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What's Next: Boundary Layer Prediction Methods (Chapter 5)

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Conceptual Boundary Layer: The Air Near Here

Chapter 5

What's Next: Boundary Layer Prediction Methods

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Abstract:

Boundary layer models are computer programs that solve equations to predict boundary layer dynamics. This chapter presents the basics of boundary layer modeling, including governing equations, computational grids, parameterizations, boundary conditions, and input data. The two major paradigms of boundary layer models - mesoscale and microscale models - are discussed in terms of resolved atmospheric processes, specifically boundary layer turbulence. Mesoscale models capture synoptic and regional scale weather features, but are too coarse to capture turbulence. Instead, they fully parameterize turbulent effects using planetary boundary layer (PBL) schemes. Microscale models, on the other hand, explicitly capture the energy containing scales of turbulent motion, and use large-eddy simulation (LES) to parameterize the unresolved scales. With this in mind, "what's next" for boundary layer prediction depends both on increases in computing power, which will allow for finer model resolution, and new scientific understanding, which will lead to better parameterizations for unresolved processes.

Key Words: Numerical weather prediction (NWP), turbulence, resolution, mesoscale, microscale, planetary boundary layer (PBL) schemes, large-eddy simulation (LES), Prognostic models, Diagnostic models

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Introduction: Why do we Need Models?

Simply put, boundary layer models are computer programs that solve equations to predict boundary layer dynamics. The wide variety of models available, the specifics of each model, and their suitability for different applications make for a rich and exciting field of study. This chapter will delve into the details of boundary layer models, providing an overview of how they work, how they're used, and what's next for boundary layer prediction.

Much of what we know about the atmospheric boundary layer comes from models. By taking advantage of the processing power of computers, we can predict atmospheric dynamics over a wide range of spatial and time scales, supplementing what we learn from observations. Although there are exceptions, observations are often limited to a small spatial extent, such as a point measurement or a vertical profile. On the other hand, models provide a four-dimensional picture of the boundary layer (three spatial dimensions plus time) and thus a more complete understanding of its dynamics.

With this in mind, we need models to predict how the boundary layer will affect our day-to-day lives. The weather forecast we check each morning comes from a model that predicts quantities like temperature, wind velocity, and precipitation. We also need models to predict boundary layer dynamics for safety or planning purposes. For example, where will the pollution from a new factory go? Or, how much power will a proposed wind farm generate?

From a scientific perspective, models are also needed to further improve our understanding of how the boundary layer works. Since we can't control the real atmosphere, models can be used to run experiments in a controlled environment. Such experiments can test cause-and-effect relationships or other theories. Imagine being able to change the land cover or incoming solar radiation and observe how atmospheric dynamics change -- models give us that ability.

Ultimately, the power of models is limited by two important caveats. First of all, model predictions are only as good as the model setup and input data. Choices made by the modeler can significantly affect the quality of the model output. Secondly, since no model can fully capture the dynamics of the real atmosphere, all models have inherent assumptions that limit their applicability. These caveats must be understood if models are to be used effectively, and will therefore guide the discussions in this chapter.

How do we Model the Boundary Layer?

Modeling Basics

Computer models of the boundary layer are built on five main components: governing equations, computational grids, parameterizations for unresolved effects, boundary conditions, and input data.

(1) **Governing equations** are mathematical relationships that describe the dynamics of the boundary layer. Most importantly, these include conservation of mass and momentum for the air in the boundary layer. Equations describing the conservation of temperature and moisture, as well as an equation of state to calculate the pressure, are also included. Optionally, evolution equations for other scalar quantities (such as chemical constituents or pollutants), can be used for specific applications.

(2) **Computational grids** represent the locations in space at which model quantities are calculated, known as "grid points" or "grid cells." Grid shapes vary from simple rectangles to more complex shapes that conform to the terrain or other features. One of the most important aspects of all boundary layer models is the "grid spacing," or the distance between each grid point. This quantity is related to the model's "resolution" and determines what physical quantities can be captured explicitly (that is, "resolved") by the model.

(3) **Parameterizations** are simplified mathematical relationships that help models account for processes which are not explicitly resolved on the model grid. For example, a turbulent eddy or a cloud that is smaller in scale than the model grid spacing is "unresolved" (see Figure 5.1), and must be accounted for using a parameterization. A large portion of boundary layer modeling research is directed toward improving model parameterizations for anything from turbulent mixing, to cloud processes, to surface fluxes.

(4) **Boundary conditions** are mathematical definitions of what is happening at the edges of the computational domain. At the surface, this includes fluxes of momentum, heat, and moisture, which are usually parameterized based on Monin-Obukhov Similarity Theory (MOST; as covered in chapter BLANK) in combination with a model of land surface effects. At the horizontal (or "lateral") edges of the domain, the boundary condition is often based on the results of a larger scale model or forecast. At the top of the domain, fluxes may also be specified, or "damping layers" may be used to prevent reflections or other undesired boundary effects.

(5) **Input data** is required to provide a starting point for model evolution. Similar to the lateral boundary conditions, input data is often derived from a larger scale model or forecast. Alternatively, observed atmospheric profiles or idealized conditions can be used to initialize the model for controlled experiments of boundary layer dynamics.

These building blocks are summarized in Figure 5.1, which shows a typical model grid with boundary conditions as well as resolved and unresolved processes. Knowing the building blocks, we can classify boundary layer models into two broad categories, called "prognostic" and "diagnostic" models (see Lundquist & Chow, 2012 for an extended discussion), which are introduced below.

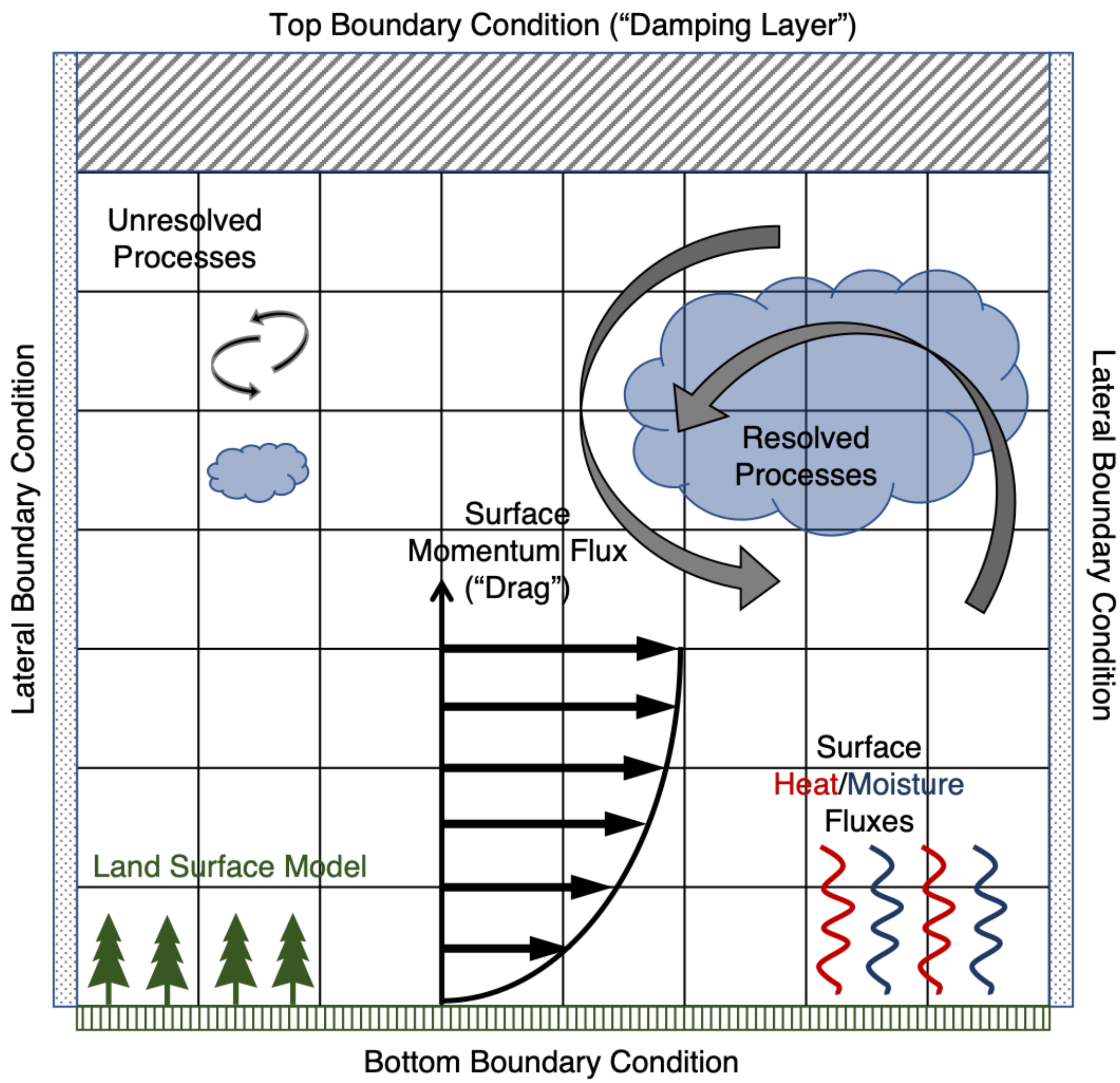

Figure 5.1: An example grid for a typical boundary layer model, depicting the boundary conditions as well as resolved and unresolved processes.
Credit: R. S. Arthur

Prognostic Models

Prognostic models solve the complete set of governing equations described in (1) above and rely on all five building blocks to model boundary layer dynamics. They are used in weather modeling and forecasting, as well as high-resolution computational fluid dynamics (CFD) studies. Due to the computational expense involved in solving prognostic equations, such models usually require the use of supercomputers in order to achieve reasonable run times.

Prognostic models numerically solve the conservation equations in order to capture the evolution of each model variable. To do so, the equations must be discretized such that they can be represented on the model's computational grid. In the most basic form of discretization used by boundary layer models, called "finite difference," gradients are approximated as simple differences, for example:

$$\frac{\partial u}{\partial x} \approx \frac{u(x + \Delta x) - u(x)}{\Delta x}.$$

Here, u is the model variable (such as velocity) and Δx is the grid spacing.

In the field of boundary layer modeling, there is a wide variety of methods available to discretize model equations. However, this is also an active area of research. The field of numerical methods is devoted to developing and testing new discretizations that are both accurate and computationally efficient. Interested readers are referred to Moin (2010) and Ferziger, et al. (2020) for more information on discretization methods and the numerical solution of equations.

Diagnostic Models

Since solving the complete set of governing equations described in (1) above can be challenging and/or computationally expensive, diagnostic models with simplified governing equations are preferable to prognostic models for situations in which speed and ease-of-use are desired. Such models can usually run on personal computers in seconds to minutes. However, these benefits are balanced by a loss in accuracy relative to prognostic models. Diagnostic models are used for a variety of applications including pollutant transport and dispersion studies, wind resource characterization, and the calculation of wind loads on buildings.

There are two flavors of diagnostic models, mass consistent models and linearized models. Mass consistent models (Sherman, 1978; Goodin, et al., 1980) extend the spatial extent of observations by first interpolating them over a given region and then enforcing conservation of mass. Linearized models (Jackson & Hunt, 1975; Hunt, et al., 1988a, 1988b) solve linear, steady state equations for flow over terrain by dividing the atmosphere into near-surface and above-surface layers with different turbulence parameterizations. Both types of diagnostic models require terrain data and surface roughness information, but otherwise simple initial and boundary conditions. Although diagnostic models are useful in many applications, the main focus of this chapter is on prognostic models, which are used for most state-of-the art forecasting and research applications.

Boundary Layer Modeling Paradigms

The most important parameter of any prognostic boundary layer model is the horizontal grid spacing. Smaller grid spacing, or finer resolution, allows more detailed atmospheric features to be captured on the computational grid. However, this results in additional computational expense as the number of grid points is increased. Due to the large range of scales of motion in the atmosphere – from global scale circulations to fine scale turbulence – the appropriate modeling approach must be chosen based on the scales of interest, balancing resolution with computational cost.

It's All About Turbulence

Two overarching paradigms of prognostic boundary layer models – "mesoscale" and "microscale" models - have been developed over time, and their use depends primarily on the scales of boundary layer turbulence. Atmospheric boundary layer turbulence can range in scale from roughly the boundary layer depth (~1 km) to the dissipative scales of turbulence (~1 mm). These scales represent the sizes of turbulent eddies, or coherent turbulent motions, that are found in the boundary layer. However, because resolving turbulence down to the dissipative scale, generally thought to be the finest scale of air motion in the atmosphere, is not practical given today's computing resources, at least some of the effects of turbulence must be parameterized. The extent to which turbulence is parameterized, in turn, determines which modeling paradigm applies.

Mesoscale models, which have horizontal grid spacings of roughly 1 km or larger, can capture mesoscale weather events such as fronts and sea breezes, as well as larger "synoptic" scale features such as high/low pressure systems. However, all turbulent effects must be parameterized because the largest scale of boundary layer turbulence is smaller than the grid spacing. In mesoscale models, turbulent effects are parameterized using planetary boundary layer (PBL) schemes, which will be discussed further below in the "Mesoscale Models" section.

Microscale models, often referred to as large-eddy simulation (LES) models, have horizontal grid spacings of roughly 100 m or smaller. Thus, LES models can resolve some portion of the scales of boundary layer turbulence, and indeed *must* capture the large (or so-called "energy containing") scales. In practice, this means that the grid scale must fall within the inertial subrange of turbulence discussed in Chapter BLANK.

However, even high-resolution LES models generally do not capture turbulence all the way down to the dissipative scale, and thus the effects of turbulence at scales smaller than the grid scale must still be parameterized. A wide variety of subgrid-scale models exist for this purpose, and will be discussed further in the "Microscale Models" section.

As a comparison of the two paradigms, imagine that you are modeling the atmospheric boundary layer over the entire continental United States for a weather forecast. A mesoscale model would be most appropriate because it would allow your model to capture the weather features of interest with limited computational expense. It would be very computationally expensive to use a horizontal grid spacing smaller than a few kilometers in this case. Alternatively, imagine that you are now modeling pollutant dispersion in a city. In this case, turbulent effects such as building wakes would be quite important, and a microscale LES model would be most appropriate. If the area of the city is only several kilometers square, it would be computationally feasible to use a grid spacing of roughly 10-100 m, providing adequate resolution for LES.

The careful reader may have noticed a gap in the modeling paradigms, between the lower limit of mesoscale grid spacing (~1 km) and the upper limit of microscale grid spacing (~100 m). This gap, known as the *terra incognita* or "gray zone" (Wyngaard, 2004) is where model grid scales are nearly the same as the larger scales of boundary layer turbulence (~1 km). In this region, neither PBL schemes nor LES turbulence models are technically appropriate. If a PBL scheme is used, some turbulent scales will be double counted (i.e., both resolved and parameterized). Furthermore an LES closure scheme cannot be used because the energy containing scales of turbulence will generally not be resolved. In both cases, turbulent effects will be parameterized incorrectly. For these reasons, boundary layer modeling in the gray zone is generally avoided. However, improving turbulence treatment in the gray zone is also an active area of research (Chow, et al., 2019).

How do we Parameterize Turbulence?

The Navier-Stokes equations describe conservation of momentum and mass for the air in the atmospheric boundary layer. More specifically, the primary governing equations in most boundary layer models are an averaged form of these equations known as the Reynolds Averaged Navier-Stokes (RANS) equations, which describe the mean flow. Due to the inherent nonlinearity of the Navier-Stokes equations, a term appears in the RANS equations containing unknown (that is, unresolved) turbulent fluctuations, referred to as the subgrid-scale (SGS) turbulent stress,

$$\tau_{ij,SGS} = -\rho\overline{u_i'u_j'},$$

where ρ is the density of air, u is the velocity, the overbar denotes Reynolds averaging, the prime denotes departures from the Reynolds average, and index notation is used with $i, j = 1,2,3$ (see for example Pope, 2000; Kundu, et al., 2012). The difficulty in calculating this term is known as the "turbulence closure problem," which was covered previously in Chapter BLANK.

In boundary layer models, the unknown subgrid-scale turbulent stress term must be parameterized using information that is known (that is, explicitly resolved) in the model. Since the subgrid-scale turbulent stress can be thought of as a turbulent flux of momentum, it is generally parameterized as a diffusive flux acting on the mean gradient, with an elevated diffusion coefficient known as the "eddy viscosity." Thus,

$$\tau_{ij,SGS} = K_M\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) = 2K_M\bar{S}_{ij},$$

where K_M is the eddy viscosity and $S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$ is the strain rate. This parameterization assumes that in an average sense, turbulent eddies create fluxes of momentum that can be modeled as diffusive fluxes. An analogous parameterization is used for turbulent fluxes of scalars such as heat and moisture, with the turbulent diffusion coefficient known as the eddy diffusivity K_H.

Ultimately, turbulence parameterizations depend on accurate approximation of the eddy viscosity and eddy diffusivity, and many techniques have been developed for this purpose. In fact, the appropriate use of mesoscale and microscale modeling paradigms depends on the appropriate calculation of these terms. While mesoscale models typically use PBL schemes, which parameterize vertical turbulent fluxes only, microscale LES models typically use three-dimensional closure schemes, which parameterize turbulent fluxes in all directions. These two approaches will be explored in greater detail in the sections that follow.

Horizontal Grid Refinement

Because the horizontal grid spacing is such a critical factor in boundary layer model performance, it can be useful to refine the computational grid in the region(s) of interest. Refining the grid in particular areas, rather than over the entire domain, provides a large savings in computational effort. Several techniques for controlled grid refinement are common in boundary layer modeling.

The first, known as grid nesting, involves placing successively smaller and finer "child" grids within larger and coarser "parent grids" (see Figure 5.2). The parent grid then supplies initial and boundary conditions to the child grid via interpolation. This technique has been adopted by many mesoscale weather models and forecast systems, including the commonly-used Weather Research and Forecasting (WRF) model (Skamarock, et al., 2019).

Grid nesting facilitates "multiscale" boundary layer modeling, in which a single model can transition seamlessly from the mesoscale to the microscale modeling paradigm as the grid is refined. Thus, depending on the grid scale, the appropriate turbulence treatment can be applied. Multiscale boundary layer modeling is an active area of research and will be used as an example below in the "Microscale modeling" section.

Other techniques for grid refinement include unstructured grids, as well as adaptive mesh refinement (AMR). Unstructured grids use irregularly shaped grid cells that can be refined in the region(s) of interest. Such grids are becoming common in global scale weather and climate models such as the recently developed Model for Prediction Across Scales (MPAS; Skamarock, et al., 2012). Furthermore, while most boundary layer models use static grids that do not change in time, adaptive mesh refinement allows the grid to be refined dynamically based on given criteria (e.g., van Hooft, et al., 2018). For example, the model could refine the grid in regions where sharp velocity or temperature gradients are detected, thus focusing computational expense in the areas where it is most needed.

Mesoscale Models

In the recent past, mesoscale models were the primary tools used for numerical weather prediction (NWP), especially continental and regional scale weather forecasting. However, as computing power increases, global models with mesoscale grids are becoming more common. PBL schemes in mesoscale models (and global models on mesoscale grids) are usually responsible not only for vertical mixing within the PBL, but for all vertical mixing. In fact, this separation of responsibility between the horizontal advection numerics and vertical PBL mixing can be thought of as a primary distinction between mesoscale and microscale models. Some schemes are also responsible for shallow clouds, which are intimately tied to the boundary layer.

The lower boundary condition for the PBL in a mesoscale model is provided by a land surface model (LSM). Although the details of LSMs are beyond the scope of this chapter, it is important to remember that they strongly constrain the PBL simulation and that they contain many physical parameters whose values are difficult to determine on large scales. Soil moisture is one such important variable.

Planetary Boundary Layer Schemes

A useful distinction is made between stable and convective boundary layers when designing parameterization schemes. Stable boundary layers are usually handled by local eddy diffusion equations similar to (above) but in the vertical direction only. The flux of a variable is represented as

$$w'\psi' = K_{M,H}\frac{\partial\psi}{\partial z}$$

Where $K_{M,H}$ are the eddy diffusivities for momentum and heat, and ψ represents any state variable. This reflects the physical reality that scales of motion in stable boundary layers are small. Performance in stable boundary layers depends on the details of the formulation, especially length scales and stability functions. The eddy diffusivities are commonly formulated as the product of a length scale l and a function of the local stability represented by the Richardson number Ri, as

$$K \simeq lf(Ri).$$

Most schemes behave well in weakly-stable boundary layers with continuous turbulence. Large differences in scheme performance arise when the boundary layer is moderately or strongly stable and turbulence may be intermittent. This is a fundamental unsolved problem. The PBL scheme may also be distorted in order to compensate for errors in other parts of the model, particularly the land surface, or to avoid numerical instability and model crashes. Usually this distortion takes the form of increasing mixing beyond what would be observed in a similar real situation.

Convective boundary layers have much larger scales of motion and cannot be fully represented by local eddy diffusion. Several methods have been developed to represent the large scale or non-local motions. One approach is to ignore them, which can be a reasonable approximation, but results in a statically unstable (super-adiabatic) buoyancy profile throughout the boundary layer. The next level of improvement is to add an artificial non-local term to the eddy diffusion equation. A more physical approach is called Eddy Diffusivity Mass Flux (EDMF; Siebesma et al. 2007), which uses one or more explicit updrafts to carry the non-local fluxes,

$$w'\psi' = K_{M,H}\frac{\partial \psi}{\partial z} + M(\psi_u - \psi),$$

where M is the updraft mass flux and ψ_u is the value of the state variable in the updraft. The updrafts are modeled as entraining plumes. Eddy diffusion is still used to model the small-scale fluxes. At the time of writing, most operational NWP models use some form of EDMF scheme, and several such schemes are available in WRF (Angevine, et al., 2018).

The boundary layer is rarely in a purely stable or purely convective equilibrium state. Most of the time over most of the globe, both the depth of the boundary layer and the intensity of turbulence are changing. A common occurrence of such changes is between night and morning, known as the morning transition, and between midday and evening, known as the afternoon or evening transition (Angevine, et al., 2020). Transitions also occur as air passes over coastlines, and internal boundary layers (multiple layers with different turbulence intensities and different histories) are common. Boundary layer schemes need to simulate these transitions and layers. For this reason, schemes that do not assume a specific profile of turbulence, but can react to the vertical buoyancy distribution presented by the rest of the model, are preferred.

Simulating a Frontal Passage

As an illustration of a mesoscale boundary layer modeling application, WRF is used to simulate a cold front passing through the central United States. The frontal passage can be considered a stability transition, which, as noted above, is an important test case for mesoscale modeling. This example is based on work by Arthur, et al. (2020), and readers are referred to their paper for additional details of the study. The model is set up in a 3-domain nested configuration with horizontal resolutions of roughly 18 km, 6 km, and 1 km (see Figure 5.2). Reanalysis data from the North American Mesoscale (NAM) Forecast System is used for initial and boundary conditions on the coarsest domain, and information is subsequently passed down to finer nests at their lateral boundaries. WRF has many PBL schemes available, and the Mellor-Yamada-Janjic (MYJ) scheme is used in this case. The WRF model also parameterizes atmospheric processes such as solar radiation, land surface dynamics, and surface fluxes.

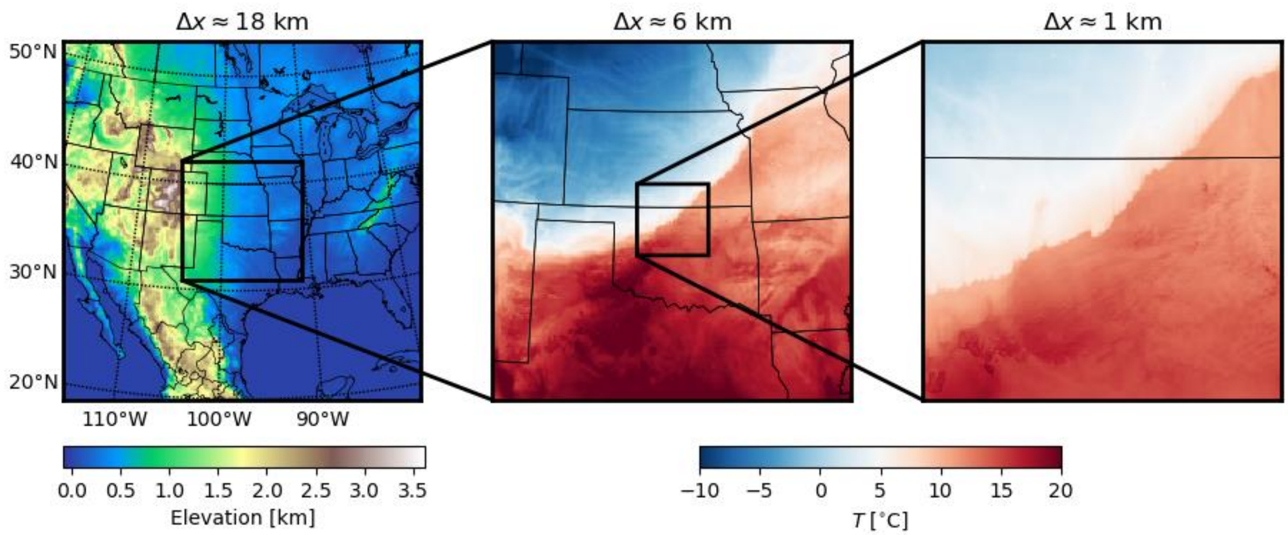

Figure 5.2: Mesoscale WRF simulation of a cold front passing through the central United States. Three nested domains with grid resolutions of roughly 18 km, 6 km, and 1 km are used. See Figure 5.3 in the next section for an extension of this example to the microscale.
Credit: Figure by R. S. Arthur, data from Arthur, et al. (2020)

As seen in Figure 5.2, the front comes in from the northwest with an accompanying change in temperature of nearly 30^{o} C. Although it is not shown in the figure, a large increase in the near-surface velocity is also associated with the front. Because this region of the United States has experienced a large amount of wind energy development, the cold front interacts with wind farms as it passes through, modulating their power output. At the end of the Microscale Modeling section, this example will be continued with a large-eddy simulation of the cold front moving through an actual wind farm. Stay tuned…

Microscale Models

Large-eddy simulation is used for fine-resolution modeling of the boundary layer, focusing on microscale, turbulent dynamics. Due to its relatively large computational demands, LES is not typically used for forecasting, although this is an emerging field of research (Bauweraerts & Meyers, 2019). This section will explore the fundamentals of subgrid-scale turbulence schemes, followed by additional details about grid resolution and surface turbulence treatment for LES models.

Subgrid-scale Turbulence Schemes

The original and most basic subgrid-scale scheme was developed by Smagorinsky (1963) and is still used today. Conceptually, the Smagorinsky scheme calculates the eddy viscosity K_M, which has units of length squared per time, by multiplying a length scale by a velocity scale. Because the computational grid determines the scale of the resolved flow in the model, the length scale is chosen as the grid scale $\Delta = (\Delta x \Delta y \Delta z)^{1/3}$ multiplied by a constant scaling coefficient c_S, which is approximately 0.2. The velocity scale is given by this length scale, $c_S\Delta$, multiplied by the magnitude of the resolved strain rate $\bar{S}_{ij}$. Thus, the eddy viscosity is calculated as

$$K_M = (c_S\Delta)^2 |\bar{S}_{ij}|.$$

Once the eddy viscosity is calculated, it can be used to estimate the unresolved turbulent stress $\tau_{ij,SGS}$.

A similar turbulence scheme based on subgrid-scale turbulence kinetic energy (TKE) E_{SGS} was also developed by Deardorff (1980). In this scheme, the length scale Δ remains the same, although a different constant coefficient $c_E = 0.1$ is used. The velocity scale is then taken as the square root of the subgrid-scale TKE such that the eddy viscosity is calculated as

$$K_M = c_E \Delta \sqrt{E_{SGS}}.$$

When this scheme is used, a separate prognostic equation for the subgrid-scale TKE must be integrated by the model, adding some computational expense.

In LES, the grid can be conceptualized as a mathematical filter because it "filters out" motions that are smaller in scale than the grid spacing. Indeed, the computational grid in LES is sometimes referred to as an implicit filter. Building on this idea, explicit filtering can also be leveraged to gain more information about the resolved turbulence in a boundary layer model. By explicitly filtering the resolved velocity at a resolution that is coarser than the grid spacing, the turbulent stresses that occur in the range of scales between this "test filter" scale and the grid filter scale can be quantified. This is the basis for many advanced subgrid-scale turbulence schemes. The mathematical details of these schemes are beyond the scope of this chapter; however, interested readers are referred to Kirkil, et al. (2012) for continued discussion.

While the discussion of grid resolution thus far has been focused on horizontal grid spacing (that is, Δx and Δy), vertical grid spacing Δz is also important, especially in LES. This is because turbulent eddies in the atmospheric boundary layer are often constrained in the vertical direction, either by the presence of the ground surface or by vertical temperature gradients. To illustrate this idea, imagine a convectively unstable boundary layer wherein the only vertical constraint on turbulent eddies is the depth of the boundary layer itself. In this case, a relatively large vertical grid spacing could still resolve the energy containing scales of turbulence. Alternatively, imagine a stable boundary layer where vertical motions are constrained by a temperature inversion. In this case, a much smaller vertical grid spacing would be necessary to resolve the largest turbulent eddies. Due to this more stringent resolution requirement, the modeling of stable boundary layers is generally more computationally expensive than the modeling of unstable boundary layers (see, e.g., Wurps, et al., 2020).

A similar restriction in the vertical length scales of turbulent eddies occurs near the ground surface, where turbulent motions are restricted by the ground itself, as well as by roughness features such as trees and buildings. This results in increased resolution requirements near the surface for accurate LES. A large portion of boundary layer modeling research is devoted to improving surface turbulence treatments, generally referred to as "surface layer models." An extended discussion of surface layer modeling can be found in Brasseur & Wei (2010).

The most common surface layer model is based on MOST, which is used in nearly all boundary layer modeling applications. It should be noted, however, that MOST includes assumptions of spatial homogeneity and steady state conditions, which are not necessarily present in fine-resolution microscale boundary layer models. If these assumptions are violated, or if near-surface vertical resolution is not adequate, errors can be introduced into the model via the subgrid-scale turbulence scheme, which will predict incorrect turbulent flux values.

Additional surface-layer treatments can alleviate these errors. For example, the near-surface eddy viscosity can be constrained to follow similarity theory, therefore overriding the value calculated by the subgrid-scale model near the surface (e.g., Mason & Thomson, 1992). The eddy viscosity can then be blended with the LES solution aloft. Furthermore, the effects of vegetation on turbulence can be captured using “canopy models,” which introduce an additional drag term to the momentum equations and/or additional dynamics in the subgrid-scale turbulence scheme (see Patton & Finnigan, 2012).

Putting it All Together: Multiscale Modeling

As a culmination of the topics covered in this chapter, we return to our example simulation of a cold front moving through the central United States. Now, using LES, we are able to simulate the interaction of the cold front with an operational wind farm (see Figure 5.3). This microscale simulation uses 10 m grid spacing with a TKE-based subgrid turbulence scheme and represents flow interaction with wind turbines using an actuator disk model. The simulation is run in WRF with a multiscale setup: using grid nesting, it is embedded within the mesoscale simulation presented previously. Thus, the boundary layer dynamics are seamlessly downscaled to the region of interest and turbulence is parameterized using the appropriate paradigm for each nested grid.

While the mesoscale simulation captured the regional-scale features of the cold front, this microscale simulation resolves fine-scale turbulent structures, including individual turbine wakes (deep purple colors in Figure 5.3). Before the frontal passage, the flow is relatively quiescent with wind speeds less than 5 m/s at turbine hub height. However, the passage of the cold front is associated with a nearly 10 m/s increase in hub-height wind speeds and much higher turbulence intensity. The increase in wind speed brings the turbines from a relatively low power production state to near their rated (that is, maximum) power production in a matter of minutes. The wakes can also affect power output by reducing the wind speed felt by downstream turbines. If wind plant operators can model or predict such abrupt changes in wind speed and wake dynamics, they can more effectively manage the wind farm's performance.

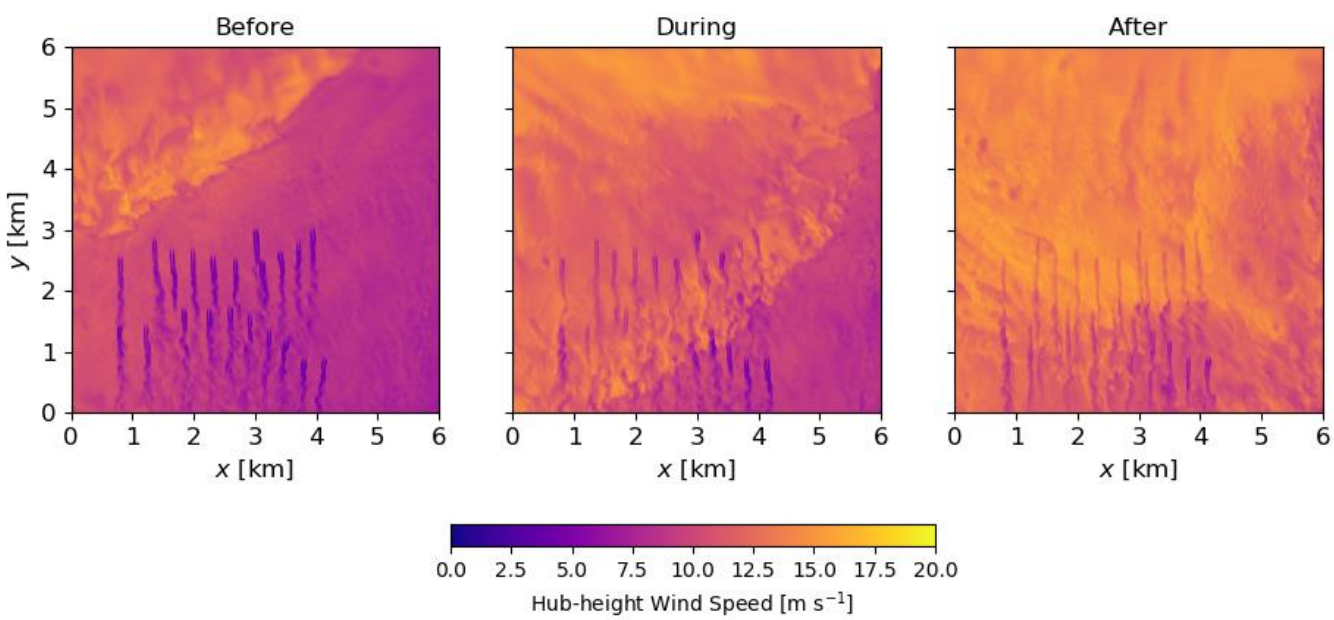

Figure 5.3: Microscale WRF simulation of a cold front passing through an operational wind farm. The simulation has 10 m grid spacing and is forced by the mesoscale simulation presented in Figure 5.2 using a multiscale WRF setup with grid nesting. Results are shown before, during, and after the frontal passage.
Credit: Figure by R. S. Arthur, data from Arthur, et al. (2020)

Summary and future outlook

This chapter has covered the basics of boundary layer modeling and prediction, including governing equations, computational grids, parameterizations, boundary conditions, and input data. As a major takeaway, consider the distinction between the mesoscale and microscale modeling paradigms. While mesoscale models resolve synoptic and regional scale weather features, they must parameterize turbulent effects using planetary boundary layer (PBL) schemes. On the other hand, microscale models resolve the energy containing scales of turbulence using large-eddy simulation (LES), bust must parameterize smaller scale dissipative effects. The appropriate use of boundary layer models depends on the appropriate turbulence treatment. In summary, it's all about turbulence!

So, what's next for boundary layer modeling and prediction? Because models depend on computers, model performance will always be linked to computing technology. As computers get more powerful and efficient, models will run faster and at finer resolution. This will enable exciting advances in global-scale modeling, multiscale modeling, LES forecasting, and improved understanding of boundary layer phenomena. However, computing power is only part of the story. As this chapter has emphasized, boundary layer models can only be as powerful as their underlying assumptions allow. In particular, model performance depends on the use of appropriate governing equations, boundary conditions, and model inputs. Furthermore, accurate parameterizations must be used for unresolved processes, such as turbulence, clouds, and land-surface interactions. The success of future models will depend on improved theories for how these processes affect the boundary layer at different scales. In this way, boundary layer modeling is intrinsically tied to other aspects of boundary layer science.

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