



AUXILIARY SPECIALTY COURSE

WEATHER

(AUXWEA)



Courtesy of Amelia Seeley

Student Study Guide

Published for Instructional Purposes Only

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16794

MEMORANDUM

From: F.T. Boross, CAPT
COMDT (CG-BSX)

To: Distribution

Subj: AUXILIARY WEATHER SPECIALTY COURSE (AUXWEA) STUDENT
STUDY GUIDE

Ref: (a) Coast Guard Auxiliary Manual, COMDTINST M16790.1 (series)

1. PURPOSE. This guide is a comprehensive training tool designed to assist Auxiliarists with completion of the Auxiliary Weather (AUXWEA) specialty course. It is published for instructional and training purposes only and does not prescribe policy. This guide shall be used in conjunction with the AUXWEA instructor guide and other associated AUXWEA training course materials.
2. ACTION. Elected and appointed leaders and program managers at all levels of the Auxiliary organization who oversee, direct, or participate in the administration, training, and activities that support the Auxiliary specialty course training program shall ensure all Auxiliarists have access to, and use, this new study guide. Internet release is authorized.
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5. DISCLAIMER. This guide is not a substitute for applicable legal requirements, nor is it itself a rule. It is intended to provide student training guidance for Auxiliarists and is not intended to, nor does it impose, legally-binding requirements on any party outside the Coast Guard.
6. MAJOR CHANGES. The guide reflects a more logical progression from basic to complex concepts. Its terminology has been updated, appropriate internet references have been incorporated, and the number of figures has increased.

7. DISTRIBUTION. This guide shall electronically reside on the Coast Guard Auxiliary web site (<http://www.cgaux.org>) and may be electronically distributed for use.
8. RECORDS MANAGEMENT CONSIDERATIONS. This guide has been thoroughly reviewed by the U.S. Coast Guard, and the promulgator has determined that no further action is required in accordance with the Federal Records Act, 44 U.S.C. 3101 et seq., NARA requirements, and Information and Life Cycle Management Manual, COMDTINST M5212.12 (series).
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10. REQUEST FOR CHANGES. Change recommendations may be submitted through the appropriate regional Auxiliary chain of leadership and management to the Auxiliary national Branch Chief – Weather (BC-TAW) within the Auxiliary national Advanced Learning Division.

#

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Preface

In 2014, the Advanced Training Division, a part of the National Training Directorate, began an effort to update and improve the content and utility of the Auxiliary specialty courses to bring them in line with the 21st Century US Coast Guard and to retool and update existing materials to incorporate new technologies and to phase out tools and methods no longer being used.

This new edition of the Auxiliary Weather Specialty Course (AUXWEA) Student Study Guide is one of the results of the project. It emphasizes practical application of the wealth of weather information now available on the internet, in applications for smart phones, and new material from government agencies such as NOAA, National Weather Service, and the USCG. The material is intended for all Auxiliarists, but especially for coxswains, boat crew, pilots, aircrew, and air observers, to aid in pre-patrol planning and on-the-water or in-the-air decision making.

Auxiliarists who are qualified as boat crew, coxswains, air crew, or pilots must be prepared to safely conduct operations in all but the most severe kinds of weather. Auxiliary instructors should be able to communicate the same philosophy to recreational boaters in public education courses. This means knowing what conditions to expect and how to cope with them, a fairly easy task if a glance at a weather forecast always provided an accurate prediction. As good as weather forecasting has become, it is still not, and never will be, an exact science. Actual conditions encountered when underway several hours later might be better or worse than the forecast. Therefore, Auxiliarists should know how to evaluate forecasts by asking and answering “what if” questions, so that they can plan ahead. This course supplies the tools that students may use to ask and answer these questions. Instead of just stating weather rules, the text uses simple physics, with simple mathematics, to explain why the atmosphere behaves as it does. It also educates the student in how to monitor the weather, update expectations, and cope with unexpected developments.

The course has been geared to accommodate non-technical students, and concentrates on providing every student with practical knowledge. The discussion of weather products has been updated to cover the various kinds of analysis and forecast charts, radar plots, satellite images, and data buoy reports now available on the internet.

The study questions at the end of each chapter have been devised mainly to reinforce the student’s grasp of concepts. In order to achieve this objective, students should read the material and answer the study questions prior to coming to class, and ask questions if they are not sure of their knowledge. Additional material can be found on srh.weather.gov/jetstream/index.htm

Students and instructors who find errors and omissions in this SSG or in the PowerPoints, are strongly encouraged to report them to the author so that future editions of this course can be improved. You can contact the author using the contact information available on the National website at auxoficer.cgaux.org/auxoff/index.php. Additionally, students or instructors may also route comments and concerns via their respective chain-of-leadership.

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USA Today has graciously given permission to use numerous figures from its book, *The Weather Book*, by Jack Williams (© 1997, Gannett New Media).

The US Power Squadrons has given permission to use many figures and images from its weather course, *Weather Systems and Forecasting for Mariners* (© 2008, US Power Squadrons)

The author is grateful to the National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service (NWS) for numerous weather products, primarily for Chapter 7, from their web site, www.weather.gov.

Several public domain images were taken from the American Meteorological Society (AMS) book *The Ultimate Guide to America's Weather* by Jack Williams (© 2009, American Meteorological Society)

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Table of Contents

Preface	ii
Acknowledgements.....	iv
Table of Contents.....	v
List of Figures.....	x
Part I—The Science of Meteorology	1
Introduction.....	2
Purpose.....	2
Course Outline	2
Using the Study Questions.....	3
Chapter 1 What Causes the Weather?	4
Section 1. Solar Radiation, Heat and Temperature.....	4
Solar Radiation	4
Specific Heat.....	6
Temperature.....	6
Heat Transfer	7
Section 2. The Coriolis Effect and Global Circulation.....	9
The Coriolis Effect.....	9
Global Circulation.....	10
Global Wind Patterns.....	10
Study Questions—Chapter 1	12
Chapter 2 Pressure and Winds.....	15
Section 1. Surface Pressure and Winds	15
Pressure.....	15
Surface Charts.....	17
Winds.....	17
Section 2. Upper-Level Pressure and Winds	20
Upper-Level Charts.....	20
Study Questions—Chapter 2	23
Chapter 3 Moisture, Latent Heat, Fog and Stability.....	26
Composition of the Atmosphere	26
Structure of the Atmosphere	26

The Properties of Water	27
Measuring Water Vapor.....	28
Types of Fog and Their Formation	29
Atmospheric Stability	30
Study Questions—Chapter 3	33
Part II—Sensible Weather	35
Chapter 4 Air Masses, Fronts, and Cyclones	36
Section 1. Air masses.....	36
What is an Air Mass?.....	36
Addition of Moisture	37
Cooling from Below	37
Heating from below	37
Removal of Moisture	37
When Air Masses Meet.....	37
High-Pressure Systems	38
Low-Pressure Systems.....	38
How they Move	38
Section 2. Fronts and Storm Systems	39
Types of Fronts	39
Cold Fronts	39
Warm Fronts	40
Stationary Fronts.....	40
Occluded Fronts.....	41
Cyclones.....	41
How is the Low Moving?	42
How Lows Form	43
Cold and Warm Core Lows	44
Study Questions—Chapter 4	45
Chapter 5 Clouds, Precipitation, and Optical Phenomena.....	48
Section 1. Clouds	48
What are Clouds?.....	48
Low Clouds.....	48
Middle Clouds.....	49

High Clouds	50
Clouds of Vertical Development	51
More Cloud Characteristics	52
Section 2. Precipitation	53
How Does Precipitation Form?.....	53
Types of Precipitation	54
Station Model.....	55
Section 3. Optical Phenomena in the Atmosphere	56
Introduction.....	56
Optical Phenomena	56
Halos and Coronas	57
Rainbows	57
Scales of Weather Events	11
Study Questions—Chapter 5	58
Chapter 6 Severe Weather	61
Section 1. Thunderstorms, Lightning, and Hail.....	61
Thunderstorms	61
Supercells.....	63
Lightning and Thunder	64
Hail.....	64
Section 2. Tornadoes	65
How they Form	65
The Fujita Scale	66
Watches and Warnings	66
Other Types of Vortices.....	67
Section 3. Tropical Storms and Hurricanes	67
Life Cycle	68
Structure.....	68
Categories	69
Storm Surge	69
Watches and Warnings	70
Study Questions—Chapter 6	71

Part III—Practical Application.....	74
Chapter 7 Observation and Forecast Data Sources	75
Section 1. Sources of Observations	75
Introduction.....	75
Surface Charts.....	75
Radar Data	77
Satellite Data.....	78
Upper Air Charts.....	80
Section 2. Sources of Forecasts	82
How Forecasts Are Made	82
Surface Forecast Charts	83
Where to Find the Forecasts	84
Chapter 8 Preparing for and Executing a Mission.....	89
Introduction.....	89
How to Plan	89
What to Consider	89
Visibility Restrictions	90
Thunderstorms	90
Wind and Waves.....	91
Temperature	92
Warm Weather Issues	92
Cold Weather Issues	93
Cold Water Immersion.....	94
Tornados and Water Spouts.....	94
Hurricanes	94
Study Questions—Chapter 8	95
Index	97
Appendix A Some More Physics.....	A-1
The Ideal Gas Law	A-1
The Relationship between Temperature and Kinetic Energy	A-1
Adiabatic Processes	A-1
The Hydrostatic Equation	A-1
Reducing Station Pressure to Sea-Level Pressure	A-2

Pressure Gradient Force.....	A-2
The Coriolis Effect.....	A-2
Doppler Shift.....	A-3
Refraction.....	A-3
Scattering.....	A-3
Why Friction Changes Wind Direction.....	A-4
Appendix B Useful Tables and Graphs.....	1
Relation among Temperature, Dew Point and RH.....	B-1
Specific Heats of Selected Substances.....	B-1
Heat Index Table.....	B-2
Wind Chill Table.....	B-2
Standard Pressure Levels and Plotted Intervals.....	B-3
Useful Conversion Factors.....	B-3
Example of a Grid for Numerical Weather Prediction.....	B-4
Relationship Between Wave Period and Wave Height.....	B-5
Station Model Symbols.....	B-6
Cloud Height Table.....	B-6
Beaufort Wind Scale.....	B-7
Cloud Chart (NOAA), With Cloud Symbols.....	B-8
Appendix C References.....	C-1
Appendix D Answers to Study Questions.....	D-1
Chapter 1.....	1
Chapter 2.....	D-5
Chapter 3.....	D-8
Chapter 4.....	D-10
Chapter 5.....	D-14
Chapter 6.....	D-17
Chapter 7.....	D-20
Chapter 8.....	D-22

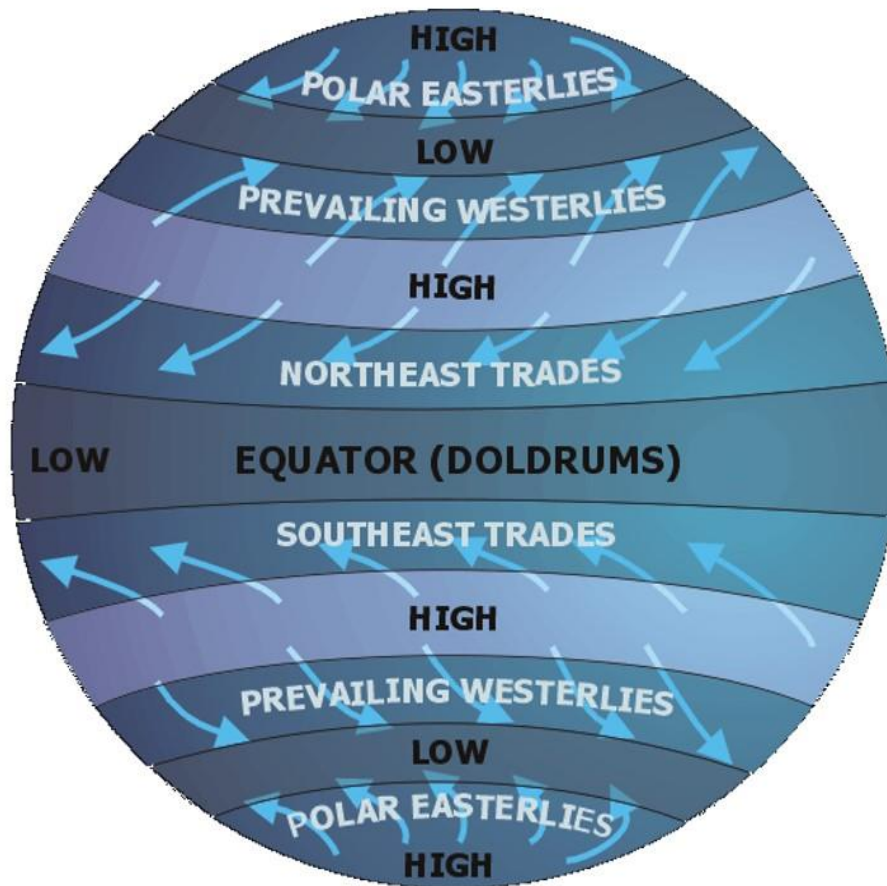
List of Figures

Figure 1.1. Solar electromagnetic spectrum at top of atmosphere (yellow) and at sea-level (red).	4
Figure 1.2. Effect of angle on energy concentration.	4
Figure 1.3 Energy from the sun decreases with increasing latitude	5
Figure 1.4 Effect of the seasons on energy distribution.	5
Figure 1.5 Simple picture of the energy balance in the atmosphere. Energy balances at the top and bottom.	7
Figure 1.6 Examples of conduction, convection, and radiation.	8
Figure 1.7. Simple global circulation expected if the Earth did not rotate. (Magnify to read better).....	9
Figure 1.8. Simplified explanation of the Coriolis Effect.	9
Figure 1.9. On a rotating Earth, the simple picture in Figure 1.7 becomes more complex.	10
Figure 1.10. The pressure bands result in the global prevailing winds.	10
Figure 1.11. On the real Earth, the pressure bands become semi-permanent pressure systems.	11
Figure 2.1. Wind speed varies with the strength of the pressure gradient force (PGF).	16
Figure 2.2. Mercury Barometer (a) and Aneroid Barometer (b).	16
Figure 2.3. Example of a simple surface chart showing highs, lows, and isobars.....	17
Figure 2.4. Air flowing out of a high pressure area	17
Figure 2.5. Air flowing into a low pressure area.	18
Figure 2.6. Effect of friction on surface winds.....	18
Figure 2.7. Example of a veering wind.	18
Figure 2.8. Example of a backing wind.	19
Figure 2.9 The Buys-Ballot law determines where the low pressure is located.	19
Figure 2.10. Sea breeze is a result of the land warming faster than the water.....	19
Figure 2.11. Land breeze is a result of the land cooling faster than the water.	19
Figure 2.12. A typical anemometer, with a propeller for measuring wind speed.....	20
Figure 2.13. Example of Rossby waves, the polar jet stream, and the polar front (located beneath the jet).	21
Figure 2.14 Example of a 500 mb chart.	22
Figure 2.15 Upper level convergence and divergence affect surface highs and lows.	22
Figure 3.1. Average vertical structure of the atmosphere at mid-latitudes.....	26
Figure 3.2. Illustration of the average environmental lapse rate in mid-latitude.....	27
Figure 3.3. Demonstration of adiabatic processes.....	27
Figure 3.4. Phase changes of water.	28
Figure 3.5. Saturation (100% RH) absolute humidity as a function of temperature.	28
Figure 3.6 Relationship among temperature and measures of moisture content.	29
Figure 3.7 Absolute stability.	30
Figure 3.8 Absolute instability.....	31
Figure 3.9 Conditional Stability.....	31

Figure 3.10 Due to a morning inversion, air is stable.	31
Figure 3.11 The air near the ground heats up, making the air unstable.....	31
Figure 4.1 Air mass source regions.	36
Figure 4.2 Cold front between cP and mT air masses.	37
Figure 4.3 Upper air convergence and divergence affect surface highs and lows.....	38
Figure 4.4 Frontal Symbols on surface charts.	39
Figure 4.5 Typical cross-section of a cold front.....	39
Figure 4.6 Typical warm front cross-section.....	40
Figure 4.7 Comparison of cold and warm fronts.....	40
Figure 4.8 Typical stationary front.....	40
Figure 4.9 Warm occlusion.	41
Figure 4.10 Cold occlusion.	41
Figure 4.11 Extra-tropical cyclone.....	42
Figure 4.12 Winds veer or back depending on where the low is passing us.	42
Figure 4.13 Classical cyclogenesis theory.	43
Figure 4.14 Cross-section of the Polar Jetstream.	43
Figure 4.15 Typical storm tracks.	43
Figure 4.16. Warm core Low.	44
Figure 4.17. Cold core Low.	44
Figure 4.18. Cold core Low with High at the Surface.....	44
Figure 4.19. Warm core Low with a High above, as in a Hurricane.	44
Figure 5.1 Comparison of a rain drop and a cloud particle.	48
Figure 5.2 Fair weather cumulus (Cu).	49
Figure 5.3 Growing Cumulus Humilis (Cu).....	49
Figure 5.4 Stratus, seen from above (St).....	49
Figure 5.5 An example of stratocumulus (Sc).....	49
Figure 5.6 Nimbostratus (Ns).....	49
Figure 5.7 Altostratus (As). The sun may or may not be visible.....	50
Figure 5.8 Altocumulus (Ac).	50
Figure 5.9 Altocumulus (Ac) in "Streets."	50
Figure 5.10 Cirrus (Ci) with "mares' tails"	50
Figure 5.11 Cirrocumulus (Cc), a mackerel sky.	50
Figure 5.12 A corona (probably altostratus)	51
Figure 5.13 Halo due to cirrostratus (ice cloud).....	51
Figure 5.14 Cumulus congestus or towering cumulus (Cu).	51
Figure 5.15 Typical cumulonimbus.	52
Figure 5.16 Multiple lenticular clouds.	52

Figure 5.17 The Base of a cumulonimbus mammatus cloud.	52
Figure 5.18 Typical wall cloud.	53
Figure 5.19 Refraction.	56
Figure 5.20 Mechanism for the Halo.	57
Figure 5.21 Mechanism for a primary rainbow.	57
Figure 5.22 Primary and secondary rainbows.	57
Figure 6.1 Three stages of a single-cell thunderstorm.	62
Figure 6.2 The structure of a super cell thunderstorm.	63
Figure 6.3 Occurrence of tornados varies across the U. S.	65
Figure 6.4 A wall cloud below a thunderstorm.	65
Figure 6.5 Typical small tornado.	66
Figure 6.6 Typical non-tornado water spout.	67
Figure 6.7 Conditions necessary for formation of tropical cyclones.	68
Figure 6.8 Typical structure of a hurricane.	69
Figure 6.9 Effect of the Bermuda High on hurricanes.	70
Figure 7.1. Surface analysis for the United States, 12Z, 16 Dec 2014.	76
Figure 7.2. Combined surface analysis and IR satellite data.	77
Figure 7.3. Combined surface analysis and radar.	77
Figure 7.4. Local Radar Display (single radar).	77
Figure 7.5 Regional radar mosaic for the NE U.S.	77
Figure 7.6. National composite radar mosaic.	78
Figure 7.7 Sites of Doppler radars in the U.S.	78
Figure 7.8. Visible composite image from GOES East and West.	79
Figure 7.9. IR1 composite from GOES East and West.	79
Figure 7.10. Water vapor composite image.	79
Figure 7.11. 12 Z 500 mb analysis, with isoheights and isotherms (red).	81
Figure 7.12. 12 Z Surface analysis for comparison.	81
Figure 7.13. 12-hour surface forecast.	83
Figure 7.14. Simple 24-hour surface forecast (compare with Figure 7.15).	83
Figure 7.15. Surface analysis for the same time as Figure 7.14, for comparison.	83
Figure 7.16. 6-hour quantitative precipitation forecast.	84
Figure 7.17. 24-hour wave direction and period forecast for mariners	84
Figure 7.18. Example of marine text forecast.	84
Figure 7.19. Short-range Forecasts at hpc.ncep.noaa.gov/basicwx/basicwx_wbg.php	85
Figure 7.20. Local Forecast Page at www.weather.gov	86
Figure 8.1. Heat Index Table.	93
Figure 8.2. Wind Chill Table.	93

Part I—The Science of Meteorology



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Introduction

Chapter 1: What Causes the Weather?

Chapter 2: Pressure and Winds

Chapter 3: Moisture, Latent Heat, Fog and Stability

Introduction

Purpose

This course is intended to train the Auxiliary weather specialist in the art of practical meteorology. The main focus will be on weather assessment for surface operations, but some attention will be paid to issues particular to air operations. Auxiliary surface units typically patrol within 20 nautical miles of shore. They are underway for 4 to 6 hours, but the duration might be extended if the crew is tasked for search and rescue (SAR) near the scheduled end of the patrol period.

A good weather brief helps to prepare for the mission. Will it be cold and windy or calm, hot, and humid? The crew needs to know what to wear and what to bring. The coxswain needs to know whether the waves might be so high that it could be too risky to take a disabled vessel in tow, or whether fog might roll in during the patrol, requiring close attention to navigation.

The real challenge comes when changes are rapid or unexpected, adjacent weather systems are competing, or a good assessment must be made several days ahead of a patrol for planning purposes. In these situations the weather specialist must consider a large area and also think in three dimensions to understand how conditions aloft might affect the weather at the surface. The rest of the text covers these topics.

What is meteorology? What is weather? What is climate? How do they relate? By the end of this course you will have a solid understanding of these. We start with simple definitions:

Meteorology is the science of the atmosphere, its physical characteristics and principles, including knowledge of sensible (what we see and feel) weather in all its forms.

Weather is the current state of the atmosphere, or its forecast state at a given time and place or defined area, over a short period of time (hours to days).

Climate is the average of weather at a given location or over a defined area, over an extended period of time (classically, 30 years or more).

Course Outline

Part I (Chapters 1 - 3) covers the basic physics of meteorology, as a basis for understanding the rest of the, more practical, material. By necessity, the presentation is based on physical principles and some elementary formulas. Since we are dealing with properties of the atmosphere, physical units must be used. The text adopts the metric system in most cases (centimeters, grams, Celsius temperature scale). The major exceptions are surface temperature and lapse rate, where the Fahrenheit scale is used. Knots are used for wind speed and current.

Chapter 1 covers the basic source of energy that drives the atmosphere—the Sun. It introduces the concepts of temperature and heat. It relates these phenomena to global circulation and the characteristics of the Coriolis Effect. Chapter 2 covers atmospheric pressure and its effect on winds. Chapter 3 covers water, its importance to meteorology,

and its relationship to latent heat, stability, and fog.

Part II (Chapters 4 - 6) describes many features of the observable weather elements, including clouds, precipitation, air masses, fronts, and weather systems on the scale of hundreds of miles (called synoptic scale). Here the basic principles of Section I are applied to the earth's atmosphere in order to show how winds develop to carry heat and moisture from one area to another.

Chapter 4 covers air masses, cyclones and fronts and their interrelationship. Chapter 5 covers clouds and precipitation. It also includes a section on optical phenomena. Chapter 6 covers severe weather, including thunderstorms, lightning, hail, tornados, and hurricanes.

Part III (Chapters 7 - 8) covers observations, forecasts, and practical tips on how to use the information available to understand the current weather and the forecast, and what to watch for while patrolling. It is generic in nature, but should generate discussion about what is best for your AOR.

Chapter 7 covers a variety of observation and forecast products issued by the National Weather Service (NWS). These include satellite images, radar plots, and weather maps that show much more detail than the maps in newspapers. It shows a series of these products, all selected for the same date and time, to guide the reader in understanding how these products can work together to develop a thorough understanding of current conditions and short-term (hours to days) forecasts. The discussion will focus on how to read and interpret these products.

Chapter 8 provides a practical guide for preparing for a patrol, watching for weather changes, and sources for real-time updates. It covers suggested actions for deteriorating

conditions, such as fog formation, unexpected thunderstorms and the like. For completeness, it also briefly covers waves and a brief discussion of effects and actions related to air operations.

In addition, there are four Appendices. You are not responsible for their content, but they are there for your additional study. Appendix A has more physics, with college-level mathematics. Appendix B has several useful tables and graphs. Appendix C is a list of references, and Appendix D contains answers to the study questions.

The text provides a foundation in the basic principles of meteorological science, but that knowledge alone does not make a good forecaster. Weather forecasting is the art of combining the principles with judgment, based on experience. By understanding the science principles, NWS weather products, and knowledge of local experts, the student can increase his or her understanding of meteorology and how to use this knowledge for planning and executing a patrol. It will also be useful in other decisions that must be made that depend on the weather, such as picnics, biking, or hiking.

Using the Study Questions

At the end of each chapter, there are study questions that allow you to self-test your knowledge of the information provided. You should first try to answer the questions without reference to the text. Where you have problems answering the questions on a given topic, check Appendix D, review that material, and ask the instructor for clarification. To do that effectively, you must read the chapter and answer the questions before you come to class. These questions will fully cover the topics and ideas that will be on the test, but may not be the exact same questions. Again, you are not responsible for material in footnotes or in the Appendices.

Chapter 1 What Causes the Weather?

Section 1. Solar Radiation, Heat and Temperature

Solar Radiation

What drives the weather? Ultimately, it is the sun that is responsible for all atmospheric processes. How? Through the seasons, it heats our world, some parts more, some less. The Earth's rotation and its year-long trip around the sun create a giant heat engine that drives the weather.

Anyone who ever wilted on a sweltering summer day can easily understand that the sun creates hot weather. However, the connections are not so clear between the sun and hurricanes, tornadoes, blizzards, the falling rain, or even long sieges of arctic cold.

The sun is a giant thermo-nuclear furnace. Only a very small share of the sun's tremendous energy output reaches the Earth, but that is enough to maintain life and drive the weather. The sun's electromagnetic energy (Figure 1.1), including visible, ultraviolet, and infrared energy, flows into the atmosphere to warm the air, oceans, and land.

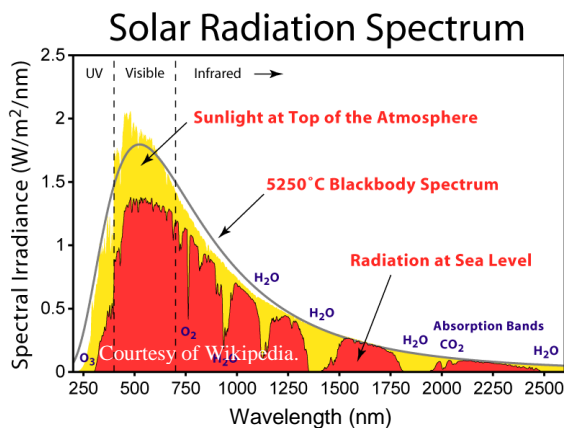


Figure 1.1. Solar electromagnetic spectrum at top of atmosphere (yellow) and at sea-level (red).

The sun, at 5250°C, emits most strongly in the visible (peaking in the green). The Earth, averaging 15°C, emits most strongly in the Infrared (at ~1000 nm in Figure 1.1).

As the seasons change, the sun bathes different parts of the Earth in widely varying amounts of energy. The result is a planet sharing frigid polar cold, sweltering tropical heat and all the temperatures in between, all at the same time.

Think of a flashlight shining on a flat surface (Figure 1.2). If it shines vertically, the light (energy) is spread over a certain area. If the same flashlight shines at an angle to the surface, the light (energy) is spread out over a larger area, so each point on the surface receives less energy than when the beam is vertical.

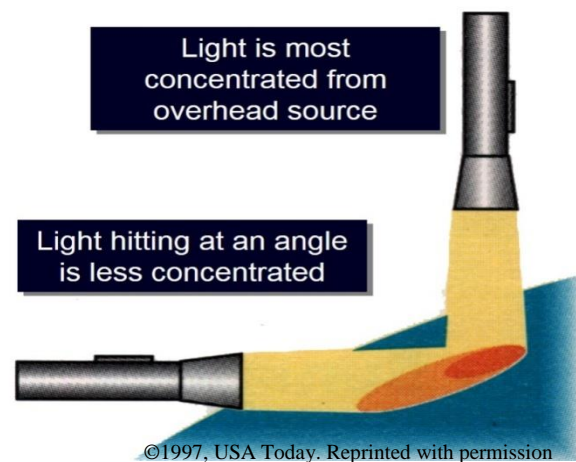
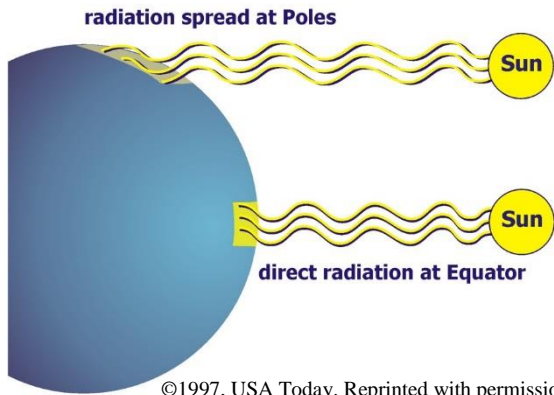


Figure 1.2. Effect of angle on energy concentration.

Now consider if the surface is curved, like that of the earth. As the light moves back and forth over the curved surface, the area of light increases or decreases based on the ori-

entation of the surface relative to the direction of the sunlight—more energy near the equator and less near the poles (Figure 1.3). This sets up a large “heat engine” in the atmosphere that powers the weather. The excess heat near the equator is transferred by global wind circulations (and ocean currents as well).



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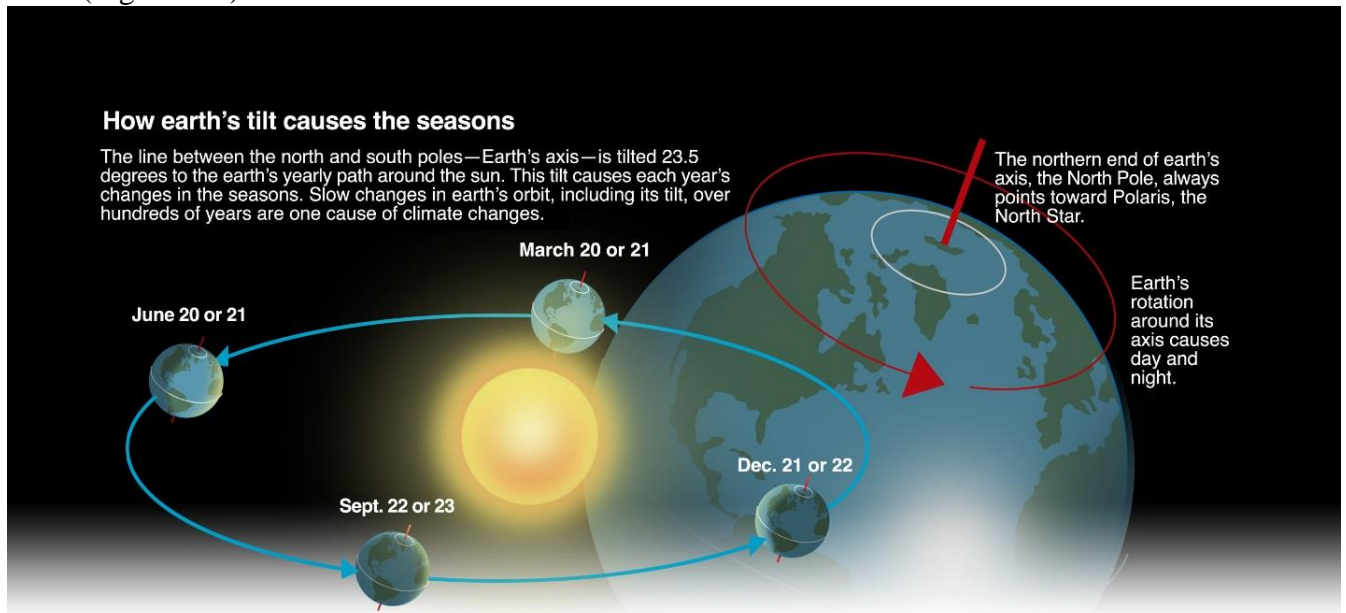
Figure 1.3 Energy from the sun decreases with increasing latitude

The seasons bring the biggest swings between hot and cold, caused by the Earth’s year-long trip around the sun, and the fact that the Earth’s axis is tilted at 23.5 degrees from a direction perpendicular to the Earth’s orbit (Figure 1.4). This means that at the

summer solstice, the sun heats the strongest at 23.5 degrees north, while the south polar region, above 66.5 degrees, is in darkness. At the *winter solstice*, the opposite is true—maximum heating at 23.5 degrees south and darkness at the north pole. At the *equinoxes*, the sun is directly over the equator.

In addition to differences caused by the seasons, the Earth heats unevenly because land absorbs and gives off heat more easily than water, so large oceans and continents further complicate the solar energy distribution. On a large scale, tropical oceans hold very large amounts of energy while polar water can be frigid year-around. Land areas, on the other hand, quickly warm and cool with the seasons.

So why aren’t the hottest days at the summer solstice (21 June most years)? The answer is in the balance between incoming solar radiation and outgoing infrared radiation from the ground and atmosphere. At the solstice, more solar energy is absorbed than infrared energy is emitted, so the Earth continues to heat until the two are in balance—usually in August.



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Figure 1.4 Effect of the seasons on energy distribution.

The same argument applies to the winter solstice, where there is more outgoing infrared energy than incoming solar energy.

The Earth's orbit determines how much energy reaches the top of the atmosphere, but not all of it reaches the ground (Figure 1.1). The difference is key to understanding the Earth's temperature. Some of the sunlight is reflected off clouds and the surface. The cloud cover and the nature of the surface (dark or light) determines how much is reflected. Thick clouds may reflect as much as 95% of the sun's energy back into space. White snow may also reflect as much as 95%, while a forest or ocean may reflect as little as 10%. The amount of energy that reaches the surface is called the *insolation*.

The energy balance of the Earth is complex and ever changing. Figure 1.5 (next page) is a simple representation of some of the parts of this balance. Anything that absorbs energy heats up. Solar energy warms the surface, which warms the lower atmosphere by conduction and convection. Absorbed ultraviolet radiation warms the upper atmosphere. Infrared energy is absorbed by the surface, clouds, and many molecules in the atmosphere (notably carbon dioxide, methane, oxides of nitrogen, and water vapor). Everything in the atmosphere that absorbs infrared also emits it, some upward and some downward. The energy balances at the top of the atmosphere and at the surface (do the calculation). This interaction is the basis of the misnamed "greenhouse effect."¹

Specific Heat

Above, we alluded to heat absorption causing warming, but did not discuss how

much warming to expect. Clearly, the amount of energy absorbed has an effect, but how much energy does it take to warm a specific amount? To answer that question, we need to define a new term—*specific heat*.

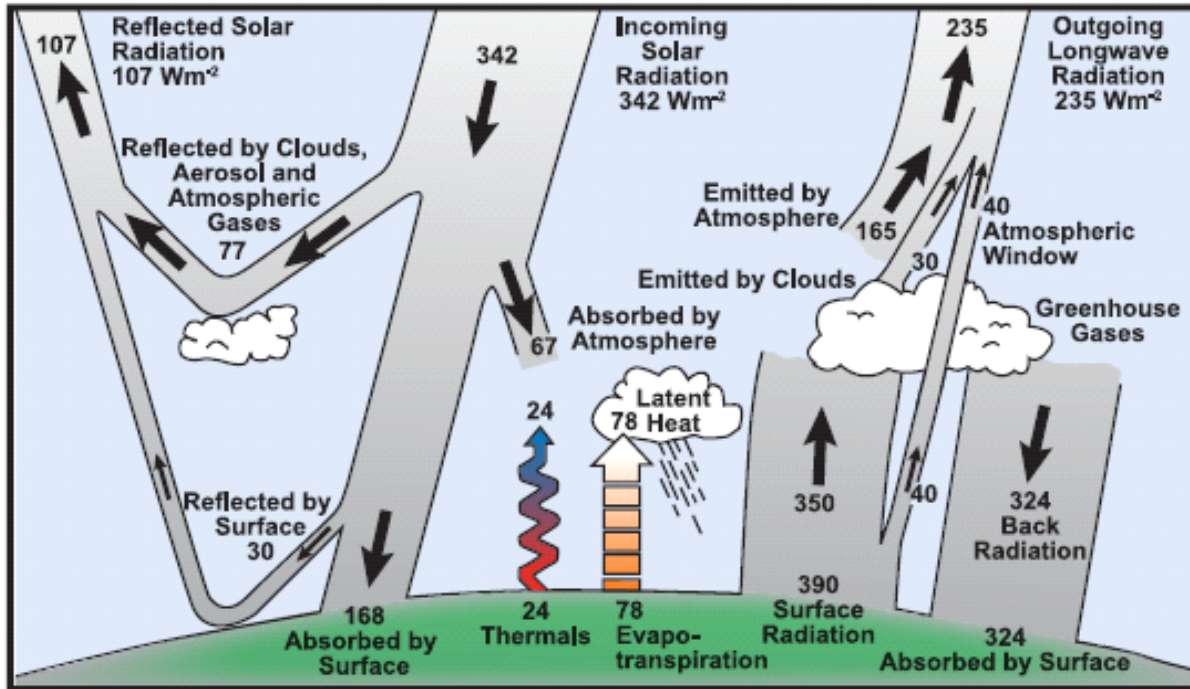
Specific heat is defined as the amount of heat energy (calories²) it takes to raise one gram of material by one degree Celsius. The calorie is defined as the amount of heat required to raise one gram of pure water by one degree Celsius, from 3.5° to 4.5° (where it is densest), at one atmosphere pressure. Therefore, the specific heat of water is one calorie per gram. The specific heat of other materials is different. For example, the average specific heat of soil is roughly one fourth that of water, so one calorie will raise the temperature of one gram about 4° Celsius. This explains why the land heats and cools faster than water. See Appendix B for the specific heats of some other substances.

Temperature

Temperature is a measure of the motion of the atoms or molecules in a substance—specifically, the kinetic energy of those atoms or molecules (see Appendix A for a mathematical definition). There are two major systems of temperature measurement—Fahrenheit and Celsius. Both are defined on the basis of the melting point and boiling point of pure water under one atmosphere of pressure. The Fahrenheit scale is 32 to 212 degrees—thus there are 180 Fahrenheit degrees between them. The Celsius scale is from 0 to 100 degrees—therefore the Celsius degree is 1.8 times larger than the Fahrenheit degree.

¹ The atmospheric "greenhouse effect" is not the same as what happens in a real greenhouse, where the main reason it remains warmer than the outside is that the roof prevents convection; but we are stuck with the name.

² The calorie used in meteorology is the gram-calorie (cal), while that used to measure the energy content of food is the kilogram-calorie (Kcal), 1000 times as large.



Courtesy of the Intergovernmental Panel on Climate Change

Figure 1.5 Simple picture of the energy balance in the atmosphere. Energy balances at the top and bottom.

There are two other temperature scales that are commonly used, both absolute temperature scales. In these scales, zero is the lack of any energy (molecular motion), often called *absolute zero*. The *Kelvin* scale is related to the Celsius scale by the equation: $^{\circ}\text{K} = ^{\circ}\text{C} + 273.15$. The *Rankin* scale is related to the Fahrenheit scale by the equation: $^{\circ}\text{R} = ^{\circ}\text{F} + 459.67$. These temperatures are used in the equations of physics (see Appendix A).

These definitions of Celsius and Fahrenheit lead to the equation for converting from one to the other:

$$^{\circ}\text{C} = \frac{5}{9} \times (^{\circ}\text{F} - 32) \text{ or}$$

$$^{\circ}\text{F} = 9/5 \times ^{\circ}\text{C} + 32$$

For example: 68 °F is 20 °C:

$$^{\circ}\text{C} = 5/9 \times (68 - 32) = 5/9 \times 36 = 20$$

There is a short-cut that allows you to calculate the Fahrenheit temperature in your

head, given Celsius: Double the Celsius temperature, subtract 10% of the result, and add 32. For the example above,

$$20 \times 2 = 40; - 4 = 36; + 32 = 68.$$

The inverse of this shortcut is not exact, but usually correct within a few tenths (Subtracting 10% of 40 is 36, but adding 10% of 36 is 39.6.).

The instrument used to measure temperature is the thermometer. There have been many types over the centuries, but the most common are the mercury thermometer, the alcohol thermometer, the bi-metal coil thermometer, and the solid state thermometer (using special electronic circuits).

Heat Transfer

We have added or subtracted heat energy in the above descriptions, but don't say how that happens. There are three basic ways that heat is transferred: Conduction, convection, and radiation (Figure 1.6).

Conduction is the movement of heat through a substance by the motion of the atoms or molecules, from hot toward cold (warming the cold part).

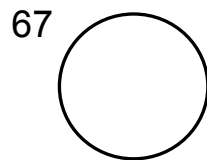
Convection is the movement of fluids (gases or liquids). In the atmosphere, for example, hot air rises and cold air falls (to be discussed more fully in Chapter 3).

Radiation is the transfer of electromagnetic energy, such as light (visible radiation) or heat (infrared radiation). It does not require a medium—it works best in a vacuum.

In the atmosphere, all of these mechanisms are at work and we will see specific examples in future chapters. For example, the lower atmosphere is heated by conduction and convection from the surface.

In addition to these, the atmosphere has a fourth way to transfer energy, which is related to convection—the transport of latent heat—more on this in Chapter 3. Finally, in meteorology, we distinguish between the vertical movement of fluids, convection, and their horizontal movement, *advection*.

Before we leave the subject of temperature and energy, let's introduce the concept of a *station model*. When weather observations are plotted on a surface chart, the various variables are plotted in a standard way. It starts with a circle, representing the location of the station. We will add other variables as we discuss them, but for now, let's add temperature to the station circle. Remember, surface temperature in the U.S. is in Fahrenheit.

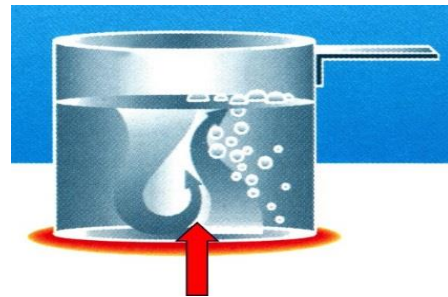


Conduction



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Convection



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Radiation



Figure 1.6 Examples of conduction, convection, and radiation.

Section 2. The Coriolis Effect and Global Circulation

The Coriolis Effect

We have learned that the sun heats the equatorial region of the Earth more than the poles, with continuous variation in between. We also learned that hot air rises and cold air sinks. This information would lead us to guess that there is a circulation from equator to poles, with air rising at the equator, moving toward the poles, where it falls and returns along the surface to the equator. Figure 1.7 shows this simple concept. This circulation is called a *Hadley cell*. Since we know that winds in the northern hemisphere are not all from the north, there must be more at work. If the Earth did not rotate, this simple circulation would be the norm (assuming a featureless earth—no land or ocean).

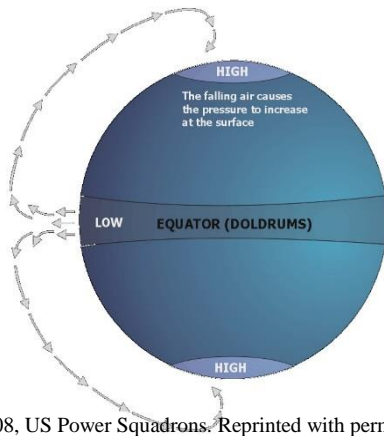


Figure 1.7. Simple global circulation expected if the Earth did not rotate. (Magnify to read better)

But the Earth does rotate and that complicates the picture. The Earth's rotation introduces a term in the equations of motion of the atmosphere that acts as if it were a separate force. This is usually called the Coriolis force, but a more correct label is "*Coriolis Effect*" since it is not a true force like gravity, but acts as though it were.

A very simple illustration of the Coriolis Effect is seen in Figure 1.8. Place a ruler over a rotating disk and draw a line from the center to the edge. Your pen moves in a straight line, but the mark on the disk curves. The same idea applies to winds on the Earth—they blow in a straight line relative to the stars (Newton's laws of motion), but as seen by an observer on the Earth, they curve.

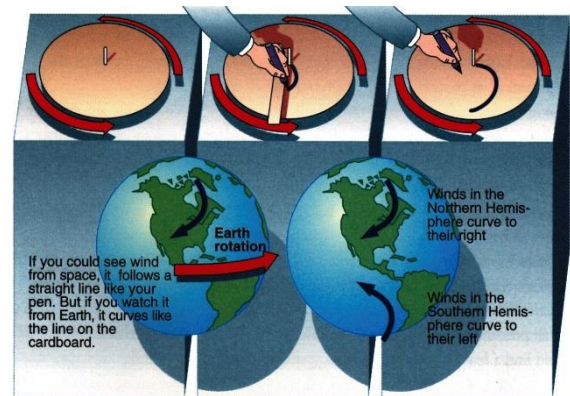


Figure 1.8. Simplified explanation of the Coriolis Effect.

This simple picture is correct at the poles, but the degree of curvature varies with latitude, and is zero at the equator.

As one looks down at the North Pole, the Earth rotates counter-clockwise, from west to east (making the sun rise in the east). Therefore, a moving body, such as a parcel of air or water, curves to the right as seen from the Earth's surface. It curves to the left in the southern hemisphere. See Appendix A for a mathematical description.

To summarize:

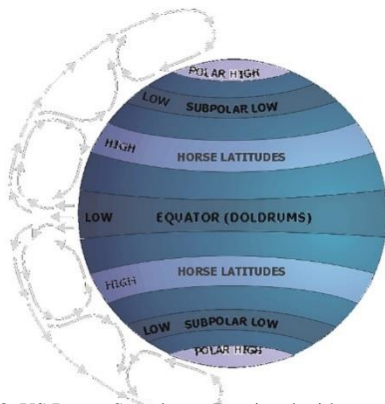
- The Coriolis Effect increases from zero at the equator to maximum at the poles.

- The Coriolis Effect increases with increasing wind speed.
- It causes moving objects to curve to the right in the northern hemisphere and to the left in the southern hemisphere.
- It operates only over long distances, does not materially affect local winds, and has no effect whatsoever on water draining out of a sink!

Global Circulation

Now, let's revisit the Hadley cell. Since a rotating Earth causes the wind to curve, the single equator-to-pole cell is not possible. A better picture (still simplified) is shown in Figure 1.9. It also assumes a featureless Earth (no mountains, continents, or oceans).

The single cell breaks down into three cells. From the equator to the poles, they are called Hadley, Ferrel, and polar cells. Since rising air creates low pressure at the surface and falling air creates high pressure, the result is bands of high and low pressure around the Earth. These regions are historically called, from equator to poles, the doldrums (low), the horse latitudes (high), the sub-polar lows, and the polar highs.

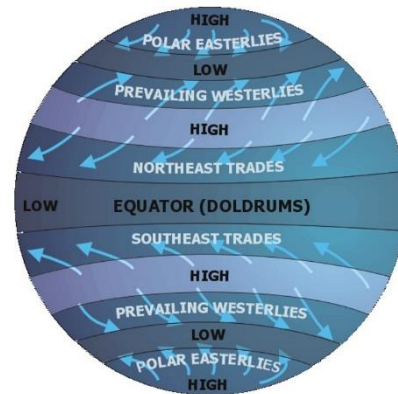


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Figure 1.9. On a rotating Earth, the simple picture in Figure 1.7 becomes more complex.

Global Wind Patterns

The Coriolis Effect also causes the winds to curve, giving the global winds shown in Figure 1.10: The trade winds (easterlies), the prevailing westerlies, and the polar easterlies. Notice that the trade winds converge near the equator, causing increased convection and a band of thunderstorms. This is called the *Inter-Tropical Convergence Zone (ITCZ)*. The prevailing westerlies and polar easterlies also converge. This give rise to the polar front. This concept is expanded in Chapter 4.



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Figure 1.10. The pressure bands result in the global prevailing winds.

Finally, with the introduction of the contrast between continents and oceans, we see the picture in Figure 1.11, showing semi-permanent highs and lows. As the sun moves north and south over the year, the location of these features moves with it and they grow and shrink. The top of the figure is the average position and size of these features in January and the bottom the average position and size in July. The solid red line near the equator is the *Inter-tropical Convergence Zone (ITCZ)*.

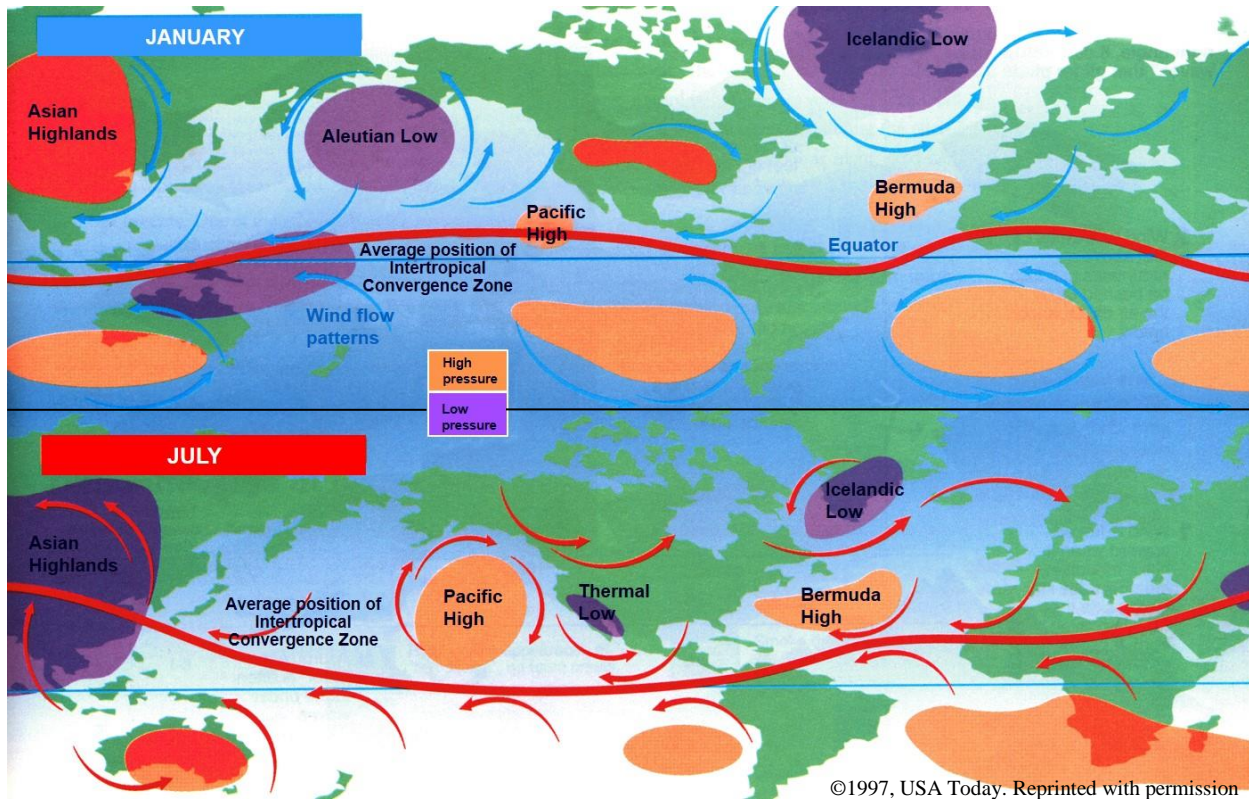


Figure 1.11. On the real Earth, the pressure bands become semi-permanent pressure systems.

Scales of Weather Events

The scale of weather systems discussed in Chapter 1 are what is called global scale (or planetary scale). In future chapters, we will discuss weather features of other scales.

Meteorologists recognize four scales, or sizes, of weather phenomena. These are global (or planetary), synoptic, mesoscale, and microscale. Below are the definitions and examples of these four scales.

Global (planetary): Last weeks to years and are of sizes from 2,500 miles to 25,000 miles. Examples are wind patterns such as the trade winds, the ITCZ and prevailing westerlies.

Synoptic: Last days to weeks and are of sizes from 250 miles to 2,500 miles. Examples include air masses, frontal systems, and the semi-permanent highs and lows, covered in Chapters 2 and 4.

Mesoscale: Last minutes to days and are of sizes from 2.5 miles to 250 miles. Examples include thunderstorms, tornados, sea breezes, Chinooks, and most clouds, covered in Chapters 4 and 6.

Microscale: Last seconds to minutes and are of sizes less than 2.5 miles. Examples include microbursts, wind gusts, and dust devils, covered in Chapter 6.

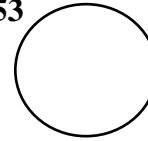
Study Questions—Chapter 1

- The electromagnetic energy that comes from the sun consists of:
 - Light.
 - Ultraviolet.
 - Infrared.
 - All of the above.
- The amount of energy per unit area that arrives at the top of the atmosphere from the sun:
 - Decreases in the winter.
 - Is the same everywhere.
 - Increases with increasing latitude.
 - Decreases with increasing latitude.
- The largest swings of hot and cold are:
 - Day to night.
 - With longitude.
 - With the seasons.
 - Between land and water.
- With the same heat input, which heats faster?
 - Water.
 - Land.
 - The Oceans.
 - None of the above.
- The amount Solar energy that is absorbed by the Earth's surface is reduced due to:
 - The extra distance traveled.
 - Reflection from clouds.
 - The nature of the surface.
 - Both b and c.
- The specific heat of a substance is:
 - The amount of energy it can hold.
 - How hot it gets before it melts.
 - The heat needed to vaporize it.
 - The rate of temperature increase for a given energy input.
- The air in the lower troposphere is heated mainly by:
 - Absorption by air of the direct radiation from the sun.
 - Radiation absorbed by dust in the atmosphere.
 - Cosmic rays.
 - Conduction and convection from the Earth's surface.
- Temperature may be defined as:
 - Energy produced by friction.
 - Change of energy from one form to another.
 - A measure of the kinetic energy of molecules.
 - The pressure of the air on the thermometer.
- In the Celsius temperature scale, zero is defined as:
 - The absence of heat.
 - The temperature at which ice is the densest.
 - The melting point of pure water ice.
 - The freezing point of sea water.
- 20° Celsius is, in Fahrenheit:
 - 52°F.
 - 40°F.
 - 68°F.
 - 75°F.
- 59° Fahrenheit is, in Celsius, to the nearest degree:
 - 27°C.
 - 15°C.
 - 6°C.
 - 32°C.

12. The transfer of heat by the horizontal movement of air is:
- Convection.
 - Conduction.
 - Advection.
 - Radiation.
13. The transfer of heat between bodies that are not in contact is:
- Convection.
 - Conduction.
 - Radiation.
 - Advection.
14. In meteorology, convection means:
- Transfer of heat by contact.
 - Conduction of heat by infrared radiation.
 - The horizontal movement of air by winds.
 - The vertical transport of heat by air.
15. Radiation is energy transfer:
- Via a medium.
 - By contact.
 - Resulting from friction.
 - In wave form, without the necessity of a medium.
16. Large land masses, as opposed to the oceans:
- Maintain a steadier temperature.
 - Are always warmer.
 - Change temperature more between night and day.
 - Are cooler during the day.
17. The cause of most weather phenomena is:
- The layers in the atmosphere.
 - The rotation of the Earth.
 - The revolution around the sun.
 - Uneven heating of the Earth's surface.

18. For the station model shown below, the temperature reported is:
- 53 °C.
 - 5.3 °F.
 - 53 °F.
 - 5.3 °C.

53



19. The Coriolis effect:
- Decreases with increasing latitude.
 - Increases with increasing wind speed.
 - Always turns winds to the right.
 - Operates over long and short distances.
20. The winds near the equator are called:
- Trade winds.
 - Doldrums.
 - Prevailing easterlies.
 - The ITCZ.
21. On a rotating, smooth Earth, the low pressure bands parallel to the equator are the _____ and the _____.
- Doldrums, Horse Latitudes.
 - Horse Latitudes, Westerlies.
 - Doldrums, Sub-polar Low.
 - Horse Latitudes, Polar Low.
22. The Doldrums is a belt of relatively:
- Low temperature.
 - Low humidity.
 - Low pressure.
 - High latitude.
23. Which of the following is not one of the primary wind belts?
- The polar westerlies.
 - The northeast trades.
 - The southeast trades.
 - The prevailing westerlies.

24. The Inter-tropical Convergence Zone (ITCZ) is located:
- a) On the equator.
 - b) 15° north of the equator.
 - c) 15° south of the equator.
 - d) Either side of the equator, depending on the season.
25. The trade winds:
- a) Vary widely in speed.
 - b) Reverse direction with the seasons.
 - c) Blow only in the northern hemisphere.
 - d) Blow from the Horse Latitudes to the Doldrums.
26. Vertical motion of air near the equator is caused by:
- a) Convergence of the trade winds.
 - b) Heating of the air by the Earth's surface.
 - c) Variation of solar energy with latitude.
 - d) All of the above.
27. Heat is transported northward and southward from the equator by:
- a) Winds.
 - b) Ocean Currents.
 - c) Neither of the above.
 - d) Both a and b.
28. Insolation is:
- a) The sun's apparent motion from east to west.
 - b) The reduction in temperature due to clouds.
 - c) The amount of energy reaching the Earth's surface.
 - d) The inclination of the Earth's axis.

Chapter 2 Pressure and Winds

Section 1. Surface Pressure and Winds

Pressure

In Chapter 1, we defined temperature. Here we define and discuss another basic property of the atmosphere—*pressure*. What is pressure? It is a force imparted by the molecules in a liquid or gas that is contained in some manner—perhaps in a jar, perhaps in a tire, or in the case of the atmosphere, constrained between the surface and the weight of the air above pulled downward by gravity. Since the only constraint on the top is due to the mass of the atmosphere above, it means that the pressure decreases with altitude. It never reaches exactly zero, but eventually merges with the inter-planetary gas and dust.

By definition, pressure is force per unit area (See Appendix A.) Force is mass times acceleration. In the case of the atmosphere, the acceleration is due to gravity. There are many different names (called physical units) for the amount of pressure. The ones most often encountered in meteorology are listed below, along with their numerical value for the *standard atmosphere*, defined by convention, and very nearly equal to the average sea-level pressure around 45 degrees latitude.

Pounds per square inch (psi)	14.7
Inches of Mercury (in Hg)	29.92
Millimeters of Mercury (mm Hg)	760
Millibars (mb) [hecto Pascals]	1013.25
Kilo Pascals (kPa) [Canada]	101.325

Pressure in the atmosphere varies not only vertically, but horizontally as well—we are all familiar with the high and low pressure

centers on weather maps. An important concept to understand is *pressure gradient*, the difference in pressure over a given distance. It is not important to know any given unit, but you should know how it varies. Where the distance remains constant, an increase in the pressure difference increases the pressure gradient. Where the pressure difference stays constant, an increase in distance causes a decrease in the gradient. (Figure 2.1)

Why is the pressure gradient important? It is the primary force that drives the wind and is known as the *pressure gradient force (PGF)*. The higher the gradient, the faster the winds. See Appendix A for more information.

The instrument that measures atmospheric pressure is called a *barometer*. There are several kinds, but we will briefly talk about three. One of the oldest is the mercury barometer, a long tube with the closed end up and the open end in a pool of mercury. The closed end contains a vacuum, so the height of the column is proportional to the pressure on the pool (Figure 2.2a).

The next common type is the aneroid barometer, consisting of a flexible box with a partial vacuum, connected by a mechanical linkage to a pointer. Decorative ship's barometers are of this type (Figure 2.2b).

Modern instruments use microelectronic sensors, which have the property of changing their electrical properties with pressure. The signal is processed and displayed digitally.

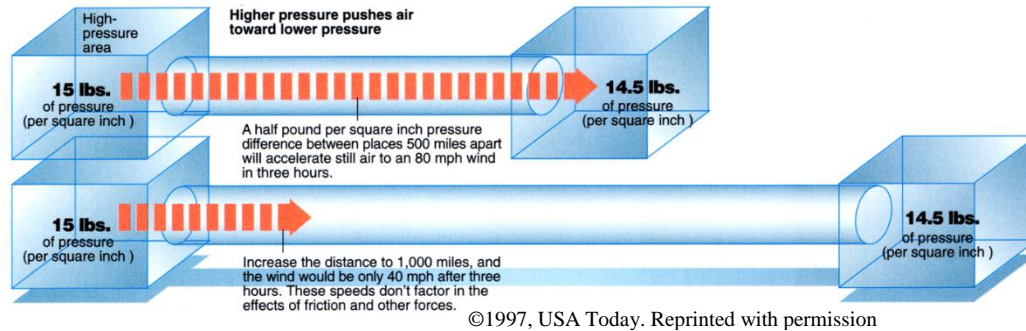


Figure 2.1. Wind speed varies with the strength of the pressure gradient force (PGF).

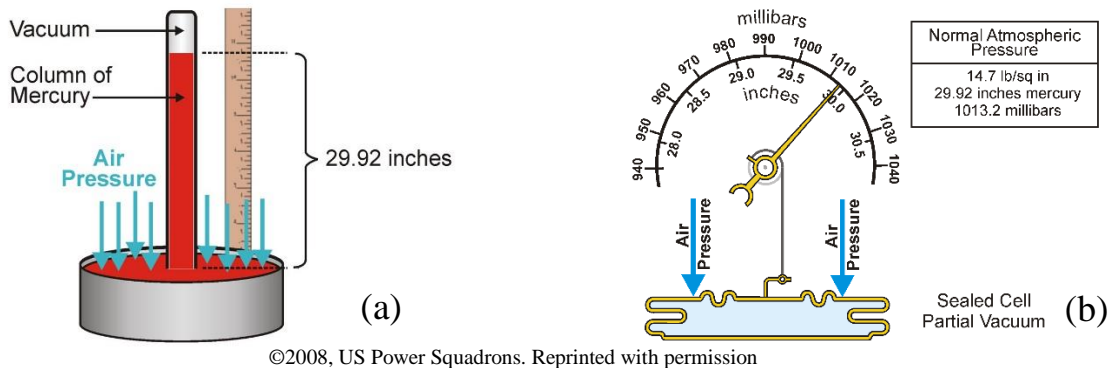


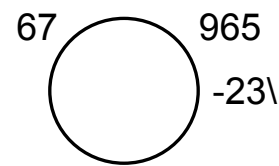
Figure 2.2. Mercury Barometer (a) and Aneroid Barometer (b).

All barometers are sensitive to error sources and must be calibrated relative to a standard. For example, mercury barometers are sensitive to both temperature and the local force of gravity.

On the station model, the pressure is written in mb to the upper right in a three-digit code that leaves off the decimal point, and the first two digits for pressures of 1000 mb or greater, or the first 9 for pressures lower than 1000 mb. Standard pressure of 1013.25 mb would therefore be written as 133 and a pressure of 996.5 mb would be written as 965.

Another item reported in synoptic observations is the *pressure tendency*, the pressure change over a 3-hour period. For forecasting purposes, it is more important than the pressure. Negative values mean pressure is falling and positive values that it is rising. It is

reported with two digits, in tenths of a millibar, and preceded by a negative (falling pressure) or positive (rising pressure) sign. For example -23\ means falling pressure of 2.3 mb over three hours, with a steady fall.



Finally, it is important to understand the difference between local pressure and *sea-level pressure*. At a sea-level station, they are the same. At higher altitudes, a correction formula is applied to calculate an estimated sea-level pressure, which is what is plotted on the chart and reported in observations and forecasts. The need for this will become clearer in the next subsection. One equation for this reduction is in Appendix A.

Besides pressure and temperature, there is a third variable that is closely related to them—*density*. It is mass per unit volume and the relationship is in Appendix A.

Surface Charts

How is pressure shown on surface weather charts? By using lines called *isobars* (literally, equal pressure). Think how difficult it would be to analyze a surface chart if local pressures would be used instead of sea-level pressures. We would end up analyzing altitudes instead of pressures.

The standard for isobars is to plot one every four millibars, starting at 1000 mb. In other words, there are isobars for 992, 996, 1000, 1004, 1008, etc. These days the analyses are usually done by a computer, but it is helpful to know how it used to be done for all charts, and how it is still often done.

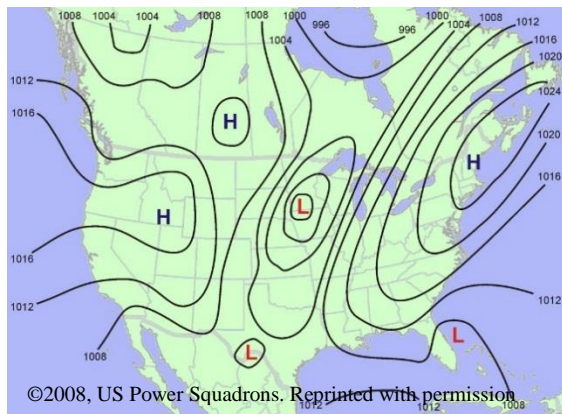


Figure 2.3. Example of a simple surface chart showing highs, lows, and isobars.

Since the plotted sea-level pressure can have any value within the normal range, to the nearest tenth, the process is to draw the lines so higher pressures are on one side and lower pressures on the other. Once the initial work is done, the lines are smoothed out (most of the atmosphere varies smoothly with distance). During that process, the analyst may choose to ignore a few of the pressure values under the assumption that there is a

very local anomaly or an error in measuring or reporting. Figure 2.3 shows an example of a surface analysis. The highest closed isobar shows the location of high pressure areas, while the lowest closed isobar shows low pressure areas. These are marked with a blue H or a red L (or both in black if color is not used). You will also see the location of fronts on a surface analysis, but these will be discussed later.

Winds

We learned above that it is the PGF that drives the wind. When there is a difference in pressure in an area, the tendency is to even out the difference. In the atmosphere, that means that air has to travel from high pressure to low pressure. If the Earth did not rotate (no Coriolis Effect), the air would move directly between them, quickly evening out the pressure. Because of the Coriolis Effect, the moving air (wind) tends to curve to the right in the northern hemisphere.

Picture wind blowing out of a high pressure area (Figure 2.4). As it starts to blow, it curves to the right and continues to do so. That results in circulation around a high that is clockwise. This pattern is called *anti-cyclonic*. The arrows represent the PGF and the Coriolis Effect, which are in balance.

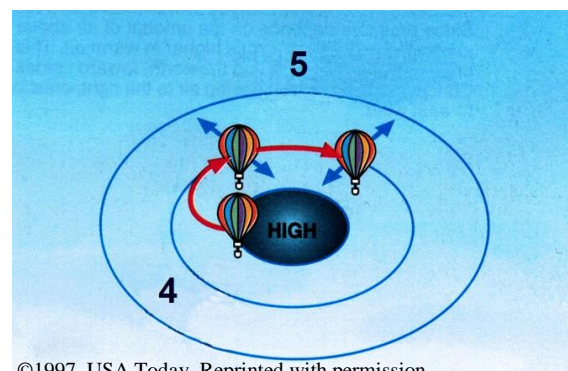


Figure 2.4. Air flowing out of a high pressure area

The case of flow around lows is not quite as obvious. As the wind blows toward the

low, it again curves to the right, however the pressure gradient force continues to pull toward the center of the low. A balance is set up between the PGF and Coriolis that causes the flow around lows to be counter-clockwise, called *cyclonic* (Figure 2.5).

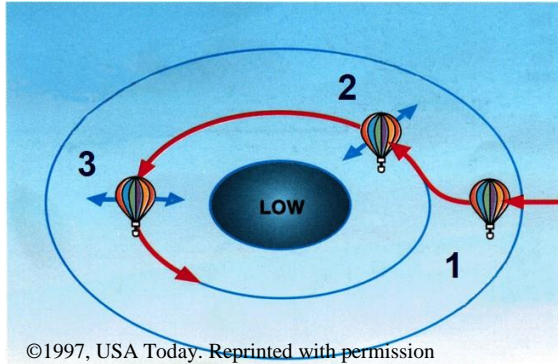


Figure 2.5. Air flowing into a low pressure area.

In the southern hemisphere, cyclonic flow is clockwise and anti-cyclonic is counter-clockwise. It is easier to talk about cyclonic and anti-cyclonic in either hemisphere without confusion. From here on, we will adopt that convention and no longer talk about clockwise and counter-clockwise flow.

The balance between PGF and Coriolis happens in both highs and lows. There is one more force that we need to introduce to provide the entire picture—that is *friction*. Friction changes the balance between PGF and Coriolis and results in the winds slowly spiraling into Lows and out of Highs. Figure 2.6 illustrates this effect. The angles given are representative averages. See Appendix A for a more complete explanation.

Friction is highest near the surface, over rough terrain, forests, etc. It is less over relatively smooth surfaces, such as calm water, bare ground, etc. It also decreases with altitude so that winds at a higher altitude more closely follow the isobars. This change in wind direction with altitude near the surface is called the *Ekman Spiral*.

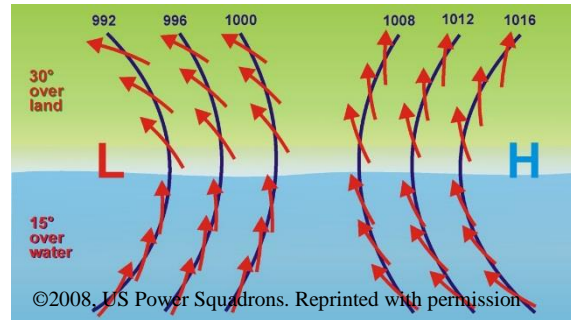


Figure 2.6. Effect of friction on surface winds.

There are a few more basic concepts about winds that one should know. The first is the convention for wind direction. As Auxiliarists, we are familiar with the concept of current direction, defined as the direction in which it flows. An easterly current flows **toward** 090. Winds are different. The direction of winds is the direction **from** which they blow. Thus, an east wind is **from** 090.

The second concept is how to describe **changes** in wind direction over time. This change is called *veering*, or *backing*. Figures 2.7 and 2.8 show the concept. If, for example, a wind changes over time from 090 to 060, it is said to be backing. If it changes from 090 to 120, it is veering. As we will see in Chapter 4, knowing the change in wind direction with time can help us locate the low pressure systems and how they are moving.

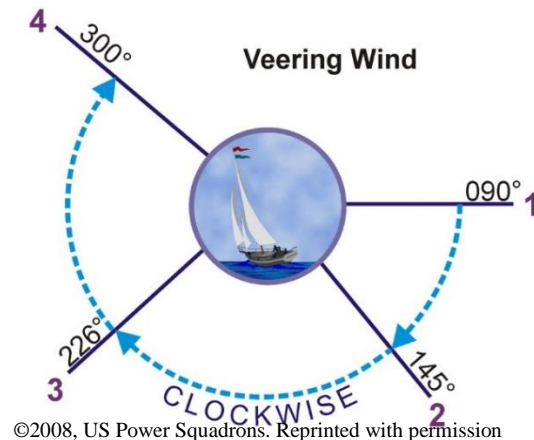
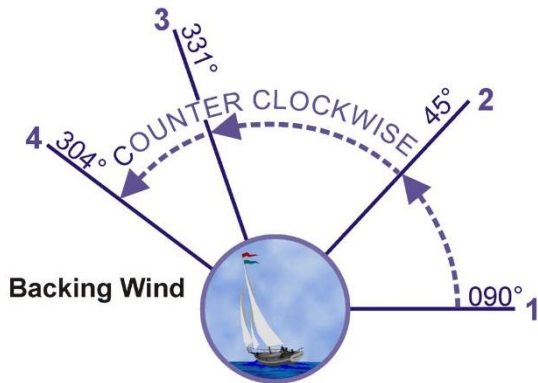
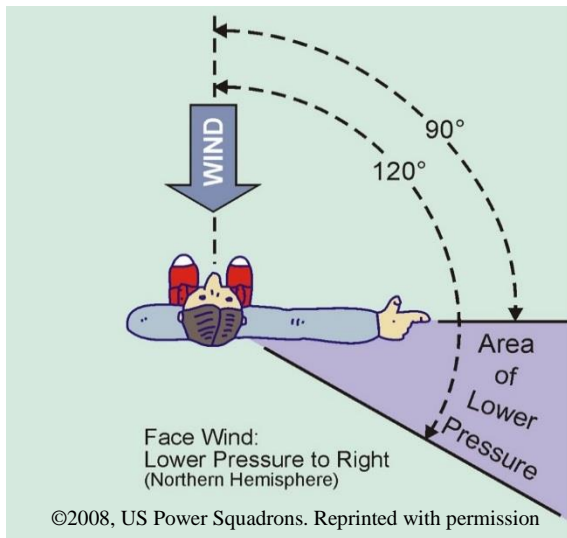


Figure 2.7. Example of a veering wind.



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 Figure 2.8. Example of a backing wind.

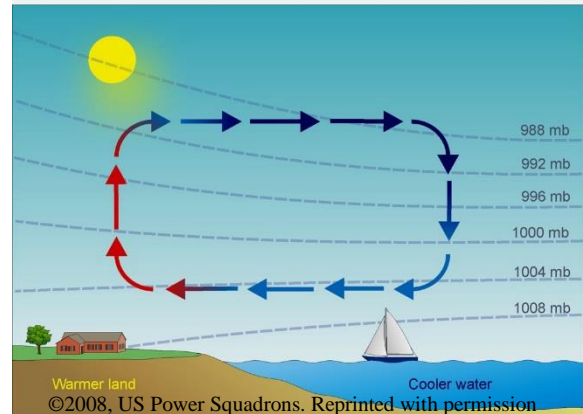
The third concept is how to tell where the Lows are. The technique for doing this is called the *Buys-Ballot Law* (Buys is pronounced “Bice”). Figure 2.9 explains it. If you stand facing the wind and raise your right arm to your side, the Low is located between that direction and 30° further back.



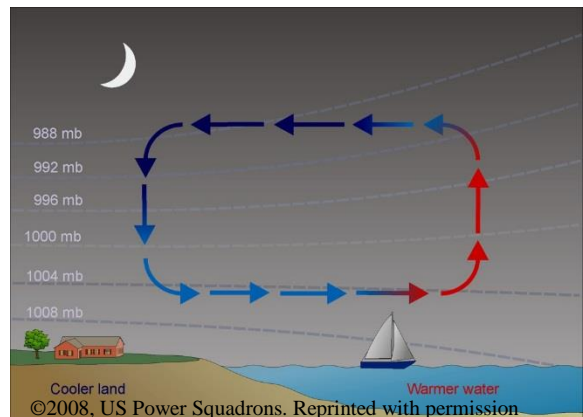
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 Figure 2.9 The Buys-Ballot law determines where the low pressure is located.

Finally, we should be aware that wind direction and speed can be greatly influenced by local phenomena. Trees or buildings can cause local changes. Valleys can channel the winds. Local heat islands (e.g. a plowed field or parking lot) can modify local winds. Of particular concern to Auxiliaries are the *sea breeze* and *land breeze*. Sea and land breezes

are caused by the fact that land heats and cools faster than water (Chapter 1). During the day, the land heats up faster and at some point the air above the land rises, drawing the colder air onto land. The result is a vertical circulation as shown in Figure 2.10. The opposite is true at night, with the land cooling faster than the water. The result is a reverse circulation, as shown in Figure 2.11.



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 Figure 2.10. Sea breeze is a result of the land warming faster than the water.



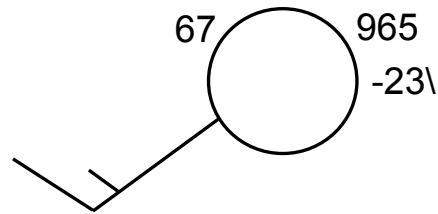
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 Figure 2.11. Land breeze is a result of the land cooling faster than the water.

The standard instrument for measuring the wind speed and direction is the *anemometer*. It normally consists of a vane that shows direction and either a propeller or a horizontally-rotating system of cups to measure speed (*Figure 2.12*).



Figure 2.12. A typical anemometer, with a propeller for measuring wind speed.

Now, let's add winds to the station model. The convention is that a line points to the wind direction (i.e. the direction from which it is blowing). At the end of this line are various kinds of barbs. A solid triangle represents 50 knots. A long line is 10 knots and a short line is five knots. The wind can, therefore, only be plotted to the nearest five knots. In the example below, the winds are from the southwest at 15 knots.



Section 2. Upper-Level Pressure and Winds

Upper-Level Charts

In the last section, we talked about surface charts. In this section, we address upper-level charts. Upper-level charts are routinely produced every 12 hours for the following pressure levels: 1000 mb, 850 mb, 700 mb, 500 mb, 300 mb, and 200 mb. Why pressure levels instead of altitudes? The reason is historic—the way that upper air data has been collected for decades. Balloons with instrument packages, called *radiosondes* and containing aneroid barometers, are launched every 12 hours. The pressure is measured directly by the aneroid barometer. The altitude is calculated by the known lift of the balloon and passage of time, as well as its direction and altitude as tracked by the receiver.

Of all the pressure levels listed above, the most useful in forecasting the development of storm systems is the 500 mb level. It is the “middle” of the atmosphere, where half of the atmosphere is below and half is above. The altitude varies with conditions, but a good round number to remember is 5,500

meters or 18,000 feet above sea level. Figure 2.14, on page 21, is an example of a 500 mb chart. The red figures are temperature, the green ones dew point (See Chapter 3), the blue barbs are winds, the red dashed lines are isotherms (lines of constant temperature), and the black lines are *isoheights* (see next paragraph).

You need to know a few things about this chart. First, instead of isobars as we saw in the surface chart, the lines are called *isoheights*. Why? Because the chart is all at the same pressure, the number plotted is the height of that pressure level. Think of it this way—if you follow a given pressure level, you will go higher and lower in altitude above sea level. The higher altitudes represent upper level “highs” and the lower altitudes represent “lows.”

These “highs” and “lows” are called *ridges* and *troughs* (or *trofs*). Troughs are where the isoheights are convex to the south, and the ridges are where the isoheights are convex to the north (northern hemisphere).

The smooth nature of the isoheights and the fact that the winds tend to be westerly is due to the temperature gradient from the equator to the pole. As the air is colder to the north, pressure decreases faster with height and the height of the pressure level decreases as you move north. This means that the PGF is directed more or less to the north and Coriolis turns the winds to the right until the PGF and the Coriolis Effect balance, resulting in the prevailing westerlies.

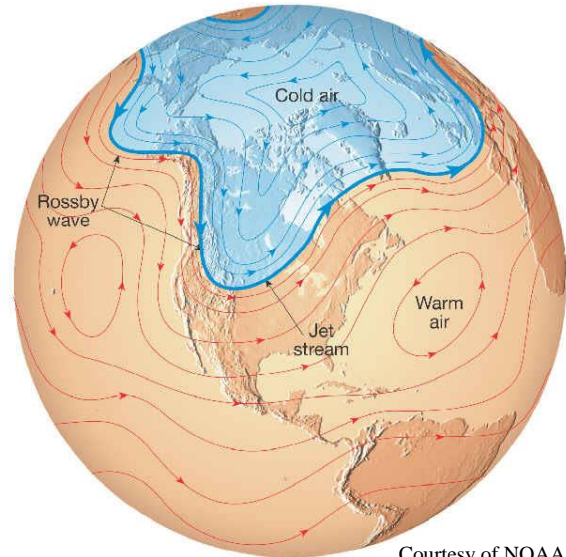
For the same reason, the PGF increases with altitude, so the wind speed increases with altitude. Because friction is much lower in the upper atmosphere, the winds tend to blow along the isoheights, unlike the situation at the surface. Troughs and ridges are shown in Figure 2.13.

If one looks at the upper atmosphere over the entire northern hemisphere, one sees a number of waves. The minimum is three, which is very rarely seen. The normal is four or five. Figure 2.13 shows five waves. Note the ridges, troughs, amplitude, and wavelength. These waves propagate from west to east and are called *Rossby waves*.

The other thing you will normally see on upper-level charts are *isotherms*, lines of constant temperature. These are important on upper-level charts because the way the temperature changes with time is important to what will happen at the surface. This change is called *temperature advection*. As the air moves, it carries its temperature with it and a change in temperature at altitude affects the density (mass of molecules per unit volume) and therefore the pressure at the surface (See Appendix A).

On the chart shown in Figure 2.14 (next page), there is little temperature advection

(the isoheights and isotherms are nearly parallel). If the temperature advection is positive (winds pushing in higher temperatures), a surface low pressure system ahead of the trough will deepen (become more intense). The opposite is true for negative temperature advection. Temperature on upper-level charts is in Celsius.



Courtesy of NOAA

Figure 2.13. Example of Rossby waves, the polar jet stream, and the polar front (located beneath the jet).

Another clue to look for on the 500 mb chart is areas of convergence and divergence (Figure 2.15), where the isoheights, and therefore the winds, come together or spread apart, respectively. Convergence aloft is a sign that there will be a surface high forming or deepening, while divergence signals the formation or deepening of a surface low.

The *polar jet stream*, a high-altitude wind current, shows up best on the 300 mb chart. It is associated with the polar front (Chapter 4). While the temperature advection at 500 mb deepens or fills in a surface low, the jet stream tends to “steer” the low pressure systems (see Chapter 4 for more detail). This is why TV forecasters usually show the jet stream in their broadcasts.

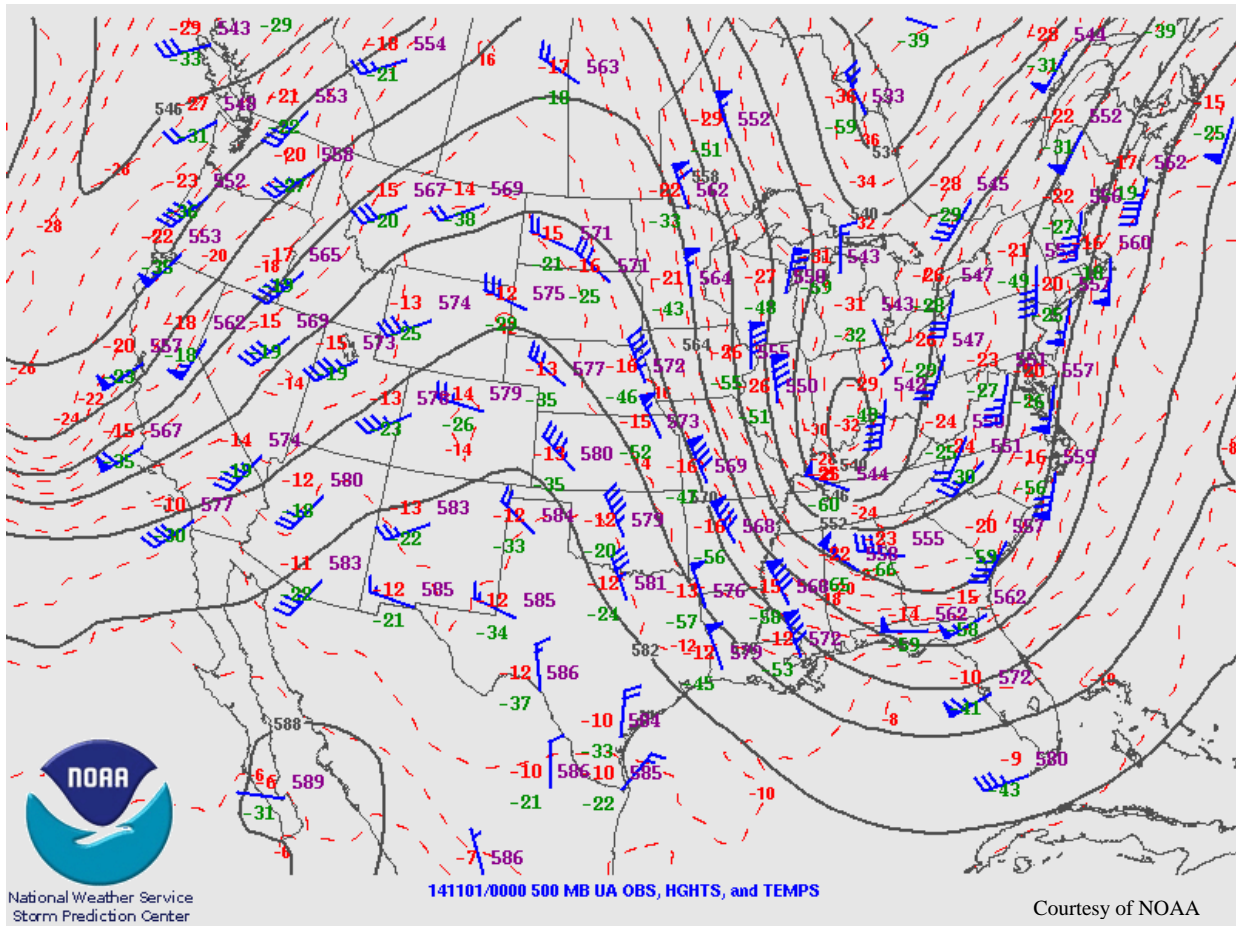
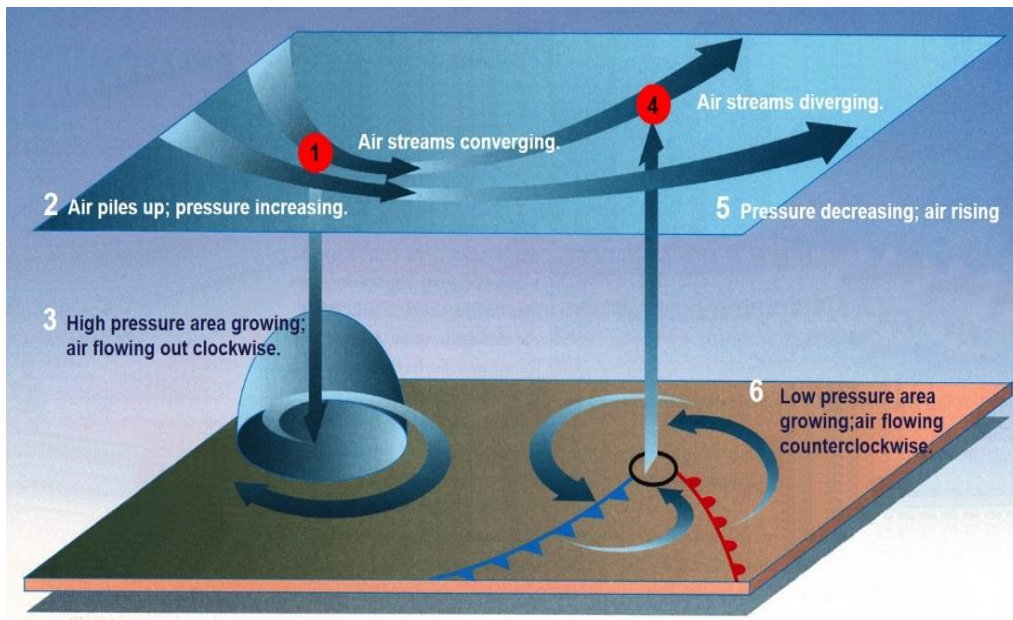


Figure 2.14 Example of a 500 mb chart.



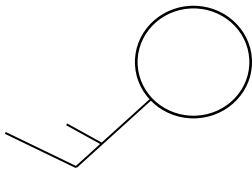
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Figure 2.15 Upper level convergence and divergence affect surface highs and lows.

Study Questions—Chapter 2

- A north wind is one:
 - Blowing toward the north.
 - Shifting toward the north.
 - Coming from the north.
 - Blowing toward the North Pole.
- Wind speeds are given in:
 - Miles per hour.
 - Kilometers per hour.
 - Feet per second.
 - Knots.
- Standard sea-level pressure is:
 - 1013.26 in Hg.
 - 29.92 psi.
 - 760 kPa.
 - 14.7 psi.
- If the barometric pressure is measured in Albuquerque, NM, the most important correction to make before reporting it is:
 - Temperature.
 - Local force of gravity.
 - Calibration.
 - Altitude.
- Station barometric pressures are “reduced to sea level”:
 - To correct instrument error.
 - To correct for the temperature.
 - So data taken at different altitudes can be compared.
 - To compensate for the lower gravity.
- Aneroid barometers are more useful on boats because they:
 - Contain less mercury.
 - Don’t need calibration.
 - Are more accurate.
 - Can be mounted in any position.
- Pressure gradient is defined as:
 - Pressure difference due to wind.
 - Pressure difference due to changing temperature.
 - Pressure change per unit distance.
 - Pressure change over 3 hours.
- The primary force generating wind is:
 - Coriolis force.
 - Pressure gradient force.
 - Temperature gradient.
 - Surface heating.
- The effect of friction on the wind is:
 - To slow the wind.
 - To increase the Coriolis effect.
 - Independent of altitude.
 - To cause the wind to follow contours.
- Cyclonic wind flow is:
 - Clockwise in the northern hemisphere.
 - Counter-clockwise in the southern hemisphere.
 - Clockwise in the southern hemisphere.
 - Counter-clockwise in both hemispheres.
- The jet stream is:
 - A warm ocean current.
 - An equatorial wind current.
 - A high altitude wind current.
 - A low altitude wind current.
- If an observer is facing the wind in the northern hemisphere, the low pressure center is approximately:
 - Ahead of him.
 - To her right.
 - To her left.
 - Behind him.

13. The Buys-Ballot law tells us:
- The wind direction in the northern hemisphere.
 - The direction the wind is shifting.
 - The location of the low pressure.
 - The way the pressure is changing.
14. A wind gradually changing in a clockwise fashion is:
- Backing.
 - Veering.
 - Increasing in speed.
 - Due to the sea breeze effect.
15. On the station model, a plotted pressure of 853 is:
- 1085.3 mb.
 - 985.3 mb.
 - 853 mb.
 - 85.3 mb.
16. A plotted pressure tendency of -26 is:
- A rise of 2.6 mb over 3 hours.
 - A fall of 2.6 mb over 1 hour.
 - A fall of 26 mb over 24 hours.
 - A fall of 2.6 mb over 3 hours.
17. Isobars are lines of constant:
- Temperature.
 - Wind direction.
 - Pressure.
 - Wind speed.
18. The station model below shows:
- A NE wind of 15 knots.
 - A SW wind of 1.5 knots.
 - A NE wind of 1.5 knots.
 - A SW wind of 15 knots.



19. Rossby waves are:
- Waves on a lake.
 - Pressure waves at the surface.
 - Large upper-level waves that propagate around the globe.
 - The meandering of the ITCZ.
20. The solid lines on a 500 mb chart are:
- Isotherms.
 - Isoheights.
 - Isobars.
 - Isopressures.
21. The pattern at 500 mb that causes surface low pressure areas to strengthen is:
- Negative temperature advection.
 - Positive temperature convection.
 - Backing winds.
 - Diverging isoheights.
22. The jet stream shows up best on the:
- 500 mb chart.
 - The surface chart.
 - The 300 mb chart.
 - The 100 mb chart.
23. Lines of constant temperature are:
- Found on upper-level charts.
 - Plotted as dashed lines.
 - Isotherms.
 - All of the above.
24. On the 500 mb chart, ridges are:
- Convex to the north.
 - Concave to the north.
 - Areas of lower pressure.
 - Convex to the south.
25. Surface pressure is caused by:
- The weight of the air in the troposphere.
 - The weight of the air above.
 - The winds striking buildings.
 - The weight of the air in the stratosphere.

26. Isobars on a standard surface chart are drawn every:
- a) 5 mb.
 - b) 4 mb.
 - c) 3 mb.
 - d) 10 mb.
27. Higher pressure gradients cause:
- a) Rising temperatures.
 - b) Falling temperatures.
 - c) Stronger winds.
 - d) Lighter winds.
28. The polar jet stream:
- a) Originates over the North Pole.
 - b) Is confined to the polar high.
 - c) Plays a role in steering weather systems.
 - d) Flows from east to west.
29. The standard instrument for measuring wind direction and speed is the:
- a) Aneroid barometer.
 - b) Psychrometer.
 - c) Anemometer.
 - d) Thermocouple thermometer.
30. Half of the total mass in the atmosphere is in the lowest:
- a) 8,000 ft.
 - b) 12,000 ft.
 - c) 18,000 ft.
 - d) 25,000 ft.

Chapter 3 Moisture, Latent Heat, Fog and Stability

Composition of the Atmosphere

By volume, 99% of the dry atmosphere is made up of two gases—nitrogen at 78% and oxygen at 21%. The other 1% is mostly argon, with small amounts of carbon dioxide, neon, helium, and methane. These gases, including all but methane, are well mixed and their relative concentration is constant below about 80 kilometers.

Added to this dry mixture is a variable amount of water vapor—up to 4% by weight in warm tropical air. This variability is one of the more important drivers of weather. Water vapor is the source of clouds and precipitation, one of the primary absorbers of heat radiated from the surface, a transporter of energy from one area to another, and the source of energy for powering storms.

Structure of the Atmosphere

Figure 3.1 shows the vertical structure of the atmosphere. The major zones are: The *troposphere*, where most weather occurs; the *stratosphere*, where the temperature increases from the *tropopause* to a maximum at the *stratopause*, then decreases through the *mesosphere*. Notice that the temperature increases in the stratosphere and decreases again in the mesosphere. The reason is the presence of ozone, which absorbs ultraviolet radiation from the sun, heating this part of the atmosphere. The temperature again increases in the *thermosphere*, this time due to the presence of the *ionosphere*, where even shorter wavelengths from the sun ionize the gases, forming electrons and ions. At higher altitudes than shown, the temperature in the thermosphere does not continue to rise indefinitely, but gradually merges with space.

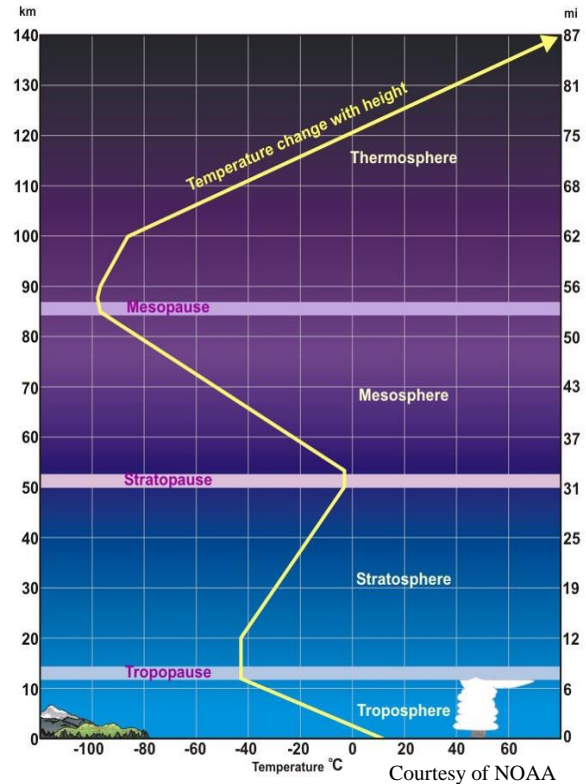


Figure 3.1. Average vertical structure of the atmosphere at mid-latitudes.

On average, the temperature decreases with height in the troposphere, but there is a great deal of variation with latitude, season, and the type of surface, among other things. The rate of change of temperature with height is called the *lapse rate*, and can be expressed in many ways, all as some form of degrees per unit height. In this course, we will adopt degrees Fahrenheit per 1,000 feet (Figure 3.2).

We are concerned with two types of lapse rates. One is the *environmental lapse rate*—the actual change with altitude in the air at any given time and place. Although it varies with location, altitude, and time in the actual atmosphere, the average for mid-latitudes is -3.5°F per 1,000 ft. The other type

is called the *adiabatic lapse rate*. It is a measure of how fast the air cools as it is forced up. It varies slightly with temperature and pressure, but is generally taken as $-5.5\text{ }^{\circ}\text{F}$ per 1,000 feet in unsaturated air. It is more properly called the *dry adiabatic lapse rate*. In saturated air, the *wet adiabatic lapse rate* is $-3.2\text{ }^{\circ}\text{F}$ per 1,000 ft. The reason for the difference is in a later section.

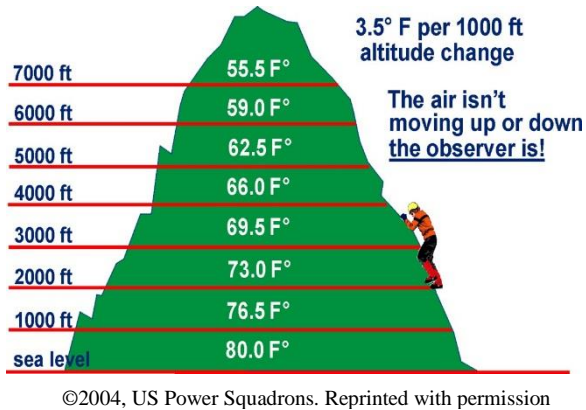


Figure 3.2. Illustration of the average environmental lapse rate in mid-latitude.

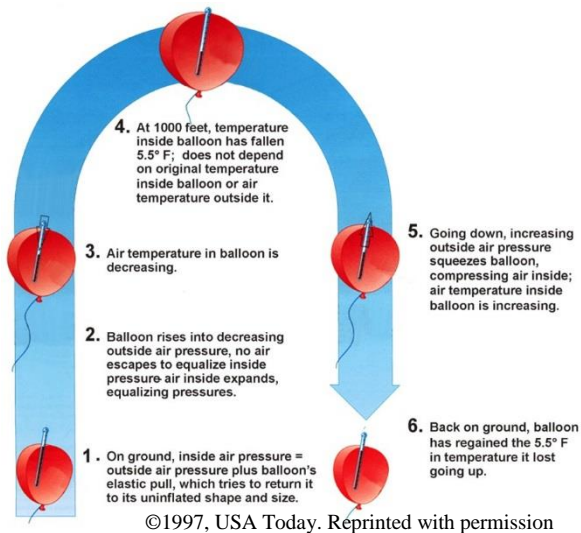


Figure 3.3. Demonstration of adiabatic processes.

These rates are called adiabatic because no heat is added or subtracted from the surrounding air. The temperature change is due to the expansion or compression of the air as it is moved up or down (Figure 3.3). An example of an adiabatic process is pumping up

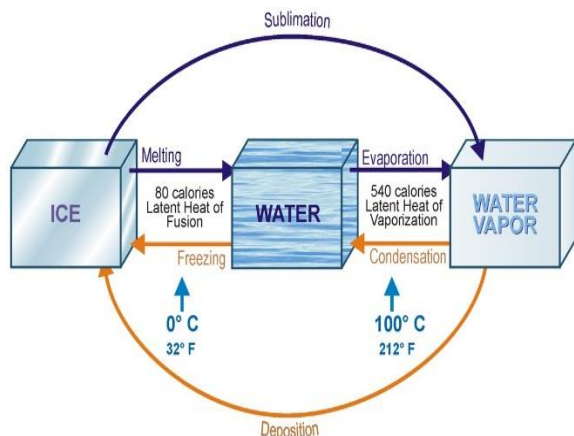
a tire with a hand pump. As the air is compressed, the pump heats up. If air is released from the tire, it is cooled because of expansion. See Appendix A for more information.

One more topic on vertical structure is important—*inversions*. An inversion occurs when the environmental lapse rate becomes positive over some height range. A positive lapse rate means the air temperature increases with altitude. Inversions can occur anywhere in the atmosphere. Surface inversions are common at night or over snow. Upper air inversions (inversions aloft) commonly occur at frontal boundaries. The ultimate inversion aloft is at the tropopause. Surface inversions can trap fog and haze. Inversions aloft can stop convective activity. You have probably seen smoke rising from a chimney. It stops at some height and spreads out horizontally. It has reached an inversion.

The Properties of Water

Earlier in this chapter, we listed some of the reasons why water is so important to the weather. To understand why, we need to discuss some of the unique properties of water. The first is that water is one of the few materials that expands as it solidifies. If ice didn't float, rivers, lakes, and oceans would freeze from the bottom up.

All substances go through three phases as the temperature changes—solid, liquid, and gas. Water is no different in this respect, but is unusual in the amount of energy it takes to melt ice and vaporize water. Figure 3.4 illustrates phase changes, names the various processes of changing from one phase to another, and shows the amount of energy needed to melt ice (80 calories per gram) and vaporize water (540 calories per gram). This energy is called *latent heat of fusion* and *latent heat of vaporization*. It is the release of this latent heat that drives storms of all kinds.



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Figure 3.4. Phase changes of water.

To understand just how much heat energy is involved, consider providing that much energy to a 150 lb person. The energy in 150 lb of water vapor will feed that person for over two weeks!³ There is truly a lot of energy locked up in water vapor.

Earlier, we introduced the dry and wet adiabatic lapse rates and said we would learn why there is such a large difference. The answer is in the latent heat of vaporization. As saturated air is lifted, some of the water vapor turns to liquid cloud droplets, releasing heat into the surrounding air. This heat release partially counteracts the adiabatic cooling due to lifting.

In Chapter 1, we listed types of energy transport (conduction, convection, and radiation) and introduced a related type, the transport of latent heat. We can see now that as water vapor is advected from one area to another, it carries its latent heat with it. Water can be vaporized in one area and condensed in another, effectively transporting that energy.

³ Remember, in meteorology we use gram calories, while for food energy, we use Kg Calories (Kcal).

Measuring Water Vapor

How do we know how much water vapor is in the air? There are three closely related measures—relative humidity, absolute humidity, and dew point temperature. Water vapor is measured with a *hygrometer*.

Absolute humidity is defined as the mass of water vapor in a given mass of dry air. The usual units are grams of water per kilogram of dry air (g/Kg). Air can only hold so much water vapor before it becomes *saturated*, and the maximum amount it can hold depends on the temperature—the higher the temperature, the more it can hold. Figure 3.5 shows a plot of the saturation absolute humidity over a normal range of temperatures.

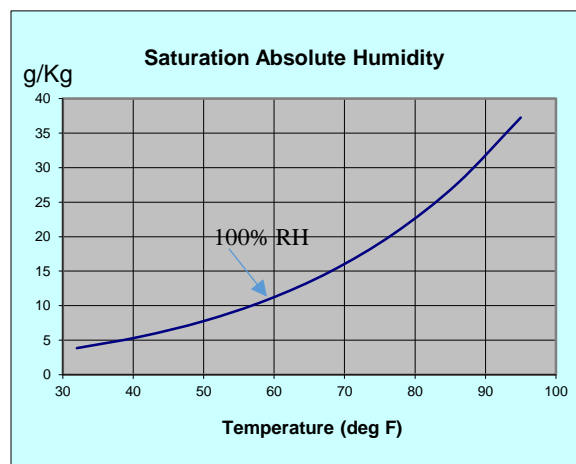


Figure 3.5. Saturation (100% RH) absolute humidity as a function of temperature.

Relative humidity (RH) is reported as a percent and compares the mass of vapor actually in the air to the mass it is capable of holding at that temperature. Saturated air therefore has a relative humidity of 100%. Very hot, dry air, such as over a desert, can have a relative humidity of just a few percent,

150 pounds is about 68,000 grams. At about ½ Kcal per gram, that is 34,000 Kilogram (food) calories.

since hot air is capable of holding a lot of water vapor compared to what is actually there

Dew point temperature is the temperature to which a sample of air would have to be cooled to become saturated (relative humidity of 100%). If it makes more sense, you can think of it as the temperature a sample of air would have if it were saturated. The dew point temperature can only be less than, or equal to, the air temperature.⁴ Figure 3.6 shows the relationship among these three measures of water vapor. See Appendix B for a graphical method of relating these variables.



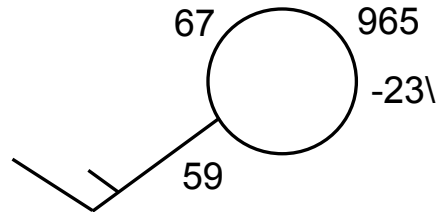
Figure 3.6 Relationship among temperature and measures of moisture content.

A related, but less common, measure of moisture content is the *dew point depression*, the temperature minus the dew point temperature. The smaller it is, the higher the relative humidity (but the relationship is not linear).

Moist air is lighter than dry air, which adds to its tendency to rise, just like higher temperatures do. Why is it lighter? Take a fixed number of molecules of dry air. As air is mostly nitrogen and oxygen, we can calculate an “average” (fictitious) “molecular weight” as 21% of 32 (O₂) and 78% of 28 (N₂), resulting in 28.7. The molecular weight

of water is 16+2 (H₂O), or 18. Therefore, for every “average” air molecule we replace with a water molecule, the molecular weight of the sample decreases by 10.7 grams for every 18 grams of water added.

In the station model, moisture is entered as the dew point, shown here as 59 °F.



Types of Fog and Their Formation

While types of weather are to be covered in Part II (Chapters 4-6), it seems appropriate to cover fog here since understanding the reasons for fog is closely related to this discussion of moisture and humidity.

Fog forms in a variety of ways, as will be discussed below, but they are all the result of one of two processes. First, the air temperature can be cooled until the dew point is reached, at which time condensation occurs and fog droplets form. Second, water vapor can be added to the air until the dew point increases to the air temperature, again causing condensation. In many cases, both may be going on simultaneously, but each fog type is dominated by one or the other process.

The six most common types will be discussed here. It is also important to know that fog will very rarely form in very pure air. The water vapor needs *condensation nuclei* around which to form. These can be dust, salt, or other aerosols.

⁴ Although pure air can become super-saturated, that only happens in very unusual circumstances.

Radiation fog occurs when the ground cools (normally at night), cooling the air above it by conduction. If the moisture content is high enough, and the air cools enough, fog will form. It will only form in very light winds, where vertical mixing doesn't occur. With the exception of a special case called valley fog, radiation fog usually dissipates quickly when heated by the sun.

Advection fog is the result of warm, moist air moving (advecting) over a cooler surface. It can form over land or water and requires moderate winds (it won't advect otherwise). The air must also be stable so convection does not occur. Advection fog can last for many hours or several days and lifts only when the conditions are changed by time or the movement of weather systems. The sun can start dissipating it from the ground up, but it often thickens again when the heating stops due to night or cloud cover.

Precipitation fog is a case where moisture is added to the air. It normally happens during rainstorms. The water in the rain drops and the newly-fallen water evaporate, raising the dew point (and lowering the temperature) until the air is saturated. It dissipates quickly once the rain stops.

Steam Fog or Sea Smoke is caused by cold air advecting over much warmer water. The water evaporates, raising the dew point to the air temperature and resulting in thin, wispy fog, often only a foot or two above the water..

Upslope Fog is where moist air is pushed up a hill or mountain, cooling the air adiabatically until it reaches the dew point.

Valley Fog is a persistent form of radiation fog, where drainage of cold air into the valley enhances the cooling due to radiation.

Valley fog can sometimes last for days, raising during the day and re-forming during the night.

Dew and *frost* form on cold surfaces. Dew forms above 0°C and frost below that.

Atmospheric Stability

We now have all the pieces we need to discuss the vertical stability of the atmosphere, its tendency to rise or fall of its own accord. The key variables are the environmental lapse rate (which can vary with altitude), the adiabatic lapse rates, and the amount of moisture present. There are three classes of stability—absolute stability, conditional stability, and absolute instability.

Absolute stability occurs when air displaced vertically becomes cooler than the surroundings and naturally returns to its former altitude. As air is pushed up, the temperature becomes less than the surrounding air, exerting a downward force. This occurs when the environmental lapse rate is less negative than the adiabatic lapse rate. (Figure 3.7)

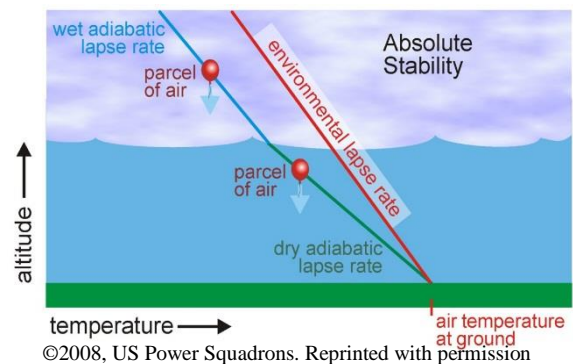


Figure 3.7 Absolute stability.

Absolute instability occurs when air rises of its own accord because, as the air initially rises, it becomes warmer than the surrounding air and so continues to rise. This is when the environmental lapse rate is more negative than the adiabatic lapse rate. (Figure 3.8)

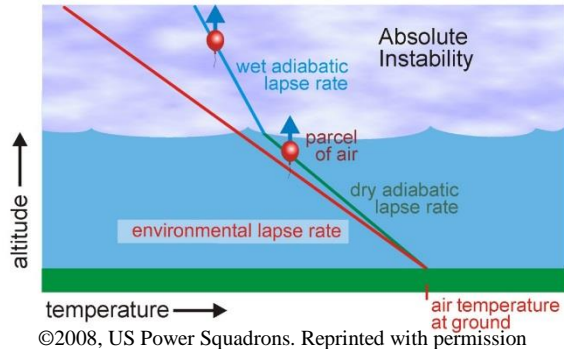


Figure 3.8 Absolute instability.

Conditional stability can occur in several ways. In all cases, if the air is pushed up a little, it returns to its former height. If, however, it is pushed up far enough, it becomes unstable. As an example (Figure 3.9), the environmental lapse rate is between the dry and wet adiabatic lapse rates. As the air is initially pushed up, it stays colder than the surroundings. If pushed up to where it becomes saturated (*lifting condensation level*), it cools at the wet adiabatic rate and eventually becomes warmer than the surroundings, so rises freely. The altitude where this happens is the *level of free convection*.

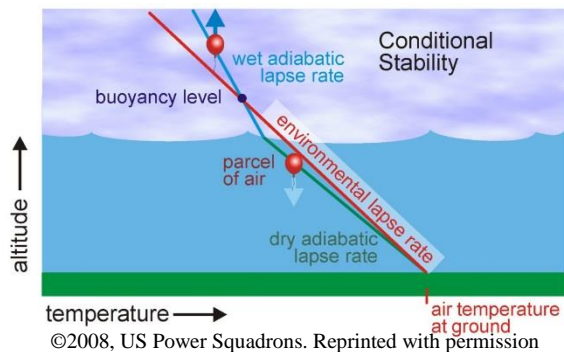


Figure 3.9 Conditional Stability.

An example of how stability can change with time is shown in Figures 3.10 and 3.11. There is a morning surface inversion due to cooling of the ground at night. Air at the surface is stable due to the inversion. As the day progresses and the sun heats the surface and its adjacent air by conduction and convection, the environmental lapse rate becomes more negative than the adiabatic lapse rate and the

air becomes unstable. This is a typical summertime afternoon convective situation.

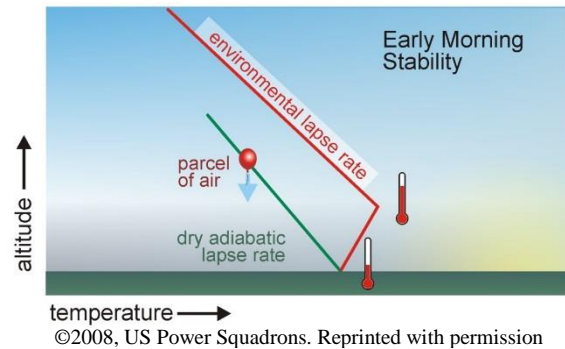


Figure 3.10 Due to a morning inversion, air is stable.

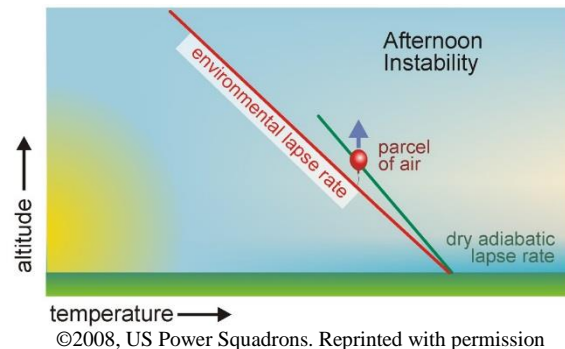


Figure 3.11 The air near the ground heats up, making the air unstable.

Above, we mentioned air being “pushed up,” but didn’t say how that happens. There are four common ways. First is *orographic* lifting, such as wind blowing up the side of a mountain. The second is *frontal wedging*, where warm air is pushed up over colder air in a cold front or over the cooler air in a warm front. The third is *surface convergence*, where winds from different directions come together and the only direction they can go is up. The fourth is surface heating.

We can wrap most of the concepts in this chapter together to explain a wind phenomenon that happens in many places. In the American west, they are called Chinook; and in Switzerland, they are called Föhn.

Moist winds push air up the side of a mountain by orographic lifting. The air cools at the dry adiabatic rate. At some level, the air

reaches saturation and clouds form, and there is often either rain or snow on the up-wind side of the mountain. It then cools at the wet adiabatic rate. The condensation adds heat to the air so it is warmer than it would be if no condensation occurred. The air then spills

over the top of the mountain and, as it travels down the lee side, heats up at the dry adiabatic lapse rate. The result is that the air on the lee side is warmer than it was on the windward side at the same altitude.

Study Questions—Chapter 3

- In the lower atmosphere, the temperature generally:
 - Increases with altitude.
 - Stays the same.
 - Decreases with altitude.
 - Varies randomly.
- The tropopause is important in weather development since it:
 - Contains most of the moisture.
 - Disappears during turbulent weather.
 - Caps the development of convective activity.
 - Is below most weather.
- One difference between the troposphere and the stratosphere is:
 - Carbon dioxide content.
 - Argon content.
 - Temperature distribution.
 - Thickness.
- The most abundant gases in the atmosphere are:
 - Nitrogen and Hydrogen.
 - Oxygen and Nitrogen.
 - Nitrogen and Argon.
 - Carbon Dioxide and Methane.
- The average environmental lapse rate in the lower atmosphere is:
 - 3.2° C per 1,000 ft.
 - +3.5°F. per 1,000 ft.
 - 2.2°C. per 1,000 ft.
 - 5.5°F. per 1,000 ft.
- A temperature increase with altitude in the lower atmosphere is called:
 - The tropopause.
 - An inversion.
 - A thermal.
 - Convection.
- A dry, warm wind descending the east side of the Rocky Mountains is a:
 - Chinook.
 - Valley breeze.
 - Land breeze.
 - Wind shear.
- Water vapor is added to the air by:
 - Condensation.
 - Evaporation.
 - Vapor pressure.
 - Deposition.
- When water vapor condenses, heat is:
 - Added.
 - Released.
 - Not changed.
 - Absorbed.
- The transition from ice to vapor without going through the liquid phase is called:
 - Effervescence.
 - Sublimation.
 - Evaporation.
 - Deposition.
- Latent heat:
 - Can be measured with a thermometer.
 - Is released when water freezes.
 - Is released when water evaporates.
 - Can be felt.
- Saturation can be accomplished by:
 - Raising absolute humidity while holding the temperature constant.
 - Lowering the temperature while the absolute humidity remains constant.
 - Either a or b.
 - None of the above.

13. The temperature at which water vapor begins to condense is called the:
- Condensation level.
 - Saturation temperature.
 - Dew point.
 - Melting point.
14. If the water vapor content of an air parcel increases at constant temperature, the relative humidity ____ and the dew point ____.
- Decreases, Increases.
 - Increases, Decreases.
 - Increases, Increases.
 - Decreases, Decreases.
15. When air is saturated with water vapor:
- The dew point depression is zero.
 - The relative humidity is 100%.
 - The air can hold no more vapor.
 - All of the above.
16. Regarding the latent heat of fusion and the latent heat of vaporization of water:
- They are the same.
 - Latent heat of fusion is higher.
 - Latent heat of vaporization is higher.
 - They are determined by the specific heat of water.
17. The term adiabatic means:
- No heat is added or subtracted.
 - The pressure is constant.
 - The temperature is constant.
 - The absolute humidity is constant.
18. The dry adiabatic lapse rate, compared to the wet adiabatic lapse rate is:
- Smaller.
 - More negative.
 - Less negative.
 - Positive.
19. The physical property or properties of water important to the weather is/are:
- It can transport energy from one location to another.
 - It takes a lot of energy to vaporize it.
 - It absorbs a lot of infrared energy.
 - All of the above.
20. The term describing the tendency of displaced air to return to its former level is:
- Absolute instability.
 - Elasticity.
 - Absolute stability.
 - Conditional stability.
21. The term describing the tendency of air to rise on its own is:
- Absolute instability.
 - Elasticity.
 - Absolute stability.
 - Conditional stability.
22. The term describing the tendency of air to rise only after it has been initially raised to some higher altitude is:
- Absolute instability.
 - Elasticity.
 - Absolute stability.
 - Conditional stability.
23. Fog that forms by adding moisture is:
- Radiation fog.
 - Advection fog.
 - Precipitation fog.
 - None of the above.
24. Fog that forms under clear skies at night is:
- Radiation fog.
 - Advection fog.
 - Precipitation fog.
 - All of the above.

Part II—Sensible Weather



Example of a Super Cell

Courtesy of NOAA

Chapter 4 Air Masses, Fronts, and Cyclones

Chapter 5 Clouds, Precipitation, and Optical Phenomena

Chapter 6 Severe Weather

Chapter 4 Air Masses, Fronts, and Cyclones

Section 1. Air masses

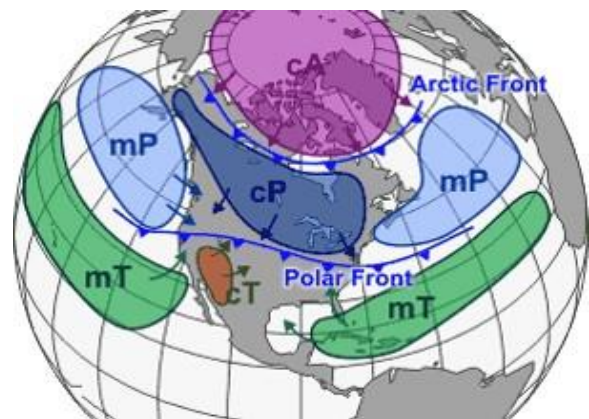
What is an Air Mass?

An air mass is a pool of air with nearly uniform characteristics (pressure, temperature, density, and moisture content). The properties do change with altitude, but they vary only by small amounts over a wide geographical area. For example, the temperature and humidity of the air mass will be almost the same at surface locations or at locations aloft at the same altitude.

An air mass is created when a pool of air sits over the same region for several days or more. During that time the air mass takes on properties derived from the underlying surface. Moisture content and temperature are the two main properties used to classify an air mass. These properties depend generally on whether the underlying surface is continental (c) or maritime (m), and whether it is located closer to polar (P) or tropical (T) latitudes. The table below summarizes the classification scheme. For example, an air mass forming over Canada is classified as continental polar (cP), meaning relatively dry and cold. The fifth type, not listed in the table below is dry and very cold, called continental arctic (cA). It sometimes brings very cold weather to the northern United States.

Classification	Polar (cold)	Tropical (warm)
Continental (dry)	cP	cT
Maritime (moist)	mP	mT

Air masses generally form when highs are present over specific geographical areas called source regions. The light winds generally found in highs allow the air to remain over a source region long enough to acquire its properties from the underlying surface. A low moving across a source region will then carry the air mass along. Winds at about 18,000 feet (500 mb) tend to steer the low pressure areas as they move. Figure 4.1 shows the source regions, and their classifications, for most of the air masses that affect the continental United States. The arrows indicate typical migration paths. They tend to move more rapidly in the winter.



Courtesy of NOAA
Figure 4.1 Air mass source regions.

An air mass is generally modified as it moves from its source region to other areas. Modification may occur in one or more of four ways. The air mass may become saturated, forming clouds, fog, and precipitation if it is cooled from below or if its dew point is raised by addition of moisture. Conversely, the air mass will clear if it is heated from below or if its dew point is decreased by removal of moisture. The following examples illustrate these processes.

Addition of Moisture

A cP air mass forming in Canada in the wintertime will have a low moisture content and temperatures well below freezing from the surface upward. If this air mass moves southeastward over the Great Lakes, the Great Lakes will add water to the air by means of evaporation. The air then becomes saturated as it reaches the lee shore, where fog or heavy snow develops.

Cooling from Below

An mT air mass moving up the East Coast is often cooled from below when it enters New England. The waters of Rhode Island Sound, Vineyard Sound, and Buzzards Bay are relatively warm, so the air remains clear over those areas but may pick up additional moisture by evaporation. However, the relatively cold waters of Cape Cod Bay and the cold land along the adjacent shore cool the air mass to its dew point. Thus, fog is formed along the coastline facing Cape Cod Bay.

Heating from below

If a Canadian cP air mass migrates along a more westerly route, west of the Great Lakes, it will encounter warmer land surfaces in the central United States. Heat exchange will then warm the air, moderating its surface temperature. For example, a wintertime air mass that formed with a surface temperature of -20°C in Canada may have a temperature of -5°C as it crosses the central states and $+1^{\circ}\text{C}$ by the time it starts to move over the southeastern states.

Removal of Moisture

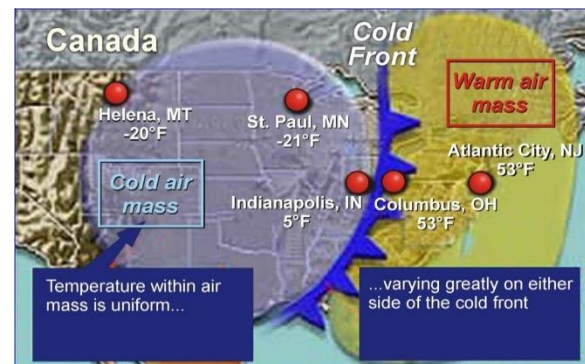
Orographic lifting is the usual process for removal of moisture from an air mass. Orographic lifting occurs when a wind moves the air across elevated topography. As the air is pushed upslope, it cools adiabatically.

Thus, the air temperature decreases to the dew point, and moisture is removed by precipitation as the air is lifted higher. The Pacific Northwest provides a well-known example.

The Pacific Northwest coastal area tends to be rainy when an mP air mass from the Bering Sea moves inland and is pushed upslope by the Cascade Mountains. Precipitation removes most of the moisture by the time the air mass has reached the peaks of the Cascades, so its dew point has decreased. The air then warms by compression as it descends on the lee side of the mountains. The result is a warm, dry wind blowing across eastern Washington and Oregon. This is the Chinook wind introduced in Chapter 3.

When Air Masses Meet

Air masses move from their source regions and meet other air masses from a different source region. The boundary that forms between these meeting air masses is called a *front*. An example is in Figure 4.2.



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Figure 4.2 Cold front between cP and mT air masses.

When they meet, the air mass that is warmer and/or moister will either ride up over the other (warm front) or be pushed up by the advancing heavier air (cold front). The details of these and other fronts are discussed in the next section.

In Section 2 of this chapter, we will discuss the types of fronts, how they move, the weather associated with them, and how to tell from local observations where a storm system, called an *extra-tropical cyclone*, is located and how it is moving.

High-Pressure Systems

The air masses discussed above are high pressure systems. The air in a high is subsiding (sinking) and the atmosphere is stable. The air spirals out of the high in an anti-cyclonic fashion (see Chapter 2). Highs tend to be more spread out than lows, with more widely-spaced isobars. The winds are weakest near the center and gradually increase with distance from the center.

Generally, the weather is clear; the sky is blue; the winds are moderate; and there is no precipitation. At night, clear skies allow the surface to cool faster and, with light winds, can produce fog, dew, or frost. The circulation tends to move warm air north on the west side of the high and colder air south on the east side (northern hemisphere).

Low-Pressure Systems

In contrast, the air in a low is spiraling into the center in a cyclonic fashion. The air

is rising and the atmosphere is unstable. The isobars are more closely spaced so the winds are stronger and increase as they approach the center. Lows are more compact than highs and mix several air masses. The boundaries between them are fronts and are discussed in the next section. The weather is stormy; the sky is cloudy; the winds are strong and shifting; and there is often precipitation.

How they Move

As we learned in Chapter 2, the winds aloft move the highs and lows and contribute to their formation and destruction. *Divergence* is air moving apart. In the upper atmosphere it can happen either by moving away from neighboring winds or by speeding up with distance. *Convergence* is the opposite, with winds approaching their neighboring streams or by slowing down with distance (piling up like a traffic jam).

Convergence causes sinking air, which builds or strengthens a high or fills a low. Divergence causes rising air, forming or strengthening a low or weakening a high. Figure 4.3 illustrates this connection between the upper air flow and the development and movement of highs and lows

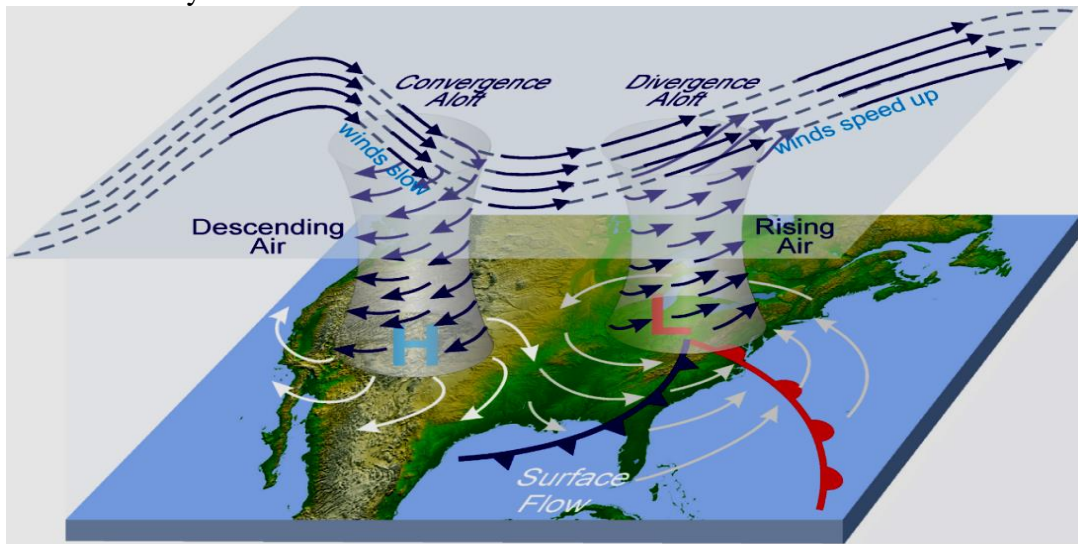


Figure 4.3 Upper air convergence and divergence affect surface highs and lows.

Section 2. Fronts and Storm Systems

Types of Fronts

Fronts are named based on what air mass is overtaking another. In a *cold front*, the cold air mass is pushing under the warm air mass, causing it to ride up over the cold air. This is a type of frontal wedging mentioned in Chapter 3.

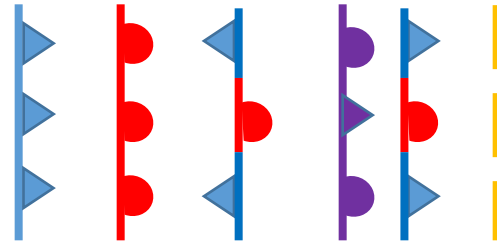
A *warm front* occurs where warm air rides up over a cooler air mass, slowly replacing it at the ground. It is also frontal wedging.

Sometimes neither air mass wins the battle over territory, in which case we have a *stationary front*. It is not truly stationary, but wanders back and forth over an area, sometimes for days.

The final type of front is the *occluded front*, where there are three air masses in proximity: cold, cool, and warm. Of course, the cold air will be on the bottom, the cool air above that, and the warm air on top. Depending on the direction of motion, it is either a *cold occlusion* or a *warm occlusion*. More on that distinction later.

Lines with “pips” indicate the type of front. On all frontal symbols, these pips indicate what direction the front is moving. For a cold front, the pips are triangular and blue (if colored). For a warm front, the pips are semi-circular and red. Stationary fronts have blue triangles on one side and red semi-circles on the other. Think of them as fighting each other and getting nowhere.

Occluded fronts have alternating triangles and semi-circles on the same side, and are purple, if colored (or alternating red and blue). Figure 4.4 shows each of these symbols. Troughs are lines of lower pressure, where a low stretches in one direction.



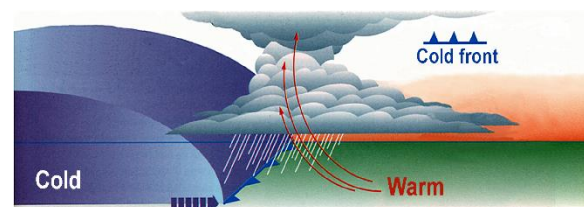
Cold Warm Stationary Occluded Trough

Figure 4.4 Frontal Symbols on surface charts.

Before going into detail on fronts, we need to briefly introduce types of clouds (a fuller discussion is in Chapter 5). Clouds are of three general types and are grouped into three altitude regimes: low, middle, and high. The types are cumuliform (puffy), stratiform (flat, layered), and cirriform (wispy). Cumuliform clouds indicate unstable air, stratiform clouds indicate stable air.

Cold Fronts

Figure 4.5 shows a typical cross-section of a cold front. The cold air is moving to the right and the warm air is being pushed up. As the warm air cools to the dew point, clouds form. The air becomes unstable, forming convective (cumuliform) clouds, and even thunderstorms. Cold fronts are fast-moving (20 to 30 knots), steeply sloped, and the winds ahead of and behind the front are strong and gusty.



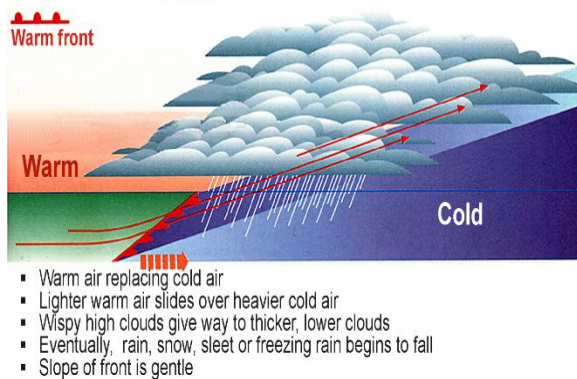
- Cold air is displacing warm air
 - Heavier, cold air is shoving under warm air, pushing it upward
 - Clouds form - can grow into thunderstorms
 - Slope of front is steep
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Figure 4.5 Typical cross-section of a cold front.

As a cold front approaches from the west, cumulus clouds will appear, winds will pick up from the south-west, and the pressure will fall. During passage, there will often be strong, rapidly varying (showery) rain and perhaps lightning and thunder. After the front passes, the pressure will rise sharply, the wind will shift to the north-west and the skies will clear rapidly.

Warm Fronts

Figure 4.6 shows a typical cross-section of a warm front. The warm air is riding over the colder air and moving it to the right, but at about half the speed at which a cold front moves. The frontal boundary slope is gentle, so the lifting action is gentle. Although convective activity is possible, it is more likely that clouds will be layered (stratiform) and the precipitation gentle and steady, rather than showery.

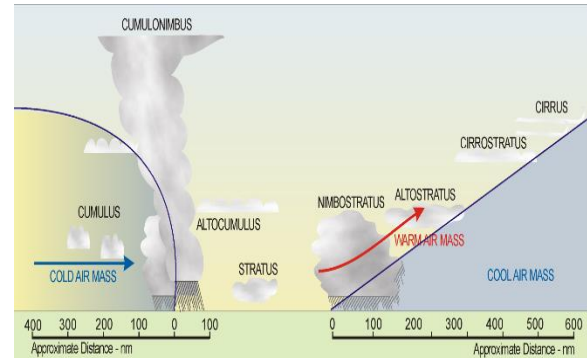


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Figure 4.6 Typical warm front cross-section.

As far as 500 miles ahead of the front, you will see high clouds, then middle clouds and finally low, solid clouds and rain, freezing rain, sleet, or snow, depending on conditions. Winds are also gentler than with cold fronts and the pressure rise and fall is much less, and more gradual as well. It is often difficult to tell exactly where the surface boundary is—it can be broad and diffuse.

A comparison of these two types is in Figure 4.7, showing the different slopes, different cloud types, and typical distance scales.

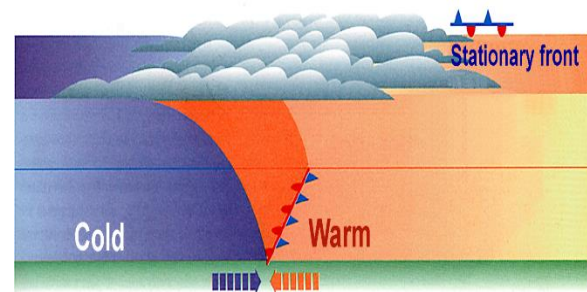


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Figure 4.7 Comparison of cold and warm fronts.

Stationary Fronts

A front is stationary when neither air mass is retreating. There may still be winds, but they will blow parallel to the front in this case. Either a warm or cold front (most often a cold front) may become stationary when a strong high-pressure area blocks the retreating air mass. Even if the front was originally a cold front, the clouds associated with a stationary front tend to become stratiform because the cold air mass has stopped moving in underneath the warm air mass. (Cumuliform clouds will redevelop if the cold air mass resumes its advance.) Figure 4.8 shows a typical stationary front.



Standoff - neither cold nor warm air is advancing.
Widespread clouds can form on both sides of frontal boundary.

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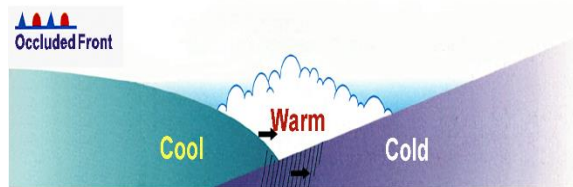
Figure 4.8 Typical stationary front.

Occluded Fronts

Occlusion (from a Latin word meaning closure) refers to situations in which a faster-moving cold front overtakes a slower-moving warm front. On the weather map, occlusions evoke the image of a zipper that has joined the two fronts, but a look at the cross section will show that they actually remain separate. Occlusions involve three air masses, which we shall call warm, cool, and cold to distinguish their temperatures. The occlusion itself is referred to as either warm or cold, depending on the relative positions and movement of the air masses.

Warm occlusions are common in the Pacific Northwest. In the example shown here, cold cP air is retreating as warm mT air advances northward. At the same time, a cool mP air mass is moving in from the Pacific, pushing the warm air eastward. The cross-section (Figure 4.9) shows where the fronts have occluded. Note that the warm air mass has actually been lifted above the surface. The clouds from the two fronts generally merge into multiple layers.

Cold occlusions are more common in the eastern states. Figure 4.10 shows an example in which cool mP air is retreating as warm mT air advances northward, while cold cP air pushes both masses eastward. This is similar to the warm occlusion, but with three differences. First is the exchange of roles between the cool and cold air masses. Second, the advancing front moves in under the warm front, instead of riding up over it as in the preceding case. Third, the greater temperature difference across the cold front (as compared with the warm occlusion case) is likely to produce a steeper slope, more lift, and consequently, more extensive vertical development of the cumuliform clouds ahead of the front.



- Cool air rises over cold air at the surface
 - Warm-cold air boundary aloft is often east of surface front
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Figure 4.9 Warm occlusion.



- Cold air is showing under cool air at Earth's surface
 - Cold-warm air boundary aloft is often west of surface front
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Figure 4.10 Cold occlusion.

Cyclones

Low pressure systems that bring weather to us are called *extra-tropical cyclones*. This is to distinguish them from *tropical cyclones*, the generic term for tropical storms, hurricanes, typhoons, etc. Cyclone simply means that the circulation is cyclonic (remember—counterclockwise in the northern hemisphere).

Contrary to tropical cyclones, extra-tropical cyclones have fronts associated with them. They occur in the mid latitudes, in the prevailing westerlies, and travel generally from west to east steered by winds at and above the 500 mb level. They are responsible for most (but not all) severe weather in this region.

Figure 4.11 (next page) is a simple picture of an extra-tropical cyclone. It shows the cold front, the warm front, the low pressure center, the wind circulation, and the general area of precipitation. Notice that the wind direction veers abruptly across the cold front. This is typical for an active system. It shifts across the warm front, but in fact the shift is not as pronounced as shown here. This is an

idealized view that we don't always see, but represents average conditions.

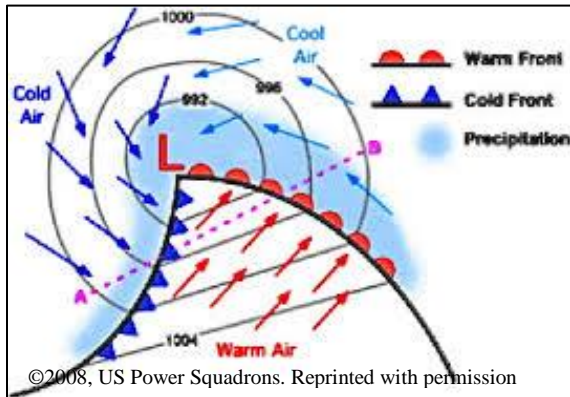


Figure 4.11 Extra-tropical cyclone.

How is the Low Moving?

In Chapter 7, we will go into great detail about the resources that are available for us to know where storms are and how they are moving, but there is a way that we can do that simply with our own observations. It

uses the Buys-Ballot law and the observation of whether the wind is veering or backing.

As we saw in Chapter 2, the Buys-Ballot law tells us where the low is. Recall that we face the wind and the low is on our right. So, we have a good idea where the low is, but how do we know its movement?

Look carefully at Figure 4.12. It shows an extra-tropical cyclone with some dotted lines that represent our movement relative to the storm (actually, the storm is moving, not us). Remember, the storm is in the prevailing westerlies and moves generally from west to east. As you can see from the figure, if the low passes to the north, we will go from X to Y and the winds will veer. If it passes to the south, we will go from A to D, and the winds will back. So, if the winds are backing, the low is passing to the south and if the winds are veering, it is passing to the north.

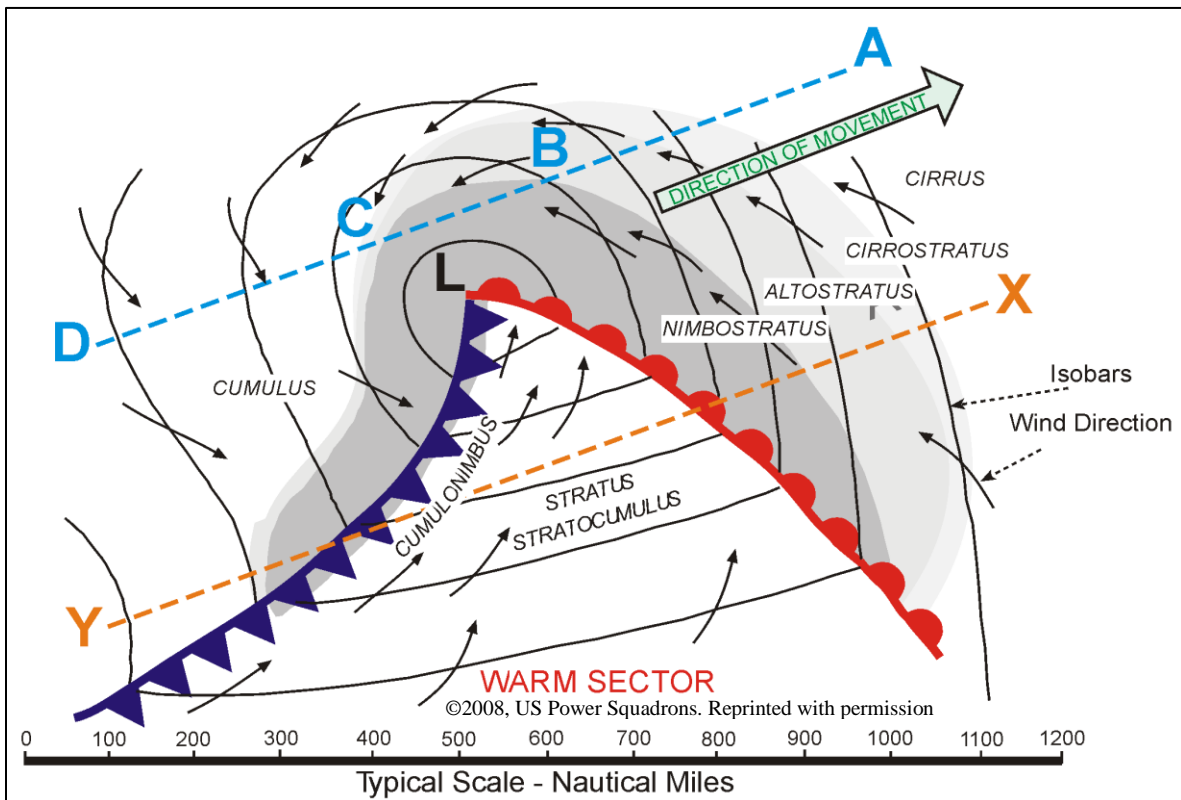


Figure 4.12 Winds veer or back depending on where the low is passing us.

How Lows Form

The formation of low pressure systems is called *cyclogenesis*. Literally, that means the generation of cyclonic circulation. To talk about cyclogenesis, we need to talk about the polar front. The polar front is a semi-permanent feature between the prevailing westerlies and the polar easterlies (Chapter 1). It is normally over Canada in the summer and over the United States in the winter. It is associated with the polar jet stream. The classical theory of cyclogenesis is shown in the series of images shown in Figure 4.13. The air flowing in opposite directions creates friction, causing the winds to change direction.

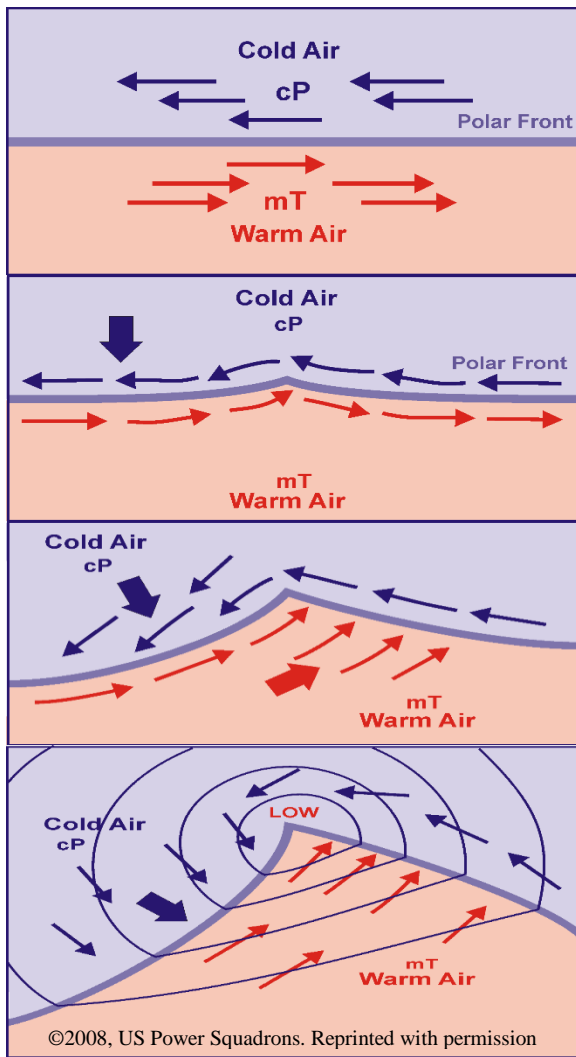


Figure 4.13 Classical cyclogenesis theory.

A disturbance in the polar front creates a wave that develops with time, forming a circulation that pushes the cold air south and the warm air north.

The subject of upper-level convergence and divergence discussed in Section 1 is the more modern theory of cyclogenesis.

The strongest influence of the upper-level winds is from the polar jet stream. It is in the upper part of the troposphere, between about 30,000 and 40,000 feet (~6-7 miles). It has speeds in the core as high as 175 knots (200 mph) and is associated with the polar front. It moves north and weakens during the summer and strengthens and moves south during the winter. See Figure 4.14.

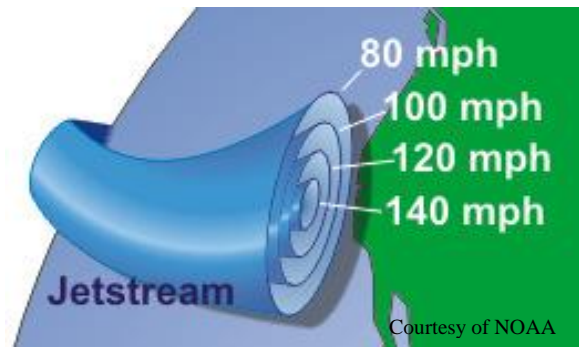


Figure 4.14 Cross-section of the Polar Jetstream.

Figure 4.15 shows typical storm tracks in the U.S. The major source regions are the Pacific Ocean, western Canada, the mid-west, and the gulf.

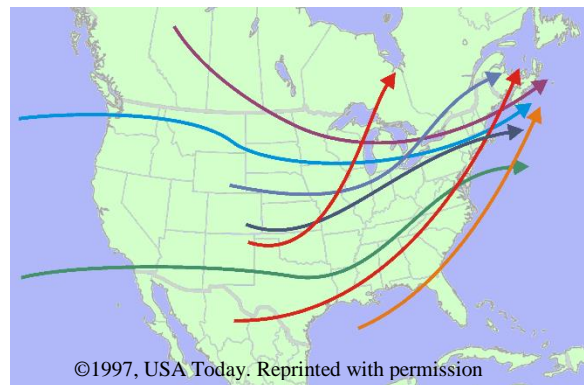


Figure 4.15 Typical storm tracks.

Cold and Warm Core Lows

Low pressure systems can get shallower (fill) with height, or deepen with height. The difference is whether they are warm core or cold core. In a warm-core low, there are warmer temperatures in the center. (Figure 4.16). In a cold-core low, there are colder temperatures in the center (Figure 4.17). In all figures, the dotted lines represent pressure surfaces.

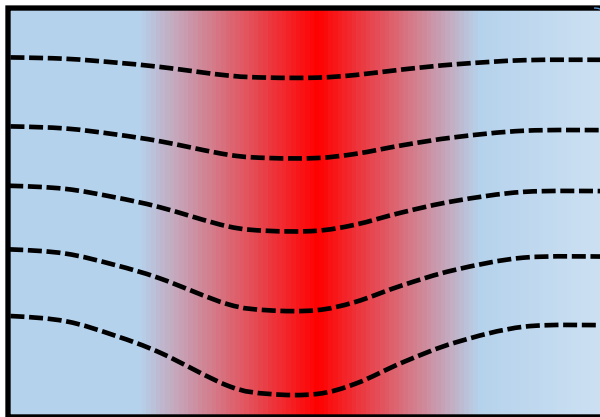


Figure 4.16. Warm core Low.

If you have a low aloft that has a warm core, the total density and therefore the weight of the air is less, so the low becomes deeper as you approach the surface (the low is deeper—see dotted lines in the figures). To put it another way, the warm air is expanded relative to the cold air, so the pressure surfaces are farther apart.

Conversely, if the low has a cold core, the density is higher and the low becomes less intense as you approach the ground (the low is shallower) and can actually become a high-pressure area at the surface (Figure 4.18). In other words, the pressure surfaces are closer together in the cold air. We will see an example of this in Chapter 7.

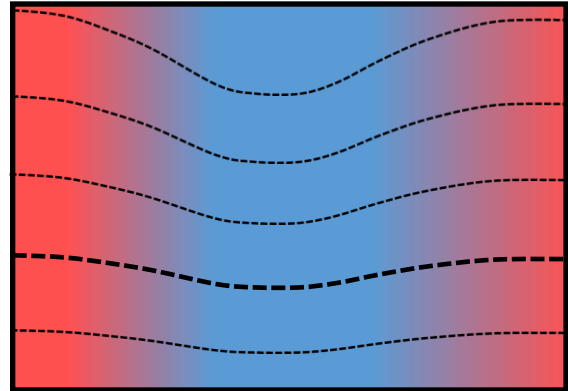


Figure 4.17. Cold core Low.

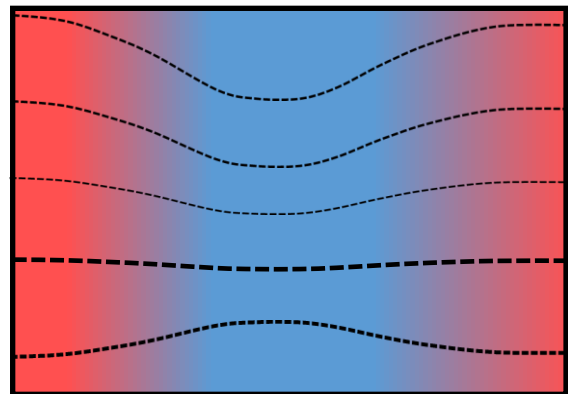


Figure 4.18. Cold core Low with High at the Surface.

A hurricane is a warm core low that turns into a high at higher altitudes. See Figure 4.19.

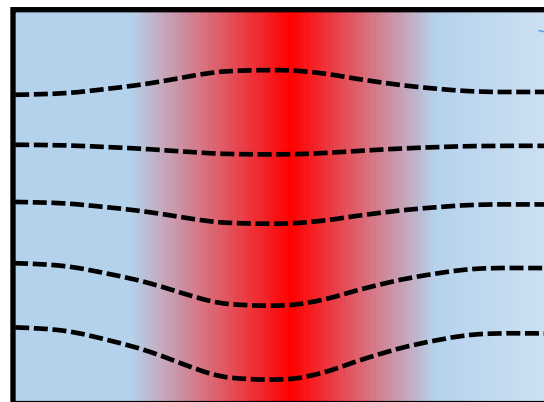
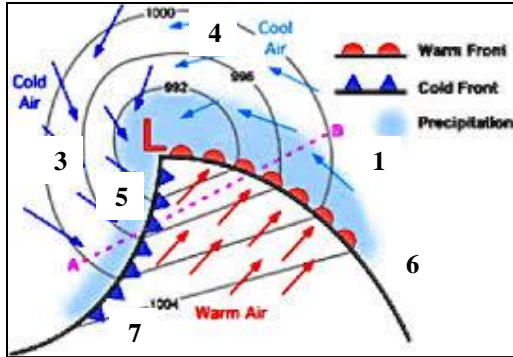


Figure 4.19. Warm core Low with a High above, as in a Hurricane.

Study Questions—Chapter 4

1. In highs, the:
 - a) Air spirals into the center.
 - b) Air rises.
 - c) Air spirals out of the center.
 - d) Weather is usually foul.
2. In lows, the:
 - a) Air spirals into the center.
 - b) Air sinks.
 - c) Air spirals out of the center.
 - d) Weather is usually fair.
3. Normally, air masses travel across the U. S.:
 - a) From east to west.
 - b) Faster in the winter than the summer.
 - c) Faster in the summer than the winter.
 - d) The same speed all year.
4. Precipitation ahead of a warm front is usually:
 - a) Short in duration and showery.
 - b) Non-existent.
 - c) Impossible to predict.
 - d) Long in duration and steady.
5. Precipitation ahead of a cold front is usually:
 - a) Short in duration and showery.
 - b) Non-existent.
 - c) Impossible to predict.
 - d) Long in duration and steady.
6. When a cold front passes, the wind:
 - a) Veers sharply.
 - b) Backs sharply.
 - c) Reverses direction.
 - d) Stops blowing.
7. As a cold front passes, the winds are:
 - a) Calm.
 - b) Strong and gusty.
 - c) From the south.
 - d) From the east.
8. Conditions after a cold front are usually:
 - a) Good visibility with low stratus clouds.
 - b) Poor visibility with low stratus clouds.
 - c) Good visibility with cumulus clouds.
 - d) Poor visibility with cumulus clouds.
9. In the occluded portion of a cyclone, the warm air:
 - a) Has moved away.
 - b) Is trapped at the surface.
 - c) Is held aloft.
 - d) Pushes under the cool air.
10. An occluded front is formed when:
 - a) A fast warm front overrides a cold front.
 - b) A fast cold front overtakes a warm front.
 - c) Moist air displaces dry air.
 - d) A cold front stalls.
11. North of a low:
 - a) There are no fronts.
 - b) The winds back as the low passes.
 - c) There is no warm sector.
 - d) All of the above.
12. The polar front forms storm systems because:
 - a) It encourages the formation of anti-cyclones.
 - b) The polar westerlies and prevailing easterlies oppose each other.
 - c) The prevailing westerlies and polar easterlies oppose each other.
 - d) None of the above.
13. The jet stream is:
 - a) An ocean current.
 - b) A low-level wind.
 - c) A high altitude wind.
 - d) Over the equator.



Use this figure to answer questions 14 - 22.

14. Clouds in area 1 are typically:
- Cumuliform.
 - Stratiform.
 - Cirriiform.
 - Absent.
15. Clouds in area 5 are typically:
- Cumuliform.
 - Stratiform.
 - Cirriiform.
 - Absent.
16. Clouds in area 3 are typically:
- Cumuliform.
 - Stratiform.
 - Cirriiform.
 - Nimbostratus.
17. The front next to 7 is a:
- Cold front.
 - Warm front.
 - Stationary front.
 - Occluded front.
18. The front next to 6 is a:
- Cold front.
 - Warm front.
 - Stationary front.
 - Occluded front.
19. The wind has veered to the NW, the thunderstorms are over and the barometer is rising rapidly. Where are you?
- 1.
 - 7.
 - 5.
 - 3.
20. It is now colder, the wind is NW, the sky is clear or partly cloudy. Where are you?
- 1.
 - 7.
 - 5.
 - 3.
21. The winds have been backing most of the day. Where are you?
- 6.
 - 7.
 - 4.
 - 3.
22. A mid-latitude cyclone like this one will typically move in the direction from:
- 5 to 1.
 - 4 to 1.
 - 6 to 1.
 - 1 to 6.
23. Divergence aloft can be caused by:
- The wind speeding up with distance.
 - The wind slowing down with distance.
 - The wind veering.
 - The temperature falling.
24. Divergence aloft encourages cyclone formation because it:
- Supports surface divergence.
 - Causes air to sink.
 - Supports surface convergence.
 - Prevents surface convergence.

25. The paths of cyclones across the U. S. are determined by:
- The cyclonic wind flow.
 - High pressure to the west and low pressure to the east.
 - Steering winds at the surface.
 - Steering winds at an above 18,000 feet.
26. Cyclones can form:
- Over the Gulf.
 - Over the Pacific Ocean.
 - Over the Great Plains.
 - All of the above.
27. The symbol for a cold front is a line with:
- Semi-circles.
 - Triangles.
 - Triangles and semi-circles on different sides.
 - Triangles and semi-circles on the same side.
28. The symbol for an occluded front is a line with:
- Semi-circles.
 - Triangles.
 - Triangles and semi-circles on different sides.
 - Triangles and semi-circles on the same side.
29. The symbol for a stationary front is a line with:
- Semi-circles.
 - Triangles.
 - Triangles and semi-circles on different sides.
 - Triangles and semi-circles on the same side.
30. The symbol for a warm front is a line with:
- Semi-circles.
 - Triangles.
 - Triangles and semi-circles on different sides.
 - Triangles and semi-circles on the same side.
31. A cP air mass moving through the midwest will:
- Cool from below.
 - Pick up additional moisture.
 - Warm from below.
 - Both b and c.
32. An mT air mass moving up the east coast will:
- Cool from below.
 - Pick up additional moisture.
 - Both a and b.
 - Neither a nor b.
33. A cold-core low does what as the altitude increases?
- Fills.
 - Deepens.
 - Expands.
 - None of the above.
34. A warm-core low does what as the altitude increases?
- Fills.
 - Deepens.
 - Expands.
 - None of the above.

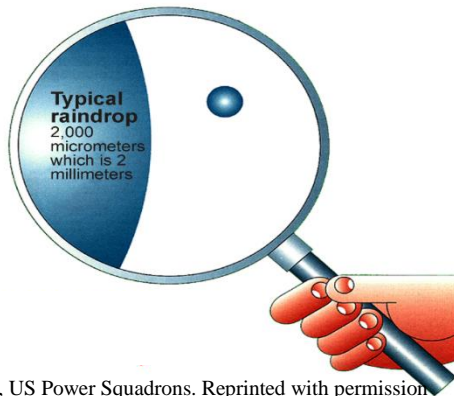
Chapter 5 Clouds, Precipitation, and Optical Phenomena

Section 1. Clouds

What are Clouds?

Clouds are made up of minute water droplets or ice crystals that have condensed from water vapor in the atmosphere. As we learned in Chapter 3, water vapor will begin to condense when the temperature is lowered to the dew point or the dew point is raised to the temperature by the addition of water vapor into the air. However, water vapor will not condense at the dew point unless there are impurities in the air called *condensation nuclei*. They can be dust, salt particles, haze, or other aerosols.

Figure 5.1 compares the size of cloud droplets to the size of a typical rain drop. Their very small size is why they appear white under most circumstances.



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Figure 5.1 Comparison of a rain drop and a cloud particle.

Clouds come in many different sizes and appearances but are classically grouped by categories. One category is appearance, or type—what the cloud looks like. The choices are: Cirriform (wispy, always high clouds); Stratiform (flat, layered, with no apparent structure); and Cumuliform (puffy, many

rounded structures). Examples of all of these types (morphologies) are shown below.

The other category is height. In this case there are four choices, but only three of them apply to more than one type. The three main categories are low, middle, and high clouds. The exact definitions of these heights vary with season and latitude. We will adopt the following definitions. See Appendix B for further information. Low clouds have bases under 6,500 feet (about 2,000 meters). Middle clouds have bases from 6,500 feet to less than 20,000 feet (a little over 7,000 meters). High clouds have bases over 20,000 feet. The fourth category is clouds of vertical development. They have bases in the low cloud range, but the tops can be in the middle or high altitude range.

In addition, there are a couple of other terms applied to clouds. The first is nimbo (as a prefix) or nimbus (as a suffix). Both terms mean the clouds are producing precipitation. This term can be applied to both stratiform and cumuliform clouds. The second additional term is fracto (as a prefix) or fractus (as a suffix). It means the clouds are broken up into small, ragged pieces. The two terms are interchangeable: fractostratus, or stratus fractus, applied mostly to stratiform clouds.

Low Clouds

Cumulus clouds (symbol Cu) are, of course, cumuliform. As low clouds, they are generally referred to “cumulus humilis” or “fair weather cumulus.” The point at which the cloud becomes “cumulus congestus” or towering cumulus” (see below) is not well defined. Examples of cumulus humilis are shown in Figures 5.2 and 5.3.



Figure 5.2 Fair weather cumulus (Cu).



Figure 5.3 Growing Cumulus Humilis (Cu).

Stratus clouds (St) are, of course, stratiform. They may be wide-spread, or fragmented, as stratus fractus, or in between. They are almost featureless, grey or light grey when seen from below, but white when seen from above. See figure 5.4.

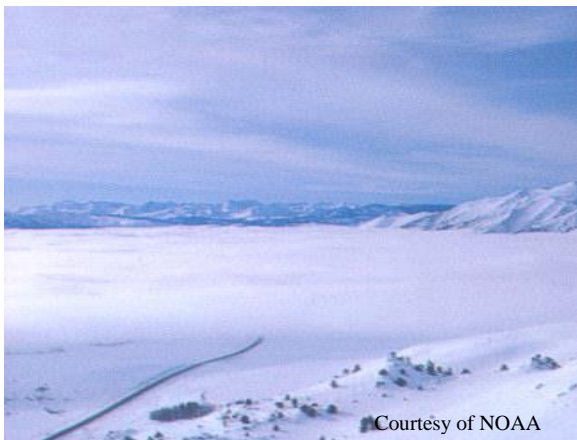


Figure 5.4 Stratus, seen from above (St).

Stratocumulus (Sc) is a form somewhat in between stratus and cumulus. It is in layers, but has a rounded shape, with fuzzy edges. See Figure 5.5.



Figure 5.5 An example of stratocumulus (Sc).

Nimbostratus (Ns) is a stratiform cloud that is raining. Figure 5.6 is an example. It is dark not because it is night, but because the Ns is so thick that little light can get through.



Figure 5.6 Nimbostratus (Ns).

Middle Clouds

Middle clouds are of two types: Altostratus (As) and Altopcumulus (Ac). Altopcumulus can be somewhat disorganized, or can form rows, called “streets.” It is sometimes difficult to tell stratus (a low cloud) from altostratus. Figure 5.7 is altostratus. Figure 5.8 is ordinary altocumulus and Figure 5.9 is altocumulus in “streets.” In the latter case, the cloud formation tells us in what direction the

winds are blowing. They are blowing perpendicular to the rows of clouds. Think of surface winds and water-wave patterns.



Figure 5.7 Altostratus (As). The sun may or may not be visible.



Figure 5.8 Altocumulus (Ac).



Figure 5.9 Altocumulus (Ac) in "Streets."

High Clouds

High clouds are of three types: Cirrus (Ci), cirrocumulus (Cc), and cirrostratus

(Cs). Cirrus clouds have a filamentary look and appear thin and wispy. If the filaments have a hook, the clouds were called "mares' tails" by sailors. Figure 5.10 shows an example that includes a few *mares' tails*.



Figure 5.10 Cirrus (Ci) with "mares' tails"

Cirrocumulus (Cc) clouds (figure 5.11 look much like Sc or Ac clouds, but the individual cells appear smaller because they are farther away. When the sky is covered with a uniform array of these cells, it is called "a mackerel sky". In the winter, they often portend good weather, but, when associated with cirrus and lowering clouds, it can storm within 24 hours. Sailors had a rhyme to remind them of this.

*Mares' tails and mackerel scales,
make tall ships trim their sails.*

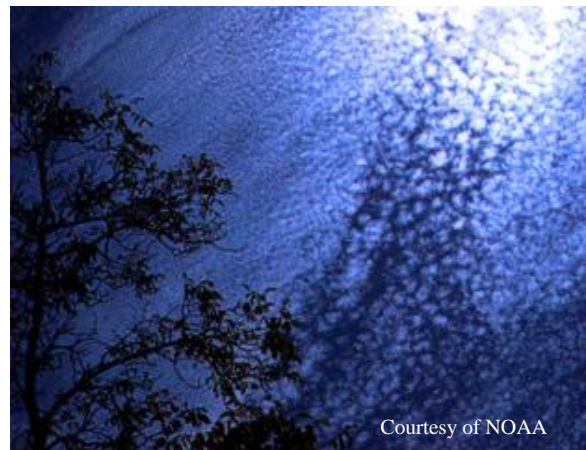


Figure 5.11 Cirrocumulus (Cc), a mackerel sky.

The final type of high cloud is cirrostratus (Cs). They can be thick and clumpy, as seen with the cirrus in Figure 5.10 or as seen in the anvil tops of thunderstorms, but are most often thin and cover a good portion of the sky in a uniform layer.

It is often difficult to tell altostratus from cirrostratus, but if the sun or moon is visible, there is a good clue—As is usually made of water droplets and Cs is usually made of ice crystals. Water droplets scatter sunlight, making it look like there is a crown around the sun. It is called a corona. Ice particles refract light and make it look as if the sun (or moon) appear to have a halo (it is in fact called a halo). Figure 5.12 shows a corona around the sun near sunset. Figure 5.13 shows a halo. This concept will be covered more thoroughly in Section 3.



Figure 5.12 A corona (probably altostratus)



Figure 5.13 Halo due to cirrostratus (ice cloud).

Clouds of Vertical Development

Cumulus clouds vary from puffy little fair weather cumulus to very large cumulonimbus (thunderstorm clouds), including super cells that can spawn several severe tornadoes. As we discussed above, standard cumulus is a low cloud. The larger cumulus clouds, cumulus congestus, towering cumulus, and cumulonimbus, have their bases in the low cloud region, but have tops into the middle cloud region (above 6,500 ft.) or into the upper cloud region (above 20,000 ft.) and are therefore classed as clouds of vertical development. Figure 5.14 shows an example of towering cumulus. It is often difficult to tell the difference between growing cumulus humilis and towering cumulus (or cumulus congestus)—the major clue is whether the height is significantly greater than the width.



Figure 5.14 Cumulus congestus or towering cumulus (Cu).

Cumulonimbus (Cb) clouds are cumulus clouds in air that is very unstable throughout the tropopause. They normally have flat bottoms (but see below) and a puffy appearance, often with a flat top of cirrostratus, called an anvil. The one thing that differentiates cumulonimbus from towering cumulus is the presence of precipitation (remember, the nimbus suffix means precipitation). They can vary in size from ordinary thunderstorms up to super cells that cover hundreds of square miles and

push up part way into the stratosphere. More on these in the next chapter. Figure 5.15 is a typical example.



Figure 5.15 Typical cumulonimbus.

More Cloud Characteristics

There are several other interesting characteristics of clouds that can help the reader better understand what he or she sees in the skies. The ones to be covered here include lenticular (or cap) clouds, cumulonimbus mammatus, wall clouds, and shelf clouds.

Lenticular (lens shaped) clouds are stratiform clouds (usually altostratus) that form over, or in the lee of, mountains. The conditions have to be just right—stable air, a steady wind over a significant depth, and humidity levels near saturation. As the wind blows over the mountain or mountain range, it sets up a wave in the atmosphere. On the back of the wave, moisture condenses into stratiform clouds. On the front, the air warms adiabatically and the cloud evaporates. Figure 5.16 shows a particularly impressive example. In this image, there are multiple narrow tongues of moisture, each forming its own cloud, and double columns of clouds, one over the mountain, and one downstream (to the left).



Figure 5.16 Multiple lenticular clouds.

In very elderly cumulonimbus clouds, the bottom sometimes takes on a lumpy appearance and they are called mammatus clouds. At one time, it was thought that these were likely to form tornados, but subsequent research has shown they are no more likely to than other large, mature thunderstorms. They are visibly impressive, though. (Figure 5.17).



Figure 5.17 The Base of a cumulonimbus mammatus cloud.

Finally, two features of large, mature cumulonimbus clouds are evidence of the possibility of tornados. The first is something called the wall cloud. It is often seen rotating just as the tornado is forming. Figure 5.18 is a typical example.

The second is called a shelf cloud and is often seen on large, mature thunderstorms, most often on super-cells. There is one in the picture of a super cell on the first page of Part II.

The details of these features, as well as their consequences and usefulness in short-term forecasting will be covered in the next chapter.



Figure 5.18 Typical wall cloud.

Section 2. Precipitation

How Does Precipitation Form?

In section 1, we discussed the relative sizes of cloud particles and rain drops. Let's go a little deeper into that subject. Cloud particles (liquid droplets or ice crystals) are so small that even if the air were totally still, it would take days for them to drift down under gravity. However, the air is always moving and it keeps cloud particles suspended indefinitely, until conditions change and they evaporate or sublime back into water vapor. Only when they grow much larger and form precipitation, can they reach the ground before evaporating.

So, how do cloud particles grow into rain, snow, sleet, or hail? That question had baffled meteorologists for centuries but there is now general agreement that there are two processes. One, the Bergeron Process, occurs in cold air (well below freezing). The other, the collision-coalescence process, occurs in warm air, such as in the tropics, where large sea-salt aerosols are abundant. In the latter case, drops drift together due to winds and convection and grow by coalescing. When

large enough, they fall, picking up droplets they collide with.

Before proceeding, we should briefly discuss the existence of super-cooled droplets. Although there are many condensation nuclei in the air (Chapter 3), there are not enough freezing nuclei. Droplets can exist in liquid form down to -10°C (14°F). Data from research aircraft have shown that between -10°C and 0°C , clouds consist largely of water droplets. Between -10°C and -20°C (-4°F), there is a mixture of water and ice particles. Below that, they are all ice particles.

The following is a simplified explanation of the Bergeron Process:

- At sub-freezing temperatures, water vapor is evaporating and re-condensing on the super-cooled droplets.
- Water vapor is more likely to deposit on the few ice crystals present because the vapor pressure of ice is lower than that of water.
- Deposition on the ice lowers the humidity, allowing more water to evaporate

from the droplets and deposit on the ice particles.

- Therefore, the ice particles grow at the expense of the water droplets.
- As the ice crystals grow larger and heavier, they fall faster, colliding with other ice crystals and with super-cooled water droplets that instantly freeze on them.
- Once they grow large enough, they can fall out of the cloud.

At this point, they are ice pellets or snow. As they fall through the atmosphere, several things can happen, depending on the nature of the vertical temperature profile.

- They can continue to fall in cold air as snow or ice pellets.
- They can melt and become rain or drizzle.
- The rain may be re-cooled to below freezing by, for example, falling into the colder air below a warm front. It is now super-cooled freezing rain and will freeze on impact.
- Rain or drizzle can re-freeze, forming sleet (rain) or small ice crystals (drizzle).

Types of Precipitation

Rain and drizzle are simply two aspects of liquid precipitation. The primary difference is the size of the drops. Drizzle drops are, by definition, less than 0.5 mm (cloud particles are around 0.02 mm). Rain drops average about 2 mm. Both are officially described as light, moderate, or heavy. The way those categories are described differs between rain and drizzle.

Rain is light if it is falling at a rate of 0.1 inches per hour or less. It is moderate from

over 0.1 to 0.3 inches per hour and heavy at over 0.3 inches per hour.

The drizzle categories are, unlike rain, based on visibility. The more drops, the lower the visibility. Light drizzle means the visibility is more than 1 km (5/8 of a mile). Moderate is from less than 1 km to 0.5 km. Heavy is less than 0.5 km (5/16 of a mile).

Sleet is simply the ice formed at altitude making it all the way to the ground. It was formed mostly by colliding with super-cooled water droplets, forming a more or less solid mass of ice. In some cases, it can be rain re-frozen during a long fall through cold air. It is also called ice pellets. It often occurs in combination with rain and snow.

Snow is formed at altitude primarily by the collision of ice particles (formless flakes) or by the deposition of water vapor directly on the hexagonal ice crystal (lacy flakes). Most snow is a mixture of these two types. A related type of precipitation is *graupel*, formed by the collision of snowflakes with super-cooled droplets. It is also called snow pellets or soft hail.

Freezing rain or drizzle, as explained above, is rain or drizzle that is super-cooled as it falls through colder air, but for a shorter distance than the sleet mechanism mentioned above. It does not re-freeze until it strikes a surface.

Hail is formed only in very large thunderstorms, where it travels many times up and down the vertical conveyor belt of a mature cumulonimbus. During its travels, it partially melts, collects rain drops, then re-freezes. More in Chapter 6.

A few more words about freezing rain. When it strikes a surface, it can either freeze on impact if the drops are small enough (e.g. drizzle), or freeze more slowly. The first case

forms rime ice, the second, glaze ice. Both are dangerous to low-flying aircraft, but glaze ice is worse for boats. It can change the center of gravity and therefore the stability.

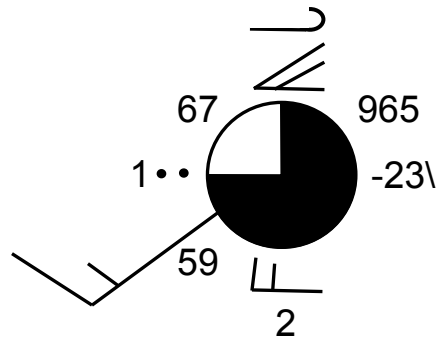
Station Model

Let's catch up on the station model. Since Chapter 3, we have discussed fog, clouds, precipitation, and visibility. Fog and precipitation are shown by the symbols for present weather to the left of the circle, with visibility in statute miles to the left of that. The present weather symbol shows the fog, precipitation, or haze primarily responsible for the visibility. Clouds are reported above and below the circle with low below, middle above, and high above that. Low cloud heights are coded under their symbol. Clouds are coded shapes. Sky cover is shown by shading in the circle.

The updated station model below shows that the present weather is continuous light rain, with a visibility of one mile; the low clouds are nimbostratus, with bases between 300 and 599 ft.; the middle clouds are thick altostratus and the high clouds are cirrus. The total sky cover is 6/8. For further information, see appendix B-6.

Remember from previous chapters, the temperature and dew point are in degrees Fahrenheit, the pressure and pressure tendency are in millibars, and the winds are in knots to the nearest five knots.

Challenge question: What is the weather situation?⁵



⁵ Most likely an approaching warm front.

Section 3. Optical Phenomena in the Atmosphere

Introduction

Why study optical phenomena? One reason is they are really cool. The more practical reason is they can tell us something about what is going on around us and therefore what to expect from the weather.

If I were to ask you to define a meteor, what would you say? If you are like most people, you will talk about objects from space, and you would be partly right. Strictly speaking, any foreign object in the atmosphere is a meteor. The definition of meteor is therefore any object in the atmosphere, such as clouds, rain, dust, “shooting stars” etc.

Clouds and precipitation are called *hydrometeors* and are the subject of the first two Sections. Dust and other aerosols are called *lithometeors* (an example would be the condensation nuclei discussed earlier). A third type, *photometeors* is the subject of this section.

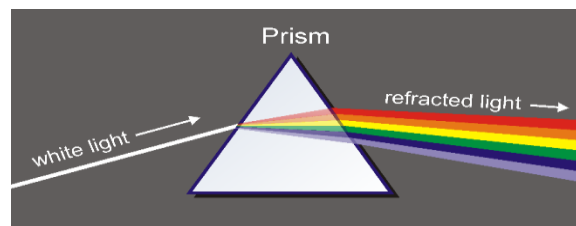
Unlike the others, photometeors do not exist as physical objects, but the name has stuck. They are the result of light interacting with the molecules in the atmosphere or with the other meteors. While there are numerous kinds, we will discuss only a few that are helpful to us as weather specialists.

In preparation, we need to discuss in a simple fashion how light interacts with matter. It does one of four things—it is absorbed, reflected, scattered, or refracted. If light is absorbed, it turns into heat energy. If it is reflected, it bounces off the surface unchanged except for the direction of propagation. The other two are much more interesting.

Scattering is a phenomenon similar to waves striking a rock in a stream. The waves

propagate in all directions (but mostly downstream). Light scattering is very similar—it scatters most strongly in the forward direction, and less as the angle away from the forward direction increases. The degree of energy decrease with angle is dependent on the comparison of the wavelength of the light to the size of the scattering particle. See Appendix A for more information.

Refraction should be familiar to all of us. Who has not put a prism in the sunlight and seen the spread of colors? The amount of refraction is dependent on the wavelength of the light, the optical properties of the object, and the angle at which the light strikes. Longer wavelengths of light (red) refract (bend) less than the short wavelengths (blue). See Figure 5.19. There is additional information in Appendix A.



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Figure 5.19 Refraction.

Optical Phenomena

Why is the sky blue? The answer is the way sunlight is scattered by the molecules in the atmosphere. Blue scatters more than red, so the molecules selectively scatter blue light to us. If there are haze or other pollutants in the air, it could look grey or brownish. A very blue sky means the air is clear—usually seen when a fresh high-pressure area is present.

Why are the clouds red at sunset and sunrise? At these times, light has farther to travel

through the atmosphere, and therefore most colors scatter away from our line of sight, but red scatters less. This leaves only the red to illuminate the clouds.

Thus, the old sailor's saying:

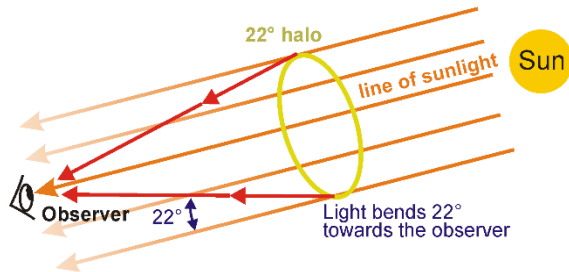
Red sky in the morning, sailor take warning.

Red sky at night, sailor's delight.

Halos and Coronas

We introduced halos and coronas earlier in the chapter as a way to distinguish altostratus from cirrostratus.

Halos are produced by light from the sun or the moon refracting through hexagonal ice crystals. In the most common case, the light is bent 22° . Figure 5.20 shows the geometry. The light is refracted by hexagonal ice crystals that are 22° from our line of sight.



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Figure 5.20 Mechanism for the Halo.

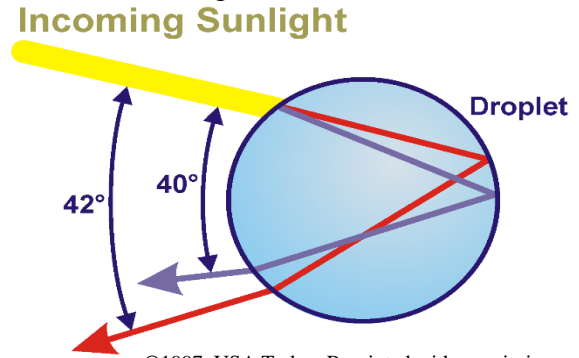
While halos are a result of refraction, coronas are the result of scattering. As the light from the sun or moon encounters the water droplets in a thin cloud, such as altostratus, particles off our line of sight scatter the light to us. Remember, forward scatter is the strongest, so the corona is brightest nearest the sun or moon.

Rainbows

Rainbows are beautiful, but how useful are they to meteorology? The answer lies in the combination of circumstances that need

to occur to see a rainbow, and show the conditions in the atmosphere. First, there must be rain drops in the atmosphere. Second, the sky in the direction of the sun must be clear so the sunlight can interact with the drops. This usually happens after a rain storm.

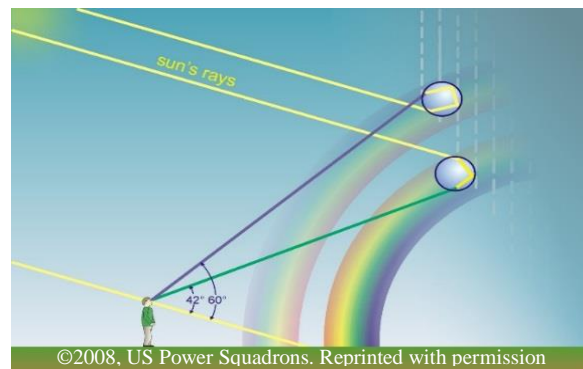
Figure 5.21 shows what happens. Light refracts into the drop, reflects off the back, and refracts again back into the air.



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Figure 5.21 Mechanism for a primary rainbow.

Of purely academic interest is the fact that there are not only primary rainbows, as shown above, but also, occasionally, secondary bows, and, very rarely, tertiary bows. The difference is in the number of times the light reflects internally in the water drop. If it reflects twice, we see a dimmer secondary bow outside the primary, with inverted colors (Figure 5.22). If it reflects three times, we can very occasionally see the tertiary bow while facing the sun.



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Figure 5.22 Primary and secondary rainbows.

Study Questions—Chapter 5

1. “Nimbo” added to a cloud name means:
 - a) High clouds.
 - b) Low clouds.
 - c) Precipitation.
 - d) Thick, dark clouds.
2. Clouds with a horizontal, layered appearance would be:
 - a) Stratiform.
 - b) Nimbostratus.
 - c) Cirriform.
 - d) Cumuliform.
3. Clouds with a wispy appearance are:
 - a) Stratiform.
 - b) Nimbostratus.
 - c) Cirriform.
 - d) Cumuliform.
4. Clouds with a lumpy appearance are:
 - a) Stratiform.
 - b) Nimbostratus.
 - c) Cirriform.
 - d) Cumuliform.
5. Which type of cloud produces precipitation?
 - a) Altocumulus.
 - b) Stratocumulus.
 - c) Nimbostratus.
 - d) Cirrostratus.
6. Middle clouds range in altitude:
 - a) Below 6,500 feet.
 - b) Between 6,500 feet and 20,000 feet.
 - c) Above 20,000 feet.
 - d) Below 10,000 feet.
7. Low clouds are found:
 - a) Below 6,500 feet.
 - b) Between 6,500 feet and 20,000 feet.
 - c) Above 20,000 feet.
 - d) Below 10,000 feet.
8. Clouds that develop vertically are:
 - a) Stratocumulus.
 - b) Nimbostratus.
 - c) Altocumulus.
 - d) Cumulus.
9. What type of cloud would you associate with the phrase “mares’ tails”?
 - a) Cirrus.
 - b) Cirrostratus.
 - c) Altocumulus.
 - d) Stratus.
10. What type of cloud would you associate with the phrase “mackerel sky”?
 - a) Altostratus.
 - b) Altocumulus.
 - c) Cirrocumulus.
 - d) Cumulonimbus.
11. Cirrus clouds consist of:
 - a) Water droplets.
 - b) Ice particles.
 - c) Super-cooled water vapor.
 - d) Fine mist.
12. Nimbostratus clouds produce:
 - a) Halos.
 - b) Beautiful sunsets.
 - c) Precipitation.
 - d) Dust storms.

13. Halos around the sun and moon are caused by:
- Altostratus.
 - Cirrostratus.
 - Nimbostratus.
 - Nimbocumulus.
14. A heavy, dark cloud from which a steady rain is falling is:
- Altostratus.
 - Nimbostratus.
 - Cumulonimbus.
 - Cumulus.
15. For precipitation to fall from a cloud:
- The air must rise adiabatically.
 - The cloud particles must coalesce.
 - The winds must be more than 20 knots.
 - The air must sink adiabatically.
16. The factor that best determines what type of precipitation occurs is:
- The vertical temperature profile.
 - The vertical wind profile.
 - The upper level winds.
 - The surface pressure.
17. Hailstones are always:
- Larger than 2 inches.
 - Smaller than $\frac{1}{4}$ inch.
 - Produced in thunderstorms.
 - Rime.
18. The wintertime deposit that can severely affect the stability of a vessel is:
- Glaze ice.
 - Snow.
 - Sleet.
 - Rime ice.
19. Rime ice is a deposit that forms when _____ comes into contact with a surface.
- Sleet.
 - Super-cooled water droplets.
 - Snow.
 - Soft hail.
20. Clouds that form “caps” on the top of mountains are called:
- Mountain clouds.
 - Lenticular clouds.
 - Chinook clouds.
 - Cirrus clouds.
21. The fact that the sky is blue results from:
- The preferential scattering of blue light by the atmosphere.
 - The refraction of red light from the sun’s rays.
 - An optical illusion.
 - The presence of thin cirrus clouds.
22. Clouds to the west at sunset are red because:
- The air to the west scatters more blue light.
 - The light has farther to travel through the atmosphere.
 - Red light is scattered less than the other colors.
 - All the above.
23. Halos are caused by:
- Thin ice clouds.
 - Ice crystals in the air.
 - The presence of cirrostratus.
 - All of the above.
24. Rainbows require:
- Rain drops and low humidity.
 - Rain drops and direct sunlight.
 - Ice crystals in the direction opposite the sun.
 - Cloud droplets behind you.
25. To see a primary rainbow, you must:
- Have your back to the sun.
 - Face the sun.
 - Have your back to the rain.
 - Have clear skies.

26. When a secondary rainbow is formed, it is fainter because:
- a) It has two reflections in the rain drop.
 - b) It is farther away.
 - c) The colors are reversed.
 - d) None of the above.
27. An example of a synoptic scale phenomenon is:
- a) A tornado.
 - b) An air mass.
 - c) The prevailing westerlies.
 - d) None of the above.
28. An example of a mesoscale phenomenon is:
- a) A thunderstorm.
 - b) A frontal system.
 - c) The semi-permanent pressure centers.
 - d) None of the above.
29. The trade winds are an example of:
- a) A global scale phenomenon.
 - b) A mesoscale phenomenon.
 - c) A synoptic scale phenomenon.
 - d) A microscale phenomenon.

Chapter 6 Severe Weather

Section 1. Thunderstorms, Lightning, and Hail

Thunderstorms

Thunderstorms are mesoscale convective systems that vary widely in severity and duration. They may or may not be part of a larger storm system.

There are about 100,000 thunderstorms a year in the United States. Thunderstorms occur in all 50 states, with the panhandle and west coast of Florida having the most. Most thunderstorms are mild, lasting 20 minutes to three hours, but about 10% are severe.

The National Weather Service (NWS) considers a thunderstorm severe if it meets one or more of the following criteria: Winds greater than 50 knots; hailstones with diameters of more than 1 inch (2.5 cm); or generates one or more tornados. Severe thunderstorms can last several hours, travel 200 miles, and have tops above 50,000 feet.

Thunderstorms require a source of moist, unstable air and a lifting mechanism. Thunderstorms can develop spontaneously in absolutely unstable air, or in conditionally stable air if there is a lifting mechanism. Remember, the four lifting mechanisms are orographic, frontal wedging, surface convergence and localized convection. There is a fifth mechanism, similar to frontal wedging, called a dry line. It occurs often in Texas and surrounding plains areas, where less dense moist air from the gulf meets dryer air from the southwest deserts. The dry air pushes under the lighter moist air, lifting it much like a cold front.

In addition to severity and lifting mechanism, thunderstorms can also be classified

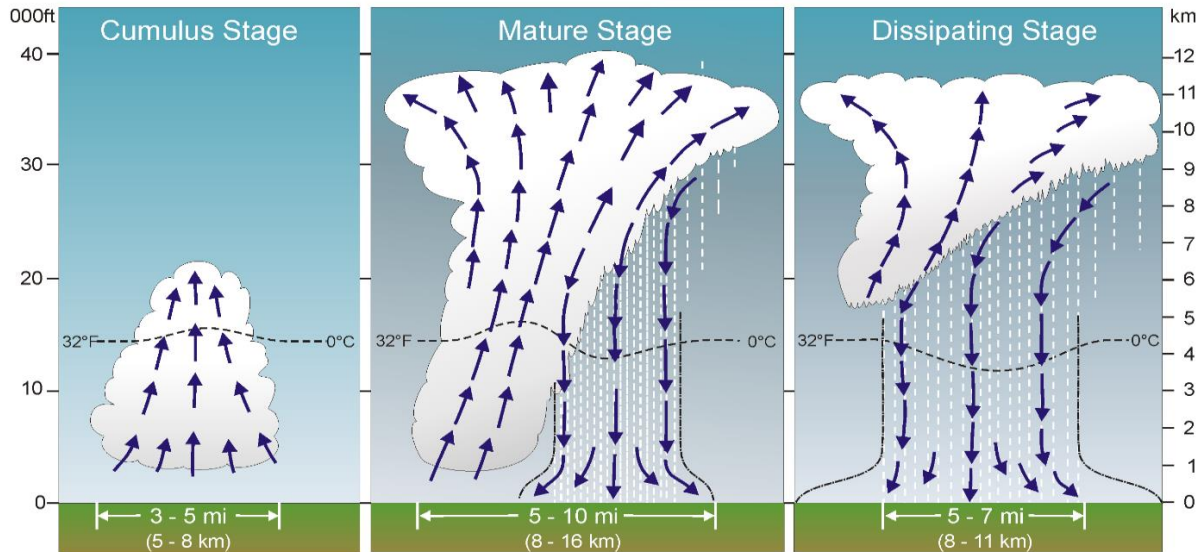
by their organization as: Single cell, Multi-cell, and Supercell.

A single-cell thunderstorm has a lifetime of an hour or less and occurs in three stages (See Figure 6.1 on the following page). In the first stage, *cumulus* (developing), the cloud is a cumulus (Cu) type, which includes cumulus congestus or towering cumulus. There are up-drafts throughout the cloud as it builds rapidly due to the release of latent heat (Chapter 3). When it grows beyond the freezing level, it begins to form precipitation by the Bergeron process (Chapter 5). This all may happen in less than 15 minutes.

In the second, the *mature* stage, there are still updrafts (normally on the up-wind side), but the precipitation initiates downdrafts, accelerated by the cooling from the evaporation of the rain and the *entrainment* (drawing in) of cool outside air. As the downdrafts reach the surface, they spread out, forming a *gust front*. Sometimes a *roll cloud* is formed at the leading edge. The roll cloud rotates opposite the direction of motion, like a street sweeper.

As the cumulonimbus (Cb) continues to develop, it frequently forms the iconic “anvil top” of cirrostratus, pointing in the direction of the upper level winds. The mature stage is the most dangerous, not only due to the shifting, gusty winds, but also the possibility of heavy precipitation, hail, and lightning.

For Auxiliarists on patrol, a sign that the storm is near is the shift from winds blowing toward the storm (Cumulus stage) to winds blowing out. (Mature or Dissipating stage).



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Figure 6.1 Three stages of a single-cell thunderstorm.

The third stage is the *dissipating* stage. The downdrafts eventually cut off the updrafts and the cell can dissipate within 15 to 30 minutes. If other cells are developing nearby, this out-flowing air can assist in their development (see multi-cell below). One clue that the cell is dissipating is that the sharp-edged clouds begin to look fuzzy.

Single cells that form due to convection are called *air mass thunderstorms*. There are two primary classes of multi-cell thunderstorm complexes: Squall lines and mesoscale convective complexes. They occur where a broad area has the conditions for thunderstorm formation (moist air, a lifting process, and unstable air). The downdrafts from adjacent dissipating cells cause surface convergence which can add to the existing lifting process and generate new thunderstorms.

Squall lines are clusters of thunderstorms in a long line. They can be up to 300 miles long and last for many hours as new cells grow to replace the dissipating cells. Some are associated with, but ahead of, cold fronts, but most occur in warm moist air

where the jet stream causes upper air divergence. They can also develop on dry lines in Texas, Oklahoma, and Kansas.

The gust front associated with squall lines acts like a small cold front, pushing moist air up and creating a dramatic dark, fast-moving wall. They can have winds as high as 60 knots, move as fast as 30 knots, and sometimes produce tornados.

Mesoscale convective complexes, unlike squall lines, occur in large groups in an oval or circular shape. They can cover an area of tens of thousands of square miles and last for 12 hours or more. The mechanism is similar to squall lines, with dissipating thunderstorms creating surface convergence, but they move more slowly. They develop from groups of air-mass thunderstorms and are common in the Midwest and Great Plains in the summer.

Supercells are long-lived, very intense systems consisting of a single cell that can have a diameter of 10 to 30 miles. They can be as tall as 60,000 feet, pushing into the stratosphere.

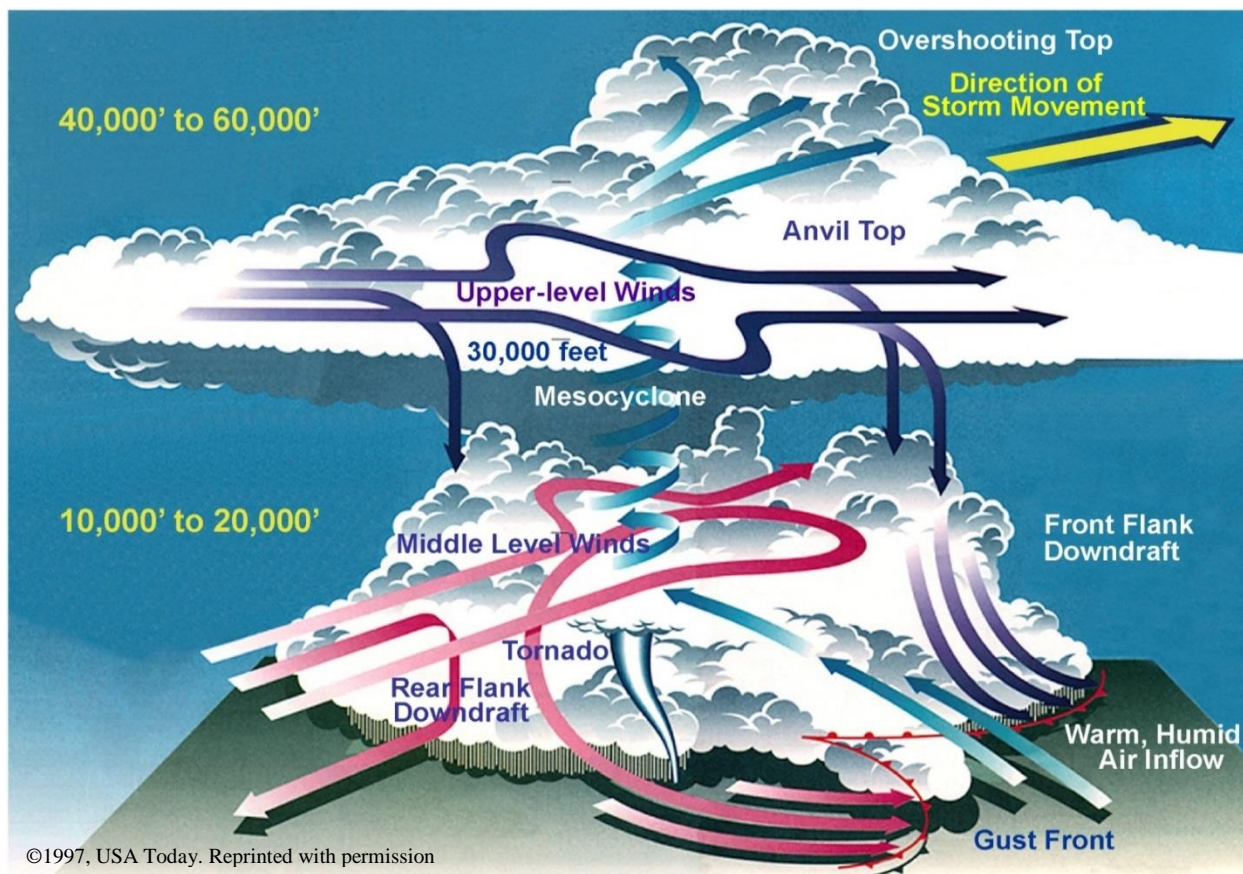


Figure 6.2 The structure of a super cell thunderstorm.

Supercells

Figure 6.2 shows the structure of a supercell and the winds associated with it. Refer to it as we discuss the various parts of a supercell and how it forms.

There are 200-300 supercells in the U.S. each year and they cause the majority of damage from thunderstorms and the most violent tornados.

The characteristic of a supercell that enables it to be so long-lasting is the presence of a large, stable *mesocyclone*, a rotating core that prevents the downdrafts from cutting off the updrafts. The rotation of the mesocyclone has several effects.

It ensures a continuing inflow of warm, humid air and the latent heat it carries, providing the energy to maintain the storm.

It supports the downward flow of cool air by adding water that increases cooling by evaporation. It directs the flow of descending air to the front and rear of the cell, not the center, so it does not interfere with the updrafts or the mesocyclone. The forward downdraft creates an extensive gust front which acts like a small cold front, pushing more moist air into the complex.

The formation of the mesocyclone is aided by vertical wind shear and an upper air inversion. Faster air above slower air forms the horizontal, rotating tube. Updrafts or downdrafts tilt the tube, making it a vertical rotation. The temperature inversion temporarily halts the growth of the cell until enough energy is available to explosively push through the inversion, creating the domed top shown in Figure 6.2. The picture on the first page of Part II is of a supercell.

Downbursts are caused when dry air is drawn into the sides of the thunderstorm, causing the precipitation to evaporate, cooling the air and forming rapid downdrafts which spread out as they reach the ground, as a gust front.

Microbursts are a particularly strong form of a downburst. They have wind speeds as high as 100 knots and cover a front of two to three miles. The strong, sudden wind shear causes more damage than the longer-lasting downburst.

Lightning and Thunder

There are approximately 25 million bolts of lightning each year. About 80% of lightning is in-cloud or cloud-to-cloud. The remaining 20% is cloud-to-ground and is the main cause of forest fires as well as most of the 55-60 lightning-related deaths, 400 injuries and over \$1 billion in damage.

Normally the surface of the Earth is negatively charged and the upper atmosphere is positively charged. Thunderstorms form local areas where these charges are reversed. The cause is not well understood, but may involve the upward and downward circulation of ice particles. This causes the lower part of the cell to be negatively charged, with upper layers being positive.

Wherever there are regions of opposite charge, the tendency is to neutralize them. Once the voltage difference becomes large enough, a bolt of lightning reduces the charge difference. As stated above, most of this is between charged areas within a cloud or between clouds.

The negative base of the thunderstorm causes a positive charge to accumulate on the ground below, and it moves with the storm. (The very bottom of the cloud may be positively charged). When the voltage is high enough, a negatively charged streamer is

drawn toward the ground, causing a positively charged streamer to be drawn up. When they meet, electrons flow between them in a series of flashes just milliseconds apart, making the lightning flicker. The bolt can have charges of 100 million volts.

This large, rapid influx of energy quickly heats the air, causing it to expand explosively. This rapid movement of air produces sound waves of all frequencies. Nearby lightning sounds like a crack. Since lower tones travel farther than higher ones, the tone of the thunder deepens with distance. This is one way to estimate how far away the lightning is, but there is another that is more accurate. Count the seconds from when you see the lightning until you hear the thunder. Dividing this time by five gives a good estimate of how many statute miles away it is.

Hail

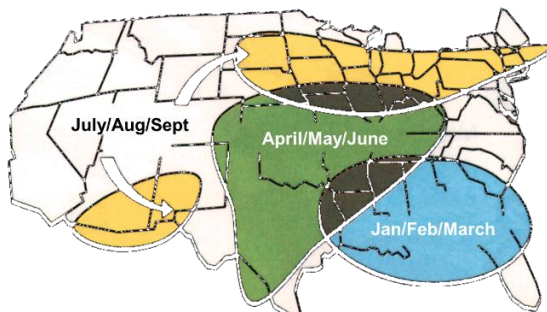
There are strong updrafts and downdrafts in mature thunderstorms. The ice particles that form in the upper levels can take several paths to solid precipitation. They can form sleet, snow, graupel, or hail. By definition, hail is larger than 0.6 cm ($\frac{1}{4}$ inch). The largest on record was 7 inches in diameter.

Under the right conditions, the updrafts in a strong thunderstorm can keep the forming ice particles suspended for long periods, giving them time to grow by collision with other particles or with super-cooled cloud droplets or rain. They will continue to grow until too heavy to be kept up by the updrafts, or the updrafts lessen.

If the thunderstorm lasts long enough and the updrafts are strong enough, the hail can take multiple trips up and down in the storm, adding layers with each trip. Sometimes softer layers (of snow or graupel) alternate with solid layers from super-cooled rain (like glaze ice).

Section 2. Tornadoes

On average, 1,000 tornadoes occur in the U.S. every year, killing 70 people and injuring 1,500. Property damage is large, primarily due to the largest, most destructive ones. They occur in all 50 states, but are most numerous in the Continental Plains with the Gulf Coast second. Tornadoes have occurred in every month and both day and night. The months with greatest frequency vary by region. See Figure 6.3.



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Figure 6.3 Occurrence of tornadoes varies across the U. S.

A tornado is a rapidly spinning column of air protruding from the bottom of a cumulonimbus cloud. Rotation is most often cyclonic. Subsidiary vortices may be embedded in the main vortex. It forms from a mesocyclone, that in an severe thunderstorms is smaller and weaker than in a super cell and is generally due to the low pressure caused by the rising air. A storm's classification as either a super cell or a severe thunderstorm is sometimes difficult.

A tornado's ground speed averages 25 knots, but has been observed as high as 60 knots. Small tornadoes have a diameter of 300 feet, travel less than a mile in less than three minutes and have wind speeds of 85 knots (100 mph). The largest tornadoes may have diameters of half a mile, travel 5 miles on average (occasionally much farther), and have

wind speeds over 250 knots (300 mph). Fortunately, most tornadoes are relatively weak.

Tornadoes are visible due to condensation, surface debris or dust, and often both. When a tornado has not touched ground, it is more properly called a *funnel cloud*. Tornadoes can form from any severe thunderstorm, but the most intense are from supercells.

How they Form

The stages in the generation of a tornado generally occur in the following sequence. First is the formation of the mesocyclone, generally about 30 minutes before the appearance of the funnel cloud. As the core is stretched by updrafts, it narrows, increasing the speed of rotation (think of a skater pulling in her arms). A dark, slowly rotating wall cloud protrudes from the base of the thunderstorm (see Fig 6.4). A thin, rapidly spinning vortex emerges from the wall cloud as a funnel cloud. Finally, as the funnel reaches the surface, it becomes a tornado and picks up dust and debris.



Figure 6.4 A wall cloud below a thunderstorm.

Destruction by tornados is primarily due to the combined action of strong rotary winds and damage from flying debris. Buildings are destroyed by the winds pushing the near wall inward. The roof is lifted up and the other walls fall outward. Contrary to popular belief, the low pressure at the center has very little effect. Most injuries and fatalities are due to flying debris.



Courtesy of NOAA

Figure 6.5 Typical small tornado.

The Fujita Scale

It is very difficult to measure the wind speed in tornados—even dedicated storm-chasers with sophisticated equipment have difficulty. Instead of wind speed, tornados are classified by the degree of damage. The Fujita scale, now modified and called the Enhanced F-scale, is the way the intensity of tornados is routinely reported. Values range from weak (EF-0) to violent (EF-5). The table in the next column provides a summary of *estimated* 3-second wind gusts for each category.

Watches and Warnings

The NWS issues watches and warnings for many types of severe weather, including severe thunderstorms and tornados. Watches are issued by the Storm Prediction Center in Norman, OK and warnings are issued by the local Weather Forecast Offices (WFO). All

watches and warnings share certain characteristics.

EF Scale	Estimated 3-second wind gust (knots)
EF-0	55 to 75
EF-1	76 to 95
EF-2	96 to 115
EF-3	116 to 145
EF-4	146 to 175
EF-5	Above 175

A tornado *watch* means that the conditions are right for the occurrence of the event. It generally covers tens of thousands of square miles for a 4-6 hour period. The public is expected to stay alert, monitor for weather updates, and be prepared to seek shelter.

A tornado *warning* means the event is occurring. It is based on sightings by people or Doppler radar. The warnings are issued for a smaller area (perhaps a city or county) and a shorter time period (30 to 60 minutes) than a watch. The public should leave mobile homes and cars and seek shelter in a sturdy building, an inner room such as a bathroom, hall, or closet, or in a basement. Do not open windows. If caught outdoors, lie down in a ditch or other low area. Do not try to outrun a tornado in your car unless you have no other choice, in which case, travel perpendicular to the tornado's path.

Other Types of Vortices

Water spouts come in two types. The first is a tornado that has moved from land to water. It has all the characteristics of a tornado. The other type is weaker, shorter lived, and not associated with a thunderstorm. It occurs under cumulus clouds that have not, and may never, become a thunderstorm. Winds are less than 55 knots and the duration is a few minutes. They can have either cyclonic or anti-cyclonic circulation. They tend to originate in warm air, over warm water, and with light winds. They are most common in tropical and sub-tropical waters, but have been seen as far north as New England. They can be dangerous to boaters. See Figure 6.6.

Gustnados are weak, short-lived vortices similar to tornados, but don't originate from a cloud. They are associated with small, intense turbulent eddies in gust fronts. Winds can be around 85 to 90 knots.



Figure 6.6 Typical non-tornado water spout.

Dust devils originate at the surface and go up into clear air. They happen most often in deserts where very hot air rises rapidly in a swirling motion. They are very short-lived and top wind speeds are in the neighborhood of 50 to 55 knots.

Section 3. Tropical Storms and Hurricanes

Tropical cyclone is the term for a category of storm systems originating in the tropics. The term encompasses all phases of these storms, from tropical depressions to hurricanes. Tropical cyclones are distinct from extra-tropical cyclones, the ones covered in Chapter 4. Tropical cyclones have a warm core, no fronts, are more or less symmetrical (round) and are vertically stacked. They are smaller and more intense than extra-tropical cyclones. The conditions needed for their formation are very different as well.

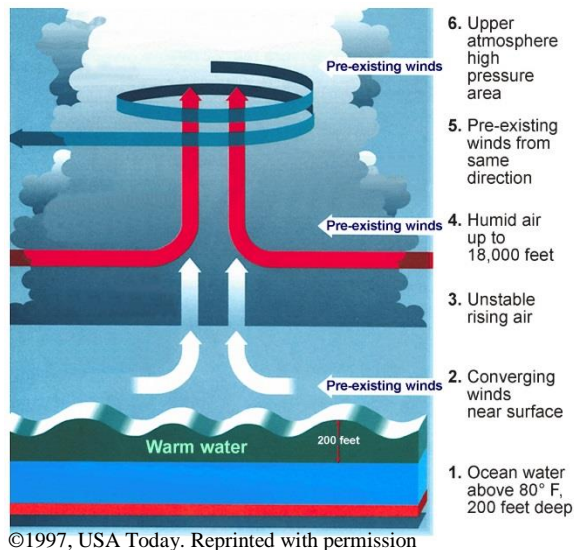
The conditions necessary for the formation of a tropical cyclone are:

- Water above 80°F, to enhance evaporation, in the top 60 meters (200 feet), to avoid stirring up colder water.

- Surface convergence, which can be from the ITCZ, a trough in the westerlies intruding into the tropics, or an easterly wave (see below).
- Unstable and humid air extending at least to the 500 mb level (18,000 ft.).
- At a latitude far enough north or south of the equator to have sufficient Coriolis Effect to cause rotation (about 5 degrees north or south latitude).
- Vertical profile of pre-existing winds from approximately the same direction and speed to keep from tearing the storm apart through wind shear.
- Divergence aloft that takes the rising air away from the storm.

Only about 8% of tropical disturbances become tropical storms. See Figure 6.7 for visual summary of required conditions (does not include the effect of latitude).

Hurricanes have different names in different parts of the world: In the western hemisphere, they are called hurricanes; in the western pacific they are called typhoons; in the Indian Ocean and NW Australia, tropical cyclones; and in NE Australia, willy-willy.



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Figure 6.7 Conditions necessary for formation of tropical cyclones.

Life Cycle

For simplicity, we will limit our discussion of life cycle to hurricanes that originate off the west coast of Africa. These are generally referred to as Cape Verde Hurricanes. The most likely lifting mechanism for these hurricanes is the easterly wave, with 60% of tropical storms and minor hurricanes and 85% of major hurricanes originating from an easterly wave. The stages are as follows:

- An *easterly wave* develops along the west coast of Africa. An easterly wave is a horizontal wave extending 2,000 to 2,500 km (1,200 to 1,500 miles) that travels to the west in the north east trade winds. It creates surface convergence

on its eastern side, one of the necessary conditions for formation of tropical cyclones.

- A *tropical disturbance* is a moving area of thunderstorms that lasts for a day or more, but has no rotary circulation. This is a common occurrence in the tropics and most dissipate without further development.
- Some of these tropical disturbances form a *tropical depression*, taking on cyclonic circulation. Winds are less than 34 knots (39 mph).
- It becomes a *tropical storm*, when it strengthens, with wind speeds of 35 to less than 64 knots (74 mph). At this point, the NWS gives the storm a name.
- It becomes a *hurricane* when the winds are 64 knots (74 mph) or more.
- It enters the *dissipation* phase when it moves over land or colder water, because it needs a constant source of warm water and an unstable lapse rate.

Structure

Tropical cyclones are essentially circular, 500 km (300 miles) wide on average, with an eye 30 to 50 km (20 to 30 miles) in diameter. A typical core sea-level pressure is 950 mb and circulation is cyclonic at lower levels, but anti-cyclonic aloft (to remove the rising air through divergence). See the discussion of warm-core lows in Chapter 4. Air spirals up around the core and exits at high altitude. This lifting motion causes low pressure at the surface, creating a large pressure gradient, which drives the high winds. The most important source of energy is the release of latent heat. The winds are strongest in the *eye wall* that surrounds the eye.

Within the eye, however, the air is descending, causing clouds to dissipate. The

eye has light winds but very confused seas, due to the surrounding winds.

Clouds line up in long bands spiraling into the center. They are also called rain bands or feeder bands. There is much convective activity in the bands, including thunderstorms, with descending air between them. They are normally 65 to 140 km (40 to 80 miles) apart. See Figure 6.8 for an example.

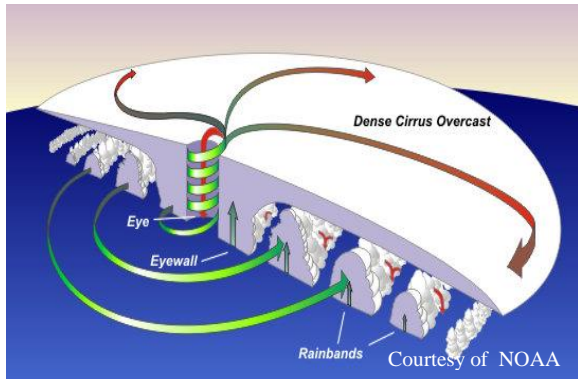


Figure 6.8 Typical structure of a hurricane.

Meteorologists have recently recognized a third type of cyclone, the semi-tropical cyclone. It has characteristics between a tropical cyclone and an extra-tropical cyclone, including fronts but with a more circular shape.

Categories

The strength of a hurricane is measured by the *Saffir-Simpson Damage Potential Scale*. The categories are 1 through 5 and are based on central pressure, wind speed, and the height of the storm surge. Category 3 or greater is considered a major hurricane.

- Category 1 (74-95 mph) will cause *minimal* damage, to things such as trees or shrubs and unanchored mobile homes.
- Category 2 (96-110 mph) will cause *moderate* damage. Trees will be blown down, there will be major damage to exposed mobile homes, and some damage to roofing, windows, and doors.
- Category 3 (111-130 mph) will cause *extensive* damage. Mobile homes will be destroyed, large trees blown down, and there will be structural damage to small buildings.
- Category 4 (131 to 155 mph) will cause *extreme* damage. Many small residences will experience complete roof failure.
- Category 5 (over 155 mph) will cause *catastrophic* damage. There will be complete failure of roofs of residential and commercial buildings. Some buildings will completely fail.

In spite of the reliance on wind speed in the above definitions, it has to be said that the most damage is not caused by sustained winds, but by flooding from rain and the storm surge. In addition, there can be tornadoes embedded in the thunderstorms, which can be expected to cause much more damage than the sustained winds.

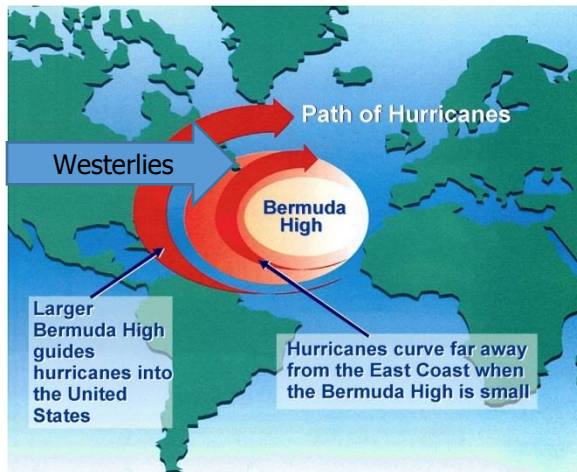
Storm Surge

The most destructive part of a hurricane is the *storm surge*. Storm surge is the water that is pushed ashore by the winds, with more on the right side (on-shore winds). It arrives not as a wall of water like a tsunami, but as a gradual rise in the tide, topped by wind-driven waves. It is worst when it coincides with the normal high tide.

Because much of the Atlantic and Gulf coast is less than 10 feet above sea level, these storm surges can inundate large areas and the waves can cause extensive damage to buildings. The level of the surge is affected by the slope of the continental shelf—the shallower the slope, the more the surge. Tides, waves and currents in confined harbors open to the winds can cause significant damage to boats.

Storm Tracks

Storm tracks are affected by both the position and intensity of the Bermuda High and the upper-level winds. Hurricanes first travel west with the trade winds, but when they get above about 30°N, the prevailing westerlies curve them to the north or northeast. If the Bermuda High is large, or the steering winds weak, the storms can make landfall in the southern U.S., the Caribbean, or Mexico. If the Bermuda High is smaller or farther north, they can make landfall on the East Coast. Strong steering westerlies and a more easterly position for the Bermuda High can result in the hurricanes remaining in the Atlantic (Figure 6.9).



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Figure 6.9 Effect of the Bermuda High on hurricanes.

Watches and Warnings

The dilemma the NWS has in issuing storm watches and warnings is that they can

err on either the optimistic or pessimistic side. The wider the area covered, the more likely it is that people will take unnecessary actions, with the increased cost as well as the negative feelings that NWS is “crying wolf.” The other side of the coin is that the narrower the area covered, the more likely that there will be preventable damage. The NWS issues the following watches and warnings for hurricanes.

A *gale warning* is issued when winds are expected to be 34 to 47 knots (39 to 54 mph).

A *storm warning* is issued when winds are expected to be 48 to 63 knots (55 to 73 mph).

A *hurricane watch* is issued for coastal areas when hurricane conditions (64 knots or greater) are expected within 48 hours.

A *hurricane warning* is issued when hurricane conditions are expected in less than 36 hours. These include winds of 64 knots (75 mph) or greater and dangerously high tides and waves.

An *extreme wind warning* is issued if winds greater than 100 knots (115 mph) are expected within an hour. This is usually due to the passage of the *eye wall*.

A *flash flood watch* is issued when flood conditions are possible in an area.

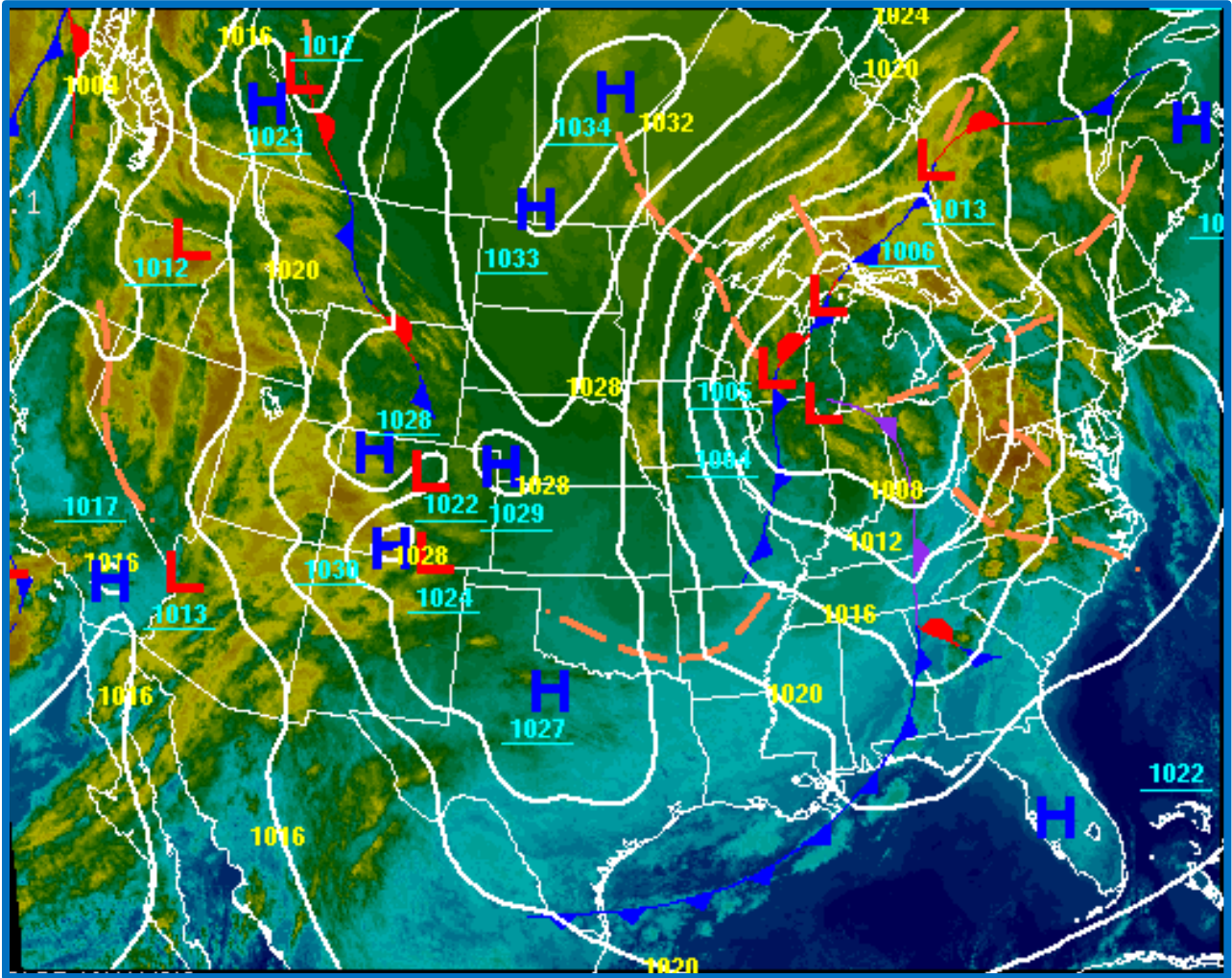
Study Questions—Chapter 6

- The life cycle of a thunderstorm has stages:
 - Synoptic, meso, and micro.
 - Cumulus, mature, and dissipating.
 - Cumulus and Cumulonimbus.
 - Updraft and down draft.
- The first stage of a thunderstorm cell has:
 - Downdrafts only.
 - Updrafts only.
 - Updrafts and downdrafts.
 - None of the above.
- The mature stage of a thunderstorm cell has:
 - Downdrafts only.
 - Updrafts only.
 - Updrafts and downdrafts.
 - None of the above.
- The dissipation stage of a thunderstorm has:
 - Cold updrafts.
 - Cold downdrafts.
 - Warm updrafts.
 - Warm downdrafts.
- Squall lines are long lasting because:
 - Existing cells cause others to develop.
 - Cells multiply by splitting.
 - Cells don't have a dissipation stage.
 - None of the above.
- The distinguishing characteristic of a super-cell is:
 - It has no downdrafts.
 - It contains a rotating mesocyclone.
 - It never produces tornados.
 - There are no other thunderstorms in the area.
- The condition(s) that favor the development of thunderstorms are:
 - A supply of warm, moist air.
 - An unstable lapse rate.
 - A lifting mechanism.
 - All of the above.
- Individual thunderstorms on a hot afternoon are most likely:
 - Orographic.
 - Air mass.
 - Frontal.
 - Squall line.
- As a thunderstorm approaches, the wind is likely to be:
 - First out of the cloud, then toward it.
 - First toward the cloud, then out of it.
 - First cold, then warm.
 - Light and variable.
- Downbursts and microbursts are associated with:
 - Nimbostratus clouds.
 - Cumulonimbus clouds.
 - Towering cumulus clouds.
 - Down-slope winds.
- Microbursts are more dangerous than ordinary downbursts because of their:
 - Tendency to form out of a clear sky.
 - Small size, high winds, and sudden onset.
 - Relatively long life and large area.
 - Association with developing thunderstorms.

12. The estimated distance to a thunderstorm if you hear the thunder 20 seconds after you see the lightning is:
- 4 kilometers.
 - 2 statute miles.
 - 4 statute miles.
 - 2 nautical miles.
13. Tornados are:
- Rotation vortices that do not touch the ground.
 - Micro-hurricanes.
 - Rotation vortices that touch the ground.
 - Severe thunderstorms.
14. Tornados have been observed in:
- Only the gulf coast and east coast.
 - All 50 states.
 - Only during the winter.
 - Only during the summer.
15. Tornados are known for their:
- Enormous destructive paths.
 - High winds.
 - Ease of forecasting.
 - Long lifetimes.
16. The most intense tornados are associated with:
- Hail.
 - Supercells.
 - Squall lines.
 - Mesoscale convective complexes.
17. The Enhanced Fujita scale for tornados is based on:
- The measured wind speed.
 - The intensity of the radar echo.
 - How long it lasts.
 - The amount of destruction.
18. Non-tornado water spouts:
- Occur in fair or foul weather.
 - Have lighter winds than tornados.
 - May rotate in either direction.
 - All of the above.
19. The inter-tropical convergence zone (ITCZ) is:
- A zone of convective activity.
 - Between the NE and SE trade winds.
 - Varies its position with the seasons.
 - All of the above.
20. The Bermuda high:
- Is larger in the winter than the summer.
 - Affects the tracks of Atlantic hurricanes.
 - Has cyclonic circulation.
 - Affects only ships at sea.
21. Compared to extra-tropical cyclones, hurricanes are:
- Smaller and more intense.
 - Larger and more intense.
 - More numerous.
 - Also have fronts.
22. The *principle* source of energy required to maintain a hurricane is:
- Latent heat.
 - Strong upper level winds.
 - Surface convergence.
 - Wind shear.
23. A tropical cyclone is given a name when:
- It becomes a hurricane.
 - It has winds of 39 mph (34 knots) or more.
 - It is expected to make land-fall.
 - A hurricane warning is issued.
24. The eye of a hurricane is an area of:
- Rising air.
 - Descending air.
 - Calm seas.
 - Maximum winds.

25. The strongest winds in a hurricane are located:
- a) In the eye.
 - b) On the outer edges.
 - c) In the eye wall.
 - d) None of the above.
26. The relatively clear area of the eye results from:
- a) Descending air.
 - b) Rising air.
 - c) Confused seas.
 - d) Wind shear.
27. After heading north, an Atlantic hurricane turns NE due to:
- a) The NE trade winds.
 - b) The circulation of the Bermuda high.
 - c) The colder water.
 - d) None of the above.
28. The National Weather Service (NWS) calls a hurricane “major” if it is:
- a) Category 5.
 - b) Category 4 or above.
 - c) Category 3 or above
 - d) Category 2 or above.
29. A hurricane watch is issued if:
- a) Hurricane conditions are expected within 48 hours.
 - b) Hurricane winds are over 80 knots.
 - c) The area will experience high winds.
 - d) The area will experience storm surges.
30. A hurricane warning means:
- a) The eye is within 300 nautical miles.
 - b) Hurricane conditions are expected within 36 hours.
 - c) There will be storm surges of over 15 feet.
 - d) The area will experience winds over 100 knots.

Part III—Practical Application



Courtesy of NOAA

Chapter 7: Observation and Forecast Data Sources

Chapter 8: Preparing for and Executing a Mission

Chapter 7 Observation and Forecast Data Sources

Section 1. Sources of Observations

Introduction

In Part I, we talked about the science of meteorology—temperature, pressure, moisture, stability, etc. In Part II, you were introduced to the various forms of sensible weather, such as clouds, precipitation, thunderstorms, hurricanes, and the like. In Part III, we will discuss the sources of both observations and forecasts that you can use in preparing for your patrols. These are legion, and the problem is not having enough information, but having too much! How do you choose what materials to refer to? Each coxswain, aircraft commander, and his or her crew, will need to experiment and settle on what works best for them.

To anticipate Chapter 8 a bit, a general approach that works well is to first look at various internet sources to see what is happening now and relate it to what you see around you, then to look at the forecasts and make a decision.

To be more specific, first study the current situation on your favorite weather web site.

Second, relate what it tells you to what you see around you—winds, humidity, temperature and clouds. Even in the most benign cases, take a quick look at local radar and satellite data.

Third, look at the surface weather forecast charts as well as the verbal descriptions

or summaries. Decide what you expect to see during your patrol.

Finally, monitor the sky and occasionally check the data sources you have available. If something changes, get more data! If unsure, you may have to make the decision to abort the mission. Safety of you, your crew, and your facility is paramount.

This chapter uses data collected for one day and time so that comparisons can more easily be made between products. The date chosen is partly due to some interesting features, but mostly due to the timing of the writing of this chapter. The observations are for 1200Z, 16 Dec 2014. Tips on what to look for and how to interpret these products are a significant part of the discussion.

Section 1 will cover the basic observational data and charts available from the NWS and then briefly review what is available from smart phone apps.

Section 2 will discuss how forecasts are made and introduce the various forecast products.

Surface Charts

Surface charts are produced every three hours by the Weather Prediction Center (WPC), at 00Z, 03Z, etc. They include highs, lows, fronts, isobars; and with or without station models that include sky cover, wind, temperature, dew point, pressure, pressure tendency, visibility, and present weather. An example is in Figure 7.1 on the next page.

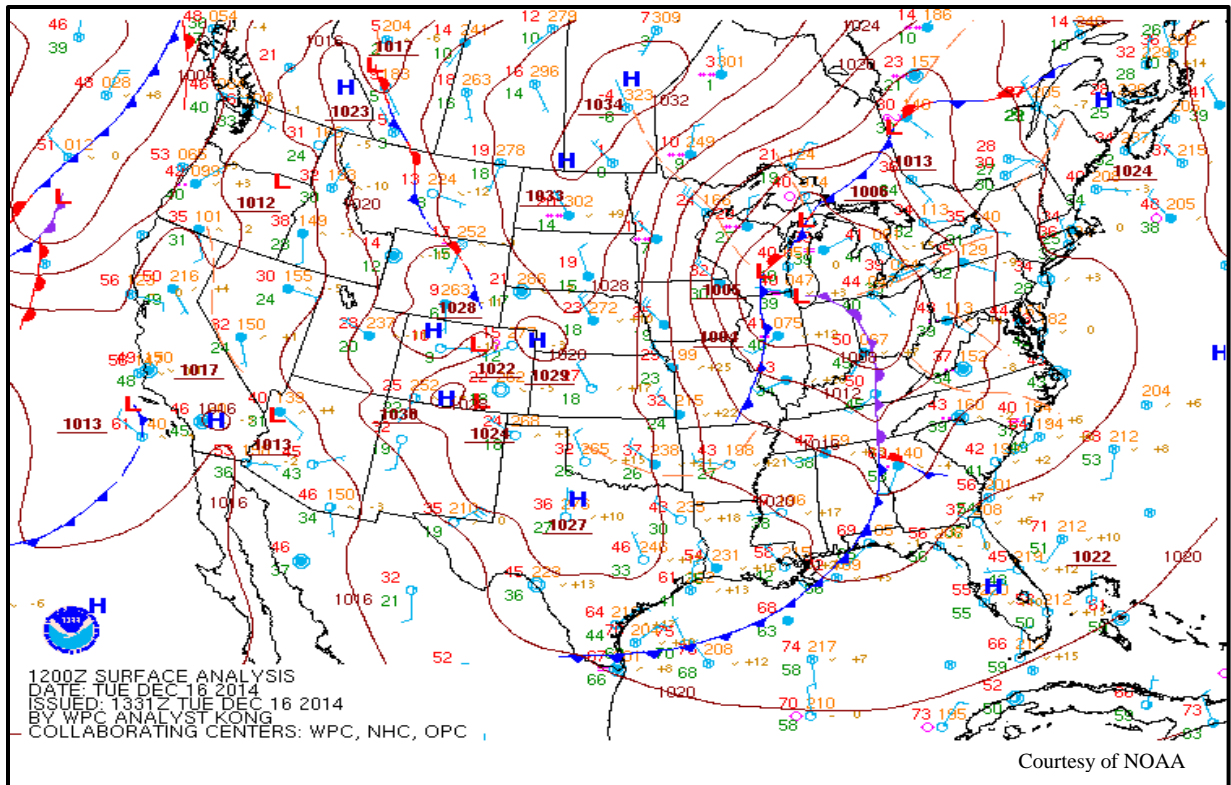


Figure 7.1. Surface analysis for the United States, 12Z, 16 Dec 2014.

This surface analysis (Figure 7.1) shows several interesting features:

- A large, deep high pressure area through the central U.S. and Canada, with a central pressure of 1024 to 1034 mb.
- A well-developed cyclone near Lake Michigan, with an occluded front, a central pressure of 1006 mb, and a large area of precipitation.
- To the north of it, a stationary front from a previous cyclone.
- To the west of it, a weaker cyclone in the process of merging with it.
- Two weak cyclones approaching the west coast.
- A cold front off the NW coast from a very deep low (central pressure 978 mb) in the Gulf of Alaska (not shown here).

Figure 7.1 is the baseline from which we will compare other products as well as the forecasts covered in Section 2

The data from those charts, along with radar and/or satellite data are combined in simpler charts, such as the one in Figure 7.2, which combines the surface analysis with infrared satellite data and Figure 7.3, which combines the analysis with radar data.

Both types of analyses, as well as many others, both B/W and color, and with or without the station models, are available at: www.wpc.ncep.noaa.gov/html/sfc2.shtml.

Other types of surface products include marine wind and wave analyses, and analyses covering much larger areas, such as North America and ocean areas.

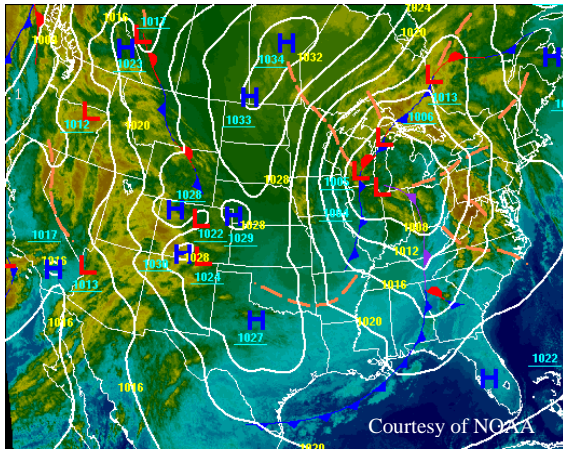


Figure 7.2. Combined surface analysis and IR satellite data.

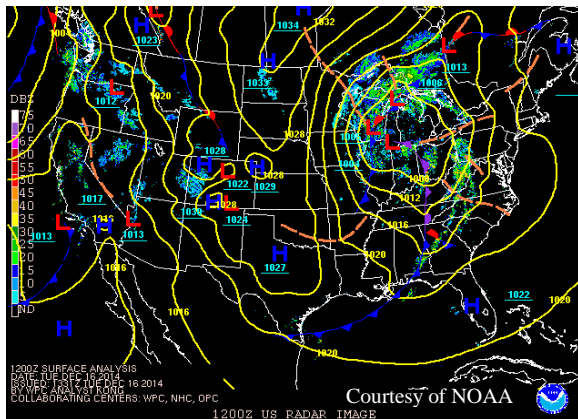


Figure 7.3. Combined surface analysis and radar.

Radar Data

Satellite and radar data are included in Figures 7.2 and 7.3. We will go into much more detail on this in the next sub-section.

These data, and the analyses above, can be reached through links on the left side of the NWS Weather Prediction Center page at: <http://www.wpc.ncep.noaa.gov/>

Radar data are available in three scales: Single radar, regional, and national. The composite displays are always from a time before the single radar displays, because it takes time to combine all the local radar data. See Figures 7.4, 7.5, and 7.6 (next page).

The color scales represent the intensity of the returns. All of these radar depictions can be looped, usually for about the past hour. There are many display options for the local radars, including counties, roads, cities, and warnings such as tornado, severe thunderstorm, flood, and special marine warnings.

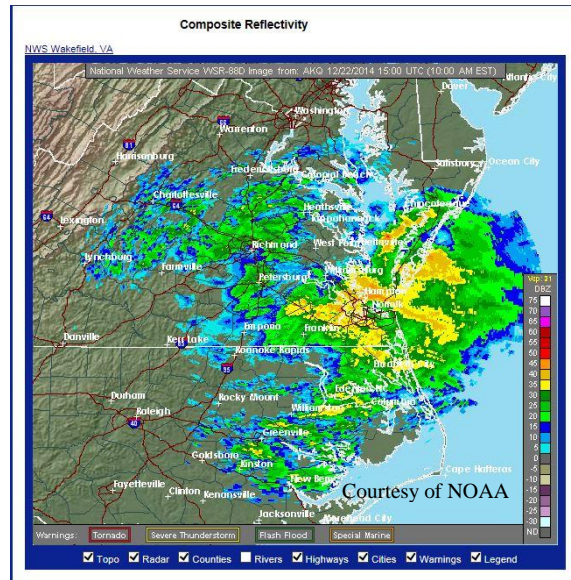


Figure 7.4. Local Radar Display (single radar).

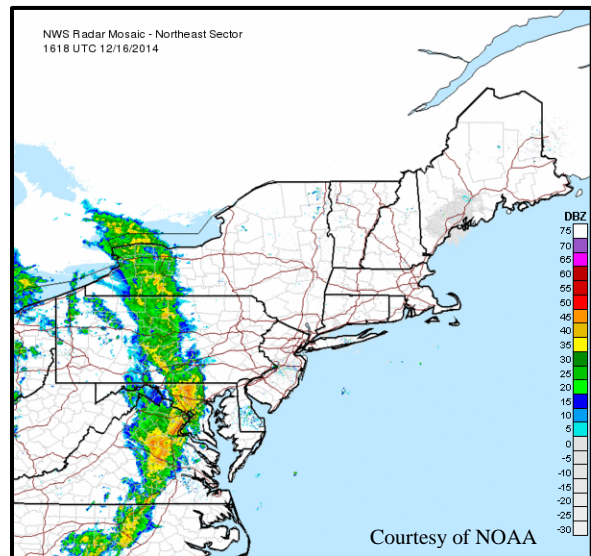


Figure 7.5 Regional radar mosaic for the NE U.S.

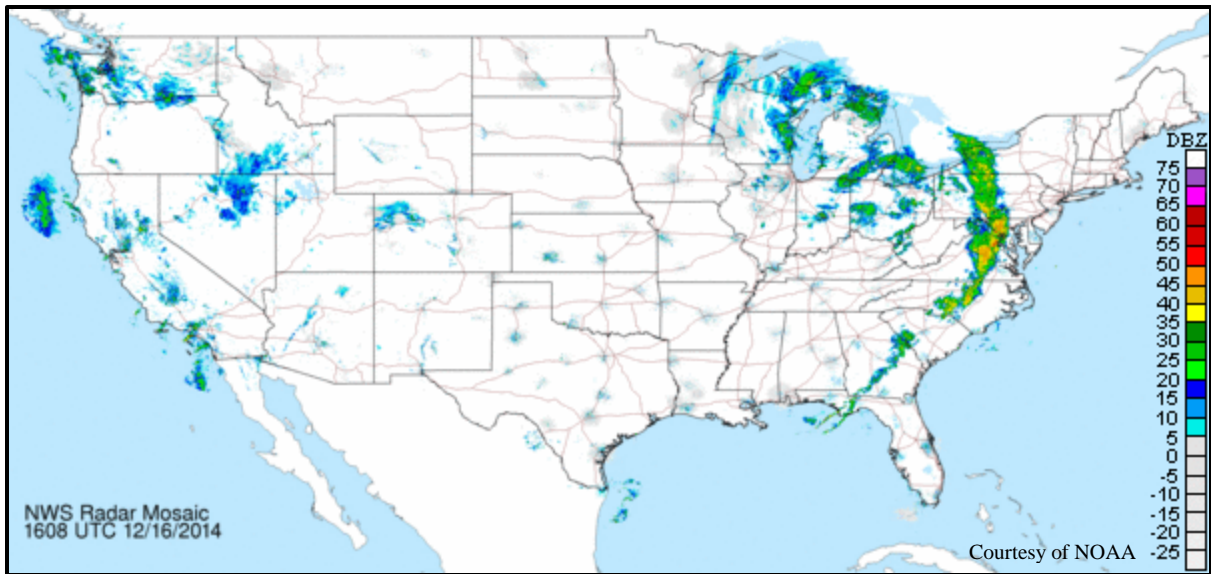


Figure 7.6. National composite radar mosaic.

Weather radars today are Doppler radars which use the Doppler Effect to measure motion in a storm toward or away from the radar (see Appendix A). This not only allows storm movement to be tracked in real time, it also allows tornados to be spotted much earlier and with greater confidence. They also have a special “slow scan” mode that can measure the movement of clear air and locate turbulence.

The development of these radars was a joint effort of the Department of Transportation (DoT), Department of Defense (DoD), and Department of Commerce (DoC), a program called NEXRAD (Next Generation Radar). The operational prototype was installed at Norman OK in 1990, and the operational deployment of 160 radars was completed in August, 1997 (Figure 7.7). The military also operates several units at overseas locations.

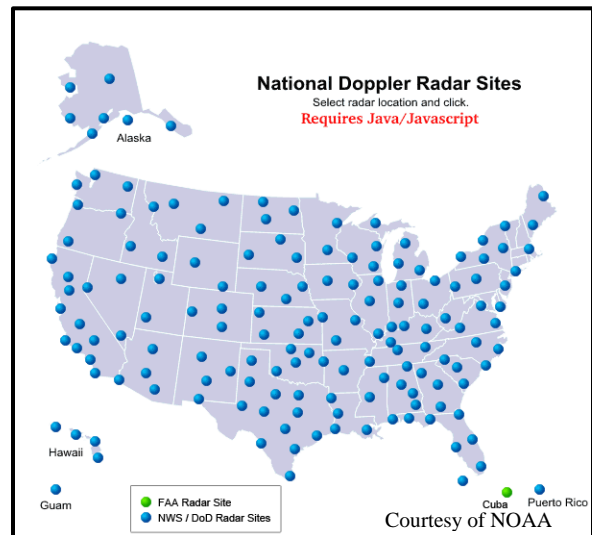


Figure 7.7 Sites of Doppler radars in the U.S.

Satellite Data

There are two basic types of weather satellites. Geostationary satellites hang essentially stationary over the equator at some longitude. The NOAA NESDIS⁶, as of this writing, has two active satellites and one spare, called GOES (Geostationary Operational Environmental Satellite). One, GOES East, is at

⁶ National Environmental Satellite Data and Information Service.

75° W longitude. The other, GOES West, is at 135° W. The primary spare, currently GOES 14, is stored at 105° W, where it can be moved in either direction to cover a failure of GOES East or West. NOAA also has access to the European Meteosat satellite data. A limitation is distortion near the poles.

Polar orbiting satellites are designed to cover N-S swaths. Each orbit takes about 90 minutes and the longitude of equator crossing moves west in such a way that the sun is always at the same angle (called sun synchronous). The orbit altitude is about 850 km, compared to the GOES altitude of almost 36,000 km. Because they are closer, they have greater resolution—that is, they can see smaller features. The NOAA polar orbiters are called NOAA-n (where n is a number). NOAA also uses the METOP satellites of the European Meteorological Satellite Agency, EUMETSAT. As of this writing, the primary PM (afternoon) satellite is NOAA-19 and the AM (morning) satellite is METOP-B. There are two NOAA and one METOP as backup.

There are also U.S. Air Force polar orbiting satellites designed especially to meet military needs. They are in orbits similar to NOAA and METOP satellites. They are called Defense Meteoroidal Satellite Program (DMSP) satellites. One unique feature is the low-light visible sensor that can operate with moonlight and can locate city lights, fires, etc. The number currently operational is not available, but there are two primary satellites. The latest, DMSP-19, was launched in April 2014. The program is managed by the Air Force, but routine operation is done by NOAA, which has access to the data.

There are many satellite products of use to professional meteorologists. Of most use to us as Auxiliarists are three wavelength bands of GOES images: Visible, Infrared (IR), and Water Vapor. Samples of these are

to the right, taken at nearly the same time as the surface data above.

The visible images are from light scattered from clouds. The visible sensor sees clouds at all altitudes, but can't determine their altitudes with much accuracy, except through visual appearance. (Figure 7.8)

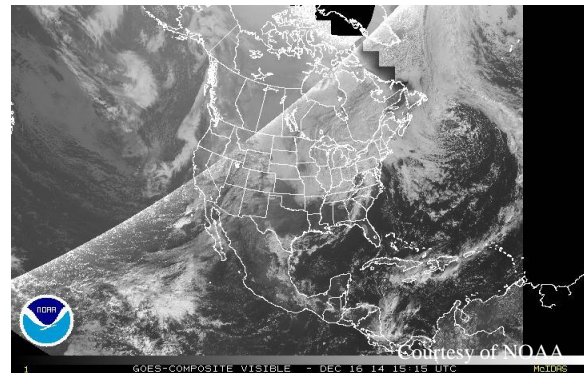


Figure 7.8. Visible composite image from GOES East and West.

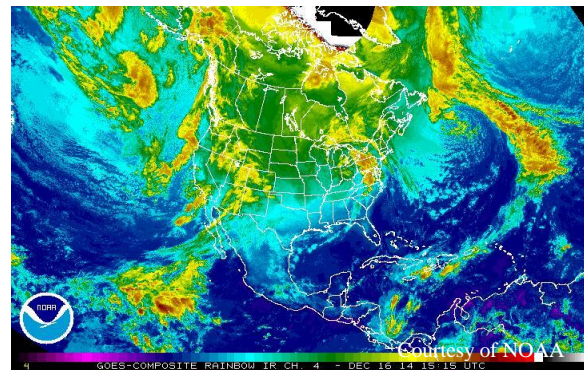


Figure 7.9. IR1 composite from GOES East and West.

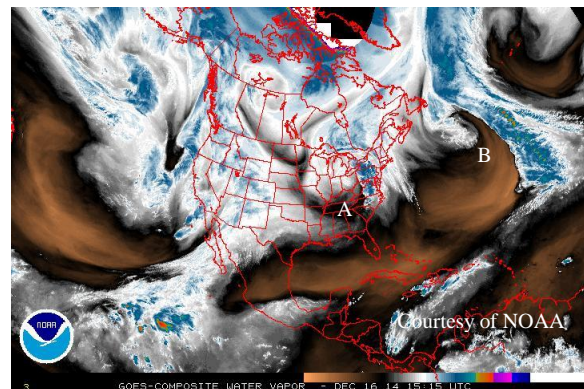


Figure 7.10. Water vapor composite image.

The IR images display the temperature of the cloud or surface, with lower temperatures signifying higher altitudes (Figure 7.9). IR 1 is in the far infrared, a thermal channel that measures temperature. Therefore, one can more easily tell stratus from altostratus or cirrostratus, for example. Note the white area in the middle of the country, from the Great Lakes to the east coast, in the visible image. In the IR image most of this area is green, signifying warmer clouds, whereas the area around the large cyclone is yellow or brown, signifying colder, and therefore higher clouds. Note that the colors are chosen arbitrarily to allow human eyes to better distinguish the subtle differences in intensity. The scale at the bottom shows warmest to coldest from left to right.

The water vapor channel on GOES measures the total amount of water vapor over the entire depth of the atmosphere at each pixel location (Figure 7.10). The color scale goes from driest on the left to moistest on the right. One can clearly see the cyclonic flow in the various storm systems (see A and B in the figure). In the center, the continental polar air is dryer, although the air mass is old enough that the water vapor has modified it considerably. Also, see the tongue of dry air being entrained into the SW section of several of the low-pressure systems (A and B).

The large area of dry air to the south is from another cP air mass that lingered over the eastern U.S. for days so did not pick up much moisture. It was not until the 15th that it was pushed to the south. This illustrates the insight gained looking at past analyses.

Upper Air Charts

Upper air analyses are produced every 12 hours, with valid times of 00Z and 12Z. They are produced for pressure surfaces of

1000, 850, 700, 500, 300, 200 and (on occasion) 100 mb. The 500 mb analysis for 12Z, 13 Dec 2014 is on the next page (Fig 7.11). The isoheights are in decameters (500 decameters is 5 km). The isotherms (dotted red) are in Celsius.

For comparison, a surface analysis is shown below the 500 mb analysis (Fig 7.12). For the comments below, refer to both charts.

The two lows in the center of the country on the 500 mb chart are quite different in their characteristics. The one over Lake Michigan is directly above the primary surface low, while the other one is to the NW of the surface lows. The western one, just north of Minnesota, has a strong cold core, which increases the air density, and is why there is not an associated surface low (See cold-core lows in Chapter 4).

The prominent ridge over Alberta and Saskatchewan, stretching through the plains states, is reflected by the large surface high over and north of the Dakotas. This is a common occurrence in the vertical structure of the atmosphere, where the pressure systems tilt to the west with altitude.

Although the lows are fairly well defined on both charts, the surface chart shows many small highs in the plains states that are due to local influences. The primary high stretches from Manitoba to Texas.

The east side of the ridge has some negative temperature advection, causing the surface high to move to the east.

There is strong divergence to the east of the trough, causing the low to move quickly to the ENE.

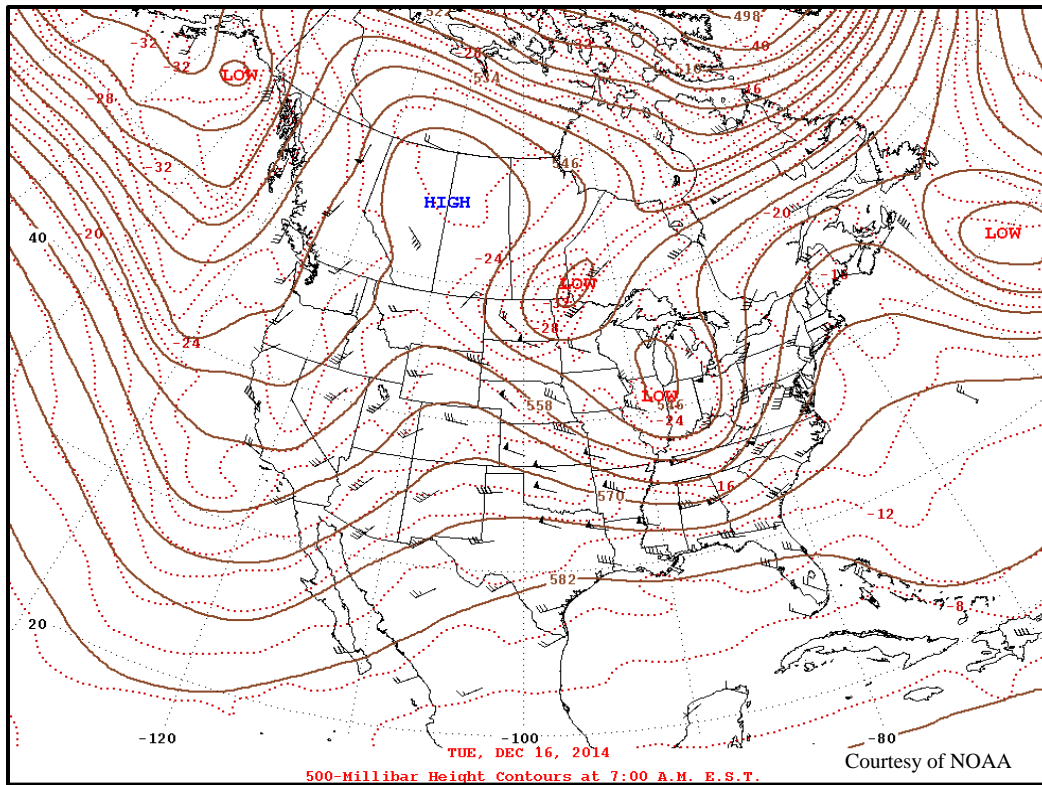


Figure 7.11. 12 Z 500 mb analysis, with isoheights and isotherms (red).

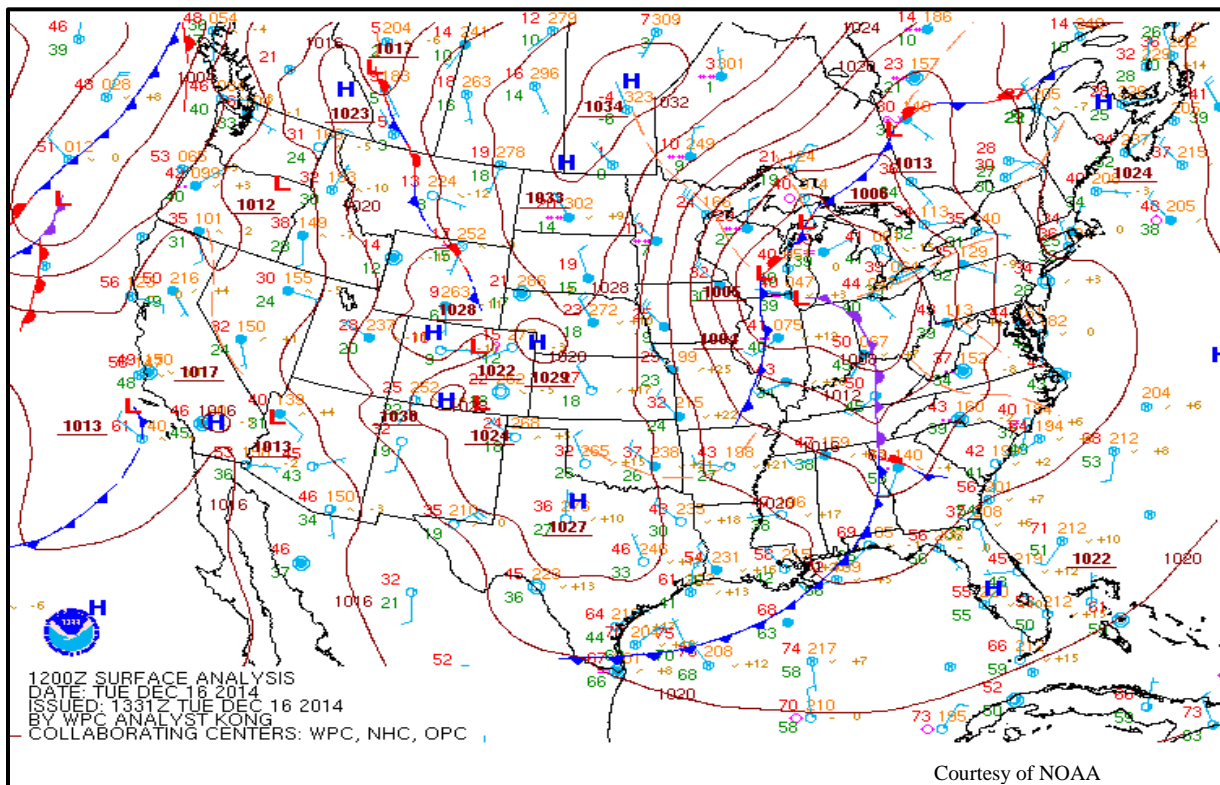


Figure 7.12. 12 Z Surface analysis for comparison.

Section 2. Sources of Forecasts

How Forecasts Are Made

There are several techniques, besides the modern computer models, to make a forecast. Each technique is applicable to some situations, but not all of them. They were all used in some form prior to the development of numerical (computer) forecasting, and some of them are still in use.

Persistence Forecasting assumes the weather does not change. How in the world could that be of any use? It's a reasonable approach over short time periods, or in areas where there is little change in the weather, such as San Diego. The weather tomorrow will be pretty much like the weather today.

Trend Forecasting (called extrapolation in the previous course) says that the movement of weather systems is linear. If a Low moved 500 km in the last 12 hours, we assume it will move 500 km in the same direction for the next 12 hours. This technique is particularly useful for short-term forecasting, such as the movement of thunderstorms, tornados, microbursts, and similar phenomena. Since the warnings for these must be issued quickly, it is often called *Nowcasting*.

Analog Forecasting (called analogy in the previous course) is based on the assumption that weather patterns repeat themselves. Forecasters find well-established patterns in the past that match (are analogous to) today's situation. This was the principal technique used prior to numerical forecasting. Obviously, the more experienced the forecaster was in his or her area, the better the forecasts. There is a form of analog forecasting still used today. It is called *pattern recognition*, and is used to improve short-range numerical forecasts.

Climatological Forecasting (called historical in the previous course) makes use of climatology data. It is useful for long-term planning for agriculture or business. Long-term climatological forecasts (decades to centuries) are an on-going area of research on climate change.

Finally, this leads us to the modern techniques of *numerical forecasting*. The mathematical equations that describe the development of weather systems are a set of what are called non-linear, partial differential equations. That's a big mouthful, but what it really means is they can't be solved by normal analytical methods, like simple algebraic equations. They can only be solved by approximations, in a repetitive series of calculations, called *iteration*, that come closer and closer to the answer.

The basic approach is that the atmosphere is divided up in a 3-D grid pattern with up to 100 layers and grid points from 2 to 50 km apart, depending on the area covered (regional or global). See Appendix B for an example. Since the observations are not on the grid points, they are interpolated to assign initial values at the grid points.

Using linear approximations to the equations, the grid for the next time-step (several minutes) is calculated. This process repeats many times, building up a forecast of hours, days, or a week or two.

The primary sources of error are that the input data are not continuous (are known only at the observation stations), and are not infinitely accurate, so small errors grow with time. The better the input data, the more accurate the forecast, but that only goes so far. It has been proven mathematically that there

will be increasing inaccuracies no matter how good the data. This is a result of *chaos theory*, which has also been called the “butterfly effect” (a butterfly flapping its wings in Brazil will eventually affect the weather in Boston). Of course that is nonsense—the effect of the butterfly will be damped out by other random occurrences.

Is there any way to improve on this situation? Actually, there are several. One is called *ensemble forecasting*. The input data are altered slightly in a variety of ways and all inputs are run by the model. They can have similar outputs or wildly different outputs. The first means the reliability of the forecast is good. The latter means one should have less confidence in the results.

A second technique is called *model output statistics*. All forecasts are verified by subsequent observations. Given enough cases and enough time, forecasters can gather information on what conditions cause the models to be less accurate. This information can then be applied to future forecasts for similar circumstances, improving the accuracy of the forecasts.

Presently, meteorologists estimate that detailed forecasts are more correct than chance out to about two weeks. Longer forecasts are still possible, but they address average conditions, not specific conditions at a specific time. Climate models are the ultimate form of this. Forecasts of basic properties like average temperature of the globe are quite good. Forecasts of future average precipitation are less reliable, and regional climate forecasts are less reliable still.

Surface Forecast Charts

Surface forecast charts take several forms, from detailed prognoses similar to analyses, to simpler charts that show only pressure centers, fronts, and precipitation.

Several examples are shown below. These are also available on the NWS web site at <http://www.wpc.ncep.noaa.gov/>. Like radar data, several of these are available as loops.

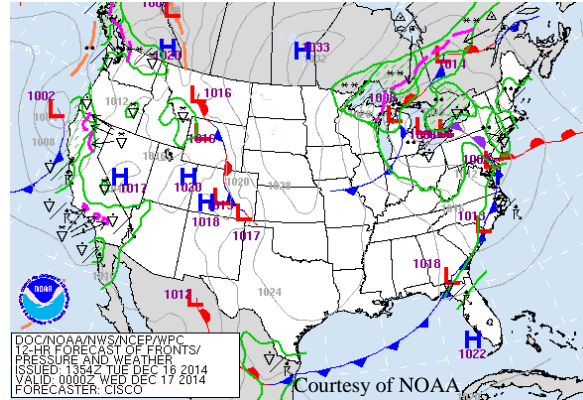


Figure 7.13. 12-hour surface forecast.

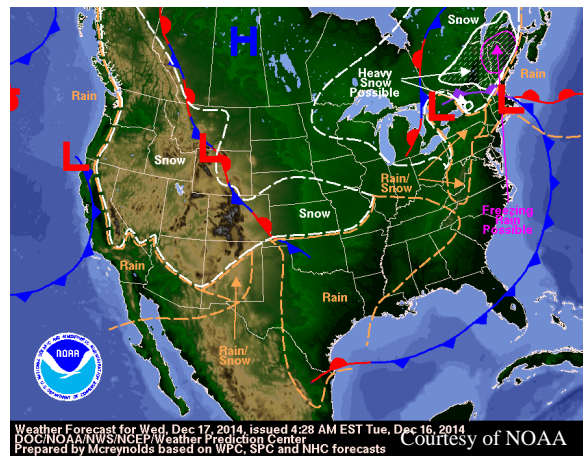


Figure 7.14. Simple 24-hour surface forecast (compare with Figure 7.15).

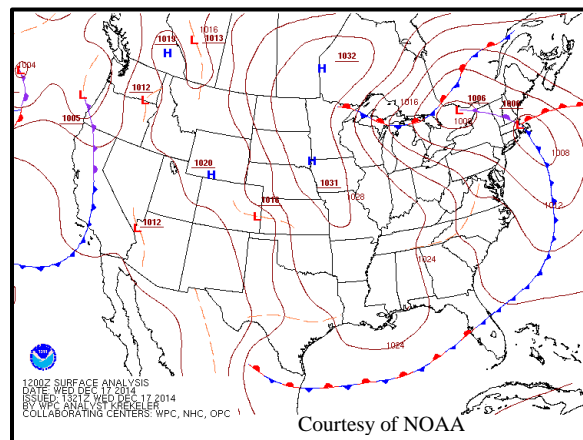


Figure 7.15. Surface analysis for the same time as Figure 7.14, for comparison.

There are specialized forecasts such as *Quantitative Precipitation Forecasts* (Figure 7.16), flood, winter weather, etc. There are also forecasts specifically for mariners, such as wave direction and period forecasts (Figure 7.17), and marine text forecasts, identical to forecasts on VHF weather channels (Figure 7.18).

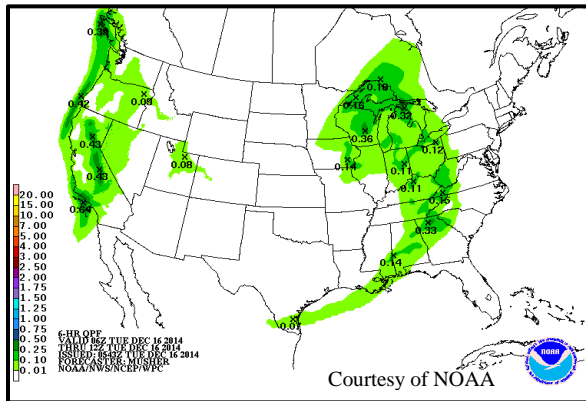


Figure 7.16. 6-hour quantitative precipitation forecast.

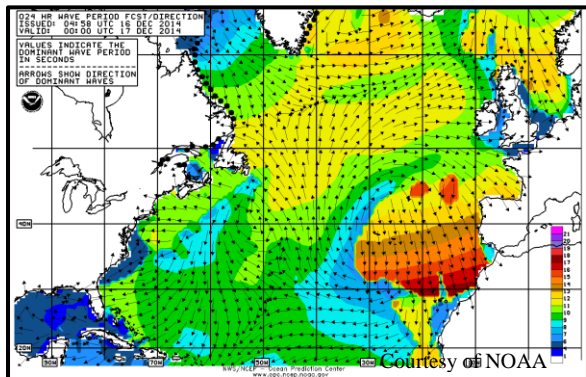


Figure 7.17. 24-hour wave direction and period forecast for mariners

Where to Find the Forecasts

Clearly, there are forecasts to satisfy almost everyone, from fire fighters, to SAR Coordinators, to farmers. The next two pages have images of some locations on the NWS web site (these are for a later time than the rest of the charts). The first is a page that has short-term forecast charts, and it can be used to navigate to just about any other forecast. Note the long list of links. The second image

is a page designed for a given local area. You can enter any city name and get this page for yourself—suggest you make it a favorite. The bottom was cropped so it would fit the page. The bottom of the page (not shown) has embedded images of (and links to) the local radar and IR satellite data. There are also small high temperature and precipitation probability forecasts and plots of data for the past 48 hours. Clicking on any of them takes you to the associated web page.

Another source for weather observation, forecasts, and radar and satellite data is apps on smart phones and tablets. There are many apps available, but none of them do everything well, so you will need several. Experiment with the free apps, then buy those you like best.

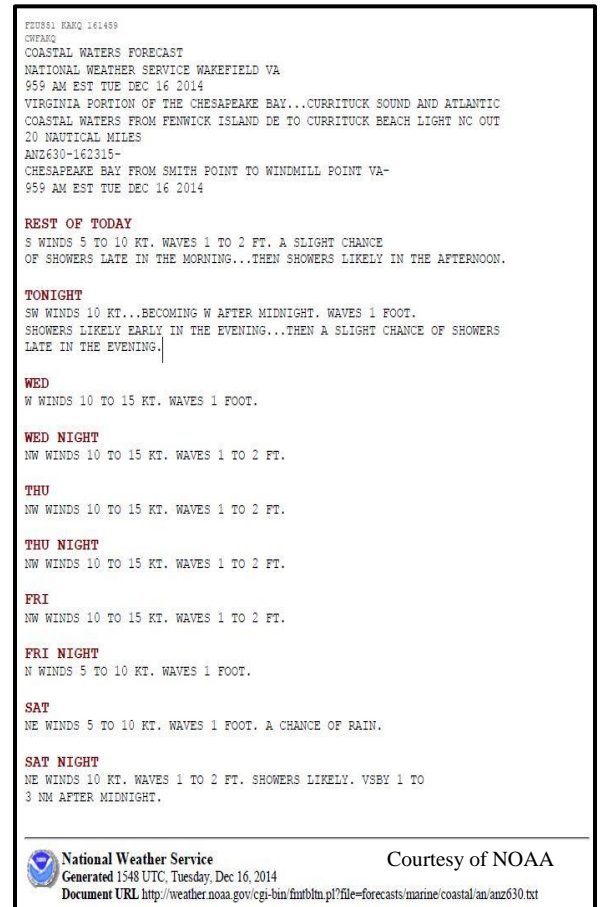




Figure 7.18. Example of marine text forecast.

weather.gov



National Weather Service

Weather Prediction Center



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[Proposed Change in the Display Options of the Short-Range Weather Charts](#)

Color

Black and White

Terrain Background

NDFD

About the NDFD graphics

Monday 00Z
Monday 06Z
Monday 12Z
Tuesday 00Z
Tuesday 12Z
Loop

[\[Legend of Surface Front Types\]](#) [\[Precipitation Areas and Symbols\]](#)

[View a larger version of the short range forecast loop](#)

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FAQs

Meteorological Calculators

Figure 7.19. Short-range Forecasts at hpc.ncep.noaa.gov/basicwx/basicwx_wbg.php.



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- [2014-2015 Wakefield Winter Outlook - YouTube Presentation \(8 minutes\)](#)
- [Christmas Climatology](#)

Current Conditions

En Español



Overcast

42°F

6°C

Humidity 52%

Wind Speed Calm

Barometer 30.37 in

Dewpoint 26°F (-3°C)

Visibility 10.00 mi

Last Update on 21 Dec 11:35 am EST

Current conditions at
West Point, Middle Peninsula Regional Airport (KFYJ)





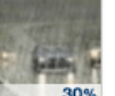




Lat: 37.82°N Lon: 76.76°W Elev: 23ft.

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Kilmarnock VA

7 Day Forecast

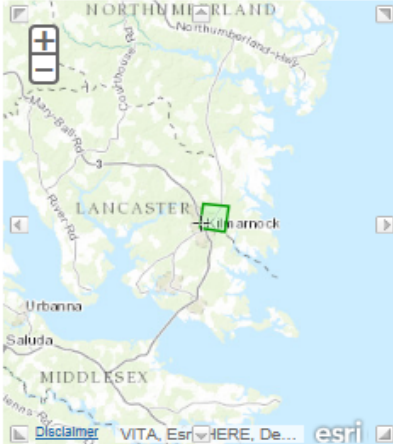
THIS AFTERNOON	TONIGHT	MONDAY	MONDAY NIGHT	TUESDAY	TUESDAY NIGHT	WEDNESDAY	WEDNESDAY NIGHT	CHRISTMAS DAY
								
Partly Sunny High: 43 °F	Mostly Cloudy Low: 30 °F	Rain High: 42 °F	Rain Likely Low: 40 °F	Chance Rain High: 54 °F	Rain Low: 51 °F	Showers High: 63 °F	Rain Likely Low: 43 °F	Mostly Sunny High: 50 °F

For More Weather Information:
[Wakefield, VA Local Forecast Office](#)

Detailed Forecast

This Afternoon	Partly sunny, with a high near 43. North wind 3 to 5 mph.
Tonight	Mostly cloudy, with a low around 30. Northeast wind 3 to 6 mph.
Monday	Rain, mainly after 11am. High near 42. Northeast wind around 8 mph. Chance of precipitation is 80%. New precipitation amounts between a quarter and half of an inch possible.
Monday Night	Rain likely, mainly before midnight. Cloudy, with a low around 40. Northeast wind 6 to 8 mph. Chance of precipitation is 60%. New precipitation amounts of less than a tenth of an inch possible.
Tuesday	A chance of rain. Cloudy, with a high near 54. Northeast wind 3 to 5 mph. Chance of precipitation is 30%. New precipitation amounts of less than a tenth of an inch possible.
Tuesday Night	Rain. Low around 51. Chance of precipitation is 80%. New precipitation amounts between a half and three quarters of an inch possible.
Wednesday	Showers. High near 63. Chance of precipitation is 90%.
Wednesday Night	Rain likely. Mostly cloudy, with a low around 43. Chance of precipitation is 70%.
Christmas Day	Mostly sunny, with a high near 50.
Thursday	Mostly clear, with a low around 36.
Friday	Sunny, with a high near 53.
Friday Night	Partly cloudy, with a low around 38.
Saturday	Partly sunny, with a high near 51.

Topographic [Click Map For Forecast](#)



Requested Location ■ Forecast Area
Lat/Lon: 37.72°N 76.37°W Elevation: 49 ft

ABOUT THIS FORECAST

Point Forecast: Point Forecast: Kilmarnock VA
37.72°N 76.37°W

Last Update: 10:21 am EST Dec 21, 2014

Forecast Valid: 12pm EST Dec 21, 2014-6pm EST Dec 27, 2014

[Forecast Discussion](#)

Courtesy of NOAA

Figure 7.20. Local Forecast Page at www.weather.gov.

Study Questions—Chapter 7

1. Surface analyses are produced:
 - a) Every 12 hours.
 - b) Every 3 hours.
 - c) Every hour.
 - d) When needed.
2. Weather radar data are available:
 - a) For each radar.
 - b) By region.
 - c) For the entire CONUS.
 - d) All of the above.
3. Current Weather radars are:
 - a) Similar to pleasure boat radars.
 - b) Located where the weather is the worst.
 - c) Based on the Doppler effect.
 - d) Out of date and will be replaced.
4. Weather satellites are:
 - a) In low orbit at the equator.
 - b) In geostationary orbit.
 - c) In polar orbit.
 - d) Both b) and c).
5. Polar orbiting weather satellites:
 - a) Stay over the same longitude.
 - b) Are sun synchronous.
 - c) Are at noon and midnight.
 - d) None of the above.
6. NOAA uses the following polar orbiting satellites:
 - a) GOES and NOAA.
 - b) NOAA and DMSP.
 - c) METOP, DMSP and NOAA.
 - d) All of the above.
7. NOAA uses the following geostationary satellites:
 - a) NOAA and GOES.
 - b) GOES and METOP.
 - c) GOES only.
 - d) GOES and Meteosat.
8. The NEXRAD Doppler weather radar was developed by:
 - a) NOAA.
 - b) NOAA and the USAF.
 - c) DoD, DoT, and DoC.
 - d) NASA.
9. NEXRAD Doppler radars can detect:
 - a) Precipitation.
 - b) Clouds.
 - c) Turbulence.
 - d) All of the above.
10. The GOES satellite produces images in the following wavebands:
 - a) Visible and Radio.
 - b) Visible, Infrared, and Water Vapor.
 - c) Visible, Infrared and Ultraviolet.
 - d) All of the above.
11. The primary GOES satellites are located at longitudes:
 - a) 90 and 180 degrees.
 - b) 135 W and 75 E.
 - c) 75 W and 135 W.
 - d) 105 W.
12. Cloud temperatures are measured by weather satellites in the:
 - a) Visible bands.
 - b) Infrared bands.
 - c) Water Vapor bands.
 - d) All of the above.

13. The visible band on weather satellites operates on:
- Reflected light.
 - Emitted energy.
 - Both of the above.
 - None of the above.
14. The water vapor band on weather satellites measures moisture:
- At the tropopause.
 - At the 500 mb level.
 - Over the entire depth of the atmosphere.
 - Near the surface only.
15. Upper air analysis charts are produced:
- Every three hours.
 - Every six hours.
 - Twice a day.
 - At noon and midnight local time.
16. Persistence forecasting is useful for:
- Long range forecasts.
 - Areas where the weather does not change much.
 - Forecasting the position of a tornado.
 - Not much at all.
17. Trend forecasting is useful for:
- Long range forecasts.
 - Areas where the weather does not change much.
 - Forecasting the position of a tornado.
 - Not much at all.
18. Analog forecasting is most useful for:
- Long range forecasts.
 - Short range forecasts.
 - Correcting numerical forecasts.
 - Use by new forecasters.
19. Numerical forecasting makes use of:
- Surface observations.
 - Upper air observations.
 - Chaos theory.
 - Both a) and b).
20. Ensemble forecasting is:
- Using large numbers of computers.
 - Averaging data from several locations.
 - Running several models on the same data.
 - None of the above.
21. Smart phones can be used to obtain:
- Local observations.
 - Local forecasts.
 - Radar data.
 - All of the above.

Chapter 8 Preparing for and Executing a Mission

Introduction

Chapter 7 briefly introduced the steps to take and the resources to use when planning a mission. This chapter goes into more detail on how to plan, what to watch for during the patrol, and what actions to take in the event you encounter adverse weather.

As discussed in Chapter 7, the approach to planning that works best is to first look at various internet sources to see what is currently happening, relate that to what you see around you, then look at the forecasts and make a decision. Even after that decision, continue to monitor the situation.

How to Plan

To be more specific, first, study the current situation on your favorite weather web site. This can be weather.gov, weather.com, wunderground.com, or another site that you prefer. Monitoring 2 to 3 days in advance can give you a better idea of how things are developing and how good the forecast is.

Second, relate what the site shows you to what you see around you—winds, temperature, humidity, clouds, and present weather (rain, snow, fog, etc.). The nearest weather station may be tens of miles away and there may be differences in your area. If there are, see if you can figure why. One advantage of wunderground.com is it has access to observations from many private weather stations, including the author's.

Third, even in the most benign cases, take a look at local radar data and satellite data. Do they agree with the other information available? How is any precipitation on the radar moving (use the loop feature)? Look at both the visible and IR satellite data.

They can give you more insight into the position of clouds and whether they portend adverse weather.

Fourth, look at the surface weather forecast charts. Decide what you expect to see during your patrol.

Finally, monitor the sky to see if it is developing as expected and occasionally check the data sources you have available. If unsure, you may have to make the decision to abort the mission. Safety of you, your crew, and your facility is paramount.

What to Consider

Are there thunderstorms in the forecast? What will you do if they occur earlier than anticipated? What about lightning? How do you plan to avoid being struck?

Is there fog or heavy precipitation in the forecast? If fog rolls in earlier than expected, what actions should you plan to take in preparation for dealing with it?

What are the winds and seas expected to be? Is there a small craft advisory? What is the expected wave height and period? Can you avoid the effects by moving the patrol into another area, such as a windward shore (windward of the vessel, leeward of the land)? Your district or sector may have a policy of getting permission from the Order Issuing Authority (OIA) or controlling station to patrol under a small craft advisory.

What are the air and water temperatures expected to be? What uniform is appropriate under the circumstances? You may be able to get water temperature from your controlling station or from data buoys.

Is icing a possibility? Will that affect the footing on your particular surface facility or affect the performance of your air facility?

For air, what are the enroute winds and what is the forecast for alternate airfields?

Think about what the weather situation means in terms of your GAR score.

The following sections discuss each of these in more detail, including planning, hazard information, and actions to take in the event the condition occurs while on patrol.

Visibility Restrictions

Fog or heavy precipitation (e.g. snow) that comes unexpectedly, or earlier than forecast, can result in navigation issues. If your GPS is working, you know where you are and where you need to go, but reduced visibility heightens the risk of collision with another vessel, ATONS, or floating debris.

Radar can help, but it won't show floating debris and the necessity of a radar watch increases the workload of your lookouts. Have a plan in place to deal with this, particularly if you have a facility under 26 feet and no extra crew. Slow down! Remember, don't just look—listen.

If you have a GPS but not a chart plotter, you will need to periodically plot your position on a chart. Make sure you have the appropriate chart and the necessary plotting tools aboard.

If you have a chart plotter, but it fails, or if your GPS fails, you need to know what compass course to steer to get to safe harbor. Situational awareness is vital in this case. Make sure you have a deviation table. If nearby electronics increases your deviation, you will need two tables—one without your

electronics operating. In appropriate situations, you can navigate by water depth if your depth sounder is working.

If you encounter reduced visibility conditions, take the following actions:

- Take a compass bearing toward your chosen safe haven while you can still see it. The easiest way is to point the bow in the direction you need to proceed—that automatically accounts for deviation. You will need this information if you have equipment failure.
- Make the proper sound signals.
- Brief your crew on your plan and any special actions they need to take.
- Assign one crew person to radar watch if you have enough crew. If not, you or your crew should look at the radar display every five minutes or so, but NOT to the exclusion of a sharp forward visual lookout.
- Assign one crew person as an aural (listening) lookout, if you have enough crew. Periodically go to idle or shut down the engine so you can hear.
- Slow down so you can stop or turn in time to avoid a collision.
- If you must anchor, do not anchor in a channel.
- Inform your controlling station of your situation and your planned actions. They will likely put you on a more frequent communications schedule, probably every 15 minutes.

Thunderstorms

One of the most difficult decisions in preparing to get underway involves the forecast for thunderstorms. Forecasts vary from “Slight Chance,” to “Likely.” What cutoff do you use in making your decision? If there is

a major front or cyclone approaching, you can at least get the timing down fairly well. The biggest uncertainty is with “air mass” thunderstorms—the ones that pop up randomly due to unstable air, usually in the afternoon or early evening. Ultimately, the decision comes down to experience and the fact that you have a plan to deal with an unexpected thunderstorm, with its accompanying heavy rain, downdrafts, and lightning.

So, what might that plan consist of? Clearly, vigilance (situational awareness) is important. Of equal importance is knowing where all of your safe havens are along your patrol route.

Make sure you have a source of up-to-date information, such as a smart phone with a radar app or a VHF set to alarm if there is a special bulletin on the weather channels. Let your crew know the importance of listening for “Securite” broadcasts on Channel 16 and switch to the appropriate channel (usually 22A) if it is a weather alert. You can also have family or friends monitor the radar and call you. If all else fails, call the station for a weather update.

As you learned in Chapter 6, thunderstorms can produce heavy rain, hail, downdrafts or microbursts, and lightning. Obviously, the best action is to stay clear of them. If, however, you get caught in a situation where you can’t make your safe haven, you should take the following actions:

- Determine a compass course to safe haven as outlined above. Lightning may disable all of your electronics and leave you with just your compass and cell phone.
- Brief your crew and notify your controlling station.
- Stow all loose gear. You may want to button up your canvas, but don’t leave

just the aft open, as that can result in carbon monoxide poisoning.

- If your boarding ladder is not permanently attached, break it out and have it ready in case you have a man overboard situation.
- Count the seconds between lightning and thunder. If they decrease with time, the thunderstorm is approaching
- Note the direction of the wind. Remember, the wind will first be toward the thunderstorm, then away from it as the downdraft or microburst occurs.
- Watch the water for ripples that announce the beginning of the gust front.
- Move perpendicular to the storm track until it is close enough for winds to be an issue, then turn into the gust front.
- If you can’t make a safe haven, try for a windward shore (i.e., to the lee of the shore but windward of the boat).
- If the thunderstorm is close and you see lightning or hear sharp thunder, turn off all unnecessary electronics and lower your antenna (communicate with the station by cell phone if possible). Brief the crew to avoid contact with metal, such as railings. You can be struck by lightning even if the storm is not directly over you, but just nearby.

Wind and Waves

For air patrols, winds are important for takeoff and landing decisions, and for enroute navigation. They can also affect turbulence. Of particular concern are the winds, ceiling and visibility at the destination as well as the alternate airfields. Strong enroute winds can also affect flight time and fuel consumption.

For surface patrols, the importance of winds is primarily how they affect the sea state. NOAA issues Small Craft Advisories

and Gale Warnings, as well as other warnings for conditions you should never even consider patrolling in. These are:

- Small Craft Advisory: Conditions vary by region. Specific conditions for your area can be found at:

[nws.noaa.gov/om/marine/cwd.htm](https://www.nws.noaa.gov/om/marine/cwd.htm)

- Gale Warning: Winds 34 to 47 knots (39 to 54 mph).

In the absence of data, wind speed over the water can be estimated using the Beaufort scale. See Appendix B for details.

Wind wave height is affected by wind speed, fetch, and the duration of the winds. Period, or wavelength of wind-driven waves, is affected primarily by water depth. Wave height is the vertical distance from trough to crest; wavelength is the horizontal distance from one crest (or trough) to the next; and period is the time from one crest or trough passing a fixed point until the next.

Wave forecasts are given as a range of heights. This range covers the most probable heights—some are higher, some lower.

Steep waves with heights over five feet and periods less than 6 seconds can be problematic for vessels less than 100 ft.

When planning a patrol where seas may be an issue, consider the duration and fetch. You may be able to avoid the worst waves by staying near a windward shore, where the fetch is short. You may be able to determine existing winds and wave heights if there are data buoys in your patrol area. Locations of buoys is found at: www.ndbc.noaa.gov/.

Seas are often worst where the wind is opposite the current, such as at the mouths of rivers. This is typically west winds on the west coast and east winds on the east coast.

If you find yourself in higher seas than expected, you should:

- Steer to cross waves at a 45 degree angle to avoid burying the bow and, perhaps, pitch-poling.
- If there are following seas, pay particular attention to the power setting—you may have to vary it to maintain sufficient steerage way on the back of waves to avoid broaching.
- With beam seas, proceed in a series of long tacks to reduce rolling.
- Plan approaches to or departures from inlets to maintain adequate steerageway in narrow channels.

Temperature

Air and water temperature have a significant effect on Auxiliary patrols. They both determine the uniform of the day, as well as the precautions we need to take on patrol.

We are fortunate that in some locations we are authorized to wear the summer patrol uniform of shorts and operations T-shirt. Not too long ago, the winter patrol uniform was “Mustangs,” more properly known as Anti-Exposure Coveralls. More recently, the Coast Guard has issued Dry Suits for winter operations. Why the change to the much more expensive Dry Suits? The answer is simple—the CG is concerned with safety and they see us as part of their team. We will discuss cold water immersion later. A non-meteorology comment: dry suits are expensive—don’t request one if you don’t plan to use it!

Warm Weather Issues

We perspire in hot weather to get rid of excess body heat, which is carried away by means of evaporation. This works well in dry weather, but the rate of evaporation de-

increases as the humidity increases. Perspiration also removes salt and other electrolytes from the body, and depletion of these chemicals may interfere with normal metabolism. We experience the result as heat exhaustion (cramps, clammy skin, nausea, etc.). If not promptly treated, heat exhaustion may progress to heat stroke. When a person suffers heat stroke, his or her body is no longer able to get rid of excess heat, and the consequent rise of internal temperature can be fatal.

The risks of heat exhaustion and heat stroke increase as air temperature and humidity increase. These effects are combined in a formula for an equivalent temperature called the *heat index*. The heat index formula gives an equivalent low humidity temperature that is estimated to pose the same level of risk as the combination of actual air temperature and humidity.

The table below (Figure 8.1) summarizes the heat index for those combinations of air temperature and humidity most likely to be encountered during hot weather patrols. The heat index is not an exact measurement because it does not account for variations in clothing, body size, or physical condition. However, it is still useful for gauging the level of risk. Larger version of this and the next table are in Appendix B.

		Relative Humidity (in percent)																						
		0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100		
Air Temp (°F)	140	125																						
	135	120	128																					
	130	117	122	131																				
	125	111	116	123	131	141																		
	120	107	111	116	123	130	139	148																
	115	103	107	111	115	120	127	135	143	151														
	110	99	102	105	108	112	117	123	130	137	143	150												
	105	95	97	100	102	105	109	113	118	123	129	135	142	149										
	100	91	93	95	97	99	101	104	107	110	115	120	126	132	138	144								
	95	87	88	90	91	93	94	96	98	101	104	107	110	114	119	124	130	136						
	90	83	84	85	86	87	88	90	91	93	95	96	98	100	102	106	109	113	117	122				
	85	78	79	80	81	82	83	84	85	86	87	88	89	90	91	93	95	97	99	102	105	108		
	80	73	74	75	76	77	77	78	79	79	80	81	81	82	83	85	86	86	87	88	89	91		
	75	69	69	70	71	72	72	73	73	74	74	75	75	76	76	77	77	78	78	79	79	80		
	70	64	64	65	65	66	66	67	67	68	68	69	69	70	70	70	71	71	71	71	71	72		

80°-90° Caution: Fatigue
 90°-104° Extreme Caution: Sunstroke, heat cramps, heat exhaustion possible
 105°-129° Danger: Sunstroke, heat cramps, heat exhaustion likely; heatstroke possible
 130° or higher Extreme Danger: Heatstroke likely except for brief exposure

Courtesy of AMS

Figure 8.1. Heat Index Table.

Prevention is the best defense against hyperthermia, heat exhaustion, and heat stroke.

- Wear light clothing, such as the summer patrol uniform. Wear your cover.
- Apply high-SPF sunscreen to all exposed areas and re-apply as needed.
- Drink plenty of water.
- The coxswain should rotate crew positions more frequently.
- If anyone shows symptoms, abort the patrol immediately and return to base. Apply first aid as needed.

Cold Weather Issues

Cold weather issues involve both the air and water temperature. In both cases, the primary danger is hypothermia.

In still air, the body warms a shallow layer of air around it, under your clothes, decreasing the rate of body heat loss. Increasing wind speeds more efficiently remove this layer, increasing the rate of heat loss.

The rate at which your body loses heat to the atmosphere in cold weather therefore depends on both the air temperature and the wind speed. The rate will increase as the temperature decreases or the wind speed increases. Both effects combine in a formula for an equivalent temperature called the *wind chill temperature*. See Figure 8.2.

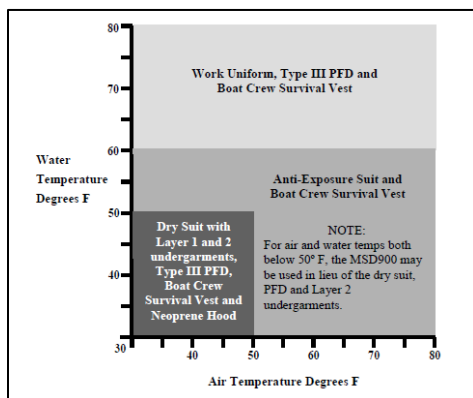
		Temperature (°F)																		
		40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	
Wind (mph)	Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	
	5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63	
	10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72	
	15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77	
	20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81	
	25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84	
	30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87	
	35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89	
	40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91	
	45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93	
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95		
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97		
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98		

Courtesy of AMS

Figure 8.2. Wind Chill Table.

Again, the best defense against hypothermia is prevention:

- Wear the appropriate uniform for the conditions. This may include the watch cap and gloves (ordinary gloves are not worn while handling lines, such as during docking or towing).
- If anti-exposure coveralls (“Mustangs”) are not required, take them with you on patrol. Coxswains may elect to keep extras aboard if available.
- If in Dry Suits, be sure to wear all layers. These include the moisture-wicking underwear; the thermal layer (“bunny suit”); and the waterproof layer, including the outer protective shell. Additional layers may be added if desired. Be sure and have your gloves and hood or Balaclava with you.
- Coxswains should enforce proper wear and ensure that personal protective equipment (PPE) is in good condition.
- Be sure to inspect dry suits quarterly and perform the required leak test annually. **NOTE:** Never wear the dry suit during leak tests without footwear, to prevent leaks from abrasion.
- The Official USCG Chart for determining the proper PPE to wear in cold weather depends on air and water temperature, shown below.



Cold Water Immersion

The potentially most serious danger during cold weather patrols is falling overboard into cold water. If winds can more quickly remove heat from the body, cold water, with its higher heat capacity, removes body heat many times faster.

According to recent research by the Coast Guard, in 40-50°F (4-10°C) water, the average body cools at 3.2 to 3.8 degrees Celsius per hour in ordinary clothing. With the anti-exposure coverall, the rate is 1 to 2 deg. C, depending on sea state. With the dry suit and hood, it is 0.5 degrees per hour. The temperature range with sea state is a result of periodically immersing the head. Clearly, the wear of proper protective clothing is important (as well as mandatory under certain conditions).

A much more detailed discussion of cold water immersion is available on the web at coldwaterbootcampusa.org and in the USCG Boat Crew Seamanship Manual.

Tornados and Water Spouts

You should never patrol under a tornado watch or a severe thunderstorm watch. Water spouts, however, can pop up unexpectedly as they are difficult to forecast.

If you do encounter a water spout, determine the direction of movement, then move perpendicular to that direction. Have the crew stow loose gear, sit down and hang on.

Hurricanes

Again, you should never patrol during a hurricane watch—within 48 hours prior to predicted arrival in your area.

If you are pleasure boating in blue water and get caught, try to stay on the left side of the hurricane track, relative to the direction of motion (you can use the Byce-Ballot law). Seas are likely to be somewhat less, and the winds will tend to push you behind the hurricane.

In preparation for an approaching hurricane, secure your facility, but top off the fuel and be ready to get underway after the storm if the Coast Guard asks you to check ATONs or respond to a SAR callout.

Study Questions—Chapter 8

1. What steps are included in using weather for planning a patrol?
 - a) Check the current weather.
 - b) Check the radar.
 - c) Check the forecast.
 - d) All the above.
2. While on patrol, visibility becomes restricted. What steps should you take?
 - a) Take a compass bearing to your safe haven.
 - b) Slow down.
 - c) Put all your crew on visual lookout.
 - d) Both a and b.
3. With regard to thunderstorms, which kind is the most difficult to deal with in the planning phase?
 - a) Frontal thunderstorms.
 - b) Squall line thunderstorms.
 - c) Air mass thunderstorms.
 - d) None of the above.
4. When a thunderstorm is approaching, you should *initially*:
 - a) Head toward it to keep the wind on the bow
 - b) Run perpendicular to the direction of storm movement.
 - c) Anchor and wait it out.
 - d) None of the above.
5. What evidence says the effects of a thunderstorm are *imminent*?
 - a) Ripples on the water.
 - b) Winds blowing toward the storm.
 - c) Static on the VHF radio.
 - d) All of the above.
6. Small craft advisories are issued under what circumstances?
 - a) Winds over 25 knots.
 - b) Seas greater than 8 feet.
 - c) Water temperature less than 40 degrees Fahrenheit.
 - d) It varies with the region of the country.
7. A gale warning is issued when winds are expected to be:
 - a) Over 25 knots.
 - b) Strong and gusty.
 - c) Over 34 knots.
 - d) None of the above.
8. The heat index is a function of:
 - a) Temperature and winds.
 - b) Cloud cover and temperature.
 - c) Temperature and relative humidity.
 - d) None of the above.

9. Wind chill is a function of:
- a) Temperature and humidity.
 - b) Temperature and wind speed.
 - c) Wind speed and humidity.
 - d) Humidity and cloud cover.
10. The effects of heat exhaustion and heat stroke increase with:
- a) Decreasing temperature in increasing wind speed.
 - b) Increasing temperature and decreasing humidity.
 - c) Increasing temperature and increasing humidity.
 - d) Decreasing temperature in decreasing wind speed.
11. The possibility of hypothermia increases with:
- a) Decreasing temperature and increasing wind speed.
 - b) Decreasing temperature and increasing humidity.
 - c) Decreasing temperature and decreasing wind speed.
 - d) Decreasing temperature and increasing humidity.

Index

Entries Refer to Initial Definitions Only

Advection.....	8	Extra-tropical cyclone.....	39
Air masses.....	34	Flash flood watch.....	68
Atmosphere		Fog	
composition of.....	25	advection.....	29
Backing.....	40	precipitation.....	29
Bergeron Process.....	51	radiation.....	28
Buys-Ballot law.....	18	Forecasting	
Chaos theory.....	81	analog.....	80
Charts		climatological.....	80
surface charts.....	73	ensemble forecasting.....	81
upper air.....	78	model output statistics.....	81
Circulation		nowcasting.....	80
anti-cyclonic.....	16	numerical.....	80
cyclonic.....	17	pattern recognition.....	80
cirriform.....	46	persistence.....	80
Cloud		quantitative precipitation forecasts.....	82
Alto cumulus.....	48	trend forecasting.....	80
Alto stratus.....	48	Freezing Rain.....	52
Cirro cumulus.....	48	Friction.....	17
Cirro stratus.....	48	Front	
Cirrus.....	48	cold.....	37
cumulonimbus.....	50	occluded.....	39
Cumulus.....	46	stationary.....	38
Lenticular.....	50	symbols.....	37
Nimbostratus.....	47	warm.....	38
Shelf.....	51	Frost.....	29
Stratocumulus.....	47	Fujita scale.....	64
Stratus.....	47	Gale Warning.....	68, 90
Wall.....	51	GOES.....	76
Cold core low.....	42	Hadley cell.....	9
Collision-coalescence process.....	51	Hail.....	52, 62
Condensation nuclei.....	28, 46	Halos.....	55
Coriolis Effect.....	9	Heat index.....	91
Coronas.....	55	Heat transfer	
Cumiform.....	46	advection.....	8
Cyclogenesis.....	41	conduction.....	8
Dew.....	29	convection.....	8
Downburst.....	62	radiation.....	8
Drizzle.....	52	Humidity	
Dust devil.....	65	absolute.....	27
Ekman Spiral.....	17	dew point depression.....	28
Equinox.....	5	dew point temperature.....	27
EUMETSAT.....	77	relative.....	27

Hurricane		Scattering	54
categories	67	Sea breeze	18
warning	68	Sleet.....	52
watch	68, 71	Small Craft Advisory	90
Hydrometeors.....	54	Snow	52
Insolation.....	5	Solar radiation.....	4
Inter-tropical Convergence Zone	10	Solstice.....	5
Isobars	16	Specific heat.....	6
Isoheights	19	Squal lines.....	60
Isotherms.....	20	Stability	
Iteration	80	absolute	29
Jet stream	20, 41	absolute instability	29
Land breeze.....	18	conditional.....	29
Lapse rate		Storm surge.....	67
adiabatic	26	Storm warning.....	68
environmental	25	Stratiform	46
Latent Heat		Stratosphere.....	25
fusion.....	26	Summer solstice	<i>See Solstice</i>
vaporization.....	26	Supercell	60
Level of free convection	30	Synoptic scale	55
Lifting		Temperature	
frontal wedging	30	absolute	7
orographic	30	Celsius.....	6
surface convergence.....	30	Fahrenheit	6
Lightning.....	62	Kelvin.....	7
Lithometeors	54	Rankin.....	7
Mesocyclone	61	Thermosphere	25
Mesoscale.....	55	Thunderstorm.....	59
Mesoscale convective complexes	60	Tornado	
Mesosphere	25	warning	64
Meteosat.....	77	watch	64
METOP satellites	77	Tropical	
Microburst.....	62	cyclone	65
Microscale.....	55	depression	66
NEXRAD.....	76	disturbance	66
Photometeors.....	54	storm	66
Polar front	41	Troposphere	25
Pressure.....	14	Veering.....	40
sea level.....	15	Wall cloud.....	63
tendency	15	Warm core low.....	42
Pressure Gradient Force	14		
Rain.....	52	Water phase change	26
Refraction.....	54	Water spout	64
Ridges and Troughs	19	Wind chill temperature	91
Rossby waves.....	20		
Saffir-Simpson scale	67		

Winds	
backing.....	17
Chinook.....	30
Föhn	30
global circulation	10
veering.....	17
Winter solstice	<i>See Solstice</i>

Appendix A Some More Physics

The Ideal Gas Law

$$PV = nR^*T$$

Where P is pressure, T is absolute temperature, V is volume, n is the number of moles of gas and R^* is a constant that depends on the units of the other three variables. In metric units, P is mb (hecto Pascals), T is °K (°C + 273.16), and V is volume in cubic centimeters. For those units, the universal gas constant is 8.3144×10^7 erg mole⁻¹ °K⁻¹. An alternative form, using density, ρ in g/cc, instead of V, where m is the molecular weight (g/mole) (average m for the atmosphere):

$$P = \rho R^*T/m$$

Regardless of the units, the point of the equation is that pressure, volume (or density) and absolute temperature are related by a constant. In other words, if P increases, then either V must decrease or T must increase, or both. In the atmosphere, P, ρ , and T all decrease with altitude in a way that the equation always holds. If air is exhausted from a container, V is constant, but P decreases, therefore T must decrease. If air is added, P increases, so T must increase.

The Relationship between Temperature and Kinetic Energy

The kinetic energy contained in a sample of material is given below, where T is the Kelvin temperature and k is the Boltzman constant, related to the gas constant by $k=R^*/\dot{A}$, where \dot{A} is Avagadro's number, the number of molecules in a mole, about 6.022×10^{23} mole⁻¹.

$$KE_{(average)} = 3kT/2 = 3R^*T/2\dot{A}$$

Adiabatic Processes

If a sample of air at pressure P_0 and temperature T_0 is lifted to a pressure P, then the temperature of that parcel will be:

$$T = T_0 (P/P_0)^k$$

Where k for dry air is 0.286. For saturated air, the result is multiplied by a term that is a very complicated function of pressure and temperature, and varies somewhat with altitude.

The Hydrostatic Equation

In a stable atmosphere, the upward force of the vertical pressure gradient must be balanced by the downward force of gravity on the air molecules. Consider a small slice of the atmosphere, from z to z + δz , over which the pressure difference will be δP . Given g as the acceleration of gravity and ρ as the air density, we have the differential equation:

$$\delta P = - \rho g \delta z \quad \text{or} \quad dP/dz = - \rho g$$

This equation says the rate of change of pressure with altitude equals the gravitational force per unit volume ($F = mg$).

Reducing Station Pressure to Sea-Level Pressure

The simplest method is to assume that the atmosphere that would exist between the surface and sea level follows the profile of the standard atmosphere. In the following equation, P_{SL} is the sea level pressure, P is the station pressure, T is the station temperature, z is the altitude, γ is the standard lapse rate at that altitude, g is the acceleration of gravity, and R^* is the gas constant:

$$P_{SL} = P(\check{T})^{g/R^*\gamma}$$

$$\text{Where } \check{T} = (T + z\gamma)/T$$

Pressure Gradient Force

Assume a small cube of air with dimensions dx , dy , and dz . In the x direction, the area of the faces are $dy dz$. The mass of the cube is $\rho dx dy dz$. The difference in pressure is $(\partial p/\partial x) dx$. Since pressure is force per unit area, force is pressure multiplied by area: $(\partial p/\partial x) dx dy dz$. Substituting the mass equation gives the following equation (the negative sign says that an increase of pressure with distance results in a force in the opposite direction):

$$PGF = - (\partial p/\partial x)/\rho$$

The Coriolis Effect

Let us use Newton's second law of motion, $F = ma$, which is valid in an inertial (non-accelerating) reference frame. We separate it into three orthogonal axes as:

$$F_x = ma_x; \quad F_y = ma_y; \quad \text{and} \quad F_z = ma_z$$

If we put these in a rotating frame with angular velocity Ω , then in time t , each axis will rotate through an angle Ωt in a plane perpendicular to the axis of rotation (equatorial plane). We take the z axis as the axis of rotation, the new positions after time t are:

$$x' = x\cos\Omega t - y\sin\Omega t; \quad y' = x\sin\Omega t + y\cos\Omega t; \quad \text{and} \quad z' = z$$

If we differentiate twice with respect to t to get accelerations, and substitute back into the first equations, after some manipulation we get two new terms. The first is the familiar centrifugal acceleration, which affects the shape of the earth and the local net force of gravity:

$$R\Omega^2 = r_e \cos(\varphi) \Omega^2$$

Where R is the perpendicular distance from the axis of rotation and is equal to the earth's radius times the cosine of the latitude (φ). The second term is:

$$2\Omega V$$

Where V is the velocity parallel to the equatorial plane. This is the Coriolis term. The term in parentheses (below) is called the Coriolis parameter. The apparent acceleration (and therefore the force per unit mass) exerted by the Coriolis Effect (where v is wind velocity and the force acts perpendicular to the wind) is:

$$(2\Omega \sin \phi) v$$

Doppler Shift

Doppler radar depends on the Doppler equation, which is:

$$\Delta\lambda/\lambda = v/c$$

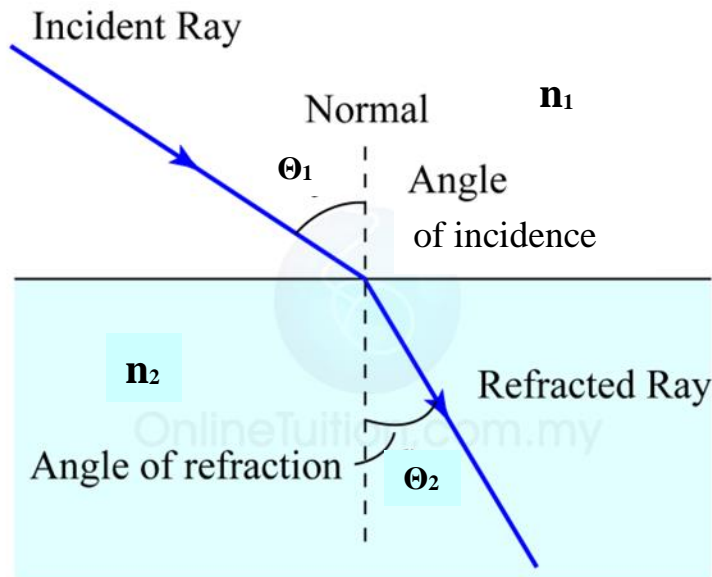
Where $\Delta\lambda$ is the wavelength shift, λ is the wavelength of the emitted radiation, v is the speed of the object relative to the observer, and c is the speed of light. The sign depends on whether the object is approaching or receding.

Refraction

First, we define the index of refraction as $n = c/v$, where c is the speed of light in a vacuum and v is the speed of light in the medium. The index of refraction of a vacuum is 1.0. The index of refraction of materials is always < 1.0 . The angle of refraction is given by Snell's Law as:

$$n_1 \cdot \sin\Theta_1 = n_2 \cdot \sin\Theta_2$$

Where Θ is the angle between the ray and the normal to the surface of the material.



Scattering

Physicists recognize two scales of scattering. Rayleigh scattering is where the particle size is much less than the wavelength of the scattered radiation. This is typical of sunlight scattering off

molecules in the atmosphere. When the particles are roughly the same size as the wavelength, or larger, it is called Mie scattering. Mie scattering is very complex and depends on the shape and refractive index of the particle. This topic will cover only Rayleigh scattering.

Scattering from a single molecule of polarizability α , in a direction at an angle Θ from the original propagation direction, gives the intensity I of the scattered beam at distance R . I_0 is the intensity of the incident beam, and λ is the wavelength.

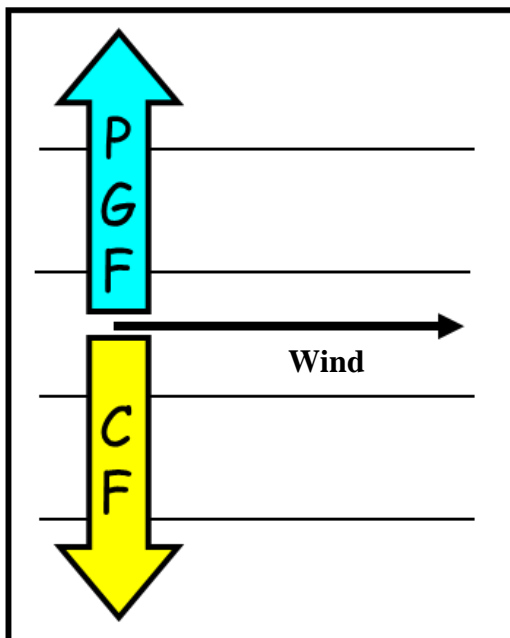
$$I = I_0 \frac{8\pi^4 \alpha^2}{\lambda^4 R^2} (1 + \cos^2 \theta).$$

One important thing to notice is that I varies as the fourth power of the wavelength and increases as the wavelength decreases. This is why the sky is blue and sunsets are red. The other thing to notice is that the term in parentheses is two (2) when Θ is zero or π (180°), and one (1) when Θ is $\pi/2$ (90°). Side scatter is half as intense as the forward and back scatter.

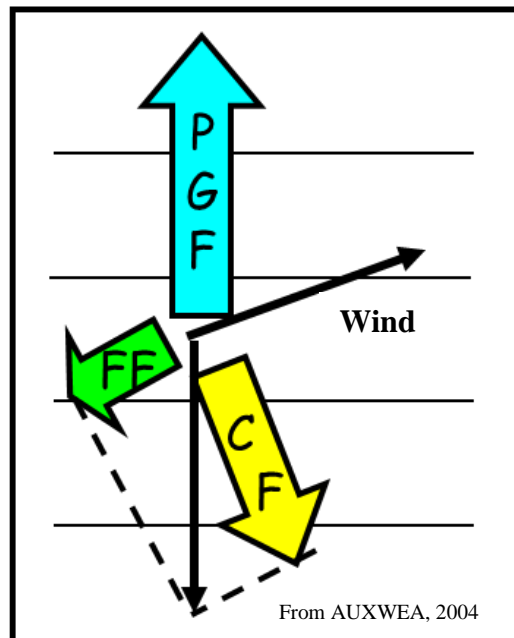
Why Friction Changes Wind Direction

Without friction, there is a balance between the pressure gradient force (PGF) and the Coriolis “Force” (CF). They are in opposite directions and equal in magnitude. Remember, the CF is always at right angles to the wind direction and the PGF is toward lower pressure. To the left below is an illustration of that situation. Next to it is the situation where there is a friction force (FF). Friction is always in the opposite direction from the wind. It reduces the wind speed, which in turn reduces the CF. The sum of the CF and FF balances the PGF.

Without Friction
Parallel To Isobars

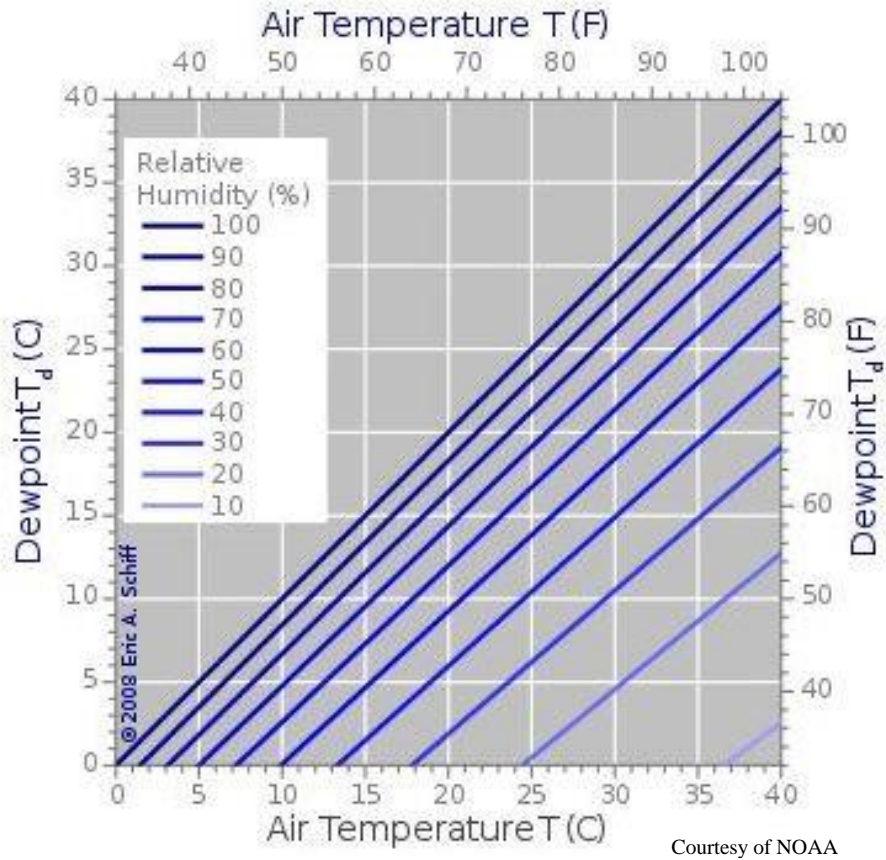


With Friction
Across Isobars



Appendix B Useful Tables and Graphs

Relation among Temperature, Dew Point and RH



Specific Heats of Selected Substances

(calories/gram)

Water	1.00	Soil (typical)	0.25
Ice	0.50	Air	0.25
Water Vapor	0.48	Aluminum	0.215
Wood (typical)	0.40	Steel	0.108

Heat Index Table

The heat index

The heat index is a general guide to how the danger of heat increases as the temperature and relative humidity increase. Effects on individuals will vary greatly. The figures are based on effects of prolonged exposure when you are in the shade. Direct sunlight can increase index values by as much as 15 degrees Fahrenheit.

		Relative Humidity (in percent)																				
		0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Air Temp (°F)	140	125																				
	135	120	128																			
	130	117	122	131																		
	125	111	116	123	131	141																
	120	107	111	116	123	130	139	148														
	115	103	107	111	115	120	127	135	143	151												
	110	99	102	105	108	112	117	123	130	137	143	150										
	105	95	97	100	102	105	109	113	118	123	129	135	142	149								
	100	91	93	95	97	99	101	104	107	110	115	120	126	132	138	144						
	95	87	88	90	91	93	94	96	98	101	104	107	110	114	119	124	130	136				
	90	83	84	85	86	87	88	90	91	93	95	96	98	100	102	106	109	113	117	122		
85	78	79	80	81	82	83	84	85	86	87	88	89	90	91	93	95	97	99	102	105	108	
80	73	74	75	76	77	77	78	79	79	80	81	81	82	83	85	86	86	87	88	89	91	
75	69	69	70	71	72	72	73	73	74	74	75	75	76	76	77	77	78	78	79	79	80	
70	64	64	65	65	66	66	67	67	68	68	69	69	70	70	70	70	71	71	71	71	72	

Courtesy of American Meteorological Society

- 80°–90° **Caution:** Fatigue
- 90°–104° **Extreme Caution:** Sunstroke, heat cramps, heat exhaustion possible
- 105°–129° **Danger:** Sunstroke, heat cramps, heat exhaustion likely; heatstroke possible
- 130° or higher **Extreme Danger:** Heatstroke likely except for brief exposure

Wind Chill Table

Wind chill chart

This is the wind chill chart that the U.S. NWS adopted in 2001. The actual numbers aren't as important as the colors showing how long frostbite of skin exposed to the cold and wind could take to occur. Any wind chill chart is at best a rough guide to the dangers of cold and wind because it doesn't include individual differences or factors such as sunshine. For example, the NWS says bright sunshine increases wind chill temperatures by 10 to 18 Fahrenheit degrees.

Frostbite Times 30 minutes 10 minutes 5 minutes

		Temperature (°F)																		
		Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
Wind (mph)	5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63	
	10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72	
	15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77	
	20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81	
	25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84	
	30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87	
	35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89	
	40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91	
	45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93	
	50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95	
	55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97	
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98		

Courtesy of American Meteorological Society

Standard Pressure Levels and Plotted Intervals

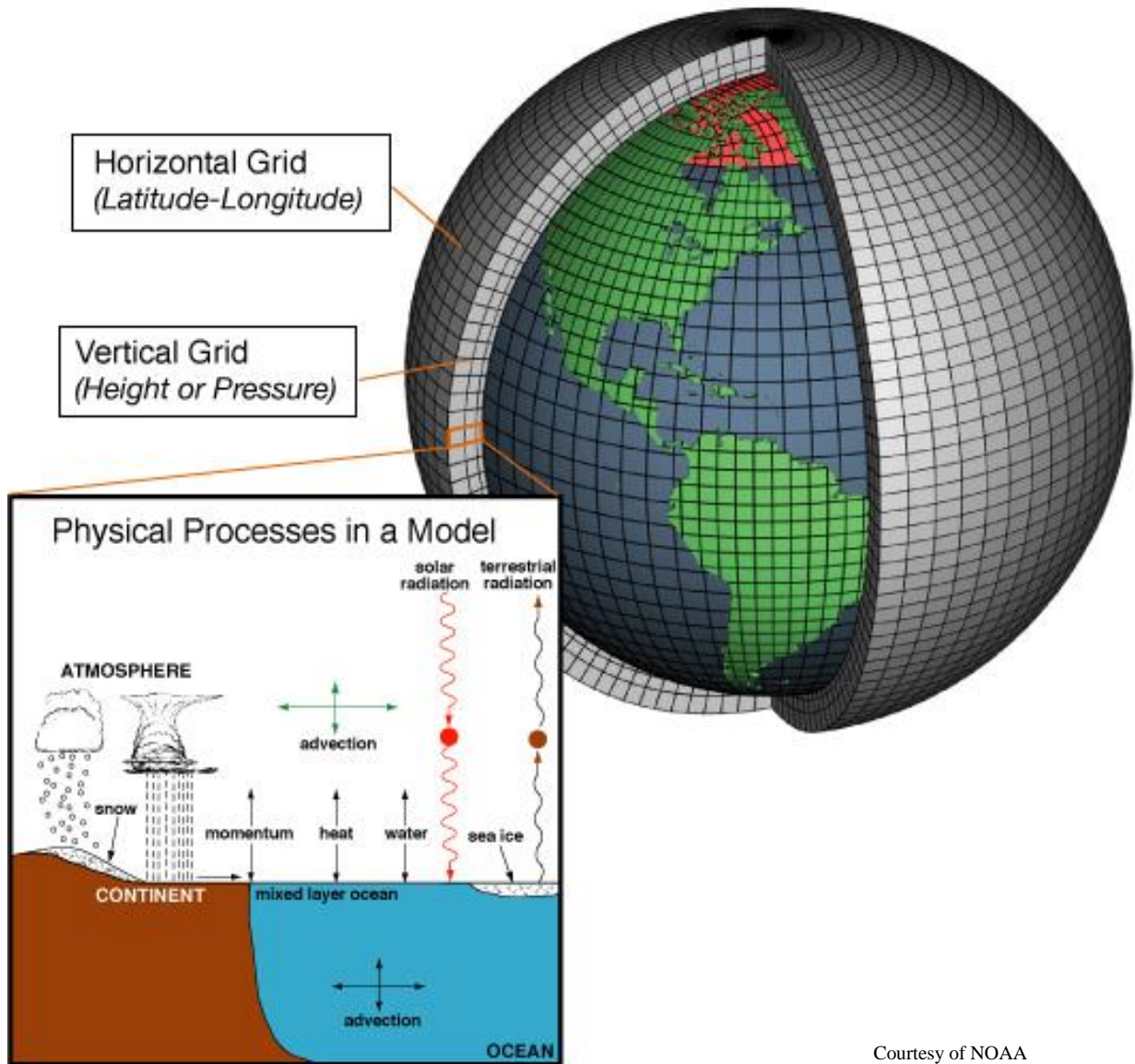
Pressure Level (mb)	Standard Height (m)	Standard Interval (m)	Coded as	Comments
850	1,500	3	500	Omit 1st digit
700	3,100	3	100	Omit 1st digit
500	5,500	40	550	Decameters
300	9,300	120	930	Decameters
200	11,800	120	180	Dm, 1st digit

Useful Conversion Factors

	Metric	English	Other
Distance	1 Km	0.6214 miles	0.54 nm
Speed	1 Km/hr	0.911 fps	0.278 m/s
Mass	1 Kg	2.2 lb	35.3 oz
Energy	1 Joule	0.000278 W-hr	0.239 cal
Pressure	1 hpa (mb)	0.0145 psi	0.0300 inHg
Density	1 Kg/liter	62.4 lbm/cu ft	1 g/cc

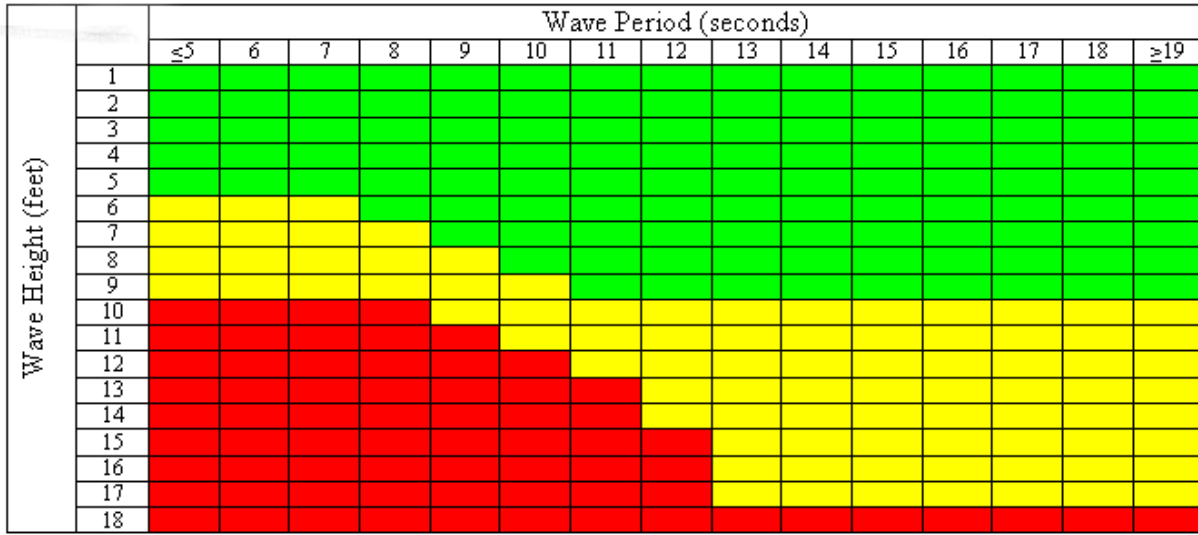
NOTE: There are many smart phone and tablet apps that will provide conversions.

Example of a Grid for Numerical Weather Prediction

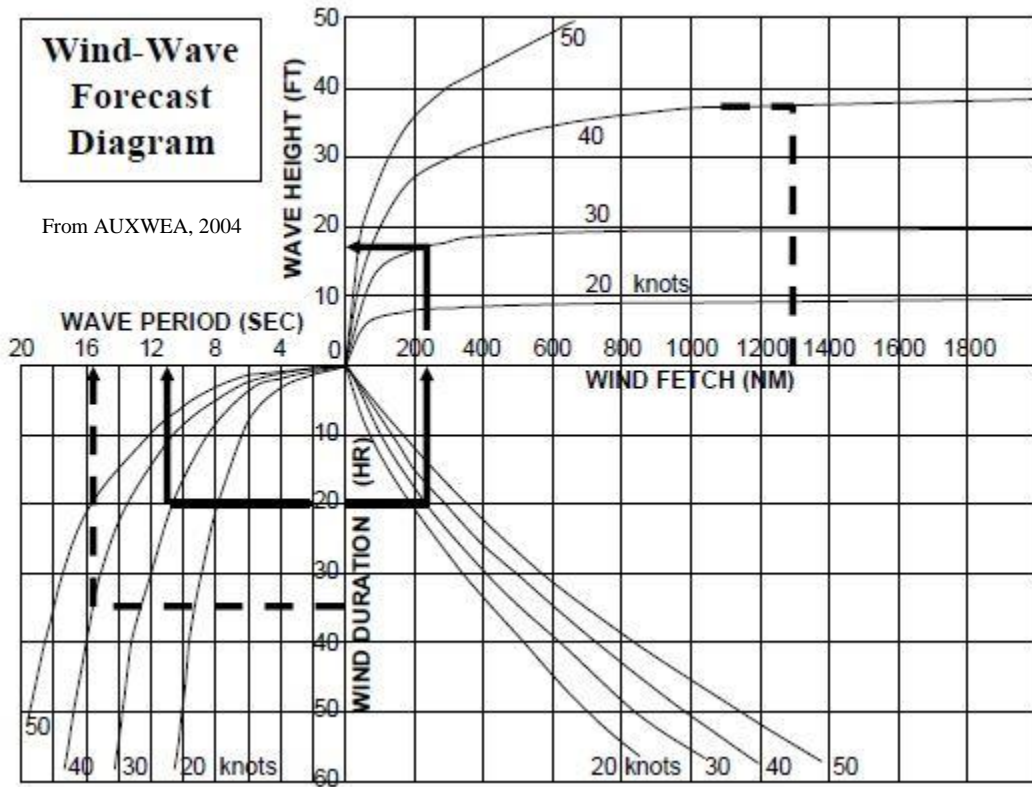


Courtesy of NOAA

Relationship Between Wave Period and Wave Height



Courtesy of NOAA



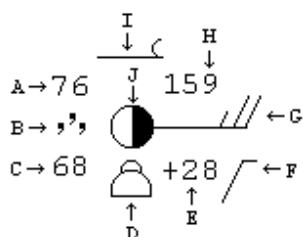
Station Model Symbols

Department of Environmental Protection

Weather Station Symbols

Cloud Coverage 	Wind Speed 	Cloud Types High Elevation Middle Elevation Low Elevation 	Weather Conditions INTERMITTENT <table border="1"> <tr> <td></td> <td>Light</td> <td>Moderate</td> <td>Heavy</td> </tr> <tr> <td>Rain</td> <td>•</td> <td>••</td> <td>•••</td> </tr> <tr> <td>Snow</td> <td>*</td> <td>**</td> <td>***</td> </tr> <tr> <td>Drizzle</td> <td>•••</td> <td>•••</td> <td>•••</td> </tr> </table> STEADY <table border="1"> <tr> <td></td> <td>Light</td> <td>Moderate</td> <td>Heavy</td> </tr> <tr> <td>Rain</td> <td>••</td> <td>•••</td> <td>••••</td> </tr> <tr> <td>Snow</td> <td>**</td> <td>**•</td> <td>**••</td> </tr> <tr> <td>Drizzle</td> <td>•••</td> <td>•••</td> <td>•••</td> </tr> </table> THUNDERSTORMS <table border="1"> <tr> <td></td> <td>Mild</td> <td>Moderate</td> <td>Severe</td> </tr> <tr> <td>Rain</td> <td>⬇</td> <td>⬇</td> <td>⬇</td> </tr> <tr> <td>Snow</td> <td>⬇*</td> <td>⬇*</td> <td>⬇*</td> </tr> <tr> <td>Hail</td> <td>⬇△</td> <td>⬇△</td> <td>⬇△</td> </tr> </table>		Light	Moderate	Heavy	Rain	•	••	•••	Snow	*	**	***	Drizzle	•••	•••	•••		Light	Moderate	Heavy	Rain	••	•••	••••	Snow	**	**•	**••	Drizzle	•••	•••	•••		Mild	Moderate	Severe	Rain	⬇	⬇	⬇	Snow	⬇*	⬇*	⬇*	Hail	⬇△	⬇△	⬇△
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Barometric Tendency																																																			
<table border="1"> <tr> <td colspan="4">Increase in Air Pressure over Last 3 Hours</td> <td colspan="4">Decrease in Air Pressure over last 3 Hours</td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>Rising, then Falling</td> <td>Rising, then Steady</td> <td>Rising Steadily</td> <td>Falling, then Rising</td> <td>Steady</td> <td>Falling, then Rising</td> <td>Falling, then Steady</td> <td>Falling Steadily</td> <td>Rising, then Falling</td> </tr> </table>				Increase in Air Pressure over Last 3 Hours				Decrease in Air Pressure over last 3 Hours													Rising, then Falling	Rising, then Steady	Rising Steadily	Falling, then Rising	Steady	Falling, then Rising	Falling, then Steady	Falling Steadily	Rising, then Falling																						
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Weather Station Model Demo



- A - Temperature
- B - Present Weather
- C - Dew Point
- D - Low Cloud Type
- E - Pressure Change
- F - Pressure Tendency
- G - Wind Speed & Direction
- H - Barometric Pressure
- I - High Cloud Type
- J - Cloud Coverage

Wigff 1995

Cloud Height Table

Level	Polar Region	Temperate Region	Tropical Region
High Clouds	10,000-25,000 feet (3-8 km)	16,500-40,000 Feet (5-13 km)	20,000-60,000 feet (6-18 km)
Middle Clouds	6,500-13,000 feet (2-4 km)	6,500-23,000 feet (2-7 km)	6,500-25,000 feet (2-8 km)
Low Clouds	Surface-6,500 feet (0-2 km)	Surface-6,500 feet (0-2 km)	Surface-6,500 feet (0-2 km)

Beaufort Wind Scale

Developed in 1805 by Sir Francis Beaufort, U.K. Royal Navy

Force	Wind (Knots)	WMO Classification	Appearance of Wind Effects	
			On the Water	On Land
0	Less than 1	Calm	Sea surface smooth and mirror-like	Calm, smoke rises vertically
1	1-3	Light Air	Scaly ripples, no foam crests	Smoke drift indicates wind direction, still wind vanes
2	4-6	Light Breeze	Small wavelets, crests glassy, no breaking	Wind felt on face, leaves rustle, vanes begin to move
3	7-10	Gentle Breeze	Large wavelets, crests begin to break, scattered whitecaps	Leaves and small twigs constantly moving, light flags extended
4	11-16	Moderate Breeze	Small waves 1-4 ft. becoming longer, numerous whitecaps	Dust, leaves, and loose paper lifted, small tree branches move
5	17-21	Fresh Breeze	Moderate waves 4-8 ft taking longer form, many whitecaps, some spray	Small trees in leaf begin to sway
6	22-27	Strong Breeze	Larger waves 8-13 ft, whitecaps common, more spray	Larger tree branches moving, whistling in wires
7	28-33	Near Gale	Sea heaps up, waves 13-19 ft, white foam streaks off breakers	Whole trees moving, resistance felt walking against wind
8	34-40	Gale	Moderately high (18-25 ft) waves of greater length, edges of crests begin to break into spindrift, foam blown in streaks	Twigs breaking off trees, generally impedes progress
9	41-47	Strong Gale	High waves (23-32 ft), sea begins to roll, dense streaks of foam, spray may reduce visibility	Slight structural damage occurs, slate blows off roofs
10	48-55	Storm	Very high waves (29-41 ft) with overhanging crests, sea white with densely blown foam, heavy rolling, lowered visibility	Seldom experienced on land, trees broken or uprooted, "considerable structural damage"
11	56-63	Violent Storm	Exceptionally high (37-52 ft) waves, foam patches cover sea, visibility more reduced	
12	64+	Hurricane	Air filled with foam, waves over 45 ft, sea completely white with driving spray, visibility greatly reduced	









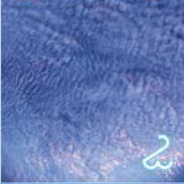


















Note: Wave heights assume open seas (very long fetch). Wave heights are less in inland waters.



Courtesy of NOAA


Cloud Chart (NOAA), With Cloud Symbols


SKY WATCHER CHART


High Clouds: cloud bases 16,000 - 50,000ft (5-15km) <http://www.weather.gov/os/brochures/cloudchart.pdf> Typical Types: Cirrus (Ci), Cirrostratus (Cs), Cirrocumulus (Cc)


								
H1: Cirrus In the form of filaments, strands, or hooks	H2: Cirrus Dense, in patches or sheaves, not increasing, or with tufts	H3: Cirrus Often anvil shaped remains of a cumulonimbus	H4: Cirrus In hooks or filaments, increasing, becoming denser	H5: Cirrostratus Cirrus bands, increasing, below 45° elevation	H6: Cirrostratus Cirrus bands, increasing, veil above 45° elevation	H7: Cirrostratus Translucent, completely covering the sky	H8: Cirrostratus Not increasing, not covering the whole sky	H9: Cirrocumulus Alone or with some cirrus or cirrostratus
<p style="color: white; font-size: small;">Middle Clouds: cloud bases 6,500 - 23,000ft (2-7km) Typical Types: Altostratus (As), Alto cumulus (Ac), Nimbostratus (Ns)</p>								
								
M1: Altostratus Mostly semi-transparent, sun or moon may be dimly visible	M2: Altostratus or Nimbostratus Dense enough to hide the sun or moon	M3: Alto cumulus Semi-transparent, one level, cloud elements change slowly	M4: Alto cumulus Lens-shaped, or continually changing shape and size	M5: Alto cumulus One or more bands or layers, expanding, thickening	M6: Alto cumulus From the spreading of cumulus or cumulonimbus	M7: Alto cumulus One or more opaque layers, w/ altostratus or nimbostratus	M8: Alto cumulus With cumulus-like tufts or turrets	M9: Alto cumulus Chaotic sky, cloud bases at several levels
<p style="color: white; font-size: small;">Low Clouds: cloud bases Up to 6,500 ft (0-2km) Typical Types: Stratus (St), Stratocumulus (Sc), Cumulus (Cu), Cumulonimbus (Cb)</p>								
								
L1: Cumulus Cumulus of fair weather with flattened appearance	L2: Cumulus Moderate/strong vertical extent, or towering cumulus	L3: Cumulonimbus Tops not fibrous, outline not completely sharp, no anvil	L4: Stratocumulus From the spreading and flattening of cumulus	L5: Stratocumulus Not from the spreading and flattening of cumulus	L6: Stratus In a continuous layer and/or ragged shreds	L7: Stratus Fractus and/or Cumulus Fractus occurs with rain or snow	L8: Cumulus & Stratocumulus Not spreading, bases at different levels	L9: Cumulonimbus With fibrous top, often with an anvil






Mammatus
Drooping underside of heavy, rain-saturated clouds


Tornado
Rapidly rotating column under a cumulonimbus cloud that touches the ground


Wall Cloud
Lowering of the rain free base of a thunderstorm, often prior to tornado formation


Shelf Cloud
Represents the leading edge of strong winds in advance of a thunderstorm


Wave Cloud
Formed by strong horizontal winds over uneven terrain

Special photo credit thanks to Jim W. Lee, Eric Kurth, Brian Klimowski, and Eric Helgeson

Courtesy of NOAA

Appendix C References

1. Anon., *Weather, Student Study Guide*, USCG Auxiliary Association, 2004.
2. Williams, J., *The Weather Book, an Easy Guide to the USA's Weather*, USA Today, 1997.
3. Brandenstein, R. E., et. al., *Weather Systems and Forecasting for Mariners*, US Power Squadrons, 2008.
4. Williams, J., *The AMS Weather Book: The Ultimate Guide to America's Weather*, American Meteorological Society, 2009.
5. Hess, S. L., *Introduction to Theoretical Meteorology*, Holt, Reinhart and Winston, 1959.
6. Haltiner, G. J. and F. L. Martin, *Dynamical and Physical Meteorology*, McGraw-Hill, 1957.
7. Huschke, R. E., ed., *Glossary of Meteorology*, American Meteorological Society, 1959.
8. Houghton, J. T., *The Physics of Atmospheres*, Cambridge University Press, 1977.
9. NOAA web, *NOAA Jet Stream*, <http://www.srh.weather.gov/jetstream/index.htm>

Appendix D Answers to Study Questions

This appendix contains all of the study questions, organized by chapter. The correct answer is in **bold** type and is followed with a page number in parentheses that tells where the information is located that supports that answer.

Students should attempt to answer the questions without reference to this appendix, then refer to it to check their answers. Wrong

answers should be looked up at the referenced page.

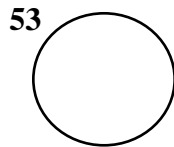
As always, if the student or instructor finds any errors in this material, he or she is asked to report that to the author (see the Preface of this Student Study Guide for further information).

Chapter 1

- The electromagnetic energy that comes from the sun consists of:
 - Light.
 - Ultraviolet.
 - Infrared.
 - All of the above. (4)**
- The amount of energy per unit area that arrives at the top of the atmosphere from the sun:
 - Decreases in the winter.
 - Is the same everywhere.
 - Increases with increasing latitude.
 - Decreases with increasing latitude. (5)**
- The largest swings of hot and cold are:
 - Day to night.
 - With longitude.
 - With the seasons. (5)**
 - Between land and water.
- With the same heat input, which heats faster?
 - Water.
 - Land. (5)**
 - The Oceans.
 - None of the above.
- The amount of solar energy that is absorbed by the surface is reduced due to:
 - The extra distance traveled.
 - Reflection from clouds.
 - The nature of the surface.
 - Both b and c. (6)**
- The specific heat of a substance is:
 - The amount of energy it can hold.
 - How hot it gets before it melts.
 - The heat needed to vaporize it.
 - The rate of temperature increase for a given energy input. (6)**

7. The air in the lower troposphere is heated mainly by:
 - a) Absorption by air of the direct radiation from the sun.
 - b) Radiation absorbed by dust in the atmosphere.
 - c) Cosmic rays.
 - d) **Conduction and convection from the Earth's surface. (8)**
8. Temperature may be defined as:
 - a) Energy produced by friction.
 - b) Change of energy from one form to another.
 - c) **A measure of the kinetic energy of molecules. (6)**
 - d) The pressure of the air on the thermometer.
9. In the Celsius temperature scale, zero is defined as:
 - a) The absence of heat.
 - b) The temperature at which ice is the densest.
 - c) **The melting point of pure water ice. (6)**
 - d) The freezing point of sea water.
10. 20° Celsius is, in Fahrenheit, to the nearest degree:
 - a) 52°F.
 - b) 40°F.
 - c) **68°F. (7)**
 - d) 75°F.
11. 59° Fahrenheit is, in Celsius, to the nearest degree:
 - a) 27°C.
 - b) **15°C. (7)**
 - c) 6°C.
 - d) 32°C.
12. The transfer of heat by the horizontal movement of air is:
 - a) Convection.
 - b) Conduction.
 - c) **Advection. (8)**
 - d) Radiation.
13. The transfer of heat between bodies that are not in contact is:
 - a) Convection.
 - b) Conduction.
 - c) **Radiation. (8)**
 - d) Advection.
14. In meteorology, convection means:
 - a) Transfer of heat by contact.
 - b) Conduction of heat by infrared radiation.
 - c) The horizontal movement of air by winds.
 - d) **The vertical transport of heat by air. (8)**
15. Radiation is energy transfer:
 - a) Via a medium.
 - b) By contact.
 - c) Resulting from friction.
 - d) **In wave form, without the necessity of a medium. (8)**
16. Large land masses, as opposed to the oceans:
 - a) Maintain a steadier temperature.
 - b) Are always warmer.
 - c) **Change temperature more between night and day. (5)**
 - d) Are cooler during the day.

17. The cause of most weather phenomena is:
- The layers in the atmosphere.
 - The rotation of the Earth.
 - The revolution around the Sun.
 - Uneven heating of the Earth's surface. (5)**
18. For the station model shown below, the temperature reported is:
- 53 °C.
 - 5.3 °F.
 - 53 °F. (8)**
 - 5.3 °C.



19. The Coriolis effect:
- Decreases with increasing latitude.
 - Increases with increasing wind speed. (9, 10)**
 - Always turns winds to the right.
 - Operates over long and short distances.
20. The winds near the equator are called:
- Trade winds. (10)**
 - Doldrums.
 - Prevailing easterlies.
 - The ITCZ.
21. On a rotating, smooth Earth, the low pressure bands parallel to the equator are the _____ and the _____.
- Doldrums, Horse Latitudes.
 - Horse Latitudes, Westerlies.
 - Doldrums, Sub-polar Low. (10)**
 - Horse Latitudes, Polar Low.

22. The Doldrums is a belt of relatively:
- Low temperature.
 - Low humidity.
 - Low pressure. (10)**
 - High latitude.
23. Which of the following is not one of the primary wind belts?
- The polar westerlies. (10)**
 - The northeast trades.
 - The southeast trades.
 - The prevailing westerlies.
24. The Inter-tropical Convergence Zone (ITCZ) is located:
- On the equator.
 - 15° north of the equator.
 - 15° south of the equator.
 - Either side of the equator, depending on the season. (10)**
25. The trade winds:
- Vary widely in speed.
 - Reverse direction with the seasons.
 - Blow only in the northern hemisphere.
 - Blow from the Horse Latitudes to the Doldrums. (10)**
26. Vertical motion of air near the equator is caused by:
- Convergence of the trade winds.
 - Heating of the air by the Earth's surface.
 - Variation of solar energy with latitude.
 - All of the above. (9, 10)**
27. Heat is transported northward and southward from the equator by:
- Winds.
 - Ocean Currents.
 - Neither of the above.
 - Both a) and b). (5)**

28. Insolation is:
- a) The sun's apparent motion from east to west.
 - b) The reduction in temperature due to clouds.
 - c) **The amount of energy reaching the Earth's surface. (6)**
 - d) The inclination of the Earth's axis.
29. An example of a synoptic scale phenomenon is:
- a) A tornado.
 - b) **An air mass. (11)**
 - c) The prevailing westerlies.
 - d) None of the above.
30. An example of a mesoscale phenomenon is:
- a) **A thunderstorm. (11)**
 - b) A frontal system.
 - c) The semi-permanent pressure centers.
 - d) None of the above.
31. The trade winds are an example of:
- a) **A global scale phenomenon. (11)**
 - b) A mesoscale phenomenon.
 - c) A synoptic scale phenomenon.
 - d) A microscale phenomenon.

Chapter 2

1. A north wind is one that is:
 - a) Blowing toward the north.
 - b) Shifting toward the north.
 - c) **Coming from the north. (18)**
 - d) Blowing from the North Pole.
2. Wind speeds on charts are given in:
 - a) Miles per hour.
 - b) Kilometers per hour.
 - c) Feet per second.
 - d) **Knots. (21)**
3. Standard sea-level pressure is:
 - a) 1013.26 in Hg.
 - b) 29.92 psi.
 - c) 760 kPa.
 - d) **14.7 psi. (15)**
4. If the barometric pressure is measured in Albuquerque, NM, the most important correction to make before reporting it is:
 - a) Temperature.
 - b) Local force of gravity.
 - c) Calibration.
 - d) **Altitude. (16)**
5. Station barometric pressures are “reduced to sea level”:
 - a) To correct instrument error.
 - b) To correct for the temperature.
 - c) **So data taken at different altitudes can be compared. (16)**
 - d) To compensate for the lower gravity.
6. Aneroid barometers are more useful on boats because they:
 - a) Contain less mercury.
 - b) Don’t need calibration.
 - c) Are more accurate.
 - d) **Can be mounted in any position. (15)**
7. Pressure gradient is defined as:
 - a) Pressure difference due to wind.
 - b) Pressure difference due to changing temperature.
 - c) **Pressure change per unit distance. (15)**
 - d) Pressure change over 3 hours.
8. The primary force generating wind is:
 - a) Coriolis force.
 - b) **Pressure gradient force. (15)**
 - c) Temperature gradient.
 - d) Surface heating.
9. The effect of friction on the wind is:
 - a) **To slow the wind. (18)**
 - b) To increase the Coriolis effect.
 - c) Independent of altitude.
 - d) To cause the wind to follow contours.
10. Cyclonic wind flow is:
 - a) Clockwise in the northern hemisphere.
 - b) Counter-clockwise in the southern hemisphere.
 - c) **Clockwise in the southern hemisphere. (18)**
 - d) Counter-clockwise in both hemispheres.
11. The jet stream is:
 - a) A warm ocean current.
 - b) An equatorial wind current.
 - c) **A high altitude wind current. (21)**
 - d) A low altitude wind current.

12. If an observer is facing the wind in the northern hemisphere, the low pressure center is approximately:

- a) Ahead of him.
- b) To her right. (19)**
- c) To her left.
- d) Behind him.

13. The Buys-Ballot law tells us:

- a) The wind direction in the northern hemisphere.
- b) The direction the wind is shifting.
- c) The location of the low pressure. (19)**
- d) The way the pressure is changing.

14. A wind gradually changing in a clockwise fashion is:

- a) Backing.
- b) Veering. (18)**
- c) Increasing in speed.
- d) Due to the sea breeze effect.

15. On the station model, a plotted pressure of 853 is:

- a) 1085.3 mb.
- b) 985.3 mb. (20)**
- c) 853 mb.
- d) 85.3 mb.

16. On the station model, a plotted pressure tendency of -26 is:

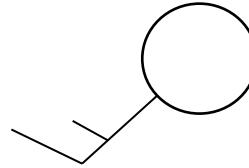
- a) A rise of 2.6 mb over 3 hours.
- b) A fall of 2.6 mb over 1 hour.
- c) A fall of 26 mb over 24 hours.
- d) A fall of 2.6 mb over 3 hours. (20)**

17. Isobars are lines of constant:

- a) Temperature.
- b) Wind direction.
- c) Pressure. (17)**
- d) Wind speed.

18. The station model below shows:

- a) A NE wind of 15 knots.
- b) A SW wind of 1.5 knots.
- c) A NE wind of 1.5 knots.
- d) A SW wind of 15 knots. (20)**



19. Rossby waves are:

- a) Waves on a lake.
- b) Pressure waves at the surface.
- c) Large upper-level waves that propagate around the globe. (21)**
- d) The meandering of the ITCZ.

20. The solid lines on a 500 mb chart are:

- a) Isotherms.
- b) Isoheights. (21)**
- c) Isobars.
- d) Isopressures.

21. The pattern at 500 mb that causes surface low pressure areas to strengthen is:

- a) Negative temperature advection.
- b) Positive temperature convection.
- c) Backing winds.
- d) Diverging isoheights (22).**

22. The jet stream shows up best on the:

- a) 500 mb chart.
- b) The surface chart.
- c) The 300 mb chart. (21)**
- d) The 100 mb chart.

23. Lines of constant temperature are:

- a) Found on upper-level charts.
- b) Plotted as dashed lines.
- c) Isotherms. (21)**
- d) All of the above.

24. On the 500 mb chart, ridges are:
- a) **Convex to the north. (20)**
 - b) Concave to the north.
 - c) Areas of lower pressure.
 - d) Convex to the south.
25. Surface pressure is caused by:
- a) The weight of the air in the troposphere.
 - b) **The weight of the air above. (15)**
 - c) The winds striking buildings.
 - d) The weight of the air in the stratosphere.
26. Isobars on a standard surface chart are drawn every:
- a) 5 mb.
 - b) **4 mb. (17)**
 - c) 3 mb.
 - d) 10 mb.
27. Higher pressure gradients cause:
- a) Rising temperatures.
 - b) Falling temperatures.
 - c) **Stronger winds. (15)**
 - d) Lighter winds.
28. The polar jet stream:
- a) Originates over the North Pole.
 - b) Is confined to the polar high.
 - c) **Plays a role in steering weather systems. (21)**
 - d) Flows from east to west.
29. The standard instrument for measuring wind direction and speed is the:
- a) Aneroid barometer.
 - b) Psychrometer.
 - c) **Anemometer. (19)**
 - d) Thermocouple thermometer.
30. Half of the total mass in the atmosphere is in the lowest:
- a) 8,000 ft.
 - b) 12,000 ft.
 - c) **18,000 ft. (20)**
 - d) 25,000 ft.

Chapter 3

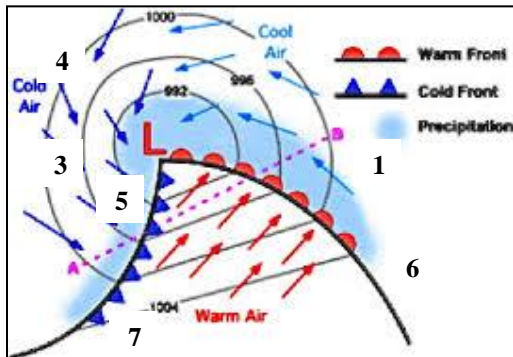
- In the lower atmosphere, the temperature generally:
 - Increases with altitude.
 - Stays the same.
 - Decreases with altitude. (26)**
 - Varies randomly.
- The tropopause is important in weather development since it:
 - Contains most of the moisture.
 - Disappears during turbulent weather.
 - Caps the development of convective activity. (26)**
 - Varies Randomly
- One difference between the troposphere and the stratosphere is:
 - Carbon dioxide content.
 - Argon content.
 - Temperature distribution. (26)**
 - Thickness.
- The most abundant gases in the atmosphere are:
 - Nitrogen and Hydrogen.
 - Oxygen and Nitrogen. (26)**
 - Nitrogen and Argon.
 - Carbon Dioxide and Methane.
- The average environmental lapse rate in the lower atmosphere is:
 - 3.2° C per 1,000 ft.
 - +3.5°F. per 1,000 ft.
 - 2.2°C. per 1,000 ft.
 - 3.5°F. per 1,000 ft. (26)**
- A temperature increase with altitude in the lower atmosphere is called:
 - The tropopause.
 - An inversion. (27)**
 - A thermal.
 - Convection.
- A dry, warm wind descending the east side of the Rocky Mountains is a:
 - Chinook. (31, 32)**
 - Valley breeze.
 - Land breeze.
 - Wind shear.
- Water vapor is added to the air by:
 - Condensation.
 - Evaporation. (29)**
 - Vapor pressure.
 - Deposition.
- When water vapor condenses, heat is:
 - Added.
 - Released. (27, 28)**
 - Not changed.
 - Absorbed.
- The transition from ice to vapor without going through the liquid phase is called:
 - Effervescence.
 - Sublimation. (28)**
 - Evaporation.
 - Deposition.
- Latent heat:
 - Can be measured with a thermometer.
 - Is released when water freezes. (29)**
 - Is released when water vaporizes.
 - Can be felt.
- Saturation can be accomplished by:
 - Raising absolute humidity while holding the temperature constant.
 - Lowering the temperature while the absolute humidity remains constant.
 - Either a) or b). (29)**
 - None of the above.

13. The temperature at which water vapor begins to condense is called the:
- Condensation level.
 - Saturation temperature.
 - Dew point. (29)**
 - Melting point.
14. If the water vapor content of an air parcel increases at constant temperature, the relative humidity ____ and the dew point ____.
- Decreases, Increases.
 - Increases, Decreases.
 - Increases, Increases. (29)**
 - Decreases, Decreases.
15. When air is saturated with water vapor:
- The dew point depression is zero.
 - The relative humidity is 100%.
 - The air can hold no more vapor.
 - All of the above. (28, 29)**
16. Regarding the latent heat of fusion and the latent heat of vaporization of water:
- They are the same.
 - Latent heat of fusion is higher.
 - Latent heat of vaporization is higher. (27)**
 - They are determined by the specific heat of water.
17. The term adiabatic means:
- No heat is added or subtracted. (27)**
 - The pressure is constant.
 - The temperature is constant.
 - The absolute humidity is constant.
18. The dry adiabatic lapse rate, compared to the wet adiabatic lapse rate is:
- Smaller.
 - More negative. (27)**
 - Less negative.
 - Positive.
19. The physical property or properties of water important to the weather is/are:
- It can transport energy from one location to another.
 - It takes a lot of energy to vaporize it.
 - It absorbs a lot of infrared energy.
 - All of the above. (27)**
20. The term describing the tendency of displaced air to return to its former level is:
- Absolute instability.
 - Elasticity.
 - Absolute stability. (31)**
 - Conditional stability.
21. The term describing the tendency of air to rise on its own is:
- Absolute instability. (30)**
 - Elasticity.
 - Absolute stability.
 - Conditional stability.
22. The term describing the tendency of air to rise only after it has been initially raised to some higher altitude is:
- Absolute instability.
 - Elasticity.
 - Absolute stability.
 - Conditional stability. (31)**
23. Fog that forms by adding moisture is:
- Radiation fog.
 - Advection fog
 - Precipitation fog. (30)**
 - None of the above.
24. Fog that forms under clear skies at night is:
- Radiation fog. (30)**
 - Advection fog.
 - Precipitation fog.
 - All of the above.

Chapter 4

1. In highs, the:
 - a) Air spirals into the center.
 - b) Air rises.
 - c) **Air spirals out of the center. (38)**
 - d) Weather is usually foul.
2. In lows, the:
 - a) **Air spirals into the center. (38)**
 - b) Air sinks.
 - c) Air spirals out of the center.
 - d) Weather is usually fair.
3. Normally, air masses travel across the U.S.:
 - a) From east to west.
 - b) **Faster in the winter than the summer. (36)**
 - c) Faster in the summer than the winter.
 - d) The same speed all year.
4. Precipitation ahead of a warm front is usually:
 - a) Short in duration and showery.
 - b) Non-existent.
 - c) Impossible to predict.
 - d) **Long in duration and steady. (40)**
5. Precipitation ahead of a cold front is usually:
 - a) **Short in duration and showery. (39)**
 - b) Non-existent.
 - c) Impossible to predict.
 - d) Long in duration and steady.
6. When a cold front passes, the wind:
 - a) **Veers sharply. (40)**
 - b) Backs sharply.
 - c) Reverses direction.
 - d) Stops blowing.
7. As a cold front passes, the winds are:
 - a) Calm.
 - b) **Strong and gusty. (37)**
 - c) From the south.
 - d) From the east.
8. Conditions after a cold front are usually:
 - a) Good visibility with low stratus clouds.
 - b) Poor visibility with low stratus clouds.
 - c) **Good visibility with cumulus clouds. (40)**
 - d) Poor visibility with cumulus clouds.
9. In the occluded portion of a cyclone, the warm air:
 - a) Has moved away.
 - b) Is trapped at the surface.
 - c) **Is held aloft. (41)**
 - d) Pushes under the cool air.
10. An occluded front is formed when:
 - a) A fast warm front overrides a cold front.
 - b) **A fast cold front overtakes a warm front. (41)**
 - c) Moist air displaces dry air.
 - d) A cold front stalls.
11. North of a low:
 - a) There are no fronts.
 - b) The winds back as the low passes.
 - c) There is no warm sector.
 - d) **All of the above. (42)**

12. The polar front forms storm systems because:
- It encourages the formation of anti-cyclones.
 - The polar westerlies and prevailing easterlies oppose each other.
 - The prevailing westerlies and polar easterlies oppose each other. (43)**
 - None of the above.
13. The jet stream is:
- An ocean current.
 - A low-level wind.
 - A high altitude wind. (43)**
 - Over the equator.



Use this figure to answer questions 14 - 22.

14. Clouds in area 1 are typically:
- Cumuliform.
 - Stratiform. (40, 42)**
 - Cirriform.
 - Absent.
15. Clouds in area 5 are typically:
- Cumuliform. (40, 42)**
 - Stratiform.
 - Cirriform.
 - Absent.

16. Clouds in area 3 are typically:
- Cumuliform. (40, 42)**
 - Stratiform.
 - Cirriform.
 - Nimbostratus.
17. The front next to 7 is a:
- Cold front. (39)**
 - Warm front.
 - Stationary front.
 - Occluded front.
18. The front next to 6 is a:
- Cold front.
 - Warm front. (40)**
 - Stationary front.
 - Occluded front.
19. The wind has veered to the NW, the thunderstorms are over and the barometer is rising rapidly. Where are you?
- 1.
 - 7.
 - 5. (38, 39)**
 - 3.
20. It is now colder, the wind is NW, the sky is clear or partly cloudy. Where are you?
- 1.
 - 7.
 - 5.
 - 3. (39)**
21. The winds have been backing most of the day. Where are you?
- 6.
 - 7.
 - 4. (42)**
 - 3.

22. A mid-latitude cyclone like this one will typically move in the direction from:
- 5 to 1. (41)**
 - 4 to 1.
 - 6 to 1.
 - 1 to 6.
23. Divergence aloft can be caused by:
- The wind speeding up with distance. (38)**
 - The wind slowing down with distance.
 - The wind veering.
 - The temperature falling.
24. Divergence aloft encourages cyclone formation because it:
- Supports surface divergence.
 - Causes air to sink.
 - Supports surface convergence. (38)**
 - Prevents surface convergence.
25. The paths of cyclones across the U. S. are determined by:
- The cyclonic wind flow.
 - High pressure to the west and low pressure to the east.
 - Steering winds at the surface.
 - Steering winds at and above 18,000 feet. (41)**
26. Cyclones can form:
- Over the gulf.
 - Over the Pacific Ocean.
 - Over the Great Plains.
 - All of the above. (43)**
27. The symbol for a cold front is a line with:
- Semi-circles.
 - Triangles. (39)**
 - Triangles and semi-circles on different sides.
 - Triangles and semi-circles on the same side.
28. The symbol for an occluded front is a line with:
- Semi-circles.
 - Triangles.
 - Triangles and semi-circles on different sides.
 - Triangles and semi-circles on the same side. (39)**
29. The symbol for a stationary front is a line with:
- Semi-circles.
 - Triangles.
 - Triangles and semi-circles on different sides. (39)**
 - Triangles and semi-circles on the same side.
30. The symbol for a warm front is a line with:
- Semi-circles. (39)**
 - Triangles.
 - Triangles and semi-circles on different sides.
 - Triangles and semi-circles on the same side.
31. A cP air mass moving through the mid-west will:
- Cool from below.
 - Pick up additional moisture.
 - Warm from below.
 - Both b and c. (37)**
32. An mT air mass moving up the east coast will:
- Cool from below.
 - Pick up additional moisture.
 - Both a and b. (37)**
 - Neither a nor b.

33. A cold-core low does what as the altitude increases?

- a) Fills.
- b) **Deepens. (44)**
- c) Expands.
- d) None of the above.

34. A warm-core low does what as the altitude increases?

- a) **Fills. (44)**
- b) Deepens.
- c) Expands.
- d) None of the above.

Chapter 5

- “Nimbo” added to a cloud name means:
 - High clouds.
 - Low clouds.
 - Precipitation. (48)**
 - Thick, dark clouds.
- Clouds with a horizontal, layered appearance would be:
 - Stratiform. (48)**
 - Nimbostratus.
 - Cirriform.
 - Cumuliform.
- Clouds with a wispy appearance are:
 - Stratiform.
 - Nimbostratus.
 - Cirriform. (48)**
 - Cumuliform.
- Clouds with a lumpy appearance are:
 - Stratiform.
 - Nimbostratus.
 - Cirriform.
 - Cumuliform. (48)**
- Which type of cloud produces precipitation?
 - Altostratus.
 - Stratocumulus.
 - Nimbostratus. (49)**
 - Cirrostratus.
- Middle clouds range in altitude:
 - Below 6,500 feet.
 - Between 6,500 feet and 20,000 feet. (48)**
 - Above 20,000 feet.
 - Below 10,000 feet.
- Low cloud bases are found:
 - Below 6,500 feet. (48)**
 - Between 6,500 feet and 20,000 feet.
 - Above 20,000 feet.
 - Below 10,000 feet.
- Clouds that develop vertically are:
 - Stratocumulus.
 - Nimbostratus.
 - Altostratus.
 - Cumulus. (51)**
- What type of cloud would you associate with the phrase “mares’ tails”?
 - Cirrus. (50)**
 - Cirrostratus.
 - Altostratus.
 - Stratus.
- What type of cloud would you associate with the phrase “mackerel sky”?
 - Altostratus.
 - Altostratus.
 - Cirrocumulus. (50)**
 - Cumulonimbus.
- Cirrus clouds consist of:
 - Water droplets.
 - Ice particles. (51)**
 - Super-cooled water vapor.
 - Fine mist.
- Nimbostratus clouds produce:
 - Halos.
 - Beautiful sunsets.
 - Precipitation. (49)**
 - Dust storms.

13. Halos around the sun and moon are caused by:
- Altostratus.
 - Cirrostratus. (51)**
 - Nimbostratus.
 - Nimbocumulus.
14. A heavy, dark cloud from which a steady rain is falling is:
- Altostratus.
 - Nimbostratus. (49)**
 - Cumulonimbus.
 - Cumulus.
15. For precipitation to fall from a cloud:
- The air must rise adiabatically.
 - The cloud particles must coalesce. (53)**
 - The winds must be more than 20 knots.
 - The air must sink adiabatically.
16. The factor that best determines what type of precipitation occurs is:
- The vertical temperature profile. (54)**
 - The vertical wind profile.
 - The upper level winds.
 - The surface pressure.
17. Hailstones are always:
- Larger than 2 inches.
 - Smaller than ¼ inch.
 - Produced in thunderstorms. (54)**
 - Rime.
18. The wintertime deposit that can severely affect the stability of a vessel is:
- Glaze ice. (55)**
 - Snow.
 - Sleet.
 - Rime ice.
19. Rime ice is a deposit that forms when _____ comes into contact with a surface.
- Sleet.
 - Super-cooled water droplets. (55)**
 - Snow.
 - Soft hail.
20. Clouds that form “caps” on the top of mountains are called:
- Mountain clouds.
 - Lenticular clouds. (52)**
 - Chinook clouds.
 - Cirrus clouds.
21. The fact that the sky is blue results from:
- The preferential scattering of blue light by the atmosphere. (56)**
 - The refraction of red light from the sun’s rays.
 - An optical illusion.
 - The presence of thin cirrus clouds.
22. Clouds to the west at sunset are red because:
- The air to the west scatters more blue light.
 - The light has farther to travel through the atmosphere.
 - Red light is scattered less than the other colors.
 - Both b. and c. (56, 57)**
23. Halos are caused by:
- Thin ice clouds.
 - Ice crystals in the air.
 - The presence of cirrostratus.
 - All of the above. (51, 57)**
24. Rainbows require:
- Rain drops and low humidity.
 - Rain drops and direct sunlight. (57)**
 - Ice crystals in the direction opposite the sun.
 - Cloud droplets behind you.

25. To see a primary rainbow, you must:
- a) **Have your back to the sun. (57)**
 - b) Face the sun.
 - c) Have your back to the rain.
 - d) Have clear skies.
26. When a secondary rainbow is formed, it is fainter because:
- a) **It has two reflections in the rain drop. (57)**
 - b) It is farther away.
 - c) The colors are reversed.
 - d) None of the above.
27. An example of a synoptic scale phenomenon is:
- e) A tornado.
 - f) **An air mass. (58)**
 - g) The prevailing westerlies.
 - h) None of the above.
28. An example of a mesoscale phenomenon is:
- i) **A thunderstorm. (58)**
 - j) A frontal system.
 - k) The semi-permanent pressure centers.
 - l) None of the above.
29. The trade winds are an example of:
- m) **A global scale phenomenon. (11)**
 - n) A mesoscale phenomenon.
 - o) A synoptic scale phenomenon.
 - p) A microscale phenomenon.

Chapter 6

1. The life cycle of a thunderstorm has stages:
 - a) Synoptic, meso, and micro.
 - b) **Cumulus, mature, and dissipating. (61)**
 - c) Cumulus and cumulonimbus.
 - d) Updraft and down draft.
2. The first stage of a thunderstorm cell has:
 - a) Downdrafts only.
 - b) **Updrafts only. (61, 62)**
 - c) Updrafts and downdrafts.
 - d) None of the above.
3. The mature stage of a thunderstorm cell has:
 - a) Downdrafts only.
 - b) Updrafts only.
 - c) **Updrafts and downdrafts. (61, 62)**
 - d) None of the above.
4. The dissipation stage of a thunderstorm has:
 - a) Cold updrafts.
 - b) **Cold downdrafts. (62)**
 - c) Warm updrafts.
 - d) Warm downdrafts.
5. Squall lines are long lasting because:
 - a) **Downbursts from existing cells cause others to develop. (62)**
 - b) Cells multiply by splitting.
 - c) Cells don't have a dissipation stage.
 - d) None of the above.
6. The distinguishing characteristic of a supercell is:
 - a) It has no downdrafts.
 - b) **It contains a large, rotating meso-cyclone. (63)**
 - c) It never produces tornados.
 - d) There are no other thunderstorms in the area.
7. The condition(s) that favor the development of thunderstorms are:
 - a) A supply of warm, moist air.
 - b) An unstable lapse rate.
 - c) A lifting mechanism.
 - d) **All of the above. (61, 62)**
8. Individual thunderstorms on a hot afternoon are most likely:
 - a) Orographic.
 - b) **Air mass. (62)**
 - c) Frontal.
 - d) Squall line.
9. As a thunderstorm approaches, the wind is likely to be:
 - a) First out of the cloud, then toward it.
 - b) **First toward the cloud, then out of it. (61)**
 - c) First cold, then warm.
 - d) Light and variable.
10. Downbursts and microbursts are associated with:
 - a) Nimbostratus clouds.
 - b) **Cumulonimbus clouds. (64)**
 - c) Towering cumulus clouds.
 - d) Down-slope winds.

11. Microbursts are more dangerous than ordinary downbursts because of their:
- Tendency to form out of a clear sky.
 - Small size, high winds, and sudden onset. (64)**
 - Relatively long life and large area.
 - Association with developing thunderstorms.
12. The estimated distance to a thunderstorm if you hear the thunder 20 seconds after you see the lightning is:
- 4 kilometers.
 - 2 statute miles.
 - 4 statute miles. (64)**
 - 2 nautical miles.
13. Tornadoes are:
- Rotation vortices that do not touch the ground.
 - Micro-hurricanes.
 - Rotation vortices that touch the ground. (65)**
 - Severe thunderstorms.
14. Tornadoes have been observed in:
- Only the gulf coast and east coast.
 - All 50 states. (65)**
 - Only during the winter.
 - Only during the summer.
15. Tornadoes are known for their:
- Enormous destructive paths.
 - High winds. (65)**
 - Ease of forecasting.
 - Long lifetimes.
16. The most intense tornadoes are associated with:
- Hail.
 - Supercells. (63)**
 - Squall lines.
 - Mesoscale convective complexes.
17. The Enhanced Fujita scale for tornadoes is based on:
- The measured wind speed.
 - The intensity of the radar echo.
 - How long it lasts.
 - The amount of destruction. (64)**
18. Non-tornado water spouts:
- Occur in fair or foul weather.
 - Have lighter winds than tornadoes.
 - May rotate in either direction.
 - All of the above. (67)**
19. The inter-tropical convergence zone (ITCZ) is:
- A zone of convective activity.
 - Between the NE and SE trade winds.
 - Varies its position with the seasons.
 - All of the above. (10,11)**
20. The Bermuda high:
- Is larger in the winter than the summer.
 - Affects the tracks of Atlantic hurricanes. (70)**
 - Has cyclonic circulation.
 - Affects only ships at sea.
21. Compared to extra-tropical cyclones, hurricanes are:
- Smaller and more intense. (67)**
 - Larger and more intense.
 - More numerous.
 - Also have fronts.
22. The *principle* source of energy required to maintain a hurricane is:
- Latent heat. (68)**
 - Strong upper level winds.
 - Surface convergence.
 - Wind shear.

23. A tropical cyclone is given a name when:
- a) It becomes a hurricane.
 - b) **It has winds of 39 mph (34 knots) or more. (68)**
 - c) It is expected to make land-fall.
 - d) A hurricane warning is issued.
24. The eye of a hurricane is an area of:
- a) Rising air.
 - b) **Descending air. (68, 69)**
 - c) Calm seas.
 - d) Maximum winds.
25. The strongest winds in a hurricane are located:
- a) In the eye.
 - b) On the outer edges.
 - c) **In the eye wall. (68, 69)**
 - d) None of the above.
26. The relatively clear area of the eye results from:
- a) **Descending air. (68)**
 - b) Rising air.
 - c) Confused seas.
 - d) Wind shear.
27. After heading north, an Atlantic hurricane turns NE due to:
- a) The NE trade winds.
 - b) **The circulation of the Bermuda high. (70)**
 - c) The colder water.
 - d) None of the above.
28. The National Weather Service (NWS) calls a hurricane “major” if it is:
- a) Category 5.
 - b) Category 4 or above.
 - c) **Category 3 or above. (69)**
 - d) Category 2 or above.
29. A hurricane watch is issued if:
- a) **Hurricane conditions are expected within 48 hours. (70)**
 - b) Hurricane winds are over 80 knots.
 - c) The area will experience high winds.
 - d) The area will experience storm surges.
30. A hurricane warning means:
- a) The eye is within 300 nautical miles.
 - b) **Hurricane conditions are expected within 36 hours. (70)**
 - c) There will be storm surges of over 15 feet.
 - d) The area will experience winds over 100 knots.

Chapter 7

1. Surface analyses are produced:
 - a) Every 12 hours.
 - b) **Every 3 hours. (74)**
 - c) Every hour.
 - d) When needed.
2. Weather radar data are available:
 - a) For each radar.
 - b) By region.
 - c) For the entire CONUS.
 - d) **All of the above. (76)**
3. Current weather radars are:
 - a) Similar to pleasure boat radars.
 - b) Located where the weather is the worst.
 - c) **Based on the Doppler effect. (77)**
 - d) Out of date and will be replaced.
4. Weather satellites are:
 - a) In low orbit at the equator.
 - b) In geostationary orbit.
 - c) In polar orbit.
 - d) **Both b) and c). (77, 78)**
5. Polar orbiting weather satellites:
 - a) Stay over the same longitude.
 - b) **Are sun synchronous. (78)**
 - c) Are at noon and midnight.
 - d) None of the above.
6. NOAA uses the following polar orbiting satellites:
 - a) GOES and NOAA.
 - b) NOAA and DMSP.
 - c) **METOP, DMSP and NOAA. (78)**
 - d) All of the above.
7. NOAA uses the following geostationary satellites:
 - a) NOAA and GOES.
 - b) GOES and METOP.
 - c) GOES only.
 - d) **GOES and Meteosat. (77, 78)**
8. The NEXRAD Doppler weather radar was developed by:
 - a) NOAA.
 - b) NOAA and the USAF.
 - c) **DoD, DoT, and DoC. (77)**
 - d) NASA.
9. NEXRAD Doppler radars can detect:
 - a) Precipitation.
 - b) Clouds.
 - c) Turbulence.
 - d) **All of the above. (77)**
10. The GOES satellite produces images in the following wavebands:
 - a) Visible and Radio.
 - b) **Visible, Infrared, and Water Vapor. (78)**
 - c) Visible, Infrared and Ultraviolet.
 - d) All of the above.
11. The primary GOES satellites are located at longitudes:
 - a) 90 and 180 degrees.
 - b) 135 W and 75 E.
 - c) **75 W and 135 W. (77, 78)**
 - d) 105 W.
12. Cloud temperatures are measured by weather satellites in the:
 - a) Visible bands.
 - b) **Infrared bands. (79)**
 - c) Water Vapor bands.
 - d) All of the above.

13. The visible band on weather satellites operates on:
- Reflected light. (78)**
 - Emitted energy.
 - Both of the above.
 - None of the above.
14. The water vapor band on weather satellites measures moisture:
- At the tropopause.
 - At the 500 mb level.
 - Over the entire depth of the atmosphere. (79)**
 - Near the surface only.
15. Upper air analysis charts are produced:
- Every three hours.
 - Every six hours.
 - Twice a day. (79)**
 - At noon and midnight local time.
16. Persistence forecasting is useful for:
- Long range forecasts.
 - Areas where the weather does not change much. (81)**
 - Forecasting the position of a tornado.
 - Not much at all.
17. Trend forecasting is useful for:
- Long range forecasts.
 - Areas where the weather does not change much.
 - Forecasting the position of a tornado. (81)**
 - Not much at all.
18. Analog forecasting is most useful for:
- Long range forecasts.
 - Short range forecasts.
 - Correcting numerical forecasts. (81)**
 - Use by new forecasters.
19. Numerical forecasting makes use of:
- Surface observations.
 - Upper air observations.
 - Chaos theory.
 - Both a) and b). (81)**
20. Ensemble forecasting is:
- Using large numbers of computers.
 - Averaging data from several locations.
 - Running several models on the same data.
 - None of the above. (82)**
21. Smart phones can be used to obtain:
- Local observations.
 - Local forecasts.
 - Radar data.
 - All of the above. (83)**

Chapter 8

1. What steps are included in using weather for planning a patrol?
 - a) Check the current weather.
 - b) Check the radar.
 - c) Check the forecast.
 - d) **All the above. (89)**
2. While on patrol, visibility becomes restricted. What steps should you take?
 - a) Take a compass bearing to your safe haven.
 - b) Slow down.
 - c) Put all your crew on visual lookout.
 - d) **Both a) and b). (90)**
3. With regard to thunderstorms, which kind is the most difficult to deal with in the planning phase?
 - a) Frontal thunderstorms.
 - b) Squall line thunderstorms.
 - c) **Air mass thunderstorms. (90, 91)**
 - d) None of the above.
4. When a thunderstorm is approaching, you initially should:
 - a) Head toward it to keep the wind on the bow.
 - b) **Run perpendicular to the direction of storm movement. (91)**
 - c) Anchor and wait it out.
 - d) None of the above.
5. What evidence should you watch for that says the effects of a thunderstorm are *imminent*?
 - a) **Ripples on the water. (90)**
 - b) Winds blowing toward the storm.
 - c) Static on the VHF radio.
 - d) All of the above.
6. Small craft advisories are issued under what circumstances?
 - a) Winds over 25 knots.
 - b) Seas greater than 8 feet.
 - c) Water temperature less than 40 degrees Fahrenheit.
 - d) **It varies with the region of the country. (92)**
7. A Gale warning is issued when winds are expected to be:
 - a) Over 25 knots.
 - b) Strong and gusty.
 - c) **Over 34 knots. (92)**
 - d) None of the above.
8. The heat index is a function of:
 - a) Temperature and winds.
 - b) Cloud cover and temperature.
 - c) **Temperature and relative humidity. (92, 93)**
 - d) None of the above.
9. Wind chill is a function of:
 - a) Temperature and humidity.
 - b) **Temperature and wind speed. (93)**
 - c) Wind speed and humidity.
 - d) Humidity and cloud cover.
10. The effects of heat exhaustion and heat stroke increase with:
 - a) Decreasing temperature in increasing wind speed.
 - b) Increasing temperature and decreasing humidity.
 - c) **Increasing temperature and increasing humidity. (93)**
 - d) Decreasing temperature in decreasing wind speed.

11. The possibility of hypothermia increases with:
- a) **Decreasing temperature and increasing wind speed. (93)**
 - b) Decreasing temperature and increasing humidity.
 - c) Decreasing temperature and decreasing wind speed.
 - d) Decreasing temperature and increasing humidity.