Coherent Flow Structures at Earth's Surface

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Registered office: John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices: 9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
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Library of Congress Cataloging-in-Publication Data

Coherent flow structures at Earths surface / edited by Jeremy G. Venditti . . . [et al.].
p. cm.
Includes bibliographical references and index.
ISBN 978-1-119-96277-9 (cloth)
1. Turbulence. I. Venditti, Jeremy G., 1971-
TA357.5.T87C64 2013
551.3–dc23

2013014152

A catalogue record for this book is available from the British Library.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover image: patagonia_amo_2010355_lrg.jpg cover photo:
The western edge of the South Atlantic ocean gyre that brings warmer, saltier water from the subtropics where it collides with cooler fresher waters flowing up from the south. The currents meet at the eastern edge of the continental shelf, pulling nutrients up from the deep ocean and resulting in a phytoplankton bloom that highlights interfacial instabilities along the edges of the ocean currents. Captured with the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite on December 21, 2010. (Image courtesy of NASA's Earth Observatory, http://earthobservatory.nasa.gov/IOTD/view.php?id=48244).
ISS030-E-162344_lrg.jpg cover photo:
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Cover design by Gary Thompson

Set in 9.25/11.5pt Minion by Aptara® Inc., New Delhi, India

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Preface

Understanding fluid flow at Earth's surface is of central importance to understanding the dynamics of Earth's surface and its lower atmosphere. These geophysical flows, in environments ranging from deserts to forests and from rivers to the oceans and atmosphere, are structured across a wide range of spatial and temporal scales, from small-scale turbulent vortices generated at the boundaries and responsible for grain motion, to large-scale circulation patterns that generate atmospheric and geomorphic features visible from space. This book derives from a conference held at Simon Fraser University, Burnaby, British Columbia, Canada, 3–5 August 2011 entitled *Coherent Flow Structures in Geophysical Flows at the Earth's Surface*. The conference built on the success of an earlier meeting entitled *Coherent Flow Structures in Open Channel Flows* held at the University of Leeds, UK, in 1995, which produced a well-cited book of the same name (edited by Ashworth, Bennett, Best and McLelland and published in 1996 by John Wiley & Sons, Ltd). The 1995 conference launched an impressive array of research into the structure of fluid flows in rivers. The 2011 meeting had a wider scope than the earlier conference, expanding beyond rivers to flows in all natural environments at Earth's surface. The 2011 conference brought together the research community that uses numerical simulations, laboratory modelling and field observation to study coherent flow structures (CFS), their interaction with sediment, vegetation, and benthic communities, the manipulation of such flow structures for managing sedimentary environments, and the key roles they play in Earth surface dynamics.

The conference would not have been possible without the dedicated volunteer efforts of a small group of graduate students, postdocs and staff at Simon Fraser University including Maureen Attard, Ryan Bradley, Megan Hendershot, Caroline Le Bouteiller, Martin Lin, John Ng, Dan Shugar and Andrea Vigna. Justin Ankenmann from SFU Meeting, Event and Conference Services arranged many of the conference logistics and made the process much easier for the organizers. The US National Science Foundation (nsf.gov), the National Center for Earth Surface Dynamics (nced.umn.edu) and TSI (tsi.com) provided funds for student conference registration and accommodation, allowing an impressive, enthusiastic and motivated group of young researchers to attend the meeting. Additional funds for coffee breaks, lunches, keynote speaker travel costs, student awards and a field trip on the Fraser River were provided through generous support from the British Society for Geomorphology (geomorphology.org.uk), the Canadian Geomorphology Research Group (cgrg.geog.uvic.ca), Dantec Dynamics (dantecdynamics.com), Golder Associates Ltd. (golder.ca), LAVision (lavision.de), Met-Flow (met-flow.com), Nortek USA (nortekusa.com), Reson (reson.com), Rockland Scientific (rocklandscientific.com), Simon Fraser University (sfu.ca), SFU Geography (sfu.ca/geography/), SonTek/YSI (sontek.com), Teledyne RD Instruments (rdinstruments.com), the Jack and Richard Threet Chair at the University of Illinois at Urbana-Champaign (illinois.edu) and Wiley (wiley.com).

There were 107 abstracts submitted to the *Coherent Flow Structures in Geophysical Flows at the Earth's Surface* conference and it was not possible to produce a book with a chapter from each contributor. With this volume, the editors attempted to compile a group of contributions that represent the very best reviews and the most exciting new research presented at the meeting, and attempted also to achieve a breadth that covers the field so that this book might become a state-of-the-art treatment on CFS in flows at Earth's surface. Ultimately, this volume illustrates how the study of coherent flow structures is now being applied to geophysical flows at Earth's surface.

The first chapter represents the editors' attempt to define what a coherent flow structure is in geophysical flows and how the idea is currently being applied. In the second chapter, Ron Adrian describes the primary coherent flow structures identified in hydraulically smooth boundary layer flows at low Reynolds numbers. Chapters 3–5 deal with the dynamics of CFS in flows at Earth's surface. Subsequent chapters deal with CFS in airflows (6–8) and through vegetation canopies (6 and 9–11). New methods for examining CFS are reviewed in Chapters 12–14. The final group of chapters deals with coherent flow structures in sediment-transporting flows. This includes chapters on CFS in estuarine tidal flows (14 and 15), morphological scale CFS in rivers (16–18), the dynamic linkage between CFS and sediment movement (19 and 20), the statistical properties of turbulence in sediment transporting flows (21 and 22) and CFS associated with gravity currents (23 and 24).

The editors are extremely grateful to the volume contributors for all their hard work, cooperation and for making this book possible. Each paper was fully peer reviewed and, where possible, by someone who attended the conference and someone who did not. The editors thank this group of reviewers for their essential, yet uncredited, contribution to the volume. The staff at Wiley, especially Rachael Ballard, Fiona Seymour and Lucy Sayer, have been very helpful and supportive in bringing this volume to publication.

CFSII

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We hope that this volume, like its predecessor, will become an authoritative record of advances in our understanding of coherent flow structures in flows at Earth's surface and that it will set the stage for new research developments in the field.

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About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/venditti/coherentflowstructures

The website includes:

- Powerpoints of all figures from the book for downloading
- PDFs of tables from the book
- Animation videos

1 What is a Coherent Flow Structure in Geophysical Flow?

Jeremy G. Venditti,[1] Richard J. Hardy,[2] Michael Church,[3] & James L. Best[4]

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ABSTRACT

Definitions exist for what constitutes a coherent flow structure (CFS) in relatively low Reynolds number, smooth boundary flows, but there is no comprehensive nomenclature for the range of dominantly turbulent motions that can be observed in flows at, and near, the Earth's surface. Here, we discuss what defines a coherent flow structure in a geophysical flow and find that the structures typically referred to as CFS have some common characteristics. They generate Reynolds stress and turbulence intensity, and possess vorticity, which implies a rotational aspect to the structure. However, these are not defining characteristics of a CFS because there are other structures that exhibit some or all of these properties, such as persistent recirculation cells or secondary flow cells in rivers. What does appear important is that they must have temporal coherence *and* spatial coherence in addition to these properties, but the structures must also not be persistent features of the mean flow. We expand towards a broader definition of CFS beyond the fundamental structures identified in low Reynolds number, smooth boundary, flows to include the larger scale structures in geophysical flows (such as macroturbulent kolks and surface boils) and structures formed by shear instabilities. We also include morphological-scale motions like long-wavelength pulsations described by Marquis and Roy (Chapter 17, this volume) and the superstructures described by Marusic *et al.* (2010).

1.1 Introduction

The interactions amongst flow structure, mobile sediment and surface morphology have become of central importance in understanding the dynamics of the Earth's surface and lower atmosphere. Understanding such flows is also a key component of sustainable engineering design and construction, and in the maintenance of ecological habitats and their diversity. All such geophysical flows, in environments ranging from deserts to forests and from rivers to the oceans and atmosphere, are structured across a wide range of spatio-temporal scales, from small-scale turbulent vortices generated at the boundaries and responsible for grain motion, to large-scale circulation patterns that generate atmospheric and geomorphic features visible from space. Substantial advances have taken place since the early 2000s – in field studies, physical experimentation and theoretical/numerical modelling – which

Coherent Flow Structures at Earth's Surface, First Edition. Edited by Jeremy G. Venditti, James L. Best, Michael Church and Richard J. Hardy.

have greatly expanded our understanding of the dynamics of these flows, and the landscapes they sculpt, across this wide range of scales.

The 24 chapters that form this volume arise from a conference held at Simon Fraser University in August, 2011, entitled *Coherent Flow Structures in Geophysical Flows at the Earth's Surface*. The 2011 conference was predicated on the success of the *Coherent Flow Structures in Open Channel Flows* conference held in Leeds, United Kingdom, in 1995, which produced the seminal and well cited book of the same name (Ashworth *et al.*, 1996). The Leeds conference largely focused on coherent flow structures in rivers, and much of the work presented was focused on field observation and laboratory measurement, which were the most widespread approaches within the research field at that time. The 2011 conference broadened this theme and brought together the research community that uses field observation, laboratory modelling and theoretical/numerical simulations to study coherent flow structures, their interaction with sediment, vegetation, and benthic communities, the manipulation of such flow structures for managing sedimentary environments, and the key roles they play in Earth surface dynamics. This volume is a selection of papers from the conference, which illustrate how the study of coherent flow structures is now being applied to geophysical flows.

An issue that arose from the conference is that there is no clear definition of what constitutes a 'coherent flow structure' (CFS) in a geophysical flow. Although definitions exist for relatively low Reynolds number, smooth boundary flows (*cf.* Cantwell, 1981; Robinson, 1991; Adrian, 2007), there is no comprehensive nomenclature for the range of dominantly turbulent motions that can be observed in flows at and near the Earth's surface. It is evident that some common structures are routinely identified as coherent flow structures, but researchers working at different scales, or in different environments, often observe different types of structures. It is presently unclear whether all these structures have a common topology and/or origin. This problem of definition is not just an issue of semantics, and becomes more acute when examining complex geophysical flows in which there are many scales of fluid motion, some of which may be due to a particular coherent flow structure and some of which may be perceived as random motions in turbulent flow. In many geophysical flows, coherent flow structures cannot be directly observed and their presence can only be inferred from observations of velocity, heat flux or deformation of the boundary – for instance of plants or sediment. Observations may also be limited to a single Eulerian time series capturing a signature of fluid motions at a specific location. Identifying coherent flow structures within such a time series is not a simple task and the lack of a definition for coherent flow structures may limit their detection in a consistent manner. Furthermore, whether CFSs observed in a particular flow have any relation to CFSs observed in other flows is complicated by lack of a definition.

Here, we discuss what defines a coherent flow structure in a geophysical flow, but do not attempt to provide a definitive answer to this question. Instead, we draw on this volume of papers to identify some constraints on what constitutes a coherent flow structure. We begin with a discussion of CFS in low Reynolds-number flows that have been the focus in the fluid dynamics literature. We then consider CFS commonly identified in the geophysical flows considered in this volume, and highlight some of the distinguishing features of CFS in geophysical contexts. We conclude by listing some areas that we consider promising areas of research to build our understanding of CFS.

1.2 From random turbulence to coherent flow structures

Early researchers studying turbulence held the view that it was an irregular, random, chaotic, and unpredictable phenomenon that could only be understood through a statistical approach (Nezu and Nakagawa, 1993; Pope, 2000). This view formed the basis of Osborne Reynolds' approach of averaging the equations of motion for viscous flows (Reynolds, 1883), Taylor's statistical theory of turbulence (Taylor, 1935) and Kolmogorov's spectral description of turbulence (Kolmogorov, 1941). The latter viewed turbulent flows as being composed of large-scale motions that are strongly influenced by the geometry of the flow, and small-scale motions within the flow that are responsible for dissipating turbulent energy. This well-known spectral view of turbulence envisages transfers of energy from the mean flow to large-scale turbulent motions that may grow in a flow but ultimately break down to smaller scales, transferring energy from the larger scales to the smaller scales until eddies are small enough that they are dissipated by molecular viscosity (Figure 1.1). The transfer of energy, from the mean flow to large- and then small- scale motions is the mechanism by which flows are slowed by interactions with boundaries, and the source of flow resistance. While this approach has certainly been the most pervasive and successful framework for understanding turbulent

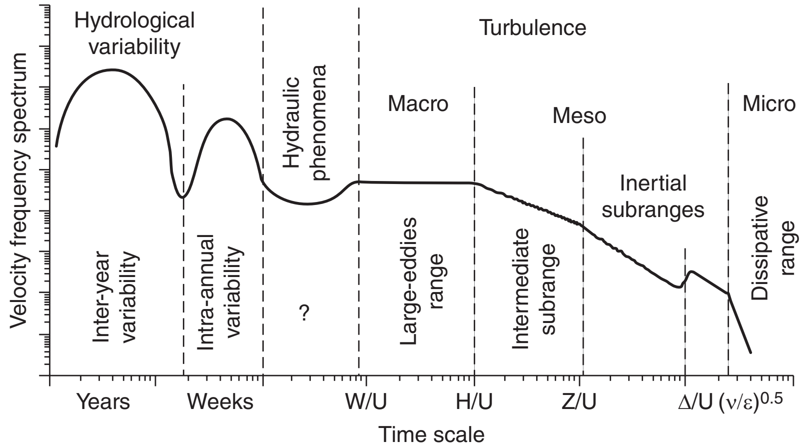

Figure 1.1 Velocity frequency spectrum of Nikora (2008). The spectrum is a conceptual model that shows the scale of variability in a river channel. It combines the scales of hydrological/climatic variability that drive flow variability in the channel and the turbulence spectum through a scale gap that corresponds to undefined hydraulic phenomena related to flow interactions with channel morphology, meanders and bars. The source of turbulent energy is the mean flow, which passes energy to turbulence via velocity shear and flow separation at the scale of the flow depth and roughness elements (bedforms, particle clasts, etc.). The macro scale corresponds to the largest eddies in the flow, which Nikora (2008) argues are clusters of bursts but could also be VLSM or long-wavelength pulsations of Marquis and Roy (this volume). The intermediate subrange corresponds to the scale of individual bursts, and the inertial subrange corresponds to regions where turbulent energy cascades from large eddies to small eddies without losing energy and exhibts the –5/3 slope typically exhibited by turbulence spectra. The dissipative micro-scale begins at the Kolmogorov microscale $(\nu/\varepsilon)^{0.5}$. W is the channel width, H is the flow depth, z is elevation above the boundary and Δ is the boundary roughness. Reprinted from Nikora, 2008, Copyright 2008, with permission from Elsevier.

flows within the past century, the morphology, structure and origin of motions embedded in the turbulent flow were largely ignored. However, with the many technological advances since the early 1970s, substantial research has been directed towards a deterministic approach to understanding turbulent flows, wherein the focus is on the fundamental self-organizing flow structures within a fluid. The central hypothesis behind this approach is that the spectral description of turbulence is a manifestation of the emergence, growth and decay of these flow structures. The macroscale of turbulence is thought to be related to these fundamental structures, which decay, passing energy to motions that become increasingly random at smaller scales (Figure 1.1). These fundamental structures have come to be known as *coherent flow structures* (Cantwell, 1981) and it is their organization that is thought ultimately to control the structure of turbulent flows.

There is, of course, a middle ground between these two approaches to understanding fluid motions. Townsend (1976) argued that the motions that generate Reynolds stresses are caused by anisotropic coherent flow structures attached to the boundary (the so-called 'attached eddies'). These CFS are surrounded by fluid that contains smaller scale, detached eddies that are statistically isotropic. Although detached eddies are thought to contribute little to the turbulence intensity and nothing to the Reynolds stresses, they dominate energy transfer to the dissipative viscous scales (Perry *et al.*, 1986; Perry and Li, 1990). In this perspective, detached eddies are viewed as the remnants of attached eddies after they have been stretched, distorted, and convected away from the near-wall region (Katul and Vidakovic, 1996).

There is an inherent attraction to understanding turbulence in geophysical flows with a deterministic perspective. Most researchers of geophysical flows use a heuristic approach. We can 'see' the scales of turbulence that affect transport and mixing of matter, momentum and heat and these are inevitably coherent motions. For example, sediment movement or waving flexible vegetation must be caused by coherent fluid motions because sediment and vegetation movements are coherent. Recognition of this requires some definition of CFS to facilitate discussion amongst various communities of investigators (e.g. fluid dynamicists, atmospheric scientists, oceanographers, geomorphologists, biologists) about CFS and the central role they play in Earth-surface morphodynamics.

A number of definitions of coherent flow structures have been proposed that have been widely adopted in the community (Cantwell, 1981; Robinson, 1991; Adrian, 2007). Robinson (1991) defined a CFS as a:

> three-dimensional region of the flow over which at least one fundamental variable (velocity component, density, temperature, etc.) exhibits significant correlation with itself or with another variable over a range of space and/or time that is significantly larger than the smallest scales of flow.

Adrian (2007), building on earlier work, defined coherent flow structures as follows:

> ... elementary organized motions ... can be thought of as individual entities if they persist for long times, i.e. if they possess temporal coherence. By virtue of fluid continuity, all motions possess some degree of spatial coherence, so coherence in space is not sufficient to define an organized motion. Only motions that live long enough to catch our eye in a flow visualization movie and/or contribute significantly to time averaged statistics of the flow merit the study and attention we apply to organized structures.

These definitions suffice for the examination of many structures but, in geophysical flows, there is a wide range of motions that possess spatial and temporal coherence, some of which may reasonably be judged to be properties of the mean flow, depending on the observer's perspective. Adrian and Marusic (2012) present a more discriminating definition, writing that

> coherent motions are recurrent, persistent motions that characterize the flow and play important roles in determining mean flow, stress and other statistical properties. They may have rotational and irrotational parts.

They go on to note that

> it suffices to think of coherent structures as building blocks of flows that are recognizable, despite randomness, by their common topological patterns, and that occur over and over again.

From these definitions, a preliminary definition of CFS in geophysical flows emerges as a fluid motion that has a recognizable spatial extent and persists for some period of time, contributing to the process under investigation (transport and/or mixing of matter, momentum and/or heat) and that is distinguishable from random motions in the flow. We build and refine this definition for geophysical flows by examining the CFS observed at low Reynolds numbers and then expand this definition by examining the CFS commonly observed in geophysical flows discussed in this volume, at a wider range of scales, in higher Reynolds-number flows.

1.3 Coherent flow structures in low Reynolds-number flows over smooth boundaries

It has long been recognized that among the principal structural components of turbulent flows are coherent flow structures variously known as hairpin, horseshoe, or cane vortices, which have been extensively studied in hydraulically smooth boundary flows at low Reynolds numbers (Figure 1.2). Smith (1996) provides a succinct review of research that led to the identification of such vortical structures within turbulent boundary layers. Adrian and Marusic (2012) recommend referring to these features as *turbines propensii* (inclined eddies) to avoid the connotation that they have a strict hairpin shape. Most of this past work has focused on low Reynolds number flows ($Re = U\delta/\nu < \mathrm{O}(10^3)$, where U is the mean velocity, δ is the boundary layer thickness, ν is the kinematic viscosity, for flows that are hydraulically smooth or transitional ($Re^* = u^* k_s/\nu < (10^1)$, where u^* is the shear velocity and k_s is a characteristic roughness height). Adrian (2007) attributes the first identification of *turbines propensii* to Theodorsen (1952), who visualized a filament of rotating fluid oriented perpendicular to the mean flow and perturbed by a small upward motion. This perturbed region of the filament is exposed to higher mean flow velocity, so it is convected downstream faster than the rest of the filament. This forms a rising head and trailing legs, in the form of a horseshoe or hairpin, which are stretched and intensified, causing the vortex to lift away from the wall. Smith (1996), Adrian (2007, this volume) and Adrian and Marusic (2012) provide excellent reviews of the structure of hydraulically-smooth boundary layers. Here, we provide a very brief summary of this structure.

Flow near the boundary is characterized by regions of low and high momentum fluid, or streaks, which are formed by counter-rotating, streamwise vortices (Smith, 1996). Where the counter-rotating motions diverge, a low-speed streak motion is formed because slower moving fluid is being carried away from the boundary. Where they converge, high-speed fluid is bought to the boundary forming a high-speed streak. Low-speed streaks intermittently lift away from the boundary into the flow in a violent bursting motion (Kline *et al.*, 1967; Smith, 1996).

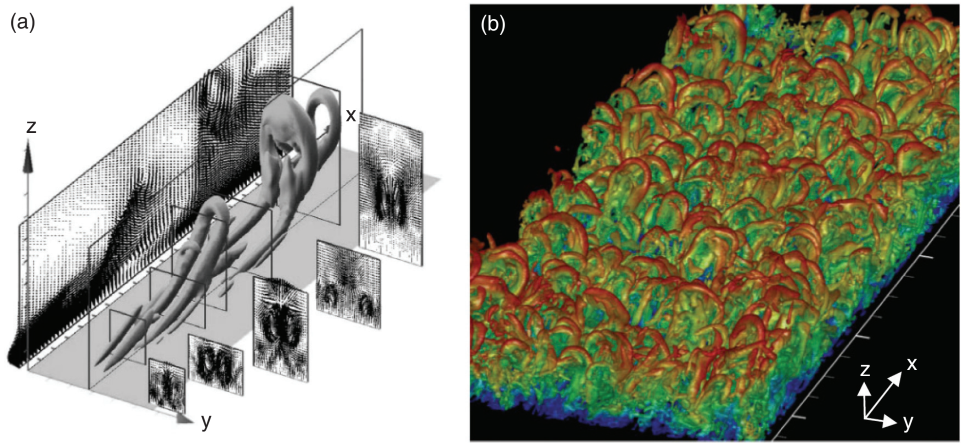

Figure 1.2 Realizations of direct numerical simulations showing hairpin vortices computed by (a) reprinted from Zhou *et al.*, 1999, with permission from Cambridge University Press and (b) reprinted from Wu and Moin, 2009, with permission from Cambridge University Press. The streamwise, spanwise and vertical directions are indicated by x, y and z.

The transverse spacing of low-speed streaks is constant across a wide range of Reynolds numbers when scaled on inner layer variables (u^*, k_s; Smith and Metzler, 1983), suggesting that, regardless of the geometry of the flow, these structures are confined to a thin layer near the boundary. The bursting motions are ejections of low-momentum fluid away from the bed, characterized by a local streamwise velocity deceleration, relative to the local mean, and an upward vertical velocity motion. Sweep motions accompany ejections and occur where the local streamwise velocity accelerates relative to the mean, and there is a vertically downward motion. Bursts drive low momentum fluid away from the boundary and sweeps drive high momentum fluid to the boundary.

These features of the flow enabled the proposition of a model for the structure of low Reynolds-number turbulent flows as being composed of low-speed streaks and quasi-streamwise vortices formed at the boundary, and hairpin-shaped vortices that develop at the boundary and advect fluid away from the boundary (see review in Smith, 1996). One of the surprising findings of the early work was that of Rao *et al.* (1971) who showed the bursting process scaled with variables that characterized the bulk (outer layer) flow properties (U_∞, δ, the subscript ∞ indicates the freestream or outer layer velocity) rather than inner layer properties (Cantwell, 1981). This poses a scale conundrum: how do bursts that originate in the inner layer grow to scale with outer layer variables? The problem is solved if hairpin vortices appear not to occur individually but are arranged into groups or 'hairpin packets'. These packets are formed when a hairpin emerges from the near boundary region with sufficient rotational strength, creating secondary hairpins upstream and downstream of the first (parent) hairpin, and then subsequent tertiary hairpins, in a process called *autogeneration* (Zhou *et al.*, 1996, 1999). These hairpin packets form the core of some conceptual models for the structure of smooth wall turbulent boundary layers. They also provide a mechanism by which features formed at the boundary can grow into structures that scale with the boundary layer depth.

Adrian (Chapter 2, this volume) uses these central ideas to describe the primary coherent flow structures as: (i) low-speed streaks and quasi-streamwise vortices, (ii) hairpin vortices and hairpin vortex packets, (iii) large-scale motions (LSM) and (iv) very large-scale motions (VLSM). Large-scale motions are bulges in the boundary layer, first observed by Falco (1977). Based on spectral considerations, Balakumar and Adrian (2007) suggest that LSM have wavelengths approximately three times the boundary layer thickness δ and rise up to about 0.5δ. Adrian (Chapter 2, this volume) debates whether vortex packets and LSM are the same structure, noting that evidence currently is lacking, but conceptually, the idea is appealing. Very large-scale motions were first discovered by Kim and Adrian (1999) in pipe flow and later examined in more detail by Guala *et al.* (2006). Balakumar and Adrian (2007) describe them as having wavelengths greater than 3δ and not extending beyond the logarithmic layer.

Hutchins and Marusic (2007) identified a class of VLSM, which they termed *superstructures*, which meander with a wavelength 15–20δ. These features have been observed both at low *Re* (Hutchins and Marusic, 2007; Dennis and Nickels, 2011a,b) as well as higher *Re* in the Great Salt Lake Desert. Marusic *et al.* (2010) depict superstructures as elongated, counter-rotating, streamwise structures that occupy the inner (logarithmic and viscous) sublayers (Figure 1.3a). The meandering superstructure is particularly well illustrated in the low Reynolds number experiments of Dennis and Nickels (2011a) (Figure 1.3b). Adrian (Chapter 2, this volume) notes that VLSM and superstructures may be concatenations of large-scale motions, themselves composed of hairpin packets (see also Kim and Adrian, 1999; Adrian and Marusic, 2012; Hutchins *et al.*, 2012). Perret and Ruiz (Chapter 11, this volume) also report that the streamwise-length scale of VLSMs is of the order of several times the

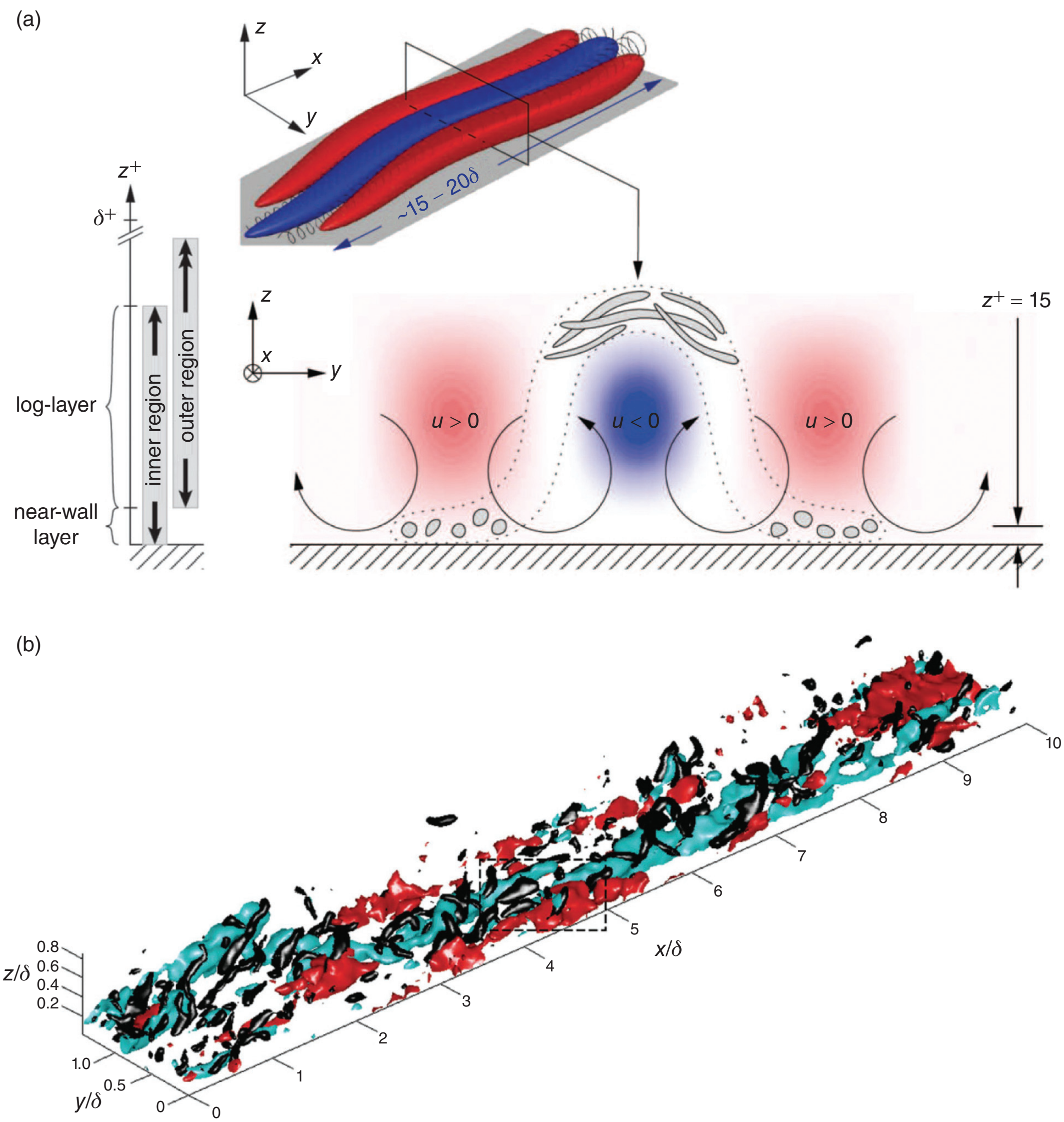

Figure 1.3 VLSM referred to as superstructures. (a) Schematization of superstructures showing their streamwise elongate morphology and circulation (x, y and z are the streamwise, spanwise and vertical directions, $\delta^+ = \delta u^*/\nu$ and $z^+ = zu^*/\nu$). From Marusic *et al.*, 2010. Reprinted with permission from AAAS. (b) High frame rate PIV of a meandering superstructure revealed as a low speed region by the green isocontour which corresponds to –0.1 U. The red isocontour is the 0.1 U and the black isocontour is 18% of the maximum swirling strength. Reprinted from Dennis and Nickels, 2011, with permission from Cambridge University Press.

height of the boundary-layer and argue that instantaneous coherent structures are animated by a spanwise motion that alters their symmetric organization.

These descriptions of coherent flow structures indicate that the hairpin vortex and its variants dominate the structure of boundary layer flows over hydraulically smooth boundaries, although the connection between hairpins, LSM, VLSM and meandering superstructures remains an area of active research. There is also mounting evidence that these same topological features are observed over rough boundaries, from roughened surfaces to gravel-bed rivers. Mejia-Alvarez *et al.* (Chapter 3, this volume) describe patterns consistent with the existence of hairpin vortex packets over turbine blades roughened by deposition of foreign materials. They also describe great spatial heterogeneity in the form of well defined, low- and high-momentum flow pathways, suggesting that these pathways could represent preferential 'channelling' of large-scale motions that are shed from the roughness and advect downstream along a common path. Channeling of such large-scale motions may also have parallels in the role of longitudinal ridges in concentrating the location of low- and high-speed streaks in the process of drag reduction (Johansen and Smith, 1986; Roon and Blackwelder, 1990), and it is one mechanism that has been used to help explain the formation of ripples on a sand bed (Best, 1992). However, there are a myriad of other mechanisms that can also form eddies over rough walls and within geophysical scale flows. There are ample locations at which eddies can form over a rough bed and shear layers caused by velocity and density gradients that may lead to the generation of coherent flow structures. These structures may or may not have the same hairpin topology observed over low Reynolds-number, hydraulically smooth flows.

1.4 Large-scale, high Reynolds-number coherent flow structures

In parallel with the emergence of an understanding of CFS in low Reynolds number flows and hydraulically-smooth flows, there has been a long history of examining CFS in rivers and the lower atmosphere. These flows typically exhibit Reynolds numbers of O(10^5 to 10^7) that are hydraulically rough ($Re^* > 70$).

In rivers, much early research focused on the dynamics of depth-scaled CFS referred to 'macroturbulence' or 'kolks' in the flow and 'boils' when they reach the water surface. These structures are ubiquitous over both sand and gravel beds and their formation has been linked to the presence of bed topography, whether the relatively regular topography of sandy bedforms or the irregular roughness of gravel. Early work by Matthes (1947) envisioned vertically oriented, tornado-like, structures that caused upwellings (boils) at the water surface. The structures have been variously described as slowly rotating, upward-tilting streamwise vortices (Matthes, 1947), circular in shape with internal upwelling in the centre and sharp boundaries marked by secondary vortices (Coleman, 1969; Jackson, 1976; Babakaiff and Hickin, 1996; Best, 2005) and hairpin-like (Müller and Gyr, 1986; Best, 2005). The observations of macroturbulence from acoustic soundings of the water column in the Fraser Estuary by Kostaschuk and Church (1993), which revealed contrasting sediment concentrations between the kolks and the ambient fluid (Figure 1.4), showed structures lifting off the bed in the lee of large-scale dunes. Babakaiff and Hickin (1996) suggested that the upwelling surface boils may appear as 'roller structures' that have an axis of rotation in the downstream-spanwise direction with ends that loop towards the centre of the feature as 'horns'. This, along with flow visualizations from small-scale flume channels (Müller and Gyr, 1986; Nezu and Nakagawa, 1993) and the form of boils on the surface of rivers, led Best (2005) to suggest that the structures have the same topology as the hairpin vortices described by Adrian (Chapter 2, this volume). This remains an area of active research, focused on elucidating the fundamental topology of these structures. Kwoll *et al.* (Chapter 15, this volume) examine the structure of kolks in tidal flows, finding that structures with a diameter on the order of the flow

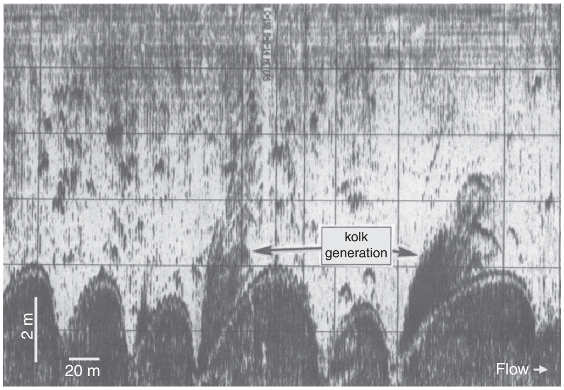

Figure 1.4 Acoustic image of macroturbulent kolks lifting off the back of dunes in the Fraser estuary. Reprinted from Kostaschuk and Church, 1993, Copyright 1993, with permission from Elsevier.

depth dominate bed material suspension processes. Jessup *et al.* (Chapter 14, this volume) use infrared imaging to show the dynamics of boils formed by coherent flow structures arising downstream of a submerged sill and produce a model for their propagation distance downstream to where they surface as boils. They also used this technique to quantify the velocity structure of upwellings on the river surface above a sand bed in an unstratified flow, and revealed features similar to those observed in the qualitative work of Babakaiff and Hickin (1996).

The origin of these macroturbulent features has attracted a great deal of attention. Early work by Jackson (1976) drew a direct analogy between these macroturbulent structures and the bursting features first identified by Kline *et al.* (1967). Jackson (1976) demonstrated that surface boils obeyed the outer layer scaling first proposed for boundary-layer bursts proposed by Rao *et al.* (1971), suggesting the possibility of a common origin for the large-scale macroturbulent features in rivers and the bursting process. This linkage has been criticized on the ground that there is a gross spatial discordance between the small-scale features developed at the bed and the dimensions of macroturbulence. This led later investigators to link their occurrence to shear layer instabilities formed in the lee of dunes in rivers (e.g. Kostaschuk and Church, 1993; Bennett and Best, 1995; Müller and Gyr, 1986; Venditti and Bennett, 2000; Best and Kostaschuk, 2002). Recent numerical modelling (Grigoriadis *et al.*, 2009; Omidyeganeh and Piomelli, 2011; Stoesser, Chapter 12, this volume) has also reproduced the origin and form of these CFS over dunes. The review by Stoesser illustrates the power of such simulations in testing our concepts of the origin of macroturbulence.

There has also been considerable work on coherent flow structures developed over rough gravel surfaces that reveal a related class of structures. The most frequently observed coherent flow structures over very rough boundaries are full depth (h) structures of alternatively slower- and faster-than average flow (Roy *et al.*, 2004). These quasi-cyclic motions have been described as alternating high-speed and low-speed 'wedges', aligned in the downstream direction, where ejected low-momentum fluid moves from the bed through the entire flow depth, while high-momentum fluid moves from the free surface towards the bed in ejection-sweep-like motions. Inclination angles of these structures vary between 20° and 36° in the downstream direction (Nezu and Nakagawa, 1993; Roy *et al.*, 2004), similar to the inclination angles typically observed for hairpins (Adrian, Chapter 2, this volume). This appears to generate roller-type instabilities (e.g. Klaven, 1966; Rood and Hickin, 1989) that scale closely with the flow depth in the vertical and $2h$ in the horizontal (Zaitsev, 1984). The downstream scale of these large-scale motions has been observed to be between 4 and $7h$, decreasing as roughness increases (Klaven, 1966) and becoming more pronounced as the Reynolds number increases (Schvidchenko and Pender, 2001; Hardy *et al.*, 2009). There is an evident similarity and possible linkage between these structures and the large-scale motions described by Falco (1977) and Adrian (2007; this volume). Yalin (1992) has suggested that these coherent flow structures are not permanent but are generated near the bed and then grow until they nearly equal the flow depth. They then become unstable and transfer turbulent kinetic energy, promoting a generation of new eddies until the eddy size declines to the dissipative scale (Nikora and Roy, 2012), causing a cycle of positive feedback, over a spatial scale of $6h$ (Shvidchenko and Pender, 2001). These large-scale CFS are three-dimensional and at least one flow component exhibits significant correlation with itself or with another flow component over a range of spatial and temporal scales (Kirkbride, 1993; Roy *et al.*, 2004; Nikora and Roy, 2012).

The macroturbulent CFS described in flows over sand beds (kolks and boils) and the depth-scaled 'wedges' or large-scale motions observed over rougher (gravel) beds have clear analogies to the large scale motions observed over smooth boundaries. Indeed, Best (2005) suggests macroturbulence over sand waves in rivers may have a hairpin topology. However, the analogy remains to be proven in many flows. Furthermore, these are not the only CFS observed in rivers, where a continuous range of variability is present, from smaller-scale turbulent motions to those related to channel hydraulics and even intra- and inter-annual hydrological variability (Figure 1.1; Nikora, 2008). Marquis and Roy (Chapter 17, this volume) identify long-wavelength pulsations that are $\gg 20h$ and last for minutes in pool-riffle morphologies in gravel-bedded rivers. These CFS have the characteristics of the low- and high-speed 'wedges' described by Roy *et al.* (2004) and may be linked to LSM, VLSM and the superstructures described over smooth boundaries, but are much longer. Marquis and Roy (Chapter 17, this volume) question whether they are VLSM resulting from self-organized amalgamation of small CFS, or large-scale flow pulsations conditioned by the channel boundary large-scale morphology (i.e. the pool spacing), which in turn controls the production of smaller macroturbulent CFS. MacVicar *et al.* (Chapter 16, this volume) also describe a class of CFS that occurs through the adverse pressure gradient formed in a pool-riffle sequence where the production of

CFS is observed by experiment to be controlled by the morphologic structure.

Atmospheric structures have largely been identified and characterized from the statistics of the wind field and of transported scalars (cf. Katul *et al.*, Chapter 6, this volume; Guala *et al.*, Chapter 7, this volume; Shaw *et al.*, Chapter 10, this volume). These statistics reveal the familiar ramp-like patterns that can be consistently interpreted as ejection- and sweep-like structures. Moreover, large eddy simulation reproduces these patterns in both the canopy and roughness sub-layers and reveals the vortical nature of the flows. Guala *et al.* (Chapter 7, this volume) provide further direct evidence of very large-scale structures, near-wall turbulent streaks, and intermediate scale ramps in a thermally-neutral boundary layer. They highlight the need to explore CFS directly in geophysical scale flows because, at laboratory scales, the spectral signatures of CFS overlap, whereas in geophysical flows there is a separation of scales. However, in thermally unstable conditions that dominate atmospheric flows, momentum and scalar fluxes become disassociated, a circumstance investigated in detail by Katul *et al.* (Chapter 6, this volume).

In addition to the structures associated with boundary-generated turbulence, there is a class of geophysical-scale coherent flow structures that arise from shear instabilities within the flow. These structures are formed by perturbation of the flow across gradients in the velocity, density or both. Lawrence *et al.* (Chapter 5, this volume) describe the common forms of these instabilities: Kelvin–Helmholtz instabilities form along sharp density and velocity gradients, Rayleigh instabilities form with a gradual velocity gradient and no density gradient and Holmboe instabilities form with a gradual velocity gradient and a sharp density gradient. The most common coherent flow structure associated with these instabilities are Kelvin–Helmholtz billows that are frequently observed in the atmosphere, along gravity current heads (c*f.* Horner-Devine *et al.*, Chapter 23, this volume; Menczel and Kostaschuk, Chapter 24, this volume), at the confluence of rivers (Best and Roy, 1991) and even along shear-interfaces caused by patches of vegetation in a flow. Nepf *et al.* (Chapter 9, this volume) describe shear-generated coherent structures formed by vegetation-flow interactions in a fluvial environment. At the individual plant scale, the length-scale of the vortices is set by the stem diameter, and this length-scale partially controls the characteristic eddy size within the canopy. However, vegetation patches that extend in the streamwise direction generate a shear-layer within the vegetation canopy, creating travelling vortices that are initiated by Kelvin–Helmholtz instability. They induce the *monami* phenomena of waving vegetation where the stems are flexible and the vortices generated are strong enough to cause this deformation (Nepf, 2012). Stoesser (Chapter 12, this volume) also explores the important role of vegetation stem spacing in affecting vortex dynamics and the interaction between vortices shed from adjacent stems.

One-sided spanwise vortices associated with Holmboe instabilities have also been found along fresh-saline water interfaces (cf. Tedford *et al.*, 2009; Lawrence *et al.*, Chapter 5, this volume). One-sided instabilities formed in the clear water-bedload layer interface also appear to set the initial length of bedforms developing from a flat sand bed (Venditti *et al.*, 2006; Lawrence *et al.*, Chapter 5, this volume). Menczel and Kostaschuk (Chapter 24, this volume) find sediment-laden gravity currents with low sediment concentrations tend to form Kelvin–Helmholtz instabilities because the density gradient is weak. However, they report that Holmboe instabilities may be formed at the top of higher sediment concentration gravity currents because of the stronger density gradient across the ambient fluid-flow interface. Shear instabilities are often invoked as the origin of macroturbulence in rivers (e.g. Kostaschuk and Church, 1993; Bennett and Best 1995; Venditti and Bennett, 2000; Best and Kostaschuk, 2002; Jessup *et al.*, this volume), although the specific mode of instability has not been investigated. Horner-Devine *et al.* (Chapter 23, this volume) also examine the 'lobe' and 'cleft' instabilities formed at the head of hypopycnal gravity currents, which are responsible for much of the production and dissipation of turbulence.

A range of CFSs in geophysical flows show some similarities, but many distinctive differences, from those documented within smooth-wall, low Reynolds-number flows. The picture that emerges from our partial listing of geophysical CFS highlights how the scale of CFS described is often predicated on the observer's point of view. Over smooth walls, the hairpin vortex and its organization into packets and VLSM's emerges as the dominant structure. Over rough walls in rivers, the class of structures easily identified appears to be depth-scaled CFS whose origin is not entirely clear, and may in fact be controlled by processes that are both boundary (shear velocity and roughness) and channel-scale (i.e. depth or width scale) dependent. Furthermore, the morphodynamic steering of flow shows that the shape of the boundary controls the largest scales of motion that are not linked to hydrological variability. In the atmosphere, it appears that LSM and VLSM or superstructures emerge as the dominant large-scale CFS.

1.5 Does scale matter?

If CFS are viewed as Reynolds number independent, the spatial and temporal scale of the flow should not matter. However, more pronounced coherent flow structures have been observed to develop at a greater flow depth and mean velocity (Schvidchenko and Pender, 2001). This does not, by itself, indicate a Reynolds number dependence. The structures that, to borrow a phrase from the CFS definition of Adrian (2007), 'catch our eye', do change with scale. Consider the major ocean gyres, tropical storms and mid-latitude cyclones, or the massive, planetary-scale storms that have been observed elsewhere in the solar system. Figure 1.5a shows an image of the western edge of the South Atlantic ocean gyre, which brings warmer, saltier water from the subtropics where it collides with cooler fresher waters flowing up from the south. The currents meet at the eastern edge of the continental shelf, pulling nutrients up from the deep ocean and resulting in a phytoplankton bloom that highlights interfacial instabilities along the edges of the ocean currents. The eddies generated along the interface between the currents would certainly seem to be coherent flow structures, but are ocean gyres themselves? At the planetary scale, these might be considered to be large-scale CFS, but to a human observer within the circulatory system, these features appear as mean flows, within which smaller CFS, over a range of scales, are embedded. Figure 1.5b reveals the same problem in the atmosphere. There are large-scale vortical structures such as low pressure cyclonic systems that, to the observer on the ground, generate a mean flow, within which CFS are embedded. Viewed on the planetary scale, these appear to be CFS. As such, it is of interest to try and define the scale limits of what is currently considered a CFS for a geophysical flow.

The lower limit must be defined by the microscale of turbulence where structures are dissipated as heat. The Kolmogorov time scale $(\nu/\varepsilon)^{1/2}$ and length scale $(\nu^3/\varepsilon)^{1/4}$ provide a formally derived microscale for turbulence (ε is the dissipation rate of turbulent kinetic energy). A more practical scale may be simply ν/u^*, as this is the scale where velocity fluctuations (scaled as u^*) become dominated by viscosity. The smallest coherent flow structures in hydraulically smooth flows appear to be near-wall, quasi-streamwise, vortices that cause low- and high-momentum streaks in the viscous sublayer over hydraulically smooth

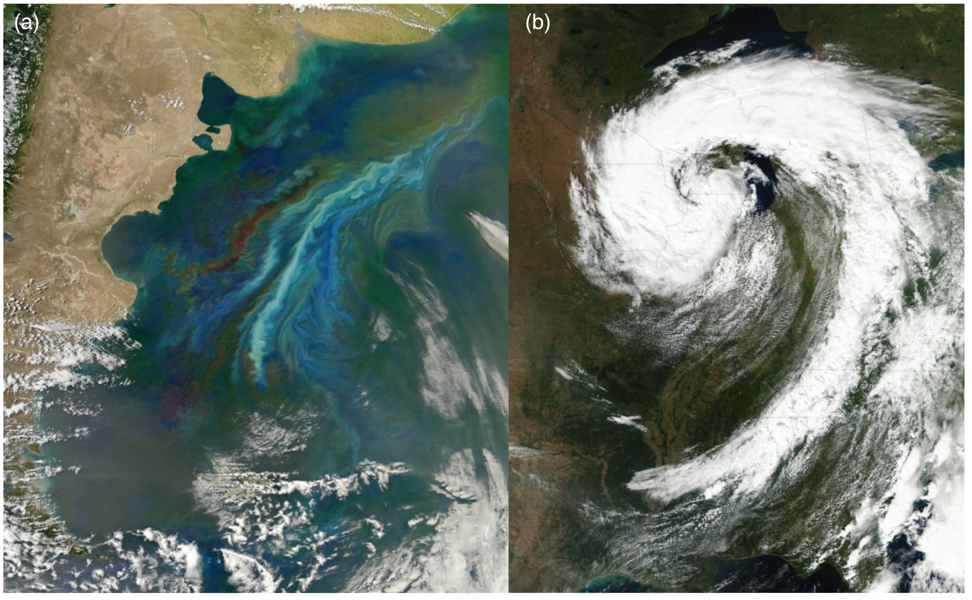

Figure 1.5 Global scale CFS. (a) The edge of the South Atlantic ocean gyre on December 21, 2010. (Image courtesy of NASA's Earth Observatory see http://earthobservatory.nasa.gov/IOTD/view.php?id=48244, accessed 25 March 2013). (b) Low pressure cyclonic system over the eastern United States and centred immediately west of Lake Michigan at 3:05 p.m. Eastern Daylight Time on September 26, 2011 (Image courtesy of NASA Goddard MODIS Rapid Response Team, http://www.flickr.com/photos/gsfc/6188946512/, accessed 25 March 2013). Both images captured with the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite.

boundaries (Adrian, Chapter 2, this volume). Associated with this scale are the hairpins that arise from the viscous sublayer of smooth boundary flows at low Reynolds numbers. Ostensibly similar features having been observed over rough surfaces at higher Reynolds numbers (see for example Grass, 1971; Roy *et al*., 2004; Diplas and Dancey, Chapter 19, this volume). It is possible, of course, that the analogy is a misleading consequence of our inability to visualize the hairpins features perfectly, but the burst-sweep cycle is a well-established feature of rough-walled flows and a characteristic (though not diagnostic) signature of CFS. One can easily accept that semi-stagnant zones between roughness elements might play the role of the viscous sublayer over rough walls (Kirkbride, 1993), leading to the episodic eruption of slowly moving water into the flow above (Hardy *et al*., Chapter 13, this volume). It is also easy to conjecture that the roughness elements themselves might spawn the characteristic hairpin structure as low momentum spanwise fluid filaments are deformed around obstacles on the bed and lifted into the flow (see Acarlar and Smith (1987)) for a study in a laminar boundary layer) – perhaps at somewhat larger scale than in low Reynolds number flow. Between the scale of boundary roughness – often characterized by bed material grain size or some simple multiple of it in geophysical flows – and the scale of the boundary layer depth δ, there lies a scaling range within which CFS are free to grow. These features may also grow along the axis of flow and it seems natural to index their scale by the limit of correlation in velocity, that is by the integral timescale of turbulence, T_E (E denoting an Eulerian perspective). We may relate temporal and spatial scales, under the 'frozen turbulence' assumption, by $L = \langle u \rangle T_E$, in which $\langle u \rangle$ denotes an appropriate mean velocity. In the statistical view of turbulence, these integral scales are often thought of as the macroscale of turbulence – the largest scales of turbulence in the flow. Sparse available data (reviewed by Church, 2008) suggest that $2 < L/\delta < 7$, encompassing the original empirical result reported by Rao *et al.* (1971) for the burst-period scaling of $L/\delta \approx 5$. This scaling is also similar to the Strouhal number, the scaled interval for eddy shedding from a bluff object (Levi, 1983; Kostaschuk and Church, 1993).

Beyond the scale of L (or of T_E), flow structures must inevitably begin to feel the constraint of δ. Rivers and other channelized flows are often depth-limited (Nowell and Church, 1979), meaning that the boundary layer never fully develops because the mean flow velocity increases right to the water surface. So the scale constraint may more legitimately be the container within which flow occurs (for example the channel width or pool-riffle spacing scales). As CFS become more extended, they are increasingly moulded by that constraint. In open channels, it appears that most VLSMs fall into this category, consistent with the findings of MacVicar *et al.* (Chapter 16, this volume) who report an association between CFS and pool-riffle sequences that have the same geometric scale. Marquis and Roy (Chapter 17, this volume) also provide intriguing evidence of the large-scale pulsations that are clearly controlled by the scale of the riffle-pool morphology within which they are formed. Above these spatial scales are the persistent secondary circulations that both shape and are shaped by the boundary, such as those investigated by McLelland (Chapter 18, this volume). These flow structures are no longer turbulent phenomena, but become a component of the persistent mean flow structure.

In the oceans or atmosphere, it is less clear what might present a geometric constraint on CFS. In the atmosphere, unconfined by lateral boundaries, and free of the constraint (in streams) that flow depth poses, CFS may grow to considerably larger dimensions and no strictly persistent secondary circulation might be detected. For the case of atmospheric flows, the largest CFS identified in this volume appear to VLSM or superstructures, which can have length scales $> 20\delta$ in a geophysical flow (Hutchins and Marusic, 2007). Some work has suggested the role of atmospheric stratification in controlling the scale of aeolian bedforms (Andreotti *et al*., 2009). It has also been conjectured that stratification may be important in limiting the evolution and extent of CFS in subaqueous density currents, whether through a Richardson number constraint, or a control by the height and magnitude of the velocity differential at the velocity maximum (Parsons and Best, 2013).

1.6 What is the difference between the mean flow and CFS?

A test of the utility of the upper limits placed on CFS in the forgoing discussion requires consideration of the possible dynamical distinction between CFS and other flow features. As discussed above, a CFS is motion that has a spatial extent and persists for some period of time (Cantwell, 1981; Robinson, 1991; Adrian, 2007), but this does not distinguish a CFS from mean flow, which is typically driven by gravity, pressure or density differences in geophysical flows. Coherent flow structures, and turbulence more generally, derive their energy from the mean flow field. As such, the mean flow field is the temporal integration of all motions and averages over all scales of motion. To consider the dynamical linkages between the mean flow field and CFS, we present a series of examples and assess whether the flow structures identified contribute to turbulence intensities and Reynolds stresses, as in the attached eddy concept of Townsend (1976), whether they have vorticity, which is a reasonable criterion for a geophysical-scale CFS, and whether they have temporal and spatial coherence.

First, consider a long wavelength pulsation in a river that persists for hours, days or even months that is caused by hydrological variability (i.e. a rainfall event). This is not considered turbulence in the spectral model of Nikora (2008; Figure 1.1) and is clearly not a CFS. Such unsteadiness in the flow derives from an external source, has no vorticity, and does not contribute to the Reynolds stresses or turbulence intensities. Although such flood events possess a defined time scale, and hence possess temporal coherence, they have no defined spatial coherence within the flow field.

At the other end of the spectrum, consider an instantaneous velocity fluctuation in a fluid that can be classified as a quadrant 2 event (vertical velocity greater than the temporal mean and streamwise velocity less than the mean). Such a fluctuation will cause a positive contribution to the Reynolds stress, possesses vorticity by virtue of creating a velocity gradient, and will contribute to the turbulence intensity. If the fluctuation is part of an ejection, and is thus likely coupled with a fluctuation that can be classed as a sweep, then the instantaneous motion also has some temporal coherence. If this quadrant 2 event is part of a sequence of temporal fluctuations, it must also have some spatial coherence in the flow, and is therefore part of the signature of a CFS. However, if the fluctuation is not part of a sequence or pattern of fluctuations, it is a random motion and should not be thought of as a CFS. Such a singular, random fluctuation is obviously in contrast to a single hairpin vortex (or, more likely, a hairpin vortex packet) that evolves over a bed of fine sand. This structure is internally generated by self-organized processes, has vorticity, contributes to the Reynolds stress and the turbulence intensity, and also possesses temporal coherence and spatial coherence within the flow. The sweep motion associated with a hairpin also has the potential to move sediment if it is strong enough to generate an impulse sufficient to overcome particle inertia (Diplas and Dancy, Chapter 19, this volume).

Between these extremes of a long wavelength hydrological pulsation and a hairpin, there is a continuum of motions. Consider the large-scale pulsations identified by Marquis and Roy (Chapter 17, this volume). The motions appear to originate from the interaction of the flow with riffle-pool morphology, so they are internally generated and self-organized. It is not clear that they contain vorticity, but similar VLSMs do, and they also contribute to the Reynolds stress and turbulence intensity. Such large-scale pulsations also possess both a spatial and temporal coherence, and thus it may be reasonable to conclude that these are coherent flow structures. In fact, it is likely that there is an entire class of these structures that has not been clearly identified in geophysical flows because it is typical to focus on shorter time series to eliminate such longer period structures.

A final case for consideration is the secondary circulation (flow normal to the time-averaged primary flow vector) identified in most open-channel flows. These features do possess vorticity, as well as temporal and spatial coherence. However, if they are persistent features of the flow field, they do not contribute to the turbulence intensity or the Reynolds stress in a channel. In a meandering channel, for example, secondary flow cells are forced by channel curvature and water surface superelevation, and have no impact on velocity fluctuations in the flow. In this case, secondary circulation is not a coherent flow structure. However, if these secondary flow structures meander and migrate in the channel through time to produce a time averaged zero mean flow, the motions might legitimately be CFS. The superstructures identified by Hutchins and Marusic (2007) appear to be secondary flow structures of this type.

1.7 Coherent flow structures within geophysical flows: future research needs

The time between the 1995 *Coherent Flow Structures in Open Channel Flows* conference held at Leeds University and the 2011 *Coherent Flow Structures in Geophysical Flows at the Earth's Surface* conference at Simon Fraser University has been marked by tremendous progress in understanding CFS in geophysical flows. The rapid growth in computer processing speed, along with a dramatic reduction in cost, has led to widespread application of direct numerical simulation (DNS), clarifying our view of CFS in low Reynolds-number flows. Similarly, the application of large eddy simulation (LES) to geophysical flows has become commonplace, simulating the fundamental nature of CFS over rough boundaries. Advances in instrumentation for field and laboratory experimentation have made rapidly-obtained and spatially-resolved observations of turbulent flow fields commonplace. Collectively, these advances in modelling and instrumentation allow for multidimensional visualization of CFS that was not previously possible. The community of researchers working on the problem in geophysical scale flows has also expanded rapidly and importantly become far more interdisciplinary in its scope and applications.

However, there remain a number of grand challenges in understanding coherent flow structures in geophysical flows:

- We still possess an incomplete picture of CFS in geophysical flows since most approaches have used the smooth boundary, low Reynolds number flow, hairpin paradigm, advanced by Adrian (Chapter 2, this volume), to explain observed patterns in flows. Moreover, we often do not have a clear topological description of CFS in geophysical flows. Application of LES and DNS holds the potential to solve the problem partially (Stoesser, Chapter 12, this volume) by testing our assumptions about how flows work, but further observations are necessary to identify common topologies across flows and scales as well as to test the models.
- Most past work on CFS in geophysical flows has considered the boundary as solid. However, in most geophysical flows, the bed is porous and there is a feedback between CFS in the flow and in the transitional region in the porous bed, below which flow is Darcian (Blois *et al.*, Chapter 4, this volume). The influence of such porous beds on small- and large-scale CFS is an area ripe for further study.
- Despite decades of work on fluid flow by the Earth surface dynamics community, the linkage between CFS and sediment transport remains unclear. The majority of CFS studies have investigated the flow with the underlying assumption that what happens in the flow must control the morphodynamics of the boundary and sediment transport. Yet, most studies end with conceptual models of how CFS and the boundary interact. Bauer *et al.* (Chapter 8, this volume) question the utility of the CFS paradigm in understanding sediment transport and morphodynamics. Yet formal linkages are beginning to emerge. Diplas and Dancey (Chapter 19, this volume) have made significant progress on this problem by linking sediment entrainment and the impulse from specific fluid motions (see also Diplas *et al.*, 2008). Singh and Foufoula-Georgiou (Chapter 21, this volume) and Wren *et al.* (Chapter 22, this volume) both explore the statistical linkages between deformation of the sediment boundary and the flow structure. More work is needed to link CFS formally with the boundary in a predictive manner if the paradigm is to significantly improve our understanding of Earth surface dynamics.
- Additionally, many studies of CFS within sediment transporting flows have assumed little or no feedback between the phases, yet recent work has shown that this is a very limited assumption. Many flows that transport sediment, especially fine-grained silts and clays, show significant modulation of the flow structure (Baas *et al.*, 2009). Bennett *et al.* (Chapter 20, this volume) suggest that reductions in the turbulent kinetic energy of the flow may be caused by sand suspension. These types of modulation affect sediment transport characteristics and deposition. Establishing the mechanics of this modulation of flow by sediment in saltation or suspension will likely significantly change how the dynamics of many Earth surface flows are viewed and modelled.
- There is a clear need to expand understanding of VLSM, superstructures and morphological-scale pulsations. It seems likely that these motions are present in all Earth surface flows and that they influence the macroscale morphodynamics and sediment transport, as well as the nature and evolution of vegetation canopies, biota and ecological communities. It may even be speculated that some aspects of the morphology of the Earth's surface and biota even evolve to modulate CFS, such as a plant canopy evolving (by any number of mechanisms) to resist CFS. Yet studies of these structures have been rare and their linkage to other components of systems at Earth's surface even rarer.

What constitutes a coherent flow structure in smooth boundary, low Reynolds-number flow does not appear much different than those currently revealed in many geophysical flows. Indeed, the definitions proposed by Robinson (1991) and Adrian (2007) appear to fit a majority of CFS in geophysical flows. However, the complexity of flows at the Earth's surface leads to qualifications about what is, and what is not, a CFS. It is evident that a continuum of structures exists from the small-scale streakiness near the boundary of geophysical flows to structures that scale with the channel dimensions in rivers and with the boundary layer depth or, potentially, stratification depths in the atmosphere and oceans. The largest CFSs discussed in this volume are the attached eddies that correspond to VLSM, superstructures and morphological-scale pulsations. Bridging the gap between these structures and the much larger atmospheric circulations and oceanic gyres observed at the Earth's surface presents a major challenge to the community studying coherent flow structures.

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