Preface

The phenomenon of turbulence in fluid mechanics has been known for many centuries. Indeed, it was for instance discussed by the Latin poet Lucretius who described in "de natura rerum" how a small perturbation ("clinamen") could be at the origin of the development of a turbulent order in an initially laminar river made of randomly agitated atoms. More recently, Leonardo da Vinci drew vortices. Analogous vortices were sketched by the Japonese school of artists called Utagawa in the 19th century, which certainly influenced van Gogh in "The Starry Night". However, and notwithstanding decisive contributions made by Bénard, Reynolds, Prandtl, von Karman, Richardson and Kolmogorov, the problem is still wide open: there is no exact derivation of the famous so-called Kolmogorov $k^{-5/3}$ cascade towards small scales, nor of the value of the transitional Reynolds number for turbulence in a pipe. Besides these fundamental aspects, turbulence is associated with essential practical questions in hydraulics, aerodynamics (drag reduction for cars, trains and planes), combustion (improvement of engine efficiency and pollution reduction), acoustics (the reduction of turbulence-induced noise is an essential issue for plane reactors), environmental and climate studies (remember the huge damage caused by severe storms in Europe at the end of 1999), and astrophysics (Jupiter's Great Red Spot and solar granulation are manifestations of turbulence). Therefore, there is an urgent need to develop models that allow us to predict and control turbulence effects.

During the last 10 years, spectacular advances have been made towards a better physical understanding of turbulence, concerning in particular coherent-vortex self-organization resulting from strong nonlinear interactions. This is due both to huge progress in numerical simulations (with the development of large-eddy simulations in particular) and the appearance of new experimental techniques such as digitized particle-image velocimetry methods. New theoretical tools for the study of fluid turbulence in three and two dimensions have appeared, sometimes borrowed from statistical thermodynamics or condensed-matter physics: multifractal analysis, Lagrangian dynamics and mixing, maximum-entropy states, wavelet techniques, nonlinear amplitude equations... These advances motivated the organization of the Les Houches 2000 School on "New Trends in Turbulence", and this book. Theoretical aspects have been blended with more practical viewpoints, where the influence on turbulence of boundaries, compressibility, curvature and rotation, helicity, and magnetic fields is looked at. Various applications of turbulence modelling and control to certain industrial or environmental issues are also considered.

The first introductory course by Akiva Yaglom deals with a "century of turbulence theory". Here the problem of turbulence is reviewed from both the linear and nonlinear points of view. Then the two main achievements of 20th century turbulence theory are considered, namely the logarithmic velocity profiles (found by T. von Karman and L. Prandtl) for the intermediate layers of flows in circular pipes, plane channels and boundary layers without pressure gradients, and the Kolmogorov–Obukhov theory of the universal statistical regime of small-scale turbulence in any flow with a large enough Reynolds number (revised in 1962 by the authors to consider intermittency, which led to predictions of the scaling for structure functions of various orders). Since Yaglom was a student of Kolmogorov and participated in the developments of the second of the above-mentioned subjects, his presentation is based on first-hand knowledge of the history of these classic discoveries and of their present status.

The basis of turbulence theory is complemented by Katepalli Sreenivasan and S. Kurien (Course 2), who provide also a very complete account of fully developed turbulence experimental data (concerning structure functions and spectra of velocity and passive scalars) both in the laboratory and the atmosphere at very high Reynolds number (up to $R_\lambda = 20\,000$). Sreenivasan insists on departures from Kolmogorov scaling in the light of anisotropy effects, which are studied with the aid of a SO(3) decomposition. This allows us to extract an isotropic component from inhomogeneous turbulence.

Olivier Métais presents in detail "Large-eddy simulations of turbulence" (LES) in Course 3. These new techniques are powerfull tools allowing us to simulate deterministically the coherent vortices formation and evolution. He reviews also methods for vortex identification based upon vorticity, pressure and the second invariant of the velocity-gradient tensor. He applies direct-numerical simulations and LES to free-shear flows and boundary layers. Métais is also involved in particular aspects related to thermal stratification and rotation, with application to deep-water formation in the ocean and atmospheric severe storms. He concludes with applications of LES to compressible turbulence in gases, with reentry of hypersonic bodies into the atmosphere, and cooling of rocket engines.

In Course 4, Michael Leschziner describes methods used for predicting statistical industrial flows, where the geometry is right now too complex to allow the use of LES. He shows how these methods can be, in simple geometric cases, assessed by comparison with DNS and LES methods. He presents very encouraging results obtained with nonlinear eddy-viscosity models and second-moment closures. Interesting applications to turbomachinery flows are provided. Still on the industrial-application side, Reda Mankbadi (NASA) provides in Course 5 a very informative review of computational aeroacoustics, with many applications to aircraft noise (in particular jet noise in plane engines). He shows linear, nonlinear and full LES methods.

The remaining chapters are more fundamental. Keith Moffatt (Course 6) presents the basis of topological fluid dynamics and stresses the importance of helicity in neutral and magnetohydrodynamic (MHD) flows. He shows in the latter case how helicity at small scales can generate a large-scale magnetic field (α-effect), a mechanism which might explain the magnetic-field generation in planets and stars. Moffatt discusses also the possibility of a finite-time singularity within Euler and even Navier–Stokes equations. During his oral presentation, he made an analogy with Euler's disk. His practical demonstration of the latter was one of the School's highlights, especially when people realized that the experiment could be done as well with the restaurant plates, which was less appreciated by the cook. Uriel Frisch and J. Bec (Course 7) speak also of finite-time singularities, but mostly on the basis of Burgers equations in one or several dimensions, with the formation of multiple shocks. They describe methods that allow us to solve these equations analytically and numerically, and the kinetic-energy decay problem. He shows how Burgers equations (in three dimensions) can, in cosmology, apply approximately to the formation of large scales in the universe.

Course 8 is a very complete account of two-dimensional turbulence provided by Joël Sommeria (Grenoble). He first presents numerous examples of 2D turbulence in the laboratory (rotating or MHD flows, plasmas), in the ocean and in planetary atmospheres (Jupiter), insisting in particular on the absence of kinetic-energy dissipation in these flows. He reviews the double cascade of enstrophy (direct) and energy (inverse) proposed by Kraichnan and Batchelor. He presents also very clearly the point-vortex statistical-thermodynamics analysis of Onsager, and the generalization of this model to finite blobs of vorticity (maximum-entropy principle). Sommeria shows applications of this model to mixing layers and to 2D oceanic flows with differential rotation. Course 9 (Marie Farge and K. Schneider) is a useful presentation of wavelet techniques, a further interesting application of which (not detailed in the book) concerns data compression. In Course 10 (Gregory Falkovich, K. Gawedzki and M. Vergassola), the Lagrangian mixing of passive scalars and the relative dispersion of several particles is discussed. For two particles in particular, Richardson's pioneering law (predicting a dispersion rate proportional to the separation raised to the 4/3 power) is revisited in the light of Kraichnan's renormalized analysis.

Let us finish this preface with some information regarding the Les Houches 2000 School "New Trends in Turbulence". A computing centre was set up thanks to Patrick Begou during the duration of the programme. The machines (Compaq ds20/2proc, Sun ultra80/4proc, IBM 44p/2proc, HP j5600/2proc, HP kayak linux/2proc) were kindly lent by the respective companies. With this important computing power, we could organize for students five working groups under the direction of a professor or senior researcher, and using databases generated using several computational programs. These groups were: (1) Jets and wakes (Olivier Métais); (2) Isotropic turbulence (Marcel Lesieur); (3) Industrial applications (Franco Magagnato); (4) Transition (Laurette Tuckerman); and (5) Environment (Elisabeth Wingate). Among the topics treated in these groups were: analysis of helicity in a wake (group 1), vortices in LES of 3D isotropic turbulence (group 2), simulation of flows in complex geometries (around cars) using Magagnato's SPARC code (group 3), transitional plane Couette flow (group 4), and dispersion of tracers in the stratosphere (group 5). The computing centre was always crowded in the non-course periods. It also gave students a very good formation in scientific computing and image processing.

The level of the students (who came from a wide range of countries) was extremely good, and their sharp questions embarrassed sometimes even the best professors. Relations between the students and the professors were excellent, and discussions continued between the courses and during the meals, in the evenings, and even on the mountain trails above Le Prarion. We had a wide participation of students coming from countries in eastern Europe, and it gave the School a distinct flavour. Contacts between the students were numerous, friendly and extremely tolerant.

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We thank very much the lecturers for their efforts in preparing and delivering their courses, and then writing the above lecture notes. We thank also Compaq, Sun, IBM and Hewlett-Packard, who lent and maintained the (extremely efficient) computers. Particular thanks go to Patrick Begou (LEGI-Grenoble) for the huge energy he spent contacting the computer suppliers, setting up the computing centre, installing the machines, making them work perfectly during the programme, and (last but not least) de-installing everything at the end.

The practical organization provided by the Les Houches Physics School was very good (especially thanks to the efforts and the patience of Ghyslaine d'Henry, Isabel Lelièvre and Brigitte Rousset), with excellent housing conditions. The food was great, and the restaurant offered a very friendly atmosphere, thanks to Claude Cauneau and his staff, who prepared unforgettable fondues, raclettes and tartiflettes. The latter dish, made of Reblochon, an excellent and not very well known cheese, is excellent.

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