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BOOK REVIEW

Wyngaard, J. C., 2010: Turbulence in the Atmosphere

Cambridge University Press, New York, 393 pp

Evgeni Fedorovich

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This book has been awaited in the atmospheric boundary-layer research community for a long time. John Wyngaard, the author of the book, is by all counts an outstanding figure in the area of atmospheric turbulence studies. His contributions to the field are both numerous and exceptional. As a person, John comprises all the principal qualities of an outstanding scientist and academic: curiosity, witty mind, breadth of thinking, depth of understanding, healthy scepticism (also with respect to his own results), and readiness to share his knowledge with colleagues and students. I happened to come across John Wyngaard's name at the beginning of the 1980s, while I was working on my Ph.D. dissertation in atmospheric boundary-layer modelling. His brilliant scientific articles profoundly shaped my interest in the quantitative aspects of boundary-layer meteorology. Apparently, they played the same role in the scientific careers of many other atmospheric boundary-layer researchers worldwide. For many of us, these studies have been sources of seminal ideas and conceptual breakthroughs in understanding various aspects of turbulent flow dynamics. Especially beneficial for me has been John's ability to masterfully apply sophisticated tools of theoretical fluid mechanics, such as scale analysis and similarity theory, not only to discover and interpret fundamental properties of atmospheric turbulent flows but also to develop physical models and parametrizations well designed for practical meteorological applications.

Turbulence in the Atmosphere (2010) is a neatly assembled compendium of critically analyzed pieces of existing knowledge in the area of atmospheric turbulence research combined with a summary of the author's own accomplishments in the area over the course of his career spanning almost 50 years. In my view, the book has met expectations of the atmospheric boundary-layer community with respect to both the scope and form of presentation. The overall strengths of the book are:

- in-depth analyses of historical developments in general and atmospheric turbulence research,
- appropriate balance between the physical interpretation and mathematical formalism in the presentation,

E. Fedorovich (✉)
School of Meteorology, University of Oklahoma, Norman, OK, USA
e-mail: fedorovich@ou.edu

- careful consideration of controversial and/or confusing concepts encountered in turbulence research,
- adequately proportional attention given to analytical, observational/ experimental, and numerical aspects of atmospheric turbulence studies, and
- elaborate selection of problems offered at the end of each chapter.

Compared to the fundamental turbulence books of Tennekes and Lumley (*A First Course in Turbulence*, 1972), Pope (*Turbulent Flows*, 2000), and Monin and Yaglom (*Statistical Fluid Mechanics*, volumes I and II; 2007a, b), Wyngaard's book offers a broader perspective on specifically atmospheric features of boundary-layer turbulent flows and associated tools for their formal description. On the other hand, as compared to widely known boundary-layer meteorology texts including those of Stull (*An Introduction to Boundary Layer Meteorology*, 1988), Sorbjan (*Structure of the Atmospheric Boundary Layer*, 1989), Garratt (*The Atmospheric Boundary Layer*, 1994), Kaimal and Finnigan (*Atmospheric Boundary Layer Flows: Their Structure and Measurement*, 1994), and Blackadar (*Turbulence and Diffusion in the Atmosphere*, 1997), as well as books on micrometeorology by Arya (*Introduction to Micrometeorology*, 2001) and Foken (*Micrometeorology*, 2008), his book provides a more detailed consideration of the fundamental properties of turbulence and quantitative approaches toward its description. In a way, the reviewed book follows in the footsteps of the text by Lumley and Panofsky (*The Structure of Atmospheric Turbulence*, 1964), but focuses on new knowledge gained in atmospheric turbulence research and new techniques of turbulence analysis developed since the beginning of the 1960s. The author, however, rather appropriately pays tribute to the way particular turbulence features are addressed in Lumley and Panofsky (1964) and Tennekes and Lumley (1972) by adapting and extending portions of material from those texts in several sections of his book.

Already in the preface to the book, the author reflects on some methodological aspects of atmospheric turbulence studies in terms that are helpful for appreciating the book as a whole. One of the most important, from my point of view, is the note that modelling and observational work in turbulence studies have "cruelly (sic!) different time scales". While observational work gradually moves out of fashion and modelling work speeds up, the models can be easily misused and misinterpreted since they "have no warning labels". This makes adequate understanding of the foundations and limitations of turbulent flow models extremely important, and I believe that the book serves the purpose of promoting such an understanding in an exemplary fashion. As the author rightfully states, though, our contemporary treatment of turbulence appears more like dealing with turbulence rather than solving the turbulence problem (probably, we will first need this problem to be clearly formulated). Coincidently, on page 78 a companion term "turbulent problem" emerges (apparently, used in the "turbulent flow problem" sense) which, in my view, quite closely reflects the state of matters in turbulence research…

The book consists of three self-contained parts. ***Part I*** (A grammar of turbulence) introduces concepts that are central to turbulence literacy, as the author puts it. This part is aimed at the development of the reader's physical understanding of turbulence as a commonly observed natural phenomenon in fluid flows.

Chapter 1 (Introduction) sets the tone and sketches the scope of the entire book. The author, in a frank manner, invites the reader to be prepared for a rather special mentality and usage of quite extravagant mathematical tricks, which the reader has probably "never seen before and might not have thought of" and which are so characteristic of our field, making it that special at the same time. The Introduction is written in a lively manner, through providing many sensible examples of turbulent flow phenomena and considering formal approaches employed to describe them. The impact of Kolmogorov's ideas on the formation of our present view on the turbulence energy cascade and spectral properties is discussed very appropriately here. This section, however, would require from the reader some pre-existing knowledge of basic fluid physics notions, like those of Reynolds number, shear stress, and turbulent flux. Most of these notions are really only explained in subsequent chapters of the book.

Chapter 2 opens with a discussion of the contrast between the instantaneous and average properties of turbulent flows and then focuses on different averaging strategies. Among other things, the author makes a very good point here regarding the concept of ensemble average, pointing out that, in fact, this average exists as a concept only, not as an actual average. He also attracts attention to another not very well-known fact that the Reynolds averaging was originally introduced as a spatial averaging. Ironically, it was forced to obey the ensemble averaging rules, which—in order to confuse things even more, apparently—are called the Reynolds averaging rules.

Equations for averaged variables are considered in detail in **Chapter 3**. Different averaging/filtering approaches and examples of their applications are described and discussed here very nicely. A reasonable emphasis is put in Section 3.2 on the sign alteration between the turbulent momentum flux and turbulent stress. Unfortunately, in other sections of the book, the author often uses these terms interchangeably.

In **Chapter 4**, ensemble averaging is used to introduce the concept of turbulent flux and to illustrate the behaviour of momentum, temperature, and scalar turbulent fluxes in boundary-layer flows. In Section 4.2, the decomposition of absolute temperature in ensemble mean and fluctuation parts, denoted by Θ and θ, respectively, may appear a little confusing to meteorologists who usually reserve these symbols for potential temperature. Also here, the consideration begins with temperature and then abruptly switches to potential temperature with the latter still undefined, which, to a certain extent, complicates the digestion of the text. The "mixture-length" versus "mixing-length" discussion in Section 4.5 is another good example of historical retrospective showing how a particular notion has been developed through contributions by different scientists sometimes unaware of each other's works.

Chapter 5 (Conservation equations for covariances) and **Chapter 6** (Large-eddy dynamics, the energy cascade, and large-eddy simulation) are rather mathematically intense and would require a good preparation on the part of the reader, especially if the reader decides to closely follow the author's equation derivations or approach problems to these chapters (good luck!). In my view, though, some interpretations outlined here appear to be slightly crumbled. For instance, it would be nice to see in Section 5.4 an interpretation of the viscous dissipation term (including its spectral interpretation) presented in a similar manner to the discussion of the molecular scalar destruction term in Section 5.3.4. Chapter 5 is concluded (Section 5.6.2) with very informative considerations of the history, status, and outlook of applications of the covariance equations in turbulence modelling. An interesting point is made here regarding the lack of universality that was a killer for the second-moment (or Reynolds stress) turbulence models.

Based on Batchelor's analysis, the author vividly explains in **Chapter 7** (Kolmogorov scaling, its extensions, and two-dimensional turbulence) what went wrong with G. I. Taylor's considerations of small-scale turbulent motions in statistical equilibrium that led him to erroneous conclusions regarding the set of parameters that determine the structure of the smallest-scale turbulent motions. Another memorable excursion into the history of turbulence research is made in one of the concluding sections of the chapter, where the role of the legendary Marseilles meeting of 1961 is discussed, which saw the presence of the titans of the field, such as Batchelor, Kolmogorov, von Kármán, and G. I. Taylor, and where the contemporary view on the turbulence dynamics was further refined (primarily, through the revision of the Kolmogorov scaling). A dichotomy in using different turbulence parameters to illustrate the local turbulence isotropy property slightly affects the smooth flow of presentation in this very well-written (in all other aspects) chapter. For instance, the Taylor-scale Reynolds number R_λ appears in Section 7.3.1 without being defined. After that, the discussion develops in terms of the previously introduced large-eddy Reynolds number R_t, yet R_λ appears later again. A reference to the Taylor microscale defined in Section 15.4.2 would be rather appropriate here.

Part II (Turbulence in the atmospheric boundary layer) employs concepts and the formal description tools introduced in Part I to describe a plethora of turbulence features in the atmospheric planetary boundary layer.

First, the author derives governing equations of turbulent boundary-layer flow in **Chapter 8** (The equations of atmospheric turbulence) through implementing an isentropic, hydrostatic base state of the atmosphere and considering balances of momentum, heat, and passive scalars in terms of deviations from this basic state. In general, this is a rather traditional approach to a formal description of atmospheric boundary-layer dynamics and thermodynamics. However, by forcing the basic-state variables (pressure, density, and temperature) to be functions of the vertical coordinate only, the author creates a situation where geostrophic and baroclinic effects in the boundary layer need to be expressed through the pressure deviation that makes these effects much less tractable within a general boundary-layer context. For instance, as becomes clear later (Section 9.6.2), in order to describe the thermal wind effect in this case one would need to assume the hydrostatic form of the third equation of motion. The Boussinesq approximation, which is the centerpiece of many atmospheric boundary-layer models, is introduced in the book in a rather loose manner—as only being associated with the neglect of the vertical variation of the base-state density (and thus, fixing it as a constant). It is somewhat different from Boussinesq's original idea, according to which density differences may be neglected in the governing flow equations except when they appear in terms multiplied by g, the acceleration due to gravity.

Chapter 9 (The atmospheric boundary layer) opens with an insightful summary of boundary-layer features. A very elaborately combined (based on physical arguments supported by an elegant interpretation of the equations) analysis of the momentum and energy balances of horizontal motion in the presence of friction is given. Relations of observed features to individual terms in the turbulence kinetic energy balance are nicely explained. The subsequent sections of the chapter discuss the role of buoyancy effects in boundary-layer dynamics and the implications of flow unsteadiness and heterogeneity. Unfortunately, some important flow parameters, such as the Obukhov length scale L and the inversion height z_i, appear here ahead of time, before they are defined in the following chapters of the book. In this respect, it would be desirable for the reader to have some previous exposure to basic atmospheric boundary-layer notions. An illustrative consideration of the sensitivity of turbulence to buoyancy forcing in Section 9.3 is slightly handicapped by ignoring the role that the sign of the forcing plays in this case. In order to quantify the contribution of the buoyancy force to the turbulence production/destruction, it would probably make more sense to consider negative versus positive buoyancy forces (per unit mass) and the associated positive/negative values of the Richardson number Ri_t. In Section 9.6, notions of stress *on the fluid* and stress *on the surface* appear without much supporting detail. Apparently, the former stress is quantitatively equivalent to the turbulent momentum flux, while the second has the opposite sign and is equivalent to the turbulent shear stress. I would wish the momentum flux and shear stress considerations to have been presented throughout the book in a less confusing manner.

Chapter 10 (The atmospheric surface layer) provides a good overview of turbulence properties in the surface layer and focuses on Monin–Obukhov similarity theory as the principal analytical technique to describe the surface-layer flow structure. In addition to considering the underlying hypotheses of the theory and demonstrating applications of the Buckingham Pi theorem to derive Monin–Obukhov similarity relationships, the author provides a thorough analysis of observed deviations from the Monin–Obukhov similarity and discusses physical mechanisms causing these deviations. He makes a valid point regarding practical difficulties associated with measuring turbulent pressure fluctuations that could provide, if they were only available, missing links in the budgets of turbulence moments in the surface layer. In my view, the influence of the aerodynamic roughness length z_0 (as well as roughness lengths for heat and moisture) on surface-layer flow structure could be given more attention in this chapter, despite the fact that it is not a parameter of the Monin–Obukhov theory. The roughness lengths appear in many practical applications of surface-layer meteorology, so their role should not be underestimated. However, z_0 is only briefly mentioned in the book, and it is not formally introduced or defined.

Two basic atmospheric boundary-layer types are considered in detail in **Chapter 11** (The convective boundary layer; CBL) and **Chapter 12** (The stable boundary layer; SBL). While discussing the CBL structure, the author makes an important point regarding uniformity of the potential temperature field in the (main portion of the) CBL by relating it to his own research in the 1980s, indicating that diffusion of a passive scalar emitted near the bottom of the atmospheric CBL, the so-called bottom-up diffusion, is rather different from the diffusion of a scalar emitted within the inversion level at the CBL top (top-down diffusion). This discovered asymmetry of turbulent transport in the CBL has had numerous implications for modelling and parametrization of the dispersion of pollutants in the lower atmosphere under unstable conditions. As explained in the book, the uniformity of the potential temperature field does not result from uniform (symmetric) mixing as is implied in most textbooks on the topic. It is, rather, a particular (and coincidental) outcome of the interaction between top-down and bottom-up diffusion mechanisms in the presence of the negative flux of entrainment of heat at the CBL top. Due to the fact that, in a typical CBL, the drier air from above the layer is entrained downward (implying that the moisture flux at the CBL top is positive), the observed specific humidity field in the CBL typically does not show the same vertical uniformity. Thus, the mixed layer is not really that "mixed".

I found the author's consideration of the interfacial layer structure and entrainment in the CBL (Section 11.4) to be much less convincing than the discussion of the bottom-up and top-down diffusion mechanisms. The derivation of the entrainment equation in Section 11.4.1 is rather confusing, particularly with respect to the reduction of the integral heat balance equation to its zero-order approximate form.

Problems offered in **Chapter 11**, on the other hand, are very thoughtful and illustrative, although rather challenging (the reader would need a deep comprehension of the contents of the chapter before even *trying* to approach the problem solutions) and, unfortunately, not always formulated in a way that allows the reader to connect an individual problem to material in the chapter.

Given that the SBL is typically observed at night and the CBL during the day, I particularly appreciated the opening statement of **Chapter 12**: "The stable boundary layer (SBL) is as different from the convective boundary layer (CBL) as night is from day". Discussing the evolution of views on the structure of SBL, the author follows the line of his own original work in the 1970s, then pays tribute to the analytical contributions from the 1980s and 1990s, and concludes with analyses of very recent results concerning the SBL structure obtained by means of numerical simulations (both direct and large eddy). He also analyzes the physical mechanisms of SBL formation as result of the late-afternoon boundary-layer transition over land and discusses the role of the inertial oscillation in the nocturnal evolution of the SBL. I was pleased to notice that the author specifically discriminates the jet-like feature in the quasi-steady SBL wind profile (shown in Section 12.1) from the nocturnal (or low-level) jet that results from the inertial oscillation (considered in Section 12.2.2). These two jet phenomena are often confused. The roles of gravity waves and sloping terrain in the formation of SBL structure are addressed as well. It is stressed that, even in the case of a very shallow slope, the stably stratified boundary-layer flow can be significantly affected by inclined terrain. Throughout the chapter, the issue of the equilibrium depth of the nocturnal SBL is discussed in sufficient detail, supplemented with a review of proposed scalings and models for the equilibrium depth.

Part III of the book (Statistical representation of turbulence) contains information essential for a formal description of turbulence and analysis of turbulence signals, either measured or numerically simulated. It opens with **Chapter 13** (Probability densities and distributions), which discusses the statistical representation of turbulence within an ensemble averaging framework. First, the probability statistics of scalar functions of a single variable (random processes) are considered, and then several examples of probability densities observed in atmospheric turbulent flows (such as the Gaussian probability density function) are presented. The notion of the stationarity (homogeneity) of a random process is introduced, and the usage of approximate stationarity in atmospheric applications is discussed. The evolution equation for the probability density is derived in the concluding section of the chapter.

In **Chapter 14** (Isotropic tensors), the basic properties of Cartesian tensors are briefly discussed, and examples of the usage of these tensors in turbulence description are demonstrated. Then, the notion of an isotropic tensor is introduced, and some forms of single-point and two-point isotropic tensors are illustrated. Section 14.4 contains an important and nicely presented discussion of isotropy implications for turbulence modelling. The Kolmogorov (1941) concept (hypothesis) of local isotropy is reviewed in an expanded manner in Section 14.5 (quoting Kolmogorov's original paper) and followed by a summary of known deviations from isotropy in small-scale turbulent motions. The mechanisms of the maintenance of anisotropy at small scales are explained using scaled conservation equations for the third moments of longitudinal and lateral scalar derivatives. In the concluding section of the chapter, implications of local anisotropy for modelling atmospheric turbulence are briefly discussed.

Chapter 15 (Covariances, correlations and spectra) extends the statistical description of turbulence, introduced in the preceding chapters, to correlation and spectral analyses. The chapter opens with consideration of the autocorrelation function of a single-variable, stochastic function, the spectral density function (spectrum), and the cross correlations and cross spectra. The spectral formalism is then extended towards random scalar functions of three spatial coordinates and eventually to vector functions of space and time. In Sections 15.3 and 15.4, very useful considerations are presented regarding the application of basic spectral techniques to the calculation of turbulence spectra from typical atmospheric measurements and the interpretation of inertial-subrange forms of atmospheric turbulence spectra. To my mind, everything presented in this chapter appears to be to the point. The described methods of evaluation of the plane spectra, for instance, prove to be quite in place given the popularity of numerical simulations of horizontally homogeneous boundary-layer flows.

Chapter 16 (Statistics in turbulence analysis) concludes the book with a presentation and discussion of two analytical techniques of turbulence research. The first technique, based on the evolution equation for a scalar spectrum, allows one to gain valuable insights into turbulence dynamics of scalars in high Reynolds number turbulent flow (Section 16.1). Relations between the ideas and findings of Kolmogorov and those of Obukhov and Corrsin are nicely illustrated here, using rather mathematically challenging analyses. Section 16.2 contains a summary of the author's own results from over three decades of work on improving the methodology of atmospheric turbulence measurements. A short, but rather informative Section 16.2.5 describes a relatively modern technique of measuring resolved and subfilter, in the large-eddy simulation sense, variables in the atmospheric surface layer.

For a text loaded with mathematical expressions, the reviewed book contains surprisingly few mathematical and typographical errors. Most of them, hopefully, will be fixed in the next edition (I am sure it will come to this). There are also some miscommunications between different sections of the book when material is not cross-referenced correctly. Another practical inconvenience, typical of texts operating with many different physical variables, is the duplicate usage of popular letter symbols, which is probably unavoidable. For instance, the symbol θ in Section 9.3.1 represents a temperature scale. In Section 8.2, it is potential temperature (a general-sense potential temperature in Section 8.2.3 and a fluctuating potential temperature in Section 8.4.2), in Section 4.2 it is a fluctuating (absolute) temperature, and in Section 2.5 it is an angle. With T, the situation is no better (which is perhaps to be expected): in Sections 1.3 and 1.5, T is the general-sense absolute temperature; in Sections 2.3 and 2.4, T is the averaging time interval; in Section 6.2, T is the Fourier transform of the filter function; in Section 10.2, T is the ensemble mean temperature; in Section 9.6.2, T could be, depending on the interpretation, either the ensemble mean temperature or the ensemble mean virtual temperature; and in Section 12.3.3, T is the complex velocity component covariance. So, while writing a book about turbulence, it is apparently impossible to avoid some "turbulence" in the presentation, which by no means diminishes the overall quality of the text.

The book appears to be a perfect textbook for advanced graduate courses in atmospheric turbulence and a good supplementary text for graduate courses in atmospheric dynamics, turbulence modelling and simulation, boundary-layer meteorology, and air-pollution meteorology. I am sure that the book will also be appreciated by turbulence researchers and modellers who will find within it much useful information regarding atmospheric turbulence and mathematical tools for its study.

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