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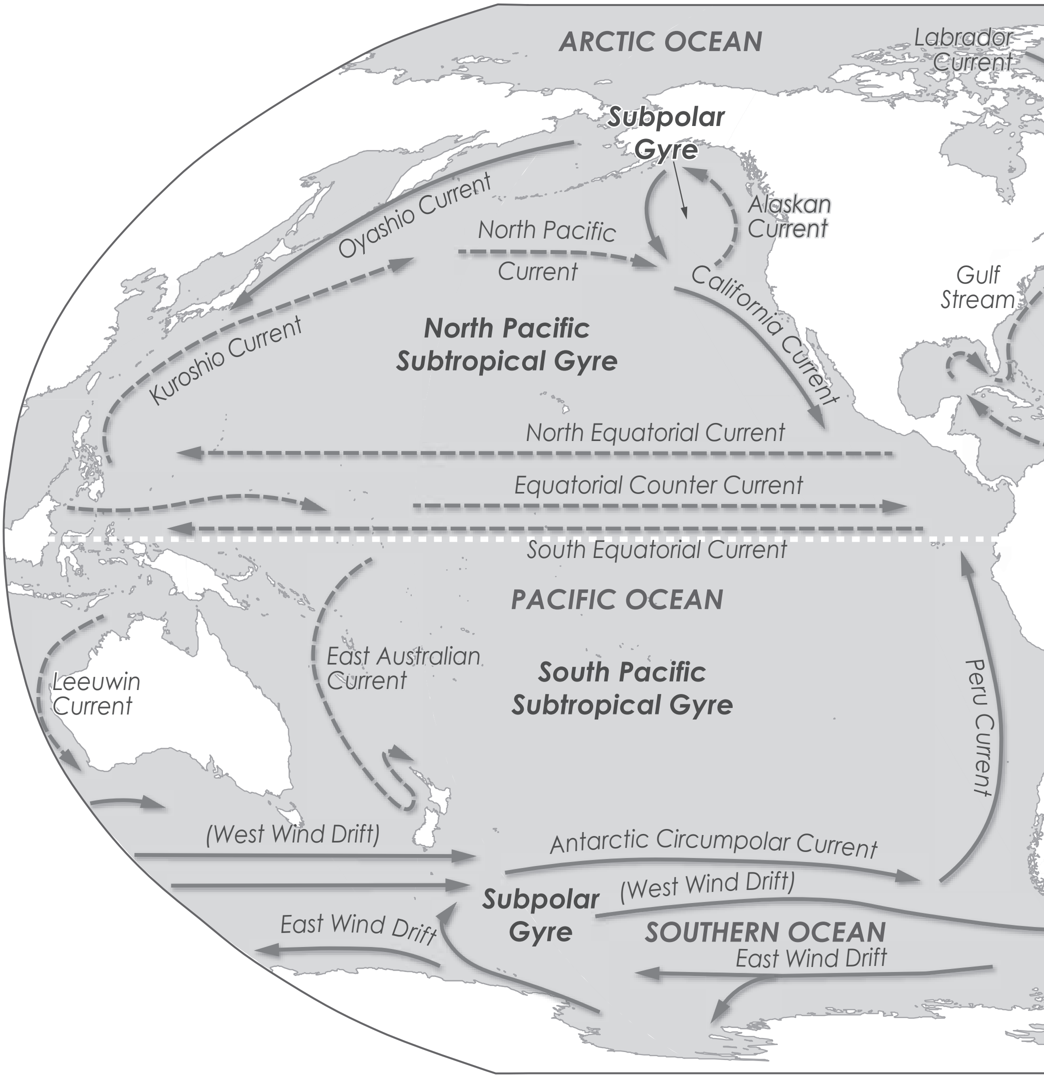

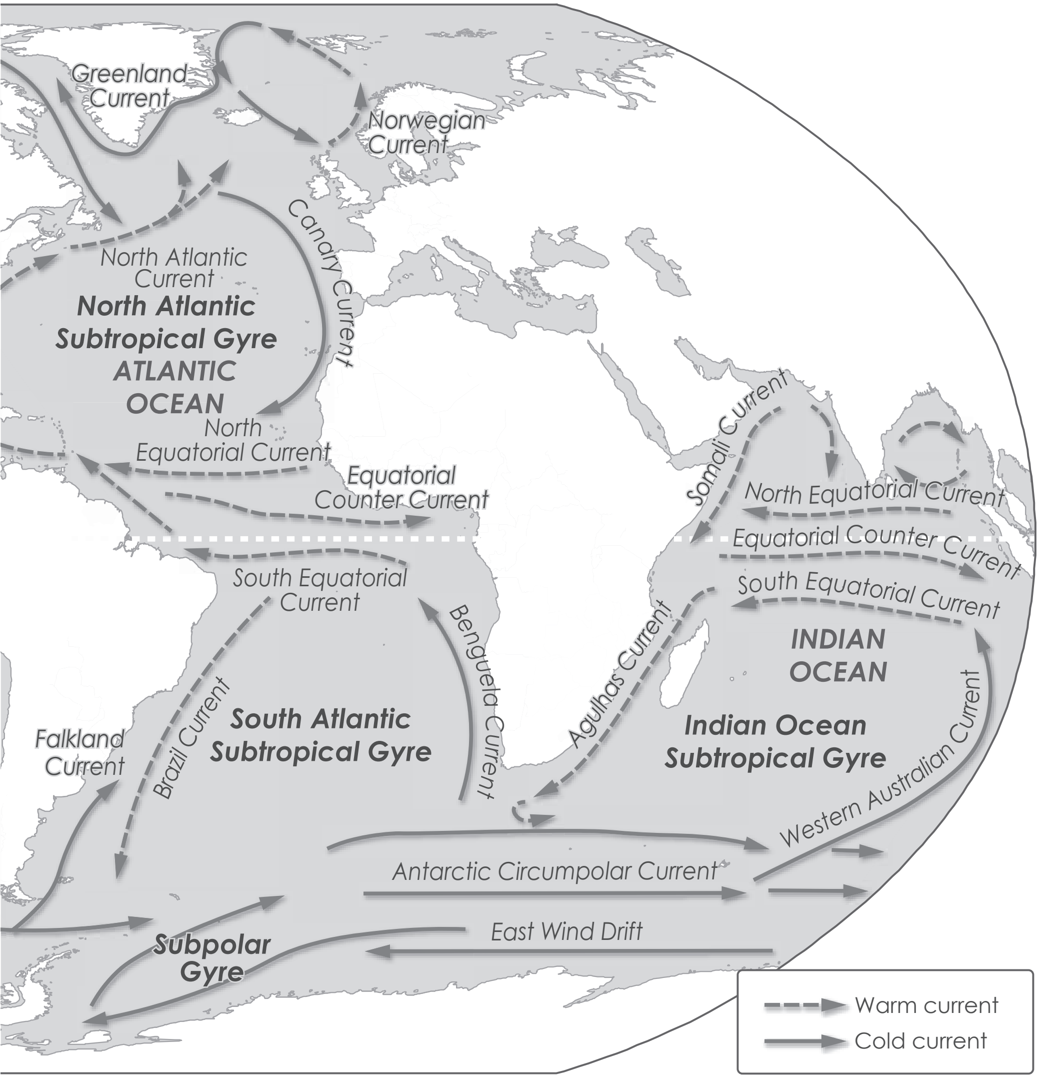
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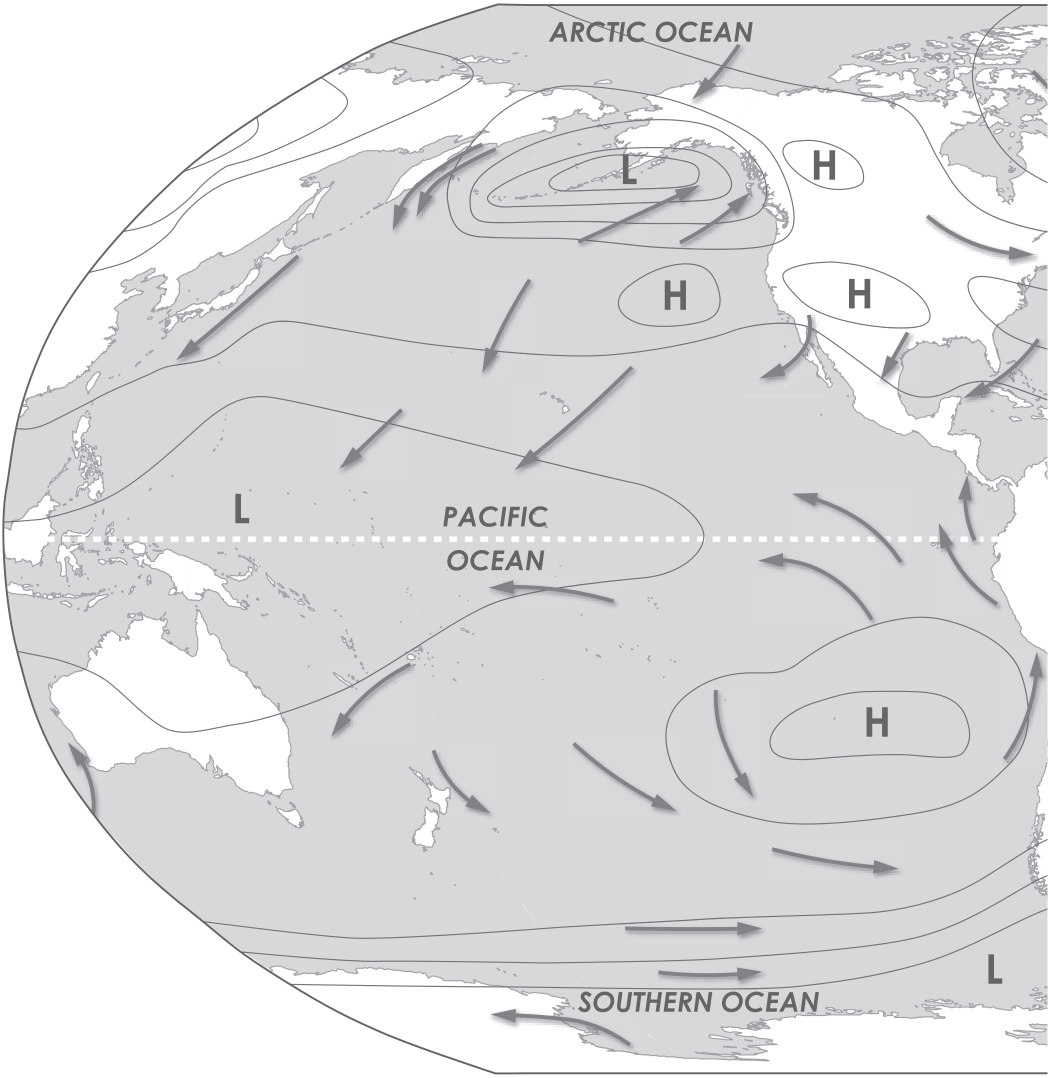

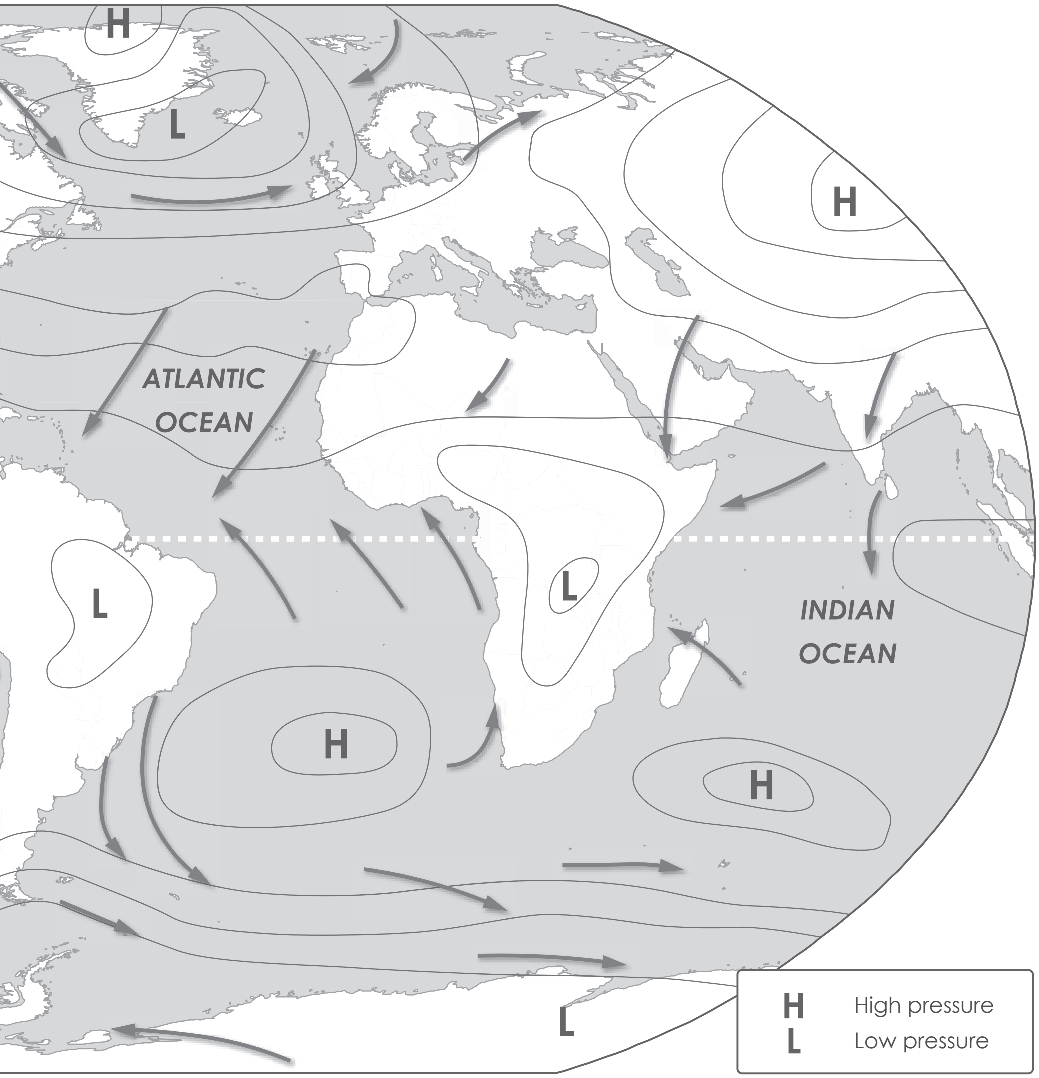
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Introduction

Equator

Our canoe floats quietly in the darkness, a tiny drifting speck dwarfed by the starry sky. We wait while deep inky blue crawls upwards from the horizon, gently extinguishing the stars as it reveals the gigantic silhouette of Haleakalā, the larger of Maui's two dormant volcanoes. The support boat bobs a few metres away, between us and the eastern horizon. I'm in the fifth seat from the front in a six-person outrigger canoe, and the *ama*, the second floating hull that connects these canoes to the ocean like no other craft, rides the water to my left. The water is flat calm and the peace is immense. We wait.

Just before the first hints of pink light wash around Haleakalā, it is time. Kimokeo Kapahulehua stands up on the side of the support boat, facing the canoe, wearing shorts and a T-shirt and a ti-leaf *lei*. He calls out to us in the canoe, and to our teammates on the support boat. I know very few Hawaiian words, but I can follow along because this is a familiar expression of the deep Hawaiian connection to the ocean. The canoe isn't just a physical object, designed for a practical purpose. Every aspect of a canoe is a symbol of teamwork – to make it, transport it, paddle it and maintain it – and it is teamwork that holds these island nations together. This is about *'ohana*, the extended family, and about taking care of the people in your canoe. The ocean is as much a part of home as the land. It's changeable, and it can be hazardous, but if you show humility, and you observe and learn, the ocean will support you and provide for you.

Today, we are setting out on a voyage around Maui's second volcano, Mauna Kahālāwai, from here in Kahului Bay all the way around to Kīhei, but we need skill and weather and luck with ocean conditions to complete the trip. Whether or not we succeed, it's the time spent together and what we learn on the way that's important. This ritual reminder lasts only a few minutes, because here at the equator the sun rises quickly. As bright lilac and pink fill the sky behind Haleakalā, Kimokeo finishes with a chant and we all join in. *E ala e* is the first and most significant chant that any Hawaiian child learns, intended for this vital moment, when sunlight first touches the ocean, and everything can begin.

Under the clear sky, we can almost feel the day's flood of intense sunlight on its way. Cam, steering the canoe from the sixth seat, just behind me, calls out: 'Hoʻomākaukau', and we raise our paddles. They hang in the air for one last moment of stillness, as the first shaft of bright sunlight touches the ocean ahead of us. Then, 'Imua!', and six paddles cut into the water simultaneously. The voyage is under way.

Pole

Five months later, I'm lying on my tummy on the edge of a giant ice floe.[1] My colleague Matt is standing on a 3 metre square wooden platform floating on the ocean, and I'm attaching a rope to the side of it. The water is −1.8°C, technically much warmer than the air (which today is −8°C) but far more effective at stealing heat, so I'm focused on keeping my fingers and the rope dry. The platform has a squat round metal dome rising from its

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[1] An ice floe is a sheet of floating ice. At 2 km across, this one was unusually large – most are much smaller.

centre, and the rest of the platform is a hive of mechanical servants tending to the dome's needs: large metal boxes and batteries, exchanging data, electrons and air with the queen bee in the centre via chunky cables. This is Matt's experiment, designed to capture and count any tiny particles that the ocean is spitting into the atmosphere. I tug on my new knot and stand up, checking that nothing has fallen out of the pockets of my heavy flotation suit. When I nod, Matt strides off across the ice floe to fetch some helping hands, the cheerful bouncing of the bobble on his hat taking the edge off any 'serious polar scientist' look he might have aspired to.

I spend a few minutes just looking at the view, a rare treat. Two kilometres away on the other side of the ice floe, I can see the Swedish icebreaker *Oden*, our home for these two months. Towards the middle of the ice floe, a large tethered red and white balloon, the size of a small camper van, bobs in the sky with today's scientific experiment dangling beneath it. In the other direction, the white sea ice stretches away for hundreds of miles. We're only a few nautical miles from the North Pole, and the summer sea ice here is about 2 metres thick. The ice floes around ours shunt and grumble, moving slowly but just enough that our work site looks different every morning. This afternoon, the clouds are lifting to reveal rare blue sky directly above, but sunlight will never beam down from that space. The sun here slinks around the horizon but never drops below it, casting astonishingly long shadows when the clouds allow. Even though this spot is in the middle of six months of constant daylight, the sunlight feels purely decorative, a cascade of soft, subtle illumination which will never keep you warm. The energy flow here is mostly invisible, directed upwards, not downwards. Around me, the Earth itself is glowing, radiating infrared light as what little heat it has seeps away into the sky. Without the clouds as an obstacle, this heat energy will just keep going out into space. A clear day today means a cold day tomorrow, as the ice and the ocean lose their energy to the universe. This process is a crucial entry in the Earth's energy budget, but we still can't predict it exactly. On this ice floe, we're in the middle of these mechanisms, surrounded by liquid clockwork, and we want to *know*. The cohort of scientists on *Oden* is here to observe, measure and analyse this spectacular environment, to use the latest equipment and logic to deduce the inner workings of the ocean and atmosphere.

Matt returns with three of our colleagues. Out in the natural environment, data are hard won, and that often means very physical effort. We want the platform to be floating away from the ice edge, so it can take measurements in open water. Hauling on long ropes in teams, and with much grunting and shoving, we manoeuvre the platform away from the edge, and watch to see whether it will stay put. Once we're happy, we anchor it in place, and prepare to return to the ship. Beneath the ice we're standing on, the ocean is deep and dark, quiet and cold, always there but only rarely the centre of attention.

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The Earth's oceans are vast, and yet they often seem invisible. We had to go into space to really appreciate that the defining feature of our planet is not land but water. The Apollo programme sent men to the moon, but I think that its most significant achievement was to let all of us see the Earth. Two of the most influential photos ever taken shifted our perspective for ever: 'Earthrise', taken in 1968 during Apollo 8, and 'The Blue Marble', taken in 1972 during Apollo 17. Once you've seen them, you can't un-see that view and its significance, the fragile blue sphere floating in the cosmos, with everything we've ever known on board. But even then, the blue was seen as the canvas on which the land was drawn, the emptiness between the great continents, and a mystery that could probably wait until after all the important stuff was sorted out. Fifty years on from Apollo, humans are finally starting to pay proper attention to what's inside those vast blue expanses. It's overdue. But those forays into space gave us the necessary starting point: a blank map to fill in.

Maps of the Earth are rich and astonishing treasure troves, and globes are even better. The anatomy of our planet is full of fascinating detail: coastlines, mountain ranges, rivers and island chains, full of patterns and yet still so varied. It seems endless because it is; the more closely you look, the more there is to see. Lumpy continents give shape to the blue oceans, and we split our home planet into land and sea. It's natural to label land with fixed features, and the labels can last for decades or centuries without change. But every wonderful map that I've seen is guilty of misleading us in one fundamental way. They make it easy to forget one of the most important and breathtaking features of our planet: the ocean *moves*.

The blue of Earth is a gigantic engine, a dynamic liquid powerhouse that stretches around our planet and is connected to every part of our lives. It has components on every scale, from the mighty Gulf Stream gliding across the Atlantic to the tiny bubbles bursting at the top of a breaking wave. This is a beautiful, elegant, tightly woven system, full of surprising connections and profound consequences. The complexity can seem overwhelming, but at the largest scale, the logic is straightforward. Those seeking to understand the cynical side of politics are advised to 'follow the money', but planetary physics is immune to human cynicism. Our task is simpler, and more fulfilling. The key to unravelling the internal logic of the oceans is to bow to the physicist's instinct and follow the energy.

Our planet intercepts a tiny fraction of the mighty energy output of the sun, preventing it from flowing onward into the universe, and diverting it on to a much slower path through the mechanisms of the Earth: ocean, atmosphere, ice, life and rocks. On its way through the planetary system, this energy is carried by atmospheric winds and ocean currents, builds both mighty oak trees and the delicate lichen on stone walls, lifts a trillion tons of water into the sky every day, fuels every human and every owl and every ant on Earth, and powers the laptop I'm typing on. The oceanic engine is the heart of this system, hosting the majority of this flowing energy either as heat or as movement. Oceans are deep and broad, home to vast currents moving in different directions at different depths as water circulates around the globe, heating and cooling its surroundings as it goes. But energy is transient, only ever a temporary house guest. Eventually, after much recycling, that energy leaks away from the Earth as heat and resumes its journey through the universe. The first law of thermodynamics states that energy can neither be created nor destroyed, so the giant flows in and out are balanced. The Earth is just a cascade of diversions, unable to stop the flood but tapping into it as it trickles past; and the ocean is an engine for converting sunlight into movement and life and complexity, before the universe reclaims the loan.

Sunlight reaches everywhere on Earth, but it's more intense close to the equator because there the sun is high overhead, so the equatorial regions receive far more of the sun's energy than the poles. However, the Earth loses heat much more evenly, and plenty of energy is lost from the polar regions. That means that over a year, the equatorial regions experience a net gain of energy from the universe, and the poles experience a net loss. That contrast leads to a very profound conclusion: the atmosphere and oceans aren't just storing the energy that flows through the system; they're redistributing it. This is the dominant pattern behind the ocean engine: the overall shunting of energy from equator to poles. All aspects of the ocean and its influence on our lives fit somewhere into this mosaic: currents and stormy seas, the evaporated ocean water that later falls as rain over the Amazon, coastal erosion, migrating fish and airborne whale snot, expelled from the blowhole of the largest mammal on Earth and temporarily meandering through the atmosphere. They all have their role to play.

Describing the ocean as an engine is not metaphorical embellishment. The definition of an engine is something that converts other forms of energy (usually heat) into movement. We're used to the sort that has solid metal pistons driving ingeniously interlinked cogs and levers, all mobilized by temperatures high enough to fry an egg. The industrial revolution is long past, and yet a small army of enthusiasts keeps the world of steam alive – how could you abandon completely a technology that oozes that much character? The steam-powered steel dragons are beautiful and satisfying in a way that's rare in the modern world, because you can see exactly how they work. This piston drives that wheel which spins this little widget and so on down the chain – the elegant sequence of cause and effect is mesmerizing. But an engine doesn't have to be made out of solid materials.

As land, ocean and atmosphere absorb the sun's energy, they heat up. Some of that heat will almost immediately drive movement through convection – warm water may heat the air above it, making it buoyant, so newly warmed air often gets pushed upwards as cooler air slides in beneath it. As the wind moves across the ocean surface, the air pushes on the water, transferring energy back into the ocean as waves, and this energy eventually dissipates back into ocean heat. But this is only one route that the incoming energy could take through this endlessly fascinating mosaic. Earth's blue is closely connected to the other global components: atmosphere, the ice, life and the land, and all five work together as a single system. But the ocean is the big beast in Earth's planetary machinery. The engine that is Earth's ocean takes sunlight and converts it into giant underwater currents and waterfalls, hauling around the ingredients for life: nutrients, oxygen and trace metals like potassium and iron, shaping our coasts and transporting heat. This isn't just another engine, it's the grandest one of all: an engine the size of a planet. It's got all the elegance of the most ingenious human-built engines but the mechanics here are more subtle and intricate. Instead of a nice tidy piston, we're faced with a flow of water that merges into the water on either side of it; it's definitely up to something, but it's hard to say where *this* pushes on *that*. But it is absolutely still an engine, converting light and heat into movement in myriad different ways.

The most frustrating thing about this engine is that it's so hard to watch directly. I was once asked what impossible invention I would most love to have, and there could only be one answer: a pair of binoculars that lets us see into the ocean the way we can see into the sky. Imagine standing on the prow of a ship and peering downward at stately currents sliding over vast mountain ranges beneath, giant plumes of tiny ocean animals on their daily vertical migration from the lower layers to the surface, and perhaps catching a glimpse of the great ocean voyagers: 4-metre-long tuna fish, turtles or a blue shark. But even though those binoculars won't be available any time soon, you can still see the engine at work if you know where to look. We humans don't live inside it, but we are affected by almost everything it does. For years, we thought we were independent observers looking out over the choppy surface out of curiosity, but we're actually tiny ants living on the shores of this great blue fluid mechanism, completely dependent on its output. It's the sort of perspective shift that can give you vertigo.

Humans and the ocean

As citizens of the Earth, we cannot escape the influence of the oceans, and we shouldn't want to. Humans have piggybacked on this deep blue engine for generations, our tiny vulnerable vessels trading and exploring where the surface took us, without regard to the inner workings of the deep. Battles have been won and lost on the basis of what the ocean threw at us, and whole societies have grown up around its fertile places, responding to unseen ocean mechanics without any knowledge of why there were fish *here* and not *there*. Even on land, the most suitable regions for agriculture are often dictated by the nearby seas. The ocean is deeply woven into human culture, and the threads always track back to the engine and, ultimately, to the energy flow. But even though they couldn't see the whole engine, intelligent and observant humans from many cultures have seen parts of the pattern, and have gained deep expertise in their own waters, more than enough to navigate, fish, explore, trade and rely on the oceans for their livelihood. Knowledge fed into culture, and myths and stories were used to explain the patterns and to provide a foundation for thinking about the ocean: what it was, why it mattered and how humans should behave towards it. Attitudes to the ocean also fed back into the culture on land, influencing even those who never went to sea. And every culture's attitude to the ocean is partly geographical accident.

Science and culture are far more intertwined than most scientists would like to admit, and it's possible that one of the reasons why ocean science hasn't really been visible is that many cultures consider the ocean to be a bit of a nuisance on a good day, and very dangerous indeed on a bad day. In Britain, for example, a trip to the local seaside is widely regarded as a necessary ritual of childhood, although sometimes viewed by the children involved as more of a duty than a pleasure. In the north-west of England, where I grew up, visits to the beach were often associated with being forced to paddle in freezing cold water, and then competing to see who could lean furthest into the wind without falling flat on their face. Looking under the sea surface didn't really occur to anyone when I was at school, partly because the water was cold, and partly because British coastal waters are often too full of sediment for anything (even your own toes) to be visible. Artists like J. M. W. Turner sometimes painted tranquil seas and idyllic coastlines, but the clear implication was that the sea was for looking at, not going into. Turner is better known for his paintings of ships being tossed about by violent seas under dark, angry clouds, an image reinforced by the British seafarers of the nineteenth and twentieth centuries recounting their adventures. As just one example, the polar explorer Ernest Shackleton wrote this of his extraordinary and heroic 1916 journey in a small boat to fetch help for his stranded crew: 'The tale of the next sixteen days is one of supreme strife amid heaving waters. The sub-Antarctic Ocean lived up to its evil winter reputation.'[2] It's not really the sort of description that encourages casual bystanders to pop along and have a look for themselves.

And it's not just the British. Iceland, perched at the top of the North Atlantic Ocean, is a nation built on the fishing industry and boasts a proud maritime heritage that has lasted for centuries. But if you walk along the harbour in Reykjavik, you meet a series of large display boards, each with a map of Iceland on it. Dotted around each coastline are black symbols designating shipwrecks, each one marked with the ship's name, the year, the type of boat and the number of men lost. Each map has 30–40 wrecks on it, and covers one decade. The maps go back 200 years, and you can't step on a boat without passing these memorials. There is no mistaking the message here: the ocean can and will kill you. I spent a while trying to ask Icelanders whether they ever went out on boats for pleasure, but the response was almost always a blank look. Up here, you go to sea to get fish, not to play. The seas around Iceland can be fierce, and fishing in those conditions is undoubtedly a dangerous pursuit. The clear

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[2] The full story of this voyage, which was supposed to be the 'Imperial Trans-Antarctic Expedition', has become famous for Shackleton's extraordinary leadership and his daring voyage for help to rescue his men after their ship was crushed in the Antarctic ice.

lesson from their local history is to think very carefully before going anywhere near such peril.

On the other side of the world, Hawaiians who live their lives enveloped in the vast Pacific Ocean see things very differently. Close to the equator, squalls and gales are relatively rare, but storms thousands of miles to the north initiate the smooth ocean swells that make Hawaiʻi such a perfect place for surfing. Mastery of the ocean waves was a recognized royal pursuit, with kings and queens having their own special surfboards. Surfing was a ritual and a right, and central to Hawaiian society. The ocean was a part of life, and being in it and on it came naturally.[3] The ocean is a vital part of Hawaiian culture, partly because these small islands are completely enveloped in it and partly because their local ocean is much more benign than that around Iceland. Our human relationships with the ocean are as rich and varied as the ocean itself.

The accidental ocean scientist

My route into ocean physics wasn't planned or expected. I grew up in Manchester in the north of England, where 'ocean' was considered a very exotic concept because what we had was the sea. Two seas, to be precise: the freezing cold North Sea to the east, and the blustery grey Irish Sea to the west. Neither seemed particularly appealing. I studied physics because I wanted to know how things worked, and occasionally thought about geology, because I was interested in how the Earth worked, but the two never seemed to overlap. When I finished my PhD in experimental explosives physics, I spent six months writing up papers

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[3] When I think of all the drab formal pictures of British kings and queens in my school history books, generally looking thoroughly miserable (and very self-consciously important), I can't help but think that a bit of surfing would probably have done them good.

and looking for another research topic, hopefully one that would let me continue to build interesting experiments, but without quite so much cleaning up after the experiment had blown itself to bits. Bubbles seemed to fit the bill, and Dr Grant Deane at the Scripps Institution of Oceanography took a chance on me and invited me to work as his postdoc for a year. I loved Scripps, and for the first three weeks in Grant's lab I felt completely at home. It was full of oscilloscopes and other familiar electronics, a giant Lego set of a lab, with drawers and cupboards housing all the bits needed to build any experiment you wanted. And then one day a giant frame turned up near the door, with buoys on the corners and waterproof boxes of sensors in the middle. It was designed to make measurements in the ocean, and it was solid and serious and lurked near the wall like a giant spider as my colleagues fussed around it. This was a type of beast I had never seen, had never imagined could be necessary. It was the absolute focus of their attention and it took me a while to realize why: it was their gateway to another world, their access to the alien realm beneath the waves. And so I stepped over the edge into the abyss of ocean knowledge that I had never known existed.

At first, I just listened and absorbed and tried to contain my astonishment. But very soon afterwards, a mystified indignation took over. How was it that no one had ever told me about any of this? How had I managed to get through three physics degrees and hundreds of books and articles and talks and *no one had ever mentioned the ocean*? This was easily the biggest scientific story I had ever heard. And so I read everything I could and learned to scuba dive and walked around ocean conferences with wide eyes and flapping ears, soaking it all up.

I'm still baffled that we don't talk about the ocean more, that this vast and crucial engine manages to be almost invisible. The more I found out about the ocean, the more jarring the invisibility became. The giant flows of the ocean engine are fascinating by themselves, but they also directly influence the parts of the

Earth that we breathe, walk about on, eat and use as raw materials; they are a huge part of the fabric of this rich and varied planet. This isn't merely a diverting tale about some salty water. This is the story that defines planet Earth.

My arrival in the world of outrigger canoes was also unplanned and unexpected. I was new to London and heard someone mention a local Pacific canoe club. I didn't know what an outrigger was, but I reckoned that if there was a group of people bonkers enough to scoot around the opaque and chilly waters of the Thames estuary in a canoe designed for the equatorial Pacific, we'd probably get on. I was right. But it was only after a year or so, when I had spent more time paddling on the ocean, that I made the deeper connection. It was unlike any other sport I'd tried because Hawaiian culture was folded into everything we did – and while that was perhaps hard for an outsider to spot, it was very obvious when you knew where to look. It was open and welcoming, respectful of everyone, social, tactile, enveloping you in the canoe *'ohana* (family). These were people who stepped up when you needed help and tolerated difference. And then I learned about the history of voyaging across the Pacific, and the astonishing skill and observation that made this possible – including observation of waves and bubbles, my scientific research topic. The Hawaiians looked at the ocean, and I looked at the ocean, but we saw different things. The connection was the canoe. The ocean became like an optical illusion – by blinking, I could switch my view from one perspective to the other. But I was sure that they weren't as separate as they seemed. I'm a scientist, but before that, I'm human. How did the people of the greatest ocean civilization on Earth, the Pacific Islanders, see all the things I measured and scrutinized and reduced to parameters in a computer program? When I saw the ocean through new eyes at Scripps, I had only seen the physical engine, not the cultural housing. When I first understood the mindset of the canoe, it felt as though I had entirely missed the point for the second time. The canoe came to symbolize the complementary perspective that my scientific education hadn't provided: the tradition and culture of the ocean.

The development of a new scientific discipline

When you splash through the waves at the beach, you're connected via seawater to every drop of water in the global ocean. You might have to go the long way round, but you can get to exotic parrotfish, hydrothermal vents, icebergs and aquatic deserts without leaving the water you're paddling in. Many of us have been to a beach at least once, so it's not as if the ocean is completely inaccessible (although I'll admit that getting to large parts of it involves overcoming a few practical problems on the way). And yet even the basic principles of how the ocean works were obscure until a few decades ago. The first dedicated global oceanographic research expedition (considered by many to mark the start of oceanography as a discipline) was carried out by HMS *Challenger* between 1872 and 1876, and it returned with a vast collection of samples and measurements and observations. But although *Challenger* travelled nearly 70,000 nautical miles around the globe, mapping temperatures and currents, and fishing up all manner of ocean beasties from below, the scientists on board could only really pluck at the edges of their subject. It was like taking a huge work of art – say the ceiling of the Sistine Chapel – and mapping 360 pinpoints of colour while looping once around the ceiling. And works of art don't generally change with the seasons and shift from one pattern to another on cycles that last decades. Those scientists came back with only the tiniest sprinkle of samples from the ocean expanses they had crossed, but this haul was already rich and fascinating. For example, the expedition discovered the Challenger Deep, the deepest part of the ocean at around 11 kilometres below sea level, but all they could say about it was that it was there. Acquiring this new scientific knowledge was still a significant achievement, and the substantial report written by the *Challenger* scientists for the Royal Society was hailed as a huge advance in humanity's knowledge of the Earth. A start had been made.

But the expense and difficulty of mounting these expeditions made for slow progress until the Second World War, when submarine warfare ruled the waves. Suddenly, the military was interested in understanding this new fighting space, and once the war was over, oceanography finally had its golden age. In the 1950s and 1960s, every expedition came back with new ideas and unexpected discoveries, and by the mid-1970s the outline of the ocean engine could finally be seen. Then came satellite data, with the potential to reveal large-scale surface patterns that connected the dots drawn by many individual ships. Now we are entering the age of autonomous buoys and vehicles, which can drift for years or dive for days in the innards of the ocean, colouring in far more detail than any cohort of oceanographers could. And we're still learning. At every stage, we discover new mechanisms, new subtleties and new links. The ocean is intimately connected to the atmosphere, ice, geology and life; and although the ocean is the great energy reservoir, its mechanics depend on these other components of the Earth system. Every scale is important – from milliseconds to decades, and from the microscopic to ocean basins thousands of kilometres across. This is a story that isn't finished, and our oceans continue to astonish even the most experienced ocean scientists.

In the past decade, the focus has shifted slightly. As we explore this liquid engine and get to grips with its inner workings, it's been impossible not to notice how much the world up here on land depends on it. It regulates our weather and climate. El Niño, the combined atmospheric and ocean waltz that spans the Pacific Ocean at the equator, has a measurable effect on the GDP of the countries surrounding it. And the ocean soaks up around 30 per cent of the additional carbon dioxide that we're putting into the atmosphere, slowing the march of global warming but with significant consequences for the ocean itself. Thinking about the ocean isn't a luxury for the curious any more. It's a major part of our life-support system and we'd better take it seriously.

We're also learning that even this vast body of water isn't big enough to shrug off the influence of humankind. An increasing awareness of our effect on the ocean is slowly seeping into the public agenda, dragging behind it a conversation that is decades overdue. But this conversation faces a massive obstacle. It's almost impossible to discuss what to do about something changing if you don't initially know how it works. If a doctor tells a patient that they have a problem with their kidneys, the patient probably already has at least a vague idea about where their kidneys are and what they're up to. They learned about that part of their own personal life-support system at school. But that's not the case for the oceans. When we see a news story about the long-term decline in the numbers of krill in the Southern Ocean, it sounds generally like a bad thing. But there's far more to it than the risk of whales going hungry. Krill are a part of the ocean engine, life that is woven into the fluid machine, and we need to understand at least some of the context before we can discuss the change and take appropriate action.

To look more deeply at the ocean is also to look more closely at our own identity, and at what it means to be a citizen of an ocean planet. Zoom out far enough, and our story starts with sunlight arriving at the Earth, and it ends with the light that leaves the Earth, light that has been altered by its passage through the planetary engine, by being reflected, scattered, absorbed, emitted and transformed into many different types of energy before becoming light again. The light that leaves us to restart its journey out into the cosmos bears the unmistakable imprint of a dynamic planet: invisible infrared, green from forests, brown from rocks, white light reflected from clouds and ice, and the blue of the water. Sharp, simple sunlight has been converted into this beautiful palette: our signature on the universe, scrawled in the handwriting of a dynamic and living planet. And that signature is dominated by blue; our message to the rest of the universe is *We are ocean*.

More than any other scientific subject I've studied, the ocean reminds me that I'm human. I have had some of the greatest adventures of my life at sea, made enduring friendships, been scared and exhilarated and bored and tired and more content than I've ever been on land. Put this scientist in a canoe and the personal and professional merge, because really, they were never separate.

Our many connections to the ocean are written all over our history and our culture and our lives, hidden in plain sight. But now it is time to highlight and talk explicitly about those connections. Our attitude to the Earth's ocean determines our behaviour towards it, and we are the first generations who can really see the consequences of our actions. We need to decide as a society how we think about the blue of our planet, which will guide how we act towards it. Scientific knowledge is essential, but this is a cultural decision. Traditional knowledge about and attitudes to the ocean will be necessary to help us with the big decisions we face. How do we reconcile our many competing interests and attitudes with our increasing awareness of what's at stake? Individual societies have faced this question before, but now we need to refresh and share our cultural attitudes to come to a global consensus. The ocean engine is critically important, and humanity's rich cultural treasure-chest can't be ignored. We humans need to address both directly. We have one planet and one global ocean, and if we want future generations to experience the best a blue planet has to offer, we cannot afford to delay.

The voyage

Understanding the ocean better sounds relatively straightforward – but then we meet the beautiful swirling nuanced reality of a shell of water surrounding a rotating planet. There are big patterns and small patterns – currents and krill, sea ice and sediments – all overlapping without clear boundaries. Like any other engine, there is an underlying structure: there are components, and there are links between those components. You need both to make things happen; even the most ingenious piston is useless unless it's connected to something else. In a steam engine, a piston usually has two connections. In the ocean, one current could have dozens, perhaps hundreds. This is an essential feature of the system and it's what makes oceans endlessly fascinating. But the system obeys some basic principles, and we can hold on to those while we explore the maze of connections and components that keep the blue machine ticking along.

This book will take you on a voyage through the global ocean, hopping between stories of history and culture, natural history and geography, animals and people, to reveal the basic shape of the blue machine. Our adventure will traverse the ocean's innards, both the physical mechanisms and the life that is woven into the liquid engine. We will see how the ocean events we observe and notice are not the results of randomness, bad luck or the whims of the gods, but are actually just the surface expression of the deep engine which is always turning beneath. The full complexity of the global ocean can't be squeezed into a single book; but we can draw its outline and set out the fundamental principles underlying how it works – enough to serve as a map for further exploration. I hope that it will change your perspective on the ocean, and perhaps on yourself as well. And it is definitely true of the ocean that the more you know, the better it gets. So let's begin.

PART ONE

WHAT IS THE BLUE MACHINE?

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The Nature of the Sea

The Earth's ocean is fickle when it comes to its appearance. Seawater can present itself as the startling turquoise of a shallow tropical bay, the ruffled grim grey of a blustery northern coast, a calm royal blue that stretches for a thousand miles – or perhaps temporarily cloaked in the cheeky orange of a sunset. When you look at the ocean, there's a wealth of detail to notice, and the most obvious visual characteristics often change by the minute. In contrast, when you walk up to the water's edge and touch the source of all that variety, the same three observations are always at the top of the list: it's noticeably warm or cold, it's salty, and it's liquid. These three fundamental features – temperature, salinity, and the weird and wonderful wetness of water – provide the foundation for everything the ocean engine does. But they are also as accessible to a ten-year-old child as they are to an experienced Polynesian navigator or an Atlantic fisherman. Each of them has a direct influence on the world we take for granted. And then once you step back from the seashore and broaden your perspective, this trio has a deeper beauty and influence to offer, as facets of a single interlinked system.

But as you zoom out, from a single breaking wave at a beach to a hundred-mile-wide bay eating into the coastline, and then further still to a whole sea, another contributor becomes apparent. We live on a rotating planet, and although no human can feel our daily pirouette around the Earth's axis, the shifting fluid ocean cannot ignore it. The effect of our globe's spin is to sculpt this liquid machine into beautiful loops and curves, giant whorls and vast underwater undulations.

It's tempting to dive straight into the patterns and the astonishing intricacies. But before we reach for the grandest perspective of the Earth's blue machine, we need to understand the major physical influences that make it work: temperature, salinity, density and spin. Since every machine needs energy to run, we will start with the way energy is stored in the ocean and the way that ocean scientists track it: temperature.

Temperature

I'm peering down through a horizontal metal grille set into a broad concrete base, and all I can see is the reflection of the sky and my face in the still water beneath. Keith Olson's face pops into the circle next to mine as he leans over the sump. 'This is probably the first time that sunlight has touched this water in a thousand years,' he says. We're in the middle of a small fenced-off section of a lava field next to the ocean in Kona, on the Big Island of Hawaiʻi. Inside the fence, four huge pipes each half a metre across crawl out of the ground, merge into two, and snake across the lava away from the ocean. There's a brilliantly obvious clue to what differentiates them in the paintwork on the pumps which are pushing water down those pipes: two are red and two are blue. This is the Natural Energy Laboratory of Hawaiʻi Authority (NELHA), and here in the middle of the Pacific Ocean they've got pristine ocean water on tap, or two taps if you're being precise: one hot and one cold. The combination of this water supply and a barren corner of an active volcano is generating an astonishing flood of fertility. And that temperature difference is the key to it all.

NELHA began as the response to a shock, back in the winter of 1973–4, when crude oil prices shot up from $24 per barrel to

$56 per barrel pretty much overnight. The state of Hawai‘i, thousands of miles from the mainland and almost entirely dependent on oil arriving by ship for its energy, decided it had better try to wean itself off fossil fuels. If you're going to do that, being a chain of volcanic islands with abundant equatorial sunshine is a very good start. But Hawai‘i's engineers realized that they had something else up their sleeve: access to the deep ocean. The Hawaiian Islands are shield volcanoes parked in a region of ocean that's 4–5 kilometres deep,[1] and as you sail outwards from their shoreline the volcanoes continue to drop away beneath you. If you run a pipe far enough down that slope, you can tap directly into something surprising: cold water. Today, NELHA's longest pipe reaches a depth of a thousand metres, and those blue pumps are bringing 5°C ocean water to the surface. The red pumps are hauling in surface water at 25°C. Between them, they pump an astonishing 113 million litres or 116,000 tonnes of ocean water into the technology park every day. But the point of all this isn't to supply water. The valuable commodity here is energy.

Water can store a surprising amount of energy as heat. Imagine two grapefruit-sized globes of water side by side,[2] one full of North Pole ocean at about −1.8°C, and one full of Persian Gulf water at about 30°C. The warmer water has more heat energy, and if you could channel all that extra energy into doing something mechanical, you could lift an SUV (weighing nearly two tons) up by about 7 metres, high enough to be level with the top

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[1] Shield volcanoes have relatively gentle and smooth slopes, due to the runny lava coming out of them. The lava spills out over the landscape gradually, creating broad, shallow-sided cones, which look like shields laid on the ground.

[2] This isn't a random choice of fruit. The average grapefruit has a diameter of about 12 cm, which means that it's got about the same volume as one kilogram of water.

of a two-storey house. This is an astonishing amount of energy, and that's just what's held in a single kilogram of water. It's really hard to heat water up, so you have to add a huge amount of energy to make even a small change to the temperature.[3] But once you've warmed up the water, you haven't lost anything – the energy is just stored as heat until the water gives it away and cools back down. This makes water astonishingly effective at storing energy. The millions of litres of warm water being pumped by NELHA are carrying many thousands of gigajoules of energy every day, just because of their temperature. There's no doubt that the energy is there. The challenge for NELHA is to extract it.

The original idea was to use the temperature difference to run a heat engine which can generate electricity. This process is known as ocean thermal energy conversion, or OTEC.[4] There's heat energy in water at any temperature, but in order to extract it, you need a contrast – the warm water has to be paired with something cold. Then you need a technology to sit between the hot and cold water and to extract some of the energy flowing between the two, which in this case is a heat engine built by Makai Ocean Engineering that runs by continuously cycling ammonia.[5] The current version, opened in

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[3] This is why your kettle is one of the most energy-hungry devices in your home.

[4] In this context, it's helpful to think of a fridge running backwards. Your fridge takes electrical energy and uses it to create a temperature difference between the inside of your fridge and the outside. What OTEC does runs the other way and achieves the opposite, converting a temperature difference into electrical energy.

[5] The way it works is beautifully simple, but of course there are lots of subtleties in the execution. Ammonia is a fluid that boils at very low temperatures and although it's a gas at room temperature, if you put it under a bit of pressure, you can move its boiling point to sit between the hot and cold water temperatures. As it passes the cold water, the ammonia cools and becomes

2015, is a demonstration plant connected to the electricity grid, and it's capable of generating 100 kilowatts of electricity. For that technology to work, you need a temperature difference of 20°C, and there are plenty of tropical islands where that's available. This energy source is an ideal baseload for the grid – it's very easy to control and you can turn it up and down as you need. The biggest stumbling block (apart from easy access to the deep ocean in the tropics) is that to make it cost-effective, you would need to scale it up considerably, and there are still questions about how you could do that, whether it's worth it and whether it would have any unintended consequences. But the concept of extracting solar energy that's currently being stored in the surface ocean undoubtedly works, if you're in the right place to do it.

Most local residents refer to the whole site as OTEC, but the demonstration energy plant is just the start. This whole corner of Kona is an incubator for small businesses that can use the hot-plus-cold ocean water supply, all perched on top of the lava field deposited by the Hualālai volcano in 1801. Keith drives me around the site, pointing out the astonishing variety of businesses hidden in unassuming buildings nestled on the black rock. There are huge tanks growing spirulina, kept at the right temperature by ocean water heating and cooling. There's a business that grows 50–60 per cent of the broodstock for one of the giants of the aquaculture world: *Litopenaeus vannamei*, the whiteleg shrimp. There's another growing abalone, a marine mollusc that is a favourite of chefs all over the world. There are hydrogen production and clam-breeding facilities, more farmed algae and a monk-seal hospital. And to top it all off, the NELHA offices are air-conditioned using ocean water. The cold salt water cools fresh water from

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liquid. Once it reaches the warmer water, it boils to form a very high-pressure gas. That can be used to drive a turbine and generate electricity, and then the cold water condenses the ammonia ready to start all over again.

the normal water supply, which is then pumped around the buildings using solar energy. I'm not generally a fan of over-air-conditioned buildings, but I can easily forgive NELHA theirs.

NELHA is only a small-scale operation, and this type of energy extraction isn't going to solve the world's energy problems. Yet it demonstrates that warm water – just warm, not even hot – is a vast store of energy. It might be tricky for humans to extract that energy, but on a planetary scale the global ocean is a gigantic heat reservoir. Even a small increase in temperature represents a huge amount of stored heat, and so the temperature of the water is the critical measure of stored energy. But that heat energy is not evenly distributed around the planet. To understand where it is and the huge influence that it has, we need to go back to where it comes from and why it ends up in some places but not others.

Why warmth?

It starts with a star. When we think about our solar system, we are often distracted by the variety and mystery of the other planets that share our sun. These wanderers through our night sky provide rich fuel for humanity's imagination, conveniently packaged into seven giant and mostly inaccessible spheres. But the sun makes up 99.86 per cent of the total mass of the solar system, and although you could argue that 99 per cent of the variety is found in the planets, our solar system is really one massive nuclear reactor surrounded by spherical specks of dust that it can't shake off. At the sun's heart, 4 million tonnes of matter is converted into energy every single second as colossal temperatures and pressures force hydrogen atoms to fuse into helium atoms. The newly released energy rattles around inside the sun for tens of thousands of years before reaching the surface, but once free of its plasma shackles it pours out into the universe in all directions in the form of infrared, visible and ultra-violet light. The fraction of this flood that the Earth receives is just less than one-billionth of the total. The laws of physics make this energy the Earth's essential currency, setting a fixed budget for everything that happens on this planet.[6]

As with all budgets, the total is quickly split up by circumstances. A third of it is reflected straight back out into the universe, barely touching the Earth system. A small chunk is intercepted by the atmosphere. Nearly two-thirds makes its way down to the surface, and if that surface is seawater then raw energy from the sun finally touches the Earth's ocean.

But reaching the surface does not guarantee entry. Physics is the gatekeeper, selecting which light rays to admit on the basis of strict criteria. Imagine looking out across the ocean to the rising sun. On a still day, the reflection of a beautiful orange sunrise can be almost perfect, as if the ocean surface was a mirror. That's because when light arrives at the water surface at a shallow angle, water does indeed behave exactly like a mirror and the light is all reflected back into the sky (or, in the case of the sunrise, into your waiting camera lens). But as the day goes on and the angle between the sun and the water surface increases, sunlight is more likely to cross the air–water boundary. This means that the best place to appreciate the effect of sunlight on the ocean is in the tropics. Close to the equator in the middle of the day, the sun is high in the sky and therefore sunlight has the highest probability of piercing the ocean surface. And if

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[6] Nuclear fission (and hopefully nuclear fusion in the future) sit outside this finite budget. But the world's total supply of nuclear energy is less than one-millionth of all the energy from the sun that arrives at the Earth. Geothermal energy contributes a bit too, along with solar and lunar tides, cosmic radiation, magnetic storms, and a few other bits and pieces. But the total of all of these is only one-fortieth of 1% of what we get from the sun (and almost all of that is geothermal).

you're near to the coast, there's a good chance that this light will illuminate the ocean's best-loved feature: the tropical coral reef.

A healthy coral reef is one of nature's most diverse and most extraordinary environments. The coral itself forms a seascape of colourful clustered bulges, large mounds, delicate fronds and branching antler-like protrusions. Brightly painted parrotfish dart about, gnawing at the coral whenever they pause. Red squirrelfish lurk in dark crevices, watching the world go by. Striking butterfly fish patrol their patch, ready to defend their territory at the slightest insult.[7] And the resident population of nudibranchs, worms, shrimps, clams, sponges and more creates a busy and diverse ocean city. Up near the surface, it looks to us as though there is oodles of light down here, generously illuminating the stripes, spots, camouflage, iridescence, sand and rock that the natural world has on display. But water isn't nearly as transparent to light as we generally think, and as you descend the surroundings get bluer and then blacker as the water absorbs all the sunlight on offer. As humans looking at the world, our focus tends to be on this visual loss.

But the laws of physics offer a different perspective: the light may disappear, but the energy can't. Visible light is converted into ocean heat, and so the photographer's loss is the thermometer's gain. Sunlight bathes the pretty reef fish twice: in light until the water has extracted its energy tax, and then in warmth. And so the ocean is heated by the sun.

This visible light – the colours of the rainbow that make up a human's visual world – is only half of what arrives from the sun. The other half of the sunlight reaching the Earth's surface is

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[7] I have always wondered why the common western names for so many reef fish are based on land animals. Goatfish, sheepshead wrasse, hawkfish . . . the list seems endless. It is true that a frogfish really can look like a lost toad, but of course a toadfish is an entirely different species.

infrared light: the colours that sit beyond the red part of the rainbow, unseen by human eyes. If you put your hand near a warm object in the dark, you can feel its warmth because it is sending out infrared light that contains energy. You know there is something hot near by even though your eyes can't detect anything. Infrared light floods downwards from the sun and it does touch the ocean, just, but water is so opaque to these wavelengths that within a fraction of a millimetre this part of the light is absorbed completely and then reradiated straight back out to the atmosphere. Counter-intuitively, the visible light is responsible for heating the ocean, and what we think of as travelling warmth – the infrared – makes no contribution at all.

Sunlight heats up ocean water wherever they touch, pouring energy into the reservoir. Less than ten minutes after leaving the sun, the energy is stashed away in long-term storage in the ocean, keeping the vigilant butterfly fish nice and warm. It takes a long time for water to heat up and cool down, so tropical waters remain pretty much the same temperature throughout day and night alike.

The heating is most dramatic at the equator, giving our planet a balmy belt inhabited by tropical fish. But as the Earth curves away from the sun in the northern and southern hemispheres, the direct heat contribution from sunlight decreases. Closer to the poles, the ocean is a very different place indeed.

The chill beneath the tropics

Just beyond the northern limit of the Atlantic Ocean, the Arctic Circle crosses Greenland and swoops eastwards across a 2,000-kilometre stretch of open ocean, barely skimming Iceland as it crosses grey choppy water towards northern Norway. At noon on the winter solstice each year the sun scrapes the horizon only briefly, and then buries itself behind the curve of the Earth, leaving the Arctic to face the unforgiving darkness of the universe for another day. Even six months later, when sunlight slants across the ocean surface for twenty-four hours continuously, the light rays are weedy, tightly rationed by the tilt of the Earth and weakened by long transit through the atmosphere. The consequence is a very different face of the global ocean: it's cold here, and relatively dark. There's still plenty of life, but the details have been tweaked by evolution to match the local challenges. Every creature carries the imprint of its environment.

Halfway between Iceland and Greenland, 400 metres below the surface, a patch of the gloom is moving. It glides slowly, taking four seconds to cover 1 metre, and its grey mottled skin hangs loosely on its long body. The sharp corners and sleek silhouette of closely related species are replaced by a softer look, reminiscent of a baggy old jumper which won't ever be thrown out because it's too comfortable. This lumpy-looking creature is 4.5 metres long and weighs a gigantic 400 kilograms. Speed is not its game. The Greenland shark never goes anywhere in a hurry. But then it has no need to. An individual of this size was probably born before the earliest glimmerings of the industrial revolution, and has been gliding around these waters for 240 years. It's thought that this species can live to be at least 300 years old (possibly more), doesn't reach sexual maturity until it's about 150 and keeps on growing throughout its life at about one centimetre each year. As far as we know, it's the world's longest-living vertebrate. This exceptional lifespan seems to be directly connected to the cold, which slows down the processes of life,[8] stretching out the shark's existence by a factor of ten. This slow giant will spend its leisurely life in water that's around 0°C, mostly hidden several hundred metres below the surface. One of the greatest mysteries carried by that baggy body is how it catches prey – adult Greenland sharks are found with stomachs full of fish like flounder and skate, and sometimes even

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[8] The name of a recent international collaboration to study this species was brilliantly to the point: 'Old and Cold – the Biology of the Greenland Shark'.

with freshly killed seal. Any of those species could easily outswim this creeping predator. Adding to the mystery, almost all Greenland sharks are at least partially blinded by a parasite that sits in one or both of their eyes. Such a hindrance won't matter in the inky blackness of the ocean depths, but it will limit their hunting nearer the surface. We often assume that the predatory thrones at the top of the food chain must be occupied by the fastest, most observant and most aggressive animals, endowed with nature's most dangerous weapons in the form of teeth, claws and heft. But in the deep dark cold, the Greenland shark shows us that there is another way to live, and another way to hunt.

The contrast between a tropical coral reef and the normal Arctic habitat of the sluggish Greenland shark shows us the broad pattern of ocean temperature in near-surface waters. It's set by exposure to sunlight, which is tightly tied to latitude and season. The sunny equatorial seas delight visitors with temperatures of around 30°C, but in the central Arctic, water temperature can drop as low as −1.8°C. The global ocean energy reservoir is bursting at the equator, but offers only slim pickings nearer the poles. And yet every detailed map of sea surface temperature is a beautiful study of minor exceptions to this rule, each one opening a new door on the complexity of the ocean beneath. There are cool patches and warm patches parked incongruously next to coastlines, elegant swirls of balmy water far from the shore, and striking, snaking intrusions of cold water into friendlier surroundings. We'll explore some of those later in this book, but the foundation that sits beneath all the beautiful complexity of these patterns is that ocean temperature varies between −2°C and 30°C and is broadly correlated with how close to the equator you are. But this pattern of energy storage isn't just about the surface. The depths have a tale to tell too.

In August 2013, the research vessel R/V *Apalachee* was working in the Gulf of Mexico, close to the site of the blowout that had killed eleven crew on the Deepwater Horizon oil rig three years earlier. The latitude of this site is close to 29°N, far closer to the equator than to the poles, and the typical surface water temperature at that time of year is around 30°C. The researchers on board, led by a team from Florida State University, were sampling deep-sea fish communities to assess the impact of the oil spill. One of the fish they hooked was brownish-grey, 3.7 metres long and quite clearly a juvenile Greenland shark. It was brought out into the hot summer sunshine in a green net stretcher and parked on deck, far warmer in death than it had ever been in life. It was the first of its kind to be captured in the Gulf of Mexico – noteworthy enough to earn a write-up on a few online news sites, but the researchers weren't that surprised. So what was a polar shark doing in the Gulf of Mexico in the height of summer?

The hook that snagged the shark had been hanging 1,749 metres below the sea surface. And down there, the water temperature was 4°C, well within the comfort zone of a Greenland shark. The upper ocean might have been warm enough to take a bath in, but the depths were not, and this is normal. The shark would have been at home at that depth anywhere between the North Pole and where it met the hook, because the deep ocean is almost all that cold. That bright colourful map of ocean surface temperatures, with the nice broad red stripe at the equator, is just that: a map of *surface* temperatures. The temperature difference between the surface water, which basks in bright sunlight, and the deeper waters that haven't been touched by sunlight for decades can be dramatic. In the Gulf of Mexico, that warm surface layer is only 100–200 metres thick, but a huge section of the ocean basin inside the Gulf is almost 4,000 metres deep. Below 1,000 metres, this basin is filled with cold salty water very similar to the cold salty water that fills much of the depths of the North Atlantic basin. It flows in from the Caribbean, continually refreshing the pool. There are also other, more subtle, layers above that.

The ocean that we humans see – the sunlit water that you can comfortably wade into, full of life and character and food – forms only a small fraction of the whole ocean. Tropical coral reefs are an exception, albeit one that is vital for life in the ocean, and one that is an enormous joy with which to share a planet. But it is essential that you don't give up on the deep ocean at this point, on the basis that it sounds best left alone. That cold dark water beneath is just as interesting and necessary and important as anything that happens at the surface. Looking down at a flat map of ocean temperature seen from above isn't enough. We also have to pay attention to how things change with depth.

Stacked water

The thin skin of salt water that encapsulates our planet, 4 kilometres deep and 12,740 kilometres in diameter, has a dramatic internal anatomy. It's written in temperature and salinity, and it's built of horizontal layers. The details change as you cross the planet: currents eventually merge with their surroundings, water sinks in some places and rises in others, and slabs of water are disrupted as they slide across giant sea-floor mountain ranges. But the overall pattern is clear. In the deep ocean basins, there is generally a stack of three or four major layers which are known to oceanographers as water masses. Each one has a distinct character and history, and these are the biggest components of the ocean engine. Lesson one about the structure of the ocean is that it's layered, and those layers generally do not mix with each other.

The most striking internal boundary in the ocean is defined by temperature, and it's known as the thermocline. A thermocline is defined as a thin layer of the ocean that undergoes a rapid temperature change with depth, marking the transition between layers which have different temperatures. But when