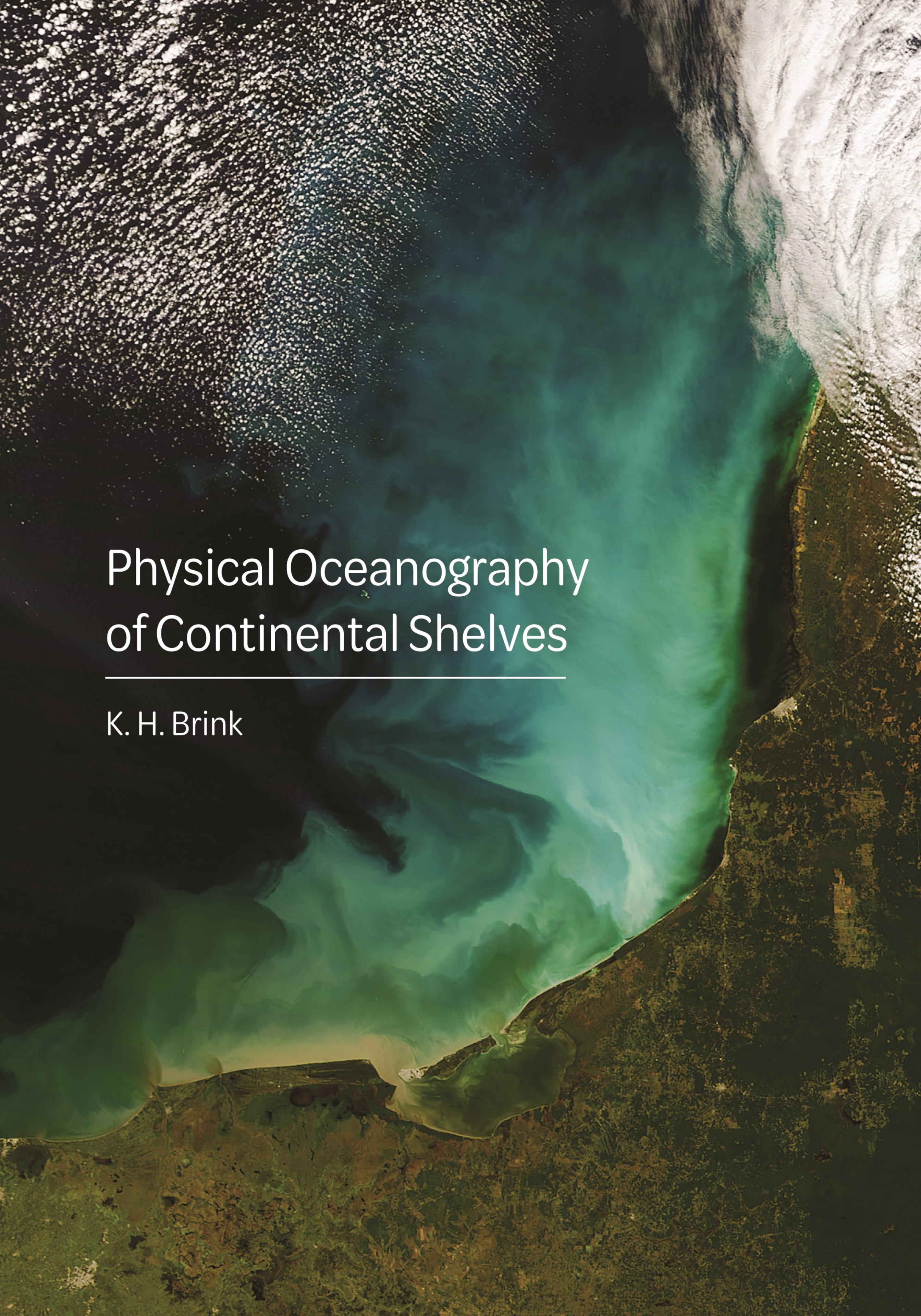
Physical Oceanography of Continental Shelves

K. H. Brink



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To my many generous teachers, past and present

Contents

Preface

This volume is an attempt to present core material about continental shelf physical oceanography in a way that begins with the basics and yet can be used as a starting point for exploring frontier areas in depth. It grew out of teaching a one-semester second-year graduate-level course in the Woods Hole/MIT Joint Program. Given this anticipated level, the reader should have some knowledge of quantitative physical oceanography, although I have attempted to provide enough background material to allow a broader audience to find its way. Even though this work is conceived as a textbook, only a few exercises (the appendix) are provided for the reader. This is largely because informative exercises are difficult to create and require extensive vetting in practice. I have on hand only this small collection. I have found, however, that a really valuable teaching tool is to assign each student an important paper to study, to present verbally, and to be able to answer critical questions.

The structure of this volume is motivated by the notion that although the global coastal ocean is tremendously diverse, locations differ mainly in how the various underlying processes interact. With that in mind, emphasis is on quantitatively exploring some of the important physical mechanisms. There are many options about which topics to include. While I believe the right choices were made, I readily admit that the content reflects my own experiences and priorities. Other scientists would perhaps have made other choices. In any case, numerous topics receive little or no attention, even though they are undeniably interesting and important. These omissions include ice-related processes (e.g., Straneo and Cenedese, 2015), estuaries (e.g., MacCready and Geyer, 2009; Geyer and MacCready, 2014; Bruner de Miranda et al., 2017), turbulent mixing (e.g., Gregg, 2021), hydraulics (Pratt and Whitehead, 2007), practical ocean numerical modeling (e.g., Pinardi et al., 2017), and the surf zone (e.g., Komar, 1998). These references are but a sampling of the many excellent books or reviews that help make my omissions less blameworthy.

Another set of choices had to be made about how to include ocean observations. No book of this sort could fail to include information about the real ocean and how it motivates and tests models. The approach here is to discuss measurements in the context of appropriate models (or vice versa), rather than to have separate chapters, sorted perhaps regionally, on observations. The difficulty with using the present approach is that some cohesiveness is lost in terms of characterizing ocean observations in a particular region. Fortunately, substantial, albeit now somewhat dated, resources exist (Robinson and Brink, 1998, 2006) that synthesize regional coastal ocean observations with nearly global coverage.

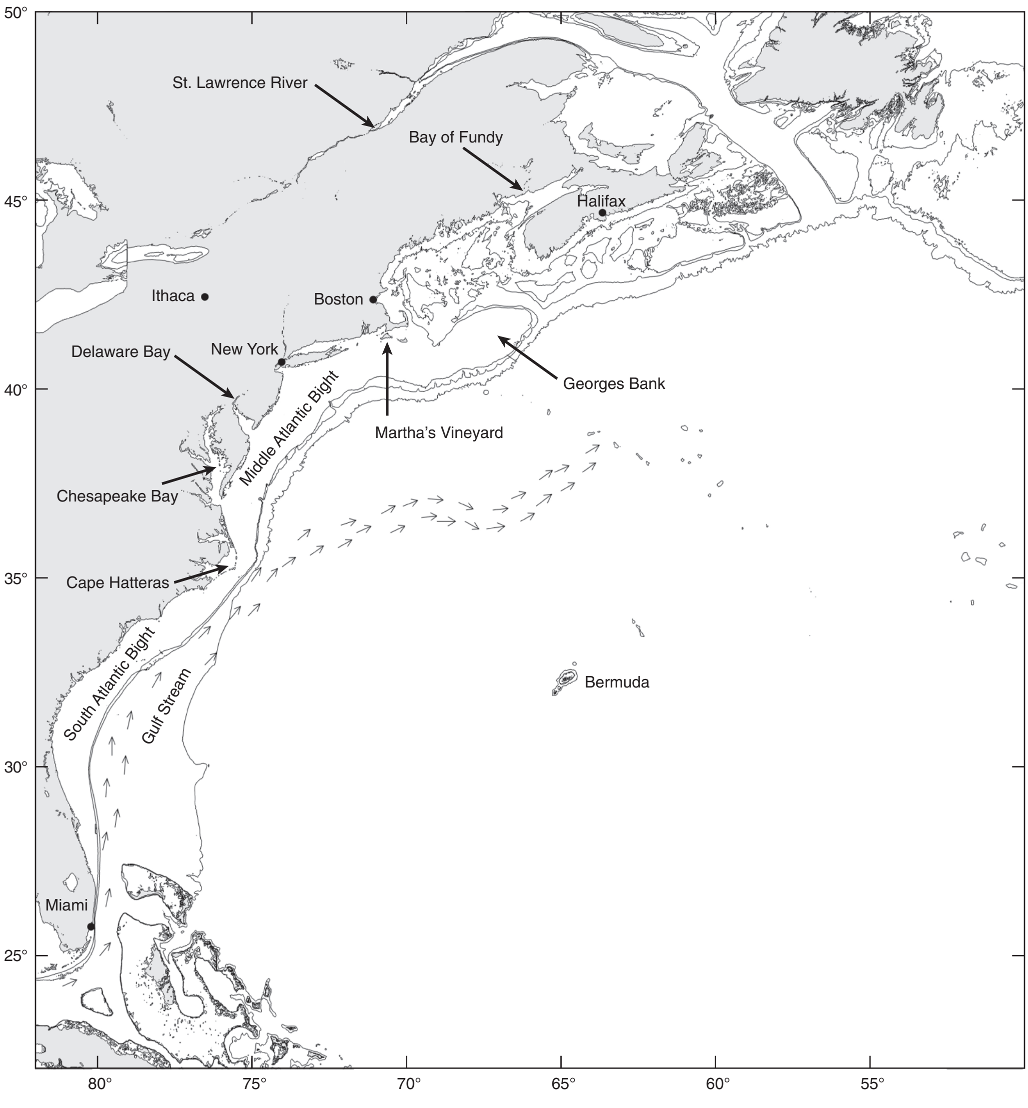
On a personal basis, I entered coastal physical oceanography in the 1970s, a time of exciting growth. I have been fortunate enough to have known and sometimes worked with a range of outstanding and pioneering figures, all of whom have been wonderful teachers in one way or another. I regret that I missed a couple of the earliest practitioners, notably June Pattullo and Henry Bryant Bigelow, but I am very grateful for the many I have known.

Finally, there are many people to thank both for my own education and for their direct or indirect contributions to this volume. Of those who have helped me, I single out my mentors: George Veronis, John Allen, Bob Smith, and Bob Beardsley. I could not imagine my life without them. For this volume I especially appreciate Steve Lentz, who was particularly helpful during the formative stages of this process. Jamie Pringle, Sasha Yankovsky, and Jim Price provided critical readings of drafts and motivated numerous improvements. Input along the way from Allan Clarke, Steve Elgar, André Paloczy, Chris Piecuch, and three anonymous reviewers is also gratefully acknowledged. Of course, any errors or shortcomings are attributable only to me. Finally, this volume would not exist if it were not for the many students I have interacted with, who motivated this effort and who taught me all sorts of things along the way.

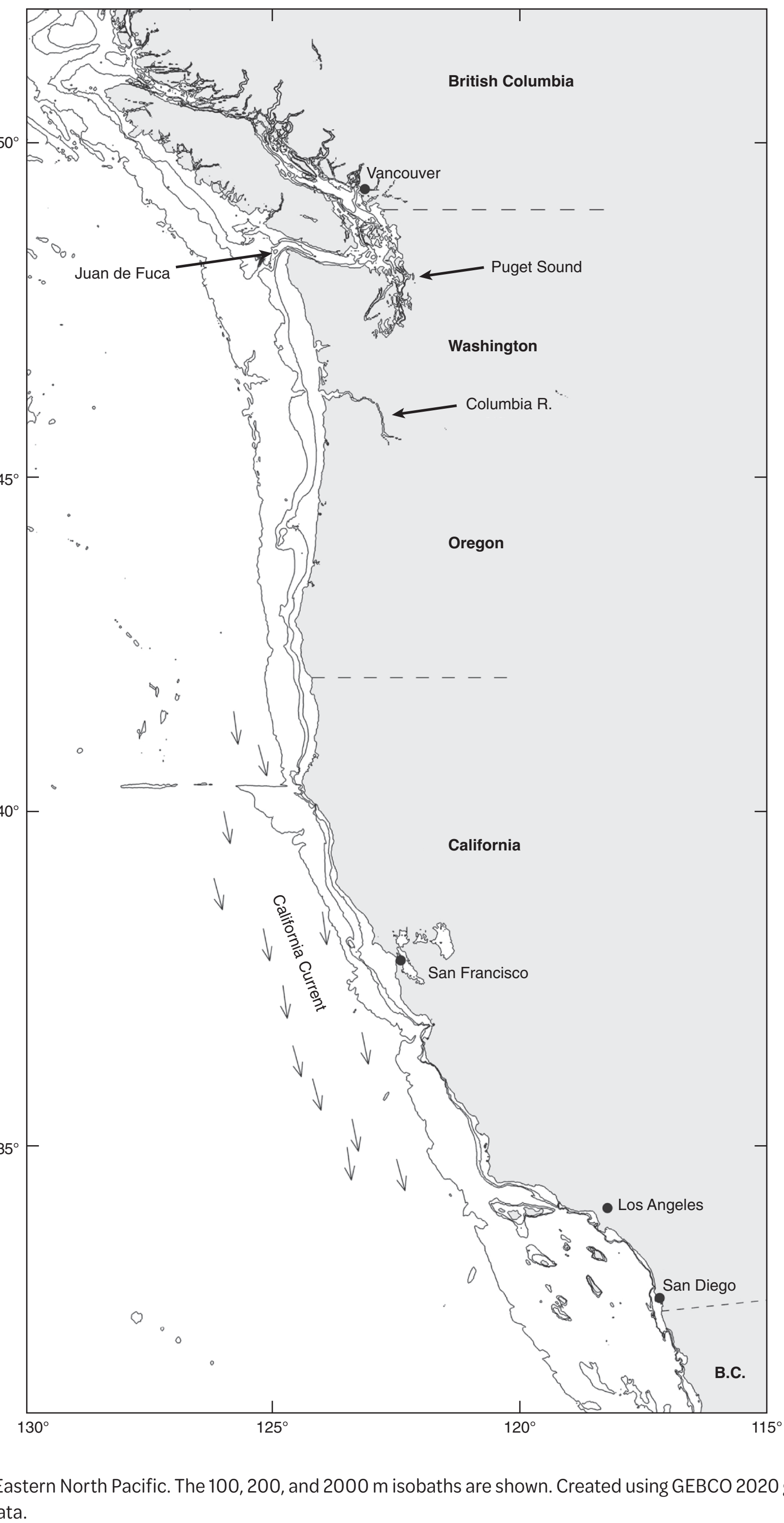
Table of Consistently Used Symbols

Symbol	Definition	Defining equation
A	Eddy viscosity	(2.3.4a)
Bu	Burger number	(4.4.7)
c	Wave speed (subscripts provide more specifics)	
c_D	Drag coefficient for quadratic stress	(3.6.7)
d	Bottom frictional parameter	(3.7.4)
D	Free-surface divergence parameter	(4.2.10)
Ek	Ekman number	(2.3.6)
f	Coriolis parameter = $2\Omega \sin \phi$, where ϕ is latitude	(2.3.1)
g	Acceleration due to gravity	
h	Spatially variable depth	
h_{ML}	Surface mixed-layer thickness	
H	Constant water depth	
i	Square root of -1	
(k, l)	Horizontal wavenumbers in the (x, y) directions	
K	Eddy diffusivity	(2.3.4b)
N	Buoyancy frequency	(2.3.7)
p	Pressure	

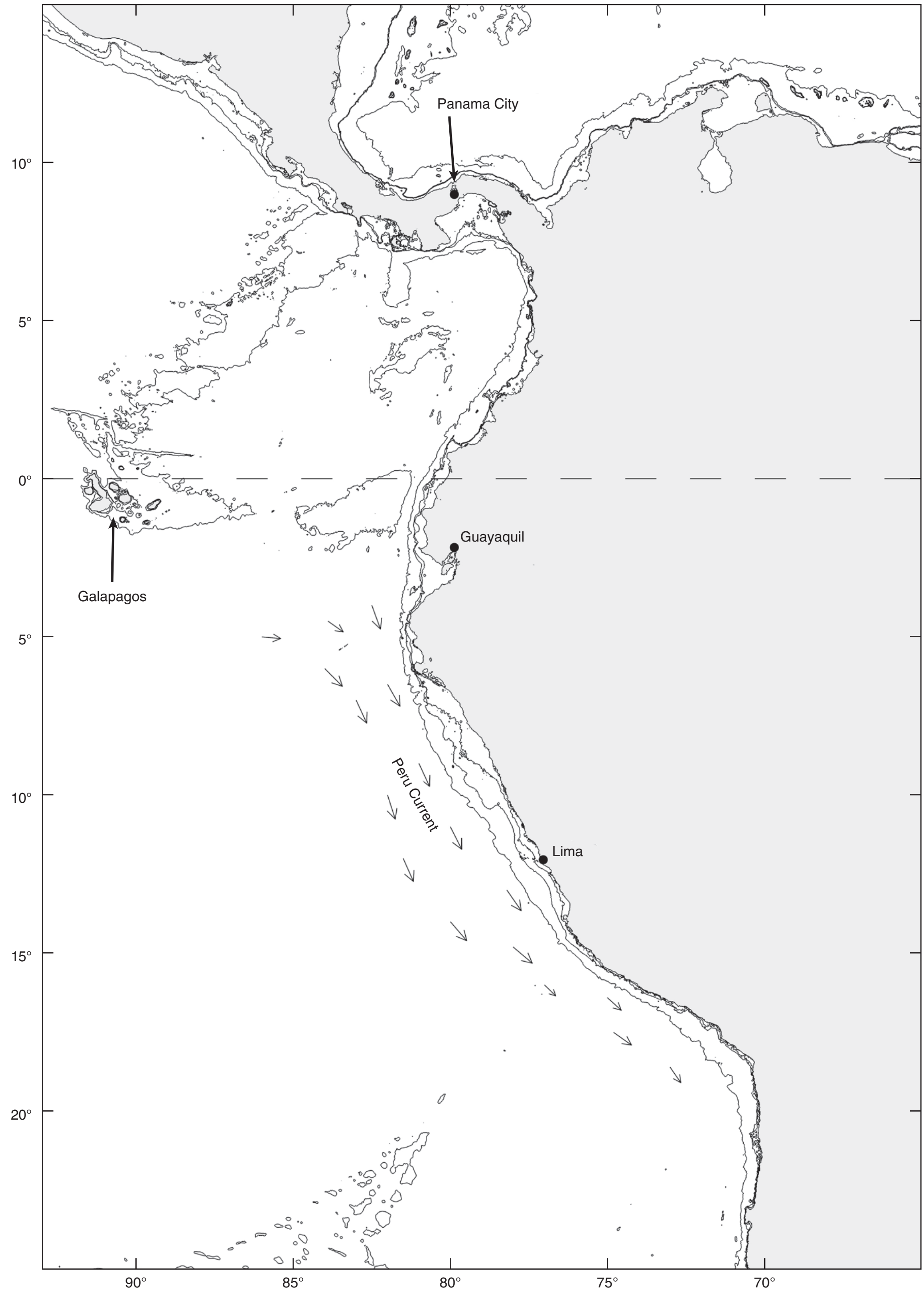
Symbol	Definition	Defining equation
r	Radial coordinate	
R_B	Bulk Richardson number	(3.5.7)
Re	Reynolds number	(2.3.2)
Ri	Gradient Richardson number	(2.3.7)
Ro	Rossby number	(2.4.7)
s	Slope Burger number	(3.7.6)
S	Salinity	
t	Time	
T	(with no subscripts) Temperature	
(u, v, w)	Velocity components in the offshore, alongshore, and vertical directions	
(x, y, z)	The offshore, alongshore, and vertical coordinates	
α	Bottom slope	
β	North-south gradient of f	(2.4.8)
δ_D	Dirac delta function	(4.4.3)
δ_E	Scale thickness of a constant eddy viscosity Ekman layer	(3.2.4)
δ_{nm}	Kronecker delta	(5.4.11)
Ξ	Cross-sectional (x, z) area	
π	3.14159 . . .	
ρ	Fluid density	
σ_F	Bottom resistance coefficient	(3.6.10)
Σ	Summation	
ω	Wave frequency	
Ω	Earth's rotation rate	



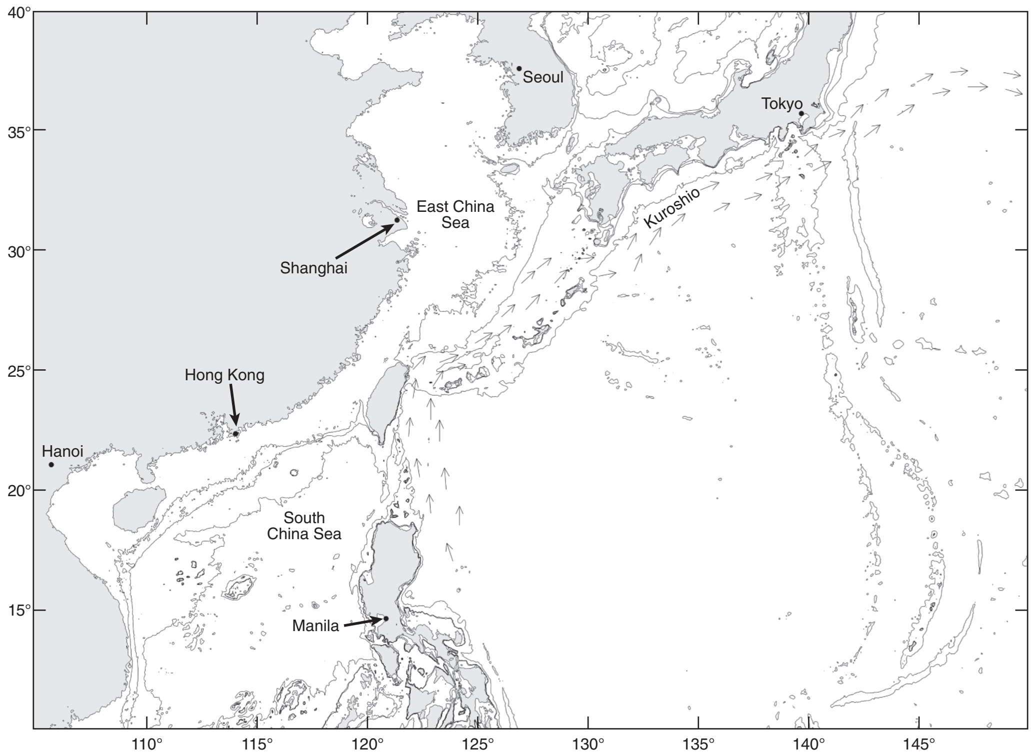
MAP 1. Western North Atlantic. The 100, 200, and 2000 m isobaths are shown. Created using GEBCO 2020 gridded digital data.



MAP 2. Eastern North Pacific. The 100, 200, and 2000 m isobaths are shown. Created using GEBCO 2020 gridded digital data.



MAP 3. Eastern Tropical Pacific. The 100, 200, and 2000 m isobaths are shown. Created using GEBCO 2020 gridded digital data.



MAP 4. Western North Pacific. The 100, 200, and 2000 m isobaths are shown. Created using GEBCO 2020 gridded digital data.

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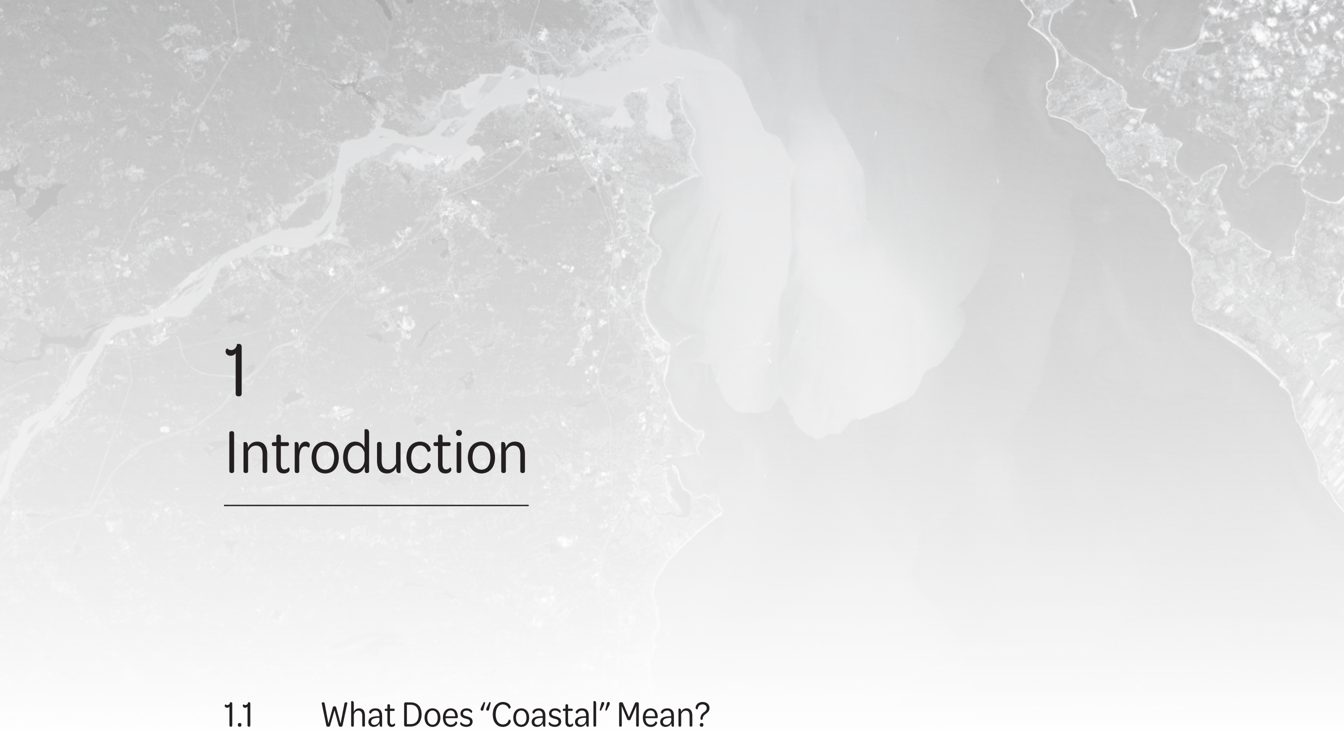

1 Introduction

1.1 What Does “Coastal” Mean?

There are many good definitions of the coastal ocean. An inclusive one might be: all the salty water adjoining continents and islands where the water is shallower than some arbitrary depth, like 1000 m. This definition would include estuaries, the surf zone, continental shelves, and continental slopes, but it needs to be supplemented by the inclusion of large enclosed freshwater bodies, such as the Laurentian Great Lakes, as coastal as well. Chapter 2 provides more detail on terminology, but, for now, the two important threads are proximity to land and the occurrence of large fractional depth changes.

1.2. Why Is the Coastal Ocean Important?

The coastal ocean, because it adjoins land, is the most visible and heavily used part of the world’s ocean. Most people may never see the deep open ocean aside from perhaps through an airplane window. Given its proximity to land, the coastal environment is used heavily for recreation (swimming, boating, diving, fishing) and enjoyed aesthetically. People are particularly aware of the coastal environment.

This nearness to land also imposes a good deal of pressure on the coastal ocean. For a range of reasons, human populations concentrate near the coast (Figure 1.1). In the United States, 39% of the population lives in counties that adjoin the ocean, according to the U.S. Census Bureau, and the number is substantially higher when land adjoining the Great Lakes is included. Globally, according to NASA, 40% of the population lives within 100 km of the ocean. Thus, settlement patterns concentrate both the observers and stressors of the coastal environment.

The connection to land extends well beyond coastal settlements, however. Rivers drain much of the world’s continental surface into the ocean. The outflow waters carry sediments (Figure 1.2), an assortment of dissolved chemicals, and other materials. Humanity, of course, can affect any of these quantities, for example, through agricultural practices, damming, and waste disposal.

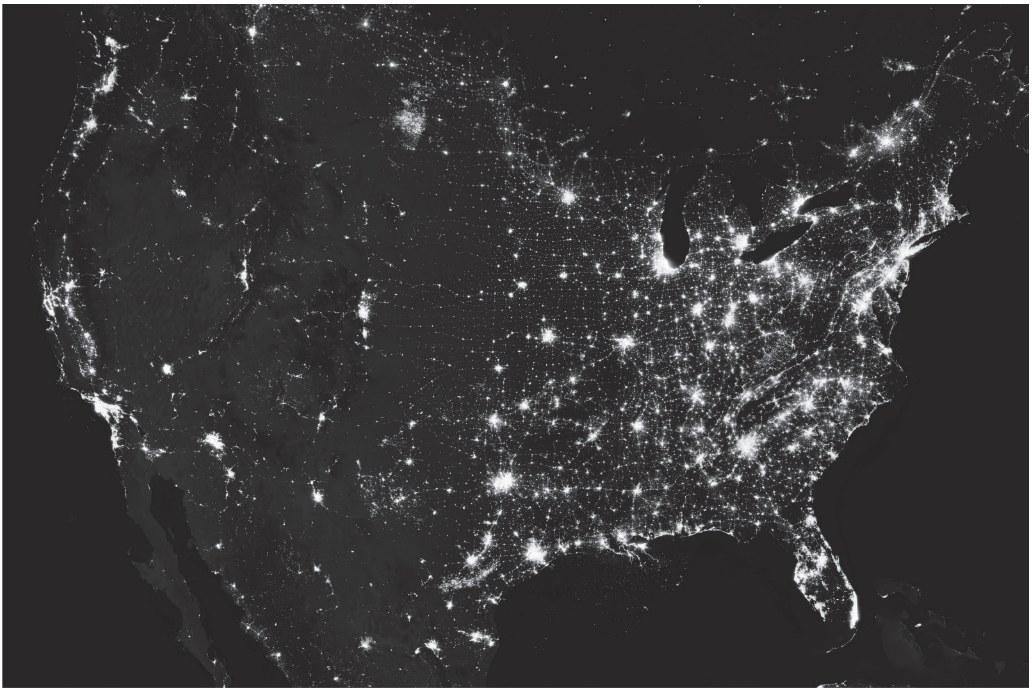

FIGURE 1.1. View of the United States at night: a composite of nighttime images from 2012. The lighting, which reflects population levels, distinctly outlines the coastline around much of the United States. From NASA Earth Observatory/ NOAA NGDC.

Some people call the coastal environment “the dirty little bathtub ring around the world’s ocean.” There is, in fact, a good deal of truth to this quip. The coastal ocean is very productive biologically for several reasons, some of which will be explained in the following chapters. Figure 1.3 shows a long-term average estimate of chlorophyll concentration in the upper ocean. Chlorophyll is a commonly used proxy for the concentration of the microscopic plants (*phytoplankton*) that are the base of ocean food chains. The important point in this figure is that the highest concentrations (light shades) all occur in the coastal ocean. The pale bands along the equator are an expression of processes analogous to (but more diffuse than) those acting near a coast. Viewed from a ship, the biologically productive waters often look green, brown, or blackish (that dirty bathtub ring), while beautiful Mediterranean-blue waters are actually an expression of the relative absence of life and are more representative of midocean conditions (the darker shades in Figure 1.3) than coastal ones. When phytoplankton are plentiful, the food web is stimulated even up to the level of fish, so it is no surprise that many of the world’s most productive fisheries (such as for anchovies off Peru) are in the coastal ocean. Palomares and Pauly (2019), for example, estimated that the coastal ocean accounts for 55% of the global fish catch even though it represents only 3% of the ocean surface.

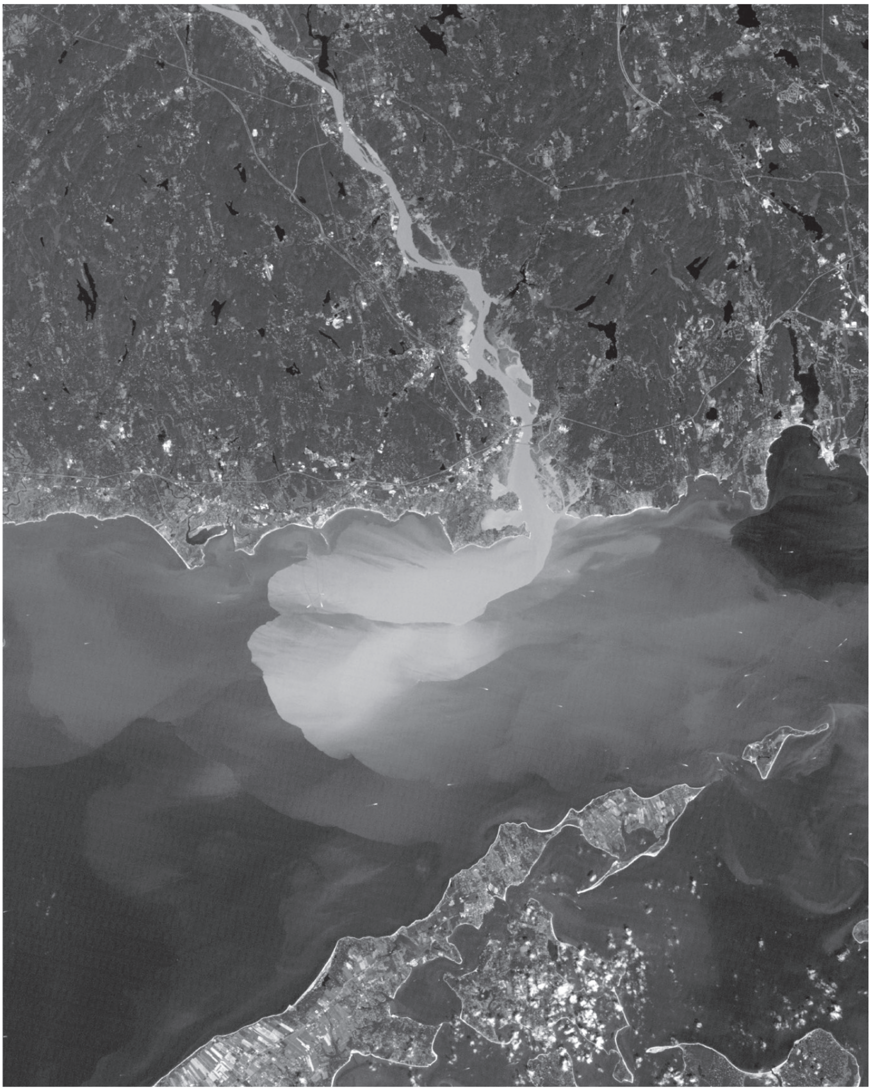

FIGURE 1.2. Daytime visual satellite image of the Connecticut River outflow during a flood stage after a hurricane (September 11, 2011). The river's suspended sediments make the muddy outflow plume quite visible as lighter shades. The outer part of Long Island is in the lower part of the image. NASA Earth Observatory image by Robert Simmon, using *Landsat 5* data from the US Geological Survey.

The abundance of coastal fisheries is not simply a matter of plentiful phytoplankton. Rather, fish need to find their prey (smaller animals), and these need to find their prey, and so on, through the food web. The locations and movements of all the levels of predator and prey are, of course, mitigated by currents and mixing. In the extreme, fish eggs generally drift entirely at the mercy of the physical setting. The success of a species depends

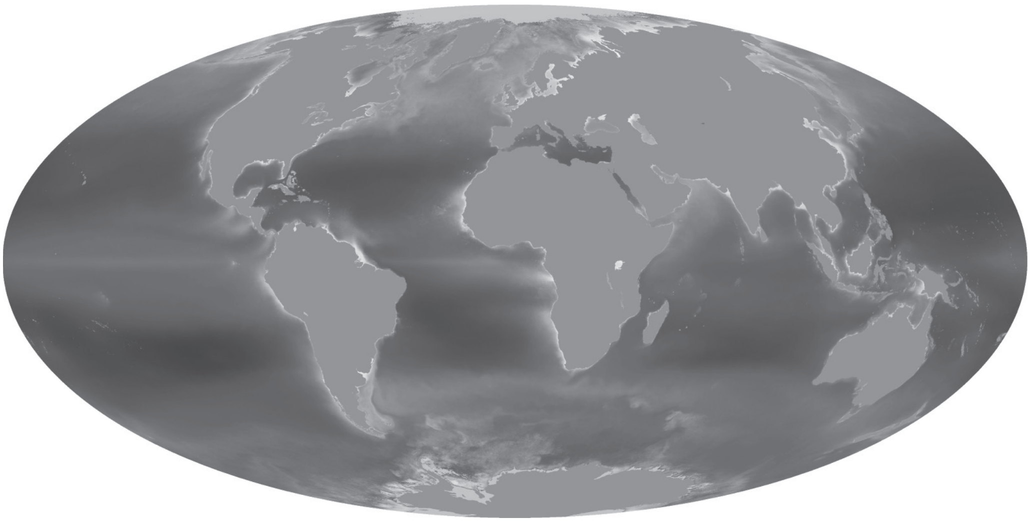

FIGURE 1.3. Global average ocean chlorophyll concentration (1997–2007) estimated from satellite images of ocean color. Lighter shades represent higher concentrations. Chlorophyll is often used as a proxy for phytoplankton biomass. Courtesy of NASA Earth Observatory.

upon how well suited the animal's evolved behavior is to its actual environment. Because the physical system is variable over time and space, it follows that ecosystem structure varies as well, even putting aside strictly biological mechanisms. This array of physical-biological couplings has motivated a good deal of research over the years, one illustrative example being described by Wiebe et al. (2002).

Biological activity in the coastal realm is not always benevolent, however. The rivers that empty into the ocean sometimes carry a heavy content of dissolved nutrients that frequently originate from excessive use of agricultural fertilizers, among other sources. These nutrients stimulate plankton growth, which eventually leads to sinking of organic material over the continental shelf. The sinking material decays, consuming oxygen. The upshot is the seasonal appearance of areas where near-bottom shelf waters are so nearly depleted in dissolved oxygen (*hypoxic*) that fish can no longer survive there. Shelf hypoxia is a growing problem globally (e.g., Rabalais et al., 2009). Another unfortunate biological effect occurs when there are blooms of plankton species that are harmful to humans and coastal animal species. These harmful algal blooms (HABs) (e.g., Anderson et al., 2012), like hypoxia, are strongly affected by aspects of the physical setting such as water column density stratification. HABs are often called "red tides," even though they only occasionally redden the water, and tidal currents are almost irrelevant.

Fishing, of course, is only one of many human activities in the coastal ocean. Shipping has been important since classical times and is increasingly so today. Transportation issues are especially pressing in areas near ports where safe and efficient navigation calls for coordination and a knowledge of the environment. Even small gains in efficiency

FIGURE 1.4. Oil platforms off the coast of California. Courtesy of the U.S. Bureau of Ocean Energy Management.

can represent important savings, given the cost of operating a large vessel. Inevitably, heavy usage leads to occasional calls for search and rescue operations, which clearly benefit from a knowledge of winds and currents. The coastal environment remains important for naval operations, since these often involve shipping (protection or prevention), or various offensive and defensive deployments near land.

There are other valuable resources in the coastal ocean. Oil and gas exploitation (Figure 1.4), which will be important for the foreseeable future, calls for knowledge about currents to enable safe and efficient operations. Petroleum, of course, is not the only coastal energy source: wind energy, as well as other renewables, stand to become increasingly important over the coming years. The continental shelf setting is particularly attractive because "land use" is perhaps not as difficult an issue as ashore and because winds are often stronger over the water than over the nearby land. Further, there are other minerals to be extracted besides fuels: sand and even diamond extraction both lead to disruption of the coastal ocean seafloor.

This cursory listing of practical concerns is far from complete and entirely without detail. The object is to emphasize how the coastal ocean is disproportionately (by area) important to our society, for a diversity of reasons. The following chapters will rarely touch explicitly on practical concerns, but applications are always nearby and will be a strong motivator to many readers.

1.3. What Makes the Coastal Ocean Different?

As simple as it may sound, probably the most distinctive aspect of the coastal ocean is the presence of a boundary. The blockage inhibits cross-shelf velocity u while having little direct effect on the alongshore current component v. This inhibition contributes heavily to the tendency for u to be much weaker than v over the continental shelf, especially on time scales longer than a few days (e.g., Figure 1.5; Lentz and Fewings, 2012). The resulting anisotropy, in turn, leads to momentum balances strikingly dependent on orientation, hence different from the more nearly isotropic open ocean. Also, the coastal barrier disrupts the cross-shelf upper-ocean transport associated with Earth's rotation and alongshore winds, effectively creating an outsized near-surface flow divergence near shore. (Such a divergence, albeit much more broadly distributed, is a key link in wind driving of the open ocean; e.g., see Gill, 1982, his chapter 12). This large divergence, in turn, means that wind-driven currents are more energetic over the shelf than in the deeper ocean. Consequently, coastal currents vary (on time scales longer than tidal periods) over periods typical of the weather: about 2–15 days. In contrast, subtidal mid-ocean currents typically fluctuate with periods defined by mesoscale eddies: many tens of days.

Another defining aspect of the coastal ocean is the large degree of bathymetric variation. Across the continental margin, bottom-depth changes are comparable to the depth itself. Given the reluctance of slowly varying flows on a rotating planet to cross *isobaths* (contours of constant depth), depth changes reinforce the boundary's tendency to make flow, on time scales longer than tidal, follow isobaths (Figure 1.5). In addition, the depth changes, through a funneling effect, tend to amplify tidal currents as the water gets shallower. Beyond that, there is the possibility of tidal resonances in the presence of a coastal wall. Strong tides, in turn, lead to a range of secondary effects, including enhanced nutrient delivery and thus biological activity. Finally, the very shallowness of the shelf's water column means that a given forcing (such as a wind stress or heat flux) is relatively more effective than in the deep ocean, where the effect might be distributed over a far greater vertical extent.

In most places in the ocean, there are turbulent boundary layers near the surface and bottom. These are typically 10–50 m thick. In the deep (thousands of meters) ocean, these boundary layers do not occupy a very large fraction of the water column. But on the continental shelf, where waters are typically 150 m deep or shallower, the boundary layers occupy a substantial part, and sometimes all, of the water column across the shelf. Consequently, turbulent mixing and dissipative processes play a particularly important role in coastal phenomena.

Finally, the coastal environment is where the continent meets the ocean. What flows out of rivers passes into coastal waters, creating distinctive alongshore buoyant currents which carry chemicals and materials that originated inland. Thus, the coastal setting is the ocean's contact zone with the terrestrial environment, and it is often here that outflows are diluted to concentrations typical of the broader open ocean.

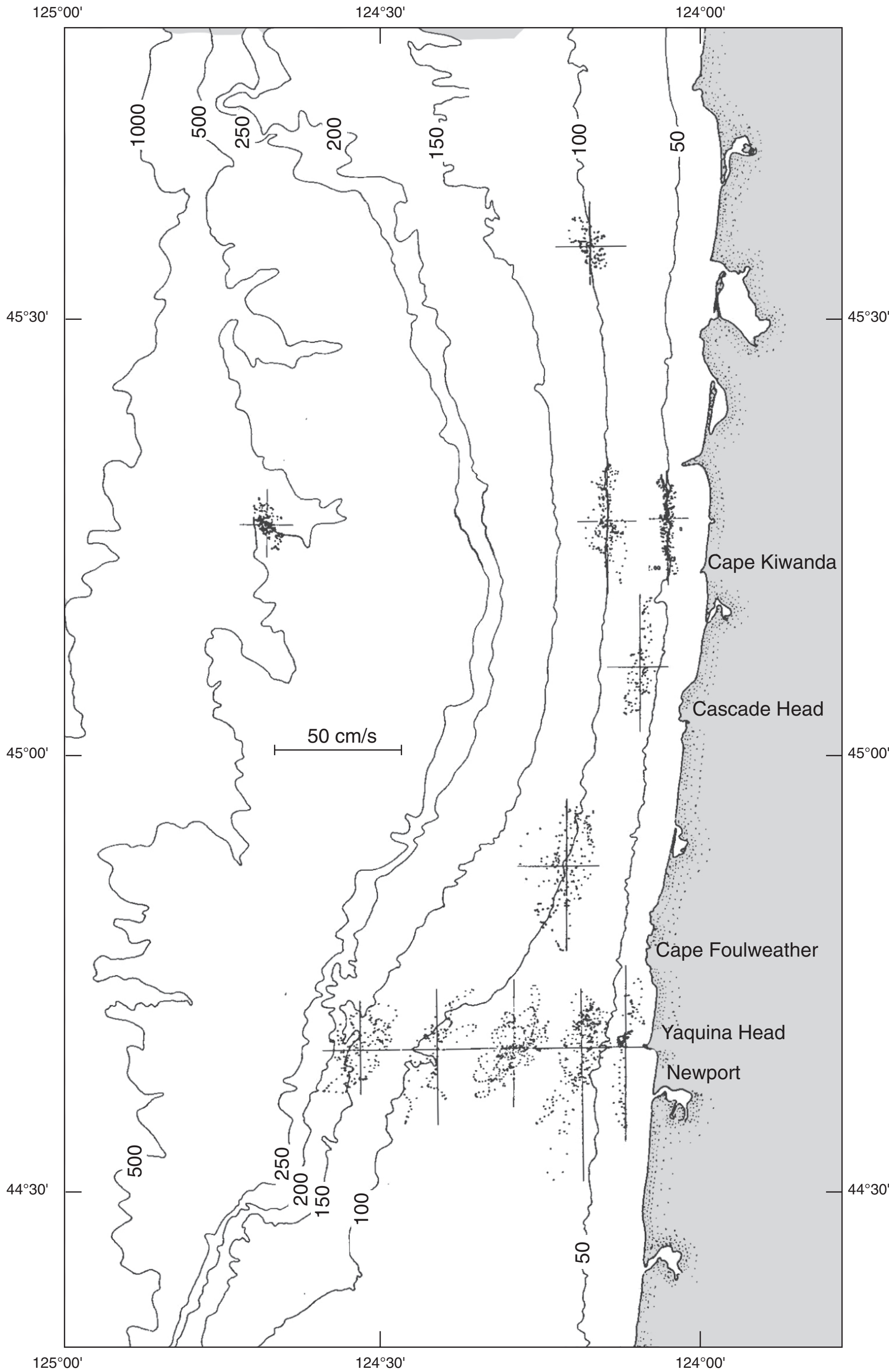

FIGURE 1.5. Scatter diagram of 40 m currents superimposed on bottom topography, demonstrating the tendency for fluctuating currents to follow isobaths. At each location, the current meter records were smoothed to remove tides and higher-frequency motions, and then the mean currents were removed. Next, at regular time intervals, the velocity vector was plotted as a dot relative to its mooring location (crosshairs). The measurements were made during the summers of 1971 and 1972. Note how the clouds of points are stretched out and aligned roughly parallel to isobaths, especially near the coast. Depths are in meters. Adapted from Kundu and Allen (1976).