1 An overview of the atmosphere

1.1 Introduction

Many instruments have been used to study the atmosphere, both by in-situ and remote methods. From anemometers to satellites, chemical sensors to balloons and rockets, the array of tools is broad. Since the early 1900s, a key instrument for such studies has been radar. RADAR stands for Radio Detection And Ranging. Radars operating in a variety of frequency bands, from wavelengths of kilometers to wavelengths of millimeters, have all found application. They have been used to study the upper ionosphere and the neutral atmosphere, right down to ground level.

In this book, we will concentrate on a class of radar generally referred to as MST radar. In this description, M stands for Mesosphere, S for Stratosphere, and T for Troposphere, where these three "spheres" refer to different height-regimes of the atmosphere which collectively cover the region from ground level up to about 90 km altitude. More exact definitions will be given shortly. For now, consider the troposphere as the region from the ground to 12 km altitude, the stratosphere as the region from 12 to 50 km altitude, and the mesosphere the region from 50 to 90 km altitude. Under the narrowest definition, the term MST radar was originally used primarily to refer to radars operating in the VHF (very high frequency) band, with special emphasis on frequencies around 50 MHz, which could probe (at least in part) all three regions. More generally it has come to refer to any radars that can be used for studies of any of these three regions of the atmosphere. These radars include MF (medium frequency), HF (high frequency), VHF, and UHF (ultra-high frequency). They also include so-called meteor radars. Generally, precipitation radars (referred to as "Doppler radars" by the meteorological community) are not considered to be MST radars, although we will discuss them a little in this book. (As an aside, we will generally refer to these radars as precipitation radars in this book. The phrase "Doppler radar" is not a good one to describe these radars, since they are most certainly not the only Doppler radars! The term "Doppler radar" arises from the fact that these radars can measure the Doppler frequency-shift of reflected signals. As we will see, almost all MST radars are also Doppler radars.) As a rule we will consider MST radars to cover the frequency range from about 1 MHz to 1 GHz, with radars operating at frequencies beyond 500 MHz being discussed less completely than the others.

The middle atmosphere is generally considered to be the height region from 10 km altitude to 100 km altitude, and therefore includes the upper troposphere, the stratosphere, the mesosphere, and the lowest few kilometers (90–100 km) of the thermosphere. (The thermosphere, in a more general context, refers to the region above the mesopause, or in other words, above about 90 km altitude.)

In this book we will concentrate on the radars that cover the frequency range between 1 MHz to about 500 MHz in the main, which are used to probe the region between 0 and 100 km altitude. Many of the radars to be discussed can probe even higher in altitude, up into the ionosphere, but we will not consider these applications here. Nevertheless, since many MST-type radars had their origins in ionospheric studies, we will discuss some ionospheric aspects of the atmosphere at times.

The focus of this book is twofold. First, there is an engineering aspect, in which we will describe hardware aspects of these radars, and these descriptions will have wider-reaching relevance than applications specific to these radars. A variety of hardware aspects will be considered that are general to all types of radars. This focus also includes signal-processing techniques. The second focus will be on the types of studies that can be performed with these radars, including the physics and dynamics of the atmosphere. Within the book, the two focuses will be somewhat interleaved.

In this chapter, we will give a very brief introduction to radar as it relates to atmospheric studies, but will largely concentrate on giving an overview of the troposphere and middle-atmosphere, our region of particular interest. Chapter 2 will then focus on the ways in which radar came to be used for atmospheric studies. In the next 8 chapters, our focus will be more on various aspects of hardware, radar application, and signal processing. Chapters 11 and 12 will then return to observational aspects, discussing in some detail various dynamical and meteorological aspects of these radars.

We will begin the next section with a brief history of the origins of these types of radar, but will leave more detailed discussions to Chapter 2. The rest of this chapter will be devoted to an overview of the basic dynamics and thermodynamics associated with the troposphere and middle atmosphere.

1.2 The origins of radar

Over the past century, radiowaves have developed a major presence in industrialized society. We use them to communicate on a day-to-day basis (both locally and globally), to transmit and receive key information, to monitor space and our environment, to transmit television and voice information, to detect remote objects, and so on and so forth. Radiowaves are a part of the electromagnetic spectrum and can generally propagate freely through the atmosphere. The “discovery” of radiowaves can be attributed to the efforts of multiple people, including Faraday, Maxwell, Hertz, Bose, Marconi, Popov, and Tesla, among others. Hertz appears to have been the first to generate and detect radiowaves, but many others were involved in improving detection and transmission devices. From the point of view of global communication, however, there is no doubt that a key experiment was the transmission of a radio signal by Marconi across the Atlantic Ocean on 12 December, 1901. Marconi’s devices utilized no less than 17 patents developed by Tesla, including the Tesla disruptive coil. Much debate exists about who should rightfully be considered the “inventor” of radio transmission. The awarding of the Nobel Prize to Marconi in 1911 was not without controversy, with Tesla laying strong claim. We will not dwell on these points here, except to comment that it is probable that the development of radio communication at the time was likely an idea whose "time had come," and it was inevitable that multiple scientists would develop similar ideas and hardware at the same or similar times.

Subsequent developments led to a variety of radio-transmission and radio-reception devices, including the famous discovery of extra-terrestrial signals by Jansky in 1931, which led, through the enthusiasm of Grote Reber, an amateur astronomer, to the very busy field of radio astronomy – still a very active field even today.

Figure 1.1 shows the relation between the electric and magnetic fields in a radiowave, and Figure 1.2 shows the approximate location of the so-called "radio band" relative to other types of electromagnetic radiation (EM) as a function of wavelength and frequency.

Radio work received a rapid jolt in pace during World War II, with all parties recognizing the value of detecting enemy aircraft tens and even hundreds of kilometers away. This led ultimately to substantial development of radar for the real-time detection of remote targets by transmission and reflection of radiowaves. Although radar has been

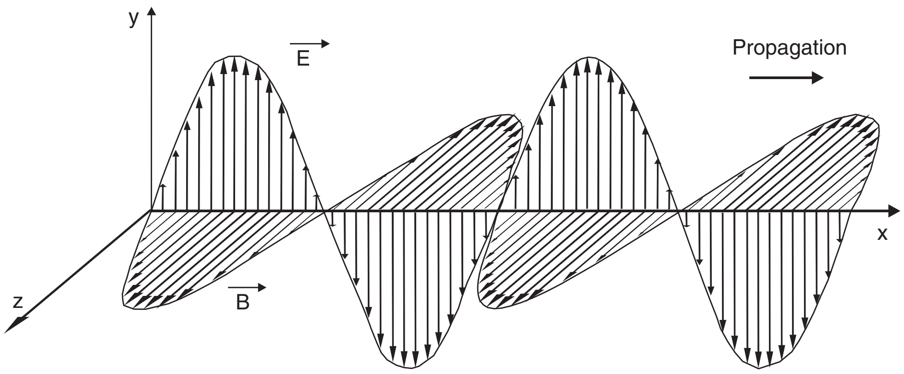

Figure 1.1 Electric and magnetic fields in an electromagnetic wave.

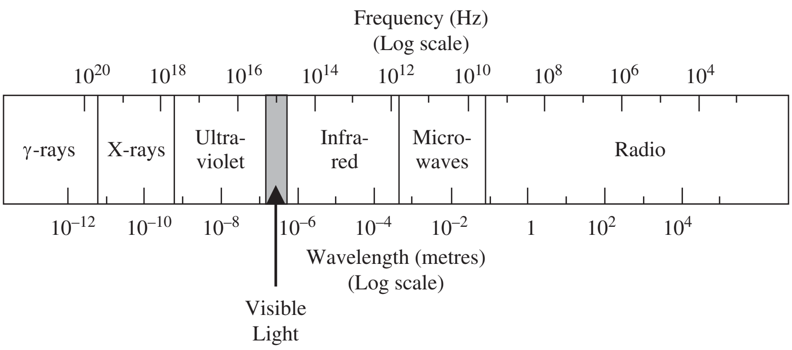

Figure 1.2 Location of radiowaves in the electromagnetic spectrum.

considered to be "invented" in 1936 by Watson-Watt (*Watson-Watt et al.*, 1936), this belief stems from the fact that he worked closely with developments of it during the 1930s and 1940s. In truth, simple radars had been demonstrated to have existed much earlier. In 1904 Christian Huelsmeyer gave public demonstrations in Germany and the Netherlands of a primitive "radar" using a simple spark-gap system as a transmitter. It is true, however, that the 1940s were when radar's real potential was realized. A key aspect of radar is the ability not only to receive signal reflected by targets, but also to determine the range to the target by using time-delay measurements, and to determine target direction. Of particular importance was the development of radars that operated at 3 000 and 10 000 MHZ (S-band and X-band), since only at these frequencies could radars with good directional capabilities be made small enough to be fitted onto aircraft and moving vehicles. Previous radars had worked at frequencies of 200 and 400 MHz. The development of the "cavity magnetron" was a key factor in allowing these high frequency S- and X-band radars to become viable, and the development of these radars in Britain and the USA well before the German development in 1943 gave the Allies a key advantage in World War II.

After World War II, radio work received another boost. Radio astronomy began in earnest and scientists started to use radar to track balloons released into the air, allowing upper level wind speeds to be determined. It was used for telemetry with rocket experiments, and of course for communication.

Radio work for human applications developed along several fronts, with two standing out – first, radar for aircraft and vehicle tracking, and second, studies involving communication. The second field of study actually arose as a result of Marconi's original transmission of radiowaves across the Atlantic Ocean, which should not have been possible since theoretical calculations suggested (after some erroneous early miscalculations!) that radiowaves should not be able to bend around the Earth. Subsequent studies led to the proposal that the Earth's atmosphere contained a layer of reflecting plasma at upper altitudes, which could be used to facilitate global communication. Heaviside and Kennelly proposed the existence of such a layer, but Appleton and Barnett were the first to prove its existence as early as 1925 (*Appleton and Barnett*, 1925; *Appleton*, 1930). At the same time as proving its existence, they were actually able to determine the height of radio reflection, using frequency adjustments of the British Broadcasting Corporation (BBC) radio transmission systems. The reflections were from what is now known as the "ionospheric E-region" (at one time called the Heaviside layer, with another layer higher up being labelled the "Appleton layer"). After a while, the plasma region was simply referred to as the "ionosphere," and that is the most common term used to describe it today. Appleton and Barnett used a swept-frequency method; an alternative method, using pulsed radar that was stepped through a variety of frequencies on successive pulses, was developed by *Breit and Tuve* (1926). Both methods are still used today.

After World War II, world-wide communication by radio signals reflected from the so-called "ionosphere" became a primary means for near-instantaneous world-wide communication. Sports matches in England were broadcast to Australia, for example. However, the ionosphere was not a stable reflector, and signals varied enormously

Table 1.1 Designations of radio bands.

Name	Frequency	Wavelength
Low frequency (LF)	30–300 kHz	10–1 km
Medium frequency (MF)	0.3–3 MHz	1000–100 m
High frequency (HF)	3–30 MHz	100–10 m
Very high frequency (VHF)	30–300 MHz	10–1 m
Ultra-high frequency	300–3000 MHz	1 m–10 cm
Microwave region	$\geq$ 3000 MHz	$\leq$ 10 cm
Further-subdivision		
L-band	1–2 GHz (1000–2000 MHz)	30–15 cm
S-band	2–4 GHz	15–7.5 cm
C-band	4–8 GHz	7.5–3.75 cm
X-band	9–12 GHz	3.75–2.5 cm
K-I (or K_u) band	12–18 GHz	2.5–1.7 cm
K-II (or K_a) band	27–40 GHz	1.2–0.75 cm

in strength, often showing fading on the order of seconds. Large scientific networks were set up to investigate and better understand this valuable transmission medium and were well funded until at least the more recent advent of under-sea cables and satellite radio-relay systems.

A variety of different radio frequencies were used for these studies, with lower frequencies generally being used for ionospheric work, and high frequencies (shorter wavelengths) being used for meteorology. Table 1.1 summarizes the main frequency bands.

The primary bands are the LF to UHF bands, but within the UHF band and into the microwave region, there are also some special frequencies which have extra designations. This nomenclature developed during World War II, and is listed under "further subdivision" in the table. Note that the "K-band" is split because there is strong water-vapor absorption between the two bands, meaning that this particular section is not useful for transmission within the Earth's atmosphere. There is also a class of amateurs who use radio communication for fun, and they have various bands designated for their purposes. Two such bands are the 30–50 MHz band (which they call the "low band" or the "six-meter band"), and a band at 148–174 MHz (which they call the "high band" or the "two-meter band").

A related effect of both radar applications and ionospheric studies was scientific investigation into the basic nature of the transmission and scattering processes, and of the nature of the media that transmitted and scattered the radio signals. In the lower atmosphere, centimeter-band radars were developed for studies of storms and precipitation, and eventually were proposed for studies of neutral turbulence (e.g., *Buehler and Lunden*, 1964; *Friend*, 1949). Studies of the ionosphere, and also other plasmas generated by processes like meteor intrusions into the atmosphere, were also vigorously pursued.

Interestingly, the prime topic of this book brings together aspects of both of these fields. MST (Mesosphere-Troposphere-Stratosphere) radars had their origins in the ionosphere, yet found strong application in the neutral lower atmosphere.

In order to understand these radar and radio techniques and to see how they have turned out to be so important in atmospheric studies, we first need to understand a little about the nature of the atmosphere itself. Although much of this book will be about studies of the neutral atmosphere, the ionospheric origins of these instruments cannot be denied. In addition, understanding radars often involves understanding plasmas. This is especially true with regard to the radar refractive index, a topic of great importance both for transmission and reflection.

Consequently, in the rest of this chapter we will introduce some fundamentals about the basic structure of the Earth's atmosphere and include not only the neutral composition but also the ionized portions. A more detailed discussion of the history of radar in atmospheric studies will follow in the next chapter.

1.3 The atmosphere – an overview

1.3.1 The Earth's neutral atmosphere and ionosphere

The atmosphere is a large system and the interactions involved are complex and intricate. From the (relatively) dense boundary layer to the tenuous remnants thousands of miles into space, there are a wealth of physical processes both fascinating and important to all inhabitants of the Earth. This complexity is indeed one of the reasons that radar studies are so useful – radar is one of the few tools that can remotely monitor many of these complex motions.

At large distances from the Earth's surface, free electrons and ions spiral freely along magnetic lines of force and interact strongly with a wind of similar particles flowing from the sun. This "plasma-sphere" extends far into space – up to around 25 to 30 Earth radii in places – and is a type of "outer region" for the atmosphere. It is is considerably beyond the scope of our topics for this book, but its presence should be recognized. Various reviews of the region exist, (e.g., *Bahnsen*, 1978). A diagram showing some of its main features can be found in Figure 1.3, and a more detailed three-dimensional version can be found in *Kelley* (1989), Figure 1.3.

In order to put things into perspective, we also show Figure 1.4, which shows the scale of the lowest 100 km of the atmosphere relative to the size of the Earth. Bearing in mind that the region of the air in which we live, the "troposphere," typically lies below 10–15 km in height (about one tenth to one sixth of the thickness of the region shown in the figure) and contains over 85 percent of the entire atmospheric mass, this figure reinforces just how thin the "practical atmosphere" is that we depend on for our existence. The huge extent of atmosphere shown in Figure 1.3 is somewhat misleading – while this region is, to some extent, under control of the Earth's gravity, it contains but a small fraction of the total atmospheric mass. Although this region can have significant impact on our lives, through auroras and magnetic storms which

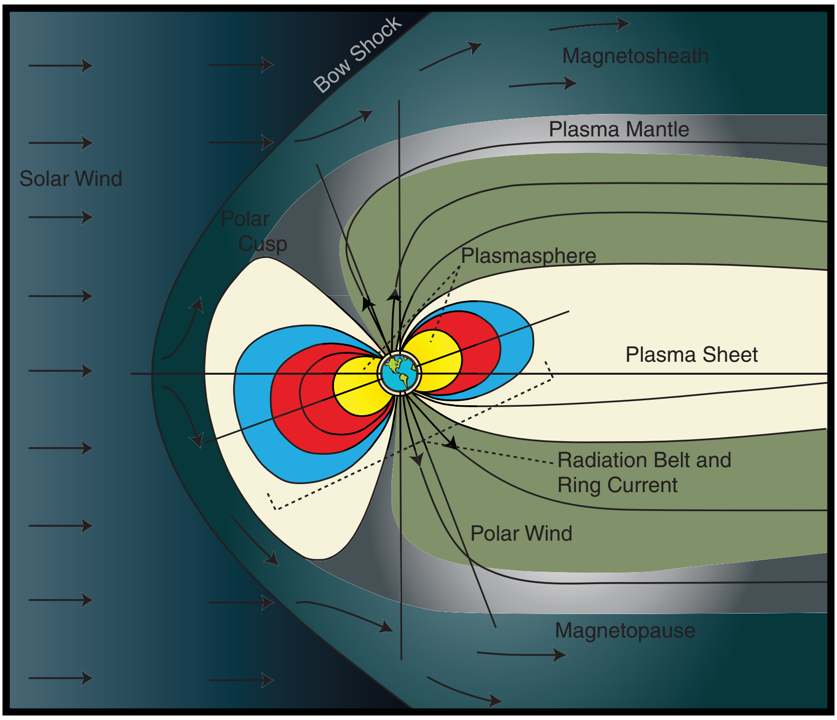

Figure 1.3 The Magnetosphere, adapted from *Bahnsen* (1978). The inner yellow region and outer blue cyan region show approximate locations of the inner and outer Van Allen radiation belts.

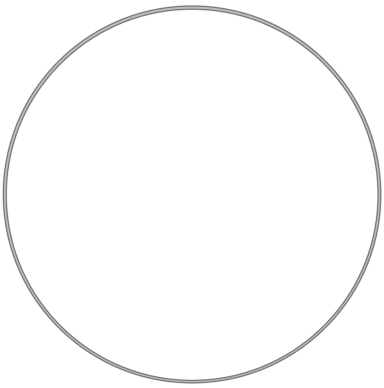

Figure 1.4 The depth of the atmosphere relative to the Earth. The thin shaded shell represents the atmosphere drawn to scale to a depth of 100 km.

may damage spacecraft and even, at times, Earth-bound power grids, the most important part is the thin shell shown in Figure 1.4. The radars discussed in this book will concentrate on that shell. The lowest regions of the atmosphere are the most dense, and the pressure and density decrease roughly exponentially as a function of height.

The reasons for this will be discussed later in this chapter – for now we accept it as a fact.

In the following sections, ways of classifying the atmosphere will be examined and some of its regimes will be briefly discussed. We will begin in the outer reaches and proceed down to the so-called middle atmosphere, which will eventually be the primary focus of this text.

We will concentrate especially on atmospheric flows, since this is something that radars can study especially well. But at the end of the chapter, we will also introduce some basic information about statics and thermodynamics which is important for understanding the atmosphere, and especially important for radar investigations of the atmosphere.

Classification of the atmosphere

Two of the most common classification schemes used in the atmosphere are based upon temperature structure and electron density. The former is more common, but for radio work it is important to acknowledge the second classification scheme.

Figure 1.5 shows these classifications. Temperature classifications give rise to the troposphere (lowest region of decreasing temperature), the stratosphere (region of increasing temperature above the troposphere), the mesosphere, (region of decreasing temperature above the stratosphere), and the thermosphere. The symbols D, E, F1, and F2 denote the ionospheric nomenclature. The E and F2 regions are local peaks in electron density, and F1 is a local peak at times (particularly during sunspot maximum summers). It is important to note that these sample profiles can only be approximate, since the temperatures and electron densities can vary substantially with time and location, and with sunspot number, especially in the ionosphere. Day-to-night variation can also be substantial. At night, T_n falls to about 600 K at sunspot minimum and about 900 K at sunspot maximum (*King-Hele*, 1978). Temperature maximum occurs at about 1600 hours local time, and minimum at about 0400 hours in the thermosphere (*King-Hele*, 1978). References for these data include *Houghton* (1977) (Appendix 5), *Roble and Schmidtke* (1979), and *Garrett and Forbes* (1978) (Figure 1). Even the heights of the various regimes can change – for instance, the tropopause height varies both latitudinally and with time of day. In the exosphere (about 500–1000 km), kinetic temperature is not a meaningful term since neutral atoms rarely collide (*King-Hele*, 1978). The hatching in the figure gives some idea of the variations in electron density which can occur. Data are taken from *Craig* (1965), Figures 9.11 and 9.15, and *Ratcliffe* (1972), Figure 3.3. Also shown are some typical E-region night-time electron densities.

One important region not presented on this diagram is the turbopause region. Up to about 100–115 km altitude, turbulence can play a major role in the dynamics of the atmosphere, but above this region, turbulence is a relatively rare phenomenon. The reason is that the mean free path of particles and the increase in temperature result in large molecular diffusion rates, and most small scale transfers of heat and particles occur by such molecular transport. The transition region between the turbulent dominated and non-turbulent regimes is quite narrow, and is called the turbopause. This is discussed in more detail elsewhere. Very rarely, patches of turbulence can be found above the

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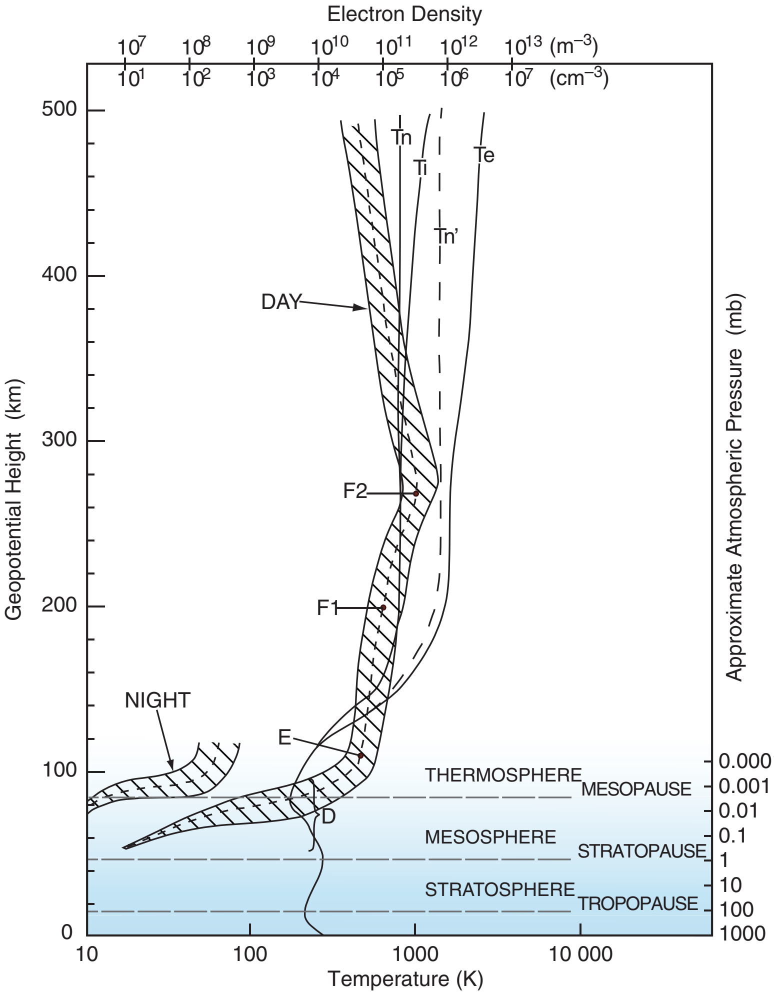

Figure 1.5 Electron-density-based and temperature classification schemes for the atmosphere. Typical daytime temperature profiles for neutral kinetic temperature T_n, the ion temperature (T_i), and T_e (the electron temperature) are also shown for sunspot minimum. T_n shows a typical daytime neutral temperature profile during sunspot maximum. Atmospheric pressure decreases approximately exponentially with increasing height, and typical values are shown on the right-hand side ordinate. There exists considerable latitudinal, seasonal, and day-to-night variability in all parameters. See text for more details. Shaded regions represent electron density profiles, with D, E, F1, and F2 layers emphasized.

turbopause. (Recently, reports of high-altitude turbulence measured by radar have been presented by *Fujiwara et al.* (2004), but these are due to erroneous interpretation of the data, not real effects, as will be demonstrated in later chapters.)

Figure 1.6 shows an expanded view of the temperature profile at below 100 km altitude, showing the temperature classifications in that region more clearly. Some brief annotation describing the reasons for the different regimes is given, and these will be elaborated upon in greater detail shortly.

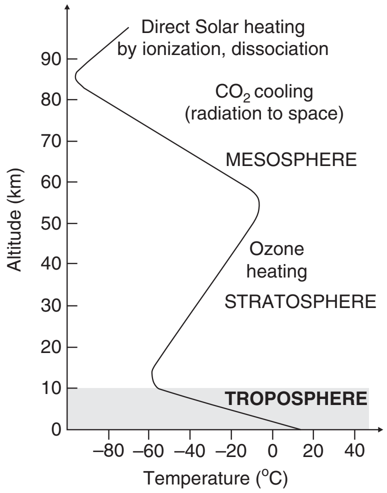

Figure 1.6 Expanded view of the temperature structure of the atmosphere below 100 km altitude.

Figure 1.7 shows typical height distribution of various neutral constituents throughout the atmosphere. Electron density and water vapor content are especially important for radar scattering, as we will see later. Ozone is especially important for understanding thermal processes in the stratosphere. CO_2 is especially important for atmospheric heating, as will be discussed later in the context of radiation transfer. One point that is especially clear is that even at 300 km the electron number densities are small compared to the total neutral density. Therefore the concept of a "plasma" in the upper atmosphere has to be considered with caution – it is far from fully ionized. It is also worth noting that even the neutrals at higher altitudes show considerable day-to-night density variations, with variations as large as a factor of 1.5 times at 200 km, and by about a factor of 6 at 600 km. Variation is maximum at around 600 km. Sunspot-cycle variations are also important.

In this figure, only some of the more important minor gases are shown below 100 km. For a more complete picture, see *Ackerman* (1979). In particular, CH_4, N_2O and CO have densities greater than or equal to the density of NO, and HNO_3, CH_3Cl, NO_2, HCl, SO_2, CCl_4, ClO, and HF have densities comparable to that of NO (about 10^9 m^{-3} at 20–40 km altitude). NO has been included because it, and O_2, are the main two constituents in the D-region directly ionizable by incoming radiation. Above the D-region, O_2, O and N_2 are the most important ionizable constituents up to 500–600 km altitude.

The dominant species varies as a function of height, because above the turbopause, each species decays in density with its own scale height. Molecules lighter in density decay more slowly than heavier ones. Below the turbopause, all the gases are well mixed and decay at the same rate. For these reasons, the region below the turbopause is called the "homosphere" (uniformly mixed) and the region above is called the "heterosphere" (where each gas decays in height largely independently of the others, due to the fact that molecules and atoms of different constituents rarely collide). At a thermospheric