1. Perpetual motion

The atmosphere *circulates*. The circulation is global in extent (Fig. 1.1). The circulating mass consists of "dry air" and three phases of water. Energy and momentum are carried with the air, but evolve in response to various processes along the way. Many of those same processes add or remove moisture.

The circulation is sustained by thermal forcing, which ultimately comes from the Sun. On the average, the Earth absorbs about 240 W m^{-2} of incoming or "incident" solar energy, of which roughly 2% is converted to maintain the kinetic energy of the global circulation against frictional dissipation. Additional, "primordial" energy leaks out of the Earth's interior, but at the relatively tiny rate of 0.1 W m^{-2} (Sclater et al., 1980; Bukowinski, 1999). The thermal forcing of the global circulation is strongly influenced by the circulation itself, e.g., as clouds form and disappear. The interactions between the circulation and the heating are fascinating but complicated.

When averaged over time, the global circulation has to satisfy various balance requirements. For example, in a time average, the infrared radiation emitted at the top of the atmosphere must balance the solar radiation absorbed, precipitation must balance evaporation, and angular momentum exchanges between the atmosphere and the ocean-solid Earth system must sum to zero. We will discuss the global circulation from this classical perspective. We will also supplement this discussion, however, with descriptions and analyses of the many and varied but inter-related phenomena of the circulation, including such things as the *Hadley and Walker circulations*, *monsoons*, *stratospheric sudden warmings*, the *Southern Oscillation*, *subtropical highs*, and *extratropical storm tracks*.

In addition, we will discuss the diabatic and frictional processes that maintain the circulation, and the ways in which these processes are affected by the circulation itself.

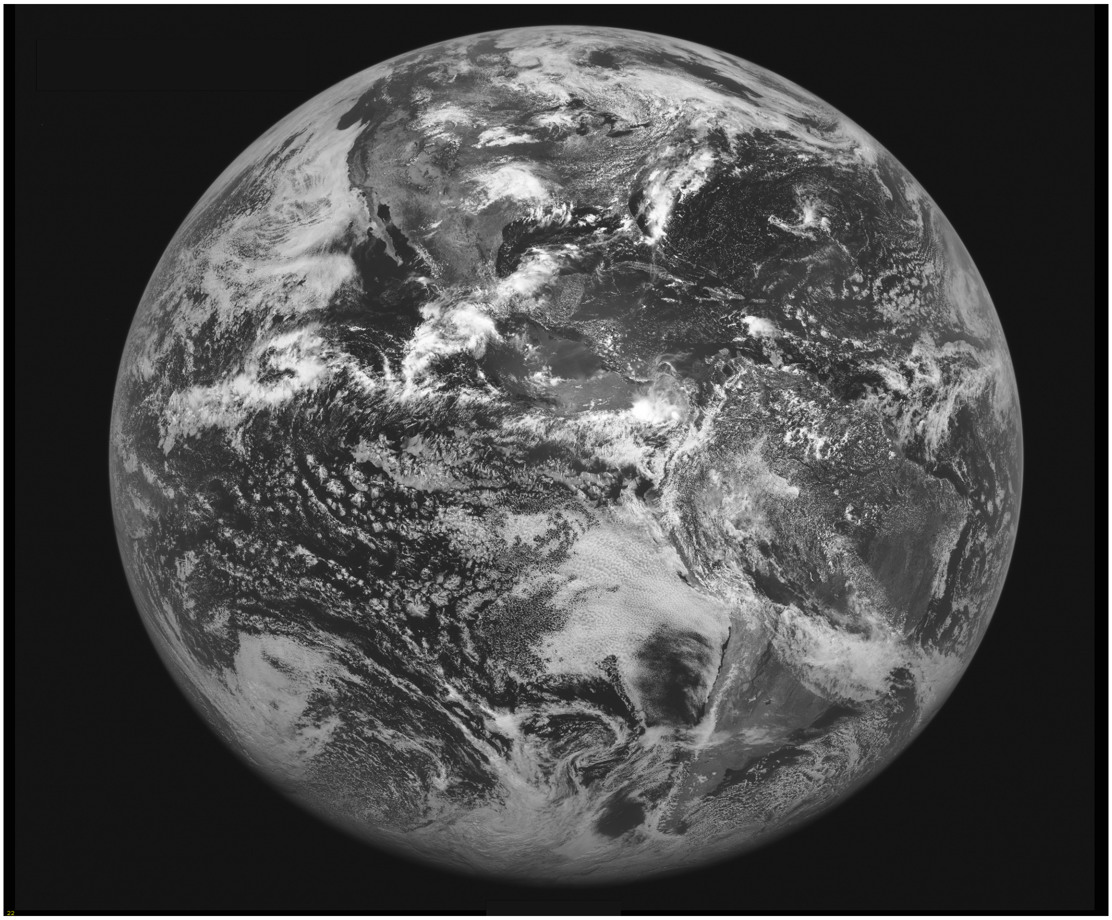

Figure 1.1: A full disk image of the Earth on July 27, 2009, looking down on the Equator, with North and South American in view. Many elements of the global circulation can be seen in this picture, including the "inter-tropical" rain band in the eastern North Pacific, swirling midlatitude storms, and the low clouds associated with the high-pressure systems over the eastern subtropical oceans. From http://cimss.ssec.wisc.edu/goes/blog/wp-content/uploads/2009/07/FIRST_IMAGE_G14_V_SSEC.gif.

The circulations of energy and water are closely linked. It takes about 2.5 million Joules of energy to evaporate one kilogram of water from the oceans, and the same amount of energy is released when the water vapor condenses to form a cloud. The energy released through condensation drives thunderstorm updrafts that in one hour or less can penetrate through a layer of the atmosphere ten or even twenty kilometers thick. The cloudy outflows from such storms reflect sunlight back to space, and block infrared radiation from the warm surface below. Shallower clouds cast shadows over vast expanses of the oceans. One of the aims of this book is to give appropriate emphasis to the role of moisture in the global circulation of the atmosphere.

It is conventional and useful, although somewhat arbitrary, to divide the atmosphere into parts. For purposes of this quick sketch, we will divide the atmosphere vertically and meridionally, only briefly mentioning the longitudinal variations. Let's start at the bottom.

Most of the solar radiation that the Earth absorbs is captured by the surface, rather than within the relatively transparent atmosphere. Several processes act to transfer the absorbed energy upward, from the ocean and land surface into the lower portion of the atmosphere. We will start at the surface and work our way into the sky.

The layer of air that is closely coupled with the Earth's surface is, by definition, the "*planetary boundary layer*," or PBL. The top of the PBL is often very sharp and well defined (Fig. 1.2). The depth of the PBL varies dramatically in space and time, but a ball-park value to remember is 1 km. The air in the PBL is turbulent, and the turbulence is associated with rapid exchanges or "fluxes" of "*sensible heat*" (essentially temperature), moisture, and momentum between the atmosphere and the surface. These exchanges are produced by the turbulence, and also promote the turbulence, through mechanisms that will be briefly discussed later. The most important exchanges are of moisture, upward into the atmosphere via evaporation from the surface, and of momentum, via friction. The "*latent heat*" associated with the surface moisture flux is a key source of energy for the global circulation, and surface friction is the primary mechanism that dissipates the kinetic energy of the global circulation.

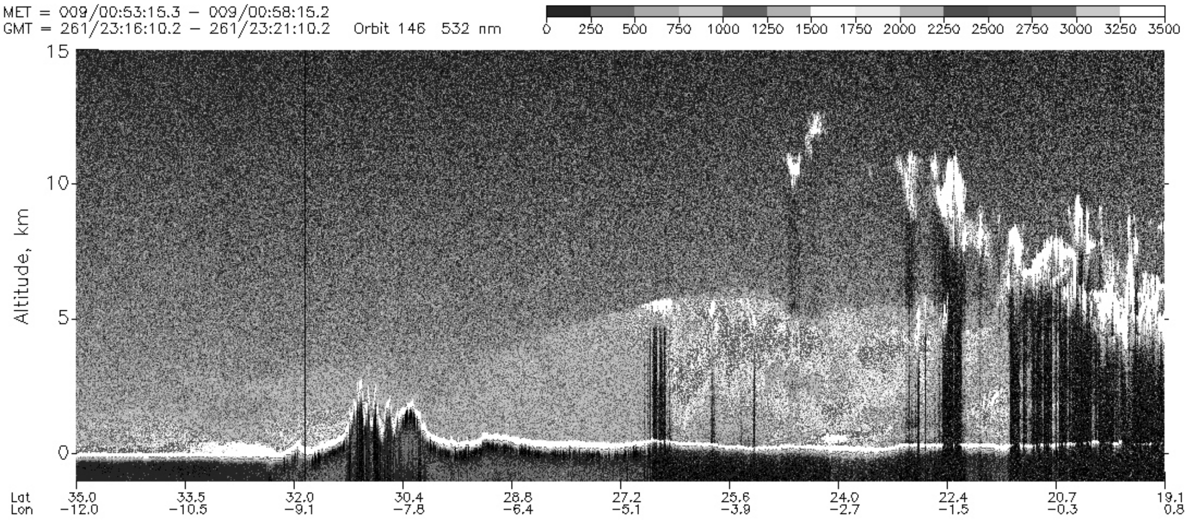

Figure 1.2: This figure shows lidar backscatter from aerosols and clouds. The figure was created using data from LITE, a lidar that flew on the space shuttle in 1994. The lidar beam cannot penetrate through thick clouds, which explains the vertical black stripes in the figure. The PBL is visible because the aerosol concentration decreases sharply upward at the PBL top. The data shown here start over the North Atlantic Ocean on the left side, and move towards the southeast, over Africa. Longitudes and latitudes are given along the bottom of the figure. Near latitude 31°N latitude, the Atlas Mountains can be seen. From http://www-lite.larc.nasa.gov/n_saharan_dust.html.

Above the PBL is the "*free troposphere*." The troposphere actually includes the PBL, so we add the prefix "free" to distinguish the part of the troposphere that is above the PBL. The free troposphere is characterized by positive *static stability*, which means that buoyancy forces resist vertical motion. The depth of the troposphere varies strongly with latitude and season.

A turbulent process called "*entrainment*" gradually incorporates free-tropospheric air into the PBL. Over the oceans, entrainment is, with a few exceptions, relatively slow but steady. Over land, entrainment is promoted by strong daytime heating of the surface, which helps to generate turbulence. As a result, the turbulent PBL rapidly deepens during the day. When the sun goes down, the processes that promote turbulence and entrainment are abruptly weakened, and the PBL reorganizes itself into a much shallower nocturnal configuration, leaving behind a layer of air that was part of the PBL during the afternoon. This diurnal deepening and shallowing of the PBL acts as a kind of "pump," which captures air from the free troposphere and adds it to the PBL starting shortly after sunrise, modifies the properties of that air during the day through strong turbulent exchanges with the surface, and then releases the modified air back into the free troposphere at sunset. This diurnal pumping is one way that the PBL exerts an influence on the free troposphere.

In addition, however, moisture and energy are carried upward from the PBL into the free troposphere by several mechanisms. Throughout the tropics and the summer-hemisphere middle latitudes, the most important of these mechanisms is cumulus convection. Cumulus clouds typically grow upward from the PBL. The updrafts inside the clouds carry PBL air into the free troposphere, where it is left behind when the clouds decay (Fig. 1.3). One of the effects of this process is to remove air from the PBL, and add it to the free troposphere.

Figure 1.3: A space shuttle photograph of tropical thunderstorms. The storms are topped by thick anvil clouds. Much shallower convective clouds can be seen in the foreground. From http://eol.jsc.nasa.gov/sseop/EFS/lores.pl?PHOTO=STS41B-41-2347

Frontal circulations can also carry air from the PBL into the free atmosphere, essentially by "peeling" the PBL off from the Earth's surface, like the rind from an orange, and lofting the detached air towards the tropopause. This process is especially active in the middle latitudes in winter.

Fig. 1.4 shows somewhat idealized observed midlatitude vertical distributions of temperature, pressure, density, and ozone mixing ratio, from the surface to the 70-km level. In the lowest 12 km, the temperature decreases monotonically upward; this is the *troposphere*. The troposphere is cooled radiatively, because it emits infrared radiation much more efficiently than it absorbs solar radiation. The net radiative cooling is balanced mainly by the release of the latent heat of water vapor, as clouds form and precipitate.

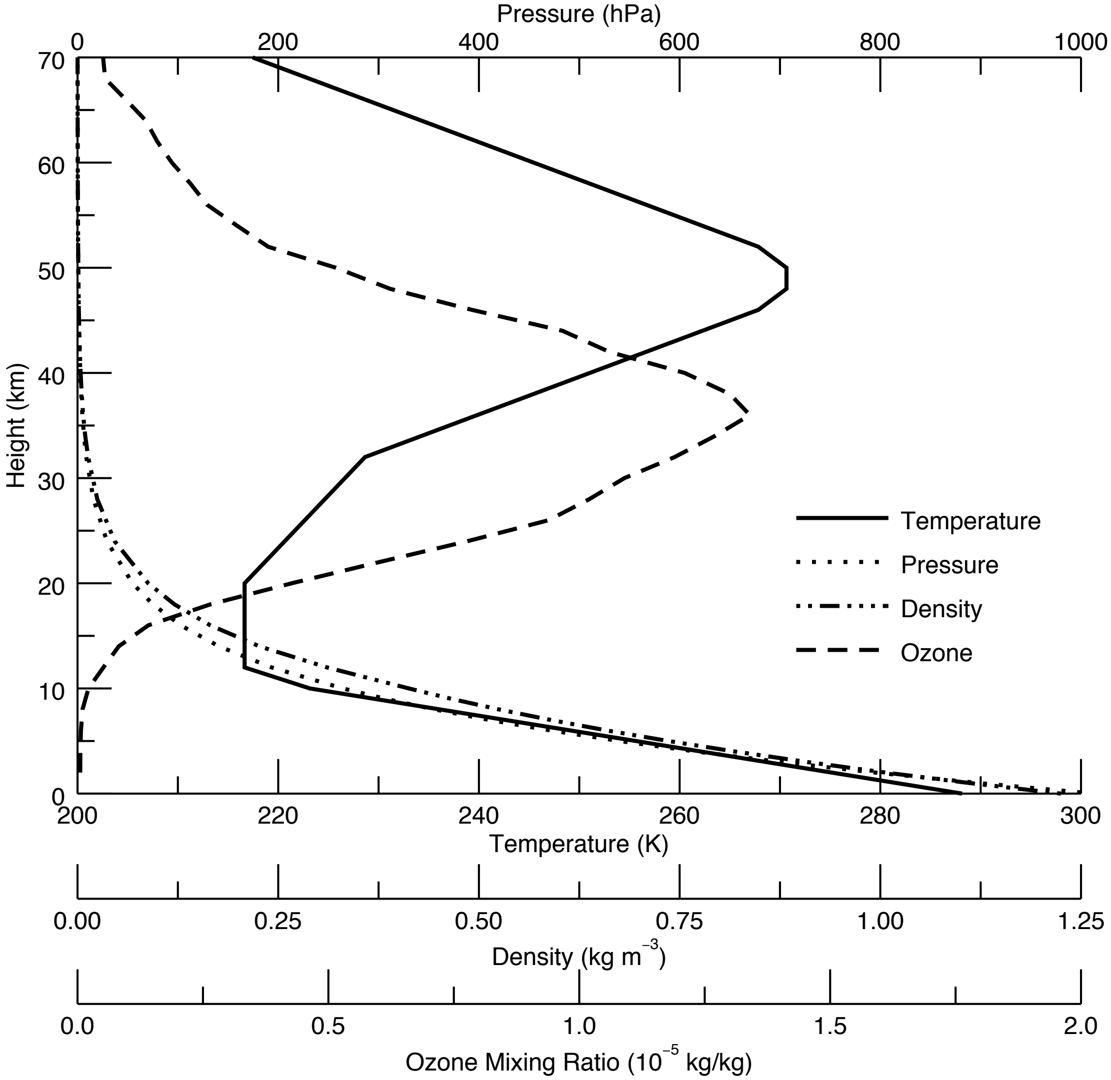

Figure 1.4: Idealized midlatitude temperature, pressure, density and ozone profiles, for the lowest 70 km of the atmosphere. The temperature, pressure, and density profiles are based on the U.S. Standard Atmosphere (1976). The ozone profile is from Krueger and Minzner (1976).

The upper boundary of the troposphere is called the *tropopause*, The height of the tropopause varies from 17 km or so in some regions of the tropics, to about half that near the poles. Above the tropopause, the temperature becomes uniform with height and then begins to increase upward. This region is the *stratosphere*. The upward increase of temperature in the stratosphere is due to the absorption of solar radiation by ozone, which is created in the stratosphere by photochemical processes. Without ozone there would be no stratosphere. The summer-hemisphere stratosphere is almost devoid of active weather, and has warm air over the pole. The winds of the summer stratosphere are predominantly "*easterly*," i.e., they blow from east to west. In contrast, the winter-hemisphere stratosphere has very cold air over the pole, with strong *westerly* winds, and experiences much more active weather, mainly due to waves propagating upward from the troposphere below. During winter, the polar stratosphere is occasionally disturbed by "*Sudden Stratospheric Warmings*," which are dramatic changes in temperature (and wind) that occur in many years in the Northern Hemisphere, and much less frequently in the Southern Hemisphere.

Even though stratosphere is very dry, its moisture budget is quite interesting. It receives small amounts of moisture from the troposphere, and it also gains some moisture through the oxidation of methane.

The upper boundary of the stratosphere, which is called the *stratopause*, occurs near the 1 hPa (~50 km) level. In this book, we consider the troposphere and the stratosphere, but we will not discuss the layers above the stratopause.

For meteorological purposes, the tropics can be defined as the region from about 20° S to 20° N. Although the tropical temperature and surface pressure are remarkably uniform, the winds and rainfall are quite variable. In many parts of the tropics deep cumulus and cumulonimbus clouds, i.e., thunderstorms, produce lots of rain and transport energy, moisture, and momentum vertically, essentially continuing the job begun closer to the surface by the turbulence of the PBL. The convective clouds often produce strong exchanges of air between the PBL and the free troposphere, in both directions: positively buoyant PBL air "breaks off" and drifts upward to form the cumuli, while negatively buoyant downdrafts associated with the evaporation of falling rain can inject free-tropospheric air into the PBL. In the convectively active parts of the tropics, the air is slowly rising in an area-averaged sense.

The mean flow in the tropical PBL is easterly; these are the "*tradewinds*." The tropical temperature and surface pressure distributions are generally very flat and monotonous, for simple dynamical reasons, discussed in Chapter 3, that are connected to the smallness of the Coriolis parameter in the tropics. The tropical moisture and wind fields are more variable than the temperature, however. The tropics is home to a variety of distinctive traveling waves and vortices, which organize the convective clouds on scales of hundreds to thousands of kilometers. Finally, the tropics is dominated by powerful and very large-scale *monsoon* systems, which are associated with continental-scale land-sea contrasts, and which actually extend into the subtropics and even middle latitudes.

The tropical atmosphere acquires the angular momentum of the Earth's rotation from the continents and oceans. The global atmospheric circulation carries the angular momentum to higher latitudes, where it is "put back" into the continents and oceans.

The tropics are home to some circulation phenomena that do not occur in higher latitudes. Most famously, *tropical cyclones* produce tremendous amounts of rainfall and strong winds. They are relatively small in scale, and highly seasonal. *Monsoons* are driven by land-sea contrasts. They also very seasonal, and much larger in spatial scale. The *Madden-Julian Oscillation,* or MJO*,* is a powerful tropical weather system that influences rainfall across about half of the tropics. *El Niño, La Niña*, and the *Southern Oscillation,* which are are collectively known as "*ENSO*," comprise a strong, quasi-regular oscillation of the ocean-atmosphere system, with a period of a few years (Philander, 1990). In an El Niño, the sea-surface temperatures warm in the eastern tropical Pacific, while in a La Niña they cool. The Southern Oscillation is a shift in the pressure and wind fields of the tropical Pacific region, which occurs in conjunction with El Niño and La Niña. The tropical stratosphere features an amazing periodic reversal of the zonal (i.e., west-to-east) wind, called the *Quasi-Biennial Oscillation*, or QBO. Its period is slightly longer than two years.

The subtropical portion of each hemisphere is roughly the region between 20° and 30° from the Equator. In many parts of the subtropical troposphere, the air is sinking in large anticyclonic circulation systems called, appropriately enough, "*subtropical highs*." The subsidence suppresses precipitation, which is why the major deserts of the world are found in the subtropics. Surface evaporation is very strong over the subtropical oceans, which have extensive systems of weakly precipitating shallow clouds. The subtropical upper troposphere is home to powerful "*subtropical jets*," which are westerly currents that are particularly strong in the winter hemisphere (Fig. 1.5).

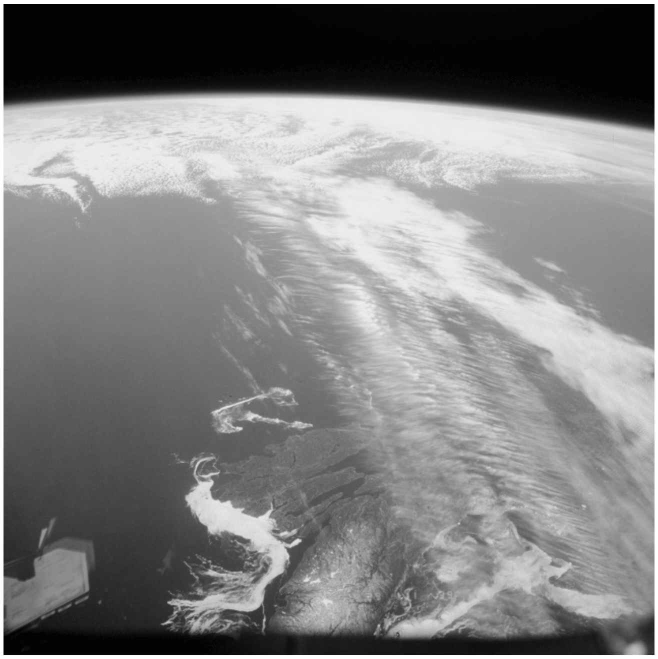

Figure 1.5: This photograph taken from the space shuttle shows cirrus clouds associated with the subtropical jet stream. http://earth.jsc.nasa.gov/sseop/efs/lores.pl?PHOTO=STS039-601-49

The tropical rising motion and subtropical sinking motion can be seen as the vertical branches of a "cellular" circulation in the latitude-height plane. This "*Hadley circulation*" transports energy and momentum poleward, and it transports moisture toward the Equator. The Hadley circulation interacts strongly with the monsoons.

The region that we call the middle latitudes extends, in each hemisphere, from about 30° to 70° from the Equator. The midlatitude surface winds are primarily westerly. The midlatitude free troposphere is filled with vigorous weather systems called *baroclinic eddies*, that have scales of a few thousand km, and grow through a process in which warm air shifts upward and poleward, and is replaced by colder air that descends as it slides toward the Equator (Fig. 1.6). These storms transport energy and moisture poleward and upward, primarily in the winter hemisphere, but also to some extent during summer. They transport westerly momentum poleward and downward, driving currents in the oceans and rustling the leaves on the continents. The energy of the storms is derived from horizontal temperature differences that can only be sustained outside the tropics. The storms produce massive cloud systems and heavy precipitation.

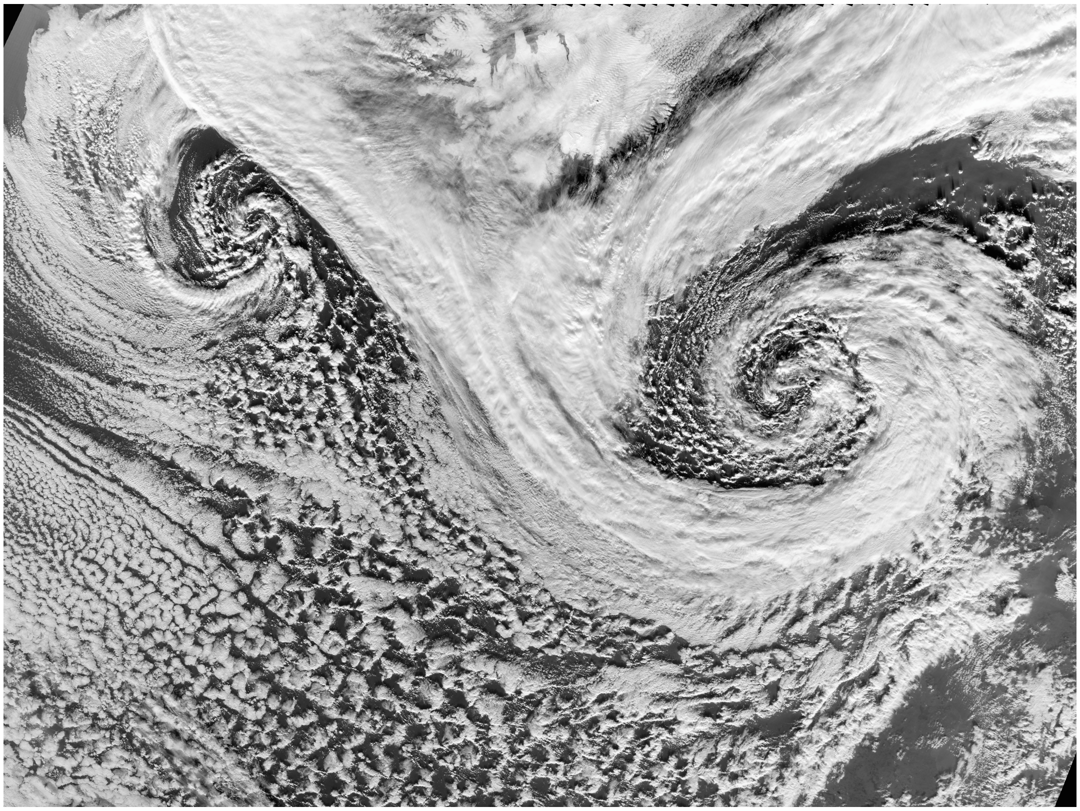

Figure 1.6: A pair of beautiful winter storms over the North Atlantic Ocean in winter. From http://earthobservatory.nasa.gov/IOTD/view.php?id=7264

On the average, the polar troposphere is characterized by sinking motion and radiative cooling to space. The North Pole is in the Arctic Ocean, which is covered with sea ice (Fig. 1.7)

Figure 1.7:An ice station used to collect data in and above the Arctic ocean during 1997-8. From http://en.wikipedia.org/wiki/CCGS_Des_Groseilliers.

and often blanketed by extensive cloudiness, while the South Pole is in the middle of a dry, mountainous continent (Fig. 1.8). Near the surface, the polar winds tend be easterly, but weak.

The polar regions and middle latitudes are home to prominent "*annular modes*," which by definition are visible even when the data are averaged over all longitudes. The annular modes fluctuate on a variety of time scales, almost uniformly in longitude. They are seen in both the stratosphere and troposphere, and make major contributions to the overall variability of the global circulation.

Figure 1.8: Cold-looking clouds over the mountains of Antarctica. From https://wp.natsci.colostate.edu/walllab/research/antarctica/wall-valley-antarctica-information/

The atmosphere cools radiatively, in an overall sense, and this cooling is balanced primarily by the release of latent heat, which in turn is made possible by surface evaporation. The net flow of energy is upward and towards the poles, carried by thunderstorms and the Hadley Circulation in the tropics, and by baroclinic eddies in middle latitudes. The energy escapes to space via infrared radiation at all latitudes, but especially in the subtropics.

The organization of this book is as follows. Chapter 2 provides an overview of the upper and lower boundary conditions on the global circulation. At the "top of the atmosphere," the observed pattern of radiation implies net poleward energy transports by the atmosphere and ocean together. Lower boundary conditions include the distributions of oceans and continents and mountains, the pattern of sea surface temperature and the directly related pattern of sea-surface saturation vapor pressure, the heat capacity of the surface, the distribution of vegetation on the land surface, and the distributions of sea ice and continental glaciers and ice sheets. These lower boundary conditions strongly affect the flows of energy and moisture across the Earth's surface. Chapter 2 closes with a brief overview of the vertically integrated energy and moisture budgets of the surface and atmosphere, and the connections between them.

With this background information out of the way, Chapter 3 presents an observational overview of some basic aspects of the global circulation. We start with the global distribution of atmospheric mass, then move to winds, temperature, and moisture. The amount of interpretation is deliberately kept to a minimum in Chapter 3. By the end of Chapter 3, many important elements of the global circulation have been introduced, giving a basis for further discussion in later chapters.

While Chapter 3 focuses on the observations, Chapter 4 is used to present a brief but intensive review of theory to be used later in the book. We start with a review of the dynamics of fluid motion on a rotating sphere. Angular momentum conservation is derived. We then turn to a detailed discussion of energy transports and transformations. The key subject of potential vorticity is introduced near the end of the chapter. The quasi-geostrophic approximation and the shallow water equations are introduced.

The term "*zonal average*" refers to an average over all longitudes. Chapter 5 deals discusses the zonally averaged circulation, and how it is influenced by sources and sinks of moisture, energy, and momentum. The chapter also presents first look at the effects of "eddies" that transport dry air, moisture, energy, and momentum along "*isentropic"* surfaces on which the entropy is uniform.

Chapter 6 gives an introduction to the effects of convective energy sources and sinks. We begin with a brief review of the nature of buoyant convection in both dry and moist atmospheres. We then outline the famous observational study of convective energy transports by Riehl and Malkus. This is followed by a discussion of the idealized but important concept of radiative-convective equilibrium, and an overview of convective cloud regimes, ranging from deep convection in the tropics to shallow stratocumulus convection in higher latitudes. The concept of convective mass flux is introduced, along with a theory that explains why cumulus updrafts tend to be separated by broad expanses of relatively dry, sinking air. We then show how the convective mass flux can be used to understand the heating and drying associated with cumulus clouds, and what determines the intensity of the convection as a function of the large-scale weather regime. Finally, we introduce the concept of conditional symmetric instability, which is particularly relevant in middle latitudes.

Chapter 7 presents the energetics of the global circulation, beginning with an in-depth discussion of *available potential energy* and the related concept of the *gross static stability*. Following Lorenz, these ideas are developed through the use of isentropic coordinates, although we also show how they can be expressed using pressure coordinates. We then discuss the mechanisms by which vertical and meridional gradients of the zonally averaged circulation can be converted into zonally varying features called *eddy variances*. This leads to a discussion of how *available potential energy* is generated, and how it is converted into *eddy kinetic energy*. The chapter closes with a discussion of the observed *energy cycle* of the global atmosphere.

Chapter 8 introduces various types of eddies, beginning with a brief discussion of the *Laplace Tidal Equations*, omitting the details of the mathematics. It presents observations of the distribution of energy with scale for midlatitude eddies. We summarize the theory of *Rossby waves forced* by flow over topography, and Matsuno's theory of *Equatorial waves*. This is followed by a discussion of the monsoons, the east-west *Walker circulation* of the tropical Pacific, and the energy balance of the tropics and subtropics. The chapter closes with a discussion of the Madden-Julian Oscillation.

Chapter 9 deals with interactions of eddies with the mean flow. We begin with the original "*non-interaction theorem*" of Eliassen and Palm, as applied to gravity waves. This is followed by a brief discussion of the importance of *gravity-wave drag* for the global circulation. We then turn to the quasi-geostrophic wave equation, and its use by Charney, Drazin, Matsuno and others to interpret the interactions of Rossby Waves with the zonally averaged circulation. This leads to a discussion of sudden stratospheric warmings.

Next we discuss the poleward and upward fluxes of sensible heat and momentum associated with winter storms. This leads to a discussion of the Eliassen-Palm Theorem as it relates to balanced flows. The theorem is developed first in pressure coordinates. We then show the additional insights and greater simplicity that come from an analysis in isentropic coordinates, including the relationship between the divergence of the Eliassen-Palm flux and the flux of potential vorticity. The chapter closes with discussions of the Quasi-Biennial Oscillation, blocking, and the Brewer-Dobson circulation as additional examples of the interactions between eddies and the zonally averaged circulation.

Chapter 10 discusses the global circulation as a kind of large-scale *turbulence*. The chapter begins with a discussion of what turbulence is, framed in terms of vorticity dynamics. We discuss the very different flows of energy between scales in two-dimensional and three-dimensional turbulence, and connect it with a description of the distribution of atmospheric kinetic energy with spatial scale. We then discuss mechanisms that allow dissipation of enstrophy (squared vorticity) without dissipation of kinetic energy. This is followed by a discussion of mixing along isentropic surfaces. Next, we discuss the predictability of the weather in a chaotic circulation regime. Finally, we explain how climate prediction differs from weather prediction.

The closing chapter briefly summarizes current trends and projected future changes in the global circulation due to increasing concentrations of atmospheric greenhouse gases.

As outlined above, the study of the thermally driven global circulation of the atmosphere brings together concepts from all areas of atmospheric science. We will touch on large-scale dynamics, convection, turbulence, cloud processes, and radiative transfer, with an emphasis on their interactions. Often these various topics are presented as if they were somehow neatly separated from each other. This book will help you to see how they fit together.

Because the global circulation spans all seasons, it brings together the concepts of atmospheric science across a wide range of conditions and contexts. For example, surface friction occurs everywhere: over the convectively disturbed tropical oceans, in the chaotic storm track north of Antarctica, over the Himalayan mountains, and over the tropical jungles. Discussions of boundary-layer meteorology are typically confined to relatively simple, horizontally uniform, cloud-free conditions, such as might be encountered on a summer morning in Kansas. Welcome to *An Introduction to the Global Circulation of the Atmosphere*; you are not in Kansas anymore. When we try to understand the global circulation, we quickly run up against the limits of knowledge in all the sub-disciplines of atmospheric science, and so we are led to push those limits outward. This makes the study of the global circulation a particularly challenging and exciting field -- as you are about to see for yourselves.