CHAPTER 1 Introduction

1.1 The nature of the subject

The atmosphere *circulates*. This circulation is global in extent. It is constantly fighting against friction, but is sustained by thermal forcing, which ultimately comes from the Sun.

The Sun provides on the average about 340 W m^{-2} of incident energy, of which a tiny fraction is converted into the kinetic energy of the general circulation. Additional, “primordial” energy leaks out of the Earth’s interior, but this rate is only about 0.08 W m^{-2} (Sclater et al., 1980; Bukowinski, 1999).

The externally imposed thermal forcing is strongly influenced by the atmospheric circulation itself, e.g. as clouds form and disappear. This coupling between the circulation and the heating that drives it is a major complication that makes the general circulation much more interesting than it would be otherwise.

The conservation equations that govern the behavior of the atmosphere can be used to formulate balance requirements that the general circulation must satisfy. In a time average, the net energy flux at the top of the atmosphere must vanish, the rates of evaporation and precipitation must balance, and the total angular momentum of the atmosphere-ocean-solid Earth system must be invariant apart from gravitational interactions with the Moon and other extraterrestrial bodies. This check-book approach to the general circulation emphasizes the sources, sinks, and transports of energy, moisture, and angular momentum. We will discuss the general circulation from this classical perspective.

It is important to supplement this viewpoint, 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. One purpose of this course is to introduce and analyze these and other phenomena of the atmospheric general circulation.

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.

The general circulation of the Earth’s atmosphere and the atmospheric component

Figure 1.1: **Full disk image, looking down on North America. Many elements of the general circulation can be seen in this picture, including the rain band in the eastern North Pacific, the midlatitude baroclinic waves, and the low clouds associated with the subtropical highs.**

of the hydrologic cycle are so thoroughly inter-dependent that a proper discussion of the general circulation must deal in detail with moist processes. One of the aims of this book is to emphasize the role of moisture in the general circulation of the atmosphere.

Much general circulation research today overlaps strongly with the study of global-scale air-sea interactions, including the now universally recognized phenomenon of El Niño, as well as a number of other processes which generally manifest themselves on time scales of years to decades. We therefore briefly discuss selected aspects of the ocean circulation, including the physics of both the upper ocean and the deep thermohaline circulation.

In addition, we occasionally compare the general circulation of the Earth's atmosphere with those of other planets in our solar system. Such comparisons are becoming increasingly useful as our knowledge and understanding of the solar system rapidly expands; they serve to emphasize not only certain similarities among the planetary circulations, but also the numerous ways in which the circulation of the Earth's atmosphere is, in our experience to date, unique.

1.2 A brief overview

Here is a qualitative, highly simplified overview of the general circulation, just to give you a feeling for the lay of the land.

It is conventional and useful, although somewhat arbitrary, to divide the atmosphere into parts. For purposes of this quick sketch, we will divide it up vertically and meridionally, glossing over the longitudinal differences.

Starting at the bottom, the layer of air in direct contact with the Earth's surface is called the "planetary boundary layer," or PBL. The air in the PBL is turbulent, and in ways

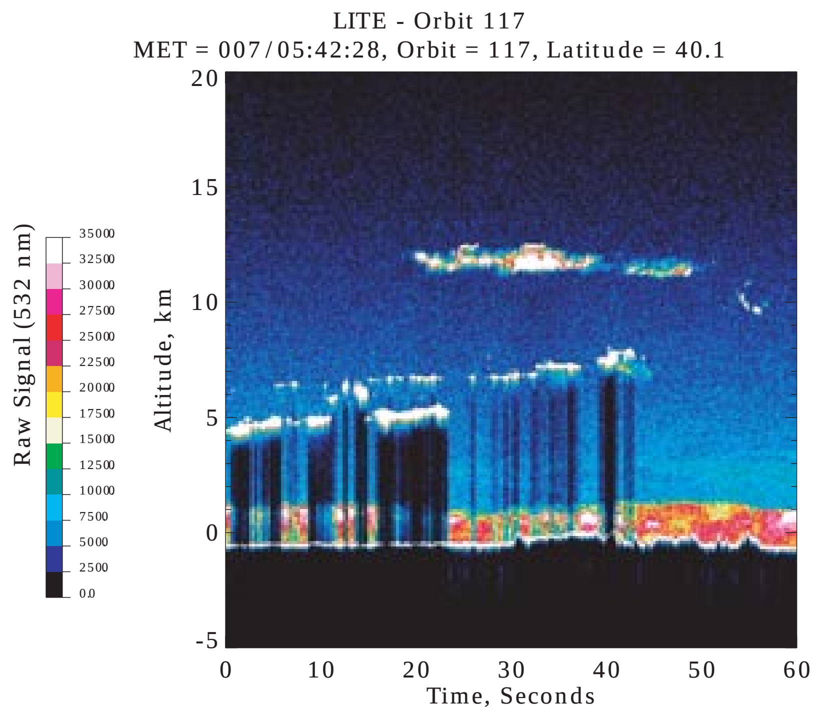

Figure 1.2: This figure shows lidar backscatter from aerosols and clouds. The figure has been created using data from LITE, a lidar that flew on the space shuttle in 1994. The lidar cannot penetrate through thick clouds, which explains the vertical black stripes in the figure. The reddish layer just above the Earth's surface is the PBL, which is visible because the aerosol concentration decreases sharply upward at the PBL top.

that we will discuss later the turbulence produces rapid exchanges of "sensible heat" (essentially temperature), moisture, and momentum between the atmosphere and the surface. The most important exchanges are of moisture, upward into the atmosphere via evaporation from the surface, and of momentum, via friction.[1] The surface moisture flux is a key energy input to the general circulation, and surface friction is the primary mechanism that dissipates the kinetic energy of the general circulation. It only a slight exaggeration to say that the sources and sinks of energy for the general circulation are at the Earth's surface, at the base of the PBL. The depth of the PBL varies dramatically in space and time, but a ball-park value to remember is 1 km.

Above the PBL is the "free troposphere." The troposphere actually includes the PBL, so it is conventional to say "free" troposphere to indicate the part of the troposphere that is not in the PBL. The free troposphere is characterized by positive but modest static stability, i.e., the potential temperature increases upward at a moderate rate. The depth of the troposphere varies strongly with latitude and with season.

For meteorological purposes, the tropics is the region from about 15° S to 15° N. The tropical free troposphere convects. What this means is that many parts of the tropics deep cumulus and cumulonimbus clouds, i.e., thunderstorms, produce lots of rain and transport energy, moisture, and momentum vertically. The convective clouds often

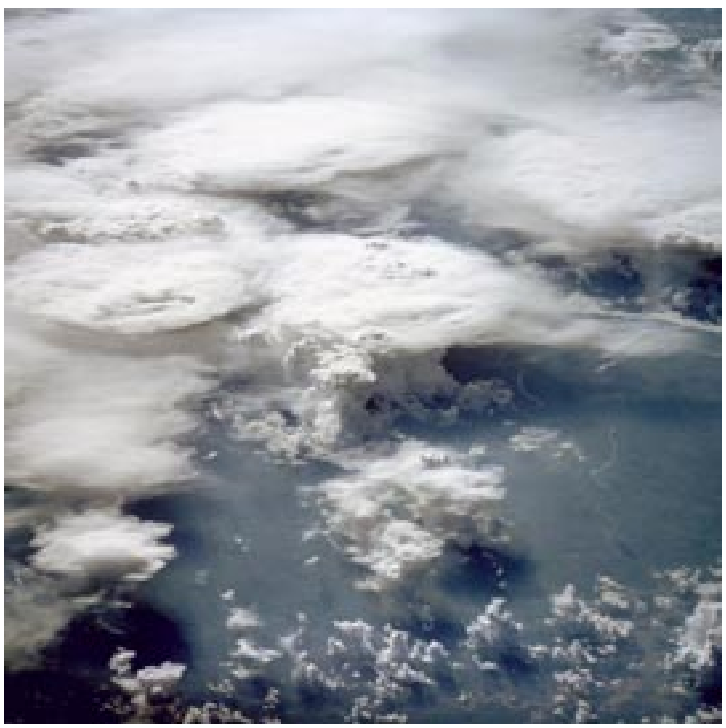

Figure 1.3: A shuttle photograph of tropical thunderstorms. The storms are topped by thick anvil clouds. Much shallower convective clouds can be seen in the foreground.

produce strong exchanges of air between the PBL and the free troposphere. The tropical air is slowly rising in an average sense, and this average rising motion is closely related to the strong but very localized updrafts of the convective clouds. The mean flow in the tropical PBL and free troposphere is easterly; these are the "tradewinds." The temperature

1. Although the general circulation is solar-powered, the solar radiation is primarily absorbed at the Earth s surface, and so the Sun s energy is provided to the atmosphere indirectly, largely in the form of latent heat, i.e., water vapor.

and surface pressure are generally very flat and monotonous in the tropics. The moisture and wind fields are more active, however. In particular, 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 has powerful monsoon systems, which are associated with continental-scale land-sea contrasts, and which actually extend into the subtropics and even middle latitudes.

The subtropics in each hemisphere is roughly the region between 15° 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 subtropics is home to the major deserts of the world. Surface evaporation is very strong over the subtropical oceans, which have extensive systems of weakly precipitating shallow clouds. The tropical upper troposphere is home to the powerful “subtropical jets,” which are westerly currents that are particularly strong in the winter hemisphere.

Figure 1.4: This shuttle photograph shows cirrus clouds associated with the jet stream.

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 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 with scales of a few thousand km, that grow through baroclinic instability. These baroclinic eddies transport energy and moisture poleward and upward, primarily in the winter hemisphere, but also to some extent in the summer hemisphere. They transport westerly momentum downward, where it is consumed by surface friction in the PBL. The baroclinicity that supports the baroclinic eddies manifests itself in strong temperature and surface pressure

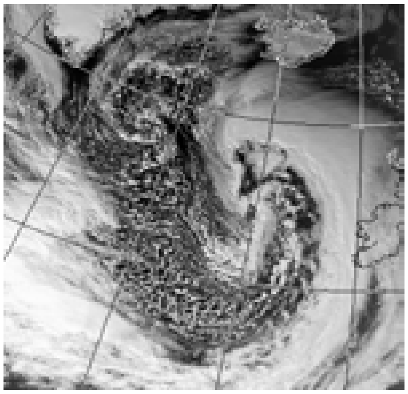

Figure 1.5: A beautiful baroclinic eddy over the North Atlantic Ocean in winter.

variations. The baroclinic waves produce massive cloud systems and strong precipitation. The midlatitude atmosphere also contains strong “stationary waves” associated with both mountains and land-sea contrast.

Finally, on the average the polar troposphere is characterized by sinking motion and radiative cooling to space. The polar regions are home to prominent “annular modes,” which fluctuate on a variety of time scales, almost uniformly in longitude. The North Pole is in the Arctic Ocean, which is covered with sea ice and often blanketed by extensive cloudiness, while the South Pole is on a mountainous continent that is largely a desert.

Figure 1.6: This ship was used to collect meteorological and oceanographic data in and above the Arctic ocean. The ship is surrounded by sea ice, and is enveloped by foggy low-level Arctic clouds.

Above the troposphere is the stratosphere, which is characterized by very strong static stability, even to the point that the temperature increases upward in the middle and upper stratosphere. This upward increase of temperature is due to the absorption of solar radiation by stratospheric ozone. The summer-hemisphere stratosphere is very quiet dynamically, and is filled with easterlies, with warm air over the pole. The winter-hemisphere stratosphere is much more active, with very cold air over the pole. The winter stratosphere occasionally produces very rapid changes of temperature and wind called “Sudden Warmings,” especially in the Northern Hemisphere. The tropical stratosphere is home to an amazing periodic reversal of the zonal wind, with a period slightly longer than two years, called the Quasi-Biennial Oscillation, or QBO. Although stratosphere is very dry, the stratospheric moisture budget is quite interesting.

As discussed later, the atmosphere cools radiatively, in an overall sense, and this

Figure 1.7: Cold-looking clouds over the mountains of Antarctica.

cooling is balanced primarily by the release of latent heat, which in turn is made possible by surface evaporation. The overall flow of energy in the atmosphere is upward into the atmosphere from the surface in the tropics and subtropics, then meridionally and further upward by the Hadley Circulation in the tropics and the baroclinic eddies in middle latitudes, and finally outward to space via infrared radiation at all latitudes, but especially in the subtropics.

1.3 Fasten your seatbelts

The study of the thermally driven general circulation of the atmosphere naturally brings together concepts from all areas of atmospheric science. We will be discussing general-circulation phenomena that involve large-scale dynamics, convection, turbulence, cloud processes, and radiative transfer. Most of all, we will be discussing the interactions among these processes. This is good, because typically in course work these various topics are presented as if they were somehow neatly separated from each other.

Because the general circulation is global and spans all seasons, the concepts of atmospheric science must be applied 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. In courses on boundary-layer meteorology, however, the discussion is typically limited to relatively simple horizontally uniform conditions, such as might be encountered on a summer’s day in Kansas.

For these reasons, when we study the general circulation, we quickly run up against the limits of our understanding in all aspects of atmospheric science, and so we are led to push those limits outward. This makes the study of the general circulation a particularly challenging and exciting field -- as you are about to see for yourselves.