Marcello Lappa

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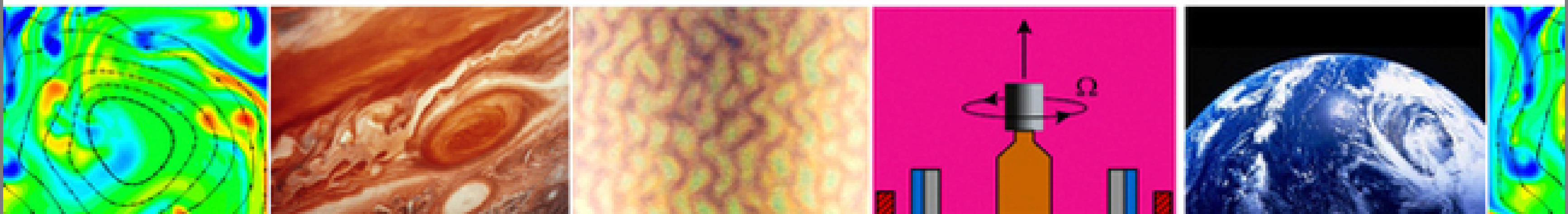
in Natural and Industrial Processes



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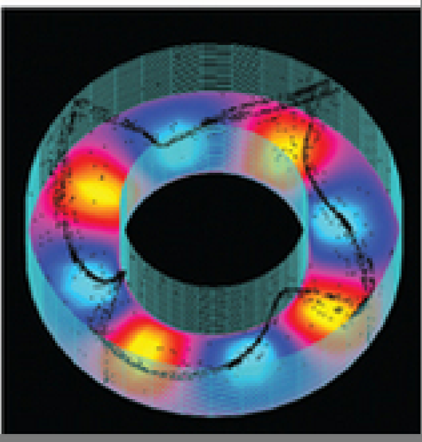

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To a red rose

Contents

Preface

The relevance of self-organization, pattern formation, nonlinear phenomena and non-equilibrium behaviour in a wide range of fluid-dynamics problems in *rotating systems*, somehow related to the science of materials, crystal growth, thermal engineering, meteorology, oceanography, geophysics and astrophysics, calls for a concerted approach using the tools of thermodynamics, fluid-dynamics, statistical physics, nonlinear dynamics, mathematical modelling and numerical simulation, in synergy with experimentally oriented work.

The reason behind such a need, of which the present book may be regarded as a natural consequence, is that in many instances pertaining to such fields one witnesses remarkable affinities between *large-scale-level processes* and the same entities on the *smaller* (laboratory) *scale*; despite the common origin (they are related to 'rotational effects'), such similarities (and the important related implications) are often ignored in typical analyses related to one or the other category of studies.

With the specific intent to extend the treatment given in an earlier Wiley text (*Thermal Convection: Patterns, Evolution and Stability*, Chichester, 2010, which was conceived in a similar spirit), the present book is entirely focused on *hybrid* regimes of convection in which one of the involved forces is represented by standard gravity or surface tension gradients (under various heating conditions: from below, from the side, etc.), while the other arises by virtue *of rotation*.

The analogies and kinships between the two fundamental classes of models mentioned above, one dealing with issues of complex behaviour at the laboratory (technological application) level and the second referring to the strong nonlinear nature of large-scale (terrestrial atmosphere, oceans and more) evolution, are defined and discussed in detail.

The starting point for such a development is the recognition that such phenomena share an important fundamental feature, a group of equations, strictly related, from a mathematical point of view, to model mass, momentum and energy transfer, and the mathematical expressions used therein for the 'driving forces'.

Although other excellent monographs that have appeared in the literature (e.g. to cite the most recent ones: Marshall and Plumb, 2007, *Atmosphere, Ocean, and Climate Dynamics*, Academic Press; Vallis, 2006, *Atmospheric and Oceanic Fluid Dynamics*, Cambridge University Press) have some aspects in common with the present book, they were expressly conceived for an audience consisting of meteorologists.

Here the use of jargon is avoided, this being done under the declared intent to increase the book's readability and, in particular, make it understandable also for those individuals who are not 'pure' meteorologists (or 'pure' professionals/researchers working in the field of materials science), thereby promoting the exchange of ideas and knowledge integration.

In this context, it is expressly shown how the aforementioned isomorphism between small and large scale phenomena becomes beneficial to the definition and ensuing development of an integrated comprehensive framework, allowing the reader to understand and assimilate the underlying quintessential mechanisms without requiring familiarity with specific literature on the subject.

A Survey of the Contents

In Chapter 1 the main book topics are placed in a precise theoretical context by introducing some necessary notions and definitions, such a melange of equations and nondimensional numbers being propaedeutical to the subsequent elaboration of more complex concepts and theories.

Chapter 2 deals with *Rayleigh–Bénard convection* in simplified (infinite and finite) geometrical models, which is generally regarded as the simplest possible laboratory system incorporating the essential forces that occur in natural phenomena (such as circulations in the atmosphere and ocean currents) and many technological applications (too numerous to list).

The astonishing richness of possible convective modes for this case is presented with an increasing level of complexity as the discussion progresses, starting from the ideal case of a system of infinite (in the horizontal direction) extent in which the role of centrifugal force is neglected (with related phenomena including the Küppers–Lortz instability, domain chaos, the puzzling appearance of patterns with square symmetry, spiral defect chaos and associated dynamics of chiral symmetry breaking), passing through the consideration of finite-sized geometries and the reintroduction of the centrifugal force, up to a presentation of the myriad of possible solutions and bifurcations in cylindrical containers under the combined effects of vertical (gravity), radial (centrifugal) and azimuthal (Coriolis) forces.

Similar concepts apply to the case of convection driven by internal heating in rotating self-gravitating spherical shells (Chapter 3), whose typical manifestation under the effect of radial buoyancy is represented by an unsteady *columnar mode* able to generate differential rotation under given circumstances. Exotic modes of convection (such as hexagons, oblique rolls, hexarolls, knot convection and so on) are also reviewed and linked to specific regions of the parameter space.

Then, attention is switched from rotating systems with bottom (or internal) heating to laterally heated configurations (temperature gradient directed horizontally, gravity directed vertically), which leads in a more or less natural way to the treatment of so-called *sloping convection* (Chapter 4), known to be the dominant mechanism producing large-scale spiralling eddy structures in Earth's atmosphere, but also eddy structures and wavy patterns in typical problems of crystal growth from the melt.

Apart from providing a general overview of so-called *quasigeostrophic theory*, Chapter 5 also gives some insights into the fundamental difference between the two main categories of fluid-dynamic instabilities in rotating fluids: one associated with problems for which the unstable modes essentially involve *mass and temperature redistribution* (e.g. Rayleigh–Bénard or Marangoni–Bénard convection considered in Chapters 2 and 7, respectively); and the other including problems such as stably stratified and unstratified shear instabilities, *barotropic and baroclinic instabilities*, which appear to be connected to the *self-excitation of waves* rather than to the direct redistribution of mass and temperature.

A number of works are reviewed, which focus on the mechanism by which mechanical and wave signals interplay to control how individual convective structures decide whether to grow, differentiate, move or die, and thereby promote pattern formation during the related process. Moreover, starting from the cardinal concept of the *Rossby wave*, some modern approaches, such as the so-called CRW (counter-propagating-Rossby-wave) perspective, an ingenious application of what has become known as 'potential vorticity thinking', are also invoked and used to elaborate a specific mathematical formalism and some associated important microphysical reasoning.

As a natural continuation of preceding chapters, Chapter 6 develops the important topic of *geostrophic turbulence*.

The basic ideas of inertial range theory are illustrated and extended phenomenologically by incorporating ideas of vortex–vortex and vortex–strain interactions that are normally present in physical and not spectral space. Then, a critical analysis of the distinctive marks of geostrophic turbulence (and its relationship with other classical models of turbulence) is developed. The main theories for *jet formation* and stability are discussed, starting from the fundamental concept of turbulent 'decascade' of energy. Subsequent arguments deal with the role played in maintaining turbulence by baroclinic effects and/or other types of 3D instabilities and on the so-called *baroclinic life cycle*. An overview of the main characteristic wavenumbers and scales relating to distinct effects is also elaborated.

Similarities between Earth's phenomena and typical features of *outer planet* (Jupiter and Saturn) dynamics are discussed as well. After the exposition of the general theory for vortex–vortex coalescence, a similar treatment is also given for phenomena of wave–wave and wave–mean-flow interference.

The remaining chapters are entirely devoted to phenomena occurring on the lab scale, thereby allowing most of the arguments introduced in earlier chapters *to spread from their traditional heartlands of meteorology and geophysics to the industrial field* (and related applications).

Along these lines, Chapter 7 is concerned with the interplay between rotation and flows induced by surface tension gradients (more specifically, *Marangoni–Bénard convection* and so-called *hydrothermal waves*, considered as typical manifestations of surface-tension-driven flows in configurations of technological interest subjected to temperature gradient *perpendicular or parallel*, respectively, to the liquid/gas interface).

The modification of the classical hydrothermal mechanism due to rotation, in particular, is discussed on the basis of concepts of system invariance breaking (due to rotation) and of the fundamental processes allowing waves to derive energy from the basic flow (an interpretation is given as well for still unexplained observations appeared in the literature).

Chapter 8 provides specific information on cases with important background applications in the realm of crystal growth from the melt, for example the Bridgman, floating zone and Czochralski (CZ) techniques, considering, among other things, the interesting subject of *interacting baroclinic and hydrothermal waves*, together with an exposition of the most recent theories about the origin of the so-called *spoke patterns*.

The CZ configuration is used as a classical example of situations in which fluid motion is brought about by different coexisting mechanisms: Marangoni convection, generated by the interfacial stresses due to horizontal temperature gradients along the free surface and gravitational convection driven by the volumetric buoyancy forces caused by thermally and/or solutally generated density variations in the bulk of the fluid, without forgetting the presence of phenomena of a rotational nature (baroclinic instability) and those deriving from temperature contrasts induced in the vertical direction by radiative or other (localized) effects.

The exposition of turbulence given in Chapter 6 about typical planetary dynamics is *extended* in this chapter to topics of crystal growth showing commonalities and differences due to 'contamination' exerted on the geostrophic flow by effects of surface-tension or gravitational nature (thermal plumes and jets).

Then a survey is given of very classical problems in rotating fluids which come under the general heading of *differential-rotation-driven flows*. This subject includes a variety of prototypical laboratory-scale models of industrial devices (among them: centrifugal pumps, rotating compressors, turbine disks, computer storage drives, turbo-machinery, cyclone separators, rotational viscometers, pumping of liquid metals at high melting point, cooling of rotating electrical motors, rotating heat exchangers, etc.).

Rotating magnetic fields are also considered (Chapter 9) as a potential technological means for counteracting undesired flow instabilities. Some attention is also devoted to so-called *swirling flow* and related higher modes of convection (Taylor-vortex flow, Görtler vortices, instabilities of the Bodewadt layer, etc.).

Last, but not least, a synthetic account is elaborated for flows produced by *angular vibrations* (i.e. situations in which the constant rotation rate considered in earlier chapters is replaced by an angular displacement varying sinusoidally with time with respect to an initial reference position) and rocking motions (Chapter 10), which complements, from a theoretical point of view, the analogous treatment given in Wiley's earlier book on *Thermal Convection* (2010) of purely translational vibrations, and may be of interest for researchers and scientists who are now coordinating their efforts to conceive new strategies for flow control.

Acknowledgements

The present book should be regarded as a natural and due extension of my earlier monograph *Thermal Convection: Patterns, Evolution and Stability* (published by Wiley at the beginning of 2010) in which I presented a critical, focused and 'comparative' study of different types of thermal convection typically encountered in natural or technological contexts (thermogravitational, thermocapillary and thermovibrational), including the effect of magnetic fields and other means of flow control. That book attracted much attention and comments, as witnessed by the many reviews that have appeared in distinct important scientific journals (R.D. Simitev (2011) *Geophys. Astrophys. Fluid Dyn*., **105** (1), 109–111; A. Nepomnyashchy (2011) *Eur. J. Mech. – B/Fluids*, **30** (1), 135; A. Gelfgat (2011) *Cryst. Res. Technol*., **46** (8), 891–892; J. A. Reizes (2011) *Comput. Therm. Sci*., **3** (4), 343–344).

The success of the 2010 book and the express requests of many referees to 'complete' the treatment of thermal convection, including the influence of Coriolis and centrifugal forces, as well as the development of turbulence, led me to undertake the present new work, for which I gratefully acknowledge also the many unknown reviewers selected by John Wiley & Sons, who initially examined the new book project, for their critical reading and valuable comments.

Following the same spirit of the earlier 2010 monograph, I envisaged to consider both natural and industrial processes, and develop a common framework so to promote the exchange of ideas between researchers and professionals working in distinct fields (in particular between the materials science and geophysical communities).

Along these lines, deep gratitude goes to many colleagues around the world pertaining to both such categories for generously sharing with me their precious recent experimental and numerical data (in alphabetical order): Prof. R. Bessaïh, Prof. F.H. Busse, Prof. R.E. Ecke, Prof. A.Yu. Gelfgat, Prof. N. Imaishi, Prof. A. Ivanova, Prof. V. Kozlov, Dr. R.P.J. Kunnen, Prof. I. Mutabazi, Prof. P.B. Rhines, Prof. P. Read, Prof. V. Shevtsova, Prof. I. Ueno.

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Last but not least, I am also indebted to my wife Paola, to whom this book is dedicated. Writing is a solitary activity; nevertheless, her good humour, sensitivity and vitality have made this project a pleasure, especially in the evening and during weekends. This new treatise is largely due to her optimism, encouragement, and patience.

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