Summary

The wind power capacity is expected to expand rapidly in the near future. The growing demand of industrial applications, especially in designing and optimizing modern wind farms, urgently requires the accurate prediction of wind farm performance under realistic weather conditions. The state-of-the-art wind farm modeling and simulations primarily assume steady wind conditions. However, the validity of this assumption degrades as modern wind farms spans tens of kilometers in space, whose performance is increasingly affected by the variation of wind conditions.

In this thesis, we shift our focus from steady-state scenarios to dynamic wind conditions. The dynamic change of local weather conditions is mainly driven by the mesoscale motions of atmosphere, which can span up from tens to hundreds of kilometers in space and last for more than 15 minutes to several hours in time. These atmospheric motions continuously modify atmospheric boundary layer flow, leading to sustained wind speed changes for wind farms. Distinguished from wind speed fluctuations driven by boundary layer turbulence, which last for seconds to minutes, the mesoscale variations are much slower and often overlooked in wind farm simulations. Understanding the impact of low-frequency wind speed variations necessities proper representation in both simulations and modeling of wind farm flow.

In Chapter 1, we developed a method to accurately represent dynamic wind speed changes in large-eddy simulations of wind farms, which allows a detailed investigation of their effects on wind farm performance under well-controlled conditions. The wake flows of wind turbines in dynamic inflow conditions significantly differ from that in steady case, which impact the power output of downstream turbines inside the wind farm. Whereas an idealized turbulent boundary layer is considered in Chapter 1, we extended the method to realistic atmospheric boundary layers in Chapter 2. In realistic scenarios, the atmospheric boundary layer is affected by both Coriolis effect and a capping layer above it, where the stable stratification limits the growth of boundary layer. Above the capping layer, the Coriolis force in free atmosphere is balanced by large-scale pressure gradient, resulting the geostrophic wind. The response of boundary layer flow under dynamic geostrophic wind speed exhibits complex physics due to the interaction of large-scale pressure gradient, Coriolis force and boundary layer turbulence. We demonstrated that the atmospheric boundary layer dynamics under time-varying geostrophic wind speed can be captured by a reduced-order approach, where the turbulence is modeled from a steady-state solution. It helps advance the understanding of dynamic inflow conditions for wind farm operations.

The focus of the thesis is shifted to the power correlation in wind farms for following chapters. In Chapter 3, we investigated the coherence of turbine power output inside a wind farm using large-eddy simulations. We examined the applicability of random sweeping models for predicting the coherence between consecutive wind turbines, and investigated the impact of turbine operation which is not considered in the original model. Specifically, the above-rated turbines introduce dynamic wake flows, which alter the coherence pattern that is not captured by random sweeping models. The effect of turbine wakes on the power coherence was investigated in detail in Chapter 4, where a wake-corrected random sweeping model was developed to incorporate the impact of turbine operations through induction factor. Large-eddy simulation results confirmed the model's validity for a wide range of wind farm scenarios.

Whereas Chapter 3 and 4 consider steady inflow conditions, the effect of dynamic wind conditions is incorporated in the coherence models introduced in Chapter 5. This new dynamic sweeping model combines the mesoscale variations, boundary layer turbulence and wake-induced coherence losses in one formulation. Compared with simulation results and field observations, this model is shown to be able to reproduce spectral identity of wind farm power fluctuations, which provides significant physical insights in the spectral behavior of aggregate power output of wind farms.

The Conclusions and Outlook summarizes the main results of all the chapters, and points out future perspectives and potentials that are beyond the scope of this thesis. With a deeper understanding of wind farm flow physics under dynamic wind and wake effects, this thesis provides perspectives in the simulations and modeling of wind farms towards more realistic scenarios. This will benefit the design, optimization and operation of modern wind farms.