



U.S. Department  
of Transportation  
Federal Aviation  
Administration

# Advisory Circular

---

**Subject:** Aviation Weather

**Date:** 8/23/16

**AC No:** 00-6B

**Initiated by:** AFS-400

**Change:**

This advisory circular (AC) was published by the Federal Aviation Administration (FAA) Flight Standards Service (AFS), with contributions from the National Weather Service (NWS). The publication began in 1943 as CAA Bulletin No. 25, Meteorology for Pilots, which at the time contained weather knowledge considered essential for most pilots. As aircraft flew farther, faster, and higher, and as meteorological knowledge grew, the bulletin became obsolete. It was revised in 1954 under a new title, The Pilots' Weather Handbook, and updated again in 1965. In 1975 it was revised under its current title.

Previous editions have suffered one common problem—they dealt in part with weather services that continually change, in keeping with current techniques and service demands. As a result, each edition was somewhat outdated almost as soon as it was published, its obsolescence growing throughout the period it remained in print.

In 1975, in order to alleviate this problem, the authors completely rewrote the AC. They streamlined it into a clear, concise, readable book, and omitted all reference to specific weather services.

The 1975 text remained valid and adequate for many years. Its companion manual, the current edition of AC 00-45, Aviation Weather Services, supplements this AC. In 2015, this supplement was updated concurrently with this text. This was done to reflect changes brought about by new products and services, particularly since this information is now available through the Internet. The companion AC describes current weather services and formats, and uses real world examples of weather graphics and text products.

The two manuals can be downloaded for free via the Internet in PDF format. Print versions are also sold separately at nominal cost, allowing pilots the opportunity to own a reference copy of the supplement to keep current with aviation weather services.

New scientific capabilities now necessitate an update to this AC. In 1975, aviation users were not directly touched by radar and satellite weather. In 2016, much of what airmen understand about the current atmosphere comes from these important data sources. This AC is intended to provide basic weather information that all airmen must know. This document is intended to be used as a resource for pilot and dispatcher training programs.

This AC cancels AC 00-6A, Aviation Weather for Pilots and Flight Operations Personnel.

John Barbagallo  
Deputy Director, Flight Standards Service

---

## CONTENTS

<b>Paragraph</b>	<b>Page</b>
Chapter 1. The Earth's Atmosphere.....	1-1
1.1 Introduction.....	1-1
1.2 Composition.....	1-1
1.2.1 Air Parcel.....	1-2
1.3 Vertical Structure.....	1-2
1.3.1 Troposphere.....	1-2
1.3.2 Stratosphere.....	1-3
1.3.3 Mesosphere.....	1-4
1.3.4 Thermosphere.....	1-5
1.3.5 Exosphere.....	1-5
1.4 The Standard Atmosphere.....	1-5
Chapter 2. Heat and Temperature.....	2-1
2.1 Introduction.....	2-1
2.2 Matter.....	2-1
2.3 Energy.....	2-1
2.4 Heat.....	2-1
2.5 Temperature.....	2-1
2.5.1 Temperature Measurement.....	2-1
2.5.2 Temperature Scales.....	2-1
2.6 Heat Transfer.....	2-3
2.6.1 Radiation.....	2-3
2.6.2 Conduction.....	2-6
2.6.3 Convection.....	2-7
2.7 Thermal Response.....	2-8
2.8 Temperature Variations with Altitude.....	2-11
2.8.1 Atmospheric Sounding.....	2-12
2.8.2 Isothermal Layer.....	2-12
2.8.3 Temperature Inversion.....	2-12

Chapter 3. Water Vapor .....	3-1
3.1 Introduction .....	3-1
3.2 The Hydrologic Cycle .....	3-1
3.2.1 Evaporation .....	3-2
3.2.2 Transpiration .....	3-2
3.2.3 Sublimation .....	3-2
3.2.4 Condensation .....	3-2
3.2.5 Transportation .....	3-2
3.2.6 Precipitation.....	3-2
3.2.7 Runoff.....	3-2
3.2.8 Infiltration.....	3-2
3.2.9 Groundwater Flow.....	3-3
3.2.10 Plant Uptake .....	3-3
3.3 Saturation .....	3-3
3.4 Relative Humidity .....	3-3
3.5 Dewpoint .....	3-4
3.6 Temperature-Dewpoint Spread (Dewpoint Depression).....	3-4
3.7 Change of Phase .....	3-5
3.7.1 Latent Heat .....	3-5
Chapter 4. Earth-Atmosphere Heat Imbalances.....	4-1
4.1 Introduction .....	4-1
4.2 The Earth-Atmosphere Energy Balance .....	4-1
4.3 Heat Imbalances Between Earth's Surface and the Atmosphere.....	4-3
4.3.1 Sensible Heating.....	4-3
4.3.2 Latent Heat .....	4-4
4.4 Heat Imbalance Variations with Latitude .....	4-4
4.5 Seasons.....	4-5
4.6 Diurnal Temperature Variation.....	4-7
Chapter 5. Atmospheric Pressure and Altimetry .....	5-1
5.1 Introduction .....	5-1

5.2 Atmospheric Pressure .....	5-1
5.2.1 Barometer .....	5-2
5.2.2 Atmospheric Pressure Units .....	5-2
5.2.3 Station Pressure .....	5-3
5.2.4 Pressure Variation .....	5-3
5.2.5 Sea Level Pressure.....	5-5
5.2.6 Constant Pressure Surface .....	5-7
5.3 Density .....	5-10
5.3.1 Volume Effects on Density .....	5-10
5.3.2 Changes in Density.....	5-11
5.3.3 Density Effects on Pressure.....	5-11
5.3.4 Temperature Effects on Density.....	5-12
5.3.5 Water Vapor Effects on Density .....	5-12
5.4 Altimetry .....	5-13
5.4.1 Altitude.....	5-13
5.5 Density Altitude .....	5-16
Chapter 6. Weather Charts.....	6-1
6.1 Introduction.....	6-1
6.2 Weather Observation Sources .....	6-1
6.3 Analysis.....	6-2
6.3.1 Analysis Procedure.....	6-2
6.4 Surface Chart.....	6-6
6.5 Constant Pressure Chart .....	6-7
Chapter 7. Wind.....	7-1
7.1 Introduction.....	7-1
7.2 Naming of the Wind.....	7-1
7.3 Forces That Affect the Wind.....	7-1
7.3.1 Pressure Gradient Force (PGF) .....	7-1
7.3.2 Coriolis Force .....	7-2
7.3.3 Friction Force .....	7-4
7.4 Upper Air Wind .....	7-5
7.5 Surface Wind.....	7-6

Chapter 8. Global Circulations and Jet Streams .....	8-1
8.1 Non-Rotating Earth Circulation System .....	8-1
8.2 Rotating Earth Circulation System .....	8-1
8.3 Jet Streams .....	8-2
8.3.1 Introduction .....	8-2
8.3.2 Direction of Wind Flow .....	8-3
8.3.3 Location.....	8-4
Chapter 9. Local Winds .....	9-1
9.1 Description .....	9-1
9.2 Hazards.....	9-2
9.3 Sea Breeze.....	9-2
9.3.1 Sea Breeze Front .....	9-3
9.3.2 Effects of Coastline Shape .....	9-3
9.4 Land Breeze .....	9-4
9.5 Lake Breeze.....	9-5
9.6 Valley Breeze .....	9-7
9.7 Mountain-Plains Wind System .....	9-8
9.8 Mountain Breeze .....	9-9
Chapter 10. Air Masses, Fronts, and the Wave Cyclone Model.....	10-1
10.1 Air Masses .....	10-1
10.1.1 Air Mass Classification .....	10-1
10.1.2 Air Mass Modification .....	10-2
10.2 Fronts.....	10-3
10.3 The Wave Cyclone Model.....	10-7
10.4 Dryline.....	10-9
Chapter 11. Vertical Motion and Cloud Formation.....	11-1
11.1 Introduction .....	11-1
11.2 Vertical Motion Effects on an Unsaturated Air Parcel.....	11-1
11.3 Vertical Motion Effects on a Saturated Air Parcel.....	11-2
11.4 Common Sources of Vertical Motion .....	11-5
11.4.1 Orographic Effects .....	11-5
11.4.2 Frictional Effects .....	11-6

11.4.3	Frontal Lift .....	11-6
11.4.4	Buoyancy.....	11-7
Chapter 12.	Atmospheric Stability.....	12-1
12.1	Introduction .....	12-1
12.2	Using a Parcel as a Tool to Evaluate Stability .....	12-1
12.3	Stability Types.....	12-1
12.3.1	Absolute Stability.....	12-1
12.3.2	Neutral Stability .....	12-2
12.3.3	Absolute Instability .....	12-3
12.3.4	Conditional Instability.....	12-4
12.3.5	Summary of Stability Types.....	12-6
12.4	Processes that Change Atmospheric Stability .....	12-7
12.4.1	Wind Effects on Stability .....	12-7
12.4.2	Vertical Air Motion Effects on Stability .....	12-7
12.4.3	Diurnal Temperature Variation Effects on Stability .....	12-8
12.5	Measurements of Stability.....	12-9
12.5.1	Lifted Index .....	12-9
12.5.2	Convective Available Potential Energy .....	12-10
12.6	Summary .....	12-11
Chapter 13.	Clouds.....	13-1
13.1	Introduction .....	13-1
13.2	Cloud Forms .....	13-1
13.3	Cloud Levels.....	13-2
13.4	Cloud Types .....	13-2
13.4.1	High Clouds.....	13-2
13.4.2	Middle Clouds .....	13-5
13.4.3	Low Clouds .....	13-9
Chapter 14.	Precipitation .....	14-1
14.1	Introduction .....	14-1
14.2	Necessary Ingredients for Formation .....	14-1
14.3	Growth Process.....	14-1
14.4	Precipitation Types.....	14-3

Chapter 15. Adverse Wind.....	15-1
15.1 Introduction .....	15-1
15.2 Crosswind.....	15-1
15.3 Gust .....	15-1
15.4 Tailwind.....	15-2
15.5 Variable Wind/Sudden Wind Shift.....	15-2
15.6 Wind Shear.....	15-2
Chapter 16. Weather, Obstructions to Visibility, Low Ceiling, and Mountain Obscuration....	16-1
16.1 Weather and Obstructions to Visibility .....	16-1
16.1.1 Fog.....	16-1
16.1.2 Mist.....	16-5
16.1.3 Haze.....	16-5
16.1.4 Smoke.....	16-5
16.1.5 Precipitation.....	16-5
16.1.6 Blowing Snow .....	16-6
16.1.7 Dust Storm.....	16-6
16.1.8 Sandstorm.....	16-6
16.1.9 Volcanic Ash .....	16-7
16.2 Low Ceiling and Mountain Obscuration.....	16-8
16.2.1 Low Ceiling.....	16-8
16.2.2 Mountain Obscuration.....	16-9
Chapter 17. Turbulence.....	17-1
17.1 Introduction .....	17-1
17.2 Causes of Turbulence .....	17-1
17.2.1 Convective Turbulence.....	17-1
17.2.2 Mechanical Turbulence .....	17-3
17.2.3 Wind Shear Turbulence.....	17-5
17.3 Turbulence Factors .....	17-6
Chapter 18. Icing.....	18-1
18.1 Introduction .....	18-1
18.2 Supercooled Water .....	18-1

18.3	Structural Icing .....	18-1
18.3.1	Rime Icing .....	18-1
18.3.2	Clear Icing .....	18-1
18.3.3	Mixed Icing .....	18-2
18.3.4	Icing Factors .....	18-2
18.3.5	Icing in Stratiform Clouds .....	18-4
18.3.6	Icing in Cumuliform Clouds .....	18-4
18.3.7	Icing with Fronts .....	18-4
18.3.8	Icing with Mountains .....	18-5
18.3.9	Icing Hazards .....	18-6
18.4	Engine Icing .....	18-7
18.4.1	Carburetor Icing .....	18-7
18.4.2	High Ice Water Content (HIWC) .....	18-7
Chapter 19.	Thunderstorms .....	19-1
19.1	Introduction .....	19-1
19.2	Necessary Ingredients for Thunderstorm Cell Formation .....	19-1
19.3	Thunderstorm Cell Life Cycle .....	19-1
19.4	Thunderstorm Types .....	19-2
19.5	Factors that Influence Thunderstorm Motion .....	19-5
19.6	Hazards .....	19-6
19.6.1	Lightning .....	19-6
19.6.2	Adverse Wind .....	19-6
19.6.3	Downburst .....	19-6
19.6.4	Turbulence .....	19-8
19.6.5	Icing .....	19-8
19.6.6	Hail .....	19-9
19.6.7	Rapid Altimeter Changes .....	19-10
19.6.8	Static Electricity .....	19-10
19.6.9	Tornado .....	19-10



Chapter 20. Weather Radar .....	20-1
20.1 Principles of Weather Radar.....	20-1
20.1.1 Antenna .....	20-1
20.1.2 Backscattered Energy.....	20-1
20.1.3 Power Output.....	20-2
20.1.4 Wavelengths .....	20-2
20.1.5 Attenuation .....	20-3
20.1.6 Resolution.....	20-4
20.1.7 Wave Propagation .....	20-7
20.1.8 Intensity of Precipitation .....	20-9
Chapter 21. Tropical Weather.....	21-1
21.1 Circulation .....	21-1
21.1.1 Subtropical High Pressure Belts.....	21-1
21.1.2 Trade Wind Belts.....	21-3
21.1.3 The Intertropical Convergence Zone (ITCZ) .....	21-5
21.1.4 Monsoon.....	21-5
21.2 Transitory Systems .....	21-7
21.2.1 Remnants of Polar Fronts and Shear Lines .....	21-7
21.2.2 Tropical Upper Tropospheric Trough (TUTT) .....	21-8
21.2.3 Tropical Wave .....	21-9
21.2.4 West African Disturbance Line (WADL) .....	21-10
21.2.5 Tropical Cyclones.....	21-11
Chapter 22. Arctic Weather .....	22-1
22.1 Introduction .....	22-1
22.2 Climate, Air Masses, and Fronts .....	22-1
22.2.1 Long Days and Nights.....	22-2
22.2.2 Land and Water .....	22-2
22.2.3 Temperature.....	22-2
22.2.4 Clouds and Precipitation .....	22-2
22.2.5 Wind .....	22-3
22.2.6 Air Masses—Winter.....	22-3

22.2.7	Air Masses—Summer .....	22-3
22.2.8	Fronts.....	22-3
22.3	Arctic Peculiarities .....	22-3
22.3.1	Effects of Temperature Inversion.....	22-3
22.3.2	Light Reflection by Snow-Covered Surfaces.....	22-3
22.3.3	Light from Celestial Bodies .....	22-3
22.4	Weather Hazards .....	22-4
22.4.1	Fog and Ice Fog.....	22-4
22.4.2	Blowing and Drifting Snow .....	22-4
22.4.3	Frost.....	22-4
22.4.4	Whiteout.....	22-4
Chapter 23.	Space Weather.....	23-1
23.1	The Sun—Prime Source of Space Weather .....	23-1
23.2	The Sun’s Energy Output and Variability .....	23-1
23.3	Sunspots and the Solar Cycle .....	23-1
23.4	Solar Wind.....	23-1
23.5	Solar Eruptive Activity.....	23-2
23.6	Geospace .....	23-2
23.7	Galactic Cosmic Radiation.....	23-3
23.8	Geomagnetic Storms .....	23-4
23.9	Solar Radiation Storms.....	23-4
23.10	Ionospheric Storms .....	23-5
23.11	Solar Flare Radio Blackouts .....	23-5
23.12	Effects of Space Weather on Aircraft Operations.....	23-6
23.12.1	Communications.....	23-6
23.12.2	Navigation and Global Positioning System (GPS) .....	23-6
23.12.3	Radiation Exposure to Flight Crews and Passengers.....	23-6
23.12.4	Radiation Effects on Avionics.....	23-6

### List of Figures

Figure 1-1.	Vertical Structure of the Atmosphere .....	1-4
Figure 1-2.	U.S. Standard Atmosphere within the Troposphere .....	1-6
Figure 2-1.	Comparison of Kelvin, Celsius, and Fahrenheit Temperature Scales .....	2-3
Figure 2-2.	Radiation Example.....	2-4
Figure 2-3.	Temperature's Effect on Radiation Wavelength.....	2-5
Figure 2-4.	Solar Zenith Angle.....	2-6
Figure 2-5.	Heat Transfer Examples.....	2-8
Figure 2-6.	Specific Heat Capacity: Water Versus Sand.....	2-10
Figure 2-7.	Variation of Mean Daily Temperatures for San Francisco (Maritime) and Kansas City (Continental) .....	2-11
Figure 2-8.	Sounding with an Isothermal Layer .....	2-12
Figure 2-9.	Sounding with a Temperature Inversion.....	2-13
Figure 3-1.	The Hydrologic Cycle.....	3-1
Figure 3-2.	Temperature Effects on Relative Humidity .....	3-4
Figure 3-3.	Temperature-Dewpoint Spread Effect on Relative Humidity .....	3-5
Figure 3-4.	Latent Heat Transactions when Water Undergoes Phase Transition.....	3-6
Figure 4-1.	Earth-Atmosphere Energy Balance.....	4-1
Figure 4-2.	Greenhouse Effect on Nighttime Radiational Cooling .....	4-2
Figure 4-3.	Development of a Thermal .....	4-3
Figure 4-4.	Example of Convection in the Atmosphere .....	4-4
Figure 4-5.	Solar Zenith Angle Variations with Latitude.....	4-5
Figure 4-6.	Solar Zenith Angle Variations with Northern Hemisphere Seasons .....	4-6
Figure 4-7.	Average Seasonal Temperature Variation in the Northern Hemisphere .....	4-6
Figure 4-8.	Clear Sky Diurnal Temperature and Radiation Variations Over Land.....	4-7
Figure 5-1.	Air Has Weight .....	5-1
Figure 5-2.	Aneroid Barometer.....	5-2
Figure 5-3.	Station Pressure.....	5-3
Figure 5-4.	Air Pressure in the Standard Atmosphere.....	5-4
Figure 5-5.	Temperature Effect on Pressure.....	5-5
Figure 5-6.	Reduction of Station Pressure to Sea Level .....	5-5
Figure 5-7.	Surface Chart Pressure Patterns .....	5-7
Figure 5-8.	Weather Balloon and Radiosonde.....	5-8

Figure 5-9.	500 Millibar Constant Pressure Chart.....	5-9
Figure 5-10.	Density is Mass (Weight) per Volume.....	5-10
Figure 5-11.	Volume Effects on Density.....	5-10
Figure 5-12.	Pressure Effects on Density in the Atmosphere.....	5-11
Figure 5-13.	Temperature Effects on Density.....	5-12
Figure 5-14.	Water Vapor Effects on Density.....	5-12
Figure 5-15.	True Versus Indicated Altitude.....	5-13
Figure 5-16.	Pressure Change Effects on Altimeter Readings.....	5-14
Figure 5-17.	Temperature Change Effects on Altimeter Readings.....	5-15
Figure 5-18.	High Density Altitude Effects on Flight.....	5-17
Figure 6-1.	Weather Observation Sources.....	6-1
Figure 6-2.	Analysis Procedure Step 1: Determine the Optimal Contour Interval and Values to be Analyzed.....	6-3
Figure 6-3.	Analysis Procedure Step 2: Draw the Isopleths and Extrema.....	6-4
Figure 6-4.	Analysis Procedure Step 3: Interpret Significant Weather Features.....	6-6
Figure 6-5.	Example of a Surface Chart.....	6-7
Figure 6-6.	Example of a 500 Millibar Constant Pressure Chart.....	6-8
Figure 7-1.	Direction of Pressure Gradient Force.....	7-1
Figure 7-2.	Magnitude of Pressure Gradient Force.....	7-2
Figure 7-3.	Illustration of Coriolis Force.....	7-2
Figure 7-4.	Coriolis Force Variations Across the Earth.....	7-3
Figure 7-5.	Coriolis Force Magnitude Variations with Wind Speed.....	7-4
Figure 7-6.	Friction Force Magnitude Variations with Terrain Roughness.....	7-4
Figure 7-7.	Friction Force Magnitude Variations with Wind Speed.....	7-4
Figure 7-8.	Geostrophic Wind.....	7-5
Figure 7-9.	Upper Air Wind Flow.....	7-5
Figure 7-10.	Surface Wind Forces.....	7-6
Figure 7-11.	Surface Wind Flow.....	7-6
Figure 8-1.	Non-Rotating, Non-Tilted, Waterless, Earth Circulation System.....	8-1
Figure 8-2.	Earth Circulation System.....	8-2
Figure 8-3.	Speed Relative to the Earth's Axis Versus Latitude.....	8-3
Figure 8-4.	Three Cell Circulations and Jet Stream Location.....	8-4
Figure 8-5.	Polar and Subtropical Jet Streams.....	8-4

Figure 8-6.	Jet Stream Wind Speeds.....	8-5
Figure 9-1.	Local Wind Circulation.....	9-1
Figure 9-2.	Sea Breeze.....	9-2
Figure 9-3.	Sea Breeze Front.....	9-3
Figure 9-4.	Effects of Coastline Shape on a Sea Breeze .....	9-4
Figure 9-5.	Land Breeze .....	9-5
Figure 9-6.	Lake Breeze .....	9-6
Figure 9-7.	Sea Breeze/Lake Breeze Example .....	9-7
Figure 9-8.	Valley Breeze.....	9-7
Figure 9-9.	Mountain-Plains Wind System .....	9-8
Figure 9-10.	Mountain Breeze.....	9-9
Figure 10-1.	Air Mass Classification.....	10-2
Figure 10-2.	Air Mass Modification—Warm, Moist Air Mass Moving Over a Cold Surface.....	10-2
Figure 10-3.	Lake Effect.....	10-3
Figure 10-4.	Fronts .....	10-4
Figure 10-5.	Cold Front .....	10-5
Figure 10-6.	Warm Front.....	10-5
Figure 10-7.	Stationary Front .....	10-6
Figure 10-8.	Occluded Front.....	10-6
Figure 10-9.	Wave Cyclone Model—Stage 1.....	10-7
Figure 10-10.	Wave Cyclone Model—Stage 2.....	10-7
Figure 10-11.	Wave Cyclone Model—Stage 3.....	10-8
Figure 10-12.	Wave Cyclone Model—Stage 4.....	10-8
Figure 10-13.	Wave Cyclone Model—Stage 5.....	10-8
Figure 10-14.	Dryline Example .....	10-9
Figure 11-1.	Unsaturated Ascending/Descending Air Parcel Example.....	11-2
Figure 11-2.	Ascending Air Parcel that Becomes Saturated Example .....	11-3
Figure 11-3.	Descending Air Parcel Example .....	11-4
Figure 11-4.	Orographic Effects Example.....	11-5
Figure 11-5.	Frictional Effects.....	11-6
Figure 11-6.	Frontal Lift .....	11-7
Figure 12-1.	Absolute Stability Example .....	12-2

Figure 12-2.	Neutral Stability Example.....	12-3
Figure 12-3.	Absolute Instability Example.....	12-4
Figure 12-4.	Conditional Instability Example .....	12-5
Figure 12-5.	Stability Types .....	12-6
Figure 12-6.	Temperature Lapse Rate Effects on Stability .....	12-7
Figure 12-7.	Vertical Motion Effects on Stability.....	12-8
Figure 12-8.	Diurnal Temperature Variation Effects on Stability.....	12-9
Figure 12-9.	Lifted Index Example .....	12-10
Figure 13-1.	Cirrus (Ci).....	13-3
Figure 13-2.	Cirrocumulus (Cc) .....	13-4
Figure 13-3.	Cirrostratus (Cs).....	13-5
Figure 13-4.	Alto cumulus (Ac).....	13-6
Figure 13-5.	Alto cumulus Standing Lenticular (ACSL) .....	13-7
Figure 13-6.	Thin Altostratus (As) .....	13-8
Figure 13-7.	Thick Altostratus (As) or Nimbostratus (Ns).....	13-9
Figure 13-8.	Cumulus (Cu) with Little Vertical Development.....	13-10
Figure 13-9.	Towering Cumulus (TCu).....	13-11
Figure 13-10.	Stratocumulus (Sc).....	13-12
Figure 13-11.	Stratus (St) .....	13-13
Figure 13-12.	Stratus Fractus (StFra) and/or Cumulus Fractus (CuFra) of Bad Weather .....	13-14
Figure 13-13.	Cumulonimbus (Cb) without Anvil .....	13-15
Figure 13-14.	Cumulonimbus (Cb) with Anvil .....	13-16
Figure 14-1.	The Collision-Coalescence or Warm Rain Process .....	14-2
Figure 14-2.	Snow Temperature Environment .....	14-3
Figure 14-3.	Ice Pellets Temperature Environment.....	14-3
Figure 14-4.	Freezing Rain Temperature Environment.....	14-4
Figure 14-5.	Rain Temperature Environment.....	14-4
Figure 15-1.	Crosswind .....	15-1
Figure 16-1.	Radiation Fog.....	16-1
Figure 16-2.	Advection Fog.....	16-2
Figure 16-3.	Advection Fog Formation .....	16-3
Figure 16-4.	Frontal Fog Formation .....	16-4
Figure 16-5.	Haboob .....	16-7

Figure 16-6.	Layer Aloft Ceiling Versus Indefinite Ceiling.....	16-9
Figure 17-1.	Convective Turbulence .....	17-2
Figure 17-2.	Thermals .....	17-2
Figure 17-3.	Mechanical Turbulence.....	17-3
Figure 17-4.	Mountain Waves .....	17-4
Figure 17-5.	Mountain Wave Clouds .....	17-5
Figure 17-6.	Wind Shear Turbulence .....	17-5
Figure 17-7.	Wind Shear Turbulence Associated with a Temperature Inversion .....	17-6
Figure 18-1.	Icing with Fronts .....	18-5
Figure 18-2.	Icing with Mountains .....	18-6
Figure 19-1.	Necessary Ingredients for Thunderstorm Cell Formation .....	19-1
Figure 19-2.	Thunderstorm Cell Life Cycle .....	19-2
Figure 19-3.	Multicell Cluster Thunderstorm.....	19-3
Figure 19-4.	Multicell Line Thunderstorm.....	19-4
Figure 19-5.	Supercell Thunderstorm.....	19-5
Figure 19-6.	Factors that Influence Thunderstorm Motion .....	19-5
Figure 19-7.	Downburst Life Cycle.....	19-7
Figure 19-8.	Landing in a Microburst.....	19-7
Figure 19-9.	Thunderstorm with Shelf Cloud.....	19-8
Figure 19-10.	Vivian, South Dakota Record Hailstone .....	19-9
Figure 20-1.	Radar Antenna .....	20-1
Figure 20-2.	Backscattered Energy.....	20-2
Figure 20-3.	Wavelengths.....	20-3
Figure 20-4.	Precipitation Attenuation .....	20-3
Figure 20-5.	Precipitation Attenuation Versus Wavelength.....	20-4
Figure 20-6.	Beam Resolution.....	20-5
Figure 20-7.	Beam Resolution Comparison Between WSR-88D and Aircraft Weather Radar .....	20-6
Figure 20-8.	Normal Refraction .....	20-7
Figure 20-9.	Subrefraction.....	20-8
Figure 20-10.	Superrefraction.....	20-8
Figure 20-11.	Ducting.....	20-9
Figure 20-12.	Reflectivity Associated with Liquid Targets .....	20-10

Figure 21-1.	Mean Worldwide Surface Pressure Distribution and Prevailing Winds Throughout the World in July.....	21-2
Figure 21-2.	Mean Worldwide Surface Pressure Distribution and Prevailing Winds Throughout the World in January.....	21-2
Figure 21-3.	A Shear Line and an Induced Trough Caused by a Polar High Pushing into the Subtropics .....	21-8
Figure 21-4.	A TUTT Moves Eastward Across the Hawaiian Islands. Extensive Cloudiness Develops East of the Trough.....	21-9
Figure 21-5.	A Northern Hemisphere Easterly Wave Progressing from A–B .....	21-10
Figure 21-6.	Vertical Cross Section along Line A–B in Figure 21-5.....	21-10
Figure 21-7.	The Tracks of Nearly 150 Years of Tropical Cyclones and their Strength Weave Across the Globe .....	21-12
Figure 21-8.	Radar Image of Hurricane Katrina Observed at New Orleans, Louisiana, on August 29, 2005.....	21-14
Figure 21-9.	Hurricane Andrew Observed by Satellite in 1992 .....	21-14
Figure 22-1.	The Arctic Circle.....	22-1

### List of Tables

Table 1-1.	Composition of a Dry Earth’s Atmosphere .....	1-1
Table 1-2.	Selected Properties of the Standard Atmosphere.....	1-6
Table 2-1.	Celsius Temperature Conversion Formulae.....	2-2
Table 2-2.	Fahrenheit Temperature Conversion Formulae .....	2-2
Table 2-3.	Heat (Thermal) Conductivity of Various Substances .....	2-7
Table 2-4.	Specific Heat Capacity of Various Substances .....	2-9
Table 3-1.	Latent Heat of Water at 0 °C .....	3-7
Table 5-1.	Units of Pressure .....	5-3
Table 5-2.	Pressure System Symbols .....	5-6
Table 5-3.	Common Constant Pressure Charts .....	5-9
Table 6-1.	Common Isopleths .....	6-2
Table 6-2.	Common Weather Chart Symbols .....	6-5
Table 11-1.	Air Parcel Vertical Motion Characteristics.....	11-4
Table 13-1.	Cloud Forms.....	13-1
Table 13-2.	Approximate Height of Cloud Bases above the Surface .....	13-2
Table 19-1.	Enhanced Fujita Scale (Enhanced F Scale) for Tornado Damage.....	19-11
Table 21-1.	Wind Speed and Characteristic House Damage for the Saffir-Simpson Hurricane Wind Scale.....	21-15



## CHAPTER 1. THE EARTH'S ATMOSPHERE

**1.1 Introduction.** The Earth's atmosphere is a cloud of gas and suspended solids extending from the surface out many thousands of miles, becoming increasingly thinner with distance, but always held by the Earth's gravitational pull. The atmosphere is made up of layers surrounding the Earth that holds the air we breathe, protects us from outer space, and holds moisture (e.g., vapor, clouds, and precipitation), gases, and tiny particles. In short, the atmosphere is the protective bubble we live in.

This chapter covers our atmosphere's composition, vertical structure and the standard atmosphere.

**1.2 Composition.** The Earth's atmosphere consists of numerous gases (see Table 1-1) with the top four making up 99.998 percent of all gases. Nitrogen, by far the most common, dilutes oxygen and prevents rapid burning at the Earth's surface. Living things need it to make proteins. Oxygen is used by all living things and is essential for respiration. Plants use carbon dioxide to make oxygen. Carbon dioxide also acts as a blanket and prevents the escape of heat to outer space.

**Table 1-1. Composition of a Dry Earth's Atmosphere**

Gas	Symbol	Content (by Volume)
Nitrogen	N <sub>2</sub>	78.084%
Oxygen	O <sub>2</sub>	20.947%
Argon	Ar	0.934%
Carbon Dioxide	CO <sub>2</sub>	0.033%
Neon	Ne	18.20 parts per million
Helium	He	5.20 parts per million
Methane	CH <sub>4</sub>	1.75 parts per million
Krypton	Kr	1.10 parts per million
Sulfur dioxide	SO <sub>2</sub>	1.00 parts per million
Hydrogen	H <sub>2</sub>	0.50 parts per million
Nitrous Oxide	N <sub>2</sub> O	0.50 parts per million
Xenon	Xe	0.09 parts per million

Gas	Symbol	Content (by Volume)
Ozone	O <sub>3</sub>	0.07 parts per million
Nitrogen dioxide	NO <sub>2</sub>	0.02 parts per million
Iodine	I <sub>2</sub>	0.01 parts per million
Carbon monoxide	CO	trace
Ammonia	NH <sub>3</sub>	trace

*Note: The atmosphere always contains some water vapor in amounts varying from trace to about four percent by volume. As water vapor content increases, the other gases decrease proportionately.*

Weather, the state of the atmosphere at any given time and place, strongly influences our daily routine as well as our general life patterns. Virtually all of our activities are affected by weather, but, of all our endeavors, perhaps none more so than aviation.

**1.2.1 Air Parcel.** An air parcel is an imaginary volume of air to which any or all of the basic properties of atmospheric air may be assigned. A parcel is large enough to contain a very large number of molecules, but small enough so that the properties assigned to it are approximately uniform. It is not given precise numerical definition, but a cubic centimeter of air might fit well into most contexts where air parcels are discussed. In meteorology, an air parcel is used as a tool to describe certain atmospheric processes, and we will refer to air parcels throughout this document.

**1.3 Vertical Structure.** The Earth's atmosphere is subdivided into five concentric layers (see Figure 1-1) based on the vertical profile of average air temperature changes, chemical composition, movement, and density. Each of the five layers is topped by a pause, where the maximum changes in thermal characteristics, chemical composition, movement, and density occur.

**1.3.1 Troposphere.** The troposphere begins at the Earth's surface and extends up to about 11 kilometers (36,000 feet) high. This is where we live. As the gases in this layer decrease with height, the air becomes thinner. Therefore, the temperature in the troposphere also decreases with height. As you climb higher, the temperature drops from about 15 °C (59 °F) to -56.5 °C (-70 °F). Almost all weather occurs in this region.

The vertical depth of the troposphere varies due to temperature variations which are closely associated with latitude and season. It decreases from the Equator to the poles, and is higher during summer than in winter. At the Equator, it is around 18-20 kilometers (11-12 miles) high, at 50° N and 50° S latitude, 9 kilometers (5.6 miles), and at the poles, 6 kilometers (3.7 miles) high. The transition boundary between the troposphere and the

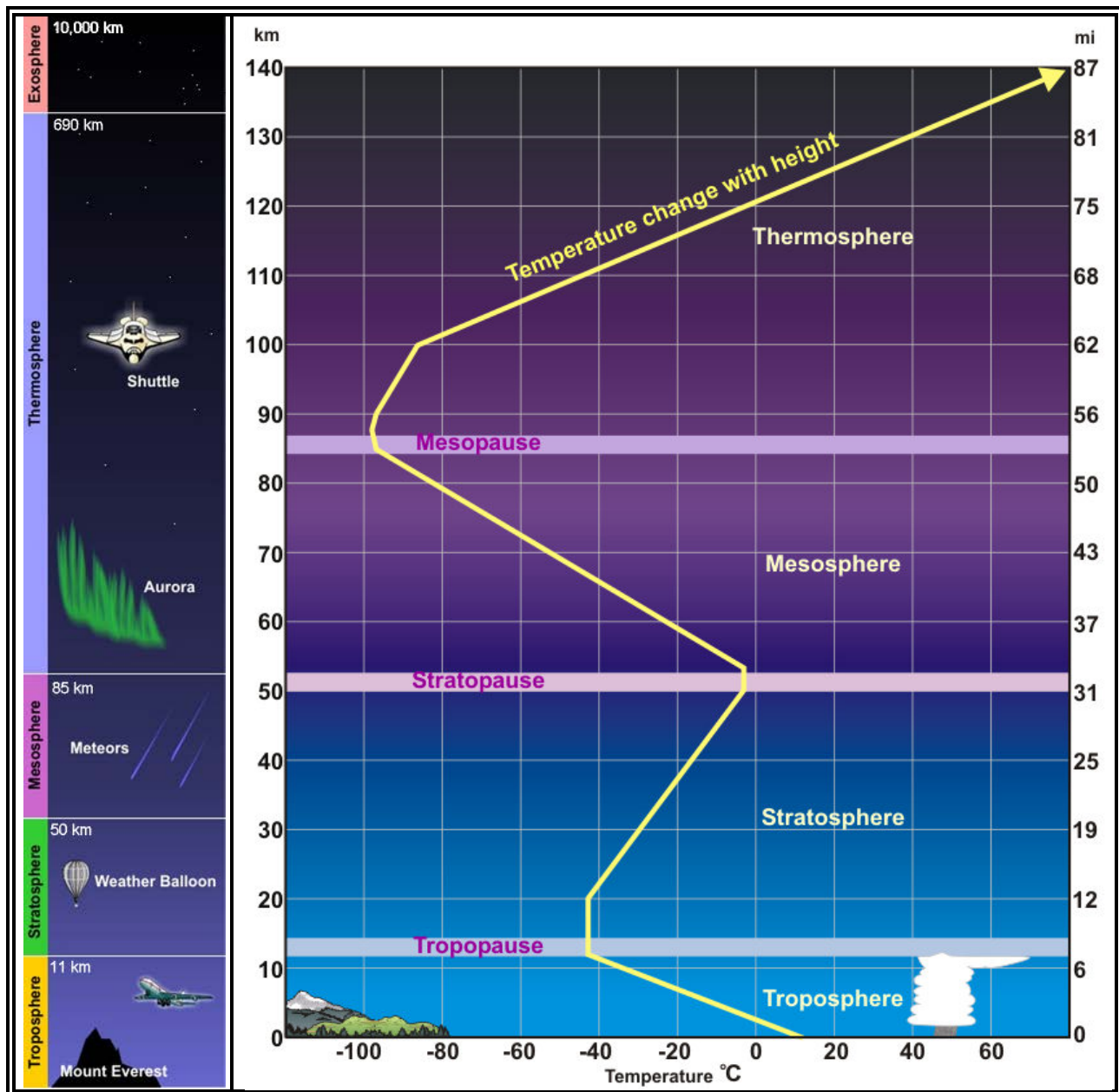
layer above is called the tropopause. Both the tropopause and the troposphere are known as the lower atmosphere.

- 1.3.2** Stratosphere. The stratosphere extends from the tropopause up to 50 kilometers (31 miles) above the Earth's surface. This layer holds 19 percent of the atmosphere's gases, but very little water vapor.

Temperature increases with height as radiation is increasingly absorbed by oxygen molecules, leading to the formation of ozone. The temperature rises from an average  $-56.6\text{ }^{\circ}\text{C}$  ( $-70\text{ }^{\circ}\text{F}$ ) at the tropopause to a maximum of about  $-3\text{ }^{\circ}\text{C}$  ( $27\text{ }^{\circ}\text{F}$ ) at the stratopause due to this absorption of ultraviolet radiation. The increasing temperature also makes it a calm layer, with movements of the gases being slow.

Commercial aircraft often cruise in the lower stratosphere to avoid atmospheric turbulence and convection in the troposphere. Severe turbulence during the cruise phase of flight can be caused by the convective overshoot of thunderstorms from the troposphere below. The disadvantages of flying in the stratosphere can include increased fuel consumption due to warmer temperatures, increased levels of radiation, and increased concentration of ozone.

Figure 1-1. Vertical Structure of the Atmosphere



*The regions of the stratosphere and the mesosphere, along with the stratopause and mesopause, are called the middle atmosphere. The transition boundary that separates the stratosphere from the mesosphere is called the stratopause.*

**1.3.3 Mesosphere.** The mesosphere extends from the stratopause to about 85 kilometers (53 miles) above the Earth. The gases, including the number of oxygen molecules, continue to become thinner and thinner with height. As such, the effect of the warming by ultraviolet radiation also becomes less and less pronounced, leading to a decrease in temperature with height. On average, temperature decreases from about  $-3\text{ }^{\circ}\text{C}$  ( $27\text{ }^{\circ}\text{F}$ ) to as low as  $-100\text{ }^{\circ}\text{C}$  ( $-148\text{ }^{\circ}\text{F}$ ) at the mesopause. However, the gases in the mesosphere

are thick enough to slow down meteorites hurtling into the atmosphere where they burn up, leaving fiery trails in the night sky.

- 1.3.4** Thermosphere. The thermosphere extends from the mesopause to 690 kilometers (430 miles) above the Earth. This layer is known as the upper atmosphere.

The gases of the thermosphere become increasingly thin compared to the mesosphere. As such, only the higher energy ultraviolet and x ray radiation from the sun is absorbed. But because of this absorption, the temperature increases with height and can reach as high as 2,000 °C (3,600 °F) near the top of this layer.

Despite the high temperature, this layer of the atmosphere would still feel very cold to our skin, because of the extremely thin air. The total amount of energy from the very few molecules in this layer is not sufficient enough to heat our skin.

- 1.3.5** Exosphere. The exosphere is the outermost layer of the atmosphere, and extends from the thermopause to 10,000 kilometers (6,200 miles) above the Earth. In this layer, atoms and molecules escape into space and satellites orbit the Earth. The transition boundary that separates the exosphere from the thermosphere is called the thermopause.

- 1.4** **The Standard Atmosphere**. Continuous fluctuations of atmospheric properties create problems for engineers and meteorologists who require a fixed standard for reference. To solve this problem, they defined a standard atmosphere, which represents an average of conditions throughout the atmosphere for all latitudes, seasons, and altitudes.

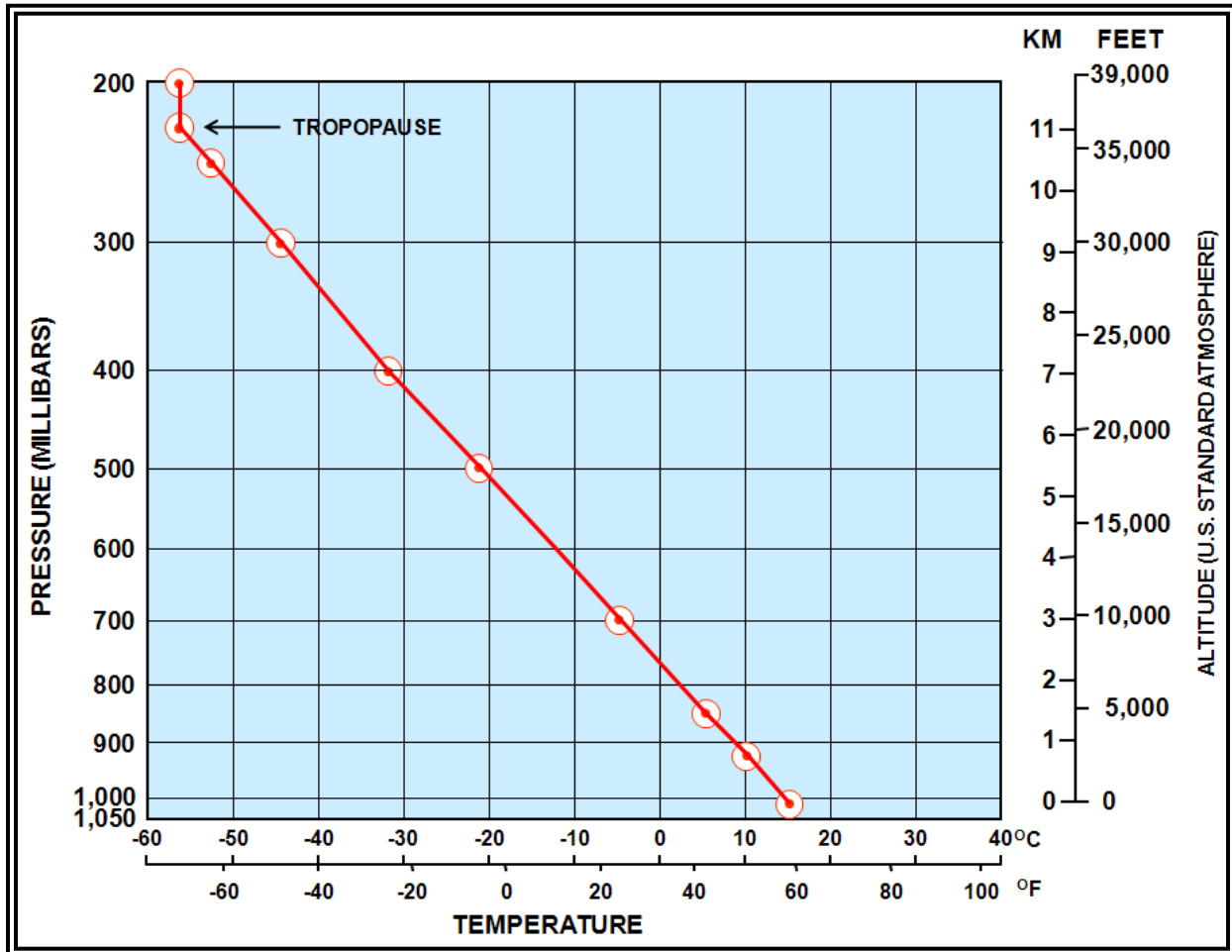
Standard atmosphere is a hypothetical vertical distribution of atmospheric temperature, pressure, and density that, by international agreement, is taken to be representative of the atmosphere for purposes of pressure altimeter calibrations, aircraft performance calculations, aircraft and missile design, ballistic tables, etc. (see Table 1-2 and Figure 1-2). Weather-related processes are generally referenced to the standard atmosphere, as are examples in this document.

**Table 1-2. Selected Properties of the Standard Atmosphere**

Property	Metric Units	English Units
Sea level pressure	1013.25 hectopascals	29.92 inches of mercury
Sea level temperature	15 °C	59 °F
Lapse rate of temperature in the troposphere	6.5 °C/1,000 meters	3.57 °F/1,000 feet
Pressure altitude of the tropopause	11,000 meters	36,089 feet
Temperature at the tropopause	-56.5 °C	-69.7 °F

*Note: 1 hectopascal = 1 millibar.*

**Figure 1-2. U.S. Standard Atmosphere within the Troposphere**



## CHAPTER 2. HEAT AND TEMPERATURE

- 2.1 Introduction.** Temperature is one of the most basic variables used to describe the state of the atmosphere. We know that air temperature varies with time from one season to the next, between day and night, and even from one hour to the next. Air temperature also varies from one location to another, from high altitudes and latitudes to low altitudes and latitudes. Temperature can be critical to some flight operations. As a foundation for the study of temperature effects on aviation and weather, this chapter describes temperature, temperature measurement, and heat transfer and imbalances.
- 2.2 Matter.** Matter is the substance of which all physical objects are composed. Matter is composed of atoms and molecules, both of which occupy space and have mass. The Earth's gravity acting on the mass of matter produces weight.
- 2.3 Energy.** Energy is the ability to do work. It can exist in many forms and can be converted from one form to another. For example, if a ball is located at the edge of a slide, it contains some amount of potential energy (energy of position). This potential energy is converted to kinetic energy (energy of motion) when the ball rolls down the slide. Atoms and molecules produce kinetic energy because they are in constant motion. Higher speeds of motion indicate higher levels of kinetic energy.
- 2.4 Heat.** Heat is the total kinetic energy of the atoms and molecules composing a substance. The atoms and molecules in a substance do not all move at the same velocity. Thus, there is actually a range of kinetic energy among the atoms and molecules.
- 2.5 Temperature.** Temperature is a numerical value representing the average kinetic energy of the atoms and molecules within matter. Temperature depends directly on the energy of molecular motion. Higher (warmer) temperatures indicate a higher average kinetic energy of molecular motion due to faster molecular speeds. Lower (colder) temperatures indicate a lower average kinetic energy of molecular motion due to slower molecular speeds. Temperature is an indicator of the internal energy of air.
- 2.5.1 Temperature Measurement.** A thermometer is an instrument used to measure temperature. Higher temperatures correspond to higher molecular energies, while lower temperatures correspond to lower molecular energies.
- 2.5.2 Temperature Scales.** Many scientists use the Kelvin (K) scale, which is a thermodynamic (absolute) temperature scale, where absolute zero, the theoretical absence of all thermal energy, is zero Kelvin (0 K). Thus, the Kelvin scale is a direct measure of the average kinetic molecular activity. Because nothing can be colder than absolute zero, the Kelvin scale contains no negative numbers.

The Celsius ( $^{\circ}\text{C}$ ) scale is the most commonly used temperature scale worldwide and in meteorology. The scale is approximately based on the freezing point ( $0^{\circ}\text{C}$ ) and boiling point of water ( $100^{\circ}\text{C}$ ) under a pressure of one standard atmosphere (approximately sea level). Each degree on the Celsius scale is exactly the same size as a degree on the Kelvin scale.

**Table 2-1. Celsius Temperature Conversion Formulae**

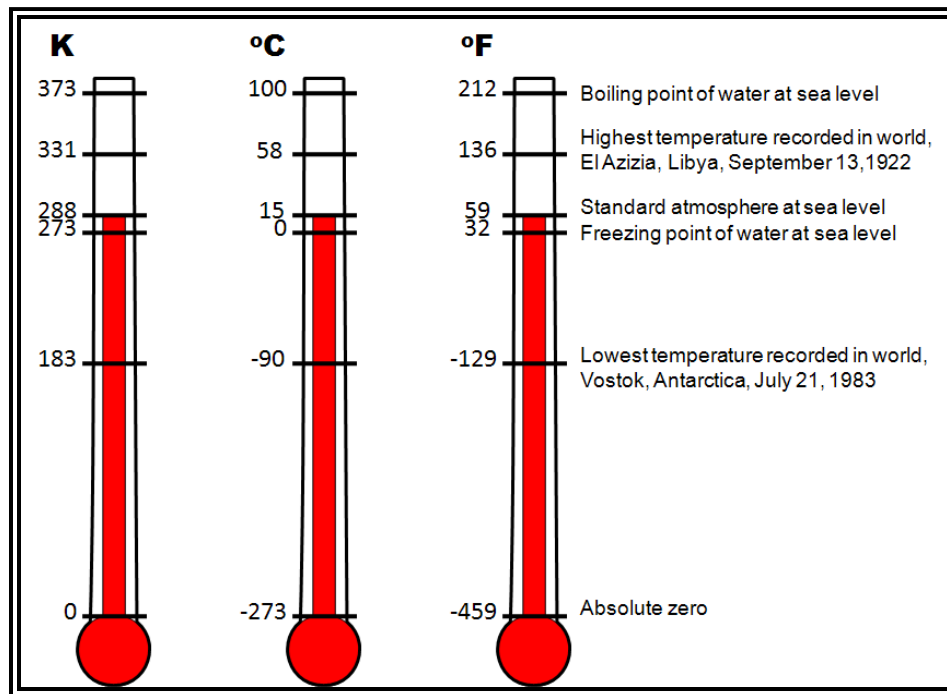
	<b>From Celsius</b>	<b>To Celsius</b>
Fahrenheit	$[\text{°F}] = ([\text{°C}] \times 9/5) + 32$	$[\text{°C}] = ([\text{°F}] - 32) \times 5/9$
Kelvin	$[\text{K}] = [\text{°C}] + 273.15$	$[\text{°C}] = [\text{K}] - 273.15$
For temperature <i>intervals</i> rather than specific temperatures, 1 °C = 274.15 K and 1 °C = 33.8 °F		

The United States uses Fahrenheit (°F) scale for everyday temperature measurements. In this scale, the freezing point of water is 32 degrees Fahrenheit (32 °F) and the boiling point is 212 degrees Fahrenheit (212 °F).

**Table 2-2. Fahrenheit Temperature Conversion Formulae**

	<b>From Fahrenheit</b>	<b>To Fahrenheit</b>
Celsius	$[\text{°C}] = ([\text{°F}] - 32) \times 5/9$	$[\text{°F}] = ([\text{°C}] \times 9/5) + 32$
Kelvin	$[\text{K}] = ([\text{°F}] + 459.67) \times 5/9$	$[\text{°F}] = ([\text{K}] \times 9/5) - 459.67$
For temperature <i>intervals</i> rather than specific temperatures, 1 °F = 255.93 K and 1 °F = -17.22 °C		



**Figure 2-1. Comparison of Kelvin, Celsius, and Fahrenheit Temperature Scales**

*A thermometer changes readings due to the addition or subtraction of heat. Heat and temperature are not the same, but they are related.*

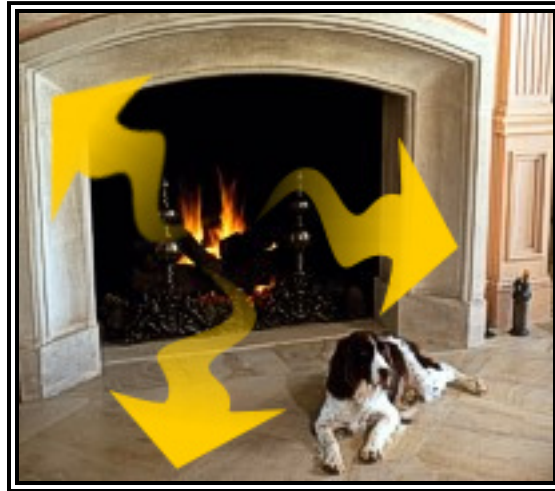
**2.6 Heat Transfer.** Heat transfer is energy transfer as a consequence of temperature difference. When a physical body (e.g., an object or fluid) is at a different temperature than its surroundings or another body, transfer of thermal energy, also known as heat transfer (or heat exchange) occurs in such a way that the body and the surroundings reach thermal equilibrium (balance). Heat transfer always occurs from a hot body to a cold body. Where there is a temperature difference between objects in proximity, heat transfer between them can never be stopped; it can only be slowed down.

The heat source for the surface of our planet is the sun. Energy from the sun is transferred through space and through the Earth's atmosphere to the Earth's surface. Since this energy warms the surface and atmosphere, some of it becomes heat energy. There are three ways heat is transferred into and through the atmosphere: radiation, conduction, convection, or any combination of these. Heat transfer associated with the heat change of water from one phase to another (i.e., liquid water releases heat when changed to a vapor, liquid water absorbs heat when it changes to ice) can be fundamentally treated as a variation of convective heat transfer. The heat transfer associated with water will be discussed later.

**2.6.1 Radiation.** If you have stood in front of a fireplace or near a campfire, you have felt the heat transfer known as radiation. The side of your body nearest the fire warms, while your other side remains unaffected by the heat. Although you are surrounded by air, the air has nothing to do with this type of heat transfer. Heat lamps that keep food warm work in the same way.

Radiation is the transfer of heat energy through space by electromagnetic radiation. These electromagnetic waves travel at the speed of light and are usually described in terms of wavelength or frequency. Frequencies range from gamma rays on the high end to radio waves on the low end. Also contained in the spectrum are x ray, ultraviolet, visible, infrared, and microwave.

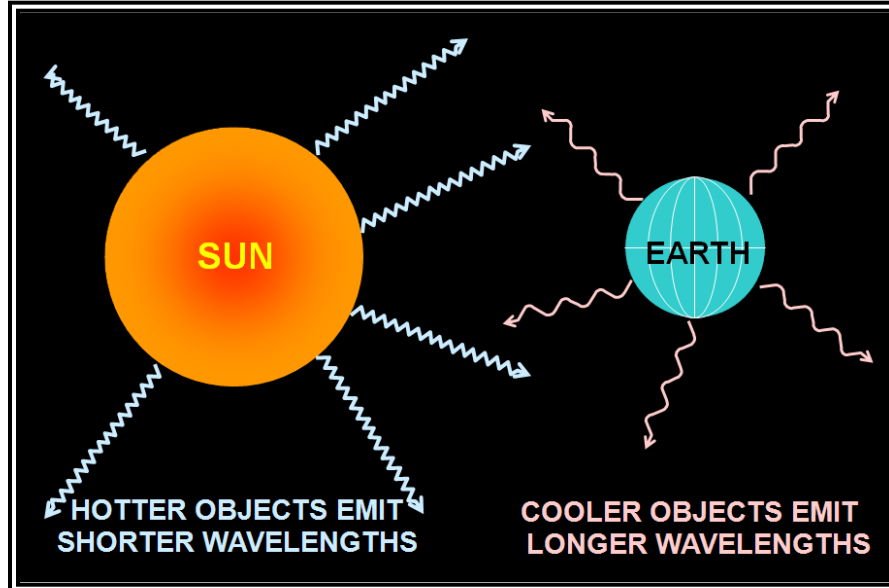
**Figure 2-2. Radiation Example**



All objects emit (radiate) energy as the heat energy within the object is converted to radiation energy. This transmitted radiation passes through entities such as air, water, or space. Along the way, the radiation can be reflected, which occurs when the wave energy changes direction when encountering an object. Eventually, the radiation is absorbed and the electromagnetic wave energy is converted to heat energy by the absorbing object. The emitting object loses heat energy, and the absorbing object gains heat energy during this process.

**2.6.1.1 Solar and Terrestrial Radiation.** All objects emit radiation energy, including the sun (solar radiation) and the Earth (terrestrial radiation). An object's wavelength of maximum radiation is inversely related to its temperature; the hotter (colder) the object, the shorter (longer) the wavelength. The sun's wavelength of maximum radiation is relatively short and is centered in the visible spectrum. The Earth's wavelength of maximum radiation is relatively long and is centered in the infrared spectrum.

**Figure 2-3. Temperature's Effect on Radiation Wavelength**

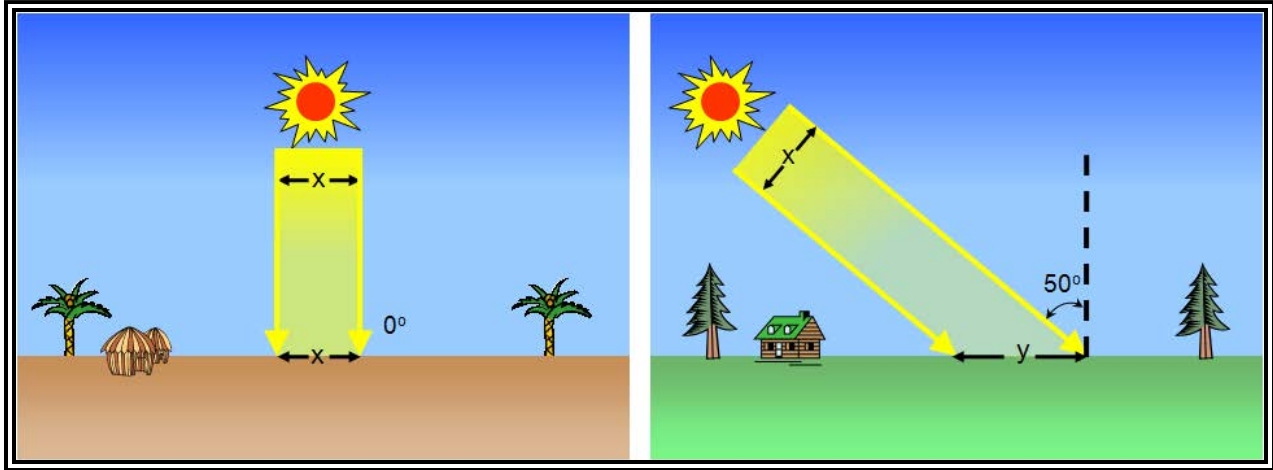


Some of the solar radiation that reaches the Earth's surface is radiated back into the atmosphere to become heat energy. Dark-colored objects such as asphalt absorb more of the radiant energy and warm faster than light-colored objects. Dark objects also radiate their energy faster than light-colored objects.

**2.6.1.2 Solar Zenith Angle.** The intensity of incoming solar radiation that strikes the Earth's surface (insolation) varies with solar zenith angle. Solar zenith angle is the angle measured from the Earth's surface between the sun and the zenith (i.e., directly overhead). Solar zenith angle varies with latitude, season, and the diurnal cycle (sunrise/sunset).

Figure 2-4 illustrates the concept. Insolation is maximized when the solar zenith angle is zero degrees ( $0^\circ$ ), which means the sun is directly overhead. With increasing solar zenith angle, the insolation is spread over an increasingly larger surface area ( $y$  is greater than  $x$ ) so that the insolation becomes less intense. Also, with increasing solar zenith angle, the sun's rays must pass through more of the Earth's atmosphere, where they can be scattered and absorbed before reaching the Earth's surface. Thus, the sun can heat the surface to a much higher temperature when it is high in the sky, rather than low on the horizon.

Figure 2-4. Solar Zenith Angle



**2.6.2** Conduction. Conduction is the transfer of energy (including heat) by molecular activity from one substance to another in contact, or through, a substance. Heat always flows from the warmer substance to the colder substance. The rate of heat transfer is greater with larger temperature differences and depends directly on the ability of the substance(s) to conduct heat. During conduction, the warmer substance cools and loses heat energy, while the cooler substance warms and gains heat energy.

Heat (thermal) conductivity is the property of a substance that indicates its ability to conduct heat as a consequence of molecular motion. Units are Watts per meter-Kelvin ( $\text{W m}^{-1} \text{K}^{-1}$ ). Table 2-3 below provides the heat (thermal) conductivity of various substances. Note that air is a poor thermal conductor.