Part I

The Land-Atmospheric Boundary Layer System

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Seeking Interdisciplinary Connections

Crossing borders is always a challenge since it involves exploring unknown territory characterized by its own language, formulations, and means of expression. Even more important, crossing disciplines requires employing new ways of thinking and applying new approaches to the challenges of the investigation. However, all fears can be allayed if we are able to establish connections and build bridges. This book aims to create links among the disciplines of atmospheric dynamics and chemistry, surface processes, and the role of vegetation in the carbon cycle in order to identify their respective influences and feedbacks. As Figure 1.1 suggests, the aim of the book is to explore how and where these fields intersect.

We focus on the lower part of the atmosphere – the first kilometer in the troposphere – during daylight hours (diurnal) over land. During this part of the twenty-four hour cycle atmospheric motions are strongly influenced and controlled by surface and vegetation conditions, causing a very turbulent flow, in contrast to nighttime conditions normally characterized by a thermally stratified flow. In turn, atmospheric conditions such as wind, temperature, and humidity can also affect the physical properties of the land surface. The picture shown in Figure 1.2 is an illustration of how surface processes – in this particular case, vegetation – interact with the lower atmosphere to form and maintain clouds. A key process in this atmospheric region is the transport and exchange of energy, moisture, and momentum between the surface and the higher tropospheric regions. Scientists have traditionally studied the individual disciplines of atmospheric dynamics and chemistry, land characteristics, and the cycles of carbon or nitrogen compounds. As Figure 1.1 shows, our aim is to identify the relationships among these different disciplines. By retaining the essential components of each field, we can reach a better understanding and representation of their interactions. In other words, we move horizontally among the various subjects, while providing a solid basis for in-depth study of the specific fields. By linking them, we can take advantage of the well-established knowledge that we find in the textbooks of atmospheric dynamics, chemistry, vegetation, and soil and begin where they either end or have paid less attention to particular aspects of the lower-atmosphere phenomena. An even more important aspect is to challenge

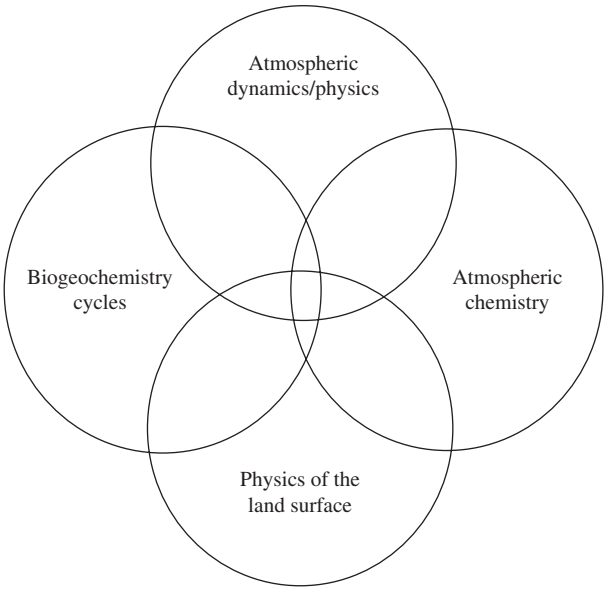

Figure 1.1. The interactions among the disciplines studied in this book occur at the interfaces and depend on soil and vegetation properties and atmospheric conditions including the presence of clouds and atmospheric compounds.

Figure 1.2. The atmospheric boundary layer is the region that extends from the grassland to the cloud top. Throughout this book, we study how this layer integrates atmospheric dynamics with chemistry, and how it acts as an integrative buffer between the vegetated surfaces and the free troposphere. Picture taken at Sterksel (The Netherlands) on 24 July 2010 at 14:47 local time.

the reader personally to find out how these interactions occur and how surface and atmospheric processes feed back on each other.

By selecting the lower part of the atmosphere, the atmospheric boundary layer (ABL), we locate ourselves in the region where the soil and vegetation have direct impacts on the atmosphere, and the atmospheric constituents are emitted and deposited. Extending vertically from the Earth's surface up to 3 to 4 kilometers and characterized by a strong diurnal variability, a very relevant advantage of centering our study in the ABL is that the ABL connects surface processes to the larger-scale processes that characterise the free troposphere. We therefore also aim to demonstrate how processes that interact at local scales (roughly less than 10 kilometers) are related to larger regional or climate scales.

Since our intention is to offer an interactive learning method, our motto throughout the book is *Learning through asking and answering questions*, or *theory meets practice*. On the basis of these propositions, we suggest exercises that start by posing questions such as the following:

- What processes control the maximum daily temperature?
- When and where do clouds form?
- What regulates evapotranspiration?
- Is the carbon dioxide concentration evolution fully controlled by plant assimilation?
- Is the maximum ozone concentration only determined by chemistry? And what is the specific role of the land cover conditions and atmospheric dynamics conditions?
- How do clouds influence the daily evolution of atmospheric moisture and ozone?

To answer these questions we propose to combine theory with hands-on exercises based on the use of the interactive software Chemistry Land-surface Atmosphere Soil Slab (CLASS). We hope and expect that by the end of the book, although most of these and other questions will have been answered, new ones will be posed. This happens because the degrees of freedom in the coupled atmosphere-land system and chemical-dynamic system increase as we improve our knowledge and the complexity of the representation of the system involved. The understanding we obtain gradually becomes a suitable platform to further in-depth study of the disciplines of interest.

1.1 Which Fields Are We Crossing?

Each sub-discipline listed in Figure 1.1 can occupy an entire scientific career. We have therefore decided to adopt a different approach and keep our goals within certain limits. We therefore need to frame our objectives for each discipline.

1.1.1 Atmospheric Dynamics

We limit our study to the atmospheric region ranging from the surface to maximum altitudes of 3 to 4 kilometers during daytime. The period covers the time from sunrise

to sunset where our modelling assumptions are valid. The influence of processes that have occurred the night before can also be taken into account, by prescribing different initial conditions in the early morning.

The atmospheric characteristics of the region under study are largely determined by its heat, momentum, and moisture budgets. At small scales (<1 km), atmospheric turbulence is the main driver of these budgets. Larger-scale meteorological systems, such as a sea breeze front passage, also play a key role in the variations of water vapour. Focusing on the small scales, our modeling framework takes advantage of the dominant role of turbulence, but without neglecting to include other main basic contributions related to ABL development. In short, the intense mixing of air driven by convective turbulence during the day yields vertically uniform values of the thermodynamic variables and atmospheric constituents; that is, variables are constant with height. This well-mixed property enables us to simplify the physical laws that govern the meteorological and atmospheric chemistry variables (the governing equations), but they still are representative of the main features of the diurnal variability within the lower troposphere.

Our main aim is limited to the diurnal boundary layer. However, the framework and knowledge acquired by understanding the dynamics of the ABL and the diurnal variability of the thermodynamic variables, such as the maximum temperature, the onset of clouds, and the evolution of pollutants, can be extrapolated to investigations that focus on larger spatial and temporal scales. To illustrate this, we can take the example of evaporation at the surface. Long-term evaporation trends depend on the diurnal variations in humidity at the surface. In our framework, we can study how evaporation varies under different temperature conditions (from a cold to a warm climate), solar radiation (from clear to dimming or overcast conditions), soil moisture content (from dry to wet), and wind characteristics (from still weather to high winds). The processes of learning and practice in this book thus provide a solid foundation for the exploration of other aspects of atmospheric dynamics.

The proposed studies on boundary layer clouds follow the idea of building up the complexity of the system, while maintaining the same modelling framework. In dealing with boundary layer clouds, our objectives are modest. Using the same modelling framework, we introduce the two main processes associated with the presence of boundary layer clouds: cooling by longwave radiation and saturation of the water vapour. To this aim and for the former process we propose to study a marine stratocumulus deck without accounting for phase changes. This enables us to understand typical features of the marine boundary layer and to show the challenges in representing stratocumulus in the atmosphere-ocean system. To introduce the role of condensation in the development of the boundary layer, we base our study on a simple representation of shallow cumuli (Figure 1.2). We here represent the essential processes such as the enhancement of vertical transport and the modifications in the sub – cloud layer characteristics. We quantify the impact of these processes

by performing sensitivity analyses on the key variables that determine cloud cover and cloud vertical velocity, and by calculating variations in the moisture budget. Note that in both stratocumulus and shallow cumulus we will not treat the impact of precipitation assuming that these sorts of clouds are relatively shallow (development in the first 3-4 km in the lower troposphere) compared to deep convective clouds.

1.1.2 Atmospheric Chemistry and Air Pollution

Atmospheric chemistry and dynamics are closely related, as shown in Figure 1.3 by an ABL characterized by high concentrations of chemical species above polluted areas. We select a chemistry mechanism that enables us to introduce the main atmospheric constituents that control ozone formation above rural and semi-rural regions. Basically, biogenic and nitrogen compounds are emitted into the ABL and mixed with chemical species that entrain from the free troposphere or are already present in the ABL. The mechanism comprises a wide range of chemical reactions characterized by different reaction rates (depending on radiation, temperature, or water vapour) and a wide range of characteristic time-scales. In addition to ozone, the system provides an excellent introduction to the study of the most characteristic cleansing component, OH, and its related radicals.

We can reproduce the essential features of ozone formation by using a limited chemical mechanism containing 22 reactants and 27 chemical species. We also include a basic chemical mechanism that reproduces the main features of nocturnal chemistry, enabling us to demonstrate the influence of night conditions on diurnal reactivity. The chemistry proposed here also enables us to study the non-linear effects on ozone formation caused by the different rates of nitrogen and biogenic emissions. This chemical mechanism can therefore act as a preliminary study of the more complex urban atmospheres, although for a complete and more exact study we should extend our chemical mechanisms. Closely related to this aspect, we include the possibility of adding the horizontal transport of a number of chemical species, which in turn enables us to determine how large-scale transport influences the local evolution of reactants. Our modelling framework thus provides a suitable basis for preliminary studies of atmospheric chemistry on regional or global scales. Finally the combination of atmospheric dynamics with chemistry aspects makes our modelling system very suitable to complement the interpretation of observations taken above the surface and in the ABL.

1.1.3 Land Processes

We aim to describe the basic features that control the interchange of energy and moisture between the vegetation and the soil. Inspired by the disciplines of soil and vegetation dynamics, we introduce relationships between the thermodynamic conditions of the soil and vegetation and relate them to atmospheric temperature,

Figure 1.3. Atmospheric boundary layer influenced by chemistry (gas and aerosol phases). The atmospheric boundary layer height is the interface between the brown and sky blue colors. Plumes emitted by three power stations characterized by higher buoyancy (higher temperature and moisture) cross this boundary layer height and penetrate in the inversion layer. This photo was taken near Cologne (Germany) at 14:06 local time (12:06 UTC). At this time the atmospheric boundary layer has fully developed.

moisture, and wind. We make an effort to limit the analysis to the essential properties that characterize soil and vegetation, to ensure the minimum requirements in reproducing the coupling between land and atmosphere in terms of (a) radiation characteristics and (b) soil-vegetation-atmosphere conditions. For this reason, we represent the radiative processes using a formulation that reproduces situations at different geographical locations and seasons of the year. The decrease in radiation intensity due to the presence of clouds is also included, making the model formulation suitable for supporting field observation campaigns and performing very complete sensitivity analyses of the land-atmosphere system.

The other two important components of the land-surface representation, vegetation and soil, are also taken into account. As a first stage, we propose a vegetation model that only regulates the exchange of heat, water, and momentum between canopy and atmosphere. Subsequently, in the section on biogeochemical cycles, we introduce a more elaborate plant physiology model that enables us simultaneously to take into account the exchange of water vapour and carbon dioxide at canopy level. Four representative types of vegetation are considered: grass, trees with needle and broad leaves, and maize. By so doing, we are able to study how different photosynthesis pathways respond to the atmosphere and surface processes. Regarding

the transfer of heat and moisture within the soil, we ensure minimal physical and biological requirements to guarantee reliability in heat, moisture, and carbon dioxide transport. As such, we consider that the land-surface representation is a suitable way to introduce the main feedbacks in the atmosphere-surface system.

1.1.4 Biogeochemical Cycles in the Land Processes

Within the carbon cycle, the soil-vegetation-atmosphere system plays an important role in the carbon budget. This budget is highly dependent on diurnal and seasonal conditions. In our aim to integrate different fields, we adopt a dynamic description of vegetation and soil that enables us to study the exchange of carbon dioxide and water vapour between the soil-vegetation and the atmosphere. The complexity of the photosynthesis and the stomatal aperture is described by a plant physiology model that reproduces the assimilation of carbon dioxide by different types of plants according to their photosynthesis pathways (C3 and C4). More importantly, our modelling framework incorporates the response of the plant to changes in the surface and atmosphere. The latter is represented by a stoma-aperture model that responds to environmental factors. The module is intended to serve as an introduction to more complex dynamic representations of vegetation, and to study the atmospheric feedbacks. The dynamic vegetation description presented here emphasizes the influence of atmospheric conditions, for instance, how temperature might influence photosynthesis or the opening of stomata and the role played by water vapour and other compounds emitted or absorbed by vegetation in atmospheric dynamics. Formulations of plant physiology processes of this sort can be extended to study other compounds in the carbon cycle processes (methane, biogenic compounds) and the nitrogen cycle. Emission and deposition of these compounds depend also on meteorologic factors such as radiation and the diurnal variability of temperature or specific moisture.

In a similar manner, we introduce the process of carbon dioxide soil respiration to account for plant respiration and microbial decomposition in the CO_2 budget. By combining CO_2 plant assimilation with soil respiration we are able to assess the flux of carbon dioxide into the land surface or the ABL. Better acquaintance with these conceptual biochemical formulations enables us to introduce the fields of atmospheric physics and plant physiology, and to relate them to each other.

1.2 Which Variables Do We Study?

Meteorological variables and atmospheric compounds play different roles in the soil-vegetation-atmosphere system. We first introduce the variables and describe their importance in connecting the different processes. We add them to the processes introduced in Figure 1.4 and put emphasis on their role in intersecting and interrelating different fields. A useful concept that is employed throughout the book is to study the behavior of each variable by quantifying its *budget*. Assuming that the

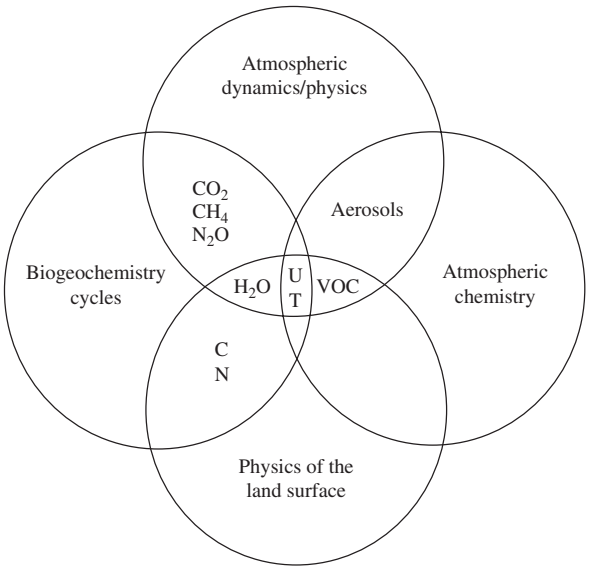

Figure 1.4. Representation of the various disciplines studied and the variables that link them.

ABL is a permeable box, each variable, meteorological or atmospheric compound, changes in time due to processes (1) at the surface, (2) within the ABL, (3) interacting with the layers aloft the ABL – the residual layer and free troposphere – and (4) due to lateral horizontal transport. By combining all these contributions, we obtain a budget of the various processes controlling the evolution of the variable on time, that is, the variable tendency. In other words, at each time we know which processes are important or irrelevant in the diurnal variation of the variable.

Let us start with a qualitative description of the variables and the processes that represent them.

- *Temperature:* This quantifies the evolution of the energy budget in the atmosphere and its exchange among the soil, vegetation, and the free troposphere. Diurnal changes in temperature influence cloud formation and atmospheric chemistry. Temperature variation with height determines the stability of the atmosphere, which controls the evolution and characteristics of the ABL. During the day, the warmer surface leads to differences in air density (and therefore temperature) with height, producing flow instabilities and consequently the creation of convection-driven turbulence, which takes the form of large energetic eddies that are very efficient in mixing the ABL. In other words, the vertical distribution of atmospheric compounds is independent of height in the ABL. For this reason the daytime ABL is known as the "well-mixed" layer or convective boundary layer. Throughout this book, we do not employ the variable temperature, but rather potential temperature (represented by θ and in degrees Kelvin, K). This variable is conserved under