1

Introduction – the overall pattern of enquiry

Excepting Mediterranean and Baltic communities, the daily pulse of the tide has always been familiar to those who live by a sea exposed to the oceans. Both the rise and fall at the shoreline and the swing of the currents offshore are obvious. The close alliteration of the Anglo-Saxon words *Zeit*, *Gezeiten, Time* and *Tide*, (which 'wait for no man'), testifies to early awareness of the tide's regularity by North Sea coastal dwellers, fishermen, navigators and pirates. 'Rules-of-thumb' expressing a relationship between times of High Water and lunar phases, based on careful observation, were embodied in medieval tide-tables and clocks (Figures 3.1, 3.2) and in archaic terminology such as 'What moon maketh a Full Sea?' (Chapter 3). For many centuries, then, or at least throughout the Christian era, the tide has been a commonplace phenomenon, apparently as predictable as sunrise and Full Moon. What, some may ask, has made it a subject for serious research up to the present day?

Leaving aside the fact that, to a professional astronomer the accurate prediction of the times of sunrise and Full Moon demands sophisticated computations, research on the oceanic tides (and later, tides of air and earth) has been driven by practical needs and by the variety of fundamental questions which have been posed. Practical needs originally stemmed from harbor management, protection from coastal and estuarine flooding, coastal navigation and surveying, but more recently have been additionally concerned with amphibious military operations, harnessing tidal power, and precise corrections to measurements to and from artificial satellites. In all such cases, easy solutions which suffice for rough purposes have proved inadequate, while every improvement in accuracy of measurement and prediction has led to further fundamental research into previously hidden details.

From the dawn of scientific enquiry, basic questions about the *mechanism* of how the moon and sun drive the tides and how the ocean responds to the driving forces have inspired distinguished philosophers and earth-scientists. Descartes and Galileo (Chapter 4) proposed theories which were later proved untenable by Isaac Newton. Pierre Simon, Marquis de Laplace, the pioneer of tidal dynamics, declared the subject to be '*… ce problème, le plus épineux de toute la mécanique céleste …*' (*the spiniest problem in all celestial mechanics*.) Solution of Laplace's tidal equations, even in seas of idealised shape, taxed mathematicians for well over a century until the advent of modern computers. Even then, some decades were to elapse before computers were large enough to represent the global ocean in sufficient detail, and techniques had improved sufficiently to give realistic results.

From a more empirical viewpoint, ever since primitive measurements from the western shores of the Atlantic became known, natural philosophers from Sir Francis Bacon onwards became curious to know how the tides behave in mid-ocean. Observing, for example, that High Water on the Atlantic coast of Florida occurs at the same time as at the Canary Islands, what happens in between? Does the tide progress northwards everywhere as observed along the coast of western Europe, or does it behave differently in the east and west Atlantic with a region of low amplitude in between? This important question was not seriously tackled until the 19th century, and then only after much speculation, – see Chapter 9 and later Chapters.

The 19th century polymath, William Whewell of Trinity College, Cambridge, became obsessed with this very question, and while unable to solve it, continually stressed the need for worldwide coastal measurements and berated the astronomers for having abandoned this fundamental science for more celestial pursuits.[1] Similar accusations have been leveled at oceanographers in the 20th century, and for analogous reasons. The fact is, that when a scientific problem does not yield to currently available tools, scientists tend to turn to other subjects which, if no easier, at least have the attraction of novelty. The tides have been an 'old subject' for a long time.

From time to time a new idea has arisen to cast fresh light on the subject. While such events have spurred some to follow up the new ideas and their implications, they have also had a negative effect by appearing superficially to solve all the outstanding problems. Newton's gravitational theory of tides (Chapter 5) explained so many previously misunderstood phenomena that British scientists in the 18th century saw little point in pursuing the subject further. The initiative passed to the French Académie Royale, culminating in the work of Laplace (Chapter 7) who took over where Newton stopped, at the dynamic response of the ocean to Newton's correctly defined force field. Similarly, William Thomson's idea of harmonic analysis, which stemmed from Laplace's theory, was so successful (after development by George Darwin) in providing for accurate predictions at any site where the tide had been measured for a long enough period of time, that one of the mainstays of research, namely from the commercial and naval producers of tide-tables, was transferred to routine computing activity. It was left to altruistic bodies like the British Association for the Advancement of Science (who had in fact promoted the development of the 'harmonic method' of prediction) to encourage further research into the *spatial* and *global* properties of tides and their currents.

When the new subject of *geophysics* began to develop towards the end of the 19th century, its investigators soon found that many of its problems involved the large-scale properties of the tides of ocean, atmosphere and the elastic earth.[2] Increasingly, these problems were seen to be global in character and solutions to them few or lacking. Of central and lasting interest was the total rate of dissipation of energy by the oceanic tides, and its implications for the apparent acceleration of the moon's longitude and (later) the rate of increase in the length of the day. Progress was now made, not by the tide-table experts, the naval hydrographers and academic mathematicians, who had hitherto kept tidal lore to themselves, but by geophysicists and by certain oceanographers inclined to mathematical physics.

The central problem of the 20th century, essential to the understanding of global energy dissipation as well as to a host of other geophysical problems, has remained that of determining the behavior of tides in the deep ocean. This is essentially the same problem as had bothered Whewell in the previous century, but at an altogether more refined level of precision than Whewell ever imagined. Persistently this problem defied formal mathematical analysis and measurement technique, and final or nearly final solutions have had to await modern technology.

Research on oceanic tides in the modern sense, then, has spanned at least four centuries. It has involved scientists from disciplines ranging from astronomy and satellite geodesy to ocean instrument technology, and activity from mathematical analysis and computing to sea-going expeditions. Relatively few people have been involved at any one time, but the subject seems to have had a peculiar fascination for 'lone workers'. As one worker has 'shot his bolt' or retired, another has taken up the challenge from a different viewpoint or discipline. Schools of expertise in different countries have led certain aspects of the field at different times, chiefly in Britain, France, Germany, Russia and USA. Only in the last decades of the 20th century, with the enormously increased power of computation and space geodesy, have the major goals been achieved. This book is therefore unusual in being concerned with the history of a science which has both a recognisable beginning and an 'end', or at least a temporary plateau, taking the reader from the earliest writings to the most recent research. The present is particularly timely for such a history.

Previous historians of tidal science have concentrated on the minutiae of limited, rather distant epochs of research, chiefly in the 16th to 18th centuries. The papers of the late E.J. Aiton in *Annals of Science*[4] (see Chapters 4 and 5) are particularly well studied in depth and have made useful guides to their epochs. Other historians from whose writings I have learnt much are Margaret Deacon on the debates about tides led by the early Royal Society of London (Chapters 4 and 6) and David Kushner on Sir George Darwin and the controversies over lunar acceleration among 19th century astronomers (Chapter 10).

Some textbooks have included a Chapter or part-Chapter on early history. Most comprehensive of these is in Book I, Part I of Rollin Harris's 5-volume monograph,[3] written very nearly a century ago and now long out-of-print. Harris's history has been widely acknowledged as the most thorough guide to early ideas on tides from antiquity to near the end of the 19th century. However, it was written as an introduction to Harris's own painstaking construction of a world map of tidal times. Ironically, he too probably thought the science was reaching the end of an era, but the dynamical theory on which his constructions were based was unsound, and was soon criticised on rigorous standards by George Darwin, though later accepted by Henri Poincaré as a reasonable compromise (Chapter 9). As one who has played a modest part in the international activity in tidal science during most of the last third of the 20th century, I feel confident that the year 1996 has a stronger claim to have reached the end of a long epoch of research, with the achievement of centuries-old objectives.

The above statements should not, however, be taken to imply that research on the tides is likely to come to a halt. Some details of the physical mechanism of energy dissipation are still unclear, and at the time of writing, *acoustic tomography* and *satellite altimetry* are revealing unexpected features of *internal waves* of tidal periodicity.[7] Tidal motion at diurnal and semidiurnal periods has also been observed for the first time in the rotation of the earth, (see Chapter 15). The small-scale dynamics of tidal motion on continental shelves, not to mention coastal engineering problems, will no doubt continue to demand attention.[5,6] This history is more concerned with the *global* aspects of tidal science, which do indeed seem to have reached a state of near-culmination.

Notes and references

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Early ideas and observations

Seafarers of all kinds have always made their own observations of the tides along the coasts they frequent, and have devised their own practical 'rules-of-thumb' for rough predictions. Their observations would have included the relationship to lunar phase but they would not have been concerned with the *cause* of the relationship. The information would have been passed from father to son and from master to apprentice as part of the lore of the sea, but no written record would be made. The subject of this Chapter is therefore somewhat fragmentary and partly based on secondary sources and legends.

The Megalithic Age

There is evidence, though of a controversial nature, that the people who erected huge stones ('megaliths') near the western shores of Europe around 2500–1000 BC chose sites for them from which the rising and/or setting of the sun and moon could be observed against distant landmarks on the horizon.[1,2] Such observations could, it is supposed, have enabled the *cognoscenti* of the Megalithic Age to keep track of the seasons and to note the variations of the moon's orbit, including conditions leading to lunar eclipses. It has even been suggested[1] that forecasting the tides could have been one of several motives for daily observing, since many of the supposed 'lunar observatories' are sited close to seas whose tides are a major hazard to navigation.

Sceptics[2] have doubted this suggestion, on the grounds that horizon positions (equivalent to declinations) give insufficient information *per se* for tide prediction, and few scholars now accept the whole theory. Against the sceptical view, one may argue that forecasting the equinoxes and solstices would be relevant to tides, and the trained observers would make more accurate assessment of lunar phase and time of transit than an average seaman. If, in addition, they could sense the *rate of change* of phase or the change in apparent diameter, indicating the approach of lunar perigee, this would be a distinct advantage, provided they knew how to use it. But, as with all 'megalithic science', applying one's own ingenuity to deduce the possible ingenuity of prehistoric man tends to weaken the logic. In any case, the complete absence of any intelligible written record makes all such ideas purely speculative.

Early Indian and Arabic civilisations

The earliest concrete evidence for mankind's interaction with the rise and fall of the tide, implying some understanding of their nature, is the discovery by Indian archeologists of a *tidal dock* off the Gulf of Cambay near Ahmedabad, dating from roughly 2000 BC.[3] A tidal dock is a large wall-sided basin with a narrow entrance to the sea, closable by a sluice-gate which is opened only at High Water to let ships in and out, then closed to prevent ships inside from grounding at Low Water. Photographs[3] show the dock to be a remarkable engineering feat for its period.

The authors of (3) quote from various early texts of religious origin which show recognition of the moon's influence on the tides. A *Puràna* document (300–400 BC) likens the ocean to 'water in a cauldron which in consequence of the heat expands, so the waters of the oceans swell with increase of the moon'. This curious notion of the moon imparting heat to the sea also occurs in an Arabic document of the 13th century AD, quoted in full by Darwin.[4] An old Icelandic document, also quoted by Darwin, refers to heating by the sun as well as the moon, in a confused attempt to account for spring tides occurring at both Full and New Moons. Explanations for the tides involving the 'pulse' or the 'breathing' of a monstrous sea god may also be found in certain Indian and oriental texts.[3,4]

In view of the long tradition of Arabian astronomy, it is very probable that port astronomers of the early Arabic civilisations concerned with navigation took note of the subtleties of local tide behavior in relation to lunar phases and the seasons. However, I have not seen any account of written Arabic documents on tides dating from before the 9th century AD. That knowledge existed before then is evident from the account by Posidonius, transcribed by Strabo,[6] of singular properties of the tides related to him or written by 'Seleucus' the astronomer, a native of the Persian Gulf. The phenomena described by Seleucus are discussed in the following section of this Chapter.

The influential 9th century treatise on astrology, including tides, by Albumasar – Chapter 3 – bespeaks a tradition of tidal knowledge at least as advanced and probably older than that generally ascribed to the pre-Christian Greeks and Romans, although by the time of Albumasar it is hard to distinguish original from derived knowledge. Indeed, the knowledge described by the early Mediterranean cultures was itself derivative from observers at oceanic ports outside the Mediterranean Sea.

The ancient Greek, Babylonian and Roman civilisations

We pass to the decidedly enlightened enquiries of members of the early Greek civilisation. The Greeks had little direct experience of tides in their home waters, but they knew of their existence outside the 'Temple of Hercules' (Gibraltar) and from the roughly contemporaneous voyages of Pytheas of Marseille to northern Europe and of Alexander the Great to the mouth of the Indus River on the Arabian sea coast, (330–324 BC).

Aristotle (384–322 BC) wrote influential books on *Physics* and *Meteorology* which cover most aspects of the then known physical world, but he had little to say about tides, probably on account of lack of personal experience of them. He commented on tidal phenomena reported from 'Gades' (Cadiz), but attributed them vaguely to the rocky nature of the coast. Curiously, during his last years, when Aristotle lived at Khalkis, he was said to be greatly perplexed by his inability to understand the so-called *Tide of the Euripus* there – oscillatory currents in the narrows between the long island of Euboea and the mainland of Greece. He was also said to be drowned in the Euripus.[5] The oscillatory currents are now known to be caused by differences in the very small tidal elevations to the north and south of the strait, a fact first suggested by Eratosthenes the geodesist (c.276–194 BC) according to writings on tides attributed to him by Strabo.[6,7] These 'tides' are highly *irregular* in the sense used by Seleucus – see below – and they are disturbed by local resonances at nontidal periods induced by weather. Aristotle may be forgiven for failing to recognise any simple rythmic pattern or causality in what is regarded even today as a very complex dynamic regime.

The Stoic, Posidonius (135–51 BC), gave the first reasonably correct and detailed account of the tides at Gades from personal observations and accounts by unnamed local people. All his original writings were lost in the fire at the library of Alexandria (47 BC), but their essence is preserved in the 17 books of the *Geography* of Strabo (64 BC to 21 AD), who quotes extensively from Posidonius.[6] Thus Strabo writes:

> 'Now he (Posidonius) asserts that the motion of the sea corresponds with the revolution of the heavenly bodies and experiences a diurnal, monthly and annual change, in strict accordance with the motion of the moon.'
>
> For the diurnal motion: '… when the moon is elevated one sign of the zodiac [30 degrees] above the horizon, the sea begins sensibly to swell and cover the shores, until she has attained her meridian; but when that satellite begins to decline, the sea again retires by degrees until the moon wants merely one sign of the zodiac from setting; it then remains stationary until the moon has set and also descended one sign of the zodiac below the horizon, when it again rises until she has attained her meridian below the earth; it then retires again until the moon is within one sign of the zodiac of her rising above the horizon, when it remains stationary until the moon has risen one sign of the zodiac above the earth, and then begins to rise as before.'
>
> For the monthly revolution: '[he says] that the spring tides occur at the time

> of the new moon, when they decrease until the first quarter; they then increase until full moon, when they again decrease until the last quarter, after which they increase until new moon; [he adds] that these increases ought to be understood both of their duration and speed.'
>
> For the annual motion: 'he says that he learned from the statements of the Gaditanians, that both the ebb and flow tides were at their extremes at the summer solstice; and that hence he conjectured that they decreased until the [autumnal] equinox; then increased to the winter solstice; then decreased again until the vernal equinox; and finally increased until the summer solstice.'

The above accounts of the diurnal (twice daily) and monthly (twice monthly) variations are quite correct. One may assume that by 'duration and speed' Posidonius or Strabo means the duration of exceeding a high level and the speed of succession of High Waters, respectively; the 'speed' is slightly greater at spring tides. But the account of the annual variation is curiously wrong, for from modern knowledge, in any semidiurnal tide regime spring-tides reach their *highest* levels around the equinoxes and their *lowest* levels at the solstices, as may be verified by study of a modern tide table for Cadiz or nearby Gibraltar. (In fact, one has to take rather careful averages to detect any systematic difference at all.)

It is conceivable that the original observations on which the account told to Posidonius was based were made in only one year which happened to be a year when 'perigean spring tides' (that is, spring tides coincident with perigee – the closest approach of the moon) occurred near the summer solstice, as happens about every $4\frac{1}{2}$ years. An unusually high perigean spring tide would be followed 15 days later by an unusually low 'apogean' spring tide, but perhaps this subtlety was overlooked. Darwin's[(4)] remarks on this issue are ambiguous, but he writes: 'I doubt whether there is any foundation for that part [of Posidonius' account] which was derived from hearsay.'

Nevertheless, the Roman sage Pliny the Elder (AD 23–79), writing less than a century after Strabo, and like him quoting from existing texts, writes in his *Natural History*:[(8)]

> … and all these (tidal) effects are likewise increased by the annual changes of the sun, the tides rising up *higher* at the equinoxes and more so at the autumnal than the vernal, while they are *lower* about the winter solstice and still more so at the summer solstice … *not exactly at the Full nor at the New Moon but after them*. [my italics]

Pliny's source thus gives the correct account of the equinoctial/solstitial inequality, contradicting the account ascribed to Posidonius, and in addition has taken note of the *age* of the tide – the delay of a day or two of spring tides after Full or New Moon. The reported inequality between the vernal and autumnal equinoxes is not true of tides today, but it was indeed correct 2000 years ago, when *perihelion* – closeness to the sun – occurred some 35 days earlier than its present date of about 2 January, and so closer to the autumnal equinox.

Returning to Posidonius, the Stoic was also the first to take note of the

Cambridge University Press
978-0-521-79746-7 - Tides: A Scientific History
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diurnal inequality, that is, the difference in heights between successive High Waters or successive Low Waters. The diurnal inequality is quite low at Cadiz, as it is in most of the North Atlantic, but it is very noticeable in the Arabian and Red Seas, and in the Persian Gulf. In fact, Posidonius obtained his information from Seleucus of Babylon, an astronomer, 'native of the country next the Erythraean (Arabian) Sea'.[6] Seleucus, Strabo writes,

> states [according to Posidonius] that the regularity and irregularity of the ebb and flow follow the different positions of the moon in the zodiac; that when she is in the equinoctial signs the tides are regular, but that when she is in the signs next the tropics, the tides are irregular both in their height and force; and that for the remaining signs the irregularity is greater or less, according as they are more or less removed from the signs just mentioned. Posidonius adds that during the summer solstice and whilst the moon was full, he himself passed many days in the Temple of Hercules at Gades, but could not observe anything of these annual irregularities.

Here, the term *irregularity* evidently means diurnal inequality, and the description of how it would appear at equinoxes and solstices accords exactly with that observed in all seas adjacent to modern Saudi Arabia, while being barely perceptible at Cadiz.

In general, the most remarkable feature of all these accounts is, as observed by Lord Kelvin, the interest, experimental ability and persistence of people 2000 years ago to record the heights of the tide throughout the year, to note quite small changes, and to relate them to the ephemerides of the moon and sun.

No writings of Seleucus survive, but from secondary sources[7] we learn that he postulated that the moon causes tides by pressing or resisting the atmosphere, assumed to extend to the moon's orbit. He supposed the pressure or resistance to set up winds which would transfer the disturbance to the ocean. Like later hypotheses involving a heating or lighting effect (Chapter 3) Seleucus's idea failed to account for the tide which is manifest when the moon is below the horizon. However, replacing the atmosphere by the 'aether', supposed to fill all space, it has some affinity with Descartes' *vortex theory* of more than 17 centuries later, which by subtle argument did purport to account for the twice daily influence of the moon (Chapter 4).

The stark facts related by Posidonius also stirred primitive superstitions and vaguely religious feelings. Pliny[8] attributes to Aristotle the enigmatic remark: 'no animal (on the ocean coast of Gaul) dies except when the tide is ebbing' – an aphorism echoed after two millennia in Charles Dickens' description of the death of Barkis, *David Copperfield,* Chapter XXX, – and is then inspired to poetic thoughts:

> Hence we may certainly conjecture that the moon is not unjustly regarded as the star of our life. This it is that replenishes the earth; when she approaches it, she fills all bodies, while when she recedes she empties them. From this cause it is that shellfish grow with her increase, and those animals that are without

blood more particularly experience her influence; also, that the blood of man is increased or diminished to the quantity of her light, and the leaves and vegetables generally, as I shall show in the proper place, feel her influence, her power penetrating all things.

From the time of Posidonius onwards, there seems to be general agreement among those writers of the civilised world who made passing reference to the tides, about their apparent relation to the motions of the moon and sun. But more than a thousand years were to pass before one finds any evidence of a written table of tide predictions, or of any constructive thought applied to understanding the *cause* of the tides. These long intervals may be cited as the first example of the peculiarity noted in the previous Chapter, that substantial advances in understanding have tended to be followed by a lull during which nobody seemed inclined to learn any more about the subject.

The 'Dark Ages'

However, the present example has special circumstances related to human history. Athens and Rome fell successively to uncivilised invaders, and the climate of leisured philosophical enquiry, for which early Greece especially is remembered, collapsed; for many, mere survival became the essence of life. By AD 500 all the countries which now comprise modern Europe were overrun by barbarous warriors, civil strife abounded, and there was no chronicler even to write down a comprehensive history, still less engage in natural philosophy. The 'Dark Ages' had begun. Only isolated groups of Christian monks managed to preserve and teach what learning there was. We shall see in Chapter 3 that the Monastic institutions of Europe did indeed produce writers who occasionally commented on the tide in their accounts of the natural world, and who sometimes added their own observations of the phenomenon.

Otherwise, occasional references to the effects of the tide on men's affairs appear in the sparse historical fragments from the Dark Ages. The Battle of Maldon (Essex) in AD 991 between defending Anglo-Saxons and Viking invaders was held up by the tide, as related with dramatic effect in an anonymous Anglo-Saxon poem.(9) The popular legend of King Canute or Knut of England, Denmark and Norway (995–1035) is probably an exaggerated embellishment of some real altercation between the king and his courtiers. Whatever the true facts, there is historical evidence that such an altercation took place close to the tidal shore of present-day Southampton where it is commemorated by a wall-plaque (Figure 2.1). The legend is also associated by some with the tidal port of Bosham, West Sussex.

Understanding of tides in ancient China

In volume 3 of his monumental treatise, *Science and Civilisation in China*, Joseph Needham (1900–1995) devotes eleven pages to accounts related to sea tides in ancient Chinese writings.(10) Needham exaggerates when he says: