1

# Introduction

*I shall never be able to express clearly whence comes this pleasure men take from aridity, but always and everywhere I have seen men attach themselves more stubbornly to barren lands than to any other. Men will die for a calcined, leafless stony mountain. The nomads will defend to the death their great store of sand as if it were a treasure of gold dust. And we, my comrades and I, we too have loved the desert to the point of feeling that it was there we had lived the best years of our lives.*

Antoine de Saint Exupéry, French aviator and writer
*Wind, Sand and Stars* (1939)

*If one is inclined to wonder at first how so many dwellers came to be in the loneliest land that ever came out of God's hands, what they do there and why stay, one does not wonder so much after having lived there. None other than this long brown land lays such a hold on the affections . . . once inhabiting there you always mean to go away without quite realizing that you have not done it.*

Mary Austin, American naturalist and writer
*The Land of Little Rain* (1903)

Deserts, in spite of the popular perception of their uniformity over vast distances, often contain within them a complex mosaic of **microclimates** and local weather. Great contrasts also exist in the **climate** and surface characteristics from one desert to the next. There are "cold" deserts and hot deserts, deserts with winter precipitation and deserts with summer precipitation, deserts with virtually no precipitation, perpetually foggy coastal deserts and continental deserts with near the maximum possible sunshine, barren deserts and heavily vegetated deserts, sand-dune deserts and deserts with rocky plains. The existence of such variety and complexity in deserts, and their ubiquity as well, are important messages of this book.

The expression "desert weather" has a peculiar ring to mid-latitude-centric meteorologists. It even strikes some as a contradiction in terms. This preconception is belied by the facts. When it does rain in the desert it sometimes results in a violence that is rarely matched in more temperate places. Dry riverbeds that have lain parched for decades pass a wall of water, after which they may lie parched again for years. In some places, the day–night temperature change is immense, and larger than that associated with most mid-latitude frontal passages. And, most who have experienced a desert sand storm or dust storm would likely tell you that the discomfort level and fear are much greater than, for example, in snow storms.

The existence and distribution of desert climates have profoundly shaped historical patterns of human travel, settlement, economic development, and communication, where the deserts seem to have curiously served as both barriers and attractions. Most of the world's early great civilizations developed at the margins of deserts. Virtually all of the world's great contemporary religions were born in desert regions: Judaism, Islam, Christianity, Hinduism, and Buddhism. The Aborigines of arid Australia are thought to have the oldest continuously maintained culture and the world's oldest language family. And the world's longest continuously inhabited human settlement is in the desert (Jericho, Jordan). Deserts are still significant as physical barriers, even in this age when technology has allowed many of us to become insulated from our environment. In some respects, the greater deserts of the world have been, and still are, more important than mountain barriers or seas in terms of inhibiting surface transportation and commerce. In addition, with a few notable exceptions in high-technology societies, recent human habitation has not encroached significantly into arid, especially highly arid, areas. It is thus arguable that the deserts represent one of the last terrestrial frontiers in terms of human dominance over, and exploitation of, the natural environment.

Most humankind understandably feel culturally, emotionally, and geographically distant from desert environments. However, the green conditions that we take for granted may be ephemeral on time scales shorter than we imagine. Prolonged and unpredictable droughts are natural and frequent occurrences in some areas, and human degradations of the environment have made vast once-green places become desert. Our perceptions can quickly change when dust fills the air, and water sources that have been taken for granted for centuries are no longer available. Fig. 1.1 illustrates that only about 3% of Earth's water is fresh (non-saline), and much of this is not readily usable because it is in the form of permanent ice and snow, and permafrost. Of the remaining water, only 1% is available at the surface in rivers, lakes and vegetation. The remainder is groundwater, some of which is not renewed by rainfall; i.e., when it is depleted to the point that it is no longer economically recoverable for greening the

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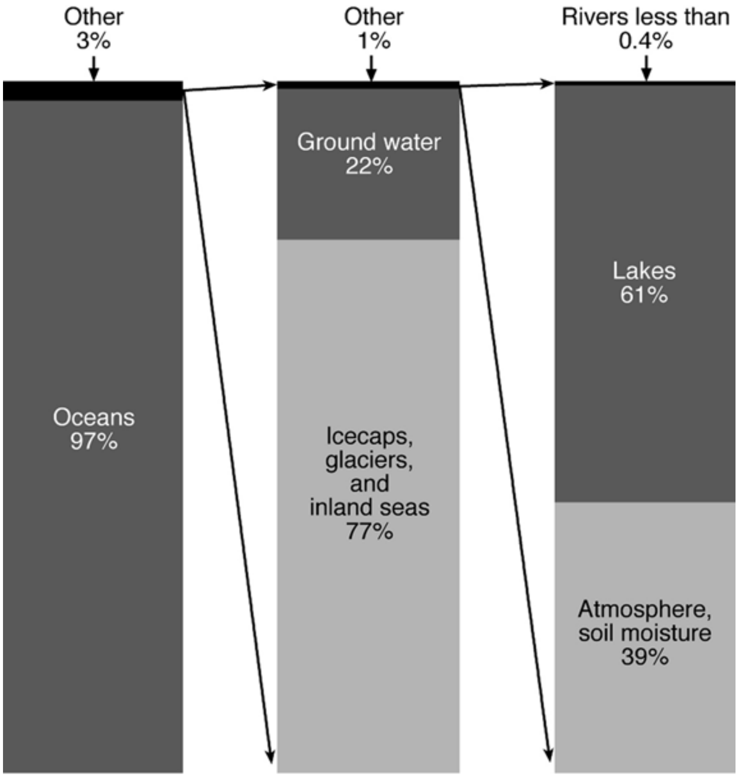


**Fig. 1.1** Distribution of water on Earth, including fresh and salt water.

surface by irrigation, the resource is permanently lost. This very small slice of the hydrosphere that sustains our civilizations and keeps most of the land green is vulnerable to overuse and abuse, and to natural variability in climate, and it should not be taken for granted that the green parts of Earth will stay that way. The thinness of this veneer of water security is one motivation for studying the dynamics of desert formation and maintenance.

Desert weather and climate have historically been primarily of academic concern to all but the few local residents, even though some broader long-term interest has existed because of military activities, the exploitation of the desert's great natural resources, agricultural reclamation through irrigation, and the perception of some regional climatic trends toward desertification. However, more recently, population growth in arid areas has often surpassed that in more temperate zones, the attractions being unpolluted air, abundant sunshine, beautiful landscapes, and endless open space. In North America, for example, population growth in urban areas of the Sonoran Desert in the second half of the twentieth century occurred much more rapidly than in New England and in the Midwest. Population growth in the arid states of the United States has been about five times the national average. Worldwide, in excess of three-quarters of a billion people, more than one in eight, are estimated to live in dry lands. This fraction will likely increase because most inhabitants of arid lands are in developing countries where the rate of population growth is greatest. Thus, deserts are becoming less deserted, and desert weather and climate are having a direct impact on a growing fraction of the world population.

Deserts also influence the weather and people far outside their borders because there are dynamic connections in the atmosphere between weather processes that are geographically remote. And the fact that warm, arid climates comprise over 30% of the land area of Earth implies that their aggregate effect on non-desert areas and global climate in general can be significant. If the state of the soil and vegetation is used, in addition to the climate, to define the area of deserts, the desert fraction of the total land area increases by another 10% because of the human degradation (UN 1978). That is, all things considered, the total is close to 40%. By comparison, only 10% of Earth's land surface is cultivated. Fig. 1.2 illustrates the fraction of the land in different arid and non-arid categories. The designated hyper-arid, arid, and semi-arid areas collectively represent Earth's traditionally defined dry climates. Dry sub-humid climates are typically grassland and prairie. The humid land area consists of mostly tropical and mid-latitude forest, grassland, and rain-fed agricultural land.

This book is motivated by the fact that, in spite of the historical and present importance of the world deserts, there is no available in-depth review of their meteorology and climate. There are numerous good *general* references on the subjects of weather (Ahrens 2000), regional climate (Yoshino 1975), land-surface physics and micrometeorology (Geiger 1966; Oke 1987; Yoshino 1975), planetary boundary-layer physics (Stull 1988; Garratt 1992a), and mesoscale dynamics (Atkinson 1981), but none provides a complete treatment of such processes for desert environments. There are also excellent standard references on the physical and biological environments of deserts (McGinnies *et al*. 1968; Petrov 1976; Mares 1999), some of which review the meteorology, but the meteorological processes are not the primary focus. In addition, desert geomorphology, the desert hydrologic system, and the desert thermal energy budget are all related to desert microclimate and weather, but the literature on these subjects is somewhat specialized and is generally not commonly read by students of atmospheric sciences. Making the study of desert meteorology especially challenging is the fact that a general knowledge of traditional meteorology may not extrapolate well to arid environments because the physical conditions in the desert are

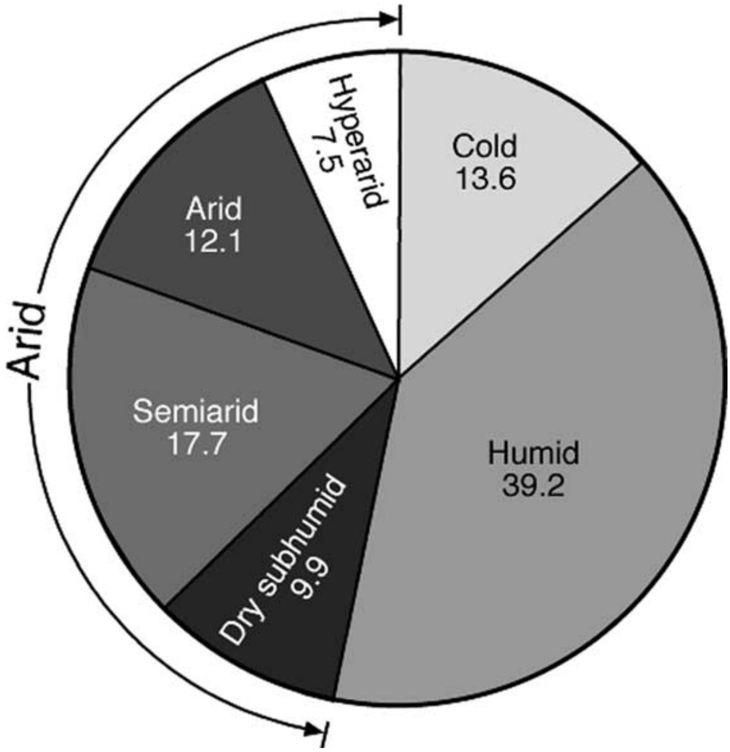


**Fig. 1.2** Global land area by aridity zone (%). (Data from UNEP 1992.)

well outside our experience base: large horizontal temperature gradients, high temperatures, large diurnal oscillations, dry soils, low relative humidity, etc. This problem is compounded by the fact that there has not been a commensurate amount of experimental work for deserts, compared with forests and agricultural land (Jury *et al.* 1981), because of their perceived low economic significance and their geographic remoteness, and this has limited our understanding of the physical system.

As a step toward satisfying this need, this book describes the large-scale and mesoscale[1.1] meteorological processes and climates of the world's deserts. To properly address the near-surface atmospheric processes, the disciplines of micrometeorology and land-surface physics must be employed. These encompass the study of *surface* and *sub-surface* thermodynamic, hydrologic, and biospheric processes, as well as processes in the atmosphere very near the ground. Thus, our study of desert meteorology and climate will need to embrace a range

[1.1] Mesoscale, as the term is most often applied, simply refers to a broad range of horizontal space scales between the familiar "synoptic" scale, or weather-map scale, and the very small microscale of turbulence.

of topics from varied disciplines such as surface hydrology, soil physics, geology, and biology. Excluded from this book is a treatment of the polar regions as deserts, even though polar latitudes are generally true deserts from a climatic sense in that there are low precipitation amounts, and in the geomorphic sense that the ground water is frozen and unavailable for vegetation. In any case, polar deserts are described well in Smiley and Zumberge (1974).

# 2

# The atmospheric dynamics of deserts

*The Bedouin of the desert, born and grown up in it, had embraced with all his soul this nakedness too harsh for volunteers, for the reason, felt but inarticulate, that there he found himself indubitably free. He lost material ties, comforts, all superfluities and other complications to achieve a personal liberty which haunted starvation and death.*

T. E. Lawrence, British writer and adventurer
*Seven Pillars of Wisdom* (1926)

*And it is an almost terrifying magnificence . . . In a distance that is much clearer than usual earthly distances, mountain chains join and overlap. They are in regular arrangements that man has not interfered with since the creation of the world. And they have harsh brittle edges, never softened by the least vegetation. The closest row of mountains is a reddish brown; then, as they stand closer to the horizon, the mountains go through elegant violet, turning a deeper and deeper blue, until they are pure indigo in the farthest chain. And everything is empty, silent, and dead. Here you have the splendor of fixed perspectives, without the ephemeral attractions of forests, greeneries, and grasslands; it is also the splendor of almost eternal stuff, freed of life's instabilities. The geological splendor from before the Creation . . . .*

Julien Viaud, French writer, soldier, painter, and acrobat
*Le Désert* (1895)

Because discussions in this chapter, and others in later chapters, will employ many concepts in basic atmospheric dynamics, the first section below will present some essential background review material. Then, the complex issue will be discussed of how we define "desert," and how we quantify degrees of aridity. There are definitions based on climatology, surface hydrology, plant communities, and soil types. Once the various definitions of aridity have been reviewed, the different dynamic causes of deserts will be described. These desert-forming and -maintaining processes will be seen to span scales from planetary to very local. There are also dynamic feedbacks between the atmosphere and surface that can contribute to the development and sustainment of deserts, and these will be discussed. Finally, the dynamics of desert heat lows will be addressed. Numerous other dynamic processes that occur in desert atmospheres are not related to maintaining the aridity, and these will be discussed in later chapters. The locations of deserts mentioned by name in this chapter can be found in Fig. 3.1.

## Some basic concepts of atmospheric structure and dynamics

It was noted earlier that it is assumed that the reader already has a basic knowledge of atmospheric sciences. Nevertheless, some particular concepts that will be employed throughout this book will be summarized here for convenience. This will not be a comprehensive review, and non-technical texts on atmospheric sciences, such as Ahrens (2000), and technical ones on atmospheric dynamics, such as Holton (1992), should be used as additional resources as needed.

### *Scales of atmospheric motion*

Atmospheric processes occur on a wide range of space and time scales. The horizontal space scale can be thought of as the typical horizontal dimension, or wavelength, of a phenomenon. On the large end of the scale are planetary waves, with only a few spanning the circumference of the planet. On the small end are turbulent eddies of air that may be only a few centimeters in size. Between these extremes, a variety of terms have been used to classify the different scales of motion. Below the largest planetary scale, there is what is labeled the **synoptic scale** by meteorologists. This is the typical weather-map scale that spans part or most of a continent. Smaller than the synoptic scale is the **mesoscale** (meso meaning middle), which is generally partitioned into three bands, mesoalpha, mesobeta and mesogamma, from large to small scales. Smaller than the mesogamma scale is the microscale, which includes small turbulent eddies. The following is a summary of the horizontal length scales associated with each term.

| | |
|---|---|
| Planetary scale | $>$ 5000 km |
| Synoptic scale | 2000–5000 km |
| Mesoscale | 2–2000 km |
| Microscale | $<$ 2 km |

Terminology used here will consistently adhere to the above definitions. In addition to these space scales, there are time scales associated with different atmospheric phenomena. Depending on usage, the term time scale can refer to the life time of an atmospheric feature, or the time period that it influences a particular location. For example, a thunderstorm complex may last most of a day as it

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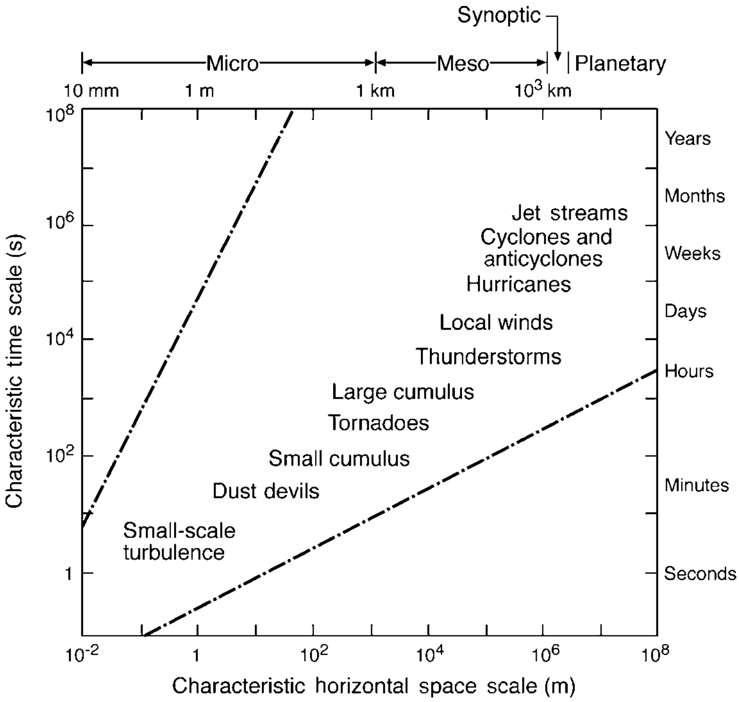


**Fig. 2.1** Horizontal space and time scales of various atmospheric phenomena. (Adapted from Smagorinsky 1974.)

traverses several states, but specific locations may only be affected by the rainfall for a half hour. Fig. 2.1 depicts the approximate time and horizontal space scales for different atmospheric phenomena. Note that *vertical* length scales are often quite different from horizontal scales because of the relatively shallow depth of the atmosphere. Vertical scales and atmospheric structure will be discussed in the next section.

### *Vertical structure of the atmosphere*

The atmosphere can be divided in the vertical into various layers according to a number of different criteria, such as the vertical temperature structure, turbulence characteristics, electrical properties, and chemical composition. The divisions based on temperature and turbulence will be important points of reference later, and are described here. Fig. 2.2 shows average vertical profiles of temperature in the winter season for different latitudes. The lower atmosphere where the temperature decreases with height is the troposphere, and above that, where the temperature increases with height, is the stratosphere. The point at which the temperature ceases to decrease rapidly with height is the tropopause, with

 

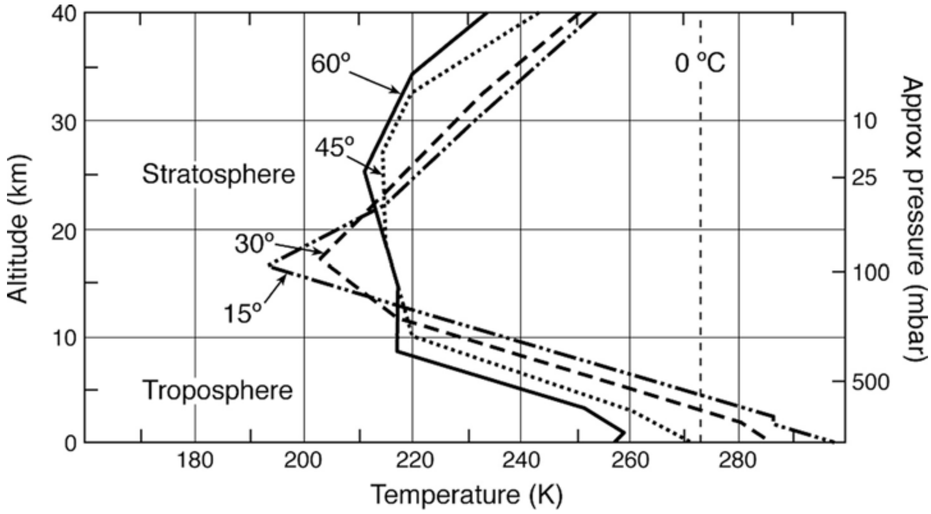


**Fig. 2.2** Standard (average) vertical profiles of temperature for the winter atmosphere, for different latitudes. (Adapted from Cole *et al.* 1965.)

the tropical troposphere being deeper than in higher latitudes. The water-vapor content of the atmosphere also generally decreases with height (not shown), because its source is surface evaporation. It is important to remember that these are average conditions, and that there is much (1) day-to-day variability that reflects changing weather regimes at a particular location; (2) horizontal variability at a particular time, associated with the spatial distribution of weather regimes; and (3) diurnal variability near the ground in response to the regular surface heating and cooling cycle.

A departure from this average that is especially relevant to our study of deserts is related to the fact that a common condition over arid areas is one in which the tropospheric air is sinking, or subsiding. An important dynamic response to this **subsidence** is that the temperature no longer decreases as rapidly with height, and in extreme cases can even increase with height over shallow layers. An important consequence of this condition is that clouds and precipitation are suppressed. Conversely, in a layer of air that is rising, the temperature will decrease more rapidly with height.

At the lower boundary of the troposphere is the **turbulent** layer through which the influence of the surface is directly transmitted to the atmosphere above. Through this **boundary layer**, or **mixed layer**, turbulent eddies transport water vapor and heat upward from their source at the surface. Also, the frictional stress exerted by the surface on the atmospheric fluid is transmitted by the turbulence. There are two causes of turbulence, or sources of turbulent energy. One is the