Cambridge University Press
978-1-107-04388-6 — Zonal Jets
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INTRODUCTION

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The World of Jets

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> To see a World in a grain of sand,
> And a Heaven in a wild flower,
> Hold Infinity in the palm of your hand,
> And Eternity in an hour.
>
> *Auguries of Innocence*
> WILLIAM BLAKE (1757–1827)

Planetary circulations are typically driven either by the thermal energy received from the primary star and/or from heat sources within a planet's interior. Via complicated conversion processes, this energy is transferred into the kinetic energy of atmospheric and oceanic circulations. Among many components of these circulations, jet flows, and especially zonal jets, i.e., those moving close to the east–west direction, are among the most fundamental 'building blocks'. Being constrained by angular momentum conservation, they can emerge as a result of directly or remotely applied body and/or surface forces, boundary conditions, wave interactions, etc.

Zonal jets are ubiquitous in geophysical and planetary systems. On some planets, such as Jupiter and Saturn, the jets are profoundly strong, their influence on the distribution of clouds is clearly visible even through relatively simple amateur telescopes, and their appearance is almost unchanging over hundreds of years since early observations. On other planets, such as Earth, some ocean jets are so weak and meandering that they are virtually undetectable without time averaging. Unsurprisingly, therefore, there is an ongoing discussion on whether or not such circulation features can even be characterised as jets.

Despite vast differences in the visual appearance of jets in various environments, their underlying physics is described by more or less the same equations, that are amenable to scaling from macroscopic planetary environments to room-sized laboratory experiments and, further, to the scales of zonal flows obtained in plasma devices such as tokamaks.

On rotating planets, many zonal jets owe their existence to the anisotropisation of kinetic energy transfer by the β-effect, where β is the meridional gradient of the Coriolis parameter $f = 2\Omega \sin\phi$ (where Ω is the planetary rotation rate and ϕ is latitude). Since β is determined by the planetary radius, a β-effect and, thus, zonal jets, generally pertain to the largest scales and fastest motions in a system. However, on planetary bodies with a very slow rotation, such as Venus and Titan, a fascinating phenomenon of superrotation occurs in their upper atmospheres where the zonal wind velocity far exceeds the velocity of the underlying surface and is, thus, at least partially decoupled from the planetary angular velocity.

Zonal jets play a critical role in the transfer of momentum and scalar substances (salt, heat, humidity, solids, gases, etc.) that determine patterns of weather and climate as well as air and water quality, dispersion of debris and aerosols, e.g., from dust storms or the spread of forest fires, and so on. It is self evident that no improvement in our understanding and modelling capabilities of all these phenomena is possible without expanding our knowledge about jet flows and their interaction with the environment.

Figure 1.1 Pieter Bruegel the Elder, *The Tower of Babel*, 1563. Kunsthistorisches Museum Vienna, Picture Gallery. Copyright: KHM-Museumsverband.

Intense research over the last several decades produced a vast body of literature in the areas of the atmospheric and planetary sciences, physical oceanography, and experimental and plasma physics. However, a disconnect between different disciplinary areas and the use of different terminologies and jargon amongst their respective communities have significantly hampered cross-disciplinary research. Gradually, we have come to realise that we have been trying to conquer the World of Jets by building a Tower of Babel.

The famous painting by Pieter Bruegel the Elder, presented in Fig. 1.1, provides a historic allegory of the human propensity to build monumental intellectual towers with perplexing connections between the chambers and long dark corridors that seemingly lead nowhere.

This book can therefore be viewed as a 'tourist guide', helping to navigate wandering readers between the chambers and corridors of the Zonal Jets edifice. It would likely be a task comparable to the labours of Sisyphus for a single author to cover all aspects of jet flows. Instead, we have opted to solicit contributions from many leading scientists who have been active in the recent development of theories of jet formation and maintenance in a number of different disciplines, and are continuing to work on improving the understanding of their dynamics in different environments. The author selection grew out from the original core team of 14 scientists who participated in a study programme at the International Space Sciences Institute (ISSI) in Bern, Switzerland, with the majority affiliated with European institutions. We are extremely grateful to ISSI for providing us with the opportunity to convene such a team. But it rapidly became clear, especially when the links and connections between geophysical jets and those in magnetised plasmas became apparent, that the task that faced us in developing this book demanded input from an even wider group of authors. We were therefore delighted that so many distinguished scientists from these many disciplines were sufficiently interested and motivated to contribute to this project.

It has long been recognised that turbulence plays a paramount role in the dynamics of planetary circulations. Defant (1921), for instance, stated that ‘The idea that the mid-latitude flow can be regarded as pronounced grand-scale turbulence should not be viewed all too venturous’ (a loose translation from the German; see Birner et al., 2013). Over the years, with the publication of seminal works by L. F. Richardson and A. N. Kolmogorov (see, e.g., Frisch, 1995), appreciation of the role of turbulence has been steadily increasing. Eady (1950) stated that ‘Any theory of the atmospheric circulation must be based on a theory of (large-scale) atmospheric turbulence. Moreover, this theory must go deeper than most existing theories of turbulence. It is futile to beg the question by introducing hypothetical coefficients of eddy-transfer. We have not only to establish the cause of the turbulence but also to derive from first principles its properties with regard to transfer of heat, angular momentum, etc.’

These visionary remarks have permeated all subsequent developments of geophysical and planetary fluid dynamics and have guided, either explicitly or implicitly, the progress of our understanding of the dynamics of zonal jets. The impact of these remarks can certainly be felt throughout this book.

Following this introduction, the book contains six parts that take the reader on a journey, first to review numerous manifestations of zonal jets in natural and laboratory environments; then to discuss a number of basic instabilities that give rise to zonal jet flows; concluding with an elaboration of analytical theories that explain numerous features of the dynamics of jets, and expounding upon the various diffusion processes associated with jets. While almost every chapter begins with its own introduction, a general overview, presented below, describes the overall structure of the book.

Part II provides a detailed discussion of zonal jets in a variety of environments of the Solar System and beyond. Chapter 2 elaborates upon terrestrial atmospheres (Venus, Earth, Mars and Titan, the largest, albeit slowly rotating, satellite of Saturn; ‘terrestrial’ is understood here in a broad sense as pertaining to planetary bodies with a solid surface); Chapter 3 deals with the Earth’s oceans; Chapter 4 is dedicated to the atmospheres and interiors of the giant planets, while Chapter 5 focuses on jets that might exist on extrasolar (or exo-) planets and stars.

Jet flows in each of these environments present their own challenges, both to observe and to explain, and Part II covers their entire gamut, from very weak jets in the oceans, particularly in the subtropics, to very strong jets on giant planets, especially on their equators, and to superrotating zonal flows on Venus and Titan. In the general account, Part II presents a comprehensive snapshot of the state of the art in observations and interpretations of zonal jets across geophysics and planetary science. Since Part II sets the tone for the rest of the book, particular attention was paid to the connections between the chapters within that part and with other chapters in the book.

Part III considers jets in various laboratory environments. Chapter 6 provides a general overview and discusses scaling arguments. Chapter 7 presents a synopsis of some experiments on the spontaneous development of zonal jets in rotating convection, using the largest available rotating flow facility at the Coriolis laboratory at Laboratoire des Écoulements Géophysiques et Industriels (LEGI) in Grenoble, France. Chapter 8 describes some further experiments on eddy-driven zonal jets using a facility that utilises altimetry for measurements of the surface velocities, a technique that is quite similar to the satellite altimetry in physical oceanography. Chapter 9 elaborates upon another facility in which zonal jets are produced by externally imposed electromagnetic forcing. This facility allows one to bypass the instabilities leading to the creation of zonal jets and rather concentrate on the jets’ dynamics.

Part IV is concerned with zonal flows in magnetically confined plasmas. Chapters 10 and 11 respectively discuss theoretical and experimental developments in this area.

Part V surveys various instabilities leading to the formation of zonal jets. It starts with Chapter 12, presenting a beautiful general mathematical theorem showing that flows on a rotating sphere have a natural propensity towards zonation, i.e. to self-organise into zonal flows. The rest of the chapters in this part are arranged in order of increasing complexity. Chapter 13 is a discussion about the generation and maintenance of zonal jets in barotropic flows under the rigid lid approximation, i.e., in the limit of an infinite Rossby deformation radius. That chapter presents a classification of different flow regimes on a β-plane in terms of the zonostrophy index, R_β, and introduces the notion of zonostrophic turbulence. This classification is used to explain and quantify the ‘latency’ of oceanic jets and the strength and robustness of zonal jets on giant planets. Chapter 14 extends this analysis to flows with a finite Rossby radius. The two chapters that follow, Chapters 15 and 16, detail the sequence of basic instabilities, both radiating and modulational, i.e. primary and secondary, that facilitate the formation of zonal jets. Chapter 17 elaborates upon the emergence of elongated zonal structures, the so-called β-plumes, in response to a localised forcing that may be induced by various sources. Chapter 18 is concerned with off-zonal and meridional jet propagation, while the focus in Chapter 19 is on the effects of baroclinicity.

Part VI presents a collection of analytical and statistical results on the genesis and maintenance of zonal jets. Most of these results are relatively recent, as they are related to the developments in other areas of statistical hydrodynamics. Chapter 20 provides an extensive introduction to statistical theories of turbulence. Chapter 21 reviews progress made in utilising the method of direct statistical simulation (DSS) as applied to describe the formation and statistical dynamics of jets. This approach can be used to explore the range of validity of quasi-linear approximations applied to describe eddy-driven jet dynamics. Chapter 22 poses the question ‘Why do zonal jets form so often in turbulent flows dominated by geostrophic balance, and do they have universal properties?’ and addresses it using the methods of equilibrium statistical mechanics. Chapter 23 demonstrates that the emergence of jets in flows containing Rossby or plasma drift waves can be explained by the presence of new quadratic invariants such as the zonostrophy (as suitably defined). Chapter 24 describes the application of the kinetic and quasi-linear theories to understand jet dynamics. The basic assumption here is that jet formation and maintenance constitute a regime in which velocity fluctuations around the base jet are very small in magnitude compared to the jet velocity itself. Such jets are continuously dissipated and forced by weak, nonzonal turbulent motions maintained by diverse sources. Chapter 25 applies statistical state dynamics (SSD) as an alternative to more traditional methods. The utility of this method is underscored by its application to a turbulent shear flow, where the SSD helped to unearth mechanisms that were previously obscure, particularly those arising from cooperative interactions among disparate turbulent scales. Chapter 26 continues the use of statistical methods to investigate the physics of zonal jets. Here, the motivation is to understand the behaviour of turbulence-driven zonal flows in magnetised plasmas. Plasmas possess their own host of complexities that are distinct from those of geophysics, including the mass differences of ions and electrons, kinetic effects such as wave–particle resonances, and electromagnetic effects. It is a marvel that despite the immense disparities between laboratory plasmas and planetary atmospheres, similar physics in each conspires to organise regular flow patterns out of turbulence. Finally, Chapter 27 treats the emergence of coherent structures in a homogeneous turbulent background as a bifurcation phenomenon. This chapter's results provide an example of a situation where a large-scale structure in barotropic turbulence, either a zonal jet or a nonzonal coherent structure, emerges and is maintained by the systematic self organisation of the turbulent Reynolds stresses by spectrally nonlocal interactions in the absence of a turbulent cascade. These results may provide a theoretical background for Chapter 18.

Part VII deals with diffusion and transport processes in flows with zonal jets. Chapter 28 analyses material transport in flows with eddies and jets, taking into account the interactions between these two flow components in oceans and atmospheres. Among many examples of the important effects of oceanic eddies are the maintenance of the stratification in the Antarctic Circumpolar Current (ACC) and of the Northern Hemisphere thermocline and control of the penetration of transient atmospheric gases into the North Atlantic. In the atmosphere, the importance of the mid-latitude eddy-induced transport for the meridional temperature structure has long been recognised; eddy mixing is widely believed to play a key role in tracer distribution. Chapter 29 relates diffusion processes in flows with jets to the dynamics of anisotropic turbulence. It is shown that the scales of flow anisotropisation can be related to the scales of transition between the regimes of Richardson and Taylor diffusion. Based upon this, the concept of dynamics–transport duality is developed. Within this concept, information on dynamics and diffusion may be interchangeable. The concept applies not only to flows with Rossby waves but also to those with internal waves. The usefulness of this concept was demonstrated by contrasting the vertical diffusion of a tracer in the ACC and the meridional diffusion of Comet Shoemaker–Levy 9 (SL9) debris in Jupiter's stratosphere.

This book provides a comprehensive survey of, and introduction to, both the phenomenology of zonal jet formation within fluid and plasma systems and the theory underpinning our current understanding of how and why they develop. Science has come a long way in elaborating this understanding, yet it remains an important and active field of research. We hope that this book will help future generations of researchers and students to gain a broad and deep appreciation of this field and the many interdisciplinary links that connect what may at first appear as very different problems involving zonal jets.