Chapter 1 | Introduction

1.1 Scope of Micrometeorology

Atmospheric motions are characterized by a variety of scales ranging from the order of a millimeter to as large as the circumference of the earth in the horizontal direction and the entire depth of the atmosphere in the vertical direction. The corresponding time scales range from a tiny fraction of a second to several months or years. These scales of motions are generally classified into three broad categories, namely, micro-, meso-, and macroscales. Sometimes, terms such as local, regional, and global are used to characterize the atmospheric scales and the phenomena associated with them.

Micrometeorology is a branch of meteorology which deals with the atmospheric phenomena and processes at the lower end of the spectrum of atmospheric scales, which are variously characterized as microscale, small-scale, or local-scale processes. The scope of micrometeorology is further limited to only those phenomena which originate in and are dominated by the shallow layer of frictional influence adjoining the earth's surface, commonly known as the atmospheric boundary layer (ABL) or the planetary boundary layer (PBL). Thus, some of the small-scale phenomena, such as convective clouds and tornadoes, are considered outside the scope of micrometeorology, because their dynamics is largely governed by mesoscale and macroscale weather systems.

In particular, micrometeorology deals with the exchanges of heat (energy), mass, and momentum occurring continuously between the atmosphere and the earth's surface, including the subsurface medium. The energy budget at or near the surface on a short-term (say, hourly) basis is an important aspect of the different types of energy exchanges involved in the earth–atmosphere–sun system. Vertical distributions of meteorological variables such as wind, temperature, and humidity, as well as trace gas concentrations and their role in the energy balance near the surface, also come under the scope of micrometeorology. In addition to the short-term averaged values of meteorological variables, more or less random fluctuations of the same in time and space around their respective average values are of considerable interest. The statistics of these so-called turbulent fluctuations are intimately related to the above-mentioned exchange processes and, hence, constitute an integral part of micrometeorology or boundary-layer meteorology.

1.1.1 *Atmospheric boundary layer*

A boundary layer is defined as the layer of a fluid (liquid or gas) in the immediate vicinity of a material surface in which significant exchange of momentum, heat, or mass takes place between the surface and the fluid. Sharp variations in the properties of the flow, such as velocity, temperature, and mass concentration, also occur in the boundary layer.

The atmospheric boundary layer is formed as a consequence of the interactions between the atmosphere and the underlying surface (land or water) over time scales of a few hours to about 1 day. Over longer periods the earth–atmosphere interactions may span the whole depth of the troposphere, typically 10 km, although the PBL still plays an important part in these interactions. The influence of surface friction, heating, etc., is quickly and efficiently transmitted to the entire PBL through the mechanism of turbulent transfer or mixing. Momentum, heat, and mass can also be transferred downward through the PBL to the surface by the same mechanism. A schematic of the PBL, as the lower part of the troposphere, over an underlying rough surface is given in Figure 1.1. Also depicted in the same figure is the frequently used division of the atmospheric boundary layer into a surface layer and an outer or upper layer. The vertical dimensions (heights) given in Figure 1.1 are more typical of the near-neutral stability observed during strong winds and overcast skies; these are highly variable in both time and space.

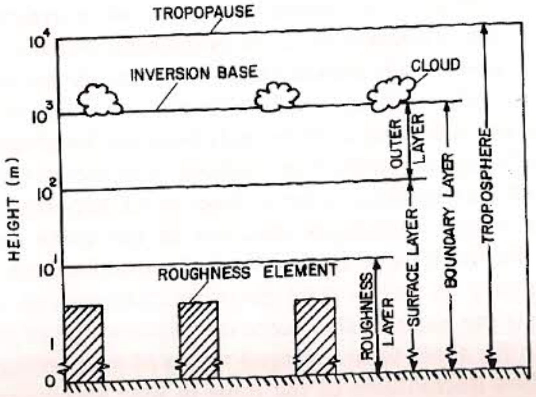

Figure 1.1 Schematic of the planetary boundary layer as the lower part of the troposphere. [From Arya (1982).]

The atmospheric PBL thickness over land surfaces varies over a wide range (several tens of meters to several kilometers) and depends on the rate of heating or cooling of the surface, strength of winds, the roughness and topographical characteristics of the surface, large-scale vertical motion, horizontal advections of heat and moisture, and other factors. In the air pollution literature the PBL height is commonly referred to as the mixing height or depth, since it represents the depth of the layer through which pollutants released from the near-surface sources are eventually mixed. As a result, the PBL is generally dirtier than the free atmosphere above it. The contrast between the two is usually quite sharp over large cities and can be observed from an aircraft as it leaves or enters the PBL.

In response to the strong diurnal cycle of heating and cooling of land surfaces during fair-weather conditions, the PBL thickness and other boundary layer characteristics also display strong diurnal variations. For example, the PBL height over a dry land surface in summer can vary from less than 100 m in the early morning to several kilometers in the late afternoon.

Following sunrise on a clear day, the continuous heating of the land surface by the sun and the resulting thermal mixing in the PBL cause the PBL depth to increase steadily throughout the day and attain a maximum value of the order of 1 km (range $\simeq$0.2–5 km) in the late afternoon. Later in the evening and throughout the night, on the other hand, the radiative cooling of the ground surface results in the suppression or weakening of turbulent mixing and consequently in the shrinking of the PBL depth to a typical value of the order of only 100 m (range $\simeq$20–500 m). Thus the PBL depth waxes and wanes in response to the diurnal heating and cooling cycle. The winds, temperatures, and other properties of the PBL may also be expected to exhibit strong diurnal variations. Diurnal variations of the PBL height and other meteorological variables are found to be much smaller over large lakes, seas and oceans, because of the small diurnal changes of the water surface temperature due to the large heat capacity of the mixed layer in water.

Other temporal variations of the PBL height and structure often occur as a result of the development and the passage of mesoscale and synoptic systems. Generally, the PBL becomes thinner under the influence of large-scale subsidence (downward motion) and the low-level horizontal divergence associated with a high-pressure system (anticyclone). On the other hand, the PBL can grow to be very deep and merge with towering clouds in disturbed weather conditions that are associated with low-pressure systems (cyclones). It is often difficult to distinguish the PBL top from in-cloud circulations under these conditions; the cloud base is generally used as an arbitrary cutoff for the boundary layer top.

Spatial variations of the PBL depth and structure occur as a result of changes in land use and topography of the underlying surface. Spatial variations of meteorological variables influenced by mesoscale and large-scale systems also lead to similar variations in the boundary layer. On a flat and homogeneous surface, however, the PBL is generally considered horizontally homogeneous.

1.1.2 The surface layer

Some investigators limit the scope of micrometeorology to only the so-called atmospheric surface layer, which comprises the lowest one-tenth or so of the PBL and in which the earth's rotational or Coriolis effects can be ignored. Such a restriction may not be desirable, because the surface layer is an integral part of and is much influenced by the PBL as a whole, and the top of this layer is not physically as well defined as the top of the PBL. The latter represents the fairly sharp boundary between the irregular and almost chaotic (turbulent) motions in the PBL and the smooth and streamlined (nonturbulent) flow in the free atmosphere above. The PBL top can easily be detected by ground-based remote-sensing devices, such as acoustic sounder, lidar, etc., and can also be inferred from temperature, humidity, and wind soundings.

However, the surface layer is more readily amenable to observations from the surface, as well as from micrometeorological masts and towers. It is also the layer in which most human beings, animals, and vegetation live and in which most human activities take place. The sharpest variations in meteorological variables with height occur within the surface layer and, consequently, the most significant exchanges of momentum, heat, and mass also occur in this layer. Therefore, it is not surprising that the surface layer has received far greater attention from micrometeorologists and microclimatologists than has the outer part of the PBL.

The lowest part of the surface layer in which the influence of individual roughness elements can readily be discerned is called the roughness layer or the canopy layer (see Figure 1.1). For bare land surfaces, it is quite thin and often ignored. For grasslands and other vegetated surfaces, the height of the roughness layer is proportional to (say, 1.5 times) the average height of vegetation. In built-up (suburban and urban) areas, the height of roughness or canopy layer may depend on the spatial distribution and heights of buildings in the particular area. Over large city centers, the roughness layer may comprise a significant portion of the urban boundary layer, especially at night.

1.1.3 Turbulence

Turbulence refers to the apparently chaotic nature of many flows, which is manifested in the form of irregular, almost random fluctuations in velocity, temperature, and scalar concentrations around their mean values in time and space. Atmospheric turbulence is always manifested in the form of gustiness of winds, so that gustiness can be regarded as a simple measure of turbulence strength or intensity. The motions in the atmospheric boundary layer are almost always turbulent. In the surface layer, turbulence is more or less continuous, while it may be intermittent and patchy in the upper part of the PBL and is sometimes mixed with internal gravity waves. The PBL top is usually defined as the level where turbulence disappears or becomes insignificant.

Near the surface, atmospheric turbulence manifests itself through the flutter of leaves of trees and blades of grass, swaying of branches of trees and plants, irregular movements of smoke and dust particles, generation of ripples and waves on water surfaces, and a variety of other visible phenomena. In the upper part of the PBL, turbulence is manifested by irregular motions of kites and balloons, spreading of smoke and other visible pollutants as they exit tall stacks or chimneys, and fluctuations in the temperature and refractive index encountered in the transmission of sound, light, and radio waves.

1.2 Micrometeorology versus Microclimatology

The difference between micrometeorology and microclimatology is primarily in the time of averaging the variables, such as air velocity, temperature, humidity, etc. While the micrometeorologist is primarily interested in fluctuations, as well as in the short-term (of the order of an hour or less) averages of meteorological variables in the PBL or the surface layer, the microclimatologist mainly deals with the long-term (climatological) averages of the same variables. The latter is also interested in diurnal and seasonal variations, as well as in very long-term trends of meteorological parameters.

In micrometeorology, detailed examination of small-scale temporal and spatial structure of flow and thermodynamic variables is often necessary to gain a better understanding of the phenomena of interest. For example, in order to determine the short-time average concentrations on the ground some distance away from a pollutant source, one needs to know not only the mean winds that are responsible for the mean transport of the pollutant, but also the statistical properties of wind gusts (turbulent fluctuations) that are responsible for spreading or diffusing the pollutant as it moves along the mean wind.

In microclimatology, one deals with long-term averages of meteorological variables in the near-surface layer of the atmosphere. Details of fine structure are not considered so important, because their effects on the mean variables are smoothed out in the averaging process. Still, one cannot ignore the long-term consequences of the small-scale turbulent transfer and exchange processes.

Despite the above-mentioned differences, micrometeorology and microclimatology have much in common, because they both deal with similar atmospheric processes occurring near the surface. Their interrelationship is further emphasized by the fact that long-term averages dealt with in the latter can, in principle, be obtained by the integration in time of the short-time averaged micrometeorological variables. It is not surprising, therefore, to find some of the fundamentals of micrometeorology described in books on microclimatology (e.g., Geiger, 1965; Oke, 1987; Rosenberg *et al.*, 1983; Geiger *et al.*, 1995). Likewise, microclimatological information is found in and serves useful purposes in texts on micrometeorology (e.g., Sutton, 1953; Munn, 1966; Arya, 1988; Stull, 1988; Sorbjan, 1989; Garratt, 1992; Kaimal and Finnigan, 1994).

1.3 Importance and Applications of Micrometeorology

Although the atmospheric boundary layer comprises only a tiny fraction of the atmosphere, the small-scale processes occurring within the PBL are useful to various human activities and are important for the well-being and even survival of life on earth. This is not merely because the air near the ground provides the necessary oxygen to human beings and animals, but also because this air is always in turbulent motion, which causes efficient mixing of pollutants and exchanges of heat, water vapor, etc., with the surface.

1.3.1 Turbulent transfer processes

Turbulence is responsible for the efficient mixing and exchange of mass, heat, and momentum throughout the PBL. In particular, the surface layer turbulence is responsible for exchanging these properties between the atmosphere and the earth's surface. Without turbulence, such exchanges would have been at the molecular scale and minuscule in magnitudes (10^{-3}–10^{-6} times the turbulent transfers that now commonly occur). Nearly all the energy which drives the large-scale weather and general circulation comes through the PBL.

Through the efficient transfer of heat and moisture, the boundary layer turbulence moderates the microclimate near the ground and makes it habitable for animals, organisms, and plants. The atmosphere receives virtually all of its water vapor through turbulent exchanges near the surface. Evaporation from land and water surfaces is not only important in the surface water budget and the hydrological cycle, but the latent heat of evaporation is also an important component of the surface energy budget. This water vapor, when condensed on tiny dust particles and other aerosols (cloud condensation nuclei), leads to the formation of fog, haze, and clouds in the atmosphere.

Besides water vapor, there are other important exchanges of mass within the PBL involving a variety of gases and particulates. Turbulence is important in the exchange of carbon dioxide between plants and animals. Its atmospheric concentration has steadily been rising due to ever increasing use of fossil fuels in energy production and other industry, heating and cooking, and forest clearing by burning. This, in conjunction with similar increasing trends in the concentrations of methane and other radiatively active gases, threatens global climate warming. Many harmful toxic substances are also released into the atmosphere by human activities. Through efficient diffusion of the various pollutants released near the ground and mixing them throughout the PBL and parts of the lower troposphere, atmospheric turbulence prevents the fatal poisoning of life on earth. The quality of air we breathe depends to a large extent on the mixing capability of the PBL turbulence. The boundary layer turbulence also picks up pollen and other seeds of life, spreads them out, and deposits them over wide areas far removed from their origin. It lifts dust, salt particles, and other aerosols from the surface and spreads them throughout the lower atmosphere. Of these, the so-called cloud condensation nuclei are an essential ingredient in the condensation and precipitation processes in the atmosphere.

Through the above-mentioned mass exchange processes between the earth's surface and the atmosphere, the radiation balance and the heat energy budget at or near the earth's surface are also significantly affected. More direct effects of turbulent transfer on the surface heat energy budget are through sensible and latent heat exchanges between the surface and the atmosphere. Over land, the sensible heat exchange is usually more important than the latent heat of evaporation, but the reverse is true over large lakes and the oceans. Heat exchanges through the underlying bodies of water are also turbulent, especially those in the immediate vicinity of the surface.

Turbulent transfer of momentum between the earth and atmosphere is also very important. It is essentially a one-way process in which the earth acts as a sink of atmospheric momentum (relative to earth). In other words, the earth's surface exerts frictional resistance to atmosphere motions and slows them down in the process. The moving air near the surface may be considered to exert an equivalent drag force on the surface. The rougher the surface, the larger would be the drag force per unit area of the surface. Some commonly encountered examples of this are the marked slowdown of surface winds in going from a large lake, bay, or sea to inland areas and from rural to urban areas. Perhaps the most vivid manifestations of the effect of increased surface drag are the rapid weakening and subsequent demise of hurricanes and other tropical storms as they move inland. Another factor responsible for this phenomenon is the marked reduction or cutoff of the available latent heat energy to the storm from the surface.

Over large lakes and oceans, wind drag is responsible for the generation of waves and currents in water, as well as for the movement of sea ice. In coastal areas, wind drag causes storm surges and beach erosion. Over land, drag exerts wind loads on vehicles, buildings, towers, bridges, cables, and other structures. Wind stress over sand surfaces raises dust and creates ripples and sand dunes. When accompanied by strong winds, the surface layer turbulence can be quite discomforting and even harmful to people, animals, and vegetation.

Turbulent exchange processes in the PBL have profound effects on the evolution of local weather. Boundary layer friction is primarily responsible for the low-level convergence and divergence of flow in the regions of lows and highs in surface pressures, respectively. The frictional convergence in a moist boundary layer is also responsible for the low-level convergence of moisture in low-pressure regions. The kinetic energy of the atmosphere is continuously dissipated by small-scale turbulence in the atmosphere. Almost one-half of this loss on an annual basis occurs within the PBL, even though the PBL comprises only a tiny fraction (less than 2%) of the total kinetic energy of the atmosphere.

1.3.2 Applications

In the following text, we have listed some of the possible areas of application of micrometeorology together with the subareas or activities in which micrometeorological information may be especially useful.

1. Air pollution meteorology
   - Atmospheric transport and diffusion of pollutants
   - Atmospheric deposition on land and water surfaces
   - Prediction of local, urban, and regional air quality
   - Selection of sites for power plants and other major industries
   - Selection of sites for monitoring urban and regional air pollution
   - Industrial operations with emissions dependent on meteorological conditions
   - Agricultural operations such as dusting, spraying, and burning
   - Military operations with considerations of obscurity and dispersion of contaminants
2. Mesoscale meteorology
   - Urban boundary layer and heat island
   - Land–sea breezes
   - Drainage and mountain valley winds
   - Dust devils, water spouts, and tornadoes
   - Development of fronts and cyclones
3. Macrometeorology
   - Atmospheric predictability
   - Long-range weather forecasting

   - Siting and exposure of meteorological stations
   - General circulation and climate modeling
4. Agricultural and forest meteorology
   - Prediction of surface temperatures and frost conditions
   - Soil temperature and moisture
   - Evapotranspiration and water budget
   - Energy balance of a plant cover
   - Carbon dioxide exchanges within the plant canopy
   - Temperature, humidity, and winds in the canopy
   - Protection of crops and shrubs from strong winds and frost
   - Wind erosion of soil and protective measures
   - Effects of acid rain and other pollutants on plants and trees
5. Urban planning and management
   - Prediction and abatement of ground fogs
   - Heating and cooling requirements
   - Wind loading and designing of structures
   - Wind sheltering and protective measures
   - Instituting air pollution control measures
   - Flow and dispersion around buildings
   - Prediction of road surface temperature and possible icing
6. Physical oceanography
   - Prediction of storm surges
   - Prediction of the sea state
   - Dynamics of the oceanic mixed layer
   - Movement of sea ice
   - Modeling large-scale oceanic circulations
   - Navigation
   - Radio transmission

Problems and Exercises

1. Compare and contrast the following terms:
(a) microscale and macroscale atmospheric processes and phenomena;
(b) micrometeorology and microclimatology;
(c) atmospheric boundary layer and the surface layer.

2. On a schematic of the lower atmosphere, including the tropopause, indicate the PBL and the surface layer during typical fair-weather (a) daytime convective and (b) nighttime stable conditions.

3. Discuss the following exchange processes between the earth and the atmosphere and the importance of boundary layer turbulence on them:
(a) sensible heat;
(b) water vapor;
(c) momentum.

Chapter 2 | Energy Budget Near the Surface

2.1 Energy Fluxes at an Ideal Surface

The flux of a property in a given direction is defined as its amount per unit time passing through a unit area normal to that direction. In this chapter, we will be concerned with fluxes of the various forms of heat energy at or near the surface. The SI units of energy flux are $\mathrm{J\,s^{-1}\,m^{-2}}$ or $\mathrm{W\,m^{-2}}$.

The 'ideal' surface considered here is relatively smooth, horizontal, homogeneous, extensive, and opaque to radiation. The energy budget of such a surface is considerably simplified in that only the vertical fluxes of energy need to be considered.

There are essentially four types of energy fluxes at an ideal surface, namely, the net radiation to or from the surface, the sensible (direct) and latent (indirect) heat fluxes to or from the atmosphere, and the heat flux into or out of the submedium (soil or water). The net radiative flux is a result of the radiation balance at the surface, which will be discussed in more detail in Chapter 3. During the daytime, it is usually dominated by the solar radiation and is almost always directed toward the surface, while at night the net radiation is much weaker and directed away from the surface. As a result, the surface warms up during the daytime, while it cools during the evening and night hours, especially under clear sky and undisturbed weather conditions.

The direct or sensible heat flux at and above the surface arises as a result of the difference in the temperatures of the surface and the air above. Actually, the temperature in the atmospheric surface layer varies continuously with height, with the magnitude of the vertical temperature gradient usually decreasing with height. In the immediate vicinity of the interface and within the so-called molecular sublayer, the primary mode of heat transfer in air is conduction, similar to that in solids. At distances beyond a few millimeters (the thickness of the molecular sublayer) from the interface, however, the primary mode of heat exchange becomes advection or convection involving air motions. The sensible heat flux is usually directed away from the surface during the daytime hours, when the surface is warmer than the air above, and vice versa during the evening