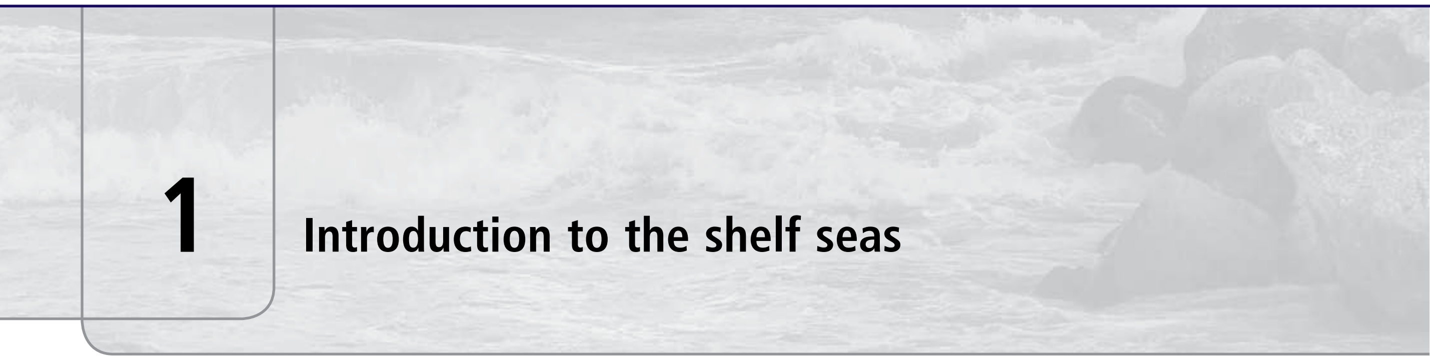
978-0-521-87762-6 - Introduction to the Physical and Biological Oceanography of Shelf Seas
John H. Simpson and Jonathan Sharples



1

Introduction to the shelf seas

In this chapter we shall introduce the reader to the shelf seas, their extent and position in the global ocean and the motivation, both fundamental and applied, behind our efforts to understand and model the complex processes which control the shelf sea environment and ecosystem. We shall then briefly explain the historical development of shelf sea science and describe the technical tools which are now available and which have facilitated the relatively rapid advances of recent years. As well as discussing the principal observational techniques, in a final section we shall consider the role of numerical modelling and its potential contribution to developing understanding.

1.1 Definition and relation to the global ocean

Between the deep oceans and the continents lie the seas of the continental shelf. These shallow areas usually have rather flat seafloors and extend out to the shelf break, where the seabed inclination generally increases rapidly at the top of the continental slope leading down to the abyssal ocean. This abrupt change of slope is clear in the map of global bathymetry shown in Fig. 1.1a. It typically occurs at a depth of ~200 metres and a contour, or isobath, at this depth is often taken as defining the outer limit of the shelf seas. This choice is not critical, however, since the continental slope is so steep (~1:10); moving from the 200- to the 500-metre isobath involves little horizontal movement. Using the basis of a 500-metre definition, Fig. 1.2a shows that the shelf seas account for ~9% of the total area of the global ocean and less than 0.5% of the volume. The shelf seas have an influence and importance quite out of proportion to these numbers.

The shelf seas act to dissipate a high proportion of the mechanical energy input to the ocean. This is most obvious in the swell waves which are generated in the deep ocean and travel great distances before delivering large quantities of energy to be consumed in wave breaking and bottom friction on the shelf. Less obviously, perhaps, energy input in the deep ocean by the tidal forces also propagates onto the shelf in the form of very long waves which are dissipated by friction in the large tidal currents of the shelf seas.

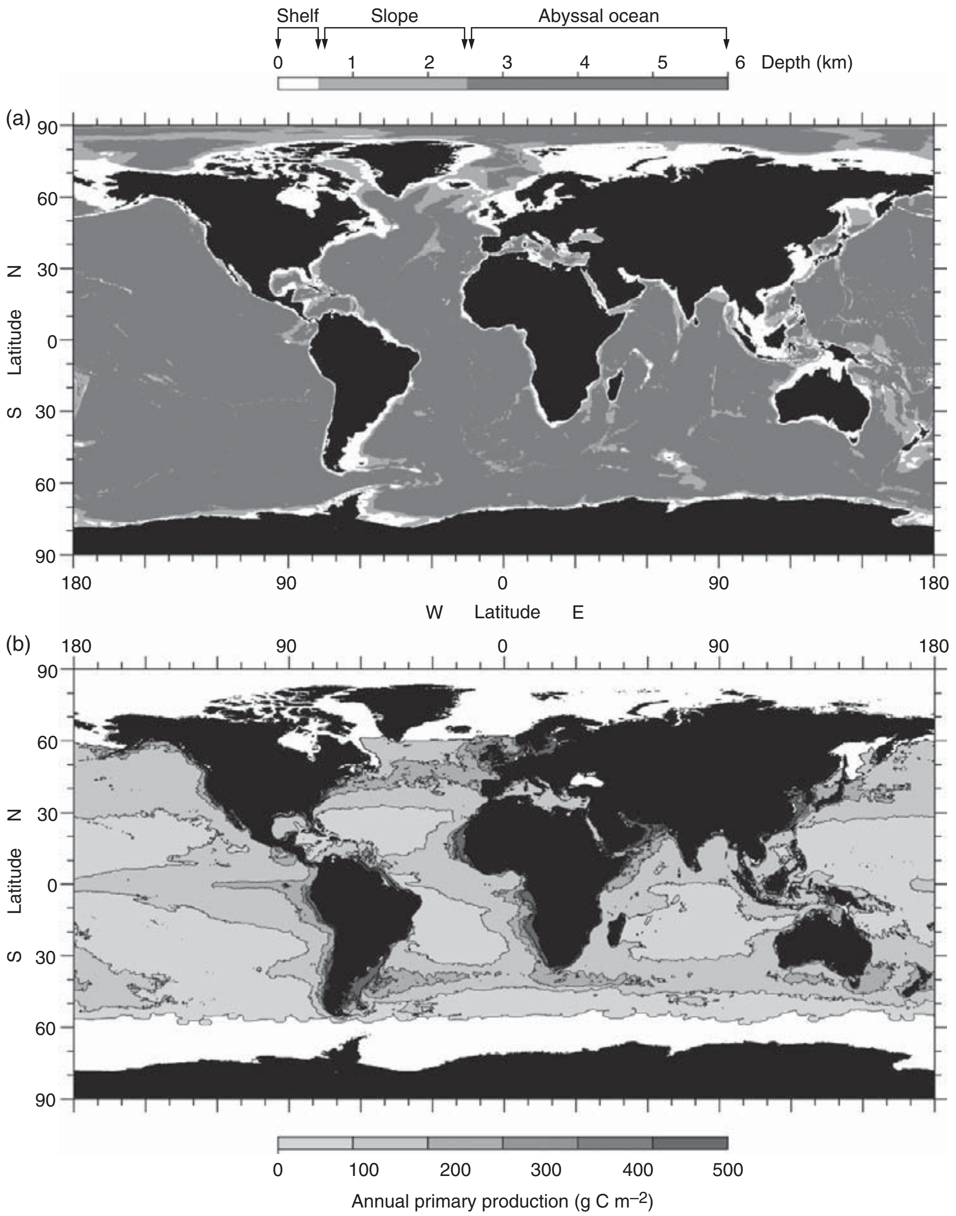


Figure 1.1 See colour plates version. (a) Global ocean depths, split by shelf, slope and abyssal ocean. Based on GEBCO bathymetry; (b) global annual primary production, using imagery from the MODIS satellite (Behrenfeld and Falkowski, 1997); data courtesy of Mike Behrenfeld, Oregon State University, USA: http://www.science.oregonstate.edu/ocean.productivity/index.php.

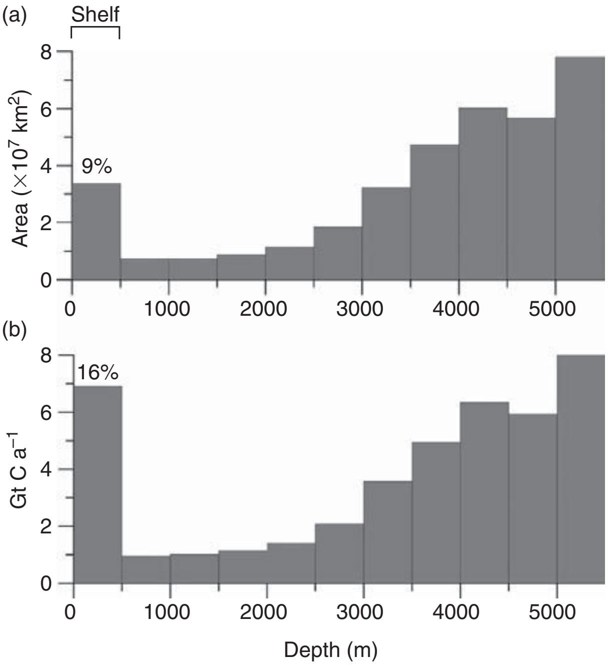


Figure 1.2 (a) The area of seabed in different depth ranges; if shelf seas are taken to be less that 500 metres depth they cover 9% of the ocean's total area. (b) Net primary production (gigatonnes of carbon per year) within different depth ranges; water shallower than 500 metres accounts for 16% of global production. The plots are based on the data in Fig. 1.1.

As a result of these external inputs and the direct action of the local wind at the surface, the shelf seas are physically energetic areas with vigorous stirring. They also receive large inputs per unit volume of solar energy which act to modify the density and thus create horizontal density gradients. Similarly, freshwater river discharge from the adjacent land, as well as rainfall, lower the density near the coast and thus contribute to density forcing of the shelf seas, which we will describe in Chapter 9. Because of the strength and variety of the forcing, the shelf seas are, in many ways, the most dynamic regions of the ocean and are host to much of the biogeochemical action. They play a major role in the growth of phytoplankton which constitutes the primary production of the oceans. A recent collation of available observations has suggested the annual primary production within the world's shelf seas is about 11 Gt C a^{-1} (Jahnke, 2010), which compares with a global total of between 45 and 60 Gt C a^{-1} (Longhurst *et al.*, 1995; Behrenfeld *et al.*, 2005). The distribution of net phytoplankton production in the ocean can be estimated from satellite imagery (Behrenfeld and Falkowski, 1997), though care needs to be taken in accounting for the contribution from subsurface phytoplankton growth (invisible to a satellite sensor) and the difficulty of linking ocean colour to chlorophyll concentrations in coastal regions where suspended sediments and dissolved organic material can influence the data (Longhurst *et al.*, 1995). Notice in the example of such a satellite-based estimate in Fig. 1.1b that the highest values of annual carbon fixation are located in narrow bands around the continents. Fig. 1.2b provides an analysis of that data showing that we can attribute ~16% of global marine primary production to the shelf seas. That amount of production occurs in 5% of the ocean surface sampled by the satellite (note in Fig. 1.1b that the satellite coverage misses the high latitudes, including substantial areas of shelf in the Arctic). A more detailed comparison between shelf and ocean production rates shows that the shelf seas have an average carbon fixation rate per unit area a factor of ~2.5 greater than in the deep ocean.

The abundant supply of phytoplankton provides the primary food source for the rich fisheries of the shelf seas. Globally the shelf seas are the dominant source of fish caught by humans; it has been estimated that over 90% of global fish catches come from the shelf seas and adjacent upwelling area over the continental slope (Pauly *et al.*, 2002). Also, primary production involves the drawdown of CO_2 from the atmosphere and the subsequent removal of some of the fixed carbon into the deep ocean. Again, despite their relatively small surface area, current best estimates are that the shelf seas are responsible for about 47% of the global annual export of particulate organic carbon (Jahnke, 2010). This high proportion of carbon export is partially a result of high primary productivity in the shelf seas, but it also arises because of the unique physical environment in shelf seas and at the shelf edge. The processes governing the shelf edge, and their biogeochemical and ecological consequences, are the subject of Chapter 10.

1.2 Economic value versus environmental health

We depend on the shelf seas not only for fisheries but for a wide range of benefits. The sediments of the shelf seas have been a major source of hydrocarbons, both oil and gas, and are also widely exploited as a source of aggregates for building. We use the shelf seas extensively for transport and for recreation, as many of us sail in them and spend our holidays on their shores. We place a high value on the coastal marine environment but, in many cases, compromise its health by using our shelf seas and estuaries as low-cost dumping grounds for our domestic and industrial wastes. The pressures on the shelf seas from human activity are the more acute because so many of us live close to the coast. Approximately 40% of the human population is located within 100 km of the sea, and coastal zones are host to much of our industrial activity. Even where direct disposal of wastes by dumping and through sewage pipelines has been stopped, rivers still carry large quantities of nutrients and pollutants from terrestrial agriculture and industry into the shelf seas where they have their first, and usually largest, impact. An excess of nutrients entering the shelf seas can have seriously adverse effects in producing nuisance blooms of phytoplankton which may themselves be toxic, or can lead to *hypoxia* (oxygen depletion) as they decay with consequent disruption of the ecosystem and the mass mortality of marine organisms. Heavy metals and organic pollutants tend to become concentrated as they progress up the food chain and may have toxic effects in higher trophic levels including humans.

In addition to these pressures through inputs from industry and agriculture, the welfare of the shelf seas is further threatened by the over-exploitation of fish stocks. It has been estimated that fishing pressures in the North Sea are such that ~25% of the total North Sea biomass is removed each year (McGlade, 2002), much of it by trawling which also ploughs up the seabed. Such intensive fishing can result in the collapse of economically important fisheries, as in the case of the cod on the Grand Banks (Hutchings, 1996). Recovery of fish stocks can take considerable time (Hutchings, 2000), and intense fishing can lead to radical changes to the ecosystem as a result of habitat disturbance and community shifts to non-commercial species (e.g. Johnson and Coletti, 2002).

In order to provide a basis for the rational management of the shelf seas, there is a clear need for a full scientific understanding of the way the shelf seas work. Improved knowledge of the processes involved is required to underpin the development of skilful numerical models which can be used to investigate the response of a given shelf sea to changes in the applied pressures, including the likely changes in sea level and atmospheric forcing which will soon arise through global warming. This is an ambitious but pressing requirement which provides strong motivation for the study of the science of the shelf seas.

1.3 The scientific challenge of the shelf seas

In addition to the important practical management requirements for improving knowledge of the shelf seas, their study is also motivated by the fundamental challenge to interdisciplinary science of understanding the diverse processes operating in the shelf seas and the way they interact. It has been increasingly recognized that this challenge is no less than that posed by the deep oceans with which it has much in common. A separate focus on the shelf seas, which has developed in recent decades, is appropriate because of the radically different regimes of the shelf and the deep ocean.

Understanding the shelf seas is thus a major interdisciplinary campaign of science; it calls on all the separate physical, chemical and biological aspects of oceanography to elucidate individual processes and aims to represent their interaction in conceptual and numerical models. This is an ambitious programme; until the latter part of the twentieth century there was only limited progress and the sole textbook on the shelf seas (Bowden, 1983) concentrated on the physical oceanography where significant progress was being made. Developments in the physics of the shelf seas during the last four decades have established a framework in which the principal physical processes are represented and which has formed the basis for interdisciplinary developments. To some extent, the problem of unravelling the complex mix of processes has been made easier by the fact that the physical system is, with a few exceptions, independent of the biogeochemistry and not subject to feedbacks from biological processes.

It is this emergence of a firm physical framework which has expedited progress in interdisciplinary areas and stimulated a number of major interdisciplinary campaigns and experiments (e.g. CalCOFI (CalCOFI, 2011), the North Sea Project (Charnock *et al.*, 1994), the PRISMA Project (Sundermann, 1997), the PISCO partnership (PISCO)). The progress resulting from such initiatives has stimulated interdisciplinary understanding and enabled the subject to advance to a point where we judged that the time was ripe for a text covering the science of the shelf seas from the physics through to the biology.

1.4 A brief history of scientific research of the shelf seas to 1960

While the scientific study of the deep ocean is generally considered to have started with the *Challenger* expedition in 1872–1876, the systematic investigation of the shallow seas did not develop until some time later. Some important early observations were made at coasts, notably of the tides which were first accurately recorded at the port of Brest in 1679. By the late nineteenth century, extensive measurements with tide gauges at coastal ports had allowed mapping of the tidal characteristics in many of the world's marginal seas and the development of reliable methods of tidal prediction (Cartwright, 1999). This early success based on measurements in shelf seas, arguably the first quantitative success of oceanography, was the exception, as the focus of marine studies was increasingly in deep water. Compared with the exciting challenge of exploring the vast interior depths of the deep ocean, the study of the more accessible shelf seas had less appeal. The *Challenger* expedition was followed by a number of similar major voyages of discovery by vessels sponsored by nations that were keen to share in the prestige of deep ocean exploration (Deacon, 1971). The shelf seas were largely neglected in these studies, which were much more concerned with discovering new forms of life in the ocean and less with mapping the physical environment and determining the processes which controlled it. A notable exception which did concentrate on the shelf seas was the German-sponsored study of the North Sea and the Baltic by the S.S. *Drache* in the period 1881–1884 which made some of the first large-scale surveys of temperature and salinity distributions in the summer regime of these regions. Victor Hensen, a German zoologist working in the North Sea and the NE Atlantic Ocean in the 1880s, is often credited as founding the discipline of biological oceanography. He recognised the fundamental importance of the plankton in supporting marine life, and coined the word 'plankton' (from the Greek 'planktos' meaning to wander or drift) that was formalised by Ernst Haeckel in 1890 to encompass all drifting organisms.

The burgeoning interest in marine science stimulated by the *Challenger* and other deep sea expeditions led to the establishment of a number of coastal marine stations. Amongst the first of these was Stazione Zoologica in Naples, Italy, established by the German zoologist Anton Dohrn in 1873 with support from several European countries to provide laboratory accommodation for marine scientists. Others included the Station Biologique Roscoff, France (1872), the Marine Biological Laboratory at Woods Hole in the United States (1885), and the Marine Biological Association Laboratory at Plymouth in the UK (1888). Initially, these marine stations were principally concerned with work in marine biology, but later they contributed to stimulating developments in other marine disciplines. Some marine stations also started long-term series of observations of physical variables, such as the remarkable record of temperature, salinity and nutrients carried out off Port Erin, Isle of Man, since 1904 (Allen *et al.*, 1998).

Early concerns about the possible effects of over-fishing led governments to set up agencies to promote scientific studies. In the United States, a Fish Commission was established in 1881, while in the UK, the Scottish Fisheries Board was given a research mandate in 1882 and many other countries established similar bodies to promote the study of marine science related to fisheries. Concerns about the impact of over-fishing were expressed at the International Fisheries Exhibition held in London in 1883 but were not shared by all. It was at that meeting that T. H. Huxley, one of the most eminent scientists of the day, famously discounted reports of scarcity of fish and asserted that

> any tendency to over-fishing will meet with its natural check in the diminution of supply, . . . this check will come into operation long before anything like permanent exhaustion has occurred.

In hindsight, such reliance on the ability of the natural system to be able to resist the increasing pressures of industrial fishing appears naïve and unfounded. Fortunately such over-optimistic views, although influential at the time, did not deter governments from investing in fisheries research. In 1902, the national fisheries science organisations joined forces to establish the International Council for the Exploration of the Sea, ICES, to promote the study of the oceans in relation to fisheries. Scientific progress in relation to process understanding, however, remained limited as much of the fisheries research effort was concentrated on the practical problems of understanding the life cycles of commercial species and making stock assessments.

Nevertheless, important surveys of the physical properties and plankton distributions were accomplished through fisheries research. For instance, in the UK the early twentieth century saw work aimed at mapping the temperature and salinity distributions in shelf waters in an effort to understand fish stock distribution. At the Marine Biological Association in Plymouth, the first complete study of the seasonal changes in the physics, chemistry and plankton of a coastal water column was carried out in the late 1920s and early 1930s (Harvey *et al.*, 1935), and in an extensive series of cruises, Matthews (1913) documented the annual cycle of temperature, salinity and density variations over a large section of the north-west European shelf (the Celtic and Irish Seas). In the United States, similar pioneering studies of a large shelf sea area on the east coast, the Gulf of Maine, were undertaken by Henry Bigelow (Fig. 1.3). During the period 1912–1928, Bigelow studied the Gulf extensively and published three monographs on the physical oceanography, plankton and fishes. Bigelow was a strong advocate of an interdisciplinary approach to the then emerging science of oceanography and realised the need to move on from fact collecting to process understanding. In arguing the case for a new Oceanographic Laboratory (to be the Woods Hole Oceanographic Institute) he wrote:

> what is really interesting in sea science is the fitting of the facts together . . . the time is ripe for a systematic attempt to lift the veil that obscures any real understanding of the cycle of events that takes place in the sea. It is this new point of view that is responsible for our new oceanographic institution.

This progression from fact collecting and mapping of the shelf seas to the testing of theories about the processes controlling the physical environment and the response

Cambridge University Press
978-0-521-87762-6 - Introduction to the Physical and Biological Oceanography of Shelf Seas
John H. Simpson and Jonathan Sharples
Excerpt
More information

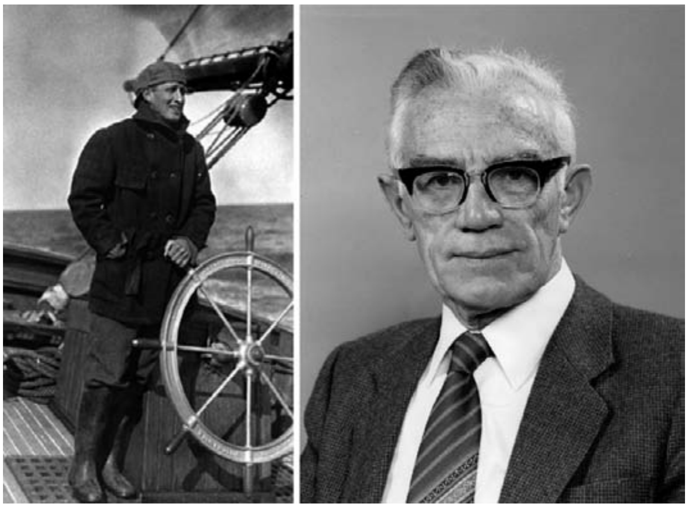


Figure 1.3 Left: Henry Bigelow at the wheel of the schooner *Grampus* in 1912 (courtesy Bigelow Laboratory). Right: Ken Bowden (courtesy University of Liverpool).

of the biological system developed gradually and only came fully to fruition in the second half of the twentieth century. A number of pioneering studies were undertaken before World War II. For example, Knudsen (1907) estimated residual flows in the North and Irish Seas using a continuity argument for mass and salt applied to the observed salinity distributions. The results revealed surprisingly small net flows; for the Irish Sea, Knudsen estimated a net northwards flow of $< 2\,\text{cm s}^{-1}$ through the North Channel. In another important development, G. I. Taylor estimated the level of tidal energy dissipation in the Irish Sea (Taylor, 1922) and showed how it fitted into the global pattern of energy loss.

By the 1950s, the continuing accumulation of data sets, mainly through the work of the fisheries agencies, stimulated investigations of the processes controlling the distribution of water properties. Important contributions in the 1950s and 1960s were made by Kenneth Bowden (Fig. 1.3), who was amongst the first to investigate the mechanisms controlling the salt and heat content of the water column. By allowing for horizontal mixing in the salt balance, he developed an improved model of transport through the Irish Sea (Bowden, 1950) and showed that the net flow is $\sim 0.5\ \text{cm s}^{-1}$, significantly lower than Knudsen's earlier estimate. This picture of weak residual flows was further supported by a study of the heat budget for the Irish Sea (Bowden, 1948), from which he concluded (correctly) that the seasonal changes in heat content can largely be accounted for by the transfer of heat through the sea surface, with the residual currents playing only a minor role. This understanding of the relative roles of advection and surface fluxes will be fundamental to our discussion of shelf sea stratification in Chapter 6.

Bowden also contributed to the understanding of tidal dynamics in shelf seas by determining the turbulent stresses in the water column which were bringing about the frictional dissipation previously estimated by G. I. Taylor. Bowden determined the stresses by inferences from the dynamical balance (Bowden and Fairbairn, 1952) and later went on to make the first direct measurements of stress in the ocean using the newly-developed electromagnetic flowmeter (Bowden and Fairbairn, 1956). With these and many other contributions, Bowden, a quiet and modest man, was responsible for stimulating progress in the physical oceanography of the shelf seas and for laying the foundation for many of the developments we shall be considering in later chapters.

At the same time, important progress was being made in understanding the biology of the shelf seas. Working over Georges Bank, Gordon Riley, along with Henry Stommel and Dean Bumpus, developed the fundamental understanding of how the spring bloom of phytoplankton is triggered by physical stability. From our twenty-first-century perspective, the idea of stability and light being key to rapid phytoplankton growth in the surface ocean can perhaps seem blindingly obvious, but in the 1930s and early 1940s there was some considerable effort aimed at demonstrating that the spring bloom was a product of grazing pressure, an idea related to a large degree to the understanding of terrestrial ecosystems. We will, however, see how grazing does play a more subtle role in determining the species that dominate the spring bloom later in Chapter 5. Riley applied statistical analyses to his careful sampling of phytoplankton biomass and growth over Georges Bank, leading to a key paper in biological oceanography (Riley, 1946) which included one of the first coupled theoretical models of physics and phytoplankton growth, the basics of which can still be seen in the codes of most coupled models today.

1.5 Instrumentation: 'Tools of the trade'

Progress in oceanography has been, and continues to be, closely linked to technical developments for making measurements in the ocean. This is true to some degree in most scientific disciplines, but in few areas is the constraint of technical limitation as severe as it is in our efforts to understand the workings of the ocean. The basic problem is that the ocean is largely impenetrable to electromagnetic radiation. Even in relatively clear water, light is absorbed on a scale of tens of metres, and at other wavelengths the absorption of energy is even more rapid. Only sound waves can travel relatively freely through the ocean, and even then, long-range propagation is restricted to low frequencies where the scope for the transmission of information is limited. So, unlike meteorologists who can watch the evolution of the atmosphere through the movement of clouds and measure velocities remotely with radar, oceanographers have to rely mainly on measurements from sensor systems lowered into the ocean or make the most of what can be learned from probing by acoustic methods. In this section, we shall consider the principal measurement tools and instrument platforms which are now available to determine the physical, chemical and biological characteristics through the water column.

Cambridge University Press
978-0-521-87762-6 - Introduction to the Physical and Biological Oceanography of Shelf Seas
John H. Simpson and Jonathan Sharples
Excerpt
More information

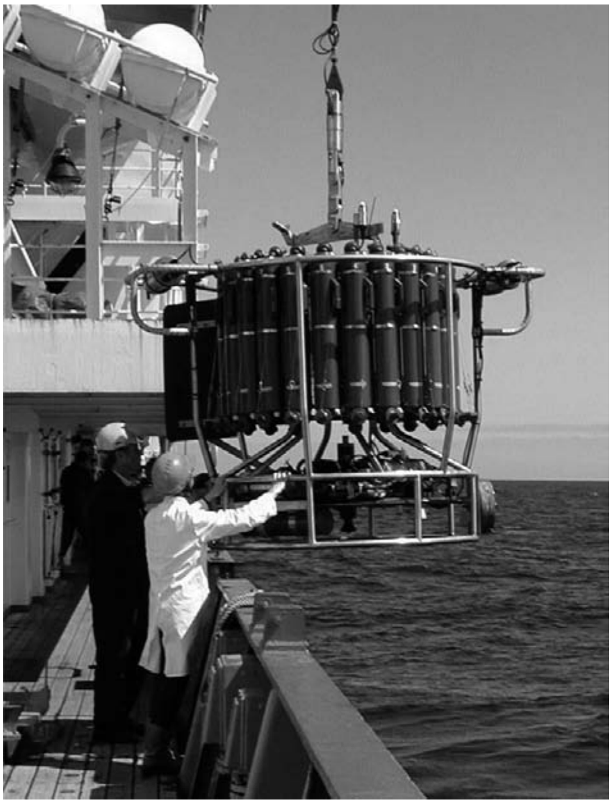


Figure 1.4 A CTD being deployed over the side of the RRS *James Clark Ross*. The CTD rests within the lower part of the frame below the grey sample bottles. This allows the instrument to sample relatively undisturbed water as the package is lowered through the water column. (Photo by J. Sharples.)

1.5.1 The measurement of temperature, salinity and pressure (the CTD)

The density of seawater is a physical parameter which, as we shall see in Chapter 3, plays an important part in the dynamics of the flow in shelf seas. Until the 1960s, density determination in the ocean was largely based on a combination of measurements using specialised mercury-in-glass thermometers to measure temperature and the collection of water samples to allow the determination of the salinity (salt content) of the water by titration or laboratory measurements of conductivity. The methods were reasonably accurate, giving temperatures to $\sim\pm 0.01\,^{\circ}\mathrm{C}$ and salinity to ~ one part in 3000, but they were also rather complicated and labour intensive.

In modern practice these early methods have been almost entirely replaced by a profiling instrument package measuring conductivity, temperature and depth and referred to simply as a CTD, shown in Fig. 1.4. As the package is lowered on a cable through the water column, information from electrical sensors is transmitted to the surface via conductors in the cable. In most modern CTDs, temperature is measured by a high-quality platinum resistance thermometer while conductivity is sensed by a conductivity cell which may be directly coupled to the seawater via electrodes or indirectly through an inductively coupled system. Pressure, which is usually measured by a strain gauge sensor, is used to determine the depth of the CTD.