# Chapter 1: Progress in Understanding and Parameterizing Fast Physics in Large-Scale Atmospheric Models

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February 9, 2023

**Abstract**

This introductory chapter discusses the atmospheric subgrid processes - collectively called "fast 11 physics" or "fast processes", and their parameterizations in large scale atmospheric models. It 12 presents a brief historical progression of the parameterization of fast processes in numerical 13 models. Despite great efforts and notable advances in understanding, progress in improving fast 14 physics parameterizations has been frustratingly slow, the underlying reasons for which are 15 explored. To guide readers, this chapter describes the main objectives and scope of this book and 16 summarizes each chapter.

# Chapter 1: Progress in Understanding and Parameterizing Fast Physics in Large- Scale Atmospheric Models

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## Abstract

This introductory chapter discusses the atmospheric subgrid processes ─ collectively called "fast physics" or "fast processes", and their parameterizations in large scale atmospheric models. It presents a brief historical progression of the parameterization of fast processes in numerical models. Despite great efforts and notable advances in understanding, progress in improving fast physics parameterizations has been frustratingly slow, the underlying reasons for which are explored. To guide readers, this chapter describes the main objectives and scope of this book and summarizes each chapter.


## 1.1 Fast physics and progress of parameterization development

Large scale atmospheric models are integral components of weather and climate models. Ongoing developments in high-resolution modeling (i.e., global storm-resolving models (GSRMs, Stevens et al., 2019); Energy Exascale Earth System Model (E3SM, Rasch et al., 2019); large-eddy simulations (LES, Gustafson et al., 2020) have resulted in ultra-high resolution numerical simulations of atmospheric systems. Despite these advancements, coarser resolution large scale models remain our main modeling capability for future climate predictions. Many atmospheric processes and phenomena that influence Earth's weather and climate occur at spatiotemporal scales that are too small to be resolved in these large-scale atmospheric models and must be parameterized ─ approximately represented by the variables that can be resolved by the model grids. In this book, we refer to this array of parameterized subgrid processes and phenomena collectively as "fast physics" or "fast processes" for convenience, including radiative transfer, aerosol/cloud physics, convection, boundary layer processes, gravity wave, and land-atmosphere interactions.

While early parameterizations of fast physics used simple and often empirical or ad hoc relationships (e.g., the Kessler bulk paramterization for representing cloud microphysical processes, Kessler, 1969), later parameterization development has become concerned with building conceptual models with increasingly detailed physical processes by leveraging theoretical analysis, observations, and/or detailed process modeling studies.

Furthermore, parallel to the continuing improvement/development of parameterizations for individual fast processes, there has been growing interest in and studies on understanding interactions/couplings among different processes. Significant progress has been made and several promising approaches have emerged since late 1900s and early 2000s. Figure 1 illustrates the approximate timelines in developing fast physis parameterizations in context of the conventional parameterizations that target individual processes and unifying efforts that addresses process interactions.

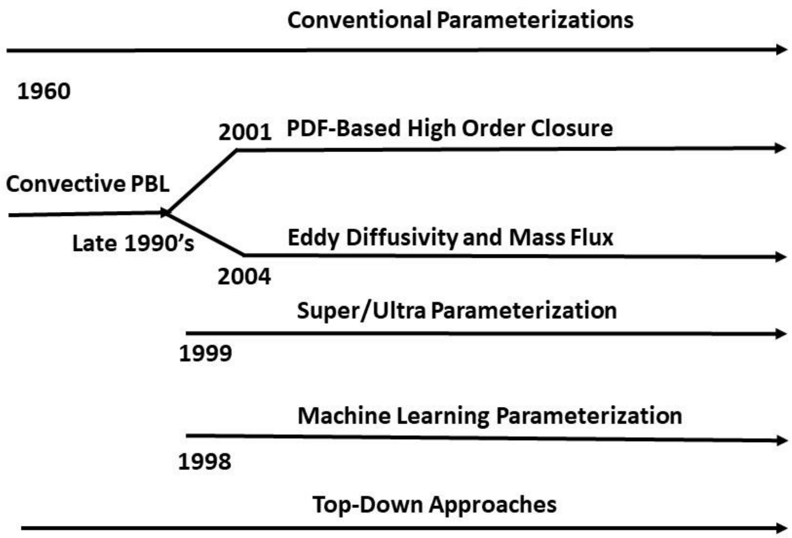


Figure 1. Schematic of the approximate timelines of development of fast physics parameterizations. Conventional parameterizations are focused on individual fast processes. The four lines of unifying efforts (PDF-based High Order Closure, Eddy Diffusivity and Mass Flux, Super/Ultra Parameterization, and Machine Learning Parameterization) aim to unify the representation of more than two physical processes. Top-Down Approaches borrow holistic ideas that have been scattered in various disciplines (e.g., nonlinear systems dynamics, statistical physics, information theory, self-organization, networks, and pattern formation).

Despite remarkable efforts and increasing recognition of the importance of these fast processes over the past few decades; progress remains frustratingly slow in improving their representation in models. As a result, their impact on future climate predictions remain poorly understood and highly uncertain. The slow progress is perhaps best attested by the historical lack of change in the ranges of climate sensitivity across models from the celebrated 1979 U.S. National Research Council report (Charney et al. 1979) to the latest ($6^{th}$) Coupled Model Intercomparison Project (CMIP6) results used in the Intergovernmental Panel on Climate Change (IPCC) report (Fig. 2). Deficient fast physics parameterizations, and especially those related to clouds, have been thought to be primarily responsible for the stubborn large spread of model climate sensitivity (Meahle et al., 2020; Zelinka et al., 2020). Aerosol climate forcing in climate models has been fraught with similarly unchanged uncertainty (see more in Chapter 3 of this book).

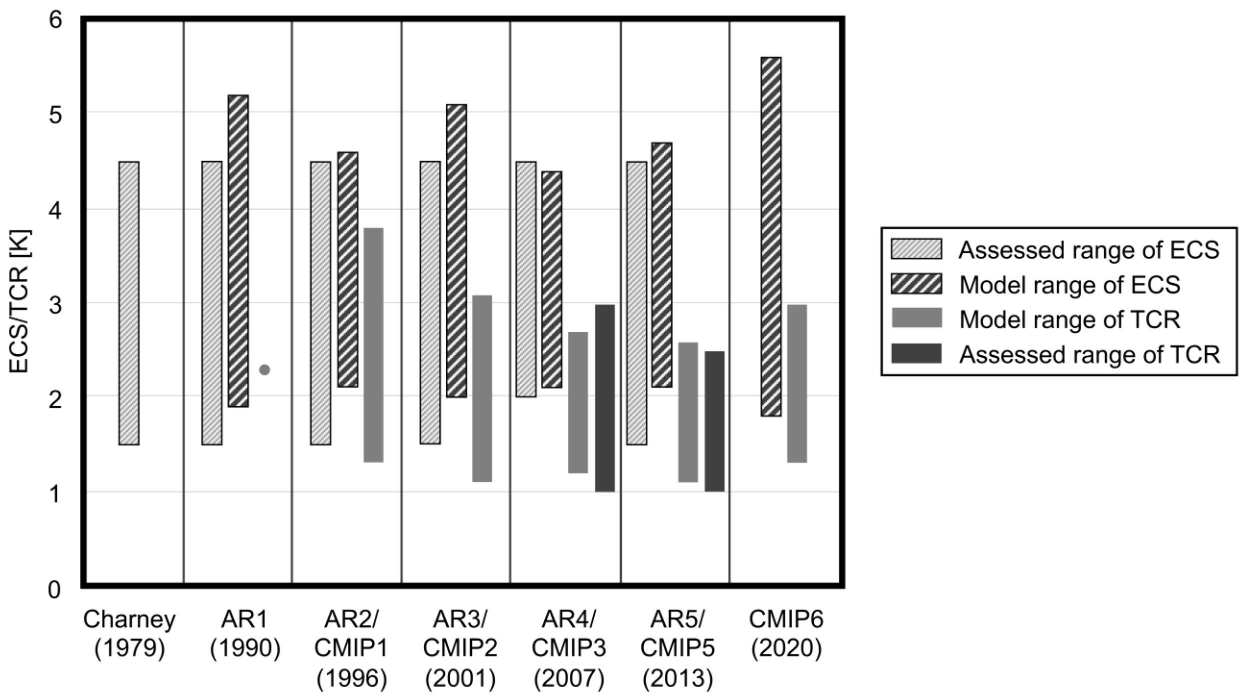


Figure 2. Historical values of equilibrium climate sensitivity (ECS) and transient climate response( TCR). Figure is modified from Fig. 1 of Meahle et al. (2020) which can be consulted for details on the data sources and definitions.

The slow progress can be attributed to two overarching types of complexities (also see Randall, 2013; Jakob, 2010). The first lies in the “4M-2N complexities” inherently accompanying the atmosphere and associated physical processes (Fig. 3). Briefly, fast processes and especially those cloud-related ones involve *multibody* (sub)systems with numerous particles of different sizes and shapes, in which multiple physical processes (*multiphysics*) occur over a wide range of spatiotemporal scales (*multiscale*) and interact with one another, and manifest themselves in a variety of cloud types such as cumulus and stratiform clouds (*multitype*). The equations describing these processes are often highly *non-linear*, and exhibit *non-Gaussian* statistics (Lovejoy and Schertzer, 2010).

The other inherent complexity lies with that model development involves an iterative cycle of developing parameterizations, implementing and evaluating parameterizations against observations to identify potential parameterization deficiencies and further improvement. This iterative procedure calls for an organic integration of the key components involved ranging from modeling to measurements, which in turn demands effective coordination of expertise in distinct areas that have proven to be extremely challenging. However, effective coordination and collaboration across different disciplines and institutions are not trivial, and such an “operational complexity” adds another layer of technological and social challenges in virtually every step of model development. The issue will become more acute as the field is moving toward more emphasis on processes interactions with ever increasing data volumes and model resolutions. To echo Jacob (2010), “ … acceleration in model development can only be achieved by significantly strengthening these weak links through additional research and better coordination across existing programs.”

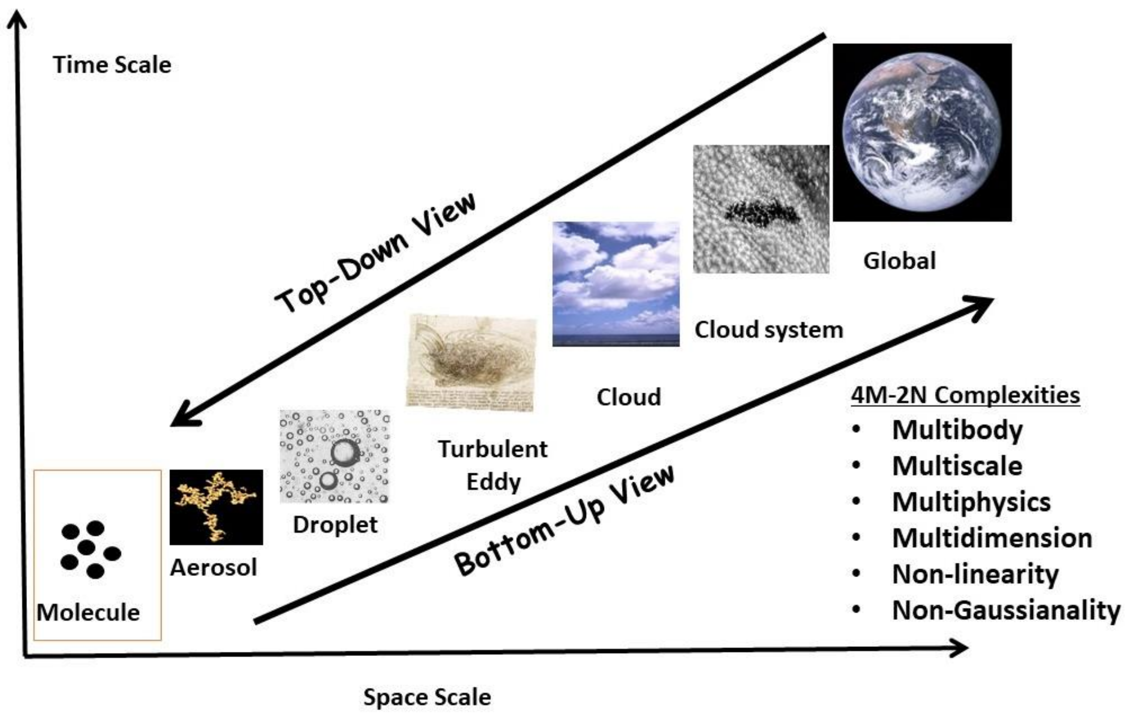


Figure 3. Schematic to illustrate the atmospheric scale hierarchy and involved "4M-2N complexities". Together with the "operational complexity" discussed in the text, these science complexities have posed and will continue to pose challenges to model development in general and fast physics parameterizations in particular.

## 1.2 Objectives and scope of the book

The objectives of this book are three-fold. First, to survey advances in understanding of key fast processes and their parameterization developments (Part I). In particular, Part II of this book is uniquely devoted to unifying efforts. Second, unlike most review articles or the book by Stensrud (2007) on fast physics parameterizations, this book includes discussions on measurement techniques and studies that use observations for model evaluation and thus covers approaches to addressing the weak link in the model development loop. Third, by surveying the recent advances in key areas, we hope to reveal new challenges, opportunities, and directions for future research.

It is worth noting that the related literature is enormous and that the selection of the material in this text is non-exhaustive and likely biased to the authors' own research interests. On the other hand, books focusing on fast physics parameterizations are rare; the only one we are aware of is Stensrud (2007), which is primarily on conventional parameterizations of individual fast processes in numerical weather prediction (NWP) models. Bringing together modeling and measurements with a common goal of parameterization development and evaluation, and including unifying efforts are unique to this book.

### 1.3 Book structure and summary of chapters

Fast physics in large scale atmospheric models involves multiple processes that occur over a wide range of spatiotemporal scales. Progress has been made on many fronts and new promising directions of research are emerging. To reflect and synthesize the multiple facets involved, this book is divided into three parts. Part I deals with the major subgrid processes, with eleven chapters (Chapters 2 to 12) covering different fast processes. Beyond conventional treatments, some promising approaches have recently emerged to unify the treatment of (some) processes and thus allows for consideration of processes interactions. Part II is devoted to such unifying efforts, with four chapters (Chapters 13 to 16) that each cover a different endeavor. Part III is devoted to measurements, model evaluation, and model-measurement integration, with four chapters (Chapters 14 to 17) that focus on satellite and airborne remote sensing measurements, surface-based remote sensing measurements, in-situ and laboratory measurements, and model evaluation and model-measurement integration, respectively.

#### 1.3.1 Process studies and parameterizations

Primary to the Earth's climate and weather and understanding climate change is the understanding and representation of the solar (shortwave) and terrestrial (longwave) radiation and of radiative transfer processes such as absorption, scattering, and transmission. In *Chapter 2, Gu and Liou* present the fundamentals of radiative transfer and its interactions with the atmosphere, and summarizes the commonly used radiative transfer parameterization schemes in atmospheric models. Also discussed are several more advanced topics in the study of the atmospheric radiation, including cloud vertical overlapping, cloud horizontal inhomogeneity, and 3D radiative transfer in both the cloudy atmosphere and over complex rugged land surfaces such as mountainous terrains. In particular, the chapter highlights that the current commonly used radiation schemes normally represent 1D transport in the vertical direction, although radiative transfer in 3D atmosphere and surfaces could play an important role in determining the radiation budget and radiative heating at the top of the atmosphere, at the surface, and within the atmosphere. Both horizontal and vertical subgrid scale inhomogeneities, and 3D radiative transfer may substantially influence the radiative transfer within clouds and cloud-radiation interactions, suggesting the need for further investigation and for improving their representations in models.

Atmospheric aerosols are suspensions of solid particles or liquid droplets in the air. Aerosols contain multiple compositions, exhibiting various morphologies and span a few orders of magnitude in sizes from a few nanometers to tens of micrometers. Aerosol radiative effects constitute one of the largest uncertainties in climate projection, and the large spread of simulated values among general circulation models (GCMs) can be traced to different representations of aerosol processes, including emissions, transport, formation and removal, and aerosol-cloud interactions. In *Chapter 3, Liu* provides an overview of atmospheric aerosols and their climatic impacts through both aerosol direct effects on radiation (aerosol-radiation interactions) and aerosol indirect effects (aerosol-cloud interactions). The authors focus on addressing topics related to three aerosol-related questions: 1) How are aerosol properties and processes as well as aerosol-cloud interactions represented and compared in current GCMs? 2) What are the major assumptions, simplifications and weaknesses of the current representations? 3) Why are there large uncertainties in the aerosol climate effects from GCMs? Several future directions are highlighted.

Although entrainment of surrounding dry air into clouds, subsequent turbulent mixing processes, and their microphysical influences haven been known to be essential in determining cloud microphysical and related properties for some time, theoretical understanding of these processes is still far from complete, and their parameterizations in atmospheric models are in their infancy. In *Chapter 4, the authors (Lu, Liu, )* discuss these issues in shallow clouds (cumulus and stratocumulus clouds), focusing on two critical yet understudied aspects: entrainment-mixing mechanisms and entrainment rate. Different conceptual models of entrainment-mixing mechanisms are reviewed, and latest studies on unifying microphysical measures to quantify different entrainment-mixing mechanisms are presented. Approaches for estimating fractional entrainment rate in cumulus clouds are summarized; relationships of entrainment rate to internal cloud properties (e.g., vertical velocity) or external properties (e.g., relative humidity in environment) are discussed as plausible parameterizations. Three approaches for estimating entrainment velocity in stratocumulus clouds are also discussed. Several topics are highlighted for future research, e.g., the connection between entrainment rate, entrainment-mixing mechanisms, and relationships to other factors (e.g., rain initiation, detrainment, spectral shape of cloud droplet size distributions, entrained aerosols, and environmental relative humidity).

Following the discussion on entrainment in shallow cumulus clouds and its role in shallow convection parameterization, *Donner* turns to deep convection from the perspective of large-scale flows *in Chapter 5*, which, as a practical matter, comprises the problem of (deep) cumulus parameterization. The chapter begins with discussing the effects of convection on large-scale flows in which it is embedded, follows with strategies for solving the problem of cumulus parameterization, and concludes with a brief overview of interactions between convection and momentum, chemistry, tracers, cloud microphysics, and aerosols. Emphasized are the roles of convective vertical velocities in treating aerosol-cloud interactions and cloud microphysics related to cloud feedbacks. Major deficiencies in existing parameterizations are discussed, including interactions between deep convection and aerosols, convection-chemistry interactions, understanding and representation of convective organization, and knowledge of convective-scale pressure-gradient forces in treating effects of convection on momentum fluxes. Limitations of mean-state perspectives and the widely used quasi-equilibrium assumption are discussed. Also touched on are connections with other topics (e.g., scale awareness, higher-order closure, multi-scale modeling frameworks and high-resolution models without conventional deep convection parameterizations, shallow convection, boundary-layer processes and gravity waves) detailed in other chapters.

Besides convective clouds, stratiform clouds including stratus and stratocumulus clouds constitues another critical component of the atmospheric system that significantly affects climate and has long been the subject of active research from many perspectives. *In Chapter 6, Dong and Minnus* provide an overview of such clouds, with a focus on what we have learned from observational studies in terms of improving their parameterization in atmospheric models. Stratus and stratocumulus cloud properties and their importance are discussed based on measurements from trained surface observers, satellite and ground-based remote sensors, and aircraft field campaigns. The processes that determine the variations in stratocumulus properties and govern where and when they occur are discussed, along with such factors as aerosols, radiation, and humidity. Retrieval methods used for extracting information about stratus and stratocumulus clouds from satellite- and ground-based sensors are also briefly reviewed, with an emphasis on the knowledge learned for improving understanding and parameterizations of such clouds in large scale models. Unique consistency between the early trained observers and the state-of-art technologies are demonstrated; synergy of different observational platforms is highlighted for future investigation. Emerging but understudied phenomena are summarized, including the impact of low-level temperature advection, veil clouds developing at the top of the marine boundary layer in areas of open-cell and unorganized cellular convection, the role of gravity waves in the subtropical jet stream in initiating Pocket of Cells (POCs) in some closed-cell stratocumulus over the southeast Pacific, and effects of land-sea breezes. Outstanding issues in profiling marine boundary layer cloud and drizzle microphysical properties are highlighted, including the need for incorporating cloud-top entrainment, drizzle, and vertical and horizontal inhomogeneities to address the issue of nonadiabatic multispectral retrievals.

As a layer between the ground surface and the free troposphere, the planetary boundary layer (PBL) is often turbulent, and particularly important because the majority of biota (including humans) and climatically important low clouds like stratocumulus and shallow cumulus reside. Even deep convection is highly related to the properties of the plumes or thermals originating in the PBL. In *Chapter 7, Ghate and Mechem* introduce the PBL structure and the commonly used theoretical approaches for investigating the PBL. A hierarchy of models for representing the boundary layer is presented, including mixed-layer models, first-order closure, 1.5-order TKE closure, and higher-order closure approaches. Challenges for evaluating the emerging advanced schemes (high order, PDF-based, or EDMF) are also discussed in context of the inherent needs for observations of joint PDFs of vertical air motion and thermodynamic variables. The discussion emphasizes the buoyancy-driven convective boundary layer but briefly mentions impacts of shear and clouds. The chapter concludes with a brief historical context and future outlook for representing the boundary layer in large scale atmospheric models. To some extent, this chapter can be viewed as an introduction to Chapters 13 and 14 where the PDF-based and EDMF schemes are detailed.

Although the focus of this book is on atmospheric processes, the weather and climate system consists of other sub-systems that strongly interact with the atmosphere over a wide range of spatiotemporal scales. In particular, various surface processes are fundamental to the exchange of heat, water and momentum between the surface and the atmosphere through PBL. As such modeling land-surface processes has been an integral component of atmospheric models. In *Chapter 8, Barlage and Chen* and focus on recent progress in understanding and modeling the biophysical effects of the human dimension, especially urbanization and agriculture, on surface water and energy budgets, and their cascading effects on weather and climate including clouds, aerosols, convection and precipitation. Well-known phenomena are discussed, including the Urban Heat Island (UHI) and urban impacts on precipitation through both cloud microphysical and/or dynamical effects. Also discussed are the unique roles of rough vegetated or urban canopy in determining turbulent fluxes (e.g., evapotranspiration over vegetated regions can exceed evaporative flux from the oceans because larger surface roughness and stronger turbulence whereas the moisture flux can be effectively shut off when the land is dry). Land-surface models (parameterizations) of 3D subgrid structures within urban or vegetation canopies are presented, including the most sophisticated multi-layer scheme ─ BEP (Building Effect Parameterization).

Challenges for evaluating and applying such a comprehensive land-surface model are discussed, including existence and specification of the large number of tunable parameters used in urban canopy models.

Atmospheric gravity waves (GW) have horizontal wavelengths ranging from 1 to 1000's of kilometers. Current climate models, and even numerical weather prediction models cannot resolve significant portions of their momentum flux and parameterizations are necessary to represent their under- or unresolved effects in atmospheric models. In *Chapter 9, the authors (Kruse, Richter, Alexander, Bacmeister, and Wei)* discuss GWs that are important at nearly all levels of the atmosphere, especially for the general circulation of the middle and upper atmosphere. GWs in the tropical stratosphere contribute significantly to the driving of the quasi-biennial oscillation and the stratospheric and mesospheric semi-annual oscillation, both primary modes of variability up there. In the extratropics, GWs contribute to the driving of the stratospheric Brewer-Dobson circulation and significantly influence the strength of the polar night jet and the corresponding polar temperatures. Additionally, GWs are responsible for the cold summer mesopause and the reversal of extratropical zonal mean winds in the mesosphere. Also discussed are both primary sources of atmospheric GWs (i.e., flows over mountains, moist convection, and imbalances in jets and frontal systems) and secondary GWs generated as a result of dissipation of primary GWs. The basic theory of GW generation, propagation, and dissipation and commonly used GW parameterizations are presented. Uncertainties, parameter tuning, and known missing processes in current parameterizations are explored as well. The importance of gravity wave in shaping clouds (*Chapter 7*) and in determining cloud microphysical properties (*Chapter 3*) are gradually recognized as well.

### 1.3.2: Unifying efforts

*Chapter 10* is the first of the four chapters that introduce the emerging efforts to unify the parameterizations of different processes, with a focus on higher-order equations closed by assuming the shape of the probability density function (PDF) of fields on the subgrid scale (PDF-based method for short). In this chapter, *Larson* presents the general equations involved. Theoretical analysis of the higher-order equations reveals that they contain the flux-of-flux terms that lead to non-local cumulus transport, along with a detailed representation of buoyant generation of turbulence, which is the essential source term of convection and can be closed by a multivariate PDF. Instead, traditional low-order closure omits the flux-of-flux terms that are crucial for representing nonlocal cumulus transport. The popular Cloud Layers Unified By Binormals (CLUBB) is detailed as an example of such PDF-based methods. Other higher-order closure models are also briefly discussed, including the Intermediately Prognostic Higher-Order Closure (IPHOC) parameterization (Cheng et al., 2010), which prognoses all the moments prognosed by CLUBB, plus two additional third-order moments of water vapor and potential temperature, the Turbulence Kinetic Energy-Scalar Variance (TKESV) parameterization of Mironov and Machulskaya (2017), which prognoses TKE and scalar variances, and optionally a third-order moment related to cloud liquid water. The connections of the PDF-based method to the conventional the mass-flux method for convection and low-order closure for turbulence are also discussed.

Another approach that seeks to unify the treatment of convection and turbulent processes in PBL is conceptually more direct, combining the widely used eddy diffusivity approach for local turbulent transport with the mass-flux scheme for convection. In *Chapter 11***,** the authors ***(****Teixeira, Suselj and Kurowski)* discuss the EDMF approach. After briefly reflecting on the early development in the late 1990s, this chapter is focused on the new stochastic multi-plume EDMF scheme that can realistically represent the dry boundary layer, stratocumulus, shallow and even deep cumulus convection within a single framework. The surface variability of updraft properties is parameterized using joint PDFs of thermodynamic properties to initialize multiple updrafts. Lateral entrainment is parameterized as a stochastic process. Furthermore, the unified EDMF parameterization explicitly considers the horizontal resolution of the model, paving the way to a scale-aware extension of the scheme. Both the fundamentals and latest results of using the new EDMF scheme are introduced. The multi-plume framework allows for the coexistence of different convective regimes (i.e., dry plumes, shallow moist convection, and even deep convection) within a single grid-box, without any artificial separations between them and with scale-adaptive capabilities for use in next-generation weather and climate models with high and variable horizontal resolutions.

The PDF-based and EDMF approaches both aim to unify the parameterizations of turbulence, PBL and convection (especially that of shallow convection). Further coupling with other processes such as cloud microphysics remains an area of active research for both approaches. Around similar times in the late 1990's and early 2000's, ideas of super-parameterization - that embed cloud-resolving models (CRM) in climate model grid column - were proposed and developed as a way to replace all the subgrid processes that the embedded CRM model represents, including turbulence, PBL, convection, cloud microphysics and radiation (Grabowski, 2001; Randall, 2013). Recently similar ideas were extended to using high resolution large eddy simulation (LES) models instead of CRMs in so-called ultra-parameterization (Parishani et al., 2017). Obviously, the benefits of such multiscale modeling approaches come at high computational cost and call for more computationally effective approaches that can be used as alternative to represent multiple fast processes together. In *Chapter 12*, *Krasnopolsky and Belochitski* describe applications of machine learning (ML) approaches to emulate existing parameterizations and developing new ML surrogate models as new parameterizations. The authors first argue that a parameterization can be formulated as a generic problem of mathematical mapping, and then argue that ML tools can be used to emulate and/or approximate the involved mathematical mappings. Four mapping complexities (physical complexity, mathematical complexity, numerical/computational complexity, and functional complexity) are discussed. Further discussed are ML applications to emulate existing parameterizations, to develop new parameterizations, to ensure physical constraints, and control the accuracy of developed applications. Some ML approaches that allow developers to go beyond the standard parameterization paradigm are discussed as well. Limitations of ML models are also discussed, including inability to provide a meaningful physical interpretation of underlying processes, requirements of large data for training and testing purposes, and their limited generalizability to out-of-sample scenarios. Given that neither an ML-only nor a physically based-only approach can be considered sufficient for complex scientific and engineering applications, the research community has been exploring the hybridization of physically-based and ML-based models, where both scientific knowledge and data are integrated in a synergistic manner. It is reasoned that this hybrid paradigm is fundamentally different from the ML mainstream where domain-specific knowledge is often considered secondary, and several differences are discussed. The concept of compound parameterization (CP) that combines an ML parameterization, the original physically-based parameterization, and a quality control procedure is introduced.

Despite the tremendous advances and different extents in dealing with the number of fast processes and their interactions discussed in the previous chapters, a common theme of those studies is that they are all essentially bottom-up-based and aim to upscale subgrid scale processes to grid variables. However, the climate system, including its atmospheric component, is a multiscale complex system that involves highly nonlinear bottom-up and top-down scale interactions (recall Fig. 3). Without considering the top-down direction, our understanding would never be complete, and the physical pictures from the unifying efforts could be as murky as understanding the output of a full GCM. As another unique addition of this book compared to existing ones, in *Chapter 13, Feingold and Koren* summarize innovative ideas that attempt to consider processes holistically but are scattered in various disciplines including nonlinear systems dynamics such as chaos theory, statistical physics, information theory, self-organization, networks, pattern formation, and general systems theory. The "top-down view" is focused on system-wide behavior and emergent phenomena, distinguishing from the traditional "bottom-up" view that focuses on individual processes. In particular, a behavior at a larger scale can emerge from interactions/couplings between detailed processes and between the involved sub-systems at a finer scale. And this type of order/emergence is not driven by an external force, but instead grows spontaneously from local interactions, or is 'self-organized'. Spatiotemporal communication between components of a system is key to development of synchronization, patterns, and self-organization. The top-down approach can yield simple holistic models that are more amenable to interrogation and digestion than complex, detailed models. Concepts and terminologies that are not that familiar to the atmospheric modeling, esp., the parameterization community, are introduced and discussed, including fixed points, attractors, limit cycles, chaotic state, bifurcation points, synchronization, information content, and entropy. In addition to their distinct foci on local and detailed physical processes vs. process interactions and emergence, this chapter also provides some intriguing examples to elucidate the conceptual differences between the bottom-up and top-down approaches from other perspectives: Reductionism vs. Holism; Basic building blocks vs. an Integrative view; Models representing a Large vs. a Reduced number of degrees of freedom; Models rooted in mathematical representation of physical/chemical/biological processes vs. Models that are an abstraction of these processes; Complexity vs. Simplicity. The authors use aerosol-cloud-precipitation system as a particular example to demonstrate the great potentials of the top-down view, and the need to integrate the complementary top-down view and bottom-up thinking in addressing the remaining challenge.

### 1.3.3 Measurements, model evaluation and model-measurement integration

Reliable observations are always important to improve our understanding of natural phenomena including atmospheric processes, and serve as the ground truth to verify and evaluate any theoretical and modeling developments. The synergy between model development and observations are becoming increasingly important as both fields progress. Earth science observations in general and atmospheric observations in particular have unique features, involving different but complementary approaches: surface-based , satellite-based and airborne remote sensing, in-situ field measurements and laboratory studies. This part is devoted to such crucial endeavors, with four chapters focusing on four different topic areas summarized next.

*Chapter 14* focuses on surface-based remote sensing for the study of the macro- and micro-physical structure of clouds, precipitation, aerosols, and the clear boundary-layer. In this chapter, the authors (*Lamer, Kollias, Amiridis, Arinou, Loehnert, Schnitt, and McComiskey*) place their emphasis on the unique ability of ground-based system to continuously characterize the atmosphere at high vertical resolution from near the surface to the top of the atmosphere effectively filling observational gaps left by spaceborne and aircraft platforms. Following an overview of the emergence of ground-based observatories details about the measurement principals of their cornerstone instruments (Cloud and Precipitation Radars, Lidars and radiometers) is given. Modern techniques to retrieve cloud and precipitation location, microphysical and dynamical properties as well as planetary boundary layer structure and aerosol properties are discussed including their underlying assumptions and uncertainties. Challenges associated with using ground-based observations for model evaluation are discussed including: 1) The fact that most measurements are related to moments of these particle size distributions that differ from those of most interest; the 0th (total number concentration) and 3rd (mass content) moments) being most desirable and the 6th and 2nd being recorded by radars and lidar, respectively. And 2) the fact that high-resolution observations and large-scale models are widely different scales; GCMs having grid resolutions ~50 km while radars have range resolution of ~30m. The growing role of synthetic Observing Systems Simulation Experiments (OSSEs), instrument simulators and sub-column generators in bridging those gaps is emphasized. The chapter closes with an outlook on the next generation of ground-based observatories that should employ scanning systems and distributed networks.

*In Chapter 15, Marshak and Davis* cover remote sensing retrievals of cloud and aerosol properties from overhead instruments, including satellite-based and airborne sensors with standoff distances ranging from NASA’s P-3B aircraft at about 3.5 km above cloud top to the Deep Space Climate Observatory (DSCOVR) platform at the Lagrange-1 point, about 1,500,000 km toward the Sun. The electromagnetic spectrum covered ranges from the ultra-violet to microwaves, and both traditional passive and relatively recent active (e.g., lidar and radar) and modalities are discussed. The emphasis is on the physics behind the sensors as well as on the retrieval algorithms. The chapter starts with remote sensing of cloud properties, introducing the popular Nakajima–King approach widely used in retrievals of cloud optical depth and particle size, and the Bréon–Goloub approach that is based on the directional signature of the polarized reflectance. Techniques for retrieving (mostly ice) cloud properties with microwave sensors is also briefly described. The chapter then switches to remote sensing of aerosol properties, describing the main aerosol remote sensing approaches used by the major satellite imagers. In addition to passive remote sensing, the active remote sensing methods for aerosol and cloud profiling are also highlighted, with an emphasis on CALIPSO and CloudSat for lidar and radar, respectively. The chapter explores oxygen A- and B-band remote sensing of cloud and aerosol layer height, along with other passive methods for estimating cloud top height. A special section is dedicated to cloud remote sensing at very high spatial resolution either from tasked imaging sensors in space or from airborne platforms deployed above the clouds of interest, such as NASA’s ER-2. New studies on the transition zone are reviewed. The chapter closes with a brief discussion of retrieval uncertainty quantification for both cloud and aerosol remote sensing.

Laboratory experiments allow more controlled, repeatable measurements of a physical quantity or phenomenon in a well-defined system of interest with known external influences. In *Chapter 16, Chandrakar and Shaw* describe in-situ measurements and laboratory experiments, with a focus on physical processes that are small in spatial or temporal scale such as cloud microphysics and small-scale turbulence. Some illustrative historical examples are given to highlight significant advances and capabilities in three areas of airborne measurement, ground-based measurements, and laboratory experiments, with a focus on cloud studies. The challenges of operating an aircraft and the inherent sampling limitation of high-speed nature and thus low spatial resolution of most measurement platforms are highlighted, and two developments are introduced to address these challenges: the emergence of un-crewed aerial vehicles (drones) for scientific purposes and the HOLODEC instrument based on digital in-line holography. The HOLODEC provides an estimate of the cloud particle size distribution and particle shape from a single sample volume of cm scales, providing unique opportunities to measure and study outstanding science questions like droplet clustering, particle breakup, and particle shattering. It is pointed out that laboratory measurements have become somewhat less common and lagged field measurement capabilities, although their contributions have been profound.

The ultimate test of any models and thus parameterizations is its performance in climate simulations and weather prediction. Efficient and effective evaluation frameworks are needed to test the parameterizations, assess their predictive skills, characterize the model behavior from process level to global scale, and identify sources of potential errors to confidently guide further development. In *Chapter 17, Lin and Xie* describe the approaches and frameworks used for testing and evaluating fast physics parameterizations in climate and weather models. An integrated yet complementary modeling and evaluation framework is advocated that promotes process-oriented evaluation and effectively bridging parameterization development with observations and modeling, with focus on two exemplary such frameworks that have been widely adopted by the modeling centers and the research community. The first is the integrated SCM-CRM-LES framework that has been widely used since it was promoted in the early 1990s. This modeling framework allows for process studies with SCMs, CRMs, and LES models with the scale ranging from a few hundred kilometers to a few tens of meters. With all the models driven by the same large-scale forcing and initial and boundary conditions, the model intercomparison studies this frame have proven useful to identify strengths and weaknesses of model parameterizations; and systematic model deficiencies have been found through these studies. The second framework is based on the idea of running climate models in "weather forecast mode with initial data from NWP analyses to take advantage of the facts that (1) the large-scale state of the atmosphere in the early periods of a forecast is realistic enough that errors may be ascribed to the parameterizations of the atmospheric physical processes; and (2) the atmospheric physical processes (e.g., moist process) are often fast (~hours) and the large-scale state changes slowly (~ days); (3) there is a strong correspondence between the short- and long-term systematic errors in climate models, particularly for those fields that are related to fast physics (e.g., clouds). Further integration of the two evaluation frameworks to better capitalize on their respective advantages are also explored. The metrics and diagnostics designed for model evaluation are also presented, including process-oriented diagnostics and metrics in support of process studies and providing more insights into model errors, and satellite/radar simulator packages that permit direct comparison of model ouputs to sensor signals without complicated retrievals.

## 1.4. How to approach the content in this book

The book is targeted at researchers and graduate students working on the relevant areas. Each chapter of this collective volume has its own foci that are closely related to other chapters, and can be read either separately as a stand-alone chapter with its own list of references or together with the other chapters with cross references as needed.

This book serves a valuable addition to existing literature on fast physics parameterizations in large scale atmospheric models, with several unique features. It would be better read together with: Stensrud (2007), the special fast physics collection in *Journal of Geophysical Research:Atmospheres* (Liu, 2019; https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)2169-8996.FASTPHYS1), and various topical review articles (e.g., Morrison et al. (2020) on parameterizations of cloud microphysical processes).

## Acknowledgments

The volume editors thank all the chapter authors for their valuable contributions to this book. Dr. Leo Donner deserves special recognition; he co-convened with the editors various sessions on related scientific topics at the AGU Fall Meetings and helped with the conception of this book. The editors' relevant research has been mainly supported by the U.S. Department of Energy's Office of Science Biological and Environmental Research program as part of the Atmospheric Systems Research (ASR) program and Earth System Modeling (ESM) program, and the Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) award number 33504. Brookhaven National Laboratory is operated by Battelle for the U.S. Department of Energy under contract DE-SC00112704.

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## Figure caption

**Figure 1**. Schematic of the approximate timelines of development of fast physics parameterizations. Conventional parameterizations are focused on individual fast processes. The four lines of unifying efforts (PDF-based High Order Closure, Eddy Diffusivity and Mass Flux, Super/ultra Parameterization, and Machine Learning Parameterization) aim to unify the representation of more than two physical processes. Top-down approaches borrow holistic ideas that have been scattered in various different disciplines (e.g., nonlinear systems dynamics, statistical physics, information theory, self-organization, networks, and pattern formation).

**Figure 2.** Historical values of equilibrium climate sensitivity (ECS) and transient climate response( TCR). Figure is modified from Fig. 1 of Meahle et al. (2020) which can be consulted for details on the data sources and definitions.

**Figure 3**. Schematic to illustrate the atmospheric scale hierarchy and involved "4M-2N complexities". Together with the "operational complexity" discussed in the text, these science complexities have posed and will continue to pose challenges to model development in general and fast physics parameterizations in particular.