THE WAVEWATCHER’S COMPANION

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One chilly February afternoon my three-year-old daughter, Flora, and I were messing around on the rocks in Cornwall. Normally, this would have been a perfect opportunity for some cloudspotting. But that day was unseasonably clear – in fact, there was not a single cloud to be seen. And as we sat at the edge of the cove, with nothing but the monotonous Atlantic horizon ahead, we found ourselves, by default, watching the motion of the water. At least, I did. Flora just wanted to clamber about on the slippery boulders.

There was nothing dramatic about that day’s waves. They weren’t barrelling breakers throwing up clouds of spray as they slammed into the headland. Nor did they have any of the regularity of the waves you see in your mind’s eye, arriving as a steady succession of crests, one after the other, tumbling in regimented fashion up the shingle.
In fact, there wasn’t the slightest order to the water’s motion. Like rush-hour commuters at a busy station, the little crests passed this way and that, crossing each other’s paths chaotically. But, unlike commuters, they passed through and over each other, combining and dividing, appearing and disappearing.

Their movement was mesmerising. I found myself unable to follow the progress of any individual crest for more than a second. No sooner had I fixed on one than the pesky little peak joined with one coming from a different direction. Then, inevitably, my eye would be distracted by a third wavelet that would sweep through just as the first two vanished.

Talking with Flora, the questions were soon coming thick and fast: ‘Why are there waves?’, ‘Where do they come from?’, ‘Why do they splash like that?’ And although they were childish questions, it was me, not Flora, who was asking them.
Although a clear blue sky had triggered my interest in waves, I now realise that cloudspotting leads naturally to wavewatching. You can’t stare at the clouds for long before realising how much their appearance is influenced by waves. I don’t mean the waves rolling over the surface of the ocean, but the ones that form up there, within the boundless airstreams of the sky. For the atmosphere is an ocean too, but an ocean of air rather than of water.

The oceans above and below the horizon are intimately related. As the Book of Genesis records, the first thing God did, when getting everything started, was to set the seas in motion:

*In the beginning God created the heaven and the earth.*
*And the earth was without form, and void; and darkness was upon the face of the deep. And the Spirit of God moved upon the face of the waters.*

The following day, He ‘divided the waters which were under the firmament from the waters which were above the firmament’. In other words, God separated the oceans below from the clouds above with an expanse of air.

This close affinity, if not common lineage, between sky and sea means that a mere cloudspotter is in fact, without even realising it, a wavewatcher, since clouds are often borne on waves of air.

These waves take the form of rising and dipping winds, which, though invisible, are revealed by the shapes of the clouds. The ‘undulatus’ species, for example, is either a continuous layer of cloud with an undulating surface or parallel bands of cloud separated by gaps. Such clouds are born in the region of wind shear that occurs between air streams of different directions or speeds. Undulatus is a beautiful, if common, example of the clouds revealing the waves of the atmosphere.

But the most spectacular example of waves in the sky has to be the rare and fleeting ‘Kelvin–Helmholtz wave cloud’. This snappily named formation looks like a long succession of what surfers call ‘pipes’ or ‘barrels’, but are more accurately described as vortices. It is an extreme example of the undulatus species in which the shearing winds are at just the right speeds to cause the cloud waves to curl.
Cloudspotters and wavewatchers are united by the beauty of the Kelvin–Helmholtz wave cloud.

over themselves. The fleeting formation appears for no more than a minute or two before dissipating. While the processes that form it have little in common with those causing an ocean wave to tumble upon the shore, this cloud surely sits slap-bang in the middle of the Venn diagram of cloud and wave enthusiasts’ interests.

A wave cloud, or any other cloud for that matter, is a collection of suspended water particles; but what exactly is an ocean wave? You may think the answer is obvious: it is a moving mound of water. But if you do think that, you are not watching carefully enough. The best way to see that it is not is to observe the effect waves have on something floating in the water – a sprig of seaweed, for example.
Before Flora and I abandoned the water's edge, I watched one such tuft of weed rise and dip and duck and weave as it kept pace with the agitated water below. The seaweed seemed less like a rushing commuter and more like a featherweight boxer. As the peaks moved this way and that below it, the bobbing seaweed remained in the same general position. It wasn’t swept along with the crests.

When we climbed on to the cliff-top, we watched how a boat moved with the passage of the waves. From up there the waves had a wholly different appearance. The chaotic criss-cross of crests now looked like just a surface texture, which reflected a glittering path of sparkles below the Sun. Beneath these shimmering wavelets, one could see that a far broader, more orderly, pattern of undulations was rolling in towards us from far out in the Atlantic. Each smooth wave was, I’d guess, some 15–20m from its predecessor, which it followed in a calm, sedate fashion. This caravan of crests could not have been more different from the little peaks that busied across its surface. But, just as they had passed under the seaweed rather than sweeping it along with them, so these gentle giants rolled in under a fishing trawler that was returning with its catch. They didn’t drag it towards the land, as they would have done had they been currents of water. Clearly, the water that the boat floated on returned to pretty much where it had started after the wave had passed through.

So if these waves, like the ones in the cove, weren’t travelling water, what exactly were they? What was moving from out at sea to the shore?

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The answer is energy.

Water is just the means by which energy moves from one place to another. It is the ‘medium’ through which the wave’s energy travels. The ocean’s surface becomes possessed by energy in the same way that a spiritual medium is supposedly animated by souls from the ‘other side’.

Well, not exactly the same.
In fact, not the same at all.

But I rather like the image of the water being like some back-room psychic, wearing jangly earrings and a lot of purple. Placing her gnarled hands on the table, she rises to her feet, animated by the ghost of your dead granny. Her eyes roll, flecks of spittle gather at the corners of her mouth and she says in a guttural voice that the telly’s not as good on the other side. Then Granny’s spirit moves on, and the old psychic flops back down into her armchair and asks you to cross her palm with money.

Does that help explain that an ocean wave is energy passing through water? Perhaps not. In fact, the water doesn’t rise straight up and down (like our possessed psychic did) as the energy passes through. Had Flora and I been able to watch the movement of a sprig of seaweed out in the deep water, where the broad, more regular waves were coming in, we might have been able to see the way it moved with the passage of crest and trough. As the wave approached, the seaweed would have been sucked slightly towards it. It would then have risen upwards as the crest arrived and, at the highest point, would have moved forward a little with the wave. Then the seaweed would have sunk back down again with the arrival of the trough, pretty much returning to where it had started. With the passage of a wave, the water at the sea surface moves in circles.

It is not easy to picture the water returning to where it started as the energy travels on, so it might be more instructive to describe a wave in a more tangible way, such as its size. There are two dimensions by which to distinguish a ripple from a tsunami: its height and its ‘wavelength’.

A wave’s height is the difference in level between crest and trough. Scientists often prefer to use the measurement known as ‘amplitude’. Generally half the wave height, since it is the level of the wave crest compared with that of still water, it makes their equations for modelling waves simpler. But it feels more intuitive to stick with the crest-to-trough dimension of wave height.

The wavelength is a measure of the distance from one crest, or peak, to the next. Although we often think of a wave as a single crest of water (and we use the term to describe any individual peak),
ocean waves never actually exist in isolation. They invariably travel in company, so the term ‘wave’ is often used interchangeably to describe a single crest as well as a succession, or ‘train’, of crests and troughs. Often, as in the Cornish cove, the undulations of the water’s surface are so jumbled and confused that it is impossible to discern any clear wavelength. Only when they have the organised appearance of the broad ones we viewed from the cliff-top is it possible to determine whether a wave has a long wavelength, its crests being widely spaced, or a short wavelength, the crests being bunched up.

These two dimensions offer a general measure of the size of waves at any given moment, but say nothing of their movement. And, as any surfer will tell you, waves are all about movement. This is where a wave’s ‘frequency’ comes in: that is, the number of crests that pass a fixed point (such as a post protruding from the water) every second. In the case of tiny ripples, such as you might see when you drop a stone into a pond, a handful will scuttle by within a second. But we don’t pay much attention to waves of this
size; these inconsequential little ripples won’t send a surfer dashing for his board, let alone damage an oil rig, as huge waves have been known to do. The ones we do pay attention to, being much larger, might have as many as sixteen seconds between the arrival of one crest and the next. In this case, it is rather awkward to talk about the waves having a frequency of one-sixteenth, or 0.0625 crests per second, so the passage of ocean waves is usually described in terms of their ‘period’, which is simply the number of seconds between one crest and the next passing a fixed point.

Besides its size and movement, the other basic characteristic used to describe an ocean wave is its shape. Some rise and fall in broad, symmetrical undulations, with a profile approaching that pure mathematical line the sine wave, as shown in the upper of the two idealised wave shapes above.

But most aren’t shaped like that. The steeper a wave, the less like a sine wave it becomes. Rather, it has a ‘trochoidal’ shape. This is slightly less symmetrical than a sine wave, having sharp peaks separated by smooth troughs. But steep doesn’t necessarily mean large. The chaotic crests that Flora and I saw in the cove were peaked, rather than rounded. The shape-defining steepness depends upon the height compared with the wavelength, not whether it is a big wave. Even small ones, when bunched up enough, will be steep, and so will have trochoidal shapes.

A wave’s shape varies with its steepness.
Clouds and ocean waves have more in common with each other than occasionally looking similar. In fact, breaking waves play a subtle role in the formation of clouds. For as the crests come tumbling in over themselves at the shore, the turbulence causes countless tiny air bubbles to form and burst, releasing a fine mist of water droplets into the air. When the water evaporates, tiny particles of salt are left floating in the air, which can become swept up into the atmosphere. These microscopic salt particles are some of the most effective ‘condensation nuclei’ on which most cloud formation depends, acting as seeds on to which the invisible water vapour in the air can start to condense and form tiny droplets that we see as low clouds. I’m not saying that breaking waves cause clouds to form directly above them, just that they ensure that condensation nuclei, important ingredients for cloud formation, are always wafting around the lower atmosphere.

It works the other way too, for clouds play a role in the formation of waves – at least, storm clouds do. This can seem surprising when you gaze at the waves gently lapping up the beach of some exotic holiday location. They look so calm and tranquil from the shade of a swaying palm: like the relaxed breathing of the ocean, each wavy exhalation ceaselessly following the last. But such a graceful arrival belies the waves’ troubled upbringing. These serene visitors will often have begun life amidst the chaotic, wind-torn tumult of a storm somewhere out at sea – one that has long since dissipated.

How do waves form in a storm? And how, for that matter, do they change from that choppy confusion into the ordered procession of crests that tumble up the beach towards you? For the answers you need to chart their journey across the ocean, to follow each stage of their development, from birth at sea to foaming death on the shore.

Their biography can be divided into five stages, at each of which the waves have a distinct character.
Let’s start at the beginning, with the birth of a wave.

Waves are formed all the time, right across the world’s oceans, but it might help to observe their formation in a clutter-free environment: perhaps on a patch of smooth, calm and wave-free sea. In reality, no such place exists. The closest approximations are probably within the ‘horse latitudes’, the bands of the seas that fall between 30° and 35° latitude in both the Northern and Southern Hemispheres, and the ‘doldrums’, the band at the equator, extending 5° or 10° to the north and south. In both regions, the winds can be feeble and inconsistent. Since wind causes waves, there are times when none are generated in parts of these regions. But on any ocean, even during the calmest weather, the glassy surface will still rock with the gentle reverberation of waves that have arrived from storms over other, distant regions.

The periods of calm can be more persistent in the perpetually high pressure of the horse latitudes. After all, the name is thought by some to derive from eighteenth-century Spanish merchant ships transporting horses to the New World having to jettison their cargo to conserve dwindling water supplies. But we don’t want to wait around forever, so let’s choose a patch of water in the doldrums. As the poet Samuel Taylor Coleridge famously described them, the winds here can be so feeble and dithering that they leave a sailing vessel ‘stuck, nor breath nor motion; / As idle as a painted ship / Upon a painted ocean.’ The word ‘doldrums’ derives from the old English word *dol*, meaning ‘dull’. But these regions experience consistently low pressure. This means that their sultry, eerie calm will soon be broken by weather of a very different character that will conveniently turn the gentle, glassy undulations into towering waves.

The warm, humid air around this equatorial belt can lead to intense atmospheric instability. This can cause the air to rise rapidly, its moisture condensing into towering storm clouds. Squalls and storms near the doldrums develop suddenly and can keep growing into enormously destructive tropical cyclones. But we don’t need anything as violent as that to bring our waves into being. A simple storm at sea will do the job.

The droplets forming within the building towers of cloud cause the air to warm as they condense, making it expand and rise as it
becomes more buoyant. So the air pressure at sea level plummets and surrounding air rushes in to fill the void. This is the wind that gives birth to our ocean waves, and heralds the first stage in their life cycle.

Once the wind’s speed has reached a couple of knots, or one metre per second, the friction it exerts on the water starts to leave subtle imprints. Tiny ripples dance across the surface, each no higher than a centimetre or so. Soon, scattered, diamond-shaped ripples, known as ‘cat’s paws’, sparkle in the light ‘where the wind’s feet shine along the sea’, to borrow a phrase from the Victorian poet Algernon Swinburne. Since a patch of these ripples looks different from the smoother surface away from the wind, it will alert a sailor to an approaching gust before it reaches his sails.

These incipient ripples are the newborns. They are the very first stage in the life cycle of a wave. The tiny crests come and go with the gusting movements of the wind, but they soon become established as they are nourished by the stiffening air currents of the building storm into an enduring roughening of the water’s surface.

And, like all infants, they soon begin to place a strain upon their parents. The roughening of the surface increases the friction between the water and the winds. The air cannot glide over the ocean’s surface as easily. Tiny eddies develop just above the capillary waves, resulting in fluctuations in the pressure that the air exerts upon the water. The ripples respond enthusiastically to such stimuli: they lift a crest here and sink a trough there and grow in size.

Their development is always a result of a clash of wills. On the one hand, there’s the force of the wind, causing the surface to lift above and sink below its flat, equilibrium level. On the other, there is the water’s tendency to resist such disturbances – to return to the calm stability that it enjoys in the absence of the wind. This tendency is, in fact, due to two factors: the water’s surface tension and its weight. The tension resists the slight stretching of the surface at a crest and the slight bunching at a trough, while the force of gravity on the water, or weight, pulls down where the surface is lifted above the equilibrium and (by means of the water pressure) pushes up where it is sunk below it. As they try to return the water to a level equilibrium, both forces have the effect of
making the wave overshoot, causing a crest to keep sinking and become a trough, causing a trough to keep rising and become a crest. Initially, when our waves are infants, the surface tension of the water is the more dominant force. This natural resistance to the stimulating influence of the wind is what causes the little ripples to progress across the surface.

Once they have risen to a couple of centimetres in height, our waves are no longer infants. The first stage of their life is complete. No longer can we call them capillary waves. They are now known as ‘gravity waves’ because the weight of the water – the force gravity exerts on it – has become the more significant influence on them. This is now the dominant force in opposing the disturbance of the wind, tending to restore the water to its level and so powering the young waves forwards through the ensuing mêlée.

Now into childhood, our waves have entered the second stage of their development, which sees them grow from wavelets to waves, as if from boisterous toddlers to delinquent teenagers. As the wind builds in force and becomes more sustained, so their appearance changes completely from the organised ranks of capillary waves. The crests and troughs now grow agitated and chaotic. They rush this way and that, running into each other, tumbling over each other, like a roomful of toddlers under the dubious guidance of a hyperactive childminder. This confused and irregular ocean surface is known simply as a ‘wind sea’. The term refers to the sea’s rough, choppy surface while it is being whipped up by the wind, as it continues to give more and more of its energy to the water. In the case of a storm, the wind sea is a stage of rapid and sustained growth for the waves.

In fact, the speed of their growth increases as the wind finds larger and larger wave faces to push against. With such a jumble of wave heights and wavelengths coexisting within the same space

* Though, confusingly, it is also sometimes described as just a ‘sea’.
of water, it is hard to give a representative measure of their collective size. To describe them in terms of the very highest waves is misleading, since, in the mess of the wind sea, the very highest ones will appear only occasionally. Instead, oceanographers often describe a range, or spectrum, of wave sizes in terms of the ‘significant wave heights’. This is defined as the average of the tallest one-third of all the waves. It might sound more complicated than the height of the tallest waves, but it is in fact a more useful and representative measure when there is a range.

Before long, the significant wave height has grown to a metre. They are waves now, rather than wavelets. The fierce storm winds have been anything but a calm, consistent influence upon them. The hyperactive wavelets have grown into aggressive and unruly waves, with steep faces and sharp, trochoidal peaks. They grow angrier and more aggravated under the wind’s abusive guardianship, until plumes of foam begin to form at their crests. The third, and most disturbed, stage of their development is about to begin.

Now emerging into adulthood, the waves have ‘badass’ written all over them. This third stage is marked by the appearance of foaming lips of white water on the larger specimens. Known as ‘whitecaps’, these are the waves beginning to tumble over themselves, under the relentless, harrying force of the gale.

If storm-force winds blow for long enough, and over a large enough area, they begin to tear plumes of spray, or ‘spindrift’, from the crests. Each wave face becomes marbled with streaks of white foam, ‘like a wall of green glass topped with snow’ as the writer Joseph Conrad described them, though they seem to me more like the furious spittle of a madman. The waves keep on growing, their significant heights eventually surpassing 5m.

Now the whitecaps have become commonplace. Mariners sometimes describe them as ‘white horses’, occasionally as ‘skipper’s daughters’ – the latter, presumably, because you don’t want to mess with them. All this foam indicates that the waves are breaking in deep water. Their crests are being knocked over by the force of
the wind. Now, as they continue to grow, the spitting mountains of water are most dangerous to ships. Not only are they steepest, they are also liable to break over the ship, bringing tonnes of seawater crashing down on to deck.

To try to avert such a danger, mariners have, since classical antiquity, had a trick up their sleeves. They have poured fish oil overboard, or hung sacks containing oil-soaked rags into the water, to calm the waves in a storm. It seems that the ancient Greeks considered that this curious effect might be explained by the film of oil that spreads over the surface, reducing friction between wind and water: ‘Is it, as Aristotle says,’ wondered the Greek historian Plutarch, ‘that the wind, slipping over the smoothness so caused, makes no impression and raises no swell?’

Perhaps this phenomenon is what lay behind a wave-calming miracle, described in the eighth century by the English monk and scholar the Venerable Bede. In his Ecclesiastical History of the English People, Bede described how a priest setting off on a voyage was given holy oil by a certain Bishop Aidan to chuck in the water if
a storm endangered his ship. In this case, the oil was supposed to have had a miraculous effect: it made the wind immediately cease and the storm subside, leaving a balmy, sunny day.7

In 1757, the American polymath Benjamin Franklin also became fascinated by the phenomenon, having noticed something peculiar about the waves in the wake of neighbouring ships on a transatlantic voyage. The waves behind two of the ships were particularly smooth, compared with the others in the fleet. His captain explained that the cooks must have emptied their greasy water through the scuppers, thus inadvertently calming the waters.

It obviously stuck in Franklin’s mind because, sixteen years later, he described in a letter to a friend, William Brownrigg, an experiment he had performed during a stay in London to study at first hand the effect of oil on wave formation:

At length being at Clapham, where there is, on the Common, a large Pond, which I observed to be one Day very rough with the Wind, I fetched out a Cruet of Oil, and dropt a little of it on the Water. I saw it spread itself with surprising Swiftness upon the Surface, but the Effect of smoothing the Waves was not produced; for I had applied it first on the Leeward Side of the Pond where the Waves were largest, and the Wind drove my Oil back upon the Shore. I then went to the Windward Side, where they began to form; and there the Oil tho’ not more than a Tea Spoonful produced an instant Calm, over a Space several yards square, which spread amazingly, and extended itself gradually till it reached the Lee Side, making all that Quarter of the Pond, perhaps half an Acre, as smooth as a Looking Glass.8

However, Franklin wasn’t able to work out quite why the oil had had this effect. The explanation is a little subtler than the Greek proposal that it makes the water more slippery, preventing the wind from gripping so well.

In fact, the effect the oil has on the water’s surface tension is the critical factor. It spreads over the surface of the water as an extremely thin film, or skin, which has a lower surface tension than the surface of water. This drop in surface tension actually makes
the water less able to ripple under the influence of the wind and form the centimetre-high capillary waves.

You’d think that tiny surface ripples would be the least of your worries among the heaving monsters of an ocean storm. But remember that in embryonic form these waves increase the friction between air and water. They give the howling winds a purchase on the faces of the rolling mounds of water, helping them transfer their energy all the more efficiently to the water. By suppressing the surface ripples, the oil can make enough of a difference to the wind’s grip to stop an enormous crest from being thrown on to, rather than under, the deck of a ship.

But before you start chucking engine oil in the water the next time you’re messing around in a dinghy and it gets a bit choppy, bear in mind that your mini-Exxon Valdez will have a minimal effect. Modern petroleum-based oils don’t work well. Only organic oils, such as those from the flesh of oily fish, spread far enough, and fast enough, to tame the skipper’s daughters.

While we’ve been distracted on Clapham Common, the storm has continued to howl and, under its abusive guardianship, the waves have grown to significant wave heights, to 12–15m brutes the size of four-storey buildings – with wavelengths of over 200m. This is now a ‘fully developed sea’, which means that the waves have grown as high as they can under these wind speeds.

The height of the waves whipped up by a storm doesn’t just depend on the strength of the wind. Oceanographers have found that there are two other important factors: the area of water over which the wind blows in a consistent direction, known as the ‘fetch area’, and the length of time it does so, or the ‘fetch duration’. These are what will eventually determine whether the storm ever leads to a fully developed sea.

For a good idea of how our waves might appear at the conclusion of their third stage of development, we need look no further than Jan Porcellis’s 1620 mini-masterpiece Dutch Ships in a Gale, in London’s National Maritime Museum.

Porcellis was hailed as the ‘Raphael of marine painters’ by a contemporary, the artist Samuel van Hoogstraten. He helped to popularise seascapes, which had featured as an artistic subject for
only about a century, by depicting the heaving surface from close to the water. Characteristically of Porcellis at this time, the painting was small – not much larger than an A4 piece of paper – but the low, dramatic perspective must have convinced members of the seventeenth-century Dutch aristocracy viewing it that they were peering through a window on to the marine equivalent of a ferocious tavern brawl. The sheer mayhem of these deranged and uncontrollable waves must have elicited feelings of horror and fascination in equal measure.

Only when the storm eventually passes and the winds die down do our waves enter the fourth stage in their lives. Surprisingly, the calming of the air currents doesn’t mean that the furious confusion of peaks and troughs simply settles back down again to a gentle,
rocking equilibrium. The waves that were generated in the wind sea continue to travel over the water – but without the need to be pushed along. They’ve changed from ‘forced waves’, driven by the winds, into ‘free waves’. And how their mood can shift as they mature and enter middle age, finally beginning to distance themselves from their past.

No longer a wind sea, the surface is now what is known as a ‘swell’, which seems an appropriately harmonious name. Although the storm may have passed, the energy it transferred to the water cannot simply disappear. The waves keep going without the need for aerial propulsion. They just roll on, doing their thing. And, as they mature, so the subtleties of their characters begin to emerge.

Waves on the surface of the sea lose remarkably little of their energy to the surroundings once they are up and running. This means that they can travel enormous distances. The little energy that they do lose, a process known as ‘attenuation’, is mostly due to white-capping and, in the case of steeper specimens, air resistance when the wind blows against them. Only the embryonic capillary waves lose much of their energy on account of the viscosity of the water itself. This means that large swells, like those generated by our storm, can travel astonishing distances across the ocean.

This was first demonstrated by Walter Munk at the Scripps Institution of Oceanography near San Diego, California. Now in his eighties, and still a Professor Emeritus at Scripps, Munk is probably the most respected and renowned oceanographer alive today. During the Second World War, he had been the first scientist ever to work out a system to predict wave heights. Crucial Allied landings in North Africa, the success of which depended upon calm seas, were scheduled according to his forecasts.

In 1957, Munk found evidence that waves reaching Guadalupe Island, off the west coast of Mexico, had originated in storms within the Indian Ocean some nine thousand miles away. A decade later, another study with colleagues from Scripps tracked the progress of ocean swells right across the Pacific from south to north. With highly sensitive wave-measuring equipment positioned at six measuring stations spaced thousands of miles apart, they were
able to track the progress of ocean waves. They followed swells originating in storms off Antarctica, recording them as they rolled past New Zealand, Samoa and Hawaii, and over the open expanse of the North Pacific. The same waves finally showed up more than seven thousand miles away in the recording equipment at Yakutat, Alaska, having taken around two weeks to get there.\textsuperscript{10, 11}

Over enormous distances like these, the heights of the ocean swells diminished to minuscule levels. The measuring equipment Munk and his colleagues used was able to detect waves a mile in wavelength and an astonishing one-tenth of a millimetre high. But this drop in height is not because the energy ebbs away. It is merely a result of the way waves spread out, fan-like, from their source, the energy imparted to the surface by the storm winds spreading over increasingly greater areas of ocean as they progress.

We all mellow with age. And, compared with the frenetic confusion of the wind sea, the waves in our mature, freely propagating ocean swell exhibit a decidedly relaxed attitude when they cross another swell. As the two enter the same stretch of sea, they simply pass through each other, like friendly ghosts, before continuing on their ways without having experienced any lasting interference.

Wise old swells pass through each other and continue with little fuss.
The sea surface can look confused as the two swells cross, but they emerge on the other side unaffected by the encounter.

As they move across the open ocean, the jumble of different-sized waves that formed in the wind sea begins to organise itself. This is because the longer waves travel faster than the short ones. It is rather like a marathon in which the speed of the runners depends on nothing more than how long their legs are – the bean-pole runners being faster than the short ones. At the sound of the starting pistol, a huge confusion of runners of different height sets off together. But the simple rule of the longer the legs, the faster the runner means that they naturally begin to arrange themselves with the beanpoles in the lead and the shorter runners lagging behind.

The same happens with the different-sized waves. As they spread out across the open ocean, the longer ocean waves move faster than the shorter – perhaps 50mph, compared with 30mph – and, as a result, the waves in our swell spread out in an orderly fashion.

As their heights decrease – a consequence of their energy being spread over wider and wider areas – our maturing waves develop a smoother shape. Gone are the steep, peaked, trochoidal crests of the wind sea. They are now far less precipitous, each crest in the train appearing as a sweeping undulation: ‘a low broad heaving of the whole ocean’, as the Victorian art critic John Ruskin described it, ‘like the lifting of its bosom by deep-drawn breath after the torture of the storm’.12

Their smoother appearance now makes them more like the swell in Claude Monet’s The Green Wave. Monet was something of a pioneer in the deployment of impressionistic techniques for rendering the sea and was described by his fellow Impressionist Edouard Manet as the ‘Raphael of Water’.

If I were Monet, I’d have felt a bit miffed that Manet couldn’t come up with a more original compliment.

The waves actually travel across the open ocean during this fourth stage of their lives in a manner that is far more intriguing and enigmatic than the marathon runners of the last analogy. In fact, the
swell is a most peculiar procession of crests. They are in the form of groups of larger waves, separated by gaps, in which the waves are smaller, and sometimes barely even there.

But that’s not the weird part. What is so strange is that each individual wave crest travels faster than the group it is in. The crest appears from the calmer water at the back of the group, travels through it and disappears again in the calmer water at the front. It is not easy to come up with an analogy to help you picture such odd behaviour. The only one I can think of is a train, on which are running not marathon runners, but the ghosts of marathon runners.

As this train chugs along in the approach to a station, it happens to be travelling at about jogging speed. Being deceased marathon runners, the ghosts on the train can’t actually stop jogging. They therefore appear at the back of each carriage, run through it and disappear again at the front. Anyone waiting in the station for the

Claude Monet’s *The Green Wave* (1866–7). Never mind the colour, just look at that smooth, orderly swell.
The peculiar behaviour of our mature waves is the result of the overlapping of waves with similar wavelengths – the longer, faster waves occupying the same water as the slightly shorter, slightly slower waves – so that their crests and troughs add and subtract like this:

Imagine two ocean waves with slightly different wavelengths...

If they are travelling together over the same region of water, they will overlap...

And, where their crests and troughs coincide, they will add, so the surface will have big waves...

But, where their crests and troughs are out of phase, they will cancel out, so the surface will be calmer...

Which results in groups of waves separated by gaps of calmer water...

The groups travel along like the carriages of a train...

And the crests travel through the groups, like the ghosts of marathon runners...

The crests appear in the calmer water at the back of the group, travel through it and disappear again in the calmer water at the front – rather like ghosts running through the train carriages.

Isn’t it nice when things are so straightforward?
If this peculiar movement of the swell seems rather difficult to understand, perhaps it is best to forget my ghost analogy and just accept that, as the poet Ralph Waldo Emerson put it, ‘illusion dwells forever in the wave’.11

All this talk of peaks and troughs might be considered rather shallow. What about the water below the surface when a wave passes through?

Do you remember how, with the passage of the wave, the water at the surface moves in a roughly circular path – how it returns to near its starting point as the wave moves on? In fact, the water below the surface moves in the same way, except that the circular paths become smaller the deeper they are. At a depth equal to half the wavelength, these circular orbits diminish to nothing. Below this ‘wave base’ the movement of the water is negligible as the wave passes overhead. This is why submarines can avoid the effects of even the fiercest storms merely by diving to 150m or so.

In fact, waves do occur deeper below the surface, where they are often far larger than the ones on the surface. Dubbed ‘internal waves’, these are the lumbering giants of the ocean. They can occur in the murky depths, wherever an abrupt boundary between layers of differing water develops. If layers of water have quite different densities, perhaps because one is much warmer than the other, or it is much saltier, the boundary between the two behaves rather like an underwater equivalent of the ocean surface. Waves can roll along this boundary, hidden from view on the surface.

These internal waves are set in motion by the action of

![Direction of Wave Movement](image_url)
the tides, rather than that of the wind. And they are often larger than their surface equivalents – a lot larger. It is not uncommon for internal waves to form with wavelengths of twelve miles and heights in excess of two hundred metres.

Submarines may be able to dive deep enough to avoid storm waves at the surface, but they cannot escape the influence of the ones lurking below. In the 1960s, one such internal wave smacked into a Russian submarine as it was trying to pass secretly through the Strait of Gibraltar, sending it crashing into an oil platform. This must have caused some red faces among the crew.

Waves are the expressions of the ocean’s moods. Placid, tranquil and benevolent is the sea that caresses the shore and rocks your dinghy in a cradle of gentle undulations. But for a sense of Nature at its most terrifying, nothing comes close to a violent storm at sea. The expressive character of waves has always made the ocean an abundant fishing ground for those in search of a good metaphor.

The seafaring adventures of Odysseus, as described by Homer, are awash with his struggles against the various tempests that Poseidon, the god of the sea, unleashes upon him. *The Odyssey* helped to establish the enduring motif of man as mariner, crossing the storm-tossed seas on the ‘journey of life’ in search of the tranquil waters of his journey’s end. But for the classical playwrights, and poets generally, stormy waves have the upper hand. Man’s confrontation with the ocean was invariably an against-the-odds battle fighting the whim and fancy of the gods – one in which his heroism and bravery could be put to the ultimate test. ‘Wonders are many, and none more wonderful than man,’ wrote the Greek playwright Sophocles 250 years after Homer, ‘the power that crosses the white sea, driven by the stormy south wind, making a path under surges that threaten to engulf him.’

The ceaseless rise and fall of waves seems to echo the arcs and cycles of life. Is this why wavewatching is so good at putting life into perspective? As you might expect, a sixty-six-year-old Walt Whitman, contemplating his navel, while gazing out on the waves
rolling in at Navesink, New Jersey, was not too bothered about whether they were spilling or collapsing breakers:

By that long scan of waves, myself call’d back, resumed upon myself,
In every crest some undulating light or shade — some retrospect,
Joys, travels, studies, silent panoramas — scenes ephemeral,
The long past war, the battles, hospital sights, the wounded and the dead,
Myself through every by-gone phase — my idle youth — old age at hand,
My three-score years of life summ’d up, and more, and past,
By any grand ideal tried, intentionless, the whole a nothing,
And haply yet some drop within God’s scheme’s ensemble — some wave, or part of wave,
Like one of yours, ye multitudinous ocean.\textsuperscript{15}

And then, of course, there’s the appeal of the wave simply as a shape. Many artists have claimed that the smooth, sinuous line of a wave is one of the most beautiful forms, mirroring, as it does, the recumbent female figure. The English painter William Hogarth included a serpentine curve in a self-portrait that he painted in 1745. The line, in the shape of a wave, appeared carved on to an artist’s palette in the bottom left-hand corner of his portrait, with the words ‘The Line of Beauty and Grace’ below it. When the painting became known, Hogarth was inundated with requests for an explanation of what seemed like a cryptic clue. In an effort to answer, the artist then wrote a treatise on aesthetics called \textit{The Analysis of Beauty}. ‘The serpentine line,’ he explained, ‘by its waving and winding at the same time different ways, leads the eye in a pleasing manner along the continuity of its variety.’\textsuperscript{16} Observing such lines as ‘formed by the pleasing movement of a ship on the waves’, Hogarth added, gave the eye the same pleasure as we derive from following ‘winding walks and serpentine rivers’.\textsuperscript{17}

Had roller-coasters existed, Hogarth might have mentioned these too. Don’t we love them because of the wave-like way the track curves? Our lives are full of ups and downs, even if in real life the highs and lows are far less compressed. We are beset by ‘uphill’ challenges that take us to new places, new heights — to
A cryptic clue from a closet wavewatcher in William Hogarth’s self-portrait, The Painter and His Pug (1745).
the crest of the wave – before the inevitable, sickening, white-knuckle descent.

Isn’t it this aspect that has made the phrase ‘emotional roller-coaster’ such an enduring cliché? I do admit, though, that when we plunge headlong into a real-life emotional trough, we generally don’t stick our hands in the air and squeal like banshees.

Could you not say that the human body is like a wave? Apparently, once you reach old age, your body can contain none of the molecules it did when you were a newborn. As you grow by incorporating what you consume, every ingredient of your infant body can eventually be replaced: all the particular oxygen, carbon, hydrogen and nitrogen atoms, and the other elements that were your nascent body, will have been replaced. You might say that we borrow the air, water and food we consume in the very way that an ocean wave borrows the water it passes through.

In this sense, you and the wave seem rather alike. Were you able to freeze-frame an ocean wave as it was rolling to shore, it would be tempting to say that the mound of water before you, held in magical suspension, is the wave. But waves aren’t frozen in time, and in reality the water within the wave at any moment will be left behind an instant later as the wave rolls on. Though the timescales are very different, a wave passes through the medium of the water in much the same way that you pass through the ‘medium’ of all the physical bits of your body.

Clearly, the contemplation of the ocean’s undulations can have a disconcerting effect on you. It can set off decidedly hippyish thoughts. Without realising it, you can be swept out into a Zen-like spiritual reverie on how everything is, like, you know, interconnected, deep down, man.

And so we come to the fifth and final stage in the life of our waves. Perhaps they have travelled in the peculiar grouped arrangement of wave adulthood for many hundreds of miles. Only as they approach landfall do they make one more transformation. It can
be the most dramatic of all, not least because it marks their death. This is the stage with which landlubbers are most familiar, when the waves release their energy in a churning, foaming crash on to the shore.

Their swansong begins as they enter shallower water. Where the wave base – that half-wavelength depth at which the water is only just moving with the wave – first makes contact with the rising seabed, the waves 'feel' the ground beneath them. The progress of their bases is slowed by friction with the seabed. As they slow, they bunch up and steepen, so that their shapes change from smooth undulations back into the sharp, trochoidal peaks of their youth, when they were harassed by the fierce storm winds of their troubled adolescence.

The transformation from deep-water to shallow-water waves is complete when the depth has diminished so much (to around one-twentieth of the wavelength) that the water is no longer able to move in circles. The motion below the surface is restricted to increasingly flattened ovals, as there is less and less water for the wave to travel through. The orbits are squeezed more and more
until the water below the surface is moving almost exclusively forwards and backwards.

Now one rule comes to dominate their behaviour: the shallower the water, the slower they travel. This simple law governs the glorious and dramatic displays as they break into a cascade of foam.

It works like this. Due to the gradient of the seabed, the crests at the front of the wave train slow down before those behind. And, just like a marathon runner stumbling so that those behind fall and ride up on top of each other, so the undulations in the water are concertinaed. As the waves are squeezed, there is nowhere for the water to go but upwards.

If the gradient is just right, and the waves have enough energy, they can rise up so dramatically that they become unstable: below the water, the wave's feet slow down, while the top keeps going, and the wave trips over itself, causing the crest to pitch forward and crash over on itself.

Oceanographers tend to divide breaking waves into three types: ‘spilling breakers’, ‘plunging breakers’ and ‘surging breakers’. Which way a wave breaks depends on the gradient of the seabed. When the slope of the beach is very shallow, the waves crumble at the crests as spillers. These fringes of white water stretch down from the lip along the front of the wave, making it look as if it is wearing one of those Tudor ruffs.

The waves depicted in Sennen Cove, Cornwall, painted by John Everett in 1919 (see overleaf), are spilling breakers. Everett made extensive voyages around the world, often aboard merchant vessels as a working member of the crew, in order to study and paint waves. He hasn’t had the acknowledgement he deserves, and I feel compelled to call him the ‘Raphael of Spilling Breakers’.

Plunging breakers form when the slope of the beach or reef is steeper, and they are the most beautiful of the three types. The lip of the wave is thrown forward so that it curls over to form a tube before crashing to the water below. At their most impressive, these breakers are the ‘barrels’ that surfers ride within, the canopy of water thrown over their heads as they disappear from view.

Surging breakers, which occur on the steepest gradients of the seabed, look completely different. They are hardly breakers at all.
The water just sloshes up against the steep shore and back again, like water at the end of the bathtub as you sit yourself down with a thump. Without any white-water ruff or cascading canopy, these are the most naked of breakers.

Some textbooks talk about ‘collapsing breakers’, which are halfway between plunging and surging, but that’s getting rather too nit-picky. In fact, there is a continuum of breaking styles, with no distinct boundaries between them. Whether we divide them up into three or four – or, indeed, ten – categories, they are no less arbitrary. A single crest can also break in more ways than one as it rolls up to the shoreline – spilling over here, before becoming smooth again and plunging over there, before a nudist streak of a surge at the end. It all depends on the changing depth near the shore due to the underwater topography, the rising and falling of the seabed, known as the ‘bathymetry’. The urge to divide the waves into types like this reflects our pervading desire to dissect and categorise the world, to make the continuous digestible. (The same could be said of my dogged attempt to neatly divide the wave’s life into five quite distinct, and completely separate, stages.)

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Spilling breakers wear ruffs of white water, as in John Everett’s Sennen Cove, Cornwall (1919).
Whatever the particular style of their demise, our waves finally
die on the unyielding shore, as their energy dissipates. They are
gone in a tumble of white water; lost, to quote that famous Matthew Arnold poem ‘Dover Beach’, within ‘the grating roar of pebbles which the waves draw back, and fling, at their return, up the high strand... and bring the eternal note of sadness in.’ And so the biography of our waves is complete.

And you thought they were all just waves?
Wavewatchers should learn the subtleties of wave-breaking.
But perhaps it is a little early to don the black armbands.

Energy never expires – all it can do is to change from one form to another. When the waves come crashing on to the shingle their energy doesn’t just disappear. It keeps on travelling, but in different forms. That ‘grating roar of pebbles’, for instance, is part of the waves’ energy transformed into sound.

And sound is a type of wave.

It is a wave not of rising and falling water but of differences in air pressure – at least it is when the sound is travelling through the air. It could hardly seem more different from the waves on the ocean, so why do we say they are both waves? What else do the two have in common besides one being the energetic afterlife of the other?

How else do the crashing ocean waves live on? There is the vibration that you feel through the ground when the sea is rough. Lie for a moment against the glistening, sable cliff face – far enough away to be safe from the breakers, but near enough to feel their salty mist on your face – and you will sense the tremors reverberating through your body. These vibrations are known as ‘microseisms’. They are mild versions of the shock waves generated by earthquakes. The energy of the breaking waves rolls on through the ground in a form that is subtler, but is a wave nonetheless.

Some of the energy from the ocean swell also turns into heat – both heat in the water and heat in the sand, shingle or rock of the water’s edge. And heat is related to infrared waves: when you see someone filmed on an infrared camera, they are visible on account of their body heat radiating away from them.

Infrared is a form of light – one that we can’t see, though some other animals can – and it too is a form of wave. If the ocean waves heat up the ground slightly as they crash against it, then the infrared light it emits is another, even subtler, form of wave afterlife. But light, whether infrared or visible, seems even more divorced from the familiar waves we see on the water.

While I’d known that these are all supposed to be waves, I’d always filed them in quite separate mental compartments. But there, at the seashore, the pigeonholes had disintegrated. Amid the glorious death of our ocean waves, the energy rises phoenix-like to
live on as other forms of wave. The foaming breakers that tumble on to the shingle mark not the end of our wave biography, simply the conclusion of its first chapter.

Waves out at sea were all very well but I had realised that the shore was where it was happening. The waves that Flora and I had watched in Cornwall had whetted my appetite. I now realised what would help me understand waves, and the seemingly mysterious role they play in the world. I would need to undertake an in-depth investigation of waves crashing ashore. I would need to immerse myself in them. I would have to take a holiday to that wavewatcher’s mecca: Hawaii.

Sorry, did I say holiday?

What I meant to say was ‘research trip’.
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