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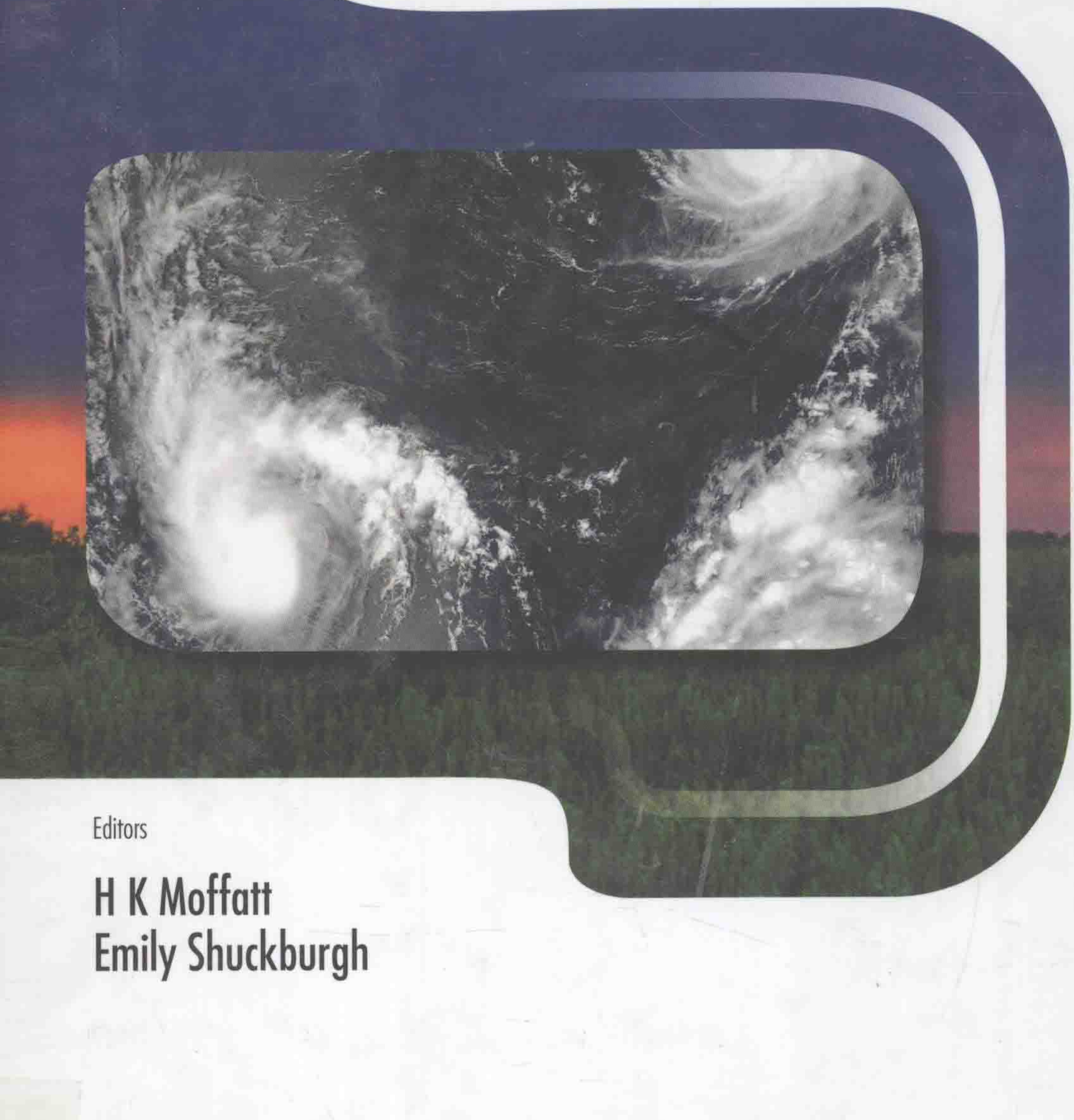

Editors

H K Moffatt
Emily Shuckburgh

ENVIRONMENTAL HAZARDS

The Fluid Dynamics and Geophysics of Extreme Events

Lecture Notes Series, Institute for Mathematical Sciences,
National University of Singapore
Vol. 21

ENVIRONMENTAL HAZARDS

The Fluid Dynamics and Geophysics of Extreme Events

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藏书章

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ENVIRONMENTAL HAZARDS
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Foreword

The Institute for Mathematical Sciences at the National University of Singapore was established on 1 July 2000. Its mission is to foster mathematical research, both fundamental and multidisciplinary, particularly research that links mathematics to other disciplines, to nurture the growth of mathematical expertise among research scientists, to train talent for research in the mathematical sciences, and to serve as a platform for research interaction between the scientific community in Singapore and the wider international community.

The Institute organizes thematic programs which last from one month to six months. The theme or themes of a program will generally be of a multidisciplinary nature, chosen from areas at the forefront of current research in the mathematical sciences and their applications.

Generally, for each program there will be tutorial lectures followed by workshops at research level. Notes on these lectures are usually made available to the participants for their immediate benefit during the program. The main objective of the Institute's Lecture Notes Series is to bring these lectures to a wider audience. Occasionally, the Series may also include the proceedings of workshops and expository lectures organized by the Institute.

The World Scientific Publishing Company has kindly agreed to publish the Lecture Notes Series. This Volume, "Environmental Hazards: The Fluid Dynamics and Geophysics of Extreme Events," is the twenty-first of this Series. We hope that through the regular publication of these lecture notes the Institute will achieve, in part, its objective of promoting research in the mathematical sciences and their applications.

January 2011

Louis H. Y. Chen
Ser Peow Tan
Series Editors

Preface

Natural environmental hazards, and their potentially disastrous consequences, have been increasingly prominent over the last decade. Chief among these are perhaps the great Sumatra-Andaman tsunami, triggered by the earthquake of 26 December 2004, which devastated large parts of the coastline of the Indian Ocean; Hurricane Katrina in the Gulf of Mexico in August 2005 with its deadly consequences for the city of New Orleans; and the catastrophic flooding in Pakistan following the exceptional monsoon rains of July–August 2010. Such geophysical phenomena have their origin in the dynamics of ocean and atmosphere on the large scales on which Coriolis effects associated with the Earth's rotation can be of dominant importance. In seeking to mitigate the disastrous consequences of such natural hazards, it is necessary to understand the fundamental fluid dynamical principles that underlie these awe-inspiring phenomena of nature. The extent to which climate change may influence the frequency and intensity of such phenomena is of course a matter of great concern, with major political implications at a global level.

It will be no surprise therefore that one of the current priority areas of the International Council for Science (ICSU) is "Natural and Human-Induced Environmental Hazards and Disasters;" and it was under this heading that a grant was awarded to two of ICSU's International Scientific Unions (IUTAM, the International Union of Theoretical and Applied Mechanics, and IUGG, the International Union of Geodesy and Geophysics) to hold a two-week Spring School (19 April–2 May 2009) on the subject "Fluid Dynamics and Geophysics of Environmental Hazards." The School, supported by ICSU's Regional Office for Asia and the Pacific Region (ROAP) in Kuala Lumpur, was aimed at graduate students and young post-docs in mathematics, physics or engineering, from Asia and the Pacific Region, with the aim of encouraging them to undertake research in this field. It was held at the Institute for Mathematical Sciences (IMS) of the National University of Singapore, attracting some 50 students from

Australia, Indonesia, Philippines, Vietnam, Malaysia, China, Japan, Korea, Bangladesh, Pakistan, India, Sri Lanka, Georgia, and Iran, as well as a number from Singapore itself (see Fig. 1).

Nine short courses of lectures were presented during morning sessions of the School; Chapters 1–9 of this volume contain the written versions of these lectures. Seminars on relevant topics were also held; one of these, on "Rogue Waves" is included in Chapter 10.

By way of supplementary activity related to the lecture courses, the students undertook research activity on nine different projects proposed by the lecturers. For this purpose, the students were divided into groups, four or five students in each group. The students worked on these projects, with guidance from the lecturers, in afternoon sessions during the first week of the School, and made presentations of their results during the afternoon sessions of the second week. Their reports are available on the School website http://www.ims.nus.edu.sg/Programs/09fluidss/index.htm. The students were uniformly enthusiastic about this style of project work, which promoted an unusual degree of international and interdisciplinary collaborative activity, and opened up research projects for the students to pursue in more depth in the future.

Three posters were prepared in advance of the School in both English and Chinese versions, for wide circulation to schools and universities. We are grateful to Andrew Burbanks (University of Portsmouth, UK) for help in the design of these posters, to Weizhu Bao (NUS) who provided the Chinese translations, and to World Scientific who printed the posters and donated them free of charge for the benefit of the School. Versions of these posters are reproduced in the following pages (see Figs. 2 to 4).

We wish to express our thanks also to Louis Chen, Director of IMS, for his constant support and encouragement and for the financial support provided by IMS for the School; and to the local organizing committee, particularly its co-chairs Boo Cheong Khoo (NUS) and Pavel Tkalich (NUS). Finally, we thank Sue Liu and Emma Boland (DAMTP, Cambridge) who have provided invaluable assistance in text preparation; and Sarah Haynes of World Scientific for her patience and understanding throughout the publication process.

September 2010

Keith Moffatt
University of Cambridge, UK

Emily Shuckburgh
British Antarctic Survey, Cambridge, UK
Editors

Fig. 1. Participants of the Spring School. *Front row, from left to right*: A. W. Jayawardena, Gerd Tetzlaff, Pavel Tkalich, Kerry Emmanuel, Ser Peow Tan, Louis Chen, Keith Moffatt, Tieh Yong Koh. Photo by Jolyn Wong.

IUTAM

IUGG
International Union of Geodesy & Geophysics

ims

ICSU

自然和人为的环境灾难

tsunami

Earthquake-triggered ocean waves
that threaten catastrophic destruction

2004年的Sumatra - Andaman大地震和海啸导致泛印度洋沿岸社区的巨大破坏。流体力学将提供对海啸现象的理解。这将为建立快速和准确海啸预警系统提供理论和技术支持。

地球的岩石圈是由被断层分隔开的巨大的板块所构成。在断层处缓慢积聚起的应力能导致板块间的突然相对移动，也就是地震。大地震在一个相当大的区域上释放巨大的能量。当地震发生在海洋下，它能导致海平面的相对涨落即产生海洋波。

这种海洋波沿海面以gh 的平方根为速度往外传播，其中g是重力加速度，h是当地海洋深度（这种表面波的波长与h成正比）。当这种波逼近海岸线时，由于能量守恒，它的振幅变得很高，并分裂成一系列具有巨大破坏能量的波浪，这就是海啸。

Graduate Spring School
Fluid Mechanics and Geophysics of Environmental Hazards
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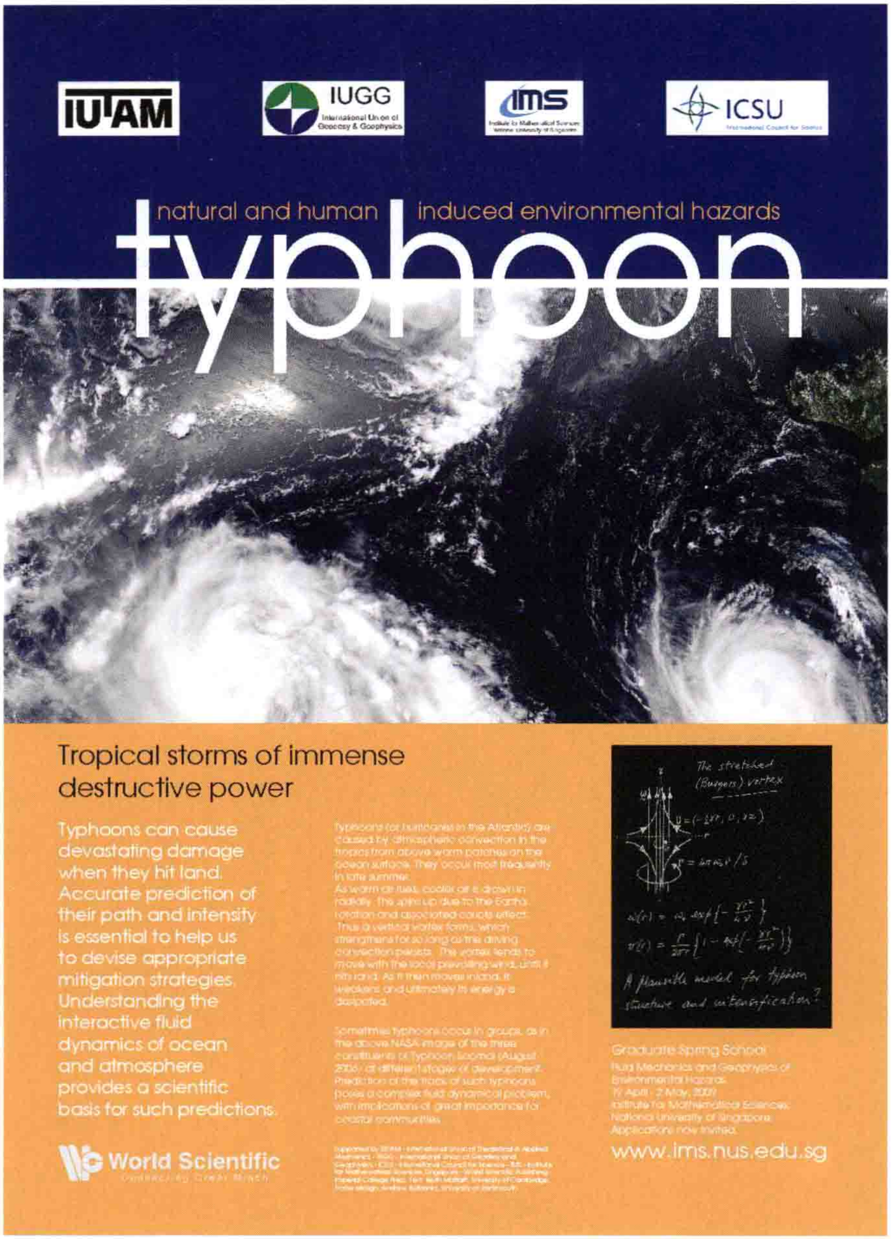
Supported by IUTAM - International Union of Theoretical & Applied Mechanics - IUGG - International Union of Geodesy and Geophysics - ICSU - International Council for Science - IMS - Institute for Mathematical Sciences, Singapore - World Scientific Publishing - Imperial College Press. Text: Keith Moffatt, University of Cambridge. Photograph: David Rydevik. Chinese translation: Bao Weizhu. Poster design: Andrew Burbanks, University of Portsmouth.

Fig. 2. Tsunami poster: Chinese version.



natural and human induced environmental hazards

typhoon

Tropical storms of immense destructive power

Typhoons can cause devastating damage when they hit land. Accurate prediction of their path and intensity is essential to help us to devise appropriate mitigation strategies. Understanding the interactive fluid dynamics of ocean and atmosphere provides a scientific basis for such predictions.

Typhoons (or hurricanes in the Atlantic) are caused by atmospheric convection in the tropics from above warm patches on the ocean surface. They occur most frequently in late summer.
As warm air rises, cooler air is drawn in radially. This spins up due to the Earth's rotation and associated Coriolis effect. Thus a vertical vortex forms, which strengthens for so long as the driving convection persists. The vortex tends to move with the local prevailing wind, until it hits land. As it then moves inland, it weakens and ultimately its energy is dissipated.

Sometimes typhoons occur in groups, as in the above NASA image of the three constituents of Typhoon Saomai (August 2006) at different stages of development. Prediction of the track of such typhoons poses a complex fluid dynamical problem, with implications of great importance for coastal communities.

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Fig. 3. Typhoon poster.

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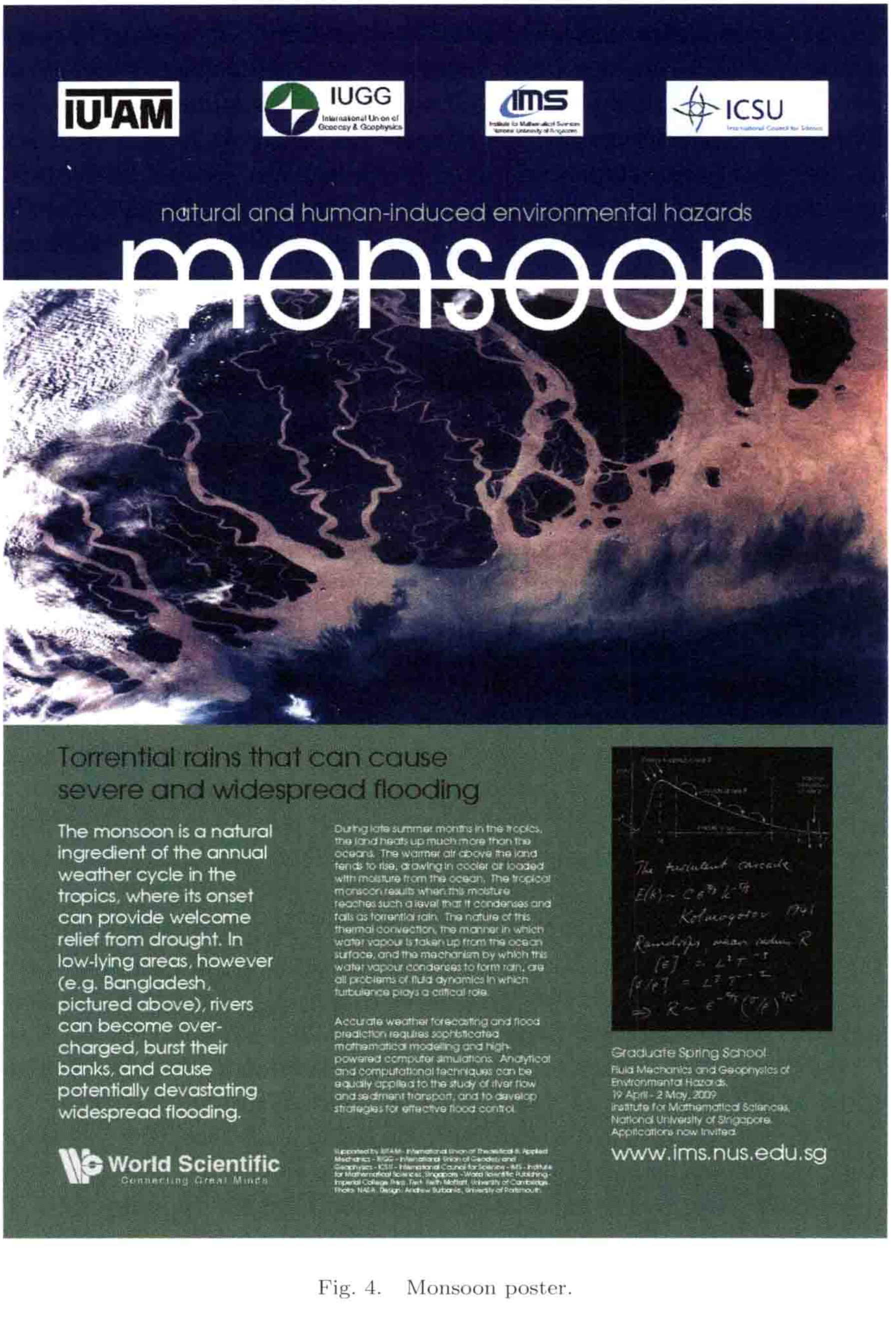

natural and human-induced environmental hazards

monsoon

Torrential rains that can cause severe and widespread flooding

The monsoon is a natural ingredient of the annual weather cycle in the tropics, where its onset can provide welcome relief from drought. In low-lying areas, however (e.g. Bangladesh, pictured above), rivers can become over-charged, burst their banks, and cause potentially devastating widespread flooding.

During late summer months in the tropics, the land heats up much more than the oceans. The warmer air above the land tends to rise, drawing in cooler air loaded with moisture from the ocean. The tropical monsoon results when this moisture reaches such a level that it condenses and falls as torrential rain. The nature of this thermal convection, the manner in which water vapour is taken up from the ocean surface, and the mechanism by which this water vapour condenses to form rain, are all problems of fluid dynamics in which turbulence plays a critical role.

Accurate weather forecasting and flood prediction requires sophisticated mathematical modelling and high-powered computer simulations. Analytical and computational techniques can be equally applied to the study of river flow and sediment transport, and to develop strategies for effective flood control.

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Fig. 4. Monsoon poster.

Contents

Chapter 1

A Brief Introduction to Vortex Dynamics and Turbulence

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The emphasis in this short introductory chapter is on those fluid dynamical phenomena that are best understood in terms of convection and diffusion of vorticity, the curl of the velocity field. Vorticity is generated at fluid boundaries and diffuses into the fluid where it is subject to convection, stretching, and associated intensification. Far from boundaries, viscous effects may be negligible, and then vortex lines are transported with the fluid. Vortex rings, which propagate under their own self-induced velocity, are a widely observed phenomenon, and a fundamental ingredient of fluid flow. Stretching and intensification is best illustrated by the "Burgers vortex" (the simplest model for a hurricane) in which these processes are in equilibrium with viscous diffusion. Instabilities of Kelvin–Helmholtz type are all-pervasive in highly sheared flow, and inexorably lead to transition to turbulence. In turbulent flow, the vorticity is random, but these fundamental processes still dictate many features of the flow. Fully three-dimensional turbulence is characterized by a cascade of energy through a broad spectrum from large scales to very small scales at which kinetic energy is dissipated by viscosity, a scenario that leads to the famous $(-5/3)$ Kolmogorov spectrum. These topics are reviewed and discussed with a view to geophysical applications. The phenomena of intermittency and concentrated vortices as revealed by direct numerical simulation are also briefly discussed.

1. Introduction

Vortex (or vorticity) dynamics is concerned with the manner in which swirling flows evolve in fluids when viscous (i.e., internal friction) effects are relatively weak, and can be neglected in a first approximation. Such flows are controlled largely by inertial effects. An understanding of vortex dynamics is an essential preliminary to a consideration of turbulent flows in which the vorticity distribution is a highly complex function of position. Its time evolution is most easily understood through the statement that "vortex lines are frozen in the fluid," i.e., they are transported with the flow like material curves of fluid particles. This is not quite the whole story however, because, insofar as the flow may be treated as incompressible, the vorticity is intensified as the vortex lines are transported, in proportion to the stretching of vortex line elements. This stretching is very persistent in a turbulent flow, leading to very strong intensification of vorticity coupled with progressive decrease of the scale of variation of the flow, an effect usually described in terms of an "energy cascade." This cascade to small scales is ultimately controlled by viscosity, no matter how weak this physical property of the fluid may be; and one of the remarkable properties of turbulent flow is that the rate of dissipation of energy by viscosity is independent of the value of viscosity even in the limit as this tends to zero, and this is because the smallest scales of the flow adjust in just such a way as to dissipate the kinetic energy at the very rate at which it cascades down from the larger scales.

The central role of vorticity in describing fluid motion was recognized by Hermann von Helmholtz (1858), who first recognized the above crucial "frozen-in" property. The 150th anniversary of the publication of this seminal paper was marked by the IUTAM symposium *150 Years of Vortex Dynamics*, recently held at the Technical University of Denmark (Aref, 2010; the 50 papers contained in this volume provide an indication of the huge scope and applications of the subject). The theory of vorticity was taken up and enthusiastically developed by William Thomson (later Lord Kelvin) (1867; 1869 and many subsequent papers), who proposed that the atomic structure of the various elements might be explained in terms of knotted vortex tubes, whose "knottedness" would be conserved under frozen field evolution. Such structures turned out to be dynamically unstable, and Kelvin was ultimately obliged to abandon his theory of "vortex-atoms." Nevertheless, his pioneering investigations opened up the new field of hydrodynamic instability, providing important clues concerning the ubiquity of turbulent, as opposed to laminar, flows in all large-scale natural systems. Figure 1 shows Helmholtz and Kelvin around 1870, when both were at the height of their powers and creativity.

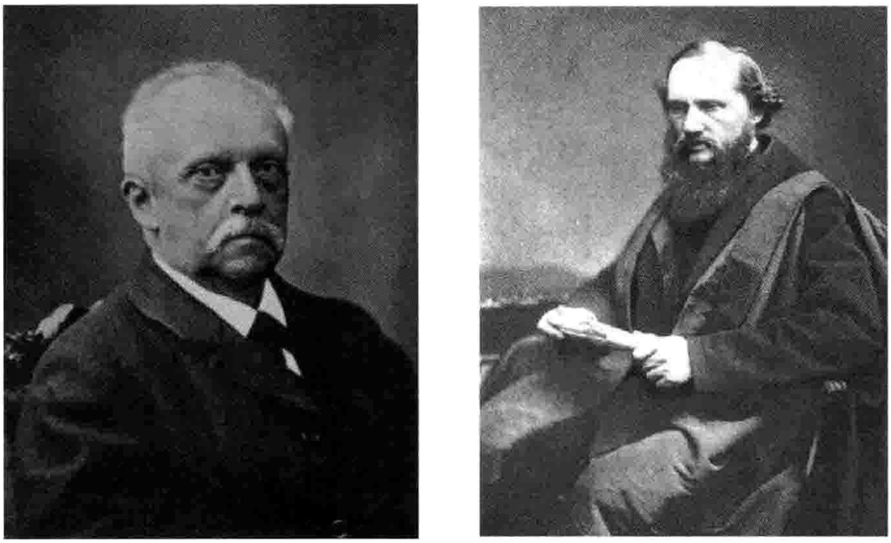

Fig. 1. Hermann von Helmholtz (left) and William Thomson (Lord Kelvin): The early pioneers of vortex dynamics.

2. Vorticity and the Biot–Savart Law

Let $\mathbf{u}(\mathbf{x}, t)$ be the velocity field in a fluid which fills all space. This is of course an idealization, relevant when we consider fluid behavior that is uninfluenced by remote fluid boundaries. We shall suppose further, for simplicity, that the fluid has uniform density ρ, and that it (or rather the flow) is incompressible, i.e., $\nabla \cdot \mathbf{u} = 0$. Under this approximation, sound waves are filtered out of the governing Navier–Stokes equations. The vorticity field $\boldsymbol{\omega}(\mathbf{x}, t)$ is defined by

$$\boldsymbol{\omega} = \nabla \times \mathbf{u}(\mathbf{x}, t)\,, \tag{2.1}$$

so that immediately $\nabla \cdot \boldsymbol{\omega} = 0$. We can conveniently think of "vortex tubes" in the flow, i.e., the set of vortex lines passing through any small material surface element δA. The "circulation" round such a tube is

$$\Gamma = \oint_C \mathbf{u} \cdot d\mathbf{x} = \iint_{\delta A} \boldsymbol{\omega} \cdot \mathbf{n}\, dA\,, \tag{2.2}$$

where C is a closed curve circling the tube once, and this is evidently constant, independent of the particular cross-section of the tube that is chosen (Fig. 2(a)). It is frequently stated that vortex lines must either be

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