

SCIENCE COURSE

Oceanography Fundamentals

10 Chapters

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OCEANOGRAPHY FUNDAMENTALS

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Oceanography Fundamentals

Course 1 · Chapter 1 · The Ocean Planet: Scope & Sources

Between December 1872 and May 1876 the British ship HMS Challenger sailed about 70,000 nautical miles around the world, lowering weighted lines and nets into water that nobody had ever properly sampled (check the figures). Its crew sounded the depths at hundreds of stations, took temperatures at different depths, dredged up animals nobody had named, and returned with material that took nearly twenty years to publish. The expedition is usually treated as the birth of oceanography as a science. This chapter sets the scene for the course: how much of the planet the ocean covers, how it is divided, how deep it goes, how little of it has been seen, and where you can look at the data yourself.

The Scale of It

Seen from space, Earth is mostly blue. A few numbers fix the scale.

Area

The ocean covers about 71 per cent of the surface, roughly 361 million square kilometres. The land is the minority.

Water

About 97 per cent of all the water on Earth is in the ocean (check the exact figure). Ice caps, groundwater, lakes, rivers and the atmosphere share the rest.

Depth

The average depth is a little under 3,700 metres, and the deepest point, the Challenger Deep in the Mariana Trench, is nearly 11,000 metres down (check the latest survey value).

A thin skin, not a deep one

Earth's radius is about 6,371 kilometres, so even the deepest trench is under two-tenths of one per cent of the way to the centre. On a school globe the ocean would be a film of water thinner than the varnish. Yet that film holds some 1.3 billion cubic kilometres of

> water (check), and it shapes the weather, the climate and most of the living space on the planet.

Ocean or Oceans?

Geographers talk of one connected world ocean, divided by convention into named basins. Water moves between them (Chapters 6 and 7), so the boundaries are administrative rather than physical.

Basin	Roughly how much of the ocean	Note
Pacific	Nearly half	Largest and deepest; larger than all the land put together
Atlantic	About a fifth to a quarter	S-shaped; the one that touches Scotland's west coast
Indian	About a fifth	Mostly in the southern hemisphere; seasonal monsoon winds drive its currents
Southern	A few per cent	Ring of water around Antarctica; recognised as a fifth ocean by the US National Geographic Society in 2021 (check)
Arctic	About 4 per cent	Smallest and shallowest; partly covered by sea ice

The proportions are approximate because they depend on where the edges and the marginal seas are drawn (check against one source). Smaller regions, such as the North Sea, the Mediterranean and the Caribbean, are called seas; many are partly enclosed by land.

Land and Water Are Not Evenly Shared

The northern hemisphere is about 60 per cent water and the southern hemisphere about 80 per cent (check). Seen from a point near New Zealand, almost the whole hemisphere is ocean. This lopsidedness matters for climate: water heats and cools more slowly than land, so oceanic regions have milder seasons than continental interiors. Edinburgh, for example, has far milder winters than places at the same latitude in central Canada, and the Atlantic is the reason.

Going Down: The Depth Zones

Light fades with depth, and so does temperature and the amount of life. Oceanographers divide the water column into layers. The boundaries below are the commonly used ones, though textbooks differ slightly.

Zone	Depth	What it is like
Epipelagic (sunlight zone)	0 to 200 m	Enough light for photosynthesis; most marine life
Mesopelagic (twilight zone)	200 to 1,000 m	Faint light; many animals that rise at night to feed
Bathypelagic (midnight zone)	1,000 to 4,000 m	No sunlight; near-freezing and high pressure
Abyssopelagic	4,000 to 6,000 m	Covers the vast abyssal plains (Chapter 2)
Hadal	Below 6,000 m	Found only in trenches; named after Hades

> **Pressure, in plain terms**
>
> Pressure rises by about one atmosphere for every ten metres of seawater (check). At the bottom of the Challenger Deep it is more than a thousand times the pressure at the surface. Chapter 3 returns to this when it looks at how seawater behaves.

How Much Do We Actually Know?

A common claim is that we know more about the surface of the Moon than the ocean floor. It is half true. Satellites measure the sea surface from space, and the slight bulges and dips caused by seafloor mountains give a coarse map of the whole seabed. But detailed maps need ships or underwater vehicles with sonar (Chapter 2), and the project Seabed 2030 reports that only about a quarter to a third of the seafloor had been mapped to modern standards by the mid-2020s (check the latest figure). The water column and its inhabitants are even less well sampled, and new species are described every year.

Claims to treat with caution

Popular articles often say "we have explored only five per cent of the ocean" or "the ocean produces most of our oxygen". Both are loosely used. "Explored" is rarely defined, and estimates of the ocean's share of oxygen production are commonly given as about half, with real uncertainty (check). Whenever you see a striking ocean statistic, ask what was measured and by whom.

Why Study It?

- **Climate.** The ocean has absorbed the large majority of the extra heat trapped by greenhouse gases in recent decades, with figures above 90 per cent often quoted (check; Chapter 8).
- **Weather.** Hurricanes draw energy from warm water, and sea temperature steers storms and rainfall (see Weather & Meteorology Fundamentals 6).
- **Food and trade.** Fisheries feed billions of people, and the great majority of world trade by volume goes by sea (check).
- **Hazards.** Tsunamis, storm surges and rising sea level threaten the many people who live near the coast.
- **Life.** The sea is the largest habitat on the planet by volume, and life probably began there.

What the Course Covers

Chapters	Theme
2–3	The seafloor and the properties of seawater
4–5	Waves and tides
6–7	Surface currents and deep circulation
8	The ocean and climate
9–10	Marine life, exploration and protection

It is an introduction for the curious, with plain language and a minimum of mathematics. It does not teach navigation or seamanship, and it does not replace a degree course.

Where to Get Data and Read More

- **National agencies.** The UK Met Office and the National Oceanography Centre publish ocean and sea-state information; in the US, NOAA publishes a very large open collection.
- **Tide tables and gauges.** The UK Hydrographic Office and port authorities publish predictions and records for most harbours.
- **Satellite sea-surface data.** Agencies such as ESA and NASA release sea-surface temperature and sea-level maps free of charge.
- **Bathymetric charts.** The GEBCO project publishes a global gridded map of the seafloor (check the current release).
- **A coast visit.** A beach at low and high tide, with a tide table in your hand, makes Chapter 5 concrete.

Exercises

EXERCISE 1

The ocean covers about 71 per cent of the surface of Earth, which is about 510 million square kilometres in total. Work out the ocean's area in square kilometres, and say what the answer tells you about the land area.

→ Solution

EXERCISE 2

Name the depth zone for each of these and say whether sunlight reaches it: (a) 50 m; (b) 600 m; (c) 2,500 m; (d) 8,000 m.

→ Solution

EXERCISE 3

Find one striking statistic about the ocean in a news article or on a website. Write three sentences saying what it claims, what it would have to measure, and whether you can trace it to an agency or a paper.

→ Solution

Quick Reference

- **Coverage:** about 71 per cent of the surface; about 97 per cent of Earth's water
- **Depth:** average a little under 3,700 m; deepest about 11,000 m (Challenger Deep)
- **Basins:** Pacific, Atlantic, Indian, Southern, Arctic, joined as one world ocean
- **Zones:** epipelagic, mesopelagic, bathypelagic, abyssopelagic, hadal
- **History:** HMS Challenger, 1872 to 1876, the first great scientific voyage
- **Knowledge gaps:** only a quarter to a third of the seafloor mapped in detail
- **Check:** basin proportions, trench depth, mapped percentage, oxygen share

Coming next

Chapter 2 goes to the bottom: the continental shelf and slope, the flat abyssal plains, the mid-ocean ridges and the deep trenches, and how sonar and satellites reveal them.

Oceanography Fundamentals

Course 1 · Chapter 2 · Basins and the Seafloor

In the 1950s the American geologist Marie Tharp, working with Bruce Heezen at Columbia University, plotted thousands of echo-sounding profiles into the first detailed maps of the Atlantic seafloor (check the dates). Women were not allowed on the research ships of the time, so she worked from the data the men brought back. Her maps showed a continuous mountain chain running down the middle of the ocean, with a deep cleft along its crest. Heezen at first dismissed the idea of a rift as "girl talk", and then came round to it (check the anecdote). That rift turned out to be one of the keys to the theory of plate tectonics. This chapter walks the seafloor from the coast to the deepest trench and explains how it is made.

A Profile from Coast to Deep

Imagine sailing west from the Scottish coast into the Atlantic and lowering a sounding line every few kilometres. The depths would trace a typical ocean-margin profile.

Feature	Typical depth	What it is
Continental shelf	0 to about 130 m	The gently sloping drowned edge of a continent; the average width is around 80 km, but it ranges from almost nothing to hundreds of kilometres (check)
Shelf break	About 130 m on average	Where the slope suddenly steepens
Continental slope	130 m to 2,000 m or more	The steep descent, often cut by submarine canyons
Continental rise	2,000 to 4,000 m	A gentle apron of sediment at the foot of the slope
Abyssal plain	3,000 to 6,000 m	The flat, muddy floor that covers a large part of the ocean bed
Trench	6,000 to 11,000 m	A narrow, very deep groove where one plate sinks beneath another

The North Sea sits entirely on the continental shelf. It averages under about a hundred metres in depth (check), which is why it was dry land in the last ice age and why the shallow, productive water supports so much fishing.

Shelf seas

Shallow, well mixed, rich in nutrients from rivers and the land. Most of the world's fishing happens here.

Abyssal plains

Among the flattest places on Earth, smoothed by a slow rain of fine sediment. Dotted with seamounts and abyssal hills.

Ridges and trenches

The mountain chains and canyons of the ocean. They mark the edges of tectonic plates and are where the crust is made and destroyed.

The Mid-Ocean Ridge

The longest mountain chain on Earth is almost entirely underwater. The mid-ocean ridge system winds through the Atlantic, Indian, Pacific and Southern Oceans for roughly 65,000 kilometres (check). The Mid-Atlantic Ridge, which runs from Iceland to the far south, is the part Tharp mapped. Iceland is a place where the ridge rises above the surface, which is why it has so many volcanoes and why you can walk between two tectonic plates at Thingvellir.

The ridge is a place where the crust is pulling apart. Molten rock rises from the mantle, cools, and becomes new seafloor on either side. This process is called **seafloor spreading**.

How the idea was proved

In the early 1960s Harry Hess proposed that the seafloor spreads out from the ridges and sinks back into the mantle at trenches (check the date). Then magnetic surveys found stripes of rock with alternating magnetic direction running parallel to the ridge, matching the known reversals of Earth's magnetic field. In 1963 Frederick Vine and Drummond Matthews explained the stripes as a tape recording made as new rock cooled on both

sides of the ridge (check). Later drilling showed that the rock and sediment get older with distance from the ridge, exactly as the theory required.

How Old Is the Ocean Floor?

Continental rocks include samples billions of years old. The ocean crust is very different: because it is constantly being made at ridges and recycled at trenches, none of it is older than about 180 million years (check; the oldest known patches are in the western Pacific and the Mediterranean region). Spreading speeds vary, from a couple of centimetres a year in the Atlantic (about the speed at which fingernails grow) to well over ten centimetres a year in parts of the Pacific (check).

Property	Continental crust	Oceanic crust
Typical thickness	About 30 to 50 km	About 7 km
Main rock	Granite-like	Basalt
Density	Lower	Higher, so it sits lower and holds the oceans
Oldest known age	Around 4 billion years	About 180 million years

Trenches, Seamounts and Hotspots

- **Trenches.** Where an oceanic plate meets another and sinks, the seafloor bends into a trench. The Pacific has most of them, including the Mariana Trench, the deepest on Earth. They also produce the largest earthquakes and the tsunamis described in Chapter 4.
- **Seamounts.** Underwater mountains, usually extinct volcanoes. There are tens of thousands, and many are hotspots for marine life (check the numbers).
- **Hotspot chains.** A plume of hot rock under a moving plate builds a line of volcanoes, like the Hawaiian Islands. Mauna Kea, measured from its base on the seafloor, is taller than Everest, though only part of it shows above the sea (check).

Connecting the courses

The plates, mantle plumes and magnetic stripes mentioned here are explained in detail in the Geology and Plate Tectonics Fundamentals course. This chapter takes the ocean's view of the same story.

How We See the Bottom

Light does not reach far, so the seafloor is mapped with sound and gravity.

Method	How it works	Strength and weakness
Lead line	A weighted rope lowered by hand	Used for centuries; one point at a time
Single-beam echo sounder	A pulse of sound, timed as it returns from the bottom	Common from the 1920s; a single line of depths under the ship
Multibeam sonar	A fan of beams across a wide swath	Detailed maps, but a ship must cover the whole area, slowly
Satellite altimetry	Radar measures sea-surface bumps caused by the gravity of seabed features	Covers everything, but at coarse resolution
Submersibles and robots	Vehicles carrying cameras and sonar close to the bottom	Very sharp detail, small areas

The sums behind an echo sounder are simple: depth equals half the speed of sound in water multiplied by the time the echo takes. Sound travels at roughly 1,500 metres per second in seawater, though the value varies a little with temperature and salinity (check; Chapter 3). So an echo that returns after four seconds means a depth of about 3,000 metres.

Maps are models

A coloured seafloor map often blends precise ship surveys with coarse satellite estimates, and the join is not always visible. When you see a vivid image of a trench or ridge, check the source and resolution. Where nobody has sailed with a sonar, the map is an inference.

Exercises

EXERCISE 1

A research ship's echo sounder records an echo returning after 6.0 seconds. Taking the speed of sound in seawater as 1,500 m/s, calculate the depth, and name the seafloor feature it is most likely to be.

→ Solution

EXERCISE 2

The Atlantic is spreading at about 2.5 cm a year. How far apart will two points on opposite sides of the ridge have moved after 10 million years? Compare the answer with the width of the Atlantic.

→ Solution

EXERCISE 3

Sketch (or describe in words) the profile of the seafloor from a coast out to a trench, labelling the shelf, slope, rise, abyssal plain and trench, and say which one is the flattest and which the steepest.

→ Solution

Quick Reference

- **Margin profile:** shelf, slope, rise, abyssal plain, with trenches at plate edges
- **Shelf break:** about 130 m on average
- **Mid-ocean ridge:** roughly 65,000 km; new crust is made here by seafloor spreading
- **Evidence:** magnetic stripes, age of rocks growing with distance from the ridge
- **Age:** ocean crust is under about 180 million years old

- **Mapping:** echo sounder (depth = speed x time / 2), multibeam sonar, satellite altimetry
- **Check:** ridge length, ages, spreading rates, shelf width

Coming next

Chapter 3 turns from the container to what it holds: seawater, with its salt, temperature, density and layers, and why sound and light behave as they do in it.

Oceanography Fundamentals

Course 1 · Chapter 3 · Seawater: Salt, Heat, Density, Light and Sound

The Challenger expedition of the 1870s brought back hundreds of bottled water samples from every ocean. The chemist William Dittmar analysed them in Britain and found something surprising: the amount of salt varied from place to place, but the proportions of the main ingredients hardly varied at all (check). Whether the water came from the Atlantic or the Pacific, chloride was always in the same ratio to sodium, and sodium to magnesium. That result, now called the principle of constant proportions, makes it possible to measure the saltiness of seawater by measuring just one thing. This chapter looks at what seawater contains, how temperature and salt together set its density, why the ocean is layered, and how light and sound behave in it.

What Is in the Water?

Seawater is, on average, about 3.5 per cent dissolved salts by mass, or roughly 35 grams per kilogram (check). Oceanographers call this the **salinity**. The salt comes from the weathering of rocks on land, carried to the sea by rivers, and from volcanic and hydrothermal activity on the seafloor.

Ion	Share of the dissolved salt, approximately
Chloride	55 per cent
Sodium	31 per cent
Sulphate	8 per cent
Magnesium	4 per cent
Calcium and potassium	about 1 per cent each

Table salt, sodium chloride, is therefore the biggest part but not all of it (check the percentages). Trace elements, dissolved gases (oxygen, carbon dioxide) and nutrients such as nitrate and phosphate are present in tiny amounts, but they matter greatly for life (Chapter 9).

Where it is saltier

In hot, dry subtropical regions, where evaporation exceeds rainfall. The Red Sea is among the saltiest open seas, at about 40 grams per kilogram (check).

Where it is fresher

Near river mouths, near melting ice and where rain is heavy, such as the tropical belt. The Baltic Sea is brackish, at only a few grams per kilogram in places (check).

Why the open ocean varies little

The open-ocean range is only about 33 to 37 grams per kilogram. The ocean is so large and well mixed that local differences are small.

Temperature

Sea-surface temperature runs from about minus 2 degrees Celsius near the poles to around 30 degrees in the warmest tropical seas (check). Most of the deep ocean, below about a kilometre, is a few degrees above freezing, whatever the latitude.

Seawater does not freeze at 0 degrees. Salt lowers the freezing point to about minus 1.9 degrees at normal salinity (check). When sea ice forms, most of the salt is pushed out into the water below, which makes that water saltier, colder and denser. This detail drives the deep circulation described in Chapter 7.

The ocean as a heat store

Water has an unusually high specific heat: it takes about four times as much energy to warm a kilogram of water by one degree as it does a kilogram of air (check). Together with its great mass, this means the top few metres of the ocean hold as much heat as the whole atmosphere above (check the figure). The sea therefore warms slowly in spring, cools slowly in autumn and keeps coastal climates mild. It is also why the ocean is central to climate change (Chapter 8).

Density and the Layered Ocean

Seawater has a density of about 1,025 kilograms per cubic metre, a little more than fresh water. Two things control it:

- **Temperature.** Colder water is denser.
- **Salinity.** Saltier water is denser.
- **Pressure** also compresses water slightly at great depth.

Dense water sinks beneath lighter water, so the ocean arranges itself in stable layers.

Layer or feature	Where	What changes sharply
Mixed layer	The top tens to a couple of hundred metres	Stirred by wind and waves, so temperature and salinity are nearly uniform
Thermocline	Below the mixed layer, to about 1,000 m	Temperature falls rapidly with depth
Halocline	Where salinity changes rapidly	Salinity changes with depth
Pycnocline	Often coincides with the above	Density increases rapidly with depth, making a barrier to mixing
Deep water	Below the thermocline	Cold, dense and little changed

> **Why the layers matter**
>
> A strong pycnocline works like a lid. It stops warm surface water mixing with cold nutrient-rich water below, which is why parts of the tropical ocean are clear, blue and nearly lifeless, while places where deep water is brought up to the surface (Chapter 6) are green and full of fish. In the North Sea and around Scotland, the summer thermocline forms in spring and is broken up by autumn gales (check).

Light in the Sea

Water absorbs light, and it absorbs different colours at different rates. Red goes first, within the top ten metres or so; orange and yellow follow; blue and green penetrate deepest. This is why the open ocean looks blue, and why a diver's red equipment looks dull and grey at depth (check

the depths). The lit layer where photosynthesis is possible, the euphotic zone, reaches about 200 metres in the clearest water but only a few tens of metres in murky coastal water, where sediment and plankton scatter and absorb the light.

Sound in the Sea

Where light fails, sound carries. Sound travels at about 1,500 metres per second in seawater, about four to five times faster than in air (check). Speed rises with temperature, salinity and pressure, so it changes with depth: it falls through the warm upper layers, reaches a minimum at around a kilometre down, and then rises again with pressure (check). Sound waves bend toward the speed minimum and can become trapped in a channel there, a feature known as the SOFAR channel. Whales are thought to use such channels for long-distance calls, and the navy and scientists use them for listening and monitoring (check).

Watch the units

Older books give salinity in parts per thousand, newer ones in practical salinity units (which are unitless) or in grams per kilogram. For ordinary purposes the numbers are close enough: 35 means about 35 grams of salt per kilogram of seawater. Check which scale a source uses before comparing figures.

Exercises

EXERCISE 1

A kilogram of seawater has a salinity of 35 g/kg. How many grams of salt, and of chloride in particular (about 55 per cent of the salt), does it contain? How much salt remains if 1 kg of it is evaporated to dryness, ignoring losses?

→ Solution

EXERCISE 2

Two water samples: A is warm (25 degrees) with salinity 36; B is cold (5 degrees) with salinity 34. Which is denser, and what happens if A is poured gently onto B? Explain

which factor wins.

→ Solution

EXERCISE 3

A diver in clear tropical water holds a bright red object. Describe what colour it appears at 1 m, at 20 m and at 100 m, and explain why, using what you know about light absorption.

→ Solution

Quick Reference

- **Salinity:** about 35 g of dissolved salt per kg; open ocean range about 33 to 37
- **Constant proportions:** the main ions are always in the same ratio, so one measurement gives the salinity
- **Freezing point:** about minus 1.9 degrees; sea ice rejects salt
- **Density:** about 1,025 kg/m3; colder and saltier means denser
- **Layers:** mixed layer, thermocline, halocline, pycnocline, deep water
- **Light:** red absorbed first, blue and green deepest; euphotic zone up to about 200 m
- **Sound:** about 1,500 m/s; trapped in a deep channel
- **Check:** ion percentages, heat-store comparison, sound-speed profile

Coming next

Chapter 4 moves to the surface, where wind raises waves: how they are made, how they travel as swell, why they break on a beach, and what makes a tsunami different.

Oceanography Fundamentals

Course 1 · Chapter 4 · Waves: Wind, Swell, Surf and Tsunamis

On 1 January 1995 the Draupner oil platform in the North Sea, about 150 kilometres off the coast of Norway, recorded a single wave about 25.6 metres high in a sea whose typical waves were around 12 metres (check the figures). Sailors had told stories of such freak waves for centuries and scientists had dismissed many of them. The Draupner measurement was one of the first instrumental records, and it helped to turn "rogue waves" from a legend into a subject of research. This chapter explains what a wave is, how wind makes waves, how they travel across oceans as swell, why they break on a beach, and what makes a tsunami a different kind of wave altogether.

Anatomy of a Wave

A wave is a disturbance that moves through the water, not water that moves along. Float a cork and it bobs up and down, and in a circle, but ends up roughly where it began. Energy travels; the water mostly stays.

Term	Meaning
Crest and trough	The highest and lowest points of the wave
Wave height (H)	The vertical distance from trough to crest
Wavelength (L)	The horizontal distance from one crest to the next
Period (T)	The time for two successive crests to pass a fixed point
Speed (c)	How fast the pattern moves: wavelength divided by period
Steepness	Height divided by wavelength; a wave becomes unstable when it gets too steep

A simple rule for deep-water waves

For waves in water deeper than half their wavelength, the speed depends only on the period: roughly c = 1.56 x T metres per second, and the wavelength is roughly L = 1.56 x T x T metres (check the constant). A wave with a 10-second period is therefore about 156

metres long and travels at about 15.6 metres per second, or 56 kilometres per hour. Longer waves are faster.

How Wind Makes Waves

Wind blowing across water drags on it and makes ripples; the ripples give the wind more to push against, and they grow. Three things set the size of the waves:

- **Wind speed.** Stronger wind, bigger waves.
- **Duration.** How long the wind has been blowing.
- **Fetch.** The distance of open water over which the wind blows.

When all three are large enough the sea is said to be fully developed, and the waves cannot grow further for that wind speed. A gale across the small Firth of Forth can only make short, steep waves because the fetch is short, whereas the same gale in the open Atlantic makes far larger ones. The Beaufort scale, devised in the early 19th century, rates wind strength from 0 to 12 by its observed effect on the sea (check).

Sea

The choppy, irregular waves raised by the local wind. A mix of many sizes, short in wavelength and steep.

Swell

Waves that have left the storm that made them. They sort themselves by speed, becoming longer, smoother and more regular.

Why swell travels

Long waves lose energy very slowly. Swell from a storm near Newfoundland can reach Scotland, and Antarctic storm swell can cross the Pacific to California (check).

What Happens at the Shore

In deep water a water particle moves in a circle, and the circles shrink with depth until they vanish at about half a wavelength down. When a wave reaches water shallower than about half its wavelength, the bottom begins to drag on it.

1. The wave slows down, but its period stays the same.
2. Since speed falls, the wavelength shortens and the wave bunches up and grows taller.
3. The front slows more than the back, so the wave becomes steeper.
4. When the height reaches roughly three-quarters of the water depth, or the wave is too steep to be stable, the crest topples forward and the wave breaks (check the figure).

Breaker type	Typical beach	What it looks like
Spilling	Very gentle slope	White foam tumbling down the front, over a long distance
Plunging	Moderate slope	The crest curls over and crashes; the surfer's wave
Surging	Steep beach	The wave rises and slides up the beach without breaking fully

Waves also bend as they approach a coast, because the part in shallower water slows first. This refraction turns wave crests to line up with the shoreline and focuses energy on headlands, which is why headlands erode faster than bays.

Tsunamis

The word comes from Japanese and means "harbour wave". A tsunami is not made by wind but by a sudden displacement of a large volume of water: most often a large undersea earthquake at a subduction zone (Chapter 2), but also submarine landslides, volcanic eruptions and, rarely, meteorite impacts.

Property	Wind wave	Tsunami
Cause	Wind on the surface	Sudden movement of the seabed or a landslide
Wavelength	Tens to hundreds of metres	Often over a hundred kilometres

Property	Wind wave	Tsunami
Period	A few to about 20 seconds	Minutes to an hour
Open-ocean height	Metres	Often under a metre, barely noticeable at sea
Speed in the open ocean	Tens of kilometres per hour	Around 700 km/h in the deep Pacific
Water moved	Only the surface layer	The whole water column, to the bottom

Because a tsunami's wavelength is so much greater than the ocean's depth, it behaves as a shallow-water wave everywhere, and its speed is given by the square root of g times d, where g is 9.8 metres per second squared and d is the depth. In 4,000 metres of water that is about 200 metres per second, or 700 kilometres per hour. As it enters shallower water it slows and grows, building up in height and sometimes arriving as a rapidly rising tide or a bore rather than a breaking wave.

> **The 2004 Indian Ocean tsunami**
>
> On 26 December 2004 a magnitude 9.1 to 9.3 earthquake off Sumatra produced a tsunami that killed roughly 230,000 people in a dozen countries (check the figures). The waves took hours to reach Sri Lanka and India and there was no warning system in the Indian Ocean. Warning networks have since been built, on the model of the long-established Pacific system. The lesson for coastal communities is simple: a strong earthquake near the coast, or a sudden withdrawal of the sea, is the warning; move inland or uphill at once.

Rogue Waves

A rogue (or freak) wave is usually defined as one more than twice the significant wave height of the sea around it, where significant wave height is the average of the highest third of the waves (check). After the Draupner record, satellite surveys and later measurements showed they happen more often than the old statistics predicted. Several mechanisms are proposed: waves of different speeds briefly stacking up, waves running against a strong current such as the Agulhas

Current off South Africa, and nonlinear effects that focus energy (check). The subject is an active research area, so be careful of claims that it is settled.

Practical note

Rip currents, not big waves, cause most beach rescues. A rip is a narrow channel of water flowing out through the surf zone. If caught in one, swim parallel to the beach until free of it, then come in; do not try to swim straight back against it.

Exercises

EXERCISE 1

A swell arriving at a Scottish beach has a period of 14 seconds. Use the deep-water rules to find its wavelength and speed, and check that the water is deep enough for the rule to apply if the ocean is 3,000 m deep.

→ Solution

EXERCISE 2

A tsunami is generated in 4,000 m of water, 5,000 km from a coast. Use speed = square root of (9.8 x depth) to estimate its speed and its travel time in hours. Then find its speed in 10 m of water near the shore.

→ Solution

EXERCISE 3

In four or five sentences, explain why a wave grows taller and finally breaks as it approaches a gently sloping beach, using the words period, speed, wavelength and depth.

→ Solution

Quick Reference

- **Wave terms:** height, wavelength, period, speed, steepness
- **Deep water:** speed about 1.56 x T m/s; wavelength about 1.56 x T x T m
- **Growth:** wind speed, duration and fetch
- **Sea and swell:** local choppy waves versus long, regular waves from distant storms
- **Breaking:** shoaling slows and steepens a wave; spilling, plunging, surging
- **Tsunami:** speed = square root of (g x depth); wavelength of 100 km or more; whole column moves
- **Rogue wave:** more than twice the significant wave height
- **Check:** Draupner figures, 2004 toll, breaking criterion

Coming next

Chapter 5 turns to the slower rise and fall of the sea itself: the tides, what the Moon and Sun do, why there are two a day, spring and neap tides, and why the range is so different from place to place.

Oceanography Fundamentals

Course 1 · Chapter 5 · Tides: Moon, Sun and Shape of the Sea

Visit the Bay of Fundy in eastern Canada at low tide and you can walk on the sea floor among boats resting on mud; six hours later the same place may be under more than ten metres of water (check). Visit the Mediterranean and you may not notice the tide at all. In 1687 Isaac Newton explained the basic cause in his Principia: the pull of the Moon (and, to a lesser extent, the Sun). But it took another two centuries to understand why the tides differ so much from place to place, and the full story still depends on computer models. This chapter explains the cause, the rhythm and the local variation, with plenty of examples from the British coast.

The Moon and the Bulges

Gravity weakens with distance. The Moon pulls most strongly on the side of Earth nearest to it, less on the centre, and least on the far side. The difference in pull across Earth is called the **tide-raising force**. It stretches the ocean into two bulges: one facing the Moon, and one on the opposite side (check the usual explanation below).

Near side

The water is pulled toward the Moon more than the Earth's centre is, so it piles up beneath the Moon.

Far side

The water is pulled less than the Earth's centre, so it is effectively left behind, making a second bulge.

Result

Earth turns under two bulges, so most places have two high tides and two low tides each day.

A common misunderstanding

Many explanations say the far-side bulge is caused by "centrifugal force". The more careful explanation is the one above: the difference in the Moon's gravity across the Earth,

measured relative to the Earth's centre, gives two bulges. Check how any source phrases it before accepting it.

Why 12 Hours 25 Minutes?

While Earth turns once in 24 hours, the Moon moves on in its orbit, so a place has to turn about 50 minutes further each day to face the Moon again. The lunar day is therefore about 24 hours 50 minutes, and the gap between successive high tides is half of that: about 12 hours 25 minutes. So tide times slide later by about 50 minutes each day, and a high tide at breakfast today becomes a high tide at about ten to seven the next morning, and so on.

Spring and Neap Tides

The Sun also raises tides, though its pull is about 46 per cent of the Moon's, since it is so much farther away (check). The two combine.

Moon phase	Sun, Earth and Moon	Tide
New Moon	In a line, Moon between Earth and Sun	Spring tide: highest highs and lowest lows
First quarter	At right angles	Neap tide: smallest range
Full Moon	In a line, Earth between Sun and Moon	Spring tide
Last quarter	At right angles	Neap tide

Springs have nothing to do with the season: the name comes from the idea of the water "springing up". The cycle repeats about every 14.8 days. Tides are larger still when a new or full Moon coincides with the Moon's closest approach to Earth, sometimes called a perigean spring tide, and combined with a storm surge these cause most coastal flooding (check).

Why the Range Varies So Much

Newton's picture predicts a rise of well under a metre in the open ocean. Real tides in some places are many times higher, because the ocean basins are not smooth: they have shapes of

their own.

Place	Approximate maximum range	Why
Bay of Fundy, Canada	About 16 m	The bay's length matches the tidal rhythm, so it resonates, like a child pushed on a swing at the right moment (check)
Severn Estuary, UK	About 14 m	A funnel-shaped estuary that squeezes the incoming tide
Firth of Forth at Leith	About 5 m on spring tides	The North Sea tide wave enters from the north and is amplified a little in the funnel of the firth (check)
Mediterranean	Often under 1 m	Almost enclosed; little tidal water can enter from the Atlantic
Open mid-ocean	Under 1 m	No coast to pile up against

Tides are waves, not bulges

The tide in a real ocean is better described as a very long wave, with a wavelength of thousands of kilometres, that is pushed along by the Moon and Sun and reflected by the coasts. Because Earth is rotating, the Coriolis effect (Chapter 6) bends the wave, and it circulates around the basin instead of simply sloshing from side to side. In the middle of each circulation pattern there is a point where the tidal range is nearly zero, an *amphidromic point*. The North Sea has a few of them (check the number), and that is why the tidal range on the east coast of England and Scotland is much greater than at the centre of the North Sea.

Types of Tide

- **Semi-diurnal.** Two highs and two lows of similar size each day. This is the usual pattern around the British Isles and the North Atlantic.
- **Diurnal.** One high and one low a day, as in parts of the Gulf of Mexico (check).
- **Mixed.** Two highs and lows of clearly different heights, as on much of the US Pacific coast.

The pattern comes from the shape of the basin and the Moon's changing position north or south of the equator.

Tidal Currents and Uses

As the water rises and falls, it also flows. These tidal currents can be fast in narrow channels: the Corryvreckan whirlpool, between two Scottish islands, is one of the best known (check). Tidal streams are predictable, which is attractive for energy, and the Pentland Firth and the Orkney waters host turbines and test sites. A tidal estuary can also produce a *bore*, a wave that runs up the river against the flow, such as on the Severn (check).

Reading a tide table

A tide table gives the time and height of each high and low water for a port. Heights are measured above chart datum, the lowest level that the tide is expected to reach, so the height of water over a rock on a chart is normally a safe minimum. The tables are computed from a sum of many known cycles (check), not from a theory of the day's weather, but a strong onshore wind or low pressure can make the real sea level differ by a metre or more.

Exercises

EXERCISE 1

High water at a harbour is at 06:00 on Monday. Using a 12 h 25 min interval, estimate the times of the next three high waters, and the time of the morning high water on Tuesday.

→ Solution

EXERCISE 2

For each of these, say whether you would expect spring or neap tides: (a) the night of the full Moon; (b) the day of the first-quarter Moon; (c) a new Moon. Explain why in a sentence for each.

→ Solution

EXERCISE 3

Why is the tidal range in the Bay of Fundy so much larger than at a small island in the mid-Atlantic? Give at least two reasons, using the terms resonance and funnel.

→ Solution

Quick Reference

- **Cause:** the difference in the Moon's (and Sun's) gravity across the Earth gives two bulges
- **Timing:** lunar day 24 h 50 min; successive highs about 12 h 25 min apart
- **Springs:** new and full Moon, Sun and Moon aligned; largest range
- **Neaps:** quarter Moons, forces at right angles; smallest range
- **Local range:** controlled by basin shape: resonance, funnelling, enclosure
- **Amphidromic point:** where the tide wave circulates around a point of almost no range
- **Types:** semi-diurnal, diurnal, mixed
- **Check:** Fundy range, Sun/Moon ratio, number of North Sea points

Coming next

Chapter 6 looks at the ocean's great rivers: the wind-driven surface currents and gyres, the Gulf Stream that keeps Scotland milder than Labrador, and the upwelling that feeds the world's richest fisheries.

Oceanography Fundamentals

Course 1 · Chapter 6 · Surface Currents: Gyres and Upwelling

In the 1760s Benjamin Franklin, then deputy postmaster for the American colonies, was puzzled that mail packets from England took about two weeks longer to reach Rhode Island than merchant ships did. A Nantucket whaling captain, Timothy Folger, told him why: the merchant captains knew of a strong current in the Atlantic and avoided sailing against it. Franklin had Folger sketch its course, and the chart was printed around 1770 (check the dates). It is the first well-known map of what we now call the Gulf Stream. This chapter explains what drives the great surface currents, why they circle the ocean basins, and what happens where they meet the coast.

What Drives Surface Currents

The winds that blow steadily over the ocean (the trade winds in the tropics, the westerlies in mid-latitudes) drag on the surface and set the top few hundred metres moving. Three other things shape the result:

- **The continents,** which block the water and turn it.
- **The Coriolis effect,** from Earth's rotation.
- **Differences in density,** which add slower movements below the surface (Chapter 7).

> **The Coriolis effect, briefly**
>
> Earth turns, so a moving object is seen from the rotating surface to be deflected: to the right in the northern hemisphere and to the left in the southern (check). The effect is zero at the equator and strongest at the poles. It is far too weak to matter in a bath or a sink, but over the distances and times of ocean currents it is decisive. It also bends the tide wave around the amphidromic points of Chapter 5.

Ekman Transport: Why Water Does Not Follow the Wind

The Norwegian explorer Fridtjof Nansen noticed, during his drift in the ship Fram in the Arctic in the 1890s, that the pack ice moved not with the wind but at an angle of 20 to 40 degrees to the

right of it (check). He asked a young Swedish physicist, Vagn Walfrid Ekman, to explain it, and Ekman worked out the answer in 1902 (check).

1. The wind drags the top layer, which is deflected a little to the right (northern hemisphere).
2. That layer drags the one below, which is deflected further, and so on.
3. Each layer moves more slowly and further to the right than the one above, making a spiral with depth (the Ekman spiral).
4. Adding up all the layers, the net movement of the water is about 90 degrees to the right of the wind in the northern hemisphere, and 90 degrees to the left in the southern.

Real oceans only approximate the ideal spiral, but the 90-degree net transport is a good rule of thumb for the upper layer (check).

The Gyres

Put these ingredients together and the water in each major ocean basin circulates in a great loop called a **gyre**. The subtropical gyres are the largest.

Northern hemisphere

Gyres turn clockwise. In the North Atlantic: the Gulf Stream and North Atlantic Drift on the west and north, the Canary Current on the east, and the North Equatorial Current on the south.

Southern hemisphere

Gyres turn anticlockwise. Examples are the South Pacific gyre, with the Humboldt (Peru) Current on its east side, and the South Atlantic gyre with the Benguela Current.

The Southern Ocean

The Antarctic Circumpolar Current flows eastward all round Antarctica, with no land in the way. It is the largest current in the world, carrying over a hundred times the flow of all the rivers on Earth (check).

Current	Ocean	Type	Note
Gulf Stream	North Atlantic	Warm, western boundary	Narrow, fast, up to roughly 100 km wide; flows north-east from Florida (check)
North Atlantic Drift	North Atlantic	Warm	The slower, broader extension toward north-west Europe
Canary Current	North Atlantic	Cool, eastern boundary	Flows south along north-west Africa; strong upwelling
Kuroshio	North Pacific	Warm, western boundary	The Pacific equivalent of the Gulf Stream
Humboldt (Peru)	South Pacific	Cool, eastern boundary	Feeds one of the world's richest fisheries
Antarctic Circumpolar	Southern Ocean	Wind and density driven	Eastward all the way round

Fast on the West, Slow on the East

The gyres are lopsided. The currents on the western edge of each ocean (the Gulf Stream, the Kuroshio) are narrow, deep, fast and warm. The ones on the eastern edge (the Canary, the California, the Humboldt) are wide, shallow, slow and cool. This *western intensification* was explained by the American oceanographer Henry Stommel in 1948, as a result of how the Coriolis effect changes with latitude (check). Oceanographers measure the flow of water in sverdrups (Sv), where 1 Sv is a million cubic metres per second. The Gulf Stream carries about 30 Sv through the Straits of Florida and more after it is joined by other water, while all the world's rivers together carry only about 1 Sv (check).

> **The Gulf Stream and Scotland: how much credit?**
>
> It is often said that the Gulf Stream makes Britain several degrees warmer than Labrador at the same latitude. The Gulf Stream and North Atlantic Drift do carry heat north, but studies suggest that the prevailing westerly winds, which carry the Atlantic's mild air over Europe, and the shape of the continents also play a big part (check). The honest answer is that the ocean as a whole, not one current, is responsible. Be wary of statements that the

Gulf Stream "will switch off" and bring an Arctic winter; the real concern is a possible slowdown of the deeper circulation, covered in Chapter 7 and Chapter 8.

Upwelling: Bringing Up the Deep

Surface water can be moved away by the wind, and deeper water rises to replace it. This is **upwelling**. The deep water is cold and rich in nutrients (nitrate, phosphate), which sinking material has carried down; when it reaches sunlit water, it feeds plankton in large numbers, and so the whole food web above it.

- **Coastal upwelling.** Wind blowing along a coast with the coast on its left in the northern hemisphere (equatorward on a western continental coast, such as California) gives Ekman transport away from the shore, and cold water rises to fill the gap. The same happens off Peru, north-west Africa, Namibia and Iberia.
- **Equatorial upwelling.** The trade winds on each side of the equator drive surface water poleward in both hemispheres, leaving a gap on the equator that is filled from below.
- **Southern Ocean upwelling.** Strong westerlies drive a transport that lifts deep water near Antarctica.

Upwelling regions cover a small part of the ocean but are credited with a very large share of the world's fish catch, with figures of around a fifth often quoted (check). The Peruvian anchoveta fishery, supported by the Humboldt upwelling, is the largest single-species fishery in the world (check) and collapses when the upwelling fails in El Niño years (Chapter 8).

Currents carry things

The gyres also collect floating objects. In 1992 a container ship lost a cargo of plastic bath toys in the Pacific, and some were found years later on distant shores, helping oceanographers test their models of surface drift (check the details). Floating plastic gathers in the centres of the subtropical gyres, in areas popularly called garbage patches. They are not solid islands but dilute zones of fragments, and the reality is less visible than the name suggests.

Exercises

EXERCISE 1

A river flows at 20,000 cubic metres per second. Express this in sverdrups, then work out how many such rivers it would take to equal a current of 30 Sv.

→ Solution

EXERCISE 2

In the northern hemisphere, a steady wind blows from the south toward the north across the open ocean. In which compass direction is the net Ekman transport of the surface layer? Repeat for the southern hemisphere.

→ Solution

EXERCISE 3

Explain, in a short paragraph, why a northerly wind blowing south along the California coast brings cold, nutrient-rich water to the surface and boosts the plankton.

→ Solution

Quick Reference

- **Drivers:** wind, Coriolis effect, continents
- **Coriolis:** deflection to the right in the north and the left in the south; zero at the equator
- **Ekman transport:** net surface movement about 90 degrees to the right (north) or left (south) of the wind
- **Gyres:** clockwise in the north, anticlockwise in the south
- **Boundaries:** western currents narrow, fast, warm; eastern currents wide, slow, cool
- **Units:** 1 Sverdrup = 1 million cubic metres per second
- **Upwelling:** deep, cold, nutrient-rich water rises where the wind moves surface water away

- **Check:** Franklin chart date, Gulf Stream width and flow, share of fish catch

Coming next

Chapter 7 descends below the wind-driven layer to the slow circulation of the deep ocean: how cold, salty water sinks near the poles and spreads through the basins over centuries, and what that means for climate.

Oceanography Fundamentals

Course 1 · Chapter 7 · Deep Circulation: The Slow Conveyor

In the 1980s the geochemist Wallace Broecker of Columbia University popularised a striking picture: a single "great conveyor belt" of water, sinking in the North Atlantic, creeping along the bottom of the ocean through the Atlantic, Indian and Pacific basins, and returning to the surface to flow back (check the date and the wording). The picture was a simplification, and Broecker himself said so, but it fixed in people's minds a real and important fact: the deep ocean is not still. It moves, very slowly, and it carries heat, carbon dioxide and oxygen with it. This chapter explains why the deep water moves, where it sinks, how long it takes, and why oceanographers watch it so closely.

A Different Kind of Current

Surface currents are pushed by the wind (Chapter 6). Deep currents are mainly driven by differences in density. Because density depends on temperature and salinity (Chapter 3), this is often called **thermohaline circulation** (from Greek words for heat and salt). Many scientists now prefer the term **meridional overturning circulation**, because wind and tides also contribute to the mixing that keeps the system running, and "overturning" describes what the water does: sinks in some places and rises in others (check).

Property	Surface currents	Deep circulation
Main driver	Wind	Density differences (cooling, evaporation, ice formation), plus mixing
Speed	Up to metres per second in the Gulf Stream	Typically millimetres to centimetres per second
Depth	Top few hundred metres	Thousands of metres
Time to cross an ocean	Months to years	Decades to centuries

Where Water Sinks

Water sinks when it becomes denser than what lies beneath it. This happens in only a few places, where surface water is made very cold and salty enough.

North Atlantic

Warm, salty water carried north by the Gulf Stream and North Atlantic Drift loses heat to the cold air of the Labrador, Greenland and Norwegian Seas. It becomes dense and sinks, forming North Atlantic Deep Water.

Antarctica

Around the edge of Antarctica, particularly in the Weddell and Ross Seas, freezing sea ice rejects salt (Chapter 3), leaving cold, very salty water that sinks down the continental slope. This is Antarctic Bottom Water, the densest water in the open ocean (check).

Why not the North Pacific?

The surface water there is fresher, so it is not dense enough to sink to great depth. The difference in salinity between Atlantic and Pacific is a key reason the conveyor is Atlantic-led (check).

Water Masses

As water sinks, it keeps the temperature and salinity it had at the surface, like a label. Oceanographers use these labels to trace the water as it spreads and to name it as a *water mass*.

Water mass	Where it forms	Where it sits
Antarctic Bottom Water	Antarctic shelf seas	Right on the bottom, spreading north into all three oceans
North Atlantic Deep Water	Labrador and Nordic seas	Above Antarctic Bottom Water, spreading south through the Atlantic
Antarctic Intermediate Water	Southern Ocean	Around 1,000 m, spreading north
Mediterranean outflow	Mediterranean, which is saltier than the Atlantic	A salty tongue at about 1,000 m, flowing out of the Strait of Gibraltar

The Loop, and How Long It Takes

1. Warm surface water flows north in the Atlantic, giving up heat to the air on the way (this is part of why north-west Europe is mild).
2. In the far north it sinks and flows south in the deep Atlantic.
3. Around Antarctica it joins the circumpolar current and meets the Antarctic Bottom Water.
4. Both spread north into the Indian and Pacific basins, where they slowly mix upward and warm.
5. Over a very long time they return to the surface, and a return flow carries the water back to the Atlantic.

The full circuit takes of the order of a thousand years (check; estimates range from several hundred to more than a thousand). Evidence comes from radiocarbon dating of dissolved carbon: water that sank long ago has lost carbon-14 by radioactive decay, and the oldest water, in the deep North Pacific, is of the order of 1,000 years since it last touched the atmosphere (check).

Measuring a current you cannot see

Since 2004 a line of moored instruments, the RAPID array, has stretched across the Atlantic at about 26.5 degrees north, from the Canary Islands to the Bahamas, measuring the northward and southward flows (check). It finds an overturning of roughly 17 sverdrups, with large variations from year to year (check). The record is still short compared with the timescales involved, which is why scientists are cautious about claiming a trend.

Why It Matters

- **Heat.** The Atlantic overturning carries heat from the tropics towards the north, helping to keep north-west Europe mild (but see the caution in Chapter 6).
- **Carbon.** Sinking water carries dissolved carbon dioxide into the deep, where it can stay for centuries. The deep ocean is by far the largest active store of carbon near the surface of the planet (check).
- **Oxygen.** Cold water holds a lot of oxygen; as it sinks it delivers oxygen to the deep, called ventilation, and without it deep water would run short of oxygen.

- **Nutrients.** Old deep water collects nutrients from sinking debris and brings them back to the surface in upwelling regions (Chapter 6).

Could the conveyor stop?

There is evidence that it has changed abruptly in the past. One idea is that a flood of meltwater into the North Atlantic about 12,900 years ago made the surface water too fresh to sink and triggered a cold snap called the Younger Dryas (check; the cause is still debated). Climate assessments say that the Atlantic overturning is very likely to weaken during this century as the climate warms, with an abrupt collapse before 2100 considered unlikely, though with low confidence (check the latest report). Disaster films exaggerate, but the question is a serious one, and it is good practice to read the actual assessment wording rather than a headline.

Try it yourself

A kitchen experiment shows the principle. Fill a clear tank with water, add food colouring to a bowl of very salty water and pour it slowly down the side: the dyed salty water sinks and creeps along the bottom. Add a little ice to one end and warm water to the other, and the fluid starts to circulate. The ocean does the same, on a scale of thousands of kilometres.

Exercises

EXERCISE 1

The ocean has a volume of about 1.3 x 10^18 cubic metres (1.3 billion cubic kilometres). If the overturning moves 17 Sv (17 x 10^6 m3/s), estimate how many years it would take to move a volume equal to the whole ocean. Does the answer fit the thousand-year timescale in the chapter?

→ Solution

EXERCISE 2

Explain why the formation of sea ice around Antarctica makes the water below it denser. Then say what you would expect to happen to the density if the same area received a large flow of meltwater from glaciers.

→ Solution

EXERCISE 3

A ship takes a water sample from the deep North Pacific and from the deep North Atlantic. Which should have the older radiocarbon age, and why? What does this tell you about the direction of the deep flow?

→ Solution

Quick Reference

- **Driver:** density differences from temperature and salinity (thermohaline), plus mixing by wind and tides
- **Sinking regions:** the North Atlantic and the Antarctic margins
- **Water masses:** Antarctic Bottom Water (densest), North Atlantic Deep Water, intermediate waters
- **Timescale:** decades to centuries to cross a basin; of the order of 1,000 years for the whole loop
- **Evidence:** temperature and salinity labels, radiocarbon ages, moored arrays
- **Roles:** heat transport, carbon storage, oxygen supply, nutrient return
- **Uncertainty:** weakening this century is likely; an abrupt collapse is considered unlikely (check)
- **Check:** Broecker date, RAPID figures, Younger Dryas explanation

Coming next

Chapter 8 puts the ocean in the climate system: how it stores heat and carbon, the El Nino cycle in the Pacific, rising sea level, and the acidification and deoxygenation that follow

from human emissions.

Oceanography Fundamentals

Course 1 · Chapter 8 · The Ocean and Climate: Heat, Carbon and El Nino

Every few years, around Christmas, the cool, fish-rich water off the coast of Peru turns warm, the anchovy catch fails and the rains come to the desert. Peruvian fishermen named the event El Nino, "the Child", for the Christ child (check). In the 1960s the Norwegian-American meteorologist Jacob Bjerknes showed that it was not a local oddity but one half of a vast pattern linking the whole tropical Pacific Ocean to the atmosphere above it (check). The ocean and the air are one system, and the ocean is the slower, heavier partner. This chapter looks at what that partnership means: the ocean as a store of heat and carbon, the best-known natural swing in the system, and the changes now being measured.

The Ocean as Heat Store

Because water holds so much heat for its mass (Chapter 3) and the ocean is so large, it has taken up most of the extra heat trapped by greenhouse gases. The Intergovernmental Panel on Climate Change reported that the ocean absorbed about 91 per cent of the excess heat gained by the climate system between 1971 and 2018, with the atmosphere taking only a few per cent (check). Measurements come from a global fleet of about 4,000 profiling floats, called Argo, that drift at depth, rise to the surface every ten days and radio back the temperature and salinity (check).

Why it matters

The ocean slows surface warming by soaking up heat, but the heat does not go away; it will continue to be released and to expand the water for centuries.

Marine heatwaves

Spells of unusually warm water, lasting days to months, damage kelp forests, coral reefs and fisheries. They have become more frequent and longer in recent decades (check).

Storm fuel

Warmer surface water gives more energy and moisture to tropical cyclones. The link to

the strength of storms is clearer than the link to their number (check).

El Nino and La Nina

In normal conditions the trade winds blow from east to west across the tropical Pacific. They pile up warm surface water in the west, near Indonesia, and allow cold water to upwell off South America (Chapter 6). The warm west has heavy rain; the cool east is dry.

Phase	Winds	Sea surface	Typical effects
Neutral	Trade winds strong	Warm west, cool east	Upwelling off Peru; rain in Indonesia
El Nino	Trade winds weaken	Warm water spreads east; upwelling shuts down	Fisheries fail off Peru; floods in Peru and Ecuador; drought in Indonesia and Australia; warmer global average year
La Nina	Trade winds strengthen	East gets cooler than normal	The reverse; often a slightly cooler global average year

The oscillation is irregular, returning every two to seven years, and peaks late in the year (check). It is known as the El Nino-Southern Oscillation, or ENSO, because the sea-surface changes go hand in hand with a seesaw in air pressure between the eastern and western Pacific, which the British scientist Gilbert Walker recognised in the 1920s (check). The effects reach far beyond the Pacific, changing rainfall in places as distant as southern Africa and North America. They reach the UK only weakly and unreliably, so be wary of claims that a particular winter in Scotland was "because of El Nino" (check).

Carbon and Acidification

The ocean also takes up carbon dioxide from the air. It has absorbed about a quarter to a third of the CO2 that humans have emitted (check). That slows the rise of the gas in the atmosphere, but it changes the chemistry of the sea.

1. CO2 dissolves in seawater and reacts with the water to form carbonic acid.

2. The acid releases hydrogen ions, which lower the pH.
3. The extra hydrogen ions react with carbonate ions, so fewer are left for animals that build shells and skeletons of calcium carbonate: corals, oysters, mussels and some plankton.

What the numbers say

The average pH of the surface ocean has fallen from about 8.2 before the industrial era to about 8.1 today (check). That looks small, but the pH scale is logarithmic: a fall of 0.1 means about a 26 per cent rise in hydrogen-ion concentration. The ocean remains slightly alkaline, so "acidification" means moving towards neutral, not becoming acid. Cold polar waters, which dissolve more CO2, are affected first (check).

Sea-Level Rise

Global mean sea level has risen by about 20 centimetres since 1900 (check), and the rate has increased, to about 3.7 millimetres a year in 2006 to 2018 and higher in the most recent years (check). There are two main causes:

- **Thermal expansion.** Warmer water takes up more room.
- **Melting land ice.** Glaciers and the Greenland and Antarctic ice sheets add water to the ocean. Melting sea ice that is already floating does not raise the level.

Local sea level also depends on the land itself. In Scotland the land is still rising after the weight of the ice sheets was removed at the end of the last ice age, a process called glacial isostatic adjustment, so the relative rise there has been smaller than in southern England, where the land is sinking slightly (check). Sea level also varies with the tides, currents and storm surges (Chapters 5 and 6), so a hundred years of record are needed to see the trend.

Losing Oxygen

Warm water holds less dissolved oxygen than cold water, and warming strengthens the layering that stops oxygen-rich surface water from mixing downward (Chapter 3). Studies suggest that the ocean has lost about 2 per cent of its oxygen since the 1960s (check), and that low-oxygen zones off the coasts of west Africa and the Americas are expanding. Fish and other animals avoid or die in water that is too low in oxygen, so the losses add pressure on top of warming and acidification.

Reading the claims

Ocean climate stories mix three kinds of statement: measured changes (Argo temperature, tide-gauge sea level), model projections (sea level by 2100) and speculation (tipping points). Treat them differently. Ask whether a figure is an observation or a projection, over what period, and for which region, and look for the original assessment (the IPCC report, national agencies) rather than a summary. Ranges and probabilities in the text are not hedging; they are the result.

Putting the pieces together

Chapters 3, 6 and 7 gave you the tools: heat capacity, upwelling and the overturning circulation. Almost every ocean-climate story is a combination of them: heat taken in at the surface, stirred downward, carried by currents, and released again somewhere else, years or centuries later.

Exercises

EXERCISE 1

The pH of the surface ocean fell by 0.1 units. Use the fact that pH is minus the base-10 logarithm of the hydrogen-ion concentration to calculate the percentage increase in that concentration.

→ Solution

EXERCISE 2

Describe what happens to the trade winds, the sea surface temperature in the eastern Pacific and the fishery off Peru during an El Nino. Then say which of these reverses in a La Nina.

→ Solution

EXERCISE 3

If sea level rises by 3.7 mm a year for 30 years, how far does it rise? What if the rate climbs to 4.5 mm a year? Explain why a steady rate is not a good assumption for planning, using the two causes in the chapter.

→ Solution

Quick Reference

- **Heat:** the ocean took up about 91 per cent of the excess heat (1971 to 2018); measured by Argo floats
- **ENSO:** weak trade winds and warm eastern Pacific (El Nino); strong winds and cool east (La Nina); every 2 to 7 years
- **Carbon:** the ocean absorbs roughly a quarter to a third of human CO2
- **pH:** down from about 8.2 to 8.1, about a 26 per cent rise in hydrogen ions
- **Sea level:** about 20 cm since 1900; thermal expansion plus land-ice melt
- **Oxygen:** about 2 per cent lost since the 1960s; warm water holds less
- **Reading claims:** observation, projection or speculation?
- **Check:** IPCC figures, rates, oxygen loss, ENSO period

Coming next

Chapter 9 turns to the living ocean: plankton at the base of the food web, how energy passes up to fish and whales, the strange communities of the deep, and the pressures of fishing.

Oceanography Fundamentals

Course 1 · Chapter 9 · Life in the Sea: Plankton, Vents and Fisheries

In February 1977 the research submersible Alvin dived to the Galapagos Rift, about 2,500 metres down, looking for hot water coming out of the seafloor. The geologists on board found it, and also something nobody had predicted: dense communities of giant tube worms, clams and crabs living in total darkness around the vents (check the details). There was no sunlight to feed them. The discovery overturned the assumption that all life depends on the Sun and showed that the deep sea holds whole ecosystems we had never imagined. This chapter surveys the living ocean, starting with its smallest and most important inhabitants, and ending with what humans take from it.

The Base of the Food Web: Plankton

Plankton are organisms that drift with the water rather than swimming against it. The word comes from Greek, meaning "wandering".

Phytoplankton

Microscopic plants and bacteria that photosynthesise: diatoms (with glassy shells), dinoflagellates and cyanobacteria. They live in the sunlit top 100 metres or so. Together they do roughly half of all the photosynthesis on Earth (check).

Zooplankton

Small animals that graze on phytoplankton, including copepods (the most numerous animals on the planet, by some counts), krill and the larvae of fish and crabs.

Bacteria and viruses

They recycle dead material and dissolved matter, and are far more numerous than anything else. One tiny cyanobacterium, *Prochlorococcus*, discovered in the 1980s, is probably the most abundant photosynthetic organism on Earth (check).

Why upwelling zones are rich

Phytoplankton need light and nutrients. In the tropical open ocean, strong layering (Chapter 3) keeps nutrients locked in the deep water, so the surface is clear and nearly barren. Where nutrients are brought up by upwelling (Chapter 6), or by the spring mixing of cold temperate seas such as the North Sea, the plankton bloom and the food web above them flourishes. A spring bloom is large enough to be seen from space as swirls of green and turquoise.

Passing Energy Up the Chain

Energy moves up the food web from plankton to small fish to larger fish, seabirds, seals and whales. At each step most of it is lost as heat or used for the animal's own life, and only a fraction, often taken as about 10 per cent as a rule of thumb, is stored in the tissues that the next animal eats (check). The practical result is that long food chains support far fewer animals at the top than at the bottom.

Level	Example	Rough energy available
Producers	Phytoplankton	100 per cent
Primary consumers	Copepods, krill	About 10 per cent
Secondary consumers	Herring, sandeel, anchovy	About 1 per cent
Tertiary consumers	Cod, seabirds, seals	About 0.1 per cent
Top predators	Sharks, orcas, tuna	About 0.01 per cent

The shortest food chains are the most productive. The baleen whales, including the blue whale, the largest animal known, feed directly on krill and other small organisms near the base of the web, which is why a very large animal can live on a small step in the chain (check). The great Peruvian anchoveta fishery (Chapter 6) works for the same reason.

The Largest Migration on Earth

Every night, in all the oceans, a vast number of animals rise from the twilight zone (200 to 1,000 metres) toward the surface to feed in the safety of the dark, and sink back at dawn. This daily vertical migration of zooplankton, shrimp and small fish is the largest movement of animals on the planet by weight (check). Early naval sonar operators found it puzzling: they recorded a false seabed that rose and fell with the day, which was later called the deep scattering layer. The migration also moves carbon: animals feed at the surface, then excrete at depth, carrying carbon out of the atmosphere's reach (check).

Life Without Sunlight

Below about 1,000 metres there is no sunlight, and food comes from above. Much of it is "marine snow", a continual drift of dead plankton, faecal pellets and other debris, and the occasional larger fall: a dead whale can feed a community of specialised animals for decades (check).

- **Hydrothermal vents.** Along the mid-ocean ridges (Chapter 2) seawater seeps into the hot crust, picks up dissolved minerals and returns as hot fluid, sometimes above 350 degrees Celsius (check). Bacteria use the chemical energy of hydrogen sulphide in this fluid to make food, a process called **chemosynthesis**. The tube worms, clams and shrimp at vents depend on those bacteria, often living with them inside their tissues.
- **Cold seeps.** Slow leaks of methane and other chemicals from the seabed support similar communities.
- **Animals of the dark.** Many deep animals make their own light (bioluminescence), have huge eyes or none at all, and eat rarely. Bioluminescence is so common in the water column that most animals there are thought to produce it (check).

Feature	Photosynthesis	Chemosynthesis
Energy source	Sunlight	Chemical energy (e.g. hydrogen sulphide, methane)
Where	Sunlit upper ocean	Vents and seeps in the dark
Main organisms	Phytoplankton, seaweeds	Bacteria and archaea, partners of tube worms and mussels

Feature	Photosynthesis	Chemosynthesis
Share of ocean production	The great majority	Small, but vital locally

Coastal Habitats

Near the coast, the sea floor itself supports habitats that are small in area but rich in life.

- **Coral reefs.** They cover well under one per cent of the ocean floor yet are home to about a quarter of marine species (check). Warm-water corals live in partnership with algae inside their tissues, which makes them very sensitive to heat (Chapter 8): in a marine heatwave the corals expel their algae and turn white, a process called bleaching.
- **Kelp forests.** Large brown seaweeds in cool rocky seas, including those off Scotland, shelter fish, urchins and otters.
- **Seagrass meadows and mangroves.** Nursery areas for fish, and stores of carbon in their sediments.
- **Salt marshes and estuaries.** The Forth and the Wash are among the British estuaries that host huge numbers of migrating birds.

Fishing

Marine fisheries provide a significant share of the animal protein for billions of people. The United Nations Food and Agriculture Organization (FAO) classifies assessed stocks as underfished, fished at a maximum sustainable level, or overfished. In its recent reports about a third of assessed stocks were overfished, but because the fish that make up the largest catches are generally managed better than the rest, a larger share of the total catch comes from sustainably fished stocks (check the latest report).

> **A cautionary tale**
>
> The Atlantic cod fishery off Newfoundland supported fleets for centuries, but the stock collapsed in the early 1990s and a moratorium was declared in 1992, putting tens of thousands of people out of work (check). The cod have recovered only slowly, in part

because the removal of a top predator changed the food web. Collapses like this are the reason for catch limits, closed areas and gear rules, which are the subject of Chapter 10.

Exercises

EXERCISE 1

Using the 10 per cent rule, how many kilograms of phytoplankton are needed to produce 1 kg of a top predator, if the chain is phytoplankton, zooplankton, small fish, large fish, top predator? How many are needed if the chain has only three steps (phytoplankton, krill, whale)?

→ Solution

EXERCISE 2

Compare photosynthesis and chemosynthesis in a short table or in a few sentences. Why can a community at a hydrothermal vent live in the dark, and why is it still indirectly dependent on the ocean's chemistry rather than on the Sun?

→ Solution

EXERCISE 3

A fish stock is assessed at 100,000 tonnes and the fishery takes 30,000 tonnes a year, while the stock grows by only 10,000 tonnes a year. Describe what will happen over a few years and what two simple measures could stop it.

→ Solution

Quick Reference

- **Plankton:** phytoplankton (producers) and zooplankton (grazers); about half of Earth's photosynthesis

- **Food web:** about 10 per cent of energy passes up each step; short chains are productive
- **Migration:** nightly rise from the twilight zone, the largest animal movement by biomass
- **Chemosynthesis:** bacteria use chemicals from vents and seeps to build food in the dark
- **Reefs:** under 1 per cent of the sea floor, about a quarter of marine species
- **Fisheries:** assessed as underfished, maximally sustainable or overfished
- **Case study:** collapse of the Newfoundland cod, 1992
- **Check:** photosynthesis share, 10 per cent rule, reef share, FAO figures

Coming next

Chapter 10 is the capstone: how we explore and monitor the ocean (ships, floats, satellites, robots), what is threatening it, how it is protected, and how to read ocean stories critically.

Oceanography Fundamentals

Course 1 · Chapter 10 · Capstone: Exploring and Protecting the Ocean

On 23 January 1960 the bathyscaphe Trieste, carrying the Swiss engineer Jacques Piccard and US Navy lieutenant Don Walsh, reached the bottom of the Challenger Deep, close to 11,000 metres down (check). They stayed about twenty minutes, saw what they thought was a flatfish on the bottom (a claim since doubted) and came back up. Then nobody went again for over fifty years, until the film director James Cameron's solo dive in 2012 and the 2019 dives by Victor Vescovo (check the dates). Most of what we have learned since has come from instruments, not people. This final chapter reviews how the ocean is studied today, what threatens it, how it is governed, and how to read what is written about it.

How We Study the Ocean Now

Tool	What it does	Strength
Research ships	Carry instruments, nets and sonar; take water samples with bottle rosettes	Most flexible; expensive and slow
Satellites	Measure sea-surface temperature, height, colour (chlorophyll), winds and ice	Global coverage, every few days; surface only
Argo floats	About 4,000 drifting profilers report temperature and salinity to about 2,000 m	Continuous global subsurface record (check)
Moorings and tide gauges	Fixed instruments, such as the Atlantic overturning array (Chapter 7)	Long records at a point
Gliders and autonomous vehicles	Robots that glide or propel themselves along a programmed path	Cheap per day; can enter storms and under ice
Remotely operated vehicles (ROVs)	Tethered robots with cameras and arms, driven from a ship	Detailed work at any depth
Models	Computer simulations of currents, waves, tides and climate	Fill gaps and make forecasts; need observations to check them

Sound and chemistry are used too: hydrophones listen for whales and earthquakes, and DNA in a water sample can reveal which species were nearby (environmental DNA). The United Nations has declared 2021 to 2030 the Decade of Ocean Science for Sustainable Development, with the aim of coordinating more of this effort and mapping the whole seafloor (check).

The Main Pressures

Warming, acidification, deoxygenation

The climate effects of Chapter 8, acting together on reefs, fisheries and polar ecosystems.

Overfishing and bycatch

Taking fish faster than they can reproduce (Chapter 9), and catching non-target animals such as turtles, seabirds and dolphins.

Pollution

Plastic, fertiliser run-off, sewage, oil and noise, described below.

Habitat loss

Coastal development, trawling of the seabed, and loss of mangroves, seagrass and reefs.

New industries

Offshore wind, aquaculture, and the possibility of deep-sea mining of mineral nodules, which raise questions about benefits and damage that are still being debated.

Invasive species

Animals and plants carried in ballast water and on ship hulls to places where they have no natural enemies.

Two pollution stories worth knowing

Plastic. A widely cited 2015 study estimated that between about 5 and 13 million tonnes of plastic waste entered the ocean in 2010 from coastal countries (check). Most of it begins on land, and much of it is fragmented into microplastics that are found from surface water to deep trenches and Arctic ice. **Nutrients.** Fertiliser washed down rivers feeds algae blooms; when the algae die and rot, they use up the oxygen, leaving "dead

zones" such as the large one that forms each summer off the mouth of the Mississippi (check). The same pattern can occur in the Baltic and in smaller coastal waters.

Who Owns the Sea?

The legal framework is the United Nations Convention on the Law of the Sea (UNCLOS), agreed in 1982 and in force from 1994 (check). Its main ideas:

- **Territorial sea.** Up to 12 nautical miles from the coast belong to the coastal state, with a right of innocent passage for ships.
- **Exclusive economic zone (EEZ).** Up to 200 nautical miles, where the coastal state controls fishing, oil and gas, and other resources. About a third of the ocean falls within EEZs (check).
- **The high seas.** Beyond the EEZs, roughly two-thirds of the ocean, are open to all and historically poorly regulated.

In 2023 the member states of the United Nations agreed a treaty on the conservation of biodiversity in areas beyond national jurisdiction, often called the High Seas Treaty, to create protected areas and set rules for environmental assessment there. It needed 60 countries to ratify it before taking effect, and the latest status should be checked (check).

Protection in Practice

Measure	What it does	Limits
Marine protected areas	Restrict fishing or other activities in a defined zone	Only fully or highly protected zones show the largest benefits; many areas are protected on paper only
Catch limits and quotas	Cap the total take of a species	Need good stock assessments and enforcement
Gear rules	Mesh sizes, bans on destructive trawling	Hard to police at sea
Pollution law	The MARPOL convention for ships; limits on discharges and run-off	Land-based sources are harder to control

Measure	What it does	Limits
Targets	The 2022 global biodiversity framework aims to protect 30 per cent of the ocean by 2030	Only a minority of the ocean is covered so far, and a smaller part strictly (check the latest figure)

Evidence suggests that well-enforced no-take reserves can increase fish numbers and size inside the reserve and sometimes supply nearby fisheries as the fish spill over (check). The Scottish seas have their own network of marine protected areas, with debate about what activities they should limit.

Reading Ocean Stories Critically

A checklist for any ocean claim

1. Is it an observation, a model projection or a guess?
2. What exactly was measured, where, over what period?
3. Is the number a rate, a total or a share, and what is it compared with?
4. Does the headline match the original source and its stated uncertainty?
5. Is it local (one bay, one stock) or global?
6. Is "the ocean" one thing in the claim? Surface and deep, Atlantic and Pacific behave differently.

What You Now Know

Chapter	Key idea
1	The ocean covers 71 per cent of Earth, is deep and little mapped
2	The seafloor is made at ridges and recycled at trenches
3	Salinity, temperature and pressure set the density and layers of seawater
4	Wind makes waves; tsunamis are a different kind of wave

Chapter	Key idea
5	Tides come from the Moon and Sun and are shaped by the basin
6	Wind and rotation drive gyres, boundary currents and upwelling
7	Density drives a slow global overturning over centuries
8	The ocean stores heat and carbon, and is changing
9	Plankton support the food web; vents show life without sunlight

Exercises

EXERCISE 1

A country has a coastline whose 200-nautical-mile exclusive economic zone covers 500,000 square kilometres. A marine protected area of 60,000 square kilometres is created in it, of which 20,000 square kilometres is fully no-take. Calculate the percentage of the EEZ that is protected at all, and the percentage that is fully protected. How do they compare with a 30 per cent target?

→ Solution

EXERCISE 2

Choose one ocean tool from the table (satellite, Argo float, ship, glider, ROV) and say which of the earlier chapters' questions it could best answer (for example the speed of the Gulf Stream, the depth of the thermocline, or the age of a deep water mass), and why the others would be less suited.

→ Solution

EXERCISE 3

Capstone: find a recent news story about the ocean and apply the six-point checklist. Write a short assessment (150 to 250 words) of what the story claims, what the

evidence is, and which chapter of this course helps you judge it.

→ Solution

Quick Reference

- **Tools:** ships, satellites, Argo floats, moorings, gliders, ROVs, models
- **Pressures:** climate change, overfishing, pollution, habitat loss, new industries, invasives
- **Law:** UNCLOS: 12 nm territorial sea, 200 nm EEZ, high seas beyond
- **Protection:** marine protected areas, quotas, gear rules, the 30 by 30 target
- **Critical reading:** observation or projection, what was measured, rate or total, source, scale
- **Check:** plastic estimate, treaty status, protection percentages

Course complete

You have finished Oceanography Fundamentals: from the shape of the seafloor and the chemistry of seawater, through waves, tides and currents, to climate, life and conservation. The next step is a real coast: a tide table, a rock pool and a windy day on the Firth of Forth will teach you more than any chapter.