Applied Atmospheric Dynamics

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Contents

Preface

Many can brook the weather that love not the wind.
W. Shakespeare, "*Love's Labour's Lost*", Act IV, Scene II

During mid-February 2003, one of the biggest winter storms on record cut a swathe through the mid-western and eastern United States. Low temperature and snowfall records were set all along the eastern seaboard. Tornadoes, extreme hail, flooding, and mudslides were all generated by the 'beast in the east'. When all was said and done, 45 people lost their lives, and 122 people were injured, as a direct result of the weather.

The weather can be a cause of disruption, despair, and even danger everywhere around the world at one time or another. Even when benign, it is a source of constant fascination for many people. Yet connecting this interest with the underpinnings of fluid mechanics has remained beyond reach for many. It is our hope with this book to make the intriguing ways in which the atmosphere moves accessible to a broader range of students and general readers. We have done this by linking real physical events with theoretical models at every possible juncture. The storm of February 2003 provides a valuable illustration of many of the important concepts in atmospheric dynamics, and we have used many other dramatic weather events as well, from the devastating Hurricane Katrina to the strong katabatic flows of Antarctica. The level of mathematics required, though not rudimentary, is pre-vector calculus, and the emphasis is always on the phenomenology.

Part I takes the reader through all of the basic concepts required to understand the development and decay of mid-latitude low-pressure systems. These concepts include balanced and unbalanced flows, vorticity, and waves. In Part II, a broader range of phenomena are considered, ranging from the tropics to the poles. These later chapters can be considered in any order. For each of the 14 chapters, review questions to test understanding and to provide practice are posed, the worked solutions of which are available. The book ends with a discussion of the role of weather systems in maintaining the global circulation.

The accompanying CD-ROM includes all of the illustrations in the book in JPEG format, and many more besides. Animations and videos of important processes, satellite pictures of interesting events, and weather maps of all varieties are collected on the CD-ROM. All of the available data for the storm of February 2003 is in a searchable database, suitable for a range of investigations. In addition, four possible research projects are included, on Atlantic hurricanes, southern hemisphere cyclones, polar lows, and tornadoes.

While only two authors are listed on the front of this book, many others contributed. Elizabeth Cassano stepped up whenever asked, to prepare content for the CD-ROM, to frame project material, and to find that last data point. Christopher Takeuchi, Mark Seefeldt, and Petteri Uotila provided a number of figures for the book and CD-ROM, which Henry Johnson and Casey Tonkin tested to breaking point. Michael Shaw provided invaluable assistance in proofreading the book from a student's perspective and solving all of the review questions. David Underwood created a number of figures and animations for the book and CD-ROM. Barbara Lynch's advice, scientific and literary, was priceless.

AHL and JJC

I want to thank the many students of atmospheric dynamics that I have taught over the years – without their enthusiasm, excellence, and well-targeted criticism, this book would not have been written. They also served as guinea pigs for many of the approaches we have used here. I also wish to thank my parents, for their boundless faith in me; my husband, for his most practical support; and my daughters, for bringing me down from the clouds.

AHL, Melbourne, Australia

I must also thank my family for their unending support in all of my life's endeavors, and in particular my parents Emilia and Vito for giving me the opportunity to pursue an educational and professional path that perhaps was not the one they had hoped I would follow. Finally, I must thank my wife Elizabeth for her love, support, and patience. Not only did she help with numerous tasks related to the writing of this book, she also provided me with the perspective to realize that there is more to life than work and weather.

JJC, Boulder, Colorado
November 2005

Part I Anatomy of a cyclone

1 Anatomy of a cyclone

1.1 A 'typical' extra-tropical cyclone

A snow emergency was declared in Boston, Massachusetts as a record snowfall paralyzed the city. Airports in Washington, DC and New York City were closed, and trains and buses were cancelled. The blizzard, dubbed 'the beast in the east' by the media, dumped heavy snow in a broad swathe from Iowa to New England on the President's Day holiday weekend of 2003 (15–17 February).

This storm had been traversing the United States for a week – leaving disaster in its wake in some places, and hardly being noticed in others. Flooding and mudslides occurred in southern California. Ten tornadoes were reported in the south-eastern United States. In Delaware, over 500 people were evacuated from a townhouse complex after water from melting snow began leaking into the electrical system. Meanwhile, hail and strong winds were reported from the southern Plains to the south-eastern United States, downing trees and power lines and removing roofs. During the period that this storm crossed the country, 45 people were killed and 122 people injured as a direct result of the weather (Angel 2003). Over US$144 million in damage was reported.

These diverse weather events were the result of a low-pressure system outside the tropics, an *extra-tropical cyclone*, that crossed the United States from 11 to 19 February 2003.

The system first approached the southern California coast on 11 February. Over the next two days it crossed the mountainous western portion of the United States, looking relatively weak and sometimes disappearing from surface maps. Then, on 13 February, the surface low-pressure center redeveloped over south-eastern Colorado, as such systems often do when crossing the Rocky Mountains during the winter months. This redeveloped low-pressure center began moving slowly east across the southern Great Plains and the lower Mississippi River Valley during the next two days. By 16 February it was located west of the southern end of the Appalachian Mountains and had started to decay once more. However, at the same time low pressure was developing just off the coast of North Carolina, along the *frontal system* of the original low-pressure center. The coastal low developed to become the main system, and moved north and east just offshore, slowly enough to allow large amounts

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of snow to fall. All-time record snowfalls were reported in the cities of Baltimore, Maryland (71.6 cm) and Boston, Massachusetts (69.9 cm).

What were the atmospheric processes responsible for the formation and evolution of this storm as it passed over the United States? Why were such diverse severe weather events as heavy snow and tornadoes reported with this one system? The study of atmospheric dynamics provides us with the tools to answer these questions, and more broadly helps us understand the processes that shape the circulation of the atmosphere. This book will use this storm as a guide in our exploration of the processes and forces that shape the circulation of the atmosphere. Weather maps that depict the evolution of the storm are provided on the accompanying CD-ROM.

1.2 Describing the atmosphere

We can consider the air that surrounds the Earth to be made up of 'columns', rising vertically from each location. As we move up through the column, the properties of the air change – its temperature, moisture, cloudiness, chemical constituents, and density all vary. The portion of the atmosphere of most interest in this book is the *troposphere*, the zone between the surface and around 10 km altitude. This is the part of the column in which 'weather' happens, and certainly where we experience it.

Before we begin our exploration of the effects of forces upon the atmosphere, the *dynamics*, we need to define some of its basic properties. These properties are essential for describing and understanding the atmosphere and can be thought of as the basic vocabulary of atmospheric dynamics.

The most familiar properties are wind speed, temperature, and density. As with all physical quantities, these are quantified using SI (Système International) or metric units. The metric system is founded upon a set of base units, of which we will use five: meter (m), kilogram (kg), second (s), kelvin (K), and mole (mol). Other units, such as for acceleration or force for example, can be derived from these basic units. There are two important quantities whose units are not in everyday use, and these require some further explanation: temperature and pressure.

1.2.1 Atmospheric temperature

Most commonly used around the world today is the Celsius scale (°C) for temperature, which was devised by Swedish astronomer Anders Celsius in 1742. The scale designates 0 °C as the freezing point of water, and 100 °C as the boiling point of water at sea level. The scale is also known as the 'centigrade' scale because it divides the interval between freezing and boiling into 100 equal units. However, this was not the scale adopted in the Système International.

In fact, in the early eighteenth century, there were many competing temperature scales. A second scale that has survived to the present day in the United States, and unofficially in many other English-speaking countries, is the Fahrenheit scale (°F). This temperature scale is named after the German physicist who suggested it in 1724.

The two references Fahrenheit chose were 0°F for the lowest temperature he could achieve and 100°F for body temperature. However, there is some dispute as to how he arrived at these reference points, and some time later the scale was recalibrated. On the present-day Fahrenheit scale, the freezing point of pure water is 32°F and the boiling point (at sea level) is 212°F.

The Kelvin temperature scale that was adopted in the Système International was designed by British scientist William Thomson (later Lord Kelvin) based on a single reference point, *absolute zero*, the hypothetically lowest temperature possible. This temperature was derived from an extrapolation of a graph showing the relationship between volume and temperature of an ideal gas, which suggested that the gas volume would become zero at a temperature of −273.16°C. The scale is often called the *absolute temperature*. Each unit on the Kelvin scale is the same magnitude as one degree on the Celsius scale, and hence the freezing point of water is around 273 K and the boiling point is around 373 K.

As we will see in Chapter 5, the physical equations we derive for application to the atmosphere assume SI units for all quantities. However, because the measurement and study of the weather has an important role across society, SI units are not always used in the reporting of the atmospheric state. This is particularly true for temperature, but also for wind speed and atmospheric pressure. Hence, it is important to be familiar with all of the units in general use, and to be able to convert between them (see Appendix B).

1.2.2 Atmospheric pressure

Of all of the properties of the atmosphere, atmospheric pressure is one of the most important. Horizontal and vertical variations in pressure give rise to the atmospheric motions which are the focus of the study of atmospheric dynamics.

Consider some air in a container. The pressure of the air on the walls of the container derives from the momentum of individual molecules as they impact the walls in their random molecular motion. If we add more molecules to the container, and that container happens to be a balloon, the difference in pressure between the interior and the exterior of the balloon will cause it to expand until a new equilibrium is reached (see Figure 1.1). Similarly, one infinitesimal volume parcel of air exerts pressure on its neighbor, and vice versa, and this force is always perpendicular to the interface between the parcels.

Hence, the pressure depends not only on the force imparted by the molecules, but also upon the area over which the force is acting. Thus, the pressure is expressed as a force per unit area, or $\mathrm{N\,m^{-2}}$, which has the SI derived unit of the *pascal*, or Pa. Since 1 Pa is a small pressure in comparison to pressures commonly observed in the atmosphere, the unit hectopascal (symbol hPa) is more widely used. The unit millibar (symbol mb) is also in common use, particularly on weather maps:

$$1\,\mathrm{hPa} = 100\,\mathrm{Pa} = 1\,\mathrm{mb}$$

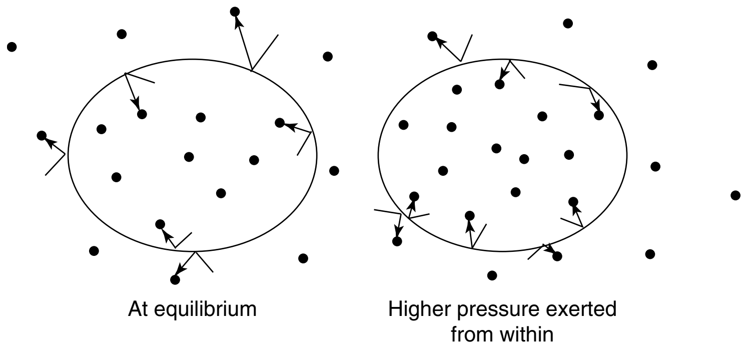


Figure 1.1 The balloon on the left has as many molecules exerting pressure from within as from without and hence is at equilibrium. The balloon on the right contains more molecules in the same volume and so (given the same temperature) is exerting more pressure from within. This balloon's walls will expand under the action of this force

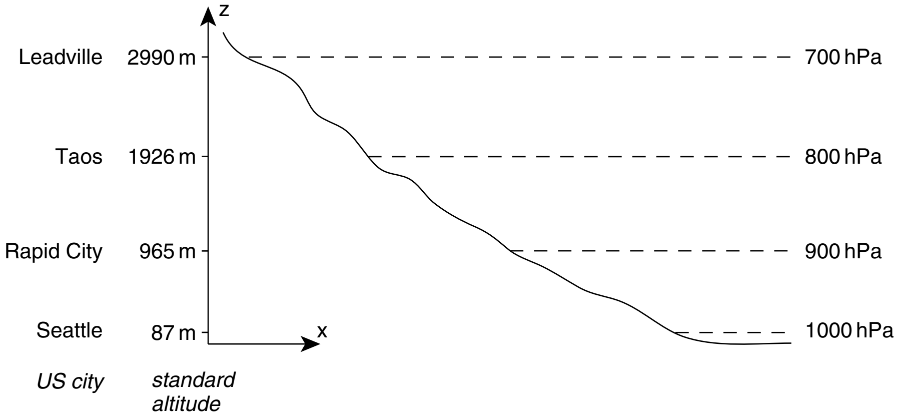


Figure 1.2 The weight of air in the column above any altitude applies a pressure on the surface below it. The axis on the left shows the standard altitude for the pressure level, and a representative US city at that elevation, for comparison

The *atmospheric pressure* at a point on the surface of the Earth is the pressure caused by the weight of air above that point (this is discussed in greater detail in Section 4.3.4). This implies that the atmospheric pressure must drop as one moves to higher altitudes (Figure 1.2) since there is less air above to exert its weight on a given point. This was first noted in 1648 by Blaise Pascal, after whom the unit of pressure is named, who made measurements of atmospheric pressure from the base to the top of the 1465 m Puy de Dôme mountain in France.

Because of this strong variation with altitude, pressure reports from meteorological stations are generally normalized to a common altitude, usually the mean sea level. This allows us to distinguish the smaller, but more important, horizontal variations

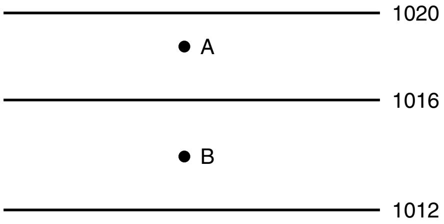


Figure 1.3 Idealized example of isobars, labeled in hPa, on a surface weather map

in surface pressure which are the ultimate cause of most motions observed in the atmosphere. The correction from surface pressure to mean sea level pressure (MSLP) is performed using the hypsometric equation, which is discussed in Section 4.3.4.

A line drawn on a weather map connecting points of equal pressure is called an *isobar*. Isobars are generated from reports of the pressure at various locations. Figure 1.3 depicts three isobars that map the observed MSLP in a particular region. At every point along the middle isobar, the pressure is taken to be 1016 hPa, while at every point along the bottom isobar, the pressure is 1012 hPa. Point A and all other points above the 1016 mb isobar have a higher pressure than 1016 hPa and points below that isobar have a lower pressure. At point B, and any other point lying in between these two isobars, the pressure must be between 1012 and 1016 hPa. Surface pressure reports are available as often as every hour in some countries, and usually every 3 or 6 hours. Isobar maps are updated with every new set of observations.

1.2.3 Station reports

For all surface weather maps around the world, the weather observations at a given location are reported using a common *station model*, an example of which is shown in Figure 1.4. The basic station model provides information on the temperature, dew point temperature, sea level pressure, wind speed and direction, cloud cover, and current significant weather. The *dew point temperature* (T_d) is used by operational meteorologists to indicate the amount of moisture contained in the atmosphere. It is defined as the temperature to which a small volume (or parcel) of air must be cooled at constant pressure in order for that air parcel to become saturated. If air near the surface of the Earth is cooled to its dew point temperature, dew will form on the surface. Higher values of dew point temperature indicate air that contains more water vapor than air with a lower dew point temperature.

The *wind speed symbols* are additive, and can be used to represent any wind speed, often reported in units of *knots* ($1\,\mathrm{kt} = 0.51\,\mathrm{m\,s^{-1}}$). A short wind barb indicates a wind speed of 5 kts, a long barb indicates a wind speed of 10 kts, and a pennant indicates a wind speed of 50 kts. It should be noted that the actual wind may be within ±2 kts of the plotted wind speed. For example, if a station model is plotted with one

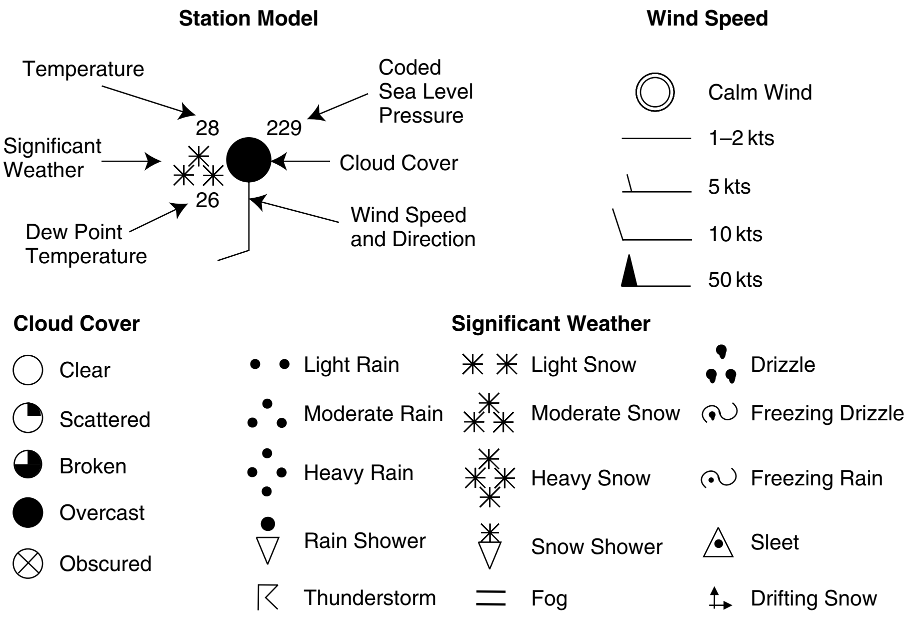


Figure 1.4 Station model for surface weather map conventions

short and one long wind barb the wind speed would be noted as 15 kts, but the actual wind speed could be anywhere from 13 to 17 kts. Similarly, a station model plotted with one pennant and two long barbs would have a nominal wind speed of 70 kts, but the actual wind speed could be anywhere from 68 to 72 kts. The wind direction is given by the angle of the line that anchors the barbs; the direction in which the line points is the direction the wind is coming *from*.

Sea level pressure is plotted in a coded format. To decode the sea level pressure report, either a 10 or 9 must be placed in front of the three-digit value, and then a decimal point added between the last two digits. If the coded sea level pressure is more than 500, a 9 is placed in front of the coded value. Otherwise, a 10 is placed in front of the coded value. The decoded sea level pressure is given in units of hPa, and using this coding system, it must range from 950.0 to 1050.0 hPa. In intense extratropical cyclones or tropical storms the sea level pressure may be less than 950 hPa. Similarly, strong high-pressure systems (anticyclones) may occasionally have sea level pressure values greater than 1050 hPa. For these situations care must be taken when decoding sea level pressure values given on weather maps.

Example What is the weather being reported in the station model shown in Figure 1.4?

First, we can see that the temperature is 28 °F (−2 °C) and the dew point temperature is 26 °F (−3 °C), corresponding to a relative humidity of around 92%. Why do we assume this is a US model? We can do so because the significant weather icon tells us that moderate snow is falling, and this is highly unlikely at 28 °C (82 °F)!

We also see that the wind is blowing from the south at around 10 kts, a brisk southerly. The skies are overcast, as we would expect while it is snowing. The coded sea level pressure is 229; this is less than 500 and so we place a 10 at the start to get 10229, and then add a decimal point between the last two digits to give us 1022.9 hPa. In total, a chilly and gray day is being reported.

As well as conforming to a standard set of observations, stations around the world also conform to a standard description of the time the observation was taken: *Universal Time (UTC)*. This time, also known as *Greenwich Mean Time (GMT)*, or simply Z, is the time at Greenwich in England, and is expressed using a 24 hour clock rather than a.m and p.m. UTC is used regardless of the local time zone of the observation.

1.3 Air masses and fronts

In the early and middle parts of the last century, weather forecasters began to understand the systematic nature underlying the apparent chaos of the weather, and to use it to advantage in weather forecasting. The foundation of this understanding was the dual concepts of air masses and fronts. Air masses, and the fronts between them, are defined by their thermodynamic properties; that is, their temperature, density, and pressure, and the amount of moisture they contain. The critical idea that developed was that weather conditions are not randomly distributed over the globe. Rather, variations in weather elements, such as temperature, in the extra-tropics tend to be concentrated in narrow bands called *fronts*. Between these bands, weather elements change very gradually, and these broad, nearly uniform regions of the lower atmosphere are called *air masses*.

1.3.1 Air masses

The best conditions for the formation of air masses are large areas where air can be in relatively constant conditions long enough to take on quite uniform characteristics. The warm, moist tropical oceans and the cold, dry polar land masses are excellent source regions. An air mass can be relatively shallow, 1–2 km deep, or may be as deep as the entire troposphere, and is often not of uniform depth across its entire horizontal extent.

A commonly used *classification of air masses*, especially in the Northern Hemisphere, is that of Tor Bergeron of the Norwegian School (see Section 1.4), who in 1928 denoted four primary air masses – continental polar (cP), continental tropical (cT), maritime polar (mP), and maritime tropical (mT). Often, additional air masses such as the Arctic (A), Antarctic (AA), and equatorial (E) are added to this list. Figure 1.5 shows the source region and typical locations impacted by these different air masses. These air masses are identified either subjectively or objectively using a range of criteria,

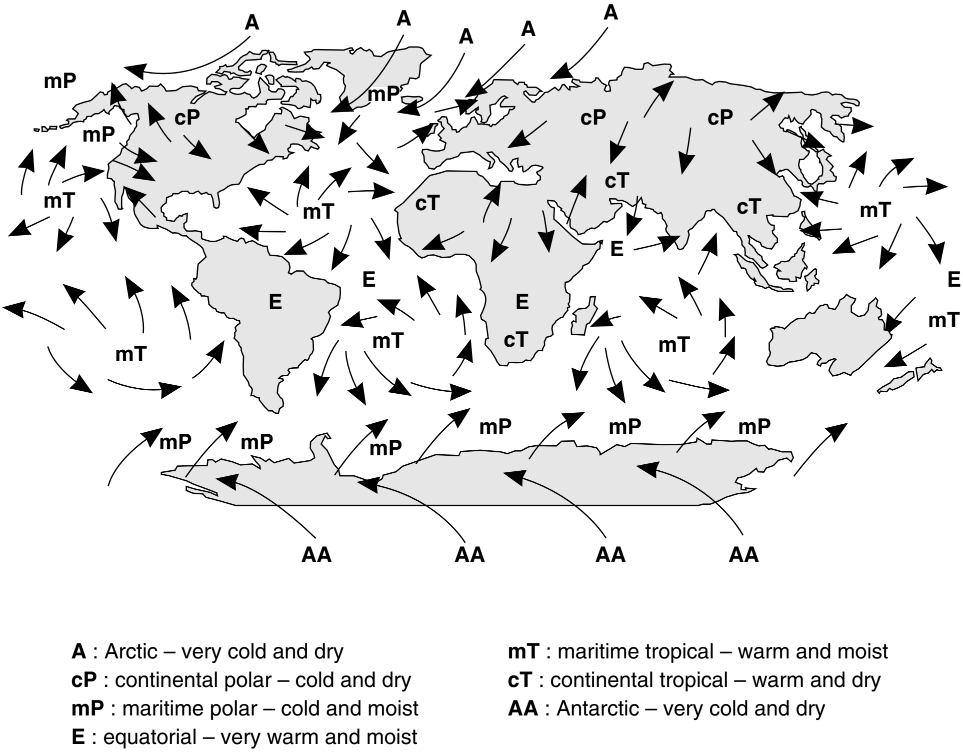


Figure 1.5 Typical distribution of air masses around the globe

but are typically identified based on near surface values of temperature and humidity. A qualitative description of the typical temperature and humidity of the different air mass types is also given in Figure 1.5. Since air masses are three-dimensional features of the atmosphere they may also be identified using atmospheric observations from balloons with instruments attached, called *radiosondes*, or by aircraft.

At any one time there are at least several dozen distinct air masses globally. Most cover thousands of square kilometers of surface area. Some have just formed, some are in the process of being modified, and some are essentially stationary.

Once an air mass moves out of its source region, it begins to be modified as it encounters surface conditions different from those found in the source region. From the point of view of atmospheric dynamics, air masses are generally of interest primarily because of the interfaces between them: the fronts.

1.3.2 Fronts

Fronts are the boundaries that separate different air masses, and are defined by thermodynamic differences across the boundary, and the direction of movement of

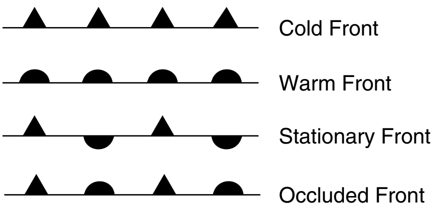


Figure 1.6 Symbols used to represent fronts on weather maps. The side on which the symbols are drawn is the direction in which the front is traveling, except for the stationary front, which is not moving

the boundary. Meteorologists define four basic *types of fronts*, although other types of fronts can also be identified. These four basic types of fronts are referred to as cold, warm, stationary, and occluded fronts. The symbols used to represent these fronts on weather maps are shown in Figure 1.6.

Typically fronts separate warm and cold air masses. If the cold air mass is advancing and the warm air mass is retreating the boundary is called a *cold front*. If the opposite occurs, with warm air advancing and cold air retreating, the boundary is called a *warm front*. Sometimes the boundary between the two air masses is nearly stationary and this type of front is called a *stationary front*. An *occluded front* separates air masses that do not have as large a temperature contrast as is found for cold or warm fronts, and typically separates cold and cool air masses. The processes that lead to the formation of an occluded front are discussed below, and are important in the life cycle of extra-tropical cyclones.

Even though fronts are most commonly seen only on surface weather maps it is important to remember that fronts are the boundaries that separate three-dimensional volumes of the atmosphere known as air masses, and can be identified both at the surface and aloft. An example of a warm, cold, and stationary front associated with the February 2003 cyclone (Section 1.1) is shown in Figure 1.7. Note how the warm front and the cold front meet at the low-pressure center.

This is a *surface weather map* of the type frequently used in the United States, showing isobars, fronts, and station reports, which indicate temperature and dew point temperature in °F, wind speed observations in knots, coded sea level pressure, and cloud cover. Weather maps used in other parts of the world typically report the temperature and dew point temperature in °C, but are otherwise equivalent. You can find examples of these types of weather maps on the companion CD-ROM.

Example Identify the warm and the cold air masses in the map shown in Figure 1.7.

Consider the station observation just to the south-east of the center of the low. The wind is 5 kts from the SSE, the weather is clear, and the temperature is 60°F (16°C). The surface pressure is 1001.1 hPa. Just to the north of this station, there is a station on the other side of the warm front. Here, the weather is overcast and foggy, and the wind is from the NE at 5 kts. The temperature is 44°F (7°C). The *dew point*

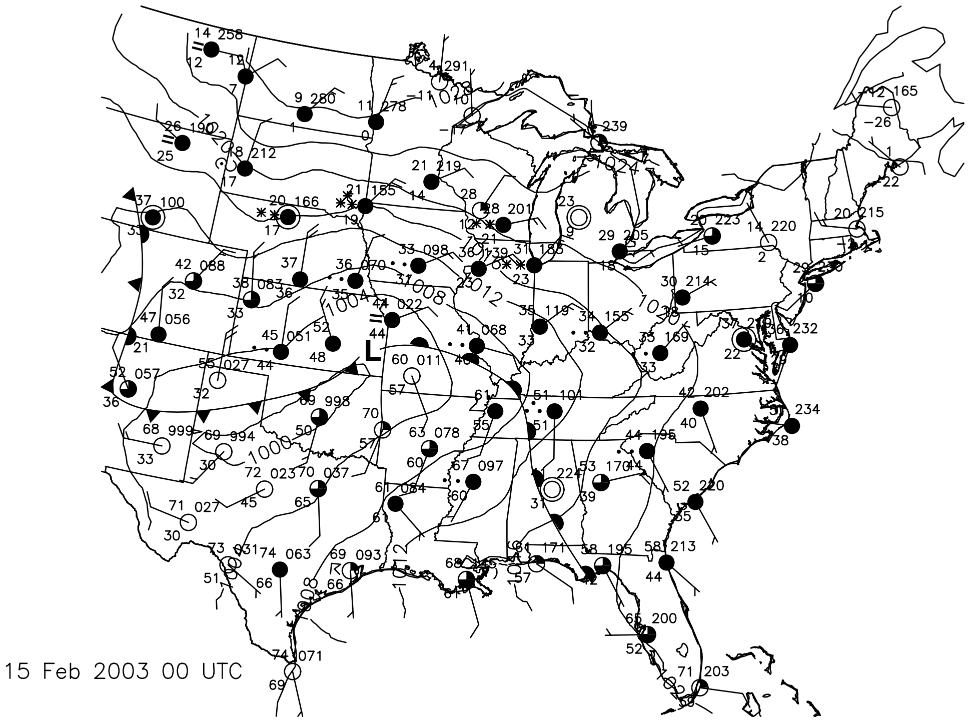


Figure 1.7 Surface weather map valid at 00 UTC 15 Feb 2003

depression, the temperature minus dew point temperature, is zero, meaning that the air is saturated. It is clear that south of the low, between the cold front and the warm front, is the warm air mass. North, and to either side of the fronts, is the cold air mass.

1.3.3 Upper level weather maps

Meteorologists around the world also use standard format maps to depict atmospheric features higher in the troposphere. By convention, these upper level maps are plotted on constant pressure surfaces rather than at specific altitudes, and hence are called *isobaric* (iso=constant; baric=pressure) maps. A convenient upper level map to look at when examining an extra-tropical cyclone is the 500 hPa map, which represents atmospheric conditions at an altitude of approximately 5.5 km. This is roughly in the middle of the troposphere, and the winds at this level are often thought to 'steer' weather disturbances.

An example of a 500 hPa map, for the same day and time as the map in Figure 1.7 is shown in Figure 1.8. The station reports plotted on this map replace the pressure code with the height (that is, the altitude) of the 500 hPa surface. For the 500 hPa constant pressure level the coded height is given in decameters (tens of meters), but the coding method varies from one constant pressure level to another. On upper level

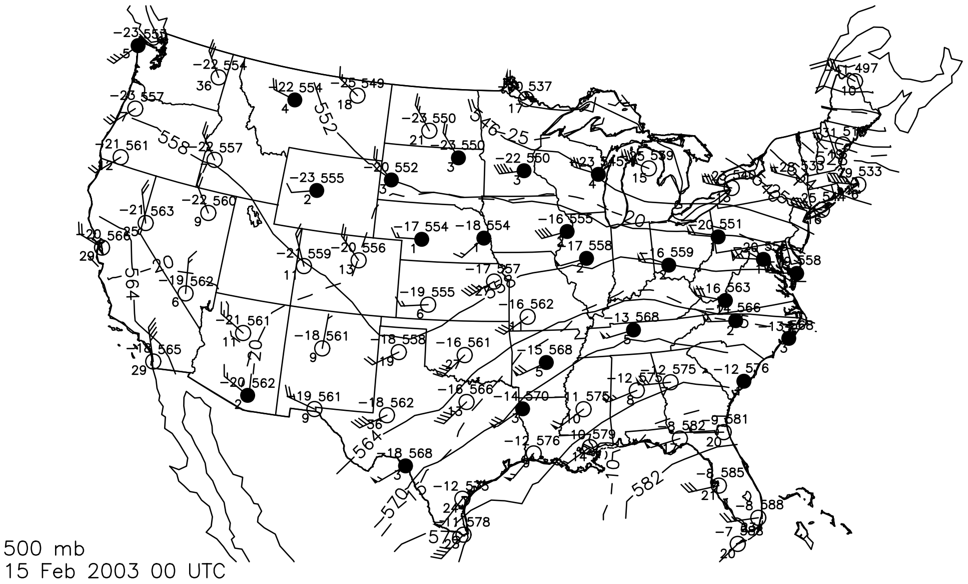


Figure 1.8 The 500 hPa weather map valid at 00 UTC 15 Feb 2003. Height contours (decameters) are shown as solid lines, and temperature contours (°C) are shown as dashed lines

maps, the temperature is always plotted with units of °C throughout the world, and as for surface weather maps is plotted in the upper left corner of the station model. The dew point depression, rather than the dew point temperature, is plotted in the lower left corner of the station model. The central circle of the station model is filled if the dew point depression is less than 5 °C, since a small dew point depression is indicative of areas that may be cloudy. Otherwise, the circle is left unfilled.

From Figure 1.8 we see that the height of the 500 hPa surface varies, with lower heights located to the north and higher heights found to the south. There are a number of ripples, or waves, superimposed on this general decrease of height from south to north. The height contours on the 500 hPa map can be thought of as being similar to the elevation contours found on topographic maps of the Earth's surface. Locations where low heights are found are referred to as *troughs* since they represent a dip in the elevation of the 500 hPa surface. *Ridges* are regions where high heights are found on the 500 hPa map. Small ripples in the 500 hPa heights are known as *short waves* while larger ripples, that extend across a whole continent for example, are known as *long waves* or *planetary waves*. In this example, a ridge is present over the west coast of the United States, while a long-wave trough is found over the center of the country.

The height of the 500 hPa surface is related to several properties of the atmospheric column. For example, as the temperature of the column decreases, the height of the 500 hPa surface would also tend to decrease (see Section 4.3.4 for more details). That is, troughs are cold, and ridges are warm, in general. This leads to lower 500 hPa heights being found near the poles and higher heights being found near the tropics.

The wind at this level generally flows roughly parallel to the height contours. Higher wind speeds are found in areas where the height contours are closely spaced and weaker wind speeds are found in areas where the height contours are more widely spaced. We will see why this is the case in Section 5.5. In the Northern Hemisphere, the winds blow with lower heights to the left of the wind direction and higher heights to the right of the wind direction. In the Southern Hemisphere, the winds blow with lower heights to the right of the wind direction. Because the 500 hPa surface slopes downward from the equator toward the poles, this means that a large component of the wind is blowing from the west almost all the time in both hemispheres. These winds are aptly called the *mid-latitude westerlies*.

In addition to the height contours on the 500 hPa map shown in Figure 1.8, contours of constant temperature, or *isotherms*, are shown. As would be expected, lower temperatures are found closer to the poles while higher temperatures are found closer to the tropics. An atmosphere in which the temperature varies across a pressure surface is referred to as being *baroclinic*. In a baroclinic atmosphere the density of air depends upon both temperature and pressure (see Section 3.2 and Equation (3.1) for more details). An atmospheric state in which temperature does not vary on a constant pressure surface is referred to as *barotropic*, and in this case density is only a function of pressure. It is a situation that occurs in the atmosphere only rarely and approximately.

1.4 The structure of a typical extra-tropical cyclone

The cyclones of middle and high latitudes are called extra-tropical cyclones. They differ from cyclones in the tropics in a number of ways, but most prominent is the fact that extra-tropical cyclones contain frontal systems while tropical cyclones do not. Consequently, extra-tropical cyclones are also known as *frontal cyclones*. In this chapter we will discuss only cyclones from the middle latitudes, reserving discussion of tropical cyclones for Chapter 12 and polar cyclones for Chapter 14.

No two cyclones are identical, but an idealized model was developed during World War I in Norway which embodies many of the important features of a frontal cyclone. See Bjerknes and Solberg (1922) in the Bibliography for the original description, which is drawn upon in this discussion. This model is known as the Norwegian model, or the Bjerknes model. The model was not widely accepted in recent decades, until research since the 1990s confirmed that the model remains a useful tool to describe the weather associated with extra-tropical cyclones. In this section, and throughout this book, we will use this model to describe the extra-tropical cyclone that traversed the United States from 11 to 19 February 2003. However, as with all conceptual models, the Norwegian model does not always apply.

Frontal cyclones are large traveling atmospheric vortices (rotating air), up to 2000 kilometers in diameter, with centers of low atmospheric pressure. An intense cyclone in middle to high latitudes may have a surface pressure as low as 970 hPa, compared to an average sea level pressure of 1013 hPa.

Frontal cyclones are the dominant weather event of the Earth's middle latitudes, and are the environment in which smaller, more intense circulations are often embedded. In the middle latitudes, they are the result of the dynamic interaction of warm tropical and cold polar air masses. The boundary between these two air masses is called the *polar front*. This larger frontal zone is distinct from the individual cold and warm fronts associated with a particular cyclone. We will now look at the idealized life cycle of an extra-tropical cyclone, as portrayed in the Norwegian model. We will need to consider not just the surface, but the middle and upper regions of the troposphere, since cyclones are three-dimensional features of the atmosphere.

1.4.1 Stages in the life cycle of an extra-tropical cyclone

As discussed in Section 1.2.2, the pressure at any location on the surface of the Earth is determined by the mass of air in the atmospheric column above. For surface pressure to decrease, air must be removed from the atmospheric column. Therefore the formation, intensification, and decay of the surface low-pressure centers that define cyclones are intimately tied to processes that add atmospheric mass (*convergence*) or remove atmospheric mass (*divergence*) from a column of the atmosphere.

According to the Norwegian school, extra-tropical cyclones form along the polar front. In this idealized model, the polar front initially runs west to east in a more or less straight line until a small perturbation in the form of a wave in the upper levels of the troposphere disturbs it (Figure 1.9). Divergence occurs in the vicinity of this upper level short-wave trough (Figure 1.9a). This divergence promotes the initial formation of the surface cyclone.

In the Northern Hemisphere, the circulation around this area of low pressure is counterclockwise and results in cold air moving southward on the west side of the surface cyclone, with the leading edge of the cold air marked by a cold front. East of the surface cyclone warm air is moving northward, with the leading edge of the warm air marked by a warm front (Figure 1.9b). The result is that the small wave along the polar front amplifies, and the cyclone is referred to as being an *open wave cyclone*.

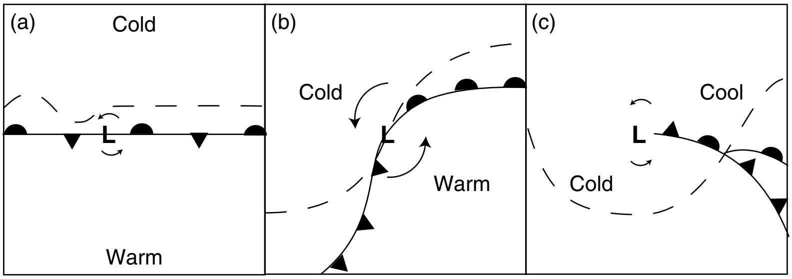


Figure 1.9 Idealized life cycle of a mid-latitude cyclone. L marks the position of the surface low-pressure center and arrows indicate the surface air circulation. Fronts are shown using standard symbols. A representative 500 hPa height contour is shown as a dashed line

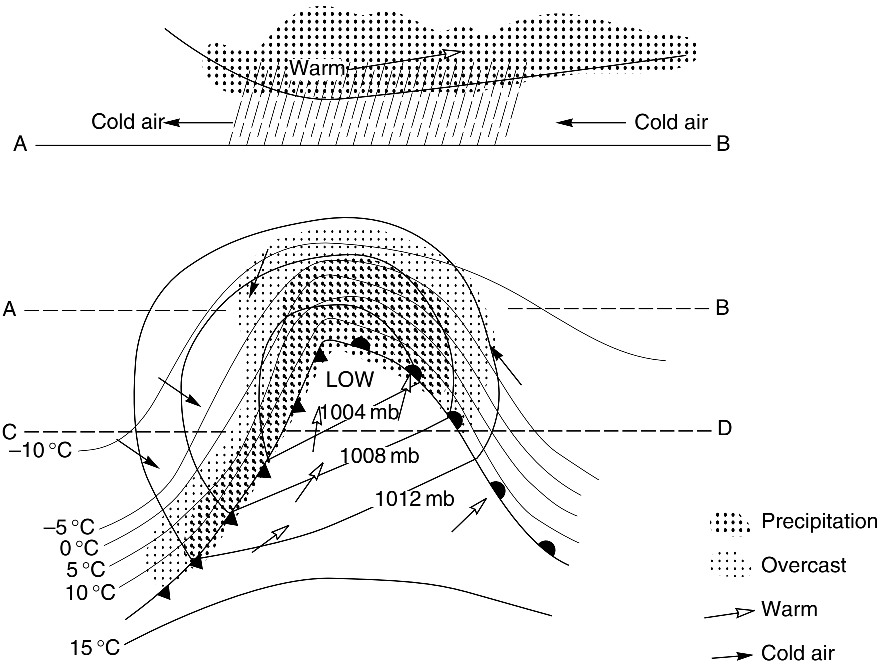
The wedge of air between the advancing cold and warm fronts (south and east of the surface cyclone in Figure 1.9b) is known as the *warm sector* of the cyclone. We discovered this sector in the example at the end of Section 1.3.2. The air mass in this sector is characterized by temperature and humidity values that are larger than behind the cold front or ahead of the advancing warm front.

At upper levels the heights of the constant pressure surfaces begin to respond to the movement of the cold and warm air masses. The height of the constant pressure surface begins to decrease in regions where cold air is advancing, forming a deeper upper level trough to the west of the surface cyclone. Conversely the height of the constant pressure surface begins to rise in regions where warm air is advancing, resulting in the formation of an upper level ridge ahead of the surface cyclone. The cyclone shows a pronounced tilt toward the west with increasing height at this time, with the upper level trough west of the surface cyclone position. This is the mature stage of the cyclone life cycle, and may last up to a few days. Figure 1.10 shows an idealized representation of a mature extra-tropical cyclone, and can be compared with the mid-latitude cyclone shown in Figure 1.7. The balance between upper level divergence and lower level convergence will determine how quickly the cyclone intensifies. During this time the cyclone tends to move in a direction that is parallel to the 500 hPa winds, and so the cyclone in Figure 1.9b will move north-eastward.

An animation of the three-dimensional circulation around a mature extra-tropical cyclone is provided on the companion CD-ROM. In this animation both the horizontal and vertical motion associated with the cyclone are shown, and the tilt of the low pressure towards the west with increasing height can be seen. Rising motion occurs near the center of the surface cyclone and ahead of the warm front, leading to the formation of clouds and precipitation. Clouds tend to be low along and just ahead of the warm front. As one moves further ahead of the warm front the clouds become higher and thinner and the precipitation decreases in intensity and eventually stops. Along the cold front there is a narrow band of rising motion associated with the cold air undercutting the air in the warm sector of the cyclone (not shown on the animation), and a narrow band of clouds and precipitation can be expected along the cold front.

The cold and warm fronts will continue to advance in response to the circulation around the surface low-pressure center as it deepens. The cold front often advances more quickly than the warm front, with the cold air undercutting the warm air in the warm sector of the storm. As the warm front advances, the warm air rises up over the cold air to the north of the warm front, and thus the warm front tends to advance more slowly. The result is that the cold front eventually catches up to the warm front at the surface (Figure 1.9c). Where the cold front has caught up to the warm front, the warm air is forced aloft and is no longer found at the surface. The boundary that was the leading edge of the cold front now separates two regions of cold air at the surface, and is called an *occluded front*. The cyclone is now said to be occluded and is often referred to as a *cold core* cyclone. In response to the change in the surface air temperature distribution the 500 hPa trough is now centered over the surface cyclone. The cyclone has now reached the end of its life cycle, and will slowly decay.

Vertical cross-section from A to B



Vertical cross-section from C to D

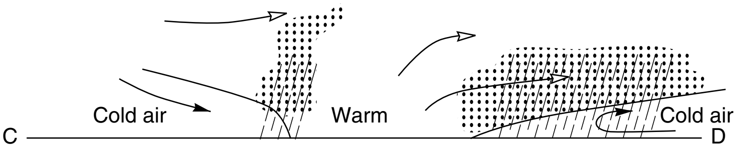


Figure 1.10 An idealized representation of a mature extra-tropical cyclone (adapted from the work of Bjerknes and Solberg 1922)

As with all models, this idealized description of the typical life cycle of an extra-tropical cyclone does not always match what is observed, and has been modified over time. Additionally, not all cyclones go through the stages illustrated in this idealized model. Some cyclones remain as small frontal waves which *propagate* (travel) rapidly eastward, while other cyclones grow rapidly but then decay before attaining the cold core occlusion stage. In some cases the cyclones become massive storms which are accompanied by changes in the entire long-wave pattern aloft. Other conceptual models of mid-latitude cyclones are in use by meteorologists and atmospheric scientists.

1.4.2 A mature cyclone – 00 UTC 15 Feb 2003

Figures 1.7 and 1.8 show the surface and 500 hPa weather maps at 00 UTC 15 Feb 2003 for this cyclone during the mature stage of its life cycle. The surface low-pressure center is located in south-eastern Kansas, with a warm front extending to the east and a cold front extending to the south-west. The warm sector of the storm is characterized by air temperatures in the upper 60s and lower 70s ° F (around 20 °C), with dew point temperatures in the upper 50s and lower 60s ° F (around 15 °C). The surface winds in the warm sector are primarily from the south or south-east.

North of the warm front the air temperature and dew point temperature are lower than in the warm sector, and the winds are from the east or north-east. Overcast skies extend from the warm front north to central Minnesota and North Dakota, associated with rising motion along and ahead of the warm front. Light rain is falling just north of the warm front, with light to moderate snow falling further north.

The air and dew point temperatures drop abruptly across the cold front, while the winds shift to the north and become strong and gusty. Along the eastern edge of the Rocky Mountains the cold front has become stationary, as is typical when a shallow cold front encounters the high elevation of the Rocky Mountains.

At the 500 hPa level a broad long-wave trough is located west of the surface cyclone position, generating south-westerly flow aloft above the surface cyclone. The positions of the surface lower and upper level troughs indicate that the cyclone is in a favorable position for further development at this time, but the cyclone maintains a nearly constant intensity over the next 48 hours, indicating that divergence at upper levels is nearly balanced by convergence of air near the surface.

1.4.3 An occluded cyclone – 00 UTC 17 Feb 2003

By 00 UTC 17 Feb 2003 the surface cyclone that had been located in south-eastern Kansas is now located on the Kentucky/Tennessee border just west of the Appalachian Mountains (Figure 1.11). A weak occluded front extends southward from the surface low-pressure center and the low is surrounded by cool air at the surface. This low has become occluded, and will slowly weaken and drift north-eastward over the next two days.

Two new surface low-pressure centers are beginning to form, with one along the Georgia/Alabama border and the other just offshore from North Carolina. Both of these lows have formed along the frontal boundaries associated with the original low-pressure center. A broad area of cloudiness and precipitation is associated with the occluded low and the frontal boundaries. North of the surface low pressure offshore of North Carolina winds are from the east, bringing moisture from the Atlantic Ocean, resulting in light snow.

At 500 hPa, a long-wave trough is located nearly overhead of the occluded surface low (Figure 1.12), as we would expect from the Norwegian cyclone model. The surface low off of the North Carolina coast is in a favorable location for further development, being located to the east of the 500 hPa trough. Further, the contrast