing. The temperature increase on the airframe is of some significance at true airspeeds above about 400 knots. However, because of the complexity of the problem, it is normally best not to rely on this to alleviate an icing problem. If this temperature increase is great enough, it will be of some aid in the prevention of ice formation.

Types of Structural Icing

Aircraft structural icing consists of three basic types: clear (glaze), rime, and frost. Also, mixtures of clear and rime are common. The type of icing—clear or rime—is dependent primarily upon the water droplet size.

Clear ice is the most serious of the various forms of ice because it adheres tenaciously to the aircraft. It is formed by the relatively slow freezing of large, supercooled liquid-water droplets, which have a tendency to spread out and assume the shape of the surface on which they freeze. As a result of the spreading of this supercooled water and its slow freezing, very few air bubbles are trapped within the ice, which accounts for its clearness. Although clear ice is expected mostly with temperatures between 0° and -10°C , it does occur with temperatures as cold as -25°C .

The atmospheric conditions which produce clear ice are encountered most frequently in cumuliform clouds. Clear ice also forms rapidly on aircraft while flying in zones of freezing rain or drizzle, as shown in Figure 11-2.

Rime ice is formed by the instantaneous freezing of small supercooled water droplets upon contact with aircraft surfaces. Fast freezing can take place when the temperature is anywhere from 0°C to -40°C , but probably is most likely between -10° and -20°C . Since the individual droplets freeze in individual spheres on the airfoil and the freezing is instantaneous, a large amount of air is trapped within the ice. This gives the ice an opaque appearance, makes it very brittle and relatively easy to break off. Rime ice does not normally

spread over an aircraft surface, but protrudes forward into the airstream along the leading edges.

Rime icing is most frequently encountered in stratiform clouds. In comparison to clear ice, rime ice is relatively easy to get rid of by conventional methods, even though it distorts the airfoil to a larger degree than does clear ice.

Frost is a deposit of a thin layer of crystalline ice that forms on the exposed surfaces of parked aircraft when the temperature of the exposed surfaces is below freezing (while the free-air temperature may even be above freezing). This deposit of ice forms during night radiational cooling in a manner similar to the formation of hoar frost on the ground.

Frost is a most deceptive form of icing. It affects the lift-drag ratio of an aircraft, and is a definite hazard during takeoff. There is no such thing as a little frost on aircraft surfaces. The only definitions that apply are none or some, and some is too much.

Frost also forms in flight when a cold aircraft descends from a zone of freezing temperatures to a zone of above freezing temperatures and high relative humidity. The air is chilled suddenly to below freezing temperature by contact with the cold surfaces of the aircraft, and sublimation (ice crystal formation directly from vapor state) occurs. Frost can cover the windshield or canopy and completely restrict outside vision. During penetration for landing, when visible moisture or high relative humidity exists, frost may form on the inner side of the canopy. This can be a definite hazard if no preventive action is taken.

Remove all frost from aircraft before take-off. Never be satisfied with less than an aerodynamically clean aircraft. Protective coverings are available at most cold weather bases, and ten minutes taken to put them on may save many hours of deicing.

Critical Icing Areas

The critical areas of structural icing are the wings, tail surfaces, and propellers in the case of conventional or turboprop aircraft. Ice forms first and faster on prop spinners; and, on jet aircraft, on the surfaces that protrude forward, such as tip tanks and drop tanks.

Propeller icing reduces the efficiency of the prop, which in turn reduces airspeed, increases fuel consumption, and causes vibration. This vibration can be disastrous, and the pilot should turn on the propeller anti-icers when he anticipates entering icing zones. Propeller rpm is a factor in that the lower the rpm, the more favorable is the situation for the formation of prop ice.

Ice occurring on the pitot tube, static pressure ports, radio antennae, and windshield can also be very dangerous. Icing does cause inaccurate airspeed and altimeter readings, which is a special problem with jet aircraft. On many jets the static ports are located on either side of the fuselage, and when icing is observed on any part of the aircraft, the pilot can accept the fact that the rate of accumulation around the static ports is as high or higher than on other areas of his aircraft.

Pitot tube icing is usually easy to prevent with pitot heat. However, if pitot heat is lost, it then becomes necessary for the pilot to fly aircraft pitch attitude in conjunction with proper power settings and not rely on the airspeed indicator. He may be able to remove ice from radio antennae by bridging the insulators, thus grounding the antenna to the aircraft frame and creating some heating. Changing altitude to warmer air or holding the transmitter closed to induce current will also help rid the pilot of the antenna icing problem. During instrument flight, the pilot can tolerate windshield ice until time for landing, but then he must have good forward visibility. Various windshield deicing systems have been designed and are being used to combat this.

INDUCTION ICING

Induction icing is a problem to both conventional and jet aircraft. It is a definite hazard to flight because engine power can be lost when least expected. Induction icing forms any time atmospheric conditions are favorable for the formation of structural icing (visible liquid moisture and freezing temperatures). In addition, induction icing can form in clear air when the relative humidity is high and the free-air temperatures generally are 10°C or colder.

Jet Aircraft

Icing poses special problems to jet aircraft and to jet engines. In flights through clouds which contain supercooled water droplets, air intake duct icing is similar to wing icing. However, the ducts may ice when skies are clear and temperatures are above freezing. While taxiing, and during takeoff and climb, reduced pressures exist in the intake system which lower temperatures to the point that condensation and/or sublimation take place, resulting in ice formation. This temperature change varies considerably with different types of engines. Therefore, if the free-air temperature is 10°C or less (especially near the freezing point) and the relative humidity is high, the possibility of induction icing definitely exists.

As airspeed increases after takeoff, the reduced-pressure cooling gradually decreases. At approximately 250 knots TAS (this airspeed varies with aircraft type), air is rammed—instead of sucked—into the intake system and no cooling occurs. Consequently, at airspeeds greater than about 250 knots, freezing temperatures are needed for induction ice formation. Thus the temperature range conducive to ice formation has been decreased. However, the idea that heating resulting from ram pressure at high speed will prevent icing is misleading. Not enough heat is generated at subsonic speeds to prevent the formation of ice.

The *rate* of engine icing for a given atmospheric icing intensity with outside air temperature below freezing is relatively constant up to an airspeed of approximately 250 knots TAS. The rate of icing increases with increasing airspeed above 250 knots TAS. Therefore, a reduction of airspeed to a safe minimum will reduce the *rate* of inlet icing.

Induction icing may be expected when the outside air temperature (OAT) is between approximately -10°C (14°F) and 5°C (41°F) if fog is present or the dew point is within 4°C or 7°F of the OAT. From 0°C (32°F) to approximately 5°C (41°F) and with the dew point within 4°C or 7°F of the OAT, conditions exist under which jet engine icing can occur without wing icing. If the OAT is in the range of 0°C (32°F) to 5°C (41°F) and water is present on the parking ramp or runway, jet engine icing may be expected.

Axial flow jet engine operation is affected by icing to a much greater extent than centrifugal compressor engine operation. Ice forms on fixed inlet screens and compressor inlet guide vanes, and restricts the flow of inlet air. This causes a loss of thrust and a rapid rise in exhaust gas temperature. As the air flow decreases, the fuel-air ratio increases which in turn raises the temperature of the gases going to the turbine. The fuel control attempts to correct any loss in engine rpm by adding more fuel which aggravates the condition. Ice build-up on inlet screens sufficient to cause turbine failure can occur in less than one minute under severe conditions. With the inlet screens out, blocking of the air passages between the inlet guide vanes can still occur in four minutes or less.

The centrifugal compressor type of engine is relatively free of icing difficulties. For example, it has been possible to ice the J-33 engine, but the icing conditions must be extremely severe. In flight, the turning of the air as it enters the engine effectively separates the water droplets from the air and deposits them on engine surfaces where icing is not considered serious.

Avoid atmospheric icing conditions whenever feasible. It is recognized that the most proficient weather services cannot always predict accurately just when or where icing may be encountered. However, many areas of probable icing conditions can be avoided by careful flight planning that utilizes available weather information.

USAF TO 1-1-469, "Operation of Aircraft with Jet Engines under Icing Conditions—All-Jet Aircraft," 25 August 1955, explains the operation of jet aircraft under icing conditions. Consult the flight manual for the operation of your particular aircraft.

Conventional Aircraft

Carburetor icing is treacherous. It occurs under a wide range of temperatures and can result in complete engine failure. Carburetor ice forms during vaporization of fuel combined with the expansion of air as it passes through the carburetor. Temperature drop in the carburetor can be as much as 40°C, but it is usually 20°C or less. So if the relative humidity is high, be alert to the possibility of carburetor icing.

Concerning induction icing in both jet and conventional aircraft, it is extremely important for the pilot to know the flight manual for his particular aircraft. In brief, he should know thoroughly the *effects* of induction icing and the remedial procedures. *The forecaster's job is to forecast meteorological conditions; it is not to forecast induction icing, although the forecaster does forecast airframe icing.* Since induction icing can occur under conditions which do not necessarily produce airframe icing, it is the pilot's responsibility to know the meteorological conditions which produce induction icing in his particular aircraft. The pilot then should be able to cope with induction icing hazards.

Jet Fuel System Icing

Water is miscible with jet fuel to such a degree as to occasionally constitute an icing hazard. When the humidity is high or when aircraft are refueled during rain, the fuel will absorb water. Under conditions of cold outside air temperature, the pilot should anticipate fuel system icing during flight. This problem can usually be coped with by proper use of the alcohol deicing system as prescribed by the flight manual.

Icing Hazards on the Ground

Frozen precipitation or frost accumulated on parked aircraft are hazards which greatly affect safe operation. If not adequately removed, they can cause considerable danger to the flight. It is common practice to place aircraft in a hangar until the ice melts, or to completely clean wing and tail surfaces prior to flight. If hangared for deicing, keep in mind that when the aircraft comes out of the hangar there will probably still be some water left on the surfaces and it will ice again if freezing temperatures exist.

Another serious condition arises from the presence of water or mud on ramps and runways during freezing temperatures. Water blown or splashed on the aircraft forms an ice cover on the under side of flaps, control surfaces, and crew observation blisters. Mud and water may freeze in the brakes and in the landing gear mechanism to the extent that

proper operation is impaired. Be alert and conduct ground operation accordingly.

Ice and snow on runways are among the weather elements that affect braking action of aircraft. Brake-friction ratio varies widely with different aircraft, and each pilot must be aware of his own aircraft's characteristics.

DEICING AND ANTI-ICING

Most military aircraft are equipped with deicing and/or anti-icing equipment. There are three common methods for eliminating ice: (1) mechanical, (2) fluids, and (3) heat.

Mechanical—The leading edges of wing and tail surfaces of some aircraft are equipped with rubber skins, or boots, that normally assume the contour of the airfoil. Compressed air is cycled through ducts in these rubber boots causing them to swell and change shape. The stress produced by the pulsating boot cracks the ice and the air stream peels it off.

Anti-icing *fluids* are used on rotating surfaces where centrifugal force spreads the fluid evenly. Such fluids are effective agents because the fluid helps prevent ice from adhering to the surfaces and the centrifugal force throws off the ice as it forms.

Heat application capability to wing, props, and tail surfaces is installed in most newer aircraft. The icing areas are heated by electrical means or by hot air which is piped from the engine manifold or jet engine compressor. This process has frequently given rise to the name *hot wing*.

WEATHER CONDUCTIVE TO AIRCRAFT ICING

The pilot should anticipate and plan for some type of icing on every flight conducted in clouds with temperatures colder than freezing. He should be familiar with the icing generally associated with different atmospheric conditions.

Air Mass Icing

Stable air masses often produce stratus-type clouds with extensive areas of relatively continuous icing conditions. These clouds represent a potentially hazardous icing condition if

the pilot is prevented or delayed from making the necessary changes in flight altitude. Data indicate that an individual cloud layer seldom exceeds 3,000 feet in thickness. However, situations are encountered where multiple layers of clouds are so close together that visual navigation between layers will not be feasible because of the variations in the tops and bases of the clouds. In such cases the maximum depth of continuous icing conditions should rarely exceed 6,000 feet. Generally, the pilot should expect rime icing in stratus-type clouds when the free-air temperature is below 0°C.

Unstable air masses generally produce cumulus clouds with limited horizontal extent of icing conditions, but the pilot can expect the icing to become more severe at higher altitudes in the clouds. The concentration of super-cooled water droplets in cumulus clouds may be several times greater than that existing in stratus clouds, thus resulting in much greater icing, but of shorter duration. Clear ice is generally associated with cumulus-type clouds.

Pilots can generally expect more icing while flying over mountainous terrain under icing conditions, than over other types of terrain with the same atmospheric conditions. When flight planning, anticipate heaviest icing around 5,000 feet above the mountain tops, and/or in the temperature range at and just below freezing —0°C to —10°C, or vicinity.

Frontal Icing

During this discussion, where reference is made to the illustrations, keep in mind that these are models and actual situations may vary considerably from those shown here.

Cold fronts and squall lines generally have a narrow weather and icing band, and the majority of the time the associated clouds will be the cumuliform type. The depth of the icing zone will often be about 10,000 feet and the type will be predominantly clear. Icing is very severe when the overrunning or lifted warm air is unstable. In the accompanying illustration, Figure 11-1, the icing zone is about 100 miles wide and covers altitudes of about 10,000 feet.

Different types of icing encountered in the clouds will generally be: clear icing, where the temperature ranges from 0° to —10°C; a mix-

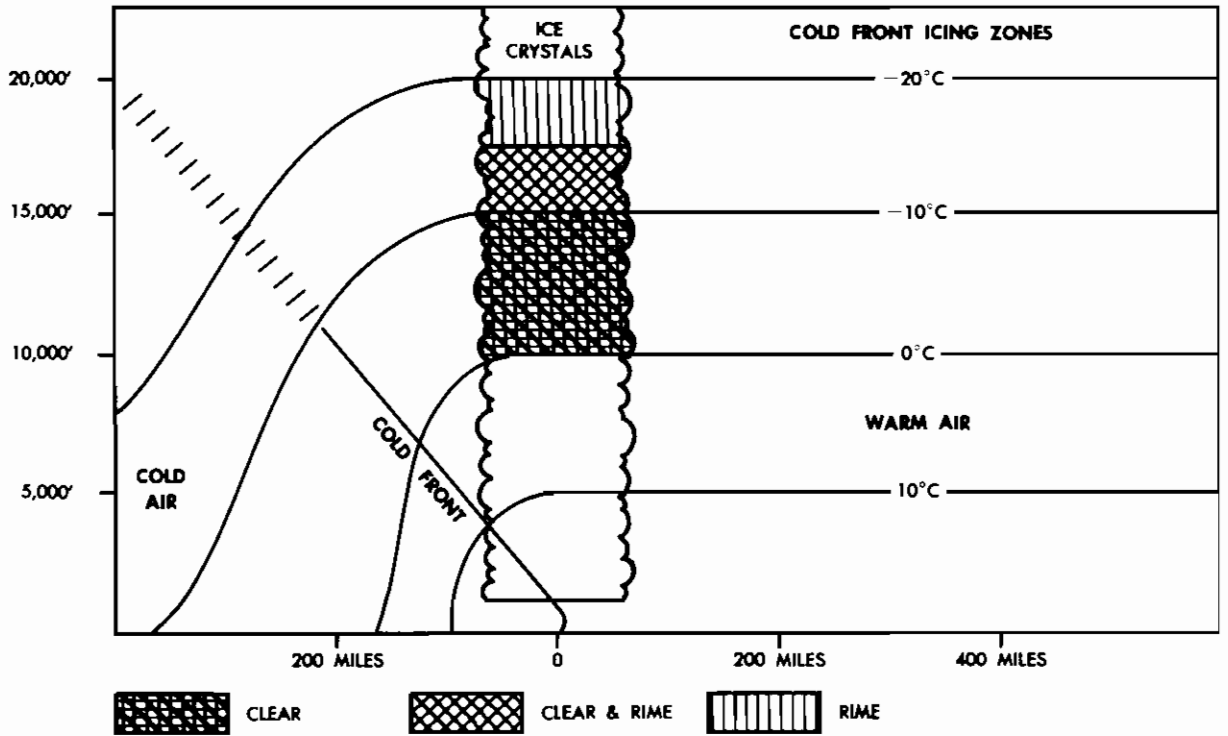
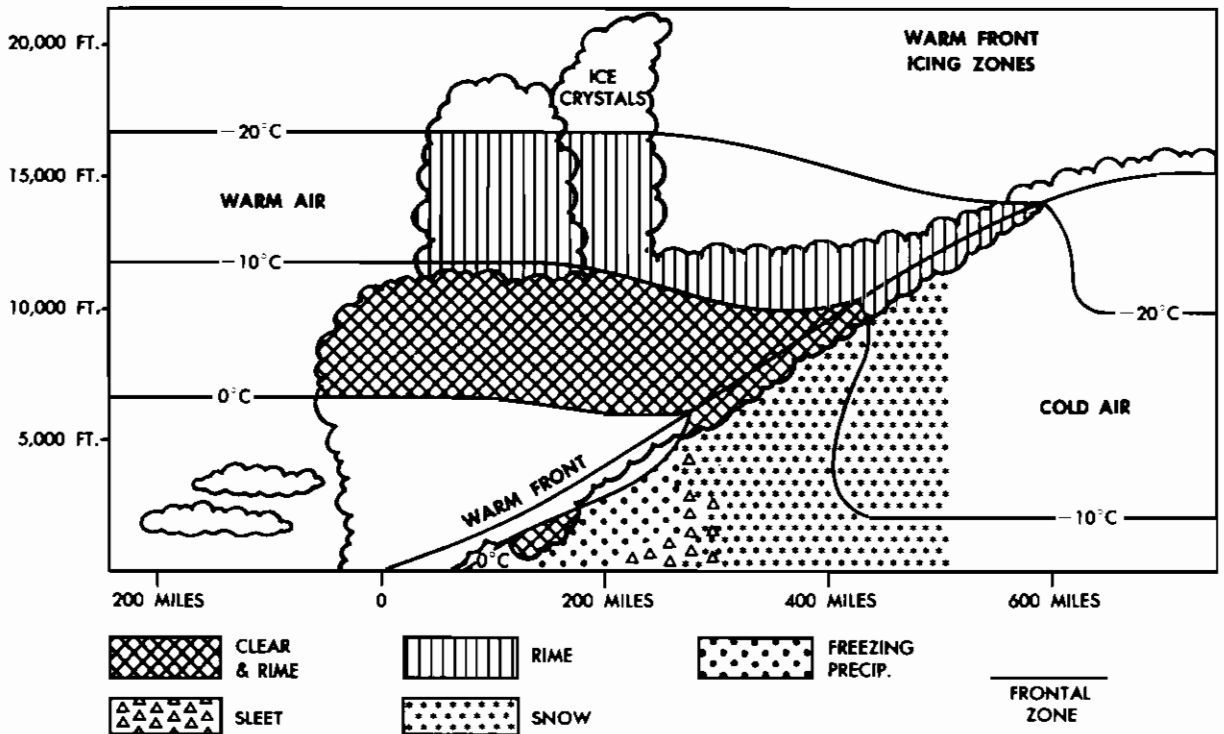


Figure 11-1. Cold Front Icing Zones

Figure 11-2. Warm Front Icing Zones



ture of clear and rime, where the temperature ranges from -10°C to -15°C ; rime icing, where the temperature ranges from -10°C to -20°C , or less. However, icing of all types may occur at much colder temperatures; -25°C for clear ice, and -40°C for rime ice are accepted lower limits.

Warm fronts and stationary fronts generally have a wide weather and icing band with stratiform clouds. The vertical depth of the icing zone will generally be about 10,000 feet, and the type of icing will be predominantly rime. If the overrunning warm air is unstable, there will also be cumuliform clouds creating a more severe icing hazard. Note in the subject illustration that the icing zone is 500 miles wide, and covers about 17,000 feet in altitude. Freezing precipitation may be extensive.

The very critical freezing precipitation area is where water is falling from warm air above when the flight level temperature is below freezing. In this case, clear ice would be encountered and the evasive action is to climb to an altitude where the temperature is above freezing. Icing in the clouds may follow this basic pattern—a mixture of clear and rime ice from 0°C to -10°C ; rime from -10°C to -20°C . Again rime icing may be expected occasionally at temperatures below -20°C .

Occluded fronts often produce a wide weather and icing band with both stratiform- and cumuliform-type clouds. The depth of the icing zone will often be about 20,000 feet, or double the depth of icing zones with other type fronts. The types of icing will be clear, mixed and rime; and if the air masses involved are unstable, aircraft icing may be very severe. In the illustration, Figure 11-3, notice that the freezing precipitation area is quite extensive, so keep in mind that when the water comes from warmer air above, the icing will be most hazardous.

The types of icing associated with the temperature ranges will generally be: clear, 0°C to -10°C ; a mixture of clear and rime -10°C to -15°C ; rime, -15°C to -20°C , with pos-

sible rime icing at lower temperatures. Notice the warm air pocket between the altitudes of 6,000 and 9,000 feet. Know the icing zones, and flight plan accordingly.

Knowledge of icing zones can be a great aid to conventional aircraft flight planning. For example, using the occluded front illustration, Figure 11-3, a pilot is flying a C-54 cleared by Air Traffic Control to maintain 9,000 feet and is approaching the front from the warm air side. The temperature at flight altitude is -4°C instead of 2°C as forecasted, and the aircraft begins to accumulate a lot of clear ice. The pilot estimates the possibility of another hour in the frontal weather, so a decision must be made concerning evasive action. Minimum altitude on this airway is 7,000 feet and with the temperature pattern as it is, the pilot would not improve the situation by descending to 7,000 feet where the temperature is 0°C . Thus the possibility of descending to warmer air below is out.

The pilot decides to climb to 17,000 feet. The choice of 17,000 feet was made by the knowledge of the general rule that the average temperature lapse rate is 2°C per 1,000 feet. Cruising at 17,000 feet, where the temperature should be around -20°C , will get the pilot out of the bad icing conditions. Of course, the higher one goes, the better it will be. The next problem is obtaining a clearance from ATC for a change in flight altitude. Seventeen thousand feet may not be approved, but if the pilot can get any altitude where the temperature is colder than -10°C , he is bettering his situation. Seventeen thousand feet is requested, but ATC clears the pilot to climb to and maintain 15,000 feet; this helps. An hour later the aircraft has passed the frontal weather and icing; then, and if desired, the pilot may request a new altitude assignment for the remainder of the flight.

Pilots of jet aircraft do not usually encounter such extended periods of structural icing as do the conventional pilots. Jet cruise altitudes are generally above the most probable icing temperature range of 0°C to -20°C . Structural icing may be encountered only during short

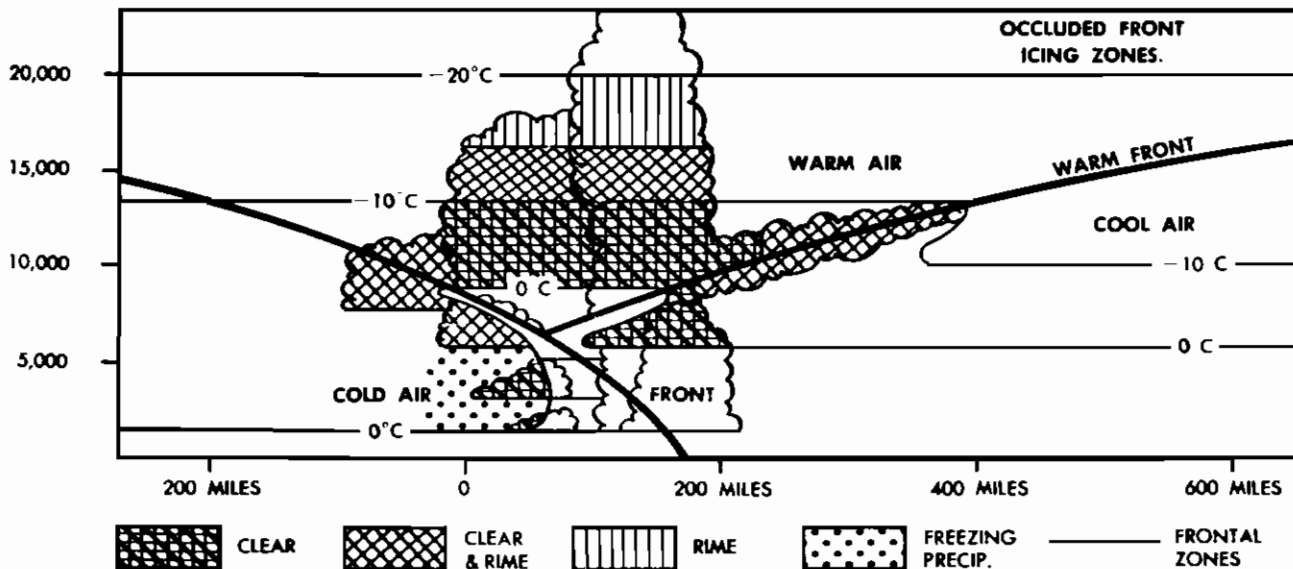


Figure 11-3. Occluded Front Icing Zones

periods of climbing to and descending from cruising altitude.

Thunderstorm Icing

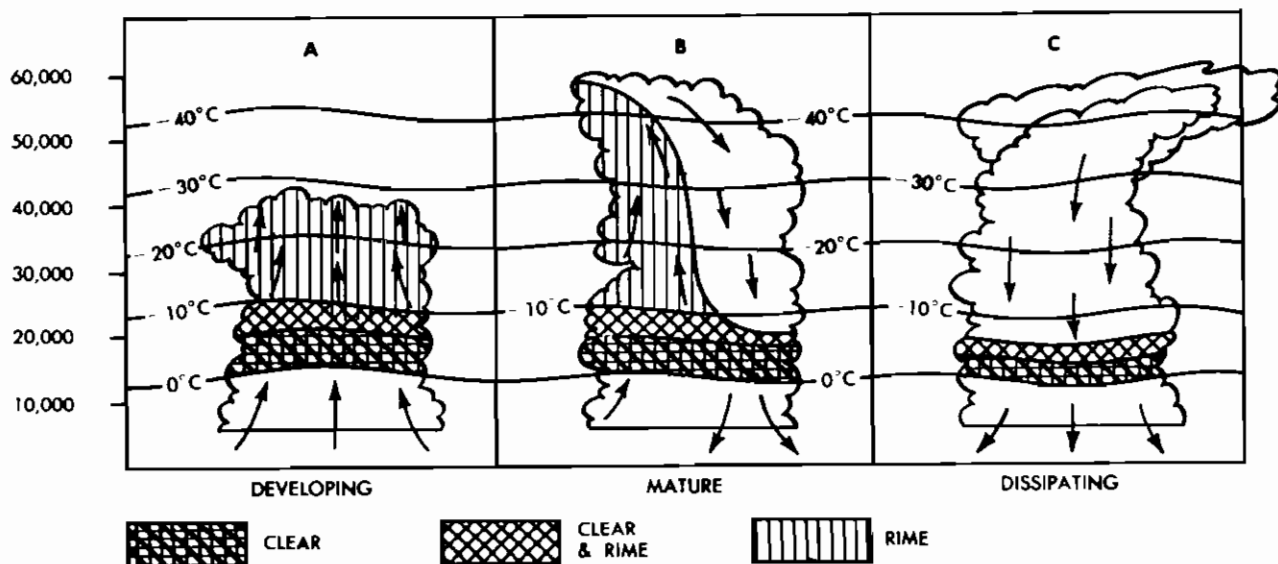
The icing areas and the type of icing in the different stages of a thunderstorm are shown in the related illustrations, Figure 11-4.

In the cumulus cloud that is developing into a thunderstorm, the cloud particles above the freezing level will, to a large extent, be liquid.

The icing will be severe due to the large number of liquid water droplets. When the top of the cloud begins to reach -20°C , ice crystals begin to form and aircraft icing will be reduced, as shown in Section A.

In the updrafts in the mature cell (Section B), the cloud particles are mostly water where the temperature is warmer than -10°C . Water droplets and ice crystals are mixed between -10° and -20°C ; and ice crystals will pre-

Figure 11-4. Thunderstorm Icing Zones



dominate at temperatures colder than -20°C . In the downdrafts, the cloud will be mixed ice and water from 0°C to -10°C , and mostly ice crystals when the temperature is colder than -10°C .

In the dissipating cell (Section C), ice crystals predominate. However, in a shallow layer near the freezing level, there is a mixture of water droplets and ice crystals where aircraft icing may take place.

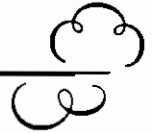
It is very difficult to tell the stage of a thunderstorm by visual observation, so the general rule is that the pilot should anticipate icing at all altitudes where the temperature is at or below freezing. Note also, that the worst icing conditions are encountered at and just above the freezing level. Icing can occur also in the cirrus anvils streaming off the upper

parts of thunderstorms because some water drops are carried out into the anvil and do not always freeze immediately.

Weather Reports

Weather personnel can not generally observe icing. They rely on pilot reports. However, forecasters can forecast the probable maximum intensity of icing that may be encountered during a flight, not necessarily the intensity of icing that will be encountered by a particular aircraft. Many variables bear upon this problem. It becomes the pilot's responsibility to make certain he obtains a complete weather briefing to include the information he deems necessary to the safe completion of his proposed flight, not only to minimize any icing hazard, but all hazards to flight.

Thunderstorms



Thunderstorms might be defined as the ultimate manifestation of the growth of a cumulus cloud. Many of the most severe weather hazards which the atmosphere has to offer are found within a thunderstorm. With approximately 44,000 thunderstorms occurring daily (16,000,000 annually) over the world, the chances of random long-range flights entering a thunderstorm are considerable. How each pilot fares will, to a large degree, depend upon the pilot's knowledge of the thunderstorm's characteristics and the application of tested procedures.

Thunderstorms occur during all seasons in the tropics, and from late winter through fall in the temperate zones (witness the severe tornado which struck St. Louis, Missouri, at 0140 (CST) on 10 February 1959, killing 21 people and injuring over 300). They have been observed as far north as the arctic regions in summer, and at mid-latitudes in winter. Thun-

derstorms generate a large portion of the earth's rainfall, and in many areas, such as Arizona, they supply most of the critically needed rain.

In early 1946 the Air Force, Navy, National Advisory Committee for Aeronautics, and the Weather Bureau initiated the *Thunderstorm Project* to collect all possible data about thunderstorms by direct observation. From this information more complete knowledge of the development, structure, and characteristics of thunderstorms was obtained. During the summers of 1946 and 1947, a total of 1,363 aircraft and glider thunderstorm penetrations were made in conjunction with this project in Florida and Ohio. Some of the results and conclusions of the data collected from these and later flights are incorporated into this chapter. (A new project of this type is under way in the Kansas-Oklahoma-Texas area which will lead to further understanding of severe storms.)

THUNDERSTORM DEVELOPMENT REQUIREMENTS

In general, a certain combination of atmospheric conditions is necessary for the formation of a thunderstorm. These factors are: unstable or conditionally unstable air, relatively high moisture content, and some type of lifting action. The reader is referred to Chapter 4 — *Stability*.

TYPES OF THUNDERSTORMS

In general thunderstorms have similar physical features, regardless of location or time. However, they do differ in intensity, degree of development, and in associated weather such as hail, turbulence, electrical discharges, and

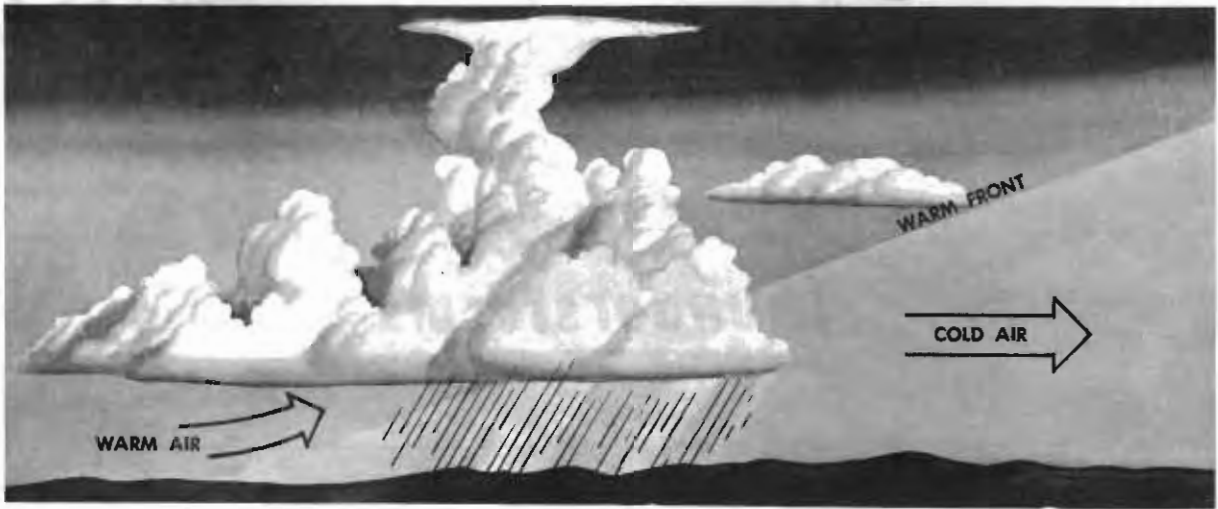


Figure 12-1. Warm Front Thunderstorm

high or gusty winds. Thunderstorms are generally classified according to the manner in which the initial lifting action is accomplished.

The different types according to this criterion are:

- Frontal Thunderstorms
 - Warm Front
 - Cold Front
 - Prefrontal (Squall Line)
 - Occluded Front
- Air Mass Thunderstorms
 - Convective
 - Orographic
 - Nocturnal

Frontal Thunderstorms

Warm Front Thunderstorms. Warm front thunderstorms usually occur when the warm, moist air overrunning the cold mass of retreating air is unstable. Notice the overrunning effect in the associated illustration. Because of the gentleness of the warm frontal slope, stratiform clouds often surround and obscure the thunderstorm clouds. For example, an aircraft flying from the right side of the illustration toward the left would fly from an area of relatively smooth conditions under the warm front into turbulence in a matter of seconds. Showery precipitation encountered in flight



Figure 12-2. Cold Front Thunderstorm

through warm fronts should be considered an indication of cumulus activity.

Cold Front Thunderstorms. Cold front thunderstorms, as seen in the subject illustration, occur in the warm air near the frontal surface. A continuous line, parallel to and along the frontal surface, is the distinguishing feature. Because most of the thunderstorms are visible, they are easy to recognize while approaching the front from any direction. The bases of cold front thunderstorms are usually lower than the warm front type. They are most active during the afternoon and are generally more violent than the warm front type.

Prefrontal or Squall Line Thunderstorms. The prefrontal squall line is found 50 to 300 miles in advance of a cold front, and is generally parallel to it. The squall line is approximately 150 to 300 miles in length, although not necessarily continuous, and as much as 35 miles in width. This band of thunderstorms is very similar to a cold front line, but is often more violent and moves faster. The cloud bases are often lower and the tops higher than most thunderstorms. The most severe conditions, such as heavy hail showers, destructive winds, and tornadoes are generally associated with squall lines.

Occluded Front Thunderstorms. Thunderstorms occurring with cold front-type occlusions, (see Chapter 7 — *Air Masses*), are similar to the cold front line of storms, but are generally not as extensive nor as severe. They are concentrated at the peak of the warm sector for a short distance along the newly formed occlusion.

On the other hand, occluded front thunderstorms are more often associated with the warm front-type of occlusion. In this case they occur along the upper cold front and are inaugurated by the rapid lifting of the warm air. They are similar to warm front type thunderstorms but often are more severe. As in the case of the warm front thunderstorm, the occluded front thunderstorms are often embedded in stratiform clouds and give little or no visible warning of their presence.

Air Mass Thunderstorms

Air mass thunderstorms have two basic characteristics: (1) they generally form within

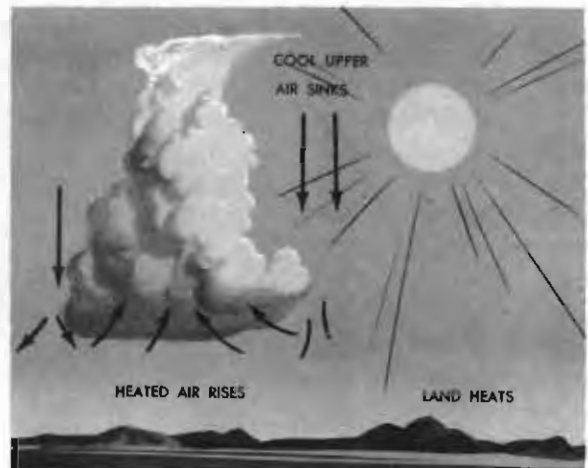
a warm, moist air mass, and (2) they are generally isolated or scattered over a large area.

Convective Thunderstorms. Convective thunderstorms occur with a greater frequency than any other type of air mass thunderstorm. They occur over land or water in most areas of the world, and are very common in the temperate zone during the summer months. The initial lifting action for these thunderstorms is provided by the convective currents produced by the heating of the lower layers of the air that are in contact with warm land or water masses.

Convective cumulus clouds normally form over land during the afternoon when the earth is receiving the maximum heating from the sun. When the air is very unstable and contains sufficient water vapor, the cumulus clouds may develop into thunderstorms. Convective thunderstorms also develop over coastal regions during the afternoon when cool, moist air from the water is heated as it moves over the warmer land surface.

Convective thunderstorms form over water at night as cool air from the land is advected over the warmer water surface. These thunderstorms are common in coastal areas, and are either isolated or scattered over a large region. They are easily recognized by their towering mass, lightning, and accompanying rain showers.

Figure 12-3. Convective Thunderstorm



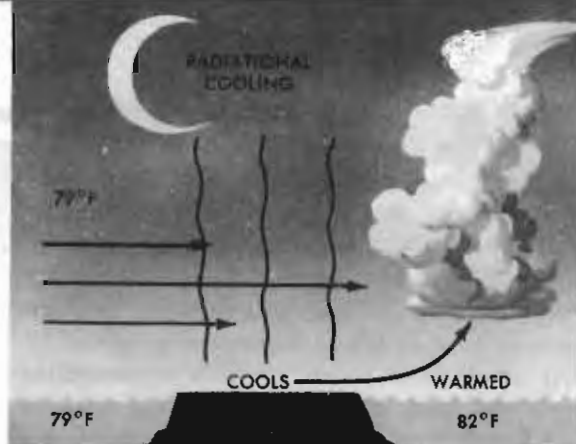
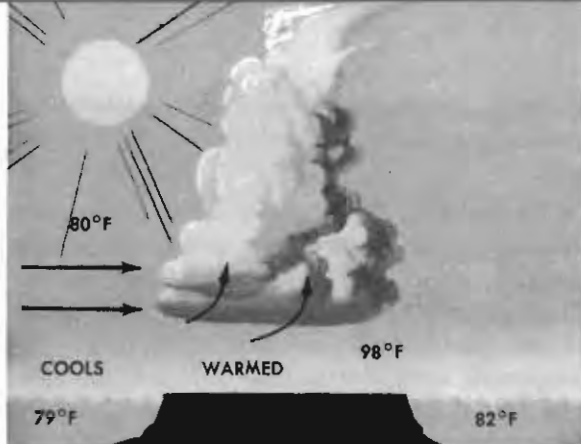


Figure 12-4. Day—Convective-Type Thunderstorms of Florida—Figure 12-5. Night

Orographic Thunderstorms. Orographic thunderstorms form when moist, unstable air is forced aloft by mountainous terrain. These storms develop rapidly and may cover large areas. They frequently remain stationary on the windward side of mountains or hills for many hours. They can form as single storms over peaks, or as a line of storms along a mountain range. Hail is common in these thunderstorms when they develop along high mountain slopes, such as the Rockies.

It is difficult to identify orographic thunderstorms when they are approached from the windward side of the mountains because they are often embedded in stratiform clouds. However, when they are approached from the lee side of the mountains, identification is usually easy.

It is not advisable to attempt a flight through the lower portion of an orographic thunderstorm because they almost always enshroud the tops of mountains and hills.

Nocturnal Thunderstorms of the Midwest. This is a peculiar type of air mass thunderstorm which occurs frequently late at night and early in the morning during the late spring and summer in the Central Plains area of the United States, from the Mississippi Valley Region westward. Its occurrence is generally considered to be possible when a relatively moist layer of air exists aloft. The trigger mechanism that sets off this type is not well understood—it may result by advection of instability at middle levels formed farther west during the afternoon, or by cooling of cloud tops from nocturnal radiation, or

complex diurnal variations in the wind structure. (Frontal and squall line thunderstorms can, of course, occur at any time—day or night.)

STRUCTURE OF THUNDERSTORMS

The fundamental structural element of the thunderstorm is the unit of convective circulation known as the *convective cell*. A thunderstorm usually contains several of these cells, each varying in diameter from about one to five miles, and each in a different stage of development. However, the circulation in each cell is generally independent of that in surrounding cells in the same storm. The model of the "convective cell" derived from the Thunderstorm Project, is the best description available, but there are indications that storms on the High Plains and in tropical areas differ somewhat from this model.

Each thunderstorm progresses through a cycle which consists of three stages: (1) the cumulus stage, (2) the mature stage, and (3) the dissipating or anvil stage.

Cumulus Stage

In its initial stage of development, the thunderstorm is a cumulus cloud. As the development progresses, several cumulus clouds may unite to form a single thunderstorm. Only a small percentage of the cumulus clouds develop into mature thunderstorms. The main feature of the cumulus or building stage is the updraft, as you can see in the related illustration. This updraft prevails throughout the entire cell. During the cumulus stage, rain

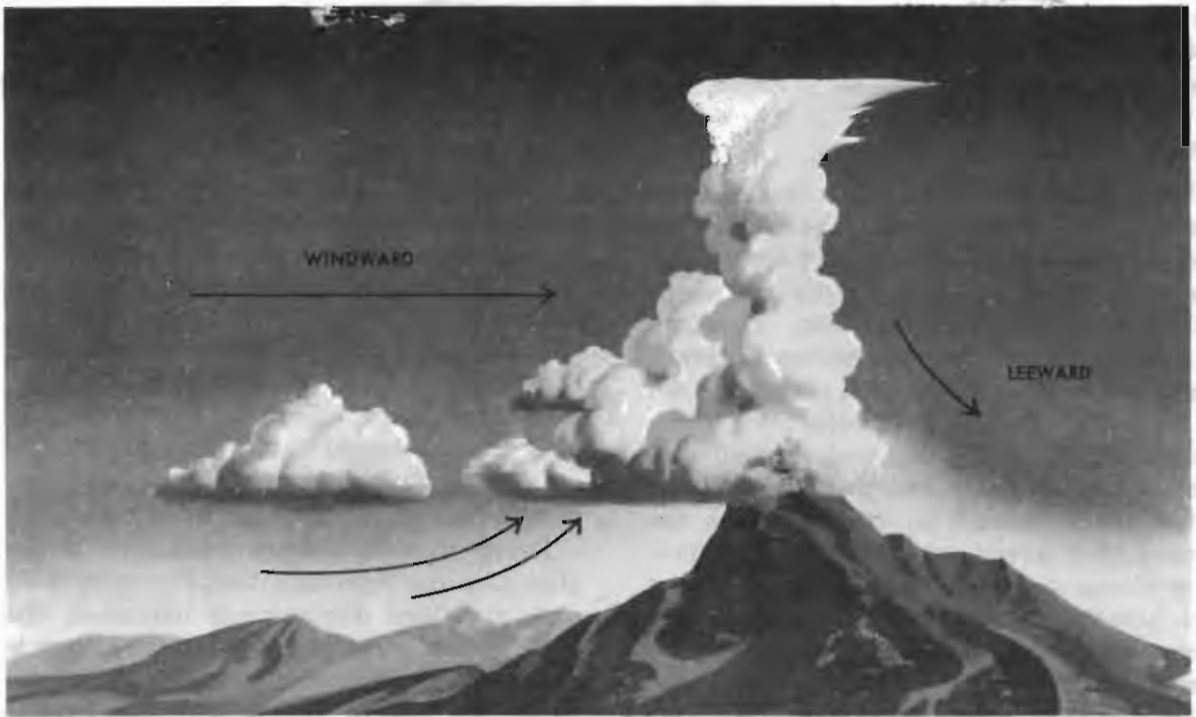


Figure 12-6. Orographic Thunderstorm

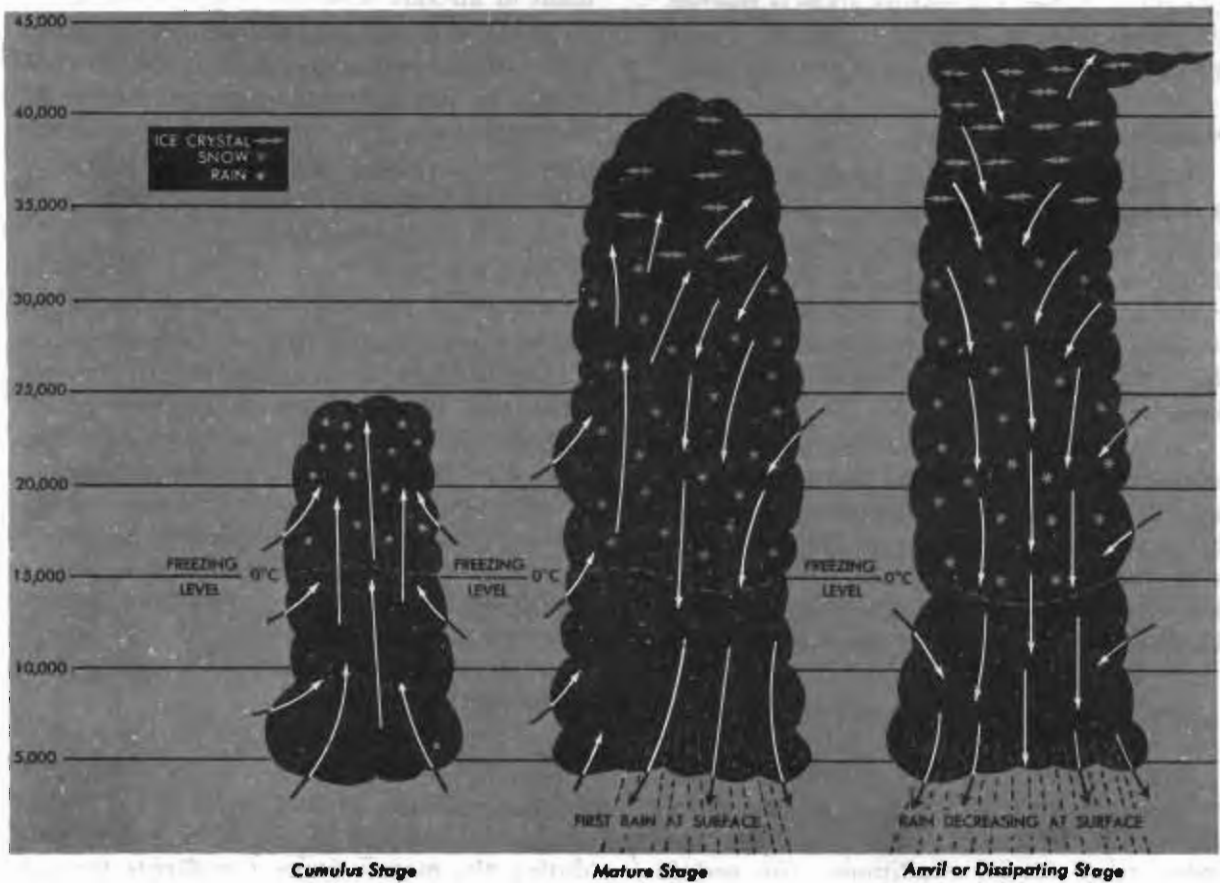


Figure 12-7. Thunderstorm Structure Stages

usually does not fall because the water droplets are carried upward or remain more or less suspended in the ascending air currents.

Mature Stage

When the water droplets in the cumulus cloud, as here shown, grow to the extent that they can no longer be supported by the updrafts they begin to fall. As the rain drops fall they drag air along with them. This drag is a major factor in the formation of downdrafts which characterize each convective cell in the mature stage. Downdrafts form in the middle regions of the cell and gradually increase, first vertically and then horizontally. When the downdraft air currents reach the surface, they spread out horizontally and produce strong and gusty surface winds. All of the hazards associated with thunderstorms seemingly reach maximum intensity during the mature stage.

Rain at the ground generally indicates the transition from the cumulus stage to the mature stage. When the mature stage is reached, the cell usually has attained a height of more than 25,000 feet (50,000 feet is not unusual).

Dissipating or Anvil Stage

Throughout the life span of the mature cell the downdrafts continue to develop, and spread vertically and horizontally. Also, as the downdrafts are developing, the updrafts are continually dissipating. As a result of this action, the middle and lower portions of the thunderstorm ultimately become an area of downdrafts.

Because of the heating and drying process produced by the downdrafts, the rainfall gradually ceases and the thunderstorm begins to dissipate. During this stage, the lower level of the thunderstorm frequently becomes stratiform in appearance, and the top of the cell develops the characteristic anvil structure.

WEATHER WITHIN THE THUNDERSTORM

Thunderstorms are characterized by turbulence, moderate to extreme up- and downdrafts, hail, icing, lightning, precipitation and, under most severe conditions, (in certain areas) tornadoes.

Turbulence (Drafts and Gusts)

Downdrafts and updrafts are vertical currents of air which are continuous over many thousands of feet of altitude, and are continuous over horizontal regions as large as a thunderstorm. Their speed is relatively constant as contrasted to gusts, which are smaller-scale discontinuities or variations in the wind flow pattern extending over short vertical and horizontal distances. Gusts are primarily responsible for the bumpiness (turbulence) usually encountered in cumuliform clouds. A draft may be considered as a river flowing at a fairly constant rate, whereas a gust is comparable to an eddy or other type of random motion of water in a river.

Drafts displace aircraft vertically. If the pilot does not *fight* or attempt to counteract such a vertical displacement too much, the possibility of structural damage or stalling is minimized. In general, the drafts encountered by aircraft used in the Thunderstorm Project were such as to indicate that vertical displacement of aircraft would increase with height.

Turbulence appears to increase in intensity with altitude in thunderstorms to within 5,000 or 10,000 feet below the tops of the clouds. Although turbulence is usually at a minimum near the bases and tops of the cloud, in some cases it may be severe in these areas.

Icing

Where the free-air temperatures are at or below freezing, icing should be expected in flights through thunderstorms. In general, icing will be associated with temperatures from 0°C to -20°C. Most severe icing occurs from 0°C to -10°C. In scattered thunderstorm areas icing will not present too serious a problem because the flight time in the storm will be relatively short. In areas of numerous thunderstorms the icing problem may be serious with prolonged exposure to icing conditions. Icing in the anvil tops is also sometimes encountered.

Hail

Unlike most of the other thunderstorm phenomena, such as rain, turbulence, updrafts and downdrafts, and lightning, hail is not found in every storm. Unfortunately, however,

usually does not fall because the water droplets are carried upward or remain more or less suspended in the ascending air currents.

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Hail

Information from the Thunderstorm Project indicates that hail is primarily encountered during the mature stage (on flights through thunderstorms in Ohio, hail was encountered

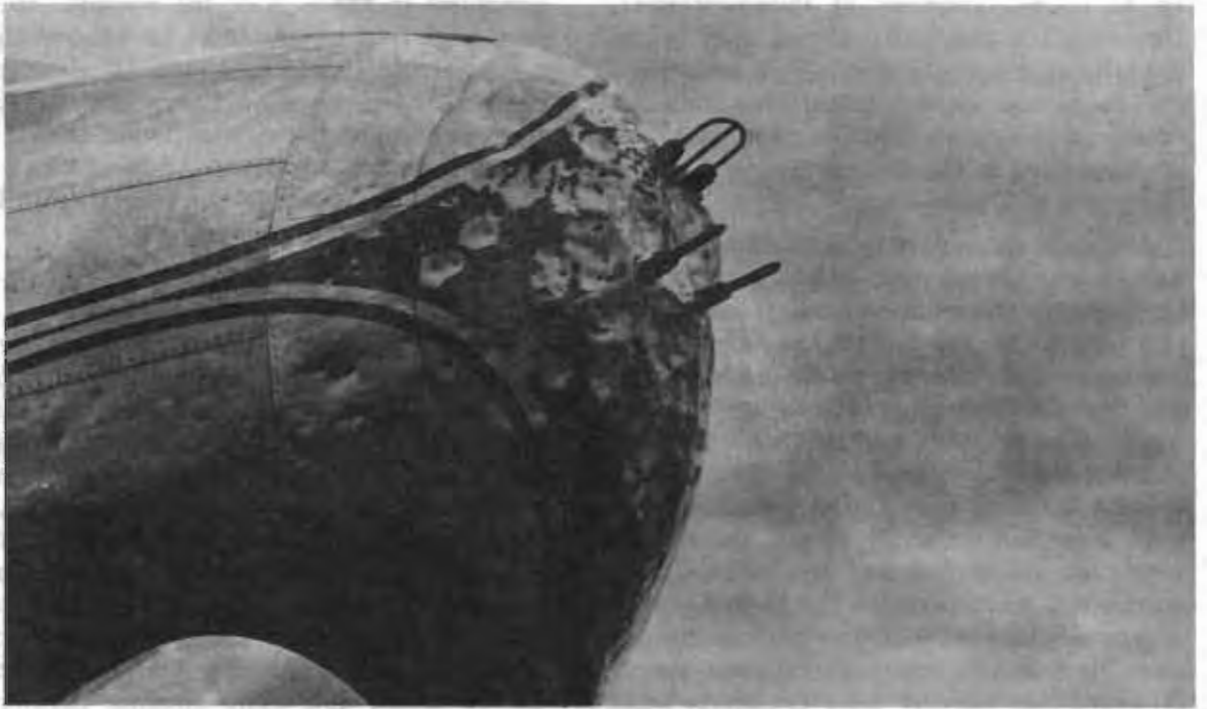


Figure 12-8. Hail Damage to Aircraft



it is not possible for either the forecaster or the pilot to differentiate with certainty between those storms that do and those that do not contain hail. Consequently, the possibility of encountering hail must be considered on every flight through or near a thunderstorm.

A number of investigations have indicated that hail is most often encountered during the mature stage of the thunderstorm cycle. The greater the height reached by the storm and the more intense the radar echo, the more likely it is to contain damaging hail. Also, in certain parts of the country, particularly the western Great Plains, hail apparently occurs at some time during most of the thunderstorms. On the other hand, in tropical and subtropical areas such as Florida and also over oceans, hail encounters are considerably less frequent. However, there is no region which can be assumed to be completely free of hail.

Based on past investigations, some 60-80 percent of hail encounters occur within the thunderstorm itself. However, the balance have occurred in the clear air surrounding the storm, particularly underneath the overhanging cirrus anvil. The hailstones are carried up by the powerful updraft in the cell, and some may be spewed out of the top to fall through the surrounding air mass. In many cases the winds aloft (e.g., 35,000 feet) are much stronger than the low-level winds, and the cell core is tilted forward (downwind). In addition, the top of the cell may be embedded in and concealed by the cirrus anvil. Thus hail may be encountered not only in the thunderstorm itself but also (1) in the clear air six to eight miles on the windward side of the storm, (2) five to fifteen miles on the downwind side of the storm (depending on the winds aloft), and (3) underneath the overhanging anvil clouds. The only safe procedure is to give every thunderstorm a wide berth, particularly on the downwind side and beneath an overhanging cirrus anvil.

Although aircraft encounters with large hail are not too common, they do occur. Hail larger than $\frac{1}{2}$ to $\frac{3}{4}$ of an inch in diameter can damage an aircraft in a matter of seconds. In many incidents, the airframe, radome, and nearly all leading edges received significant

damage. Even smaller hailstones ($\frac{1}{4}$ to $\frac{1}{2}$ inch) can harm jet engines when ingested.

Forecasting regions of possible and probable hail has greatly improved; however, with every thunderstorm possessing unknown and unique qualities, the pilot must be aware of the possibility of hail in and near every thunderstorm.

Rain

In thunderstorms a pilot can expect to encounter considerable quantities of visible moisture, which may not necessarily be falling to the ground as rain. These water droplets may be suspended in, or moving with, the updrafts. Rain will be encountered below the freezing level in almost all penetrations of fully developed thunderstorms. Above the freezing level, however, there is a sharp decline in the frequency of rain.

There seems to be a definite correlation between turbulence and precipitation. The intensity of turbulence, in most cases, varies directly with the intensity of precipitation. This relationship indicates that most rain and snow in thunderstorms is held aloft by drafts.

Lightning

During the thunderstorm penetrations, lightning proved to be a minor hazard. Aircraft struck by lightning only received small punctures in the skin of the aircraft. However, more recent experiences have shown that aircraft with large amounts of electronic equipment can be subjected to considerable damage by lightning strikes. Other factors to consider are the temporary blinding effect at night, and the possible permanent error induced into the magnetic compass.

Precipitation Static

When an aircraft flies through an area which contains clouds, precipitation, or a concentration of solid particles (dust, sand, ice, etc.), it accumulates a static electric charge. When this static electricity discharges onto a nearby surface or as a corona into the air, a noisy disturbance called *precipitation static*, is picked up by radio receivers and interferes with radio reception, especially at lower frequencies. This is overcome by certain tech-

on 51 of 812 traverses of thunderstorms). However, it is frequently carried aloft in the updrafts, cast out into the clear air away from the clouds, and appears to fall from the anvil or side of the cloud. Thus, occasionally, hail is encountered in the clear air near a thunderstorm (up to 5 miles out).

Although encounters by aircraft with large hail are not too common, hail larger than $\frac{1}{2}$ - or $\frac{3}{4}$ -inch in diameter can damage an aircraft in a very few seconds. Often the airframe and particularly radome material, are damaged significantly. The conclusion is reached that many if not most mid-latitude thunderstorms, particularly those in the Great Plains, contain hail sometime during their life-cycle, with most hail occurring during the mature stage. In subtropical and tropical thunderstorms hail seldom reaches the ground, and it is generally believed that they contain less hail aloft than middle and high latitude storms. However, this has not been proven to mean aircraft run no risk from hail in the tropics.

Forecasting possible hail has improved tremendously, but with every thunderstorm possessing unknown individual qualities, the pilot should be prepared for hail in any thunderstorm.

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THUNDERSTORM SURFACE PHENOMENA

The rapid change in wind direction and speed immediately prior to a thunderstorm passage is a significant surface hazard associated with thunderstorm activity. The strong winds which accompany thunderstorm passages are the result of the horizontal spreading out of downdraft currents from within the storm as they approach the surface of the earth.

This spreading-out activity is depicted in the accompanying illustration. Wind speeds at the leading edge of the thunderstorm are ordinarily far greater than those at the trailing edge. The initial wind surge observed at the surface is known as the *first gust*. The speed of the first gust is normally the highest recorded during the storm passage and may vary as much as 180° in direction from the surface wind direction which previously existed. The mass of cooled air spread out from downdrafts of neighboring thunderstorms (especially in squall lines) often becomes organized into a small, high-pressure area called a *bubble-high* or *meso-high*, which persists for some time as an entity that can sometimes be

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THUNDERSTORM ALTIMETRY

During the passage of a thunderstorm, rapid and marked surface pressure variations generally occur. These variations usually occur in a particular sequence characterized by: (1) an abrupt fall in pressure as the storm approaches, (2) an abrupt rise in pressure associated with rain showers as the storm moves overhead (very often associated with the "first gust"), and (3) a gradual return to normal pressure as the storm moves on and the rain ceases. Such pressure changes may result in significant altitude errors on landing, if the altimeter setting of a landing aircraft is not corrected. (In general for the lower levels of the atmosphere, .10' mercury is approximately equivalent to 100 feet of altitude.)

During the Thunderstorm Project, for each of the days on which one or more thunderstorms occurred, the maximum pressure rise and fall were converted to the equivalent altimeter error and tabulated. In 22% of the cases if a pilot landed during the maximum pressure using an altimeter setting given to him only a few minutes earlier, his altimeter would indicate that he was 60 feet or more below the true altitude.

Of greater concern to the pilot are pressure altitude readings which are too high. If a pilot used an altimeter setting given to him during the maximum pressure and landed after the pressure had fallen, on 26% of the days he would have found that his altimeter still read 60 feet or more above the true altitude after he was on the ground. On two occasions, the altimeter would have read over 140 feet above the true altitude when he landed.

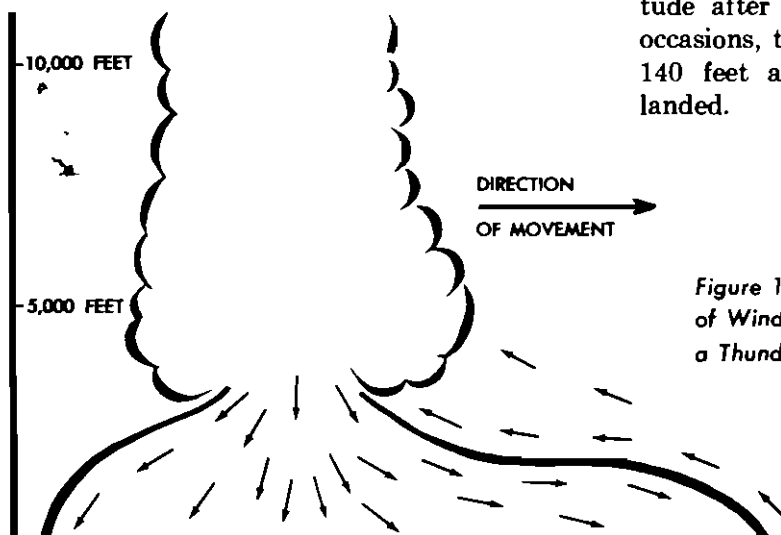


Figure 12-9. Schematic Presentation of Winds Near Surface Accompanying a Thunderstorm

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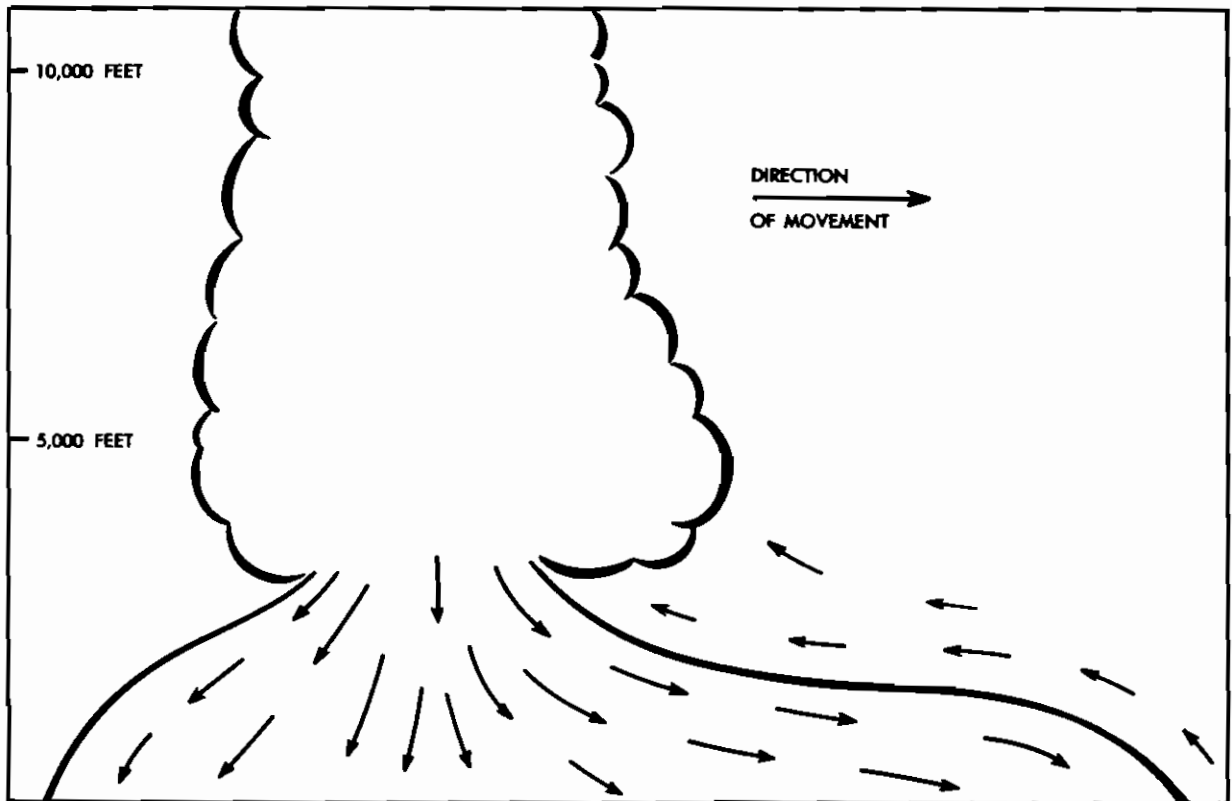


Figure 12-9. Schematic Presentation of Winds Near Surface Accompanying a Thunderstorm

TORNADOES

Tornadoes are violent circular whirlpools of air shaped like a funnel from a cumulonimbus or associated cloud, and are commonly several hundreds of yards in diameter where they intersect the ground. The low pressure encountered in the center of the tornado, and its high wind speeds are very destructive. Their paths over the ground are often only a few miles long, and they move at speeds of 25 to 50 knots. Although maximum wind speeds associated with tornadoes have never been precisely measured, property damage and other effects indicate that they probably exceed 300 mph. Tornadoes are bred from thunderstorms or other highly convective clouds in the form of *twister* (*funnel*)

clouds which descend erratically to the earth and rotate in a counterclockwise (cyclonic) manner in the Northern Hemisphere.

Tornadoes are rare in most areas of the world, except Australia and the United States. In these areas a large number are reported each year. In the United States they occur most frequently in the belt extending from Oklahoma to Iowa, as is evident in the illustration. They also occur frequently in the Southeastern states. Tornadoes are called *waterspouts* when they occur over water. However, not all waterspouts are tornadoes. Some waterspouts are formed by rapidly converging and convecting air, as are also the dust devils over land. These can rotate either clockwise or counterclockwise, and do not contain the destructive tornadic force.

Figure 12-10. Tornado Buildup, Gottenburg, Neb.



(A)

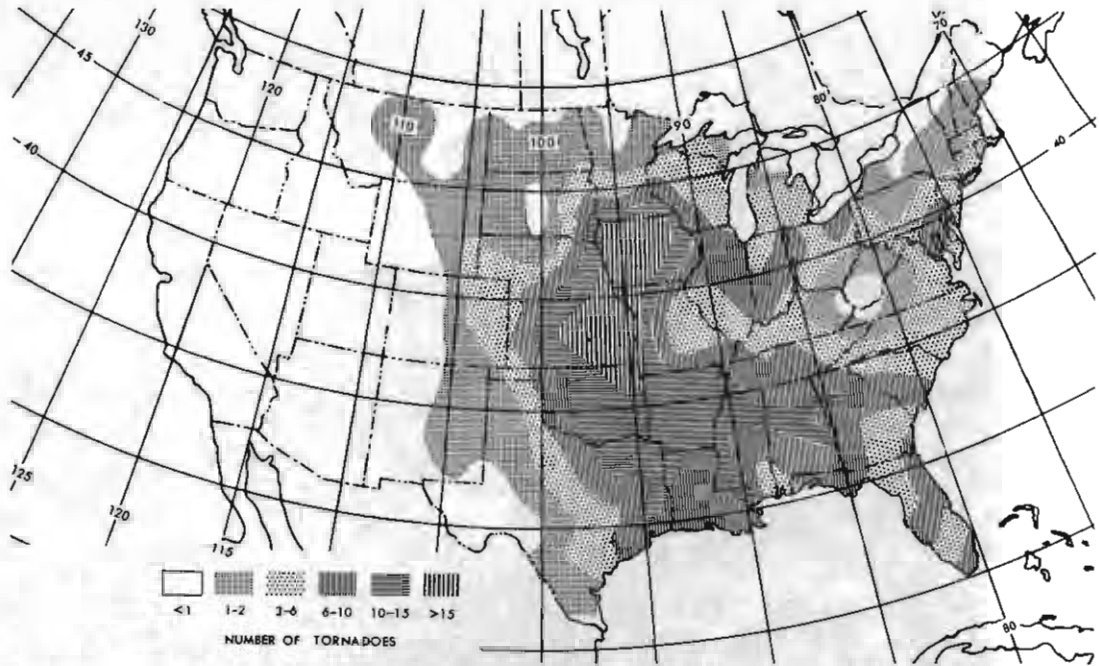


(B)

Courtesy US Weather Bureau, Mrs. Ray Homer

Figure 12-11. Total Number of Tornadoes per 50-Mile Square Reported in the Period 1920-1949
 A list of States in decreasing order of frequency would read:

- (1) Iowa, (2) Kansas, (3) Arkansas, (4) Oklahoma, (5) Mississippi, (6) Alabama, (7) Missouri, (8) Indiana, (9) Illinois, (10) Ohio, (11) Georgia, and (12) Texas.



(C)



(D)

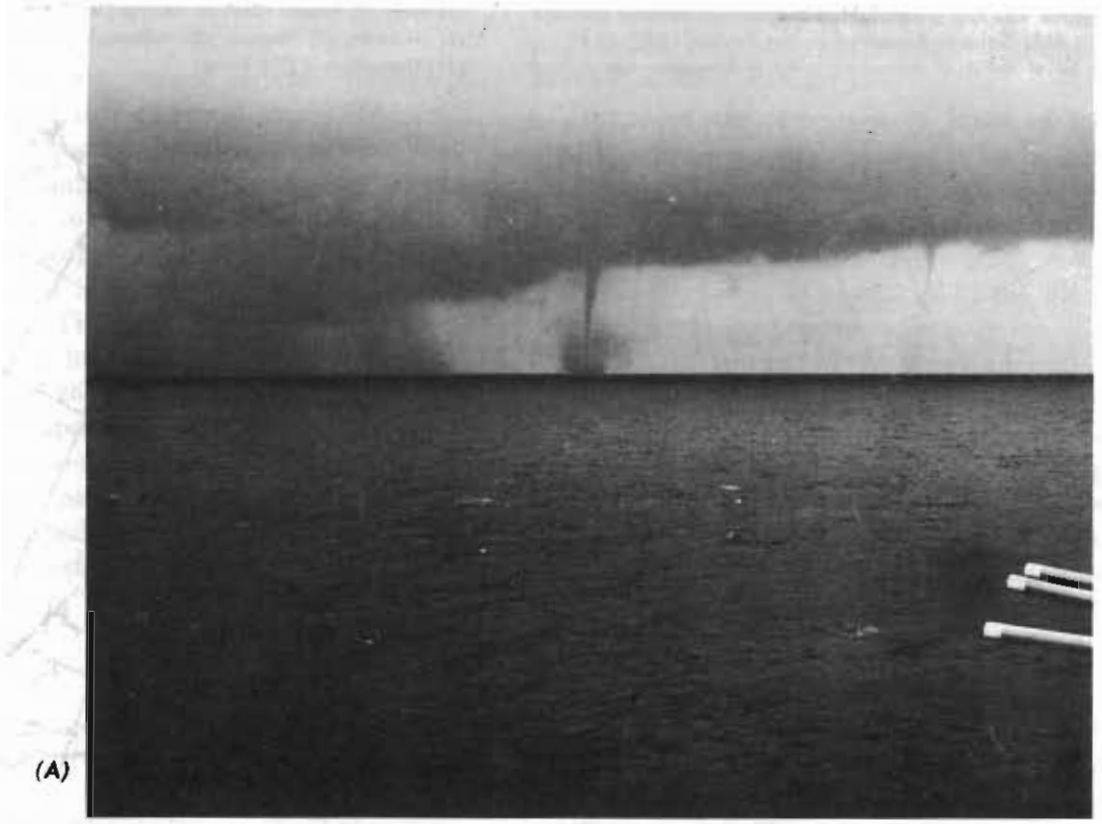
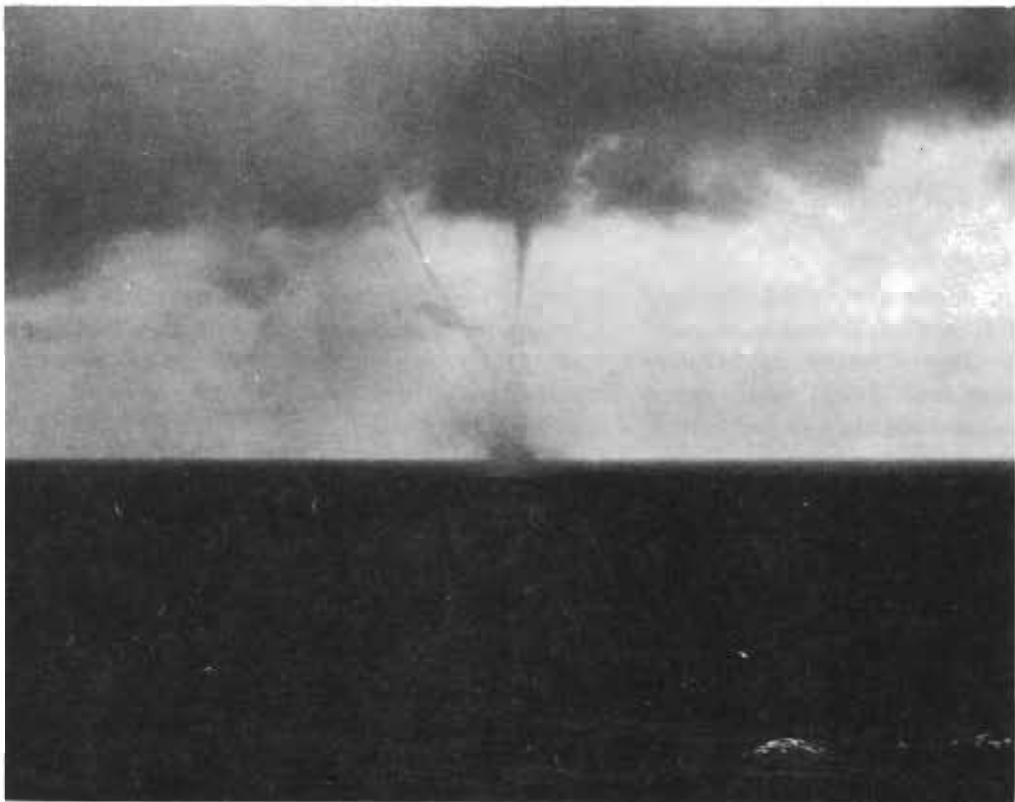


Figure 12-12. A Tornado Over Water (Waterspout)





(B)



(D)

Courtesy US Navy

Summary

Penetration of the thunderstorm should be accomplished by reference to attitude instruments and a known power setting. (An aircraft's angle of attack must also be watched when flying either within or over thunderstorms. Jet engine compressor stalls have been encountered in flight over the top of thunderstorms.) Attitude flight will lessen the stresses imposed on the aircraft. Known power settings for various altitudes are recommended because the airspeed indicator gives false readings in vertical drafts or in heavy rain.

Penetration speeds may be determined by reference to the *Turbulent Air Penetration Speed* in the applicable technical order (flight operating instructions). In high-altitude flying, where the cruising indicated airspeed is lower than the published penetration airspeed, the cruising indicated airspeed will usually

serve as a safe penetration airspeed provided a safe margin above stall speed is maintained. Practice in clear air will acquaint the pilot with airspeeds resulting from power settings at various altitudes.

It is recommended that the pilot avoid the freezing level in thunderstorm penetrations because of the excess of dangerous icing and turbulence. For high altitude penetrations select an altitude within the safe operating capabilities of the aircraft.

Because of the dangers, an aircrew member should bail out in a thunderstorm only as a last resort.

In general, thunderstorm turbulence, blinding lightning, icing, *heavy* rainfall, and high winds, present very definite hazards to flying. With a basic knowledge of thunderstorm activity, a pilot should be better able to cope with these hazards. However, the astute action is to *avoid all thunderstorms if possible*.

Tropical Weather

This chapter is designed to acquaint the aircrew member with a knowledge of certain weather characteristics of the tropics. The tropics may generally be considered as that vast region of the earth lying between 25° north latitude and 25° south latitude.

One of the chief differences between the weather in the tropics and weather observed in mid-latitudes is that tropical weather occurs within air masses as contrasted to the high frequency of frontal weather in the mid-latitudes. On rare occasions in winter, polar fronts

are strong enough to move into the tropics. These fronts are accompanied by thunderstorms, rain showers, wind shifts, and some reduction in temperature. Also observed in areas of large tropical land masses are transition zones separating warm, moist air from dry air. In general, however, most tropical weather occurs from changes within air masses rather than along frontal zones between air masses. Consequently, the weather analysis techniques used in the tropics differ somewhat from those used in middle and high latitude areas.

WEATHER VARIATIONS WITHIN THE TROPICS

The extensive region of the tropics is primarily oceanic. However, since this region contains mountainous islands, coastal areas and large portions of some continents, some discussion must be given to the variations in tropical weather in each of these situations.

Island and Coastal Tropical Weather

Weather conditions are similar along coastal areas and over the various mountainous islands of the tropics. During the day as warm, moist air moves inland and is lifted over the terrain, large cumuliform clouds develop. These clouds are common in coastal areas. The lifting of moist air on the windward side of mountainous islands also produces tower-

ing cumulus clouds which may frequently be seen from long distances, indicating the presence of an island ahead. Low islands also cause more clouds and rain than over the water, but the clouds tend to increase downwind to a maximum near the lee-end of the island. Cumuliform clouds and precipitation are more abundant over island and coastal areas than over the open oceans, except in the vicinity of certain tropical weather circulation systems, such as hurricanes, the inter-tropical convergence zone, and easterly waves.

Continental Tropical Weather

The greatest temperatures and pressure variations in the tropics are found in con-

tinental areas. The temperature on continents undergoes a significant daily temperature variation, becoming very warm in the afternoon and becoming cool during the night.

Cloudiness and precipitation are at a minimum over desert areas; visibility is usually good except locally in blowing sand and dust on the surface, and in haze aloft. Cloudiness and precipitation are at a maximum for the tropics over land areas which are exposed to air flow from ocean areas. This helps account for tropical jungle areas. Visibility over jungle areas is often restricted in rain showers, low clouds, and radiation fogs which may briefly follow these rain showers.

Oceanic Tropical Weather

Typical weather over the tropical oceans is characterized by cumuliform clouds, although all forms of clouds are observed. Though most oceanic cumulus clouds have a common base of approximately 2,000 feet, occasionally lowering to 1,500 feet or 1,000 feet in precipitation, there is great variation in the heights of the tops, which depends primarily on the area in which they form. Dol-drum cumulus, which form in the areas of light winds, common to the equatorial trough, have tops varying from 6,000 to 60,000 feet, with the most frequent height at about 25,000 feet. The term, *trade cumulus*, applies to cumulus clouds that develop in the broad easterly wind stream between latitudes 10° and 30°. The characteristic height of trade cumulus tops varies from about 3,000 to 10,000. Tall cumulus clouds occur only at widely scattered intervals in the trade winds. Seen from the air, the low trade cumulus have a characteristic arrangement in bands paralleling the wind flow. Scattered rain showers are common from these cumulus clouds, and visibilities are good except in the rain showers.

Generally speaking, the mean daily range of temperature over land in the tropics is about 10°F, while the difference between the mean temperature of the warmest and coolest months ranges from about 2°F near the equator to 20°F or more in the subtropics. The dew points at tropical stations also show little day to day variation. The relative humidity will vary with the temperature at a given station,

but the dew points remain nearly constant. (With nearly constant dew point, the relative humidity will vary inversely with the temperature; i.e., the higher the temperature, the lower the relative humidity.)

Wind is the most important factor in tropical weather, even over open ocean areas. When there is convergence (coming together) of wind flow, there is a piling up of air locally. This lifting action in warm, moist air results in cumuliform clouds and precipitation. These cumuliform clouds often develop to great heights in these zones of converging winds, and heavy showers are frequently observed.

EASTERLY WAVE

One common phenomenon of tropical weather is a disturbance called the *easterly wave*. These waves normally occur in the trade winds. They are characterized by north-easterly winds and falling pressure (often clear skies, too) ahead of the waves, as they move slowly westward. The movement of the wave is usually at a speed much less than the normal wind flow, which is from east to west in the trade wind belt. The wave is preceded by fair weather, and followed by extensive cloudiness with the clouds and moist air built up to great heights behind the wave. As the waves move slowly westward, they may have the appearance of an active cold front in the temperate zone. These easterly waves are ob-

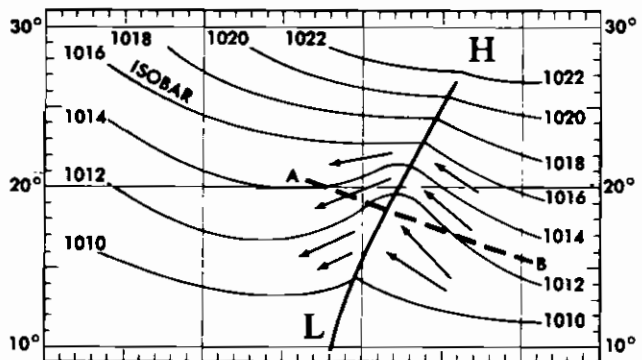


Figure 13-1. Diagram of Surface Pressure Pattern Associated with a Well-developed Easterly Wave in the Northern Hemisphere

served in all seasons of the year, but are more numerous and more extensively developed during the summer.

EQUATORIAL TROUGH AND EQUATORIAL FRONT

The equatorial trough is the low pressure belt that lies between the northeast and southeast trade belts (the northeast trade belt in the Northern Hemisphere; the southeast trade belt in the Southern Hemisphere). It is characterized by broad, flat areas of lower pressure and light winds (*doldrums* or *belts of calms*). The equatorial trough departs from the area of the equator during the summer seasons.

When the trough moves north in the Northern Hemisphere's summertime, convergence is increased along the trough and a narrow zone of unsettled, convective weather often develops. This results in the trough being called

the *intertropical convergence zone* (sometimes incorrectly and misleadingly called the "inter-tropical front"). As a result of this convergence, a band of cumulonimbus clouds often develops and extends above 40,000 feet, with extensive high sheets of cirrus spreading north and south, Figure 13-3.

TROPICAL CYCLONES

There are many regional names for tropical cyclones of great intensity. In the Atlantic and eastern Pacific Oceans they are called *hurricanes*; in the western Pacific they are called *typhoons*. Near Australia they are called *willy willy's*; and in the Indian Ocean *cyclones*. In this manual, the term *tropical cyclone* refers to symmetrical, clearly-developed cyclones of any intensity which form over tropical oceans.

Tropical cyclones apparently originate from

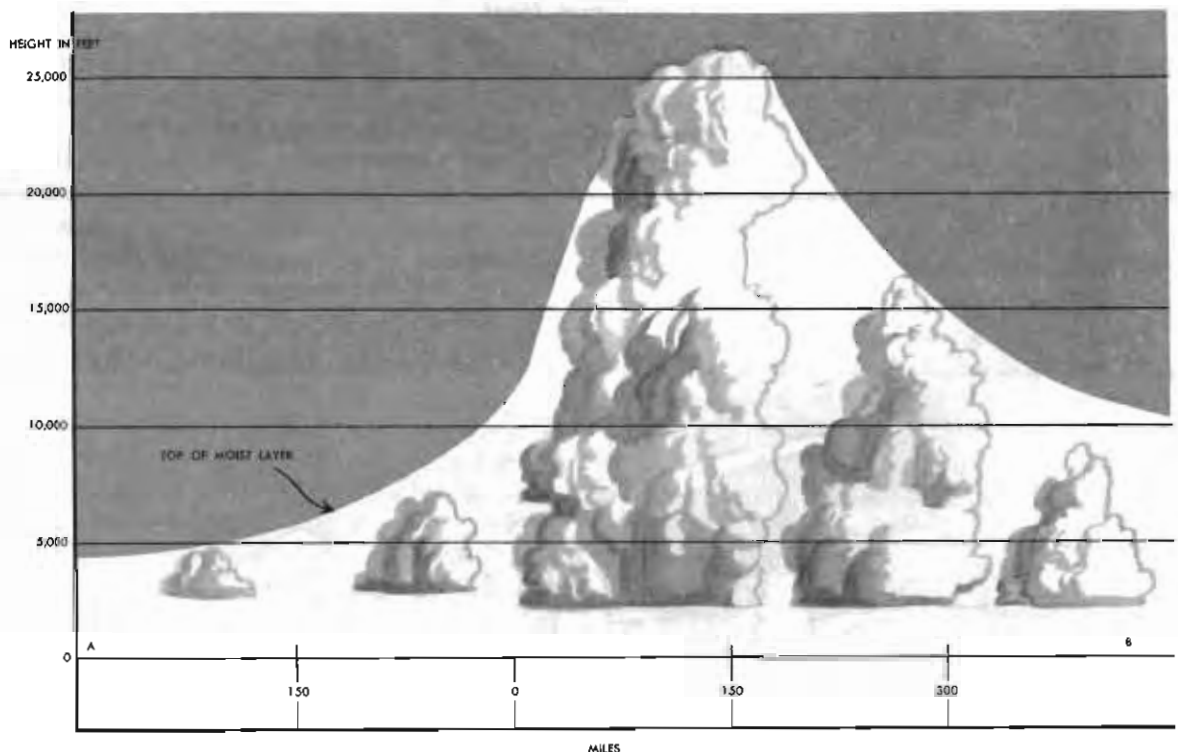


Figure 13-2. Diagram of Vertical Cross Section (along line AB in the preceding figure) Showing Distribution of Cloudiness and Precipitation with a Well-developed Easterly Wave

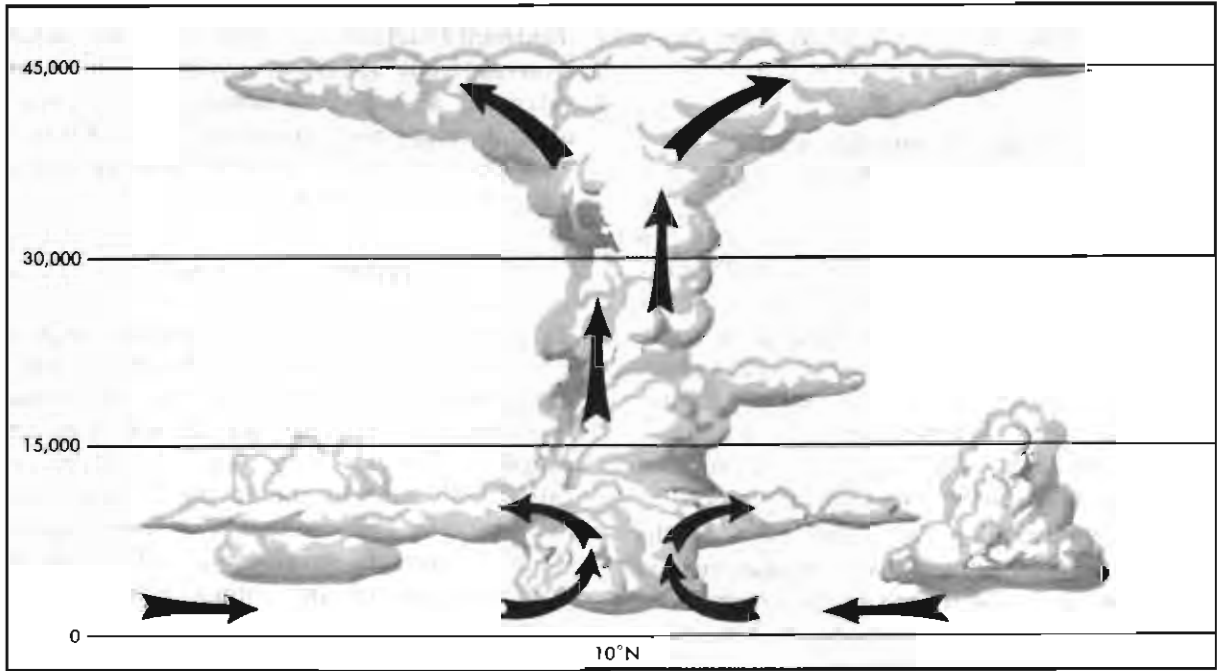
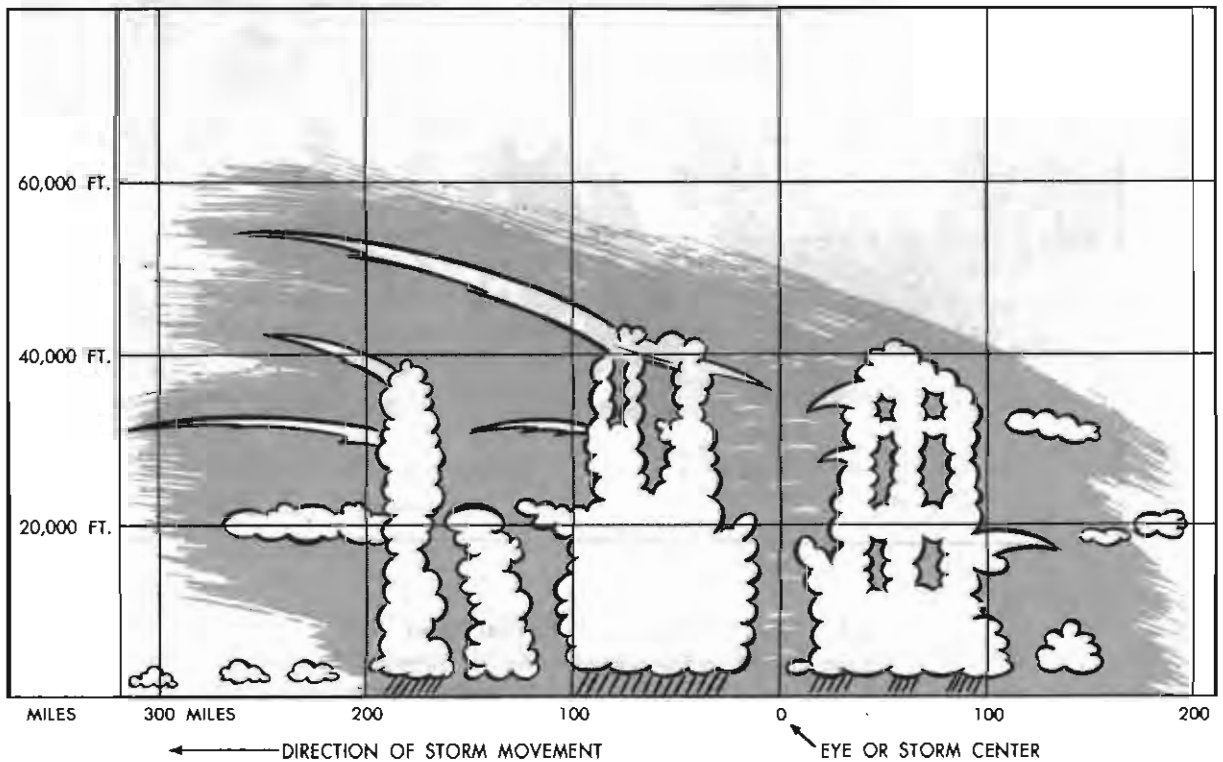


Figure 13-3. Vertical Cross Section Through the Equatorial Trough and Intertropical Convergence Zones

Figure 13-4. Vertical Cross Section of Typical Hurricane Over Water



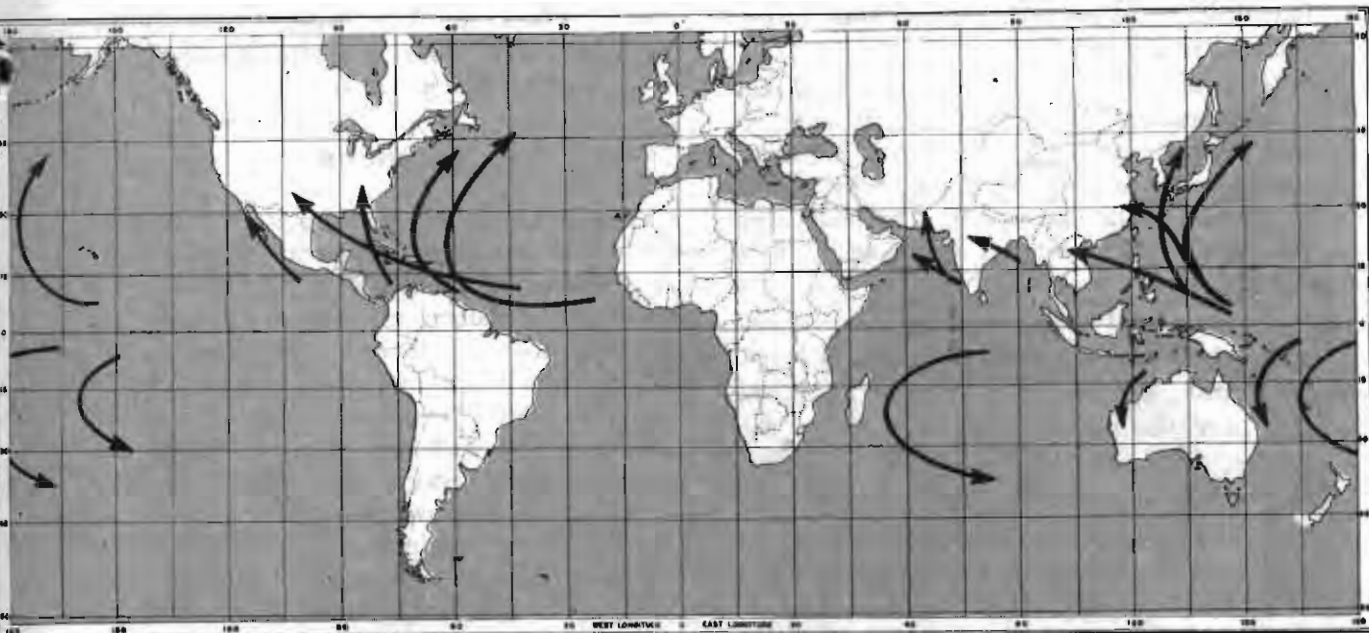


Figure 13-5. Arrows Indicate Principal Regions of World Where Tropical Cyclones Form and the Approximate Direction of Their Movement

several sources. Some cyclones originate as vortices that develop in easterly waves. These storms derive their energy, in a large measure, from the release of the latent heat of condensation of water vapor (heat is required to evaporate water; when water vapor condenses back to liquid water—the reverse of evaporation—approximately the same amount of heat originally required to evaporate the water is released). Not all of these vortices, however, increase in intensity.

A tropical cyclone may develop through several stages to full maturity. In the formative stage, it is called a *tropical depression*, with winds up to 34 knots. It may continue to develop into a *tropical storm*, with winds of 35 to 64 knots. In the mature stage, the cyclone reaches *hurricane intensity* and is characterized by winds of 65 knots or higher. Frequently, these winds are in excess of 100 knots and, indeed, have been recorded as high as 175 knots in a mature tropical cyclone (hurricane or typhoon).

These tropical cyclones (hurricanes) are characterized by heavy, squally rains, extensive cloudiness, and heavy thunderstorms with moderate to severe turbulence. Each storm

has a relatively clear area in the center called the *eye*, which is an area of comparatively calm wind, and sea birds have been known to remain in the *eye* for several days for this reason. The diameter of an *eye* in a well developed storm is generally 15 to 30 miles, while the storm itself may vary from 60 to 1,000 miles in diameter.

These storms usually originate between 5° and 20° latitude and, in the Northern Hemisphere, move in a westerly or northwesterly direction until they reach approximately 30° latitude. At this point they often begin to recurve and move in a northeasterly direction. Hence, they are steered by the general wind flow in which they are embedded.

Increased surface friction, cooler surface temperatures, and inflow of drier air (from land), cause a hurricane to decay. During the recurvature period, (the period when movement becomes easterly, or with a component toward the east) or shortly thereafter, the storms usually begin to lose their tropical storm characteristics and move rapidly north-eastward as extratropical (outside the tropics) lows. Weather reconnaissance pilots have

found the roughest flying conditions during this transition period.

If flight is necessary in the vicinity of one of these storms, circumnavigation is a necessary flight procedure. Circumnavigation should be made by keeping the storm center to the left of the flight path. This maneuver will result in the aircraft experiencing tailwinds.

A network of storm warning centers has been set up near the seasonal tracks of tropical storms. These centers are fully equipped and have the responsibility of tracking the storms, forecasting the intensity, direction and speed of movement, and disseminating this information to using agencies.

The tropical storm season in the Northern Hemisphere is during the months of August, September and October. They are rare from December until May.

SHEAR LINES

As strong polar fronts move into the area of the subtropical highs, a trough formation between the polar and subtropical highs is frequently observed, and a line of cumulus

clouds often develops with thunderstorm activity, gusty winds, and rain squalls. This area is called a *shear line*.

MONSOON

The *monsoon* is actually a large-scale seasonal land and sea breeze, a wind regime which reverses its direction twice a year. The monsoon affects many continents, but the degree of influence on climatic conditions varies greatly. Southern and southeastern Asia is the continental area most affected by this seasonal land and sea breeze. During the winter season, because of the large Siberian high, polar air flows southward across the Himalayan Mountain range toward the equator (although the mountains interfere significantly with the flow and keep the coldest air from reaching India). This air is relatively dry and is warmed adiabatically as it flows down the southern slopes of the mountains. This is the dry or winter monsoon.

During the summer season, air from an equatorial source flows up over the mountains from the south. The lifting of moist air in this area produces extensive cloudiness and widespread rain. The summer monsoon is responsible for some of the heaviest rains on earth. There are stations in India which report more than 400 inches of rainfall in a year, and most of it between the months of June and October. The related diagrams show the seasonal land and sea breeze effect, called the monsoon.

TRADE INVERSION

One very significant phenomenon in the tropics is the presence of very dry, warm air aloft, sometimes called *superior air*. This air is a result of subsidence (sinking) aloft in the subtropical anticyclones (highs). The lower boundary of this dry, warm air aloft generally coincides with an inversion or a layer of more marked stability than below or above, with the moist, tropical air present in the lower levels. There is a definite demarcation between these layers, characterized by a rapid decrease of moisture, even when the temperature differences are not so marked (as often

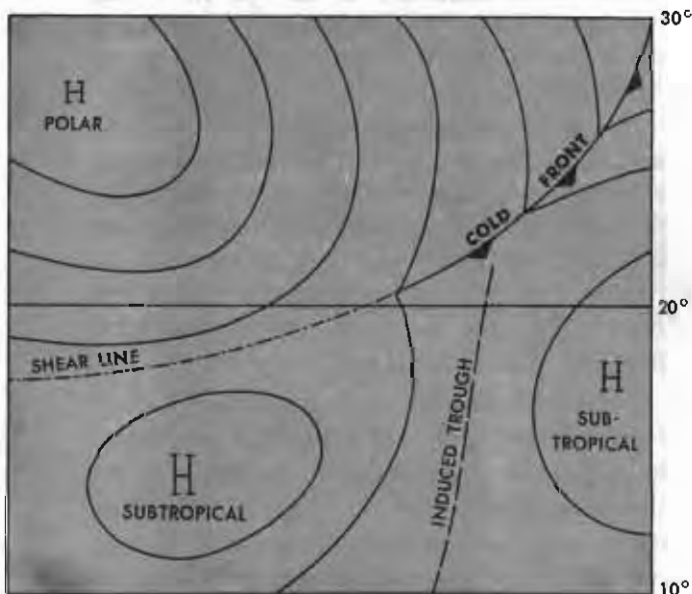


Figure 13-6. Shear Line Resulting when the Polar High Invades the Tropics and Reinforces the Subtropical High

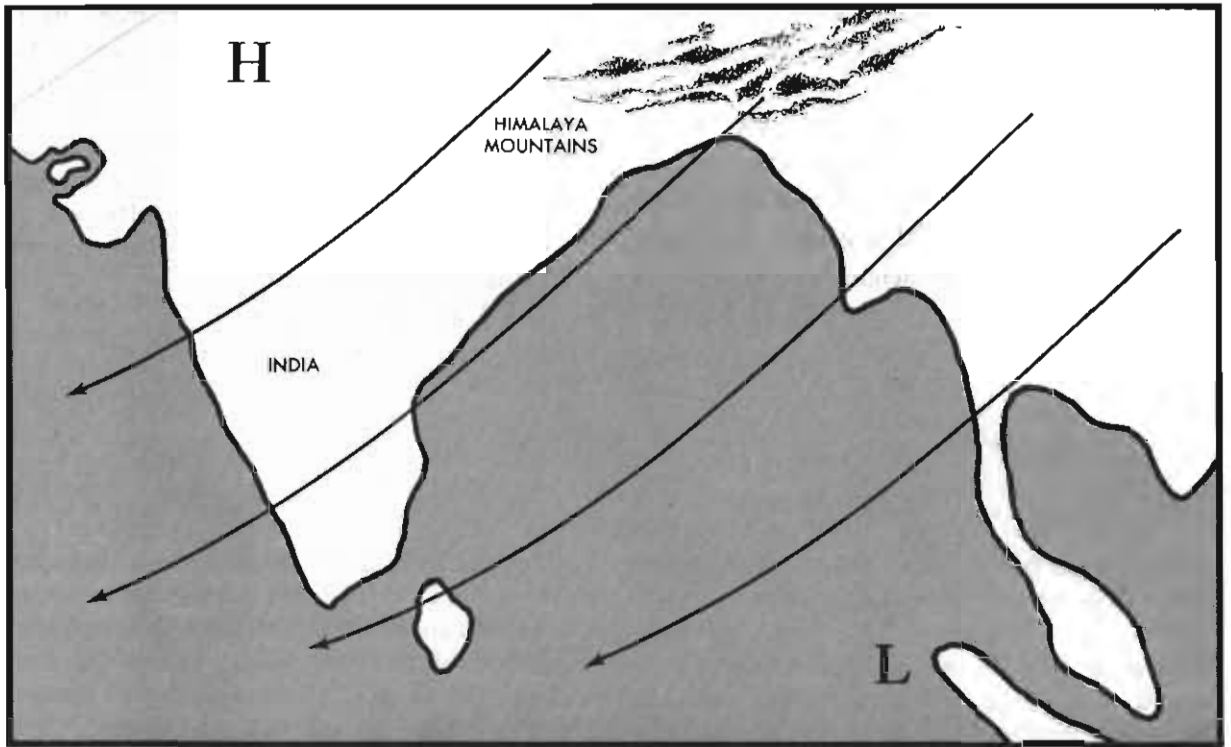
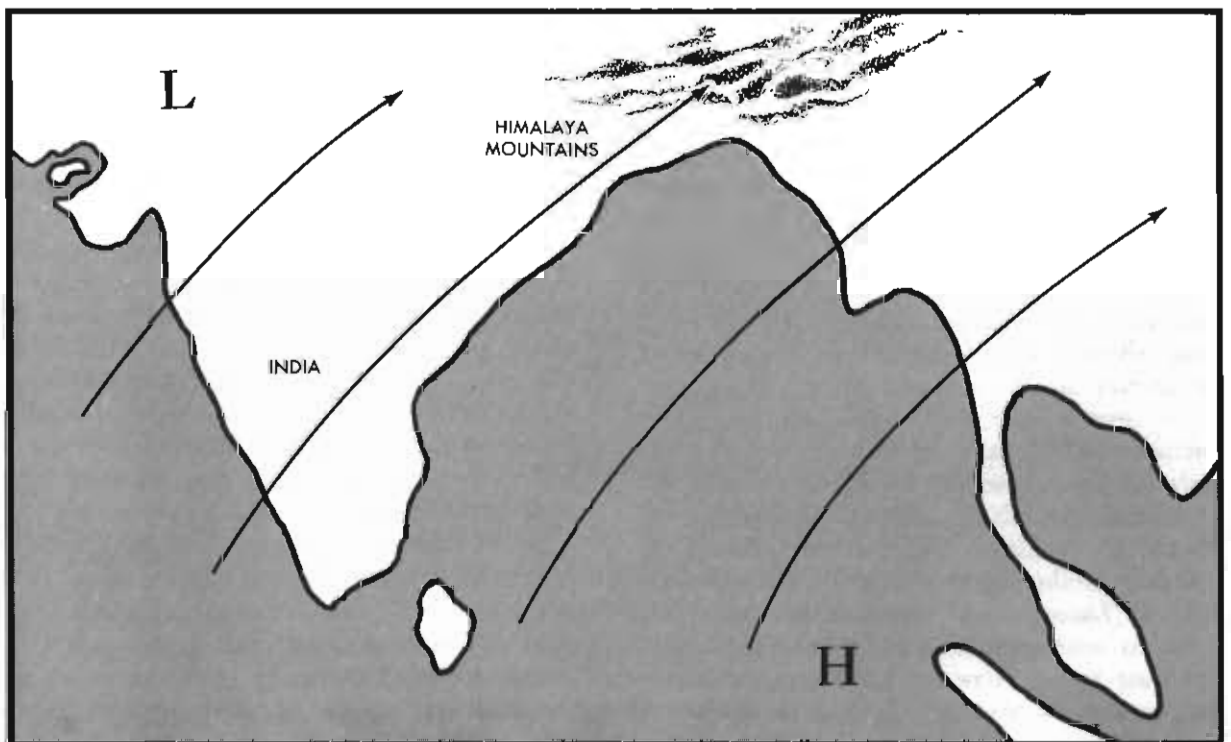


Figure 13-7. Winter Monsoon Over Southeast Asia

Figure 13-8. Summer Monsoon Over Southeast Asia



happens toward the western sides of the subtropical highs). This phenomenon is called the *trade inversion*.

The height of the trade inversion has a significant effect on tropical weather. When the base of the trade inversion is at a high altitude, the moist layer has greater thickness, clouds build to greater heights and cloud cov-

erage is more extensive; rain is more likely. When the base of the trade inversion is low in altitude, moisture is confined to lower levels, there is less cloud cover and cloud tops are much lower; rain is unlikely. Weather is better when the trade inversion is at a low altitude, except over the cold water belts near the west coasts of the continents, where fog and stratus are common.