Oceanography & its Branches

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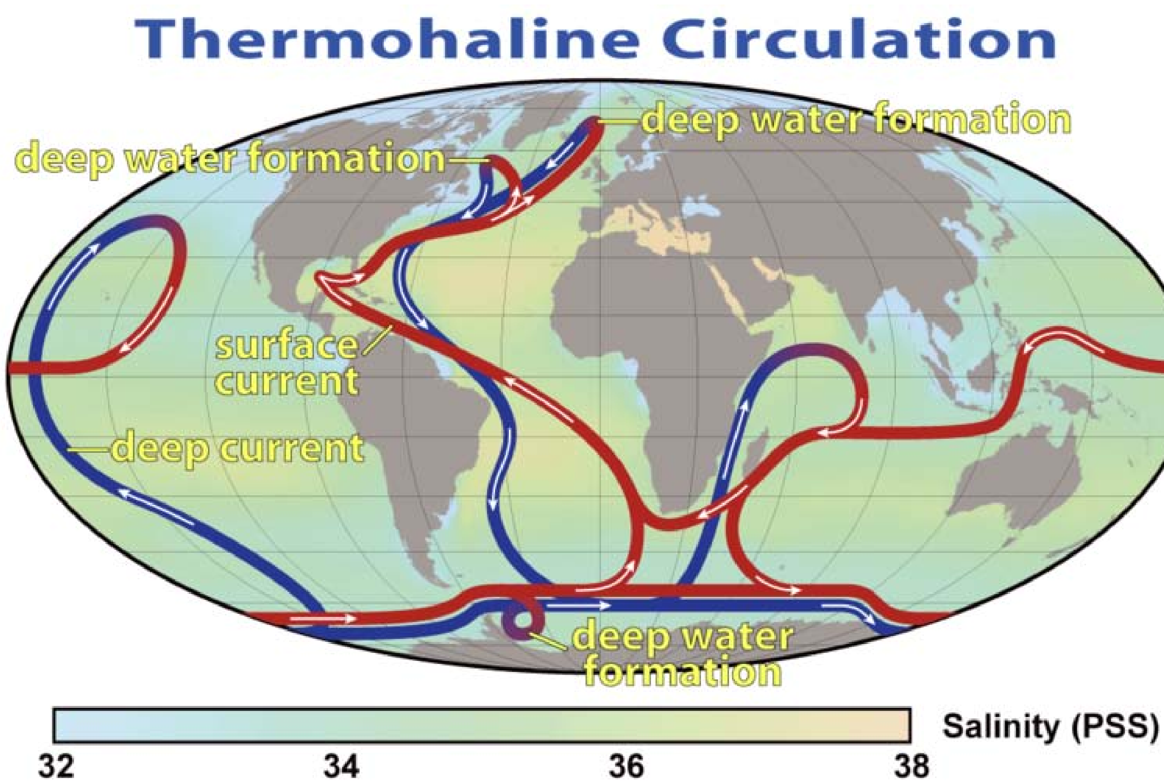
Oceanography



Thermohaline circulation

Oceanography (compound of the Greek words *ωκεανός* meaning "ocean" and *γράφω* meaning "to write"), also called **oceanology, oceanonomy,** or **marine science**, is the branch of Earth science that studies the ocean. It covers a wide range of topics, including marine organisms and ecosystem dynamics; ocean currents, waves, and geophysical fluid dynamics; plate tectonics and the geology of the sea floor; and fluxes of various chemical substances and physical properties within the ocean and across its boundaries. These diverse topics reflect multiple disciplines that oceanographers blend to further knowledge of the world ocean and understanding of processes within it: biology, chemistry, geology, meteorology, and physics as well as geography.

History

Map of the Gulf Stream by Benjamin Franklin, 1769-1770.

Humans first acquired knowledge of the waves and currents of the seas and oceans in pre-historic times. Observations on tides are recorded by Aristotle and Strabo. Early modern exploration of the oceans was primarily for cartography and mainly limited to its surfaces and of the creatures that fishermen brought up in nets, though depth soundings by lead line were taken.

Although Juan Ponce de León in 1513 first identified the Gulf Stream, and the current was well-known to mariners, Benjamin Franklin made the first scientific study of it and gave it its name. Franklin measured water temperatures during several Atlantic crossings and correctly explained the Gulf Stream's cause. Franklin and Timothy Folger printed the first map of the Gulf Stream in 1769-1770.

When Louis Antoine de Bougainville, who voyaged between 1766 and 1769, and James Cook, who voyaged from 1768 to 1779, carried out their explorations in the South Pacific, information on the oceans themselves formed part of the reports. James Rennell wrote the first scientific textbooks about currents in the Atlantic and Indian oceans during the late 18th and at the beginning of 19th century. Sir James Clark Ross took the first modern sounding in deep sea in 1840, and Charles Darwin published a paper on reefs and the formation of atolls as a result of the second voyage of HMS *Beagle* in 1831-6. Robert FitzRoy published a report in four volumes of the three voyages of the *Beagle*. In 1841–1842 Edward Forbes undertook dredging in the Aegean Sea that founded marine ecology.

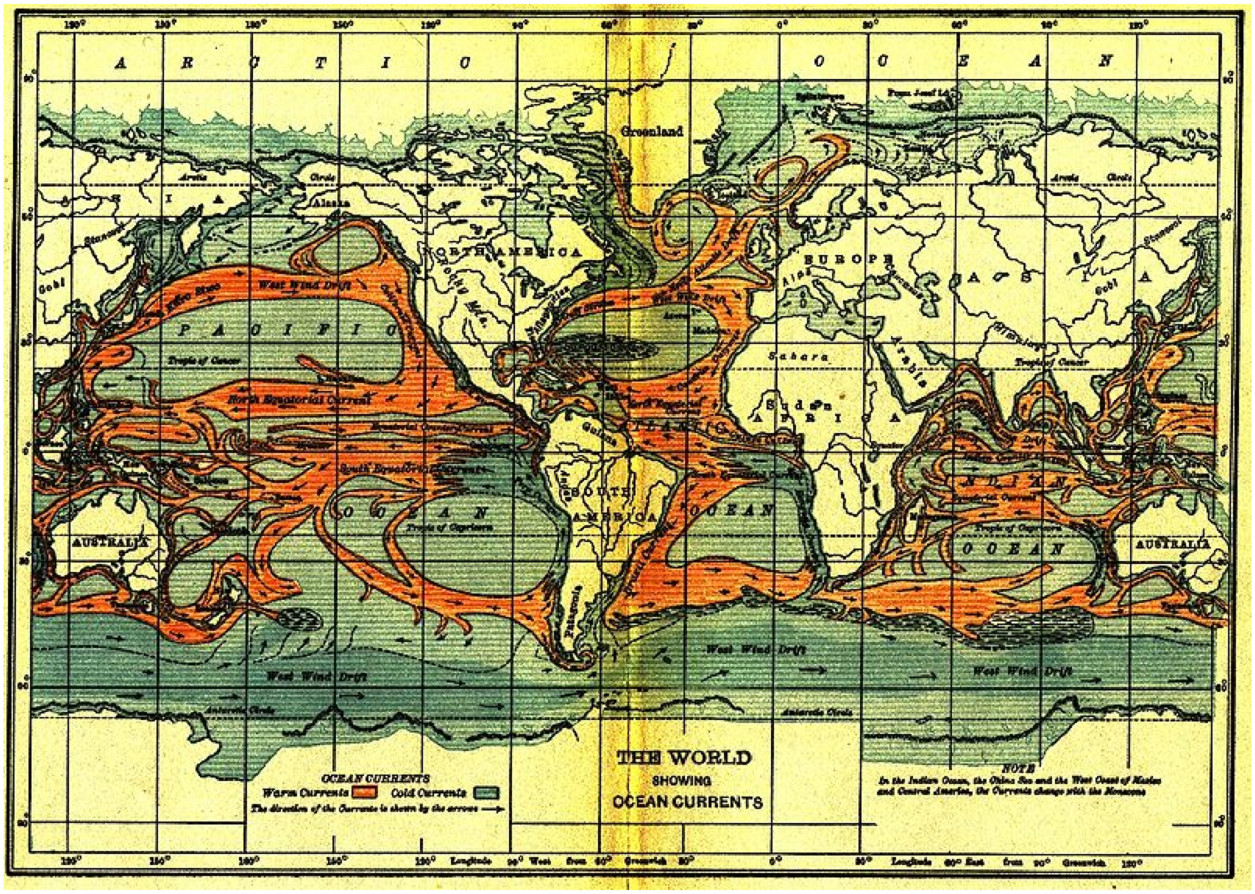
As first superintendent of the United States Naval Observatory (1842–1861) Matthew Fontaine Maury devoted his time to the study of marine meteorology, navigation, and charting prevailing winds and currents. His *Physical Geography of the Sea*, 1855 was the first textbook of oceanography. Many nations sent oceanographic observations to Maury at the Naval Observatory, where he and his colleagues evaluated the information and gave the results worldwide distribution.

The steep slope beyond the continental shelves was discovered in 1849. The first successful laying of transatlantic telegraph cable in August 1858 confirmed the presence of an underwater "telegraphic plateau" mid-ocean ridge. After the middle of the 19th century, scientific societies were processing a flood of new terrestrial botanical and zoological information.

In 1871, under the recommendations of the Royal Society of London, the British government sponsored an expedition to explore world's oceans and conduct scientific investigations. Under that sponsorship the Scots Charles Wyville Thompson and Sir John Murray launched the Challenger expedition (1872–1876). The results of this were published in 50 volumes covering biological, physical and geological aspects. 4417 new species were discovered.

Other European and American nations also sent out scientific expeditions (as did private individuals and institutions). The first purpose built oceanographic ship, the "Albatros" was built in 1882. The four-month 1910 North Atlantic expedition headed by Sir John Murray and Johan Hjort was at that time the most ambitious research oceanographic and marine zoological project ever, and led to the classic 1912 book *The Depths of the Ocean*.

Oceanographic institutes dedicated to the study of oceanography were founded. In the United States, these included the Scripps Institution of Oceanography in 1892, Woods Hole Oceanographic Institution in 1930, Virginia Institute of Marine Science in 1938, Lamont-Doherty Earth Observatory at Columbia University, and the School of Oceanography at University of Washington. In Britain, there is a major research institution: National Oceanography Centre, Southampton which is the successor to the Institute of Oceanography. In Australia, CSIRO Marine and Atmospheric Research, known as CMAR, is a leading center. In 1921 the International Hydrographic Bureau (IHB) was formed in Monaco.



Ocean currents (1911)

In 1893, Fridtjof Nansen allowed his ship "Fram" to be frozen in the Arctic ice. As a result he was able to obtain oceanographic data as well as meteorological and astronomical data. The first international organization of oceanography was created in 1902 as the International Council for the Exploration of the Sea.

The first acoustic measurement of sea depth was made in 1914. Between 1925 and 1927 the "Meteor" expedition gathered 70,000 ocean depth measurements using an echo sounder, surveying the Mid atlantic ridge. The Great Global Rift, running along the Mid Atlantic Ridge, was discovered by Maurice Ewing and Bruce Heezen in 1953 while the mountain range under the Arctic was found in 1954 by the Arctic Institute of the USSR. The theory of seafloor spreading was developed in 1960 by Harry Hammond Hess. The Ocean Drilling Project started in 1966. Deep sea vents were discovered in 1977 by John Corlis and Robert Ballard in the submersible "Alvin".

In the 1950s, Auguste Piccard invented the bathyscaphe and used the "Trieste" to investigate the ocean's depths. The nuclear submarine Nautilus made the first journey under the ice to the North Pole in 1958. In 1962 there was the first deployment of FLIP (Floating Instrument Platform), a 355 foot spar buoy.

Then, in 1966, the U.S. Congress created a *National Council for Marine Resources and Engineering Development*. NOAA was put in charge of exploring and studying all aspects of Oceanography in the USA. It also enabled the National Science Foundation to award *Sea Grant College* funding to multi-disciplinary researchers in the field of oceanography.

From the 1970s, there has been much emphasis on the application of large scale computers to oceanography to allow numerical predictions of ocean conditions and as a part of overall environmental change prediction. An oceanographic buoy array was established in the Pacific to allow prediction of El Niño events.

1990 saw the start of the World Ocean Circulation Experiment (WOCE) which continued until 2002. Geosat seafloor mapping data became available in 1995.

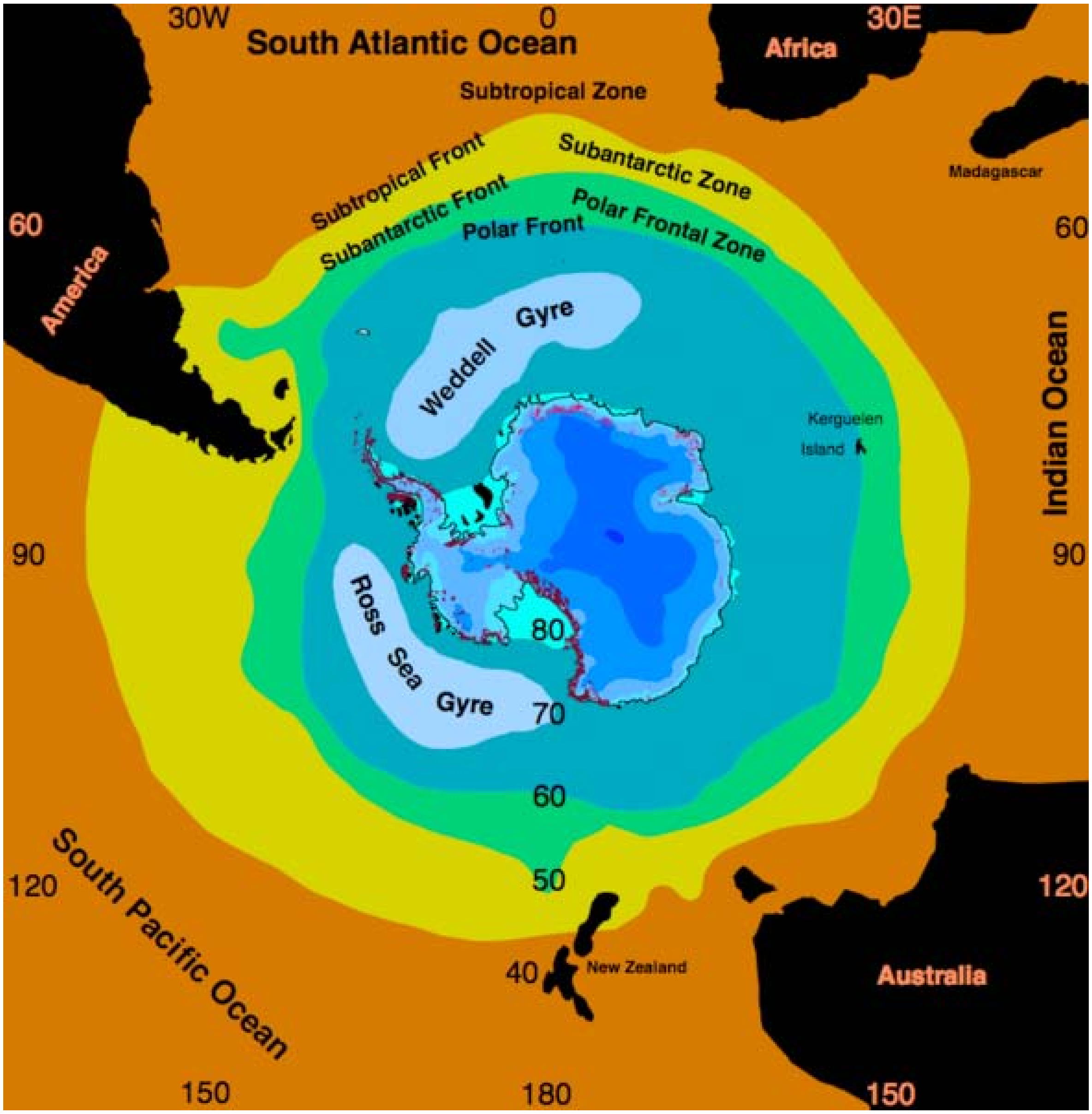
In 1942, Sverdrup and Fleming published "The Ocean" which was a major landmark. "The Sea" (in three volumes covering physical oceanography, seawater and geology) edited by M.N. Hill was published in 1962 while the "Encyclopedia of Oceanography" by Rhodes Fairbridge was published in 1966.

Connection to the atmosphere

The study of the oceans is linked to understanding global climate changes, potential global warming and related biosphere concerns. The atmosphere and ocean are linked because of evaporation and precipitation as well as thermal flux (and solar insolation). Wind stress is a major driver of ocean currents while the ocean is a sink for atmospheric carbon dioxide.

Our planet is invested with two great oceans; one visible, the other invisible; one underfoot, the other overhead; one entirely envelopes it, the other covers about two thirds of its surface.
—Matthew F. Maury, *The Physical Geography of the Seas and Its Meteorology (1855)*

Branches



Oceanographic frontal systems on the Southern Hemisphere

The study of oceanography is divided into branches:

- **Biological oceanography**, or **marine biology**, is the study of the plants, animals and microbes of the oceans and their ecological interaction with the ocean;
- **Chemical oceanography**, or **marine chemistry**, is the study of the chemistry of the ocean and its chemical interaction with the atmosphere;
- **Geological oceanography**, or **marine geology**, is the study of the geology of the ocean floor including plate tectonics;

- **Physical oceanography**, or **marine physics**, studies the ocean's physical attributes including temperature-salinity structure, mixing, waves, internal waves, surface tides, internal tides, and currents. Of particular interest is the behavior of sound (acoustical oceanography), light (optical oceanography) and radio waves in the ocean.

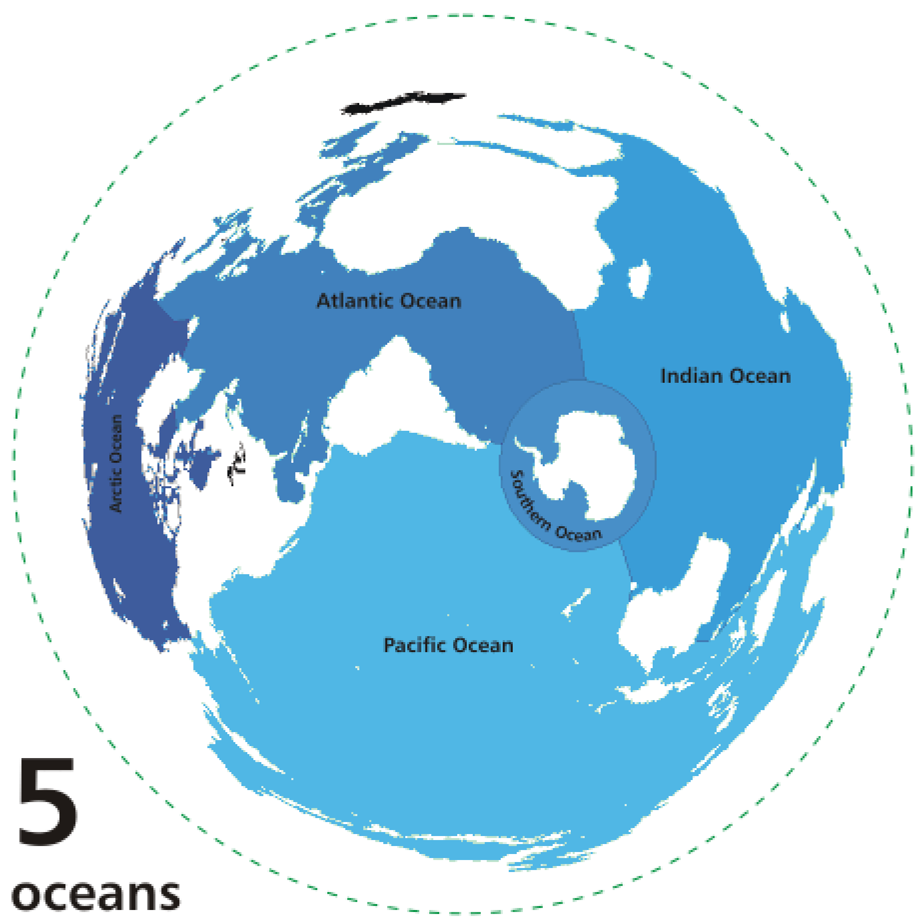
These branches reflect the fact that many oceanographers are first trained in the exact sciences or mathematics and then focus on applying their interdisciplinary knowledge, skills and abilities to oceanography.

Data derived from the work of Oceanographers is used in **marine engineering**, in the design and building of oil platforms, ships, harbours, and other structures that allow us to use the ocean safely.

Oceanographic data management is the discipline ensuring that oceanographic data both past and present are available to researchers.

Chapter- 2

Marine Biology



World Marine Environment

Marine biology is the scientific study of organisms in the ocean or other marine or brackish bodies of water. Given that in biology many phyla, families and genera have some species that live in the sea and others that live on land, marine biology classifies species based on the environment rather than on taxonomy. Marine biology differs from marine ecology as marine ecology is focused on how organisms interact with each other and the environment, and biology is the study of the animal itself.

Marine life is a vast resource, providing food, medicine, and raw materials, in addition to helping to support recreation and tourism all over the world. At a fundamental level, marine life helps determine the very nature of our planet. Marine organisms contribute significantly to the oxygen cycle, and are involved in the regulation of the Earth's climate. Shorelines are in part shaped and protected by marine life, and some marine organisms even help create new land.

Marine biology covers a great deal, from the microscopic, including most zooplankton and phytoplankton to the huge cetaceans (whales) which reach up to a reported 48 meters (125 feet) in length.

The habitats studied by marine biology include everything from the tiny layers of surface water in which organisms and abiotic items may be trapped in surface tension between the ocean and atmosphere, to the depths of the oceanic trenches, sometimes 10,000 meters or more beneath the surface of the ocean. It studies habitats such as coral reefs, kelp forests, tidepools, muddy, sandy and rocky bottoms, and the open ocean (pelagic) zone, where solid objects are rare and the surface of the water is the only visible boundary.

A large amount of all life on Earth exists in the oceans. Exactly how large the proportion is unknown, since many ocean species are still to be discovered. While the oceans comprise about 71% of the Earth's surface, due to their depth they encompass about 300 times the habitable volume of the terrestrial habitats on Earth.

Many species are economically important to humans, including food fish. It is also becoming understood that the well-being of marine organisms and other organisms are linked in very fundamental ways. The human body of knowledge regarding the relationship between life in the sea and important cycles is rapidly growing, with new discoveries being made nearly every day. These cycles include those of matter (such as the carbon cycle) and of air (such as Earth's respiration, and movement of energy through ecosystems including the ocean). Large areas beneath the ocean surface still remain effectively unexplored.

Subfields

The marine ecosystem is large, and thus there are many subfields of marine biology. Most involve studying specializations of particular animal groups, such as phycology, invertebrate zoology and ichthyology.

Other subfields study the physical effects of continual immersion in sea water and the ocean in general, adaptation to a salty environment, and the effects of changing various oceanic properties on marine life. A subfield of marine biology studies the relationships between oceans and ocean life, and global warming and environmental issues (such as carbon dioxide displacement).

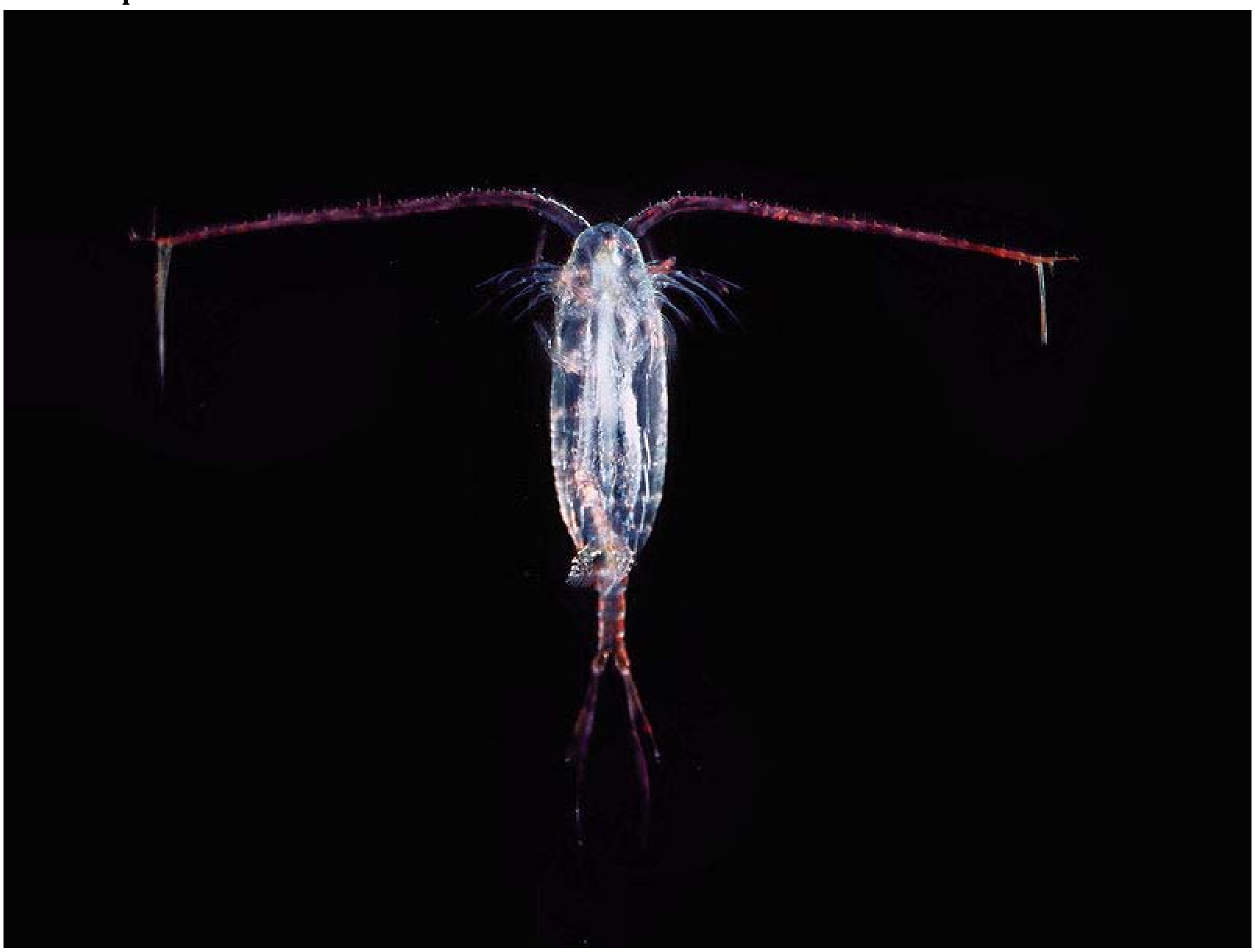
Recent marine biotechnology has focused largely on marine biomolecules, especially proteins, that may have uses in medicine or engineering. Marine environments are the home to many exotic biological materials that may inspire biomimetic materials.

Related fields

Marine biology is a branch of oceanography and is closely linked to biology. It also encompasses many ideas from ecology. Fisheries science and marine conservation can be considered partial offshoots of marine biology (as well as environmental studies).

Lifeforms

Microscopic life



A copepod

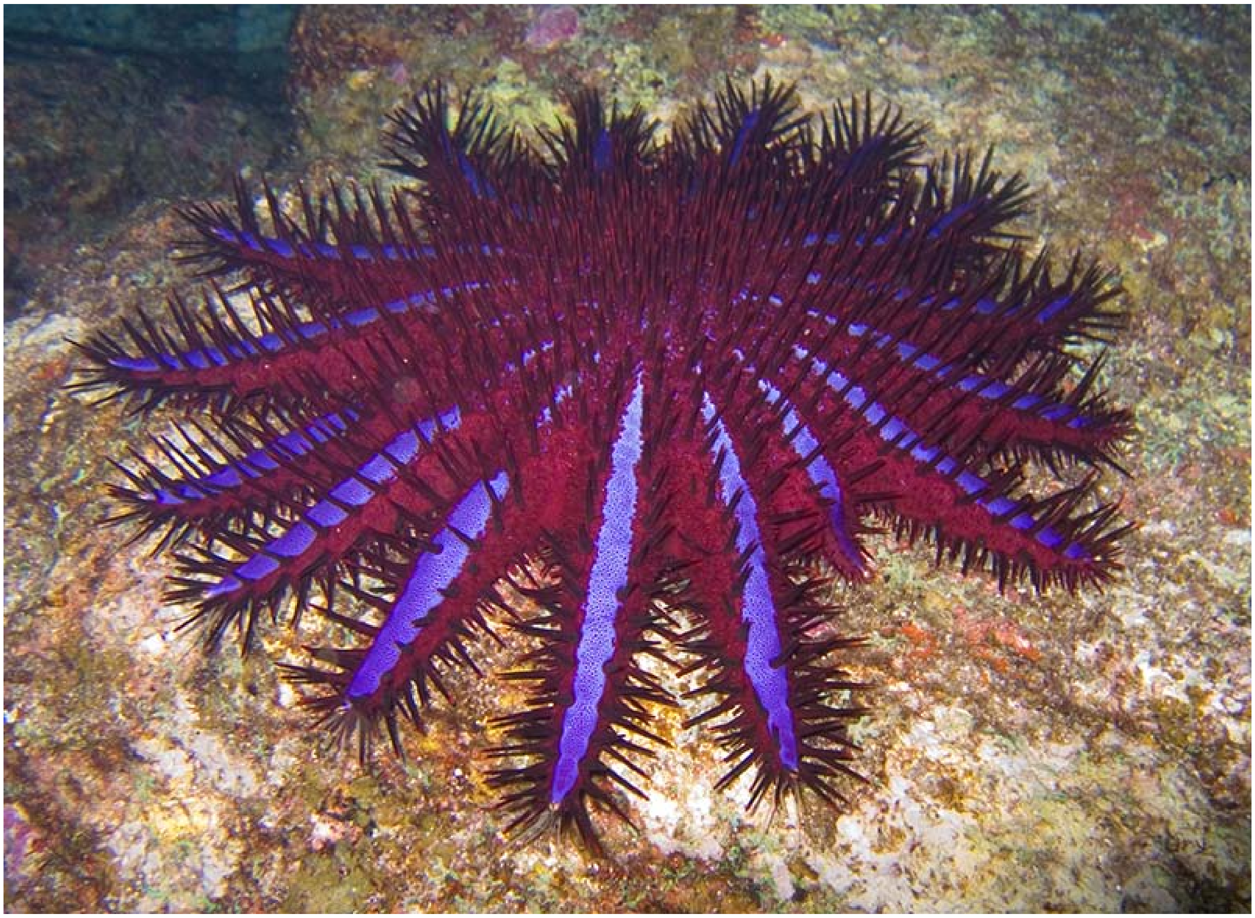
Microscopic life undersea is incredibly diverse and still poorly understood. For example, the role of viruses in marine ecosystems is barely being explored even in the beginning of the 21st century.

The role of phytoplankton is better understood due to their critical position as the most numerous primary producers on Earth. Phytoplankton are categorized into cyanobacteria (also called blue-green algae/bacteria), various types of algae (red, green, brown, and yellow-green), diatoms, dinoflagellates, euglenoids, coccolithophorids, cryptomonads, chrysophytes, chlorophytes, prasinophytes, and silicoflagellates.

Zooplankton tend to be somewhat larger, and not all are microscopic. Many Protozoa are zooplankton, including dinoflagellates, zooflagellates, foraminiferans, and radiolarians. Some of these (such as dinoflagellates) are also phytoplankton; the distinction between plants and animals often breaks down in very small organisms. Other zooplankton include cnidarians, ctenophores, chaetognaths, molluscs, arthropods, urochordates, and annelids such as polychaetes. Many larger animals begin their life as zooplankton before they become large enough to take their familiar forms. Two examples are fish larvae and sea stars (also called starfish).

Plants and algae

Plant life is widespread and very diverse under the sea. Microscopic photosynthetic algae contribute a larger proportion of the worlds photosynthetic output than all the terrestrial forests combined. Most of the niche occupied by sub plants on land is actually occupied by macroscopic algae in the ocean, such as *Sargassum* and kelp, which are commonly known as seaweeds that create kelp forests. The non algae plants that survive in the sea are often found in shallow waters, such as the seagrasses (examples of which are eelgrass, *Zostera*, and turtle grass, *Thalassia*). These plants have adapted to the high salinity of the ocean environment. The intertidal zone is also a good place to find plant life in the sea, where mangroves or cordgrass or beach grass might grow. Microscopic algae and plants provide important habitats for life, sometimes acting as hiding and foraging places for larval forms of larger fish and invertebrates.



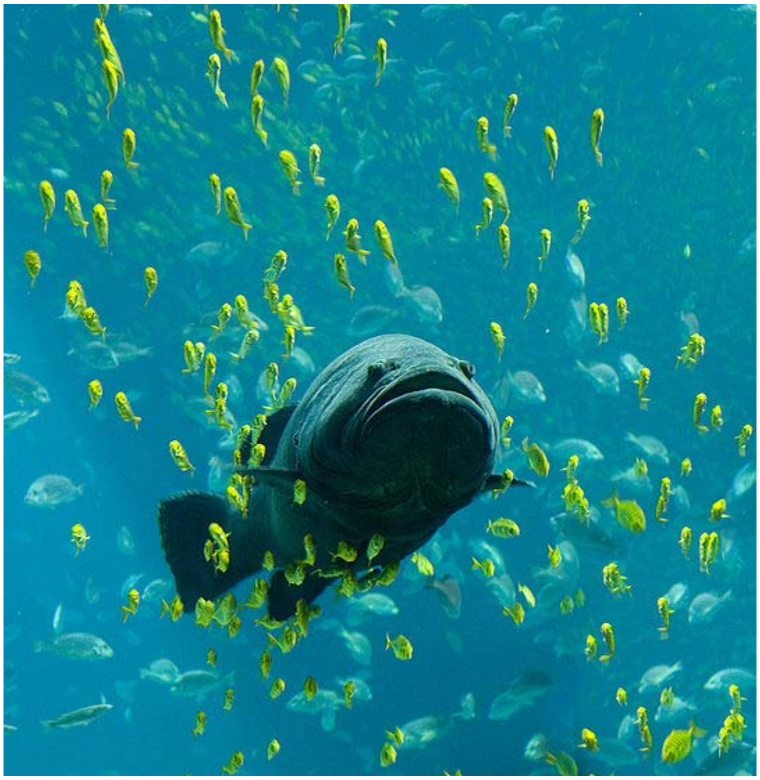
A crown-of-thorns starfish

Marine invertebrates

As on land, invertebrates make up a huge portion of all life in the sea. Invertebrate sea life includes Cnidaria such as jellyfish and sea anemones; Ctenophora; sea worms including the phyla Platyhelminthes, Nemertea, Annelida, Sipuncula, Echiura, Chaetognatha, and Phoronida; Mollusca including shellfish, squid, octopus; Arthropoda including Chelicerata and Crustacea; Porifera; Bryozoa; Echinodermata including starfish; and Urochordata including sea squirts or tunicates.

Fish

Fishes Fossil range: Ordovician–Neogene



A giant grouper at the Georgia Aquarium, seen swimming among schools of other fish

The ornate lionfish as seen from a head-on view

Scientific classification	
Kingdom:	Animalia
Phylum:	Chordata
(unranked)	Craniata
Included groups	
Jawless fishes †Armoured fishes Cartilaginous fishes Ray-finned fishes Lobe-finned fishes	
Excluded groups	
Tetrapods	

A **fish** is any aquatic vertebrate animal that is covered with scales, and equipped with two sets of paired fins and several unpaired fins. Most fish are "cold-blooded", or ectothermic, allowing their body temperatures to vary as ambient temperatures change. Fish are abundant in most bodies of water. They can be found in nearly all aquatic environments, from high mountain streams (e.g., char and gudgeon) to the abyssal and even hadal depths of the deepest oceans (e.g., gulpers and anglerfish). At 31,500 species, fish exhibit greater species diversity than any other class of vertebrates.

Food prepared from animals classified as fish is also referred to as fish, and is an important human food source. Commercial and subsistence fishers "hunt" fish in wild fisheries or "farm" them in ponds or in cages in the ocean. They are also caught by recreational fishers and raised by fishkeepers, and are exhibited in public aquaria. Fish have had a role in culture through the ages, serving as deities, religious symbols, and as the subjects of art, books and movies.

Diversity of fish

The term "fish" most precisely describes any non-tetrapod craniate (i.e. an animal with a skull and in most cases a backbone) that has gills throughout life and whose limbs, if any, are in the shape of fins. Unlike groupings such as birds or mammals, fish are not a single clade but a paraphyletic collection of taxa, including hagfishes, lampreys, sharks and rays, ray-finned fishes, coelacanths, and lungfishes.

A typical fish is ectothermic, has a streamlined body for rapid swimming, extracts oxygen from water using gills or uses an accessory breathing organ to breathe atmospheric oxygen, has two sets of paired fins, usually one or two (rarely three) dorsal fins, an anal fin, and a tail fin, has jaws, has skin that is usually covered with scales, and lays eggs.

Fish come in many shapes and sizes. This is a sea dragon, a close relative of the seahorse. Their leaf-like appendages enable them to blend in with floating seaweed.

Each criterion has exceptions. Tuna, swordfish, and some species of sharks show some warm-blooded adaptations—they can heat their bodies significantly above ambient water temperature. Streamlining and swimming performance varies from fish such as tuna, salmon, and jacks that can cover 10–20 body-lengths per second to species such as eels and rays that swim no more than 0.5 body-lengths per second. Many groups of freshwater fish extract oxygen from the air as well as from the water using a variety of different structures. Lungfish have paired lungs similar to those of tetrapods, gouramis have a structure called the labyrinth organ that performs a similar function, while many catfish, such as *Corydoras* extract oxygen via the intestine or stomach. Body shape and the arrangement of the fins is highly variable, covering such seemingly un-fishlike forms as seahorses, pufferfish, anglerfish, and gulpers. Similarly, the surface of the skin may be naked (as in moray eels), or covered with scales of a variety of different types usually defined as placoid (typical of sharks and rays), cosmoid (fossil lungfishes and coelacanths), ganoid (various fossil fishes but also living gars and bichirs), cycloid, and ctenoid (these last two are found on most bony fish). There are even fishes that live mostly on land. Mudskippers feed and interact with one another on mudflats and go underwater to hide in their burrows. The catfish *Phreatobius cisternarum* lives in underground, phreatic habitats, and a relative lives in waterlogged leaf litter.

Fish range in size from the huge 16-metre (52 ft) whale shark to the tiny 8-millimetre (0.3 in) stout infantfish.

Many types of aquatic animals commonly referred to as "fish" are not fish in the sense given above; examples include shellfish, cuttlefish, starfish, crayfish and jellyfish. In earlier times, even biologists did not make a distinction – sixteenth century natural historians classified also seals, whales, amphibians, crocodiles, even hippopotamuses, as well as a host of aquatic invertebrates, as fish. In some contexts, especially in aquaculture, the true fish are referred to as **finfish** (or **fin fish**) to distinguish them from these other animals.

Taxonomy

Fish are a paraphyletic group: that is, any clade containing all fish also contains the tetrapods, which are not fish. For this reason, groups such as the "Class Pisces" seen in older reference works are no longer used in formal classifications.

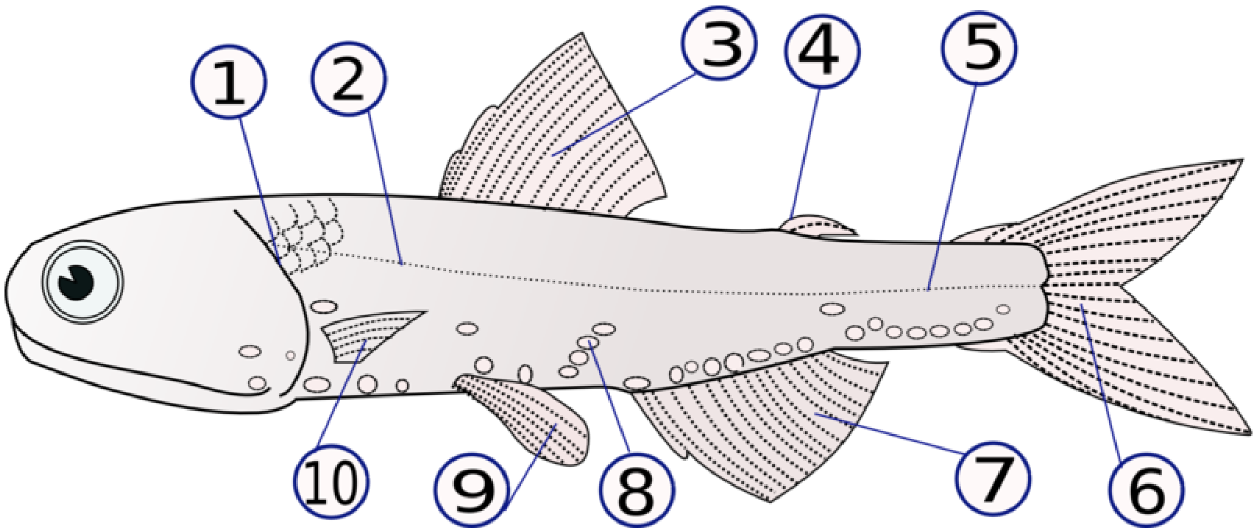
Fish are classified into the following major groups:

- Subclass Pteraspidomorphi (early jawless fish)
- Class Thelodonti
- Class Anaspida
- (unranked) Cephalaspidomorphi (early jawless fish)
    - (unranked) Hyperoartia or Petromyzontida
        - Petromyzontidae (lampreys)
    - Class Galeaspida
    - Class Pituriaspida
    - Class Osteostraci
- Infraphylum Gnathostomata (jawed vertebrates)
    - Class Placodermi (armoured fishes, extinct)
    - Class Chondrichthyes (cartilaginous fish)
    - Class Acanthodii (spiny sharks, extinct)
    - Superclass Osteichthyes (bony fish)
        - Class Actinopterygii (ray-finned fish)
            - Subclass Chondrostei
                - Order Acipenseriformes (sturgeons and paddlefishes)
                - Order Polypteriformes (reedfishes and bichirs).
            - Subclass Neopterygii
                - Infraclass Holostei (gars and bowfins)
                - Infraclass Teleostei (many orders of common fishes)
        - Class Sarcopterygii (lobe-finned fish)
            - Subclass Coelacanthimorpha (coelacanths)
            - Subclass Dipnoi (lungfish)

Some palaeontologists contend that because Conodonta are chordates, they are primitive fish.

The various fish groups account for more than half of vertebrate species. There are almost 28,000 known extant species, of which almost 27,000 are bony fish, with 970 sharks, rays, and chimeras and about 108 hagfishes and lampreys. A third of these species fall within the nine largest families; from largest to smallest, these families are Cyprinidae, Gobiidae, Cichlidae, Characidae, Loricariidae, Balitoridae, Serranidae, Labridae, and Scorpaenidae. About 64 families are monotypic, containing only one species. The final total of extant species may grow to exceed 32,500.

Anatomy



The anatomy of *Lampanyctodes hectoris*
(1) – operculum (gill cover), (2) – lateral line, (3) – dorsal fin, (4) – fat fin, (5) – caudal peduncle, (6) – caudal fin, (7) – anal fin, (8) – photophores, (9) – pelvic fins (paired), (10) – pectoral fins (paired)

Respiration

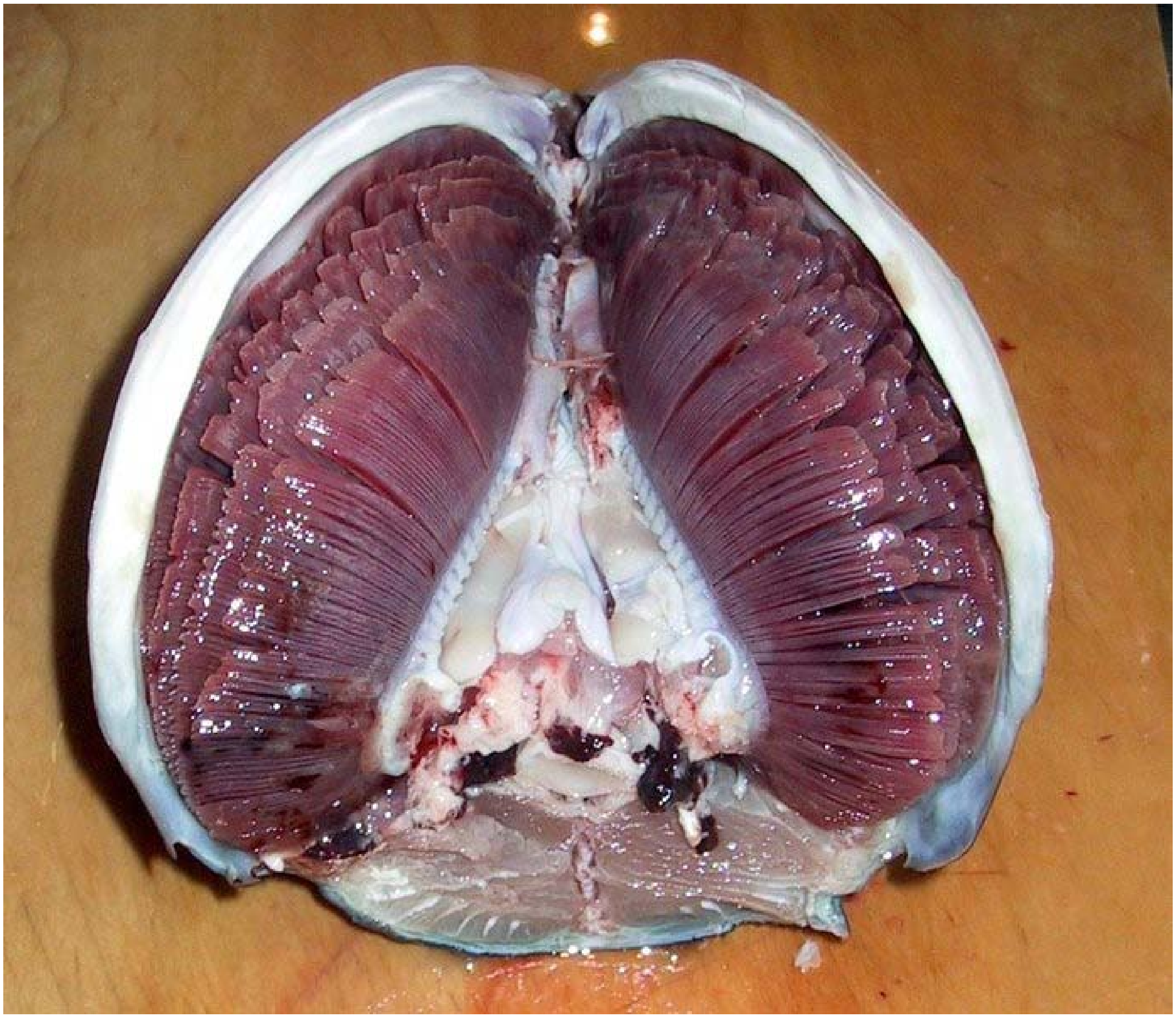
Most fish exchange gases using gills on either side of the pharynx. Gills consist of threadlike structures called filaments. Each filament contains a capillary network that provides a large surface area for exchanging oxygen and carbon dioxide. Fish exchange gases by pulling oxygen-rich water through their mouths and pumping it over their gills. In some fishes, capillary blood flows in the opposite direction to the water, causing counter current exchange. The gills push the oxygen-poor water out through openings in the sides of the pharynx. Some fishes, like sharks and lampreys, possess multiple gill openings. However, most fishes have a single gill opening on each side. This opening is hidden beneath a protective bony cover called an operculum.

Juvenile bichirs have external gills, a very primitive feature that they share with larval amphibians.

Swim bladder of a Rudd (Scardinius erythrophthalmus)

Many fish can breathe air via a variety of mechanisms. The skin of anguillid eels may absorb oxygen. The buccal cavity of the electric eel may breathe air. Catfishes of the families Loricariidae, Callichthyidae, and Scoloplacidae absorb air through their digestive tracts. Lungfish and bichirs have paired lungs similar to those of tetrapods and must surface to gulp fresh air through the mouth and pass spent air out through the gills. Gar and bowfin have a vascularized swim bladder that functions in the same way. Loaches, trahiras, and many catfish breathe by passing air through the gut. Mudskippers breathe by absorbing oxygen across the skin (similar to frogs). A number of fishes have evolved so-called **accessory breathing organs** that extract oxygen from the air. Labyrinth fish (such as gouramis and bettas) have a labyrinth organ above the gills that performs this function. A few other fish have structures resembling labyrinth organs in form and function, most notably snakeheads, pikeheads, and the Clariidae catfish family.

Breathing air is primarily of use to fish that inhabit shallow, seasonally variable waters where the water's oxygen concentration may seasonally decline. Fishes dependent solely on dissolved oxygen, such as perch and cichlids, quickly suffocate, while air-breathers survive for much longer, in some cases in water that is little more than wet mud. At the most extreme, some air-breathing fish are able to survive in damp burrows for weeks without water, entering a state of aestivation (summertime hibernation) until water returns.



Tuna gills inside of the head. The fish head is oriented snout-downwards, with the view looking towards the mouth.

Fish can be divided into **obligate air breathers** and **facultative air breathers**. Obligate air breathers, such as the African lungfish, *must* breathe air periodically or they suffocate. Facultative air breathers, such as the catfish *Hypostomus plecostomus*, only breathe air if they need to and will otherwise rely on their gills for oxygen. Most air breathing fish are facultative air breathers that avoid the energetic cost of rising to the surface and the fitness cost of exposure to surface predators.

Circulation

Fish have a closed-loop circulatory system. The heart pumps the blood in a single loop throughout the body. In most fish, the heart consists of four parts, including two chambers and an entrance and exit. The first part is the sinus venosus, a thin-walled sac that collects blood from the fish's veins before allowing it to flow to the second part, the atrium, which is a large muscular chamber. The atrium serves as a one-way antechamber, sends blood to the third part, ventricle. The ventricle is another thick-walled, muscular chamber and it pumps the blood, first to the fourth part, bulbous arteriosus, a large tube, and then out of the heart. The bulbus arteriosus connects to the aorta, through which blood flows to the gills for oxygenation.

Digestion

Jaws allow fish to eat a wide variety of food, including plants and other organisms. Fish ingest food through the mouth and break it down in the esophagus. In the stomach, food is further digested and, in many fish, processed in finger-shaped pouches called pyloric caeca, which secrete digestive enzymes and absorb nutrients. Organs such as the liver and pancreas add enzymes and various chemicals as the food moves through the digestive tract. The intestine completes the process of digestion and nutrient absorption.

Excretion

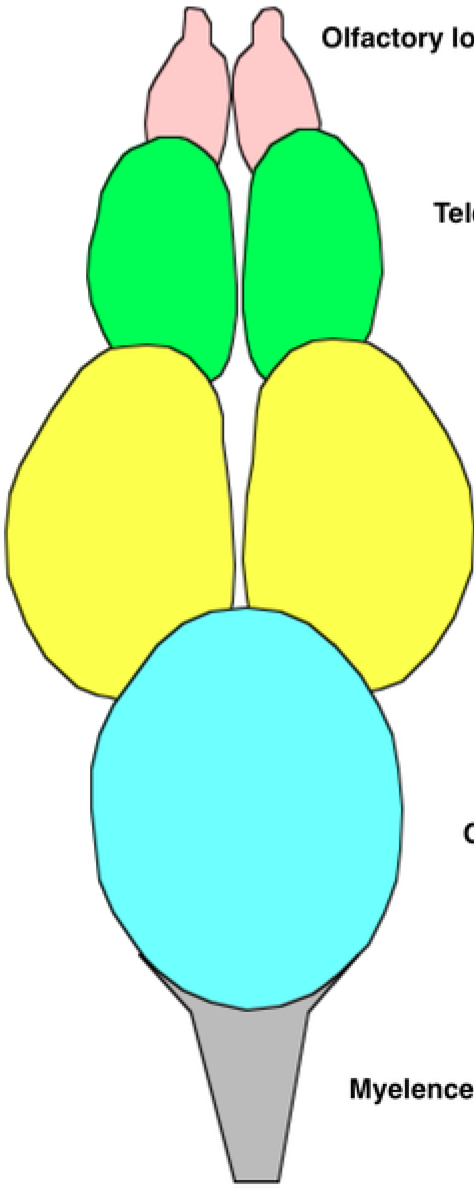
As with many aquatic animals, most fish release their nitrogenous wastes as ammonia. Some of the wastes diffuse through the gills. Blood wastes are filtered by the kidneys.

Saltwater fish tend to lose water because of osmosis. Their kidneys return water to the body. The reverse happens in freshwater fish: they tend to gain water osmotically. Their kidneys produce dilute urine for excretion. Some fish have specially adapted kidneys that vary in function, allowing them to move from freshwater to saltwater.

Scales

The scales of fish originate from the mesoderm (skin); they may be similar in structure to teeth.

Sensory and nervous system



Dorsal view of the brain of the rainbow trout

Central nervous system

Fish typically have quite small brains relative to body size compared with other vertebrates, typically one-fifteenth the brain mass of a similarly sized bird or mammal. However, some fish have relatively large brains, most notably mormyrids and sharks, which have brains about as massive relative to body weight as birds and marsupials.

Fish brains are divided into several regions. At the front are the olfactory lobes, a pair of structures that receive and process signals from the nostrils via the two olfactory nerves. The olfactory lobes are very large in fishes that hunt primarily by smell, such as hagfish, sharks, and catfish. Behind the olfactory lobes is the two-lobed telencephalon, the structural equivalent to the cerebrum in higher vertebrates. In fishes the telencephalon is concerned mostly with olfaction. Together these structures form the **forebrain**.

Connecting the forebrain to the **midbrain** is the diencephalon (in the diagram, this structure is below the optic lobes and consequently not visible). The diencephalon performs functions associated with hormones and homeostasis. The pineal body lies just above the diencephalon. This structure detects light, maintains circadian rhythms, and controls color changes.

The midbrain or mesencephalon contains the two optic lobes. These are very large in species that hunt by sight, such as rainbow trout and cichlids.

The **hindbrain** or metencephalon is particularly involved in swimming and balance. The cerebellum is a single-lobed structure that is typically the biggest part of the brain. Hagfish and lampreys have relatively small cerebellae, while the mormyrid cerebellum is massive and apparently involved in their electrical sense.

The **brain stem** or myelencephalon is the brain's posterior. As well as controlling some muscles and body organs, in bony fish at least, the brain stem governs respiration and osmoregulation.

Sense organs

Most fish possess highly developed sense organs. Nearly all daylight fish have color vision that is at least as good as a human's. Many fish also have chemoreceptors that are responsible for extraordinary senses of taste and smell. Although they have ears, many fish may not hear very well. Most fish have sensitive receptors that form the lateral line system, which detects gentle currents and vibrations, and senses the motion of nearby fish and prey. Some fish, such as catfish and sharks, have organs that detect low-level electric current. Other fish, like the electric eel, can produce electric current.

Fish orient themselves using landmarks and may use mental maps based on multiple landmarks or symbols. Fish behavior in mazes reveals that they possess spatial memory and visual discrimination.

Capacity for pain

Experiments done by William Tavolga provide evidence that fish have pain and fear responses. For instance, in Tavolga’s experiments, toadfish grunted when electrically shocked and over time they came to grunt at the mere sight of an electrode.

In 2003, Scottish scientists at the University of Edinburgh and the Roslin Institute concluded that rainbow trout exhibit behaviors often associated with pain in other animals. Bee venom and acetic acid injected into the lips resulted in fish rocking their bodies and rubbing their lips along the sides and floors of their tanks, which the researchers concluded were attempts to relieve pain, similar to what mammals would do. Neurons fired in a pattern resembling human neuronal patterns.

Professor James D. Rose of the University of Wyoming claimed the study was flawed since it did not provide proof that fish possess "conscious awareness, particularly a kind of awareness that is meaningfully like ours". Rose argues that since fish brains are so different from human brains, fish are probably not conscious in the manner humans are, so that reactions similar to human reactions to pain instead have other causes. Rose had published a study a year earlier arguing that fish cannot feel pain because their brains lack a neocortex. However, animal behaviorist Temple Grandin argues that fish could still have consciousness without a neocortex because "different species can use different brain structures and systems to handle the same functions."

Animal welfare advocates raise concerns about the possible suffering of fish caused by angling. Some countries, such as Germany have banned specific types of fishing, and the British RSPCA now formally prosecutes individuals who are cruel to fish.

Muscular system

Most fish move by alternately contracting paired sets of muscles on either side of the backbone. These contractions form S-shaped curves that move down the body. As each curve reaches the back fin, backward force is applied to the water, and in conjunction with the fins, moves the fish forward. The fish's fins function like an airplane's flaps. Fins also increase the tail's surface area, increasing speed. The streamlined body of the fish decreases the amount of friction from the water. Since body tissue is denser than water, fish must compensate for the difference or they will sink. Many bony fishes have an internal organ called a swim bladder that adjusts their buoyancy through manipulation of gases.

Homeothermy

A 3-tonne (3.0 LT; 3.3 ST) great white shark off Isla Guadalupe

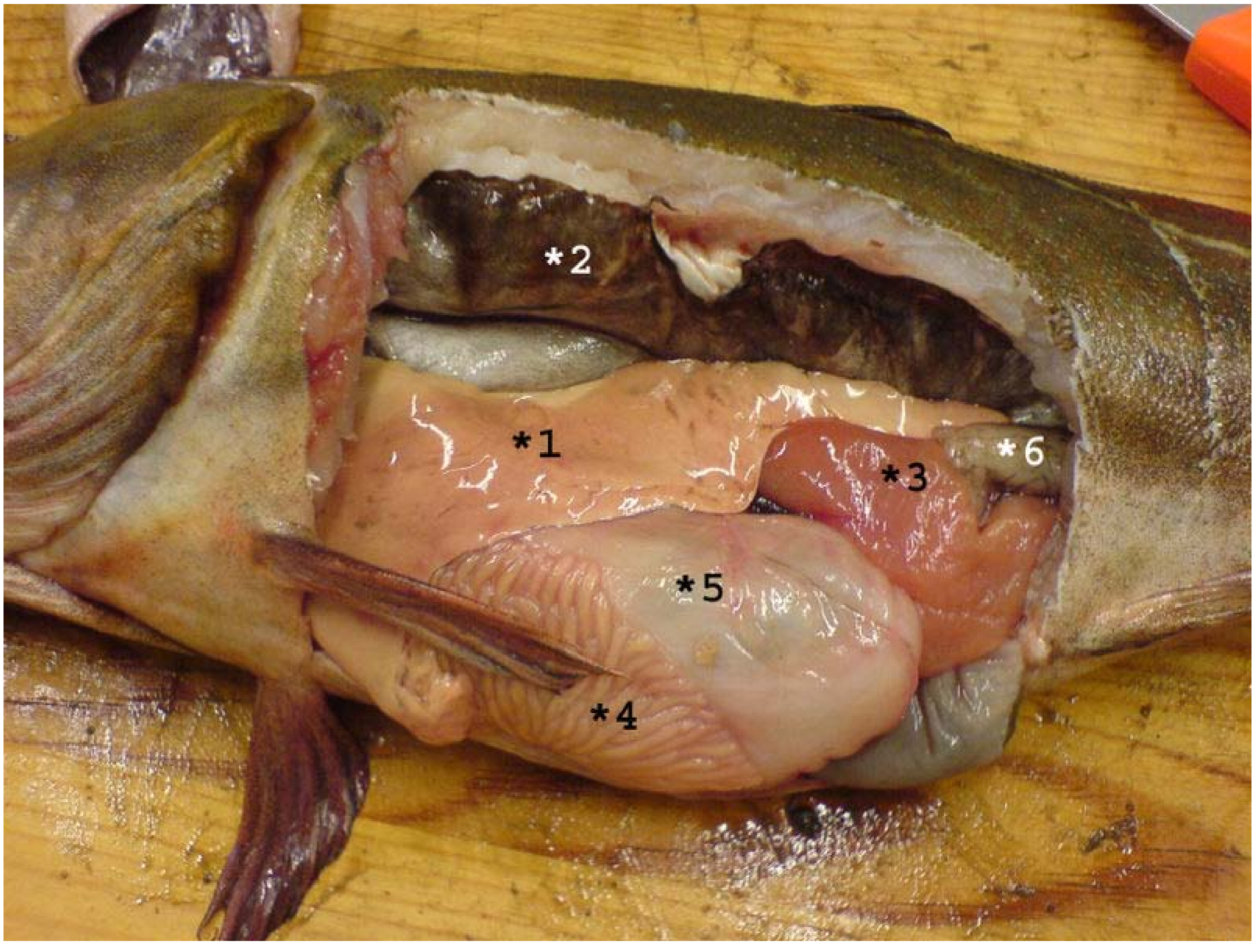
Although most fish are exclusively aquatic and ectothermic, there are exceptions to both cases.

Fish from multiple groups can live out of the water for extended time periods. Amphibious fish such as the mudskipper can live and move about on land for up to several days.

Certain species of fish maintain elevated body temperatures. Endothermic teleosts (bony fishes) are all in the suborder Scombroidei and include the billfishes, tunas, and one species of "primitive" mackerel (*Gasterochisma melampus*). All sharks in the family Lamnidae – shortfin mako, long fin mako, white, porbeagle, and salmon shark – are endothermic, and evidence suggests the trait exists in family Alopiidae (thresher sharks). The degree of endothermy varies from the billfish, which warm only their eyes and brain, to bluefin tuna and porbeagle sharks who maintain body temperatures elevated in excess of 20 °C above ambient water temperatures. Endothermy, though metabolically costly, is thought to provide advantages such as increased muscle strength, higher rates of central nervous system processing, and higher rates of digestion.

Reproductive system

Organs



Organs: 1. Liver, 2. Gas bladder, 3. Roe, 4. Pyloric caeca, 5. Stomach, 6. Intestine

Fish reproductive organs include testes and ovaries. In most species, gonads are paired organs of similar size, which can be partially or totally fused. There may also be a range of secondary organs that increase reproductive fitness.

In terms of spermatogonia distribution, the structure of teleosts testes has two types: in the most common, spermatogonia occur all along the seminiferous tubules, while in Atherinomorph fishes they are confined to the distal portion of these structures. Fishes can present cystic or semi-cystic spermatogenesis in relation to the release phase of germ cells in cysts to the seminiferous tubules lumen.

Fish ovaries may be of three types: gymnovarian, secondary gymnovarian or cystovarian. In the first type, the oocytes are released directly into the coelomic cavity and then enter the ostium, then through the oviduct and are eliminated. Secondary gymnovarian ovaries shed ova into the coelom from which they go directly into the oviduct. In the third type, the oocytes are conveyed to the exterior through the oviduct. Gymnovaries are the primitive condition found in lungfish, sturgeon, and bowfin. Cystovaries characterize most teleosts, where the ovary lumen has continuity with the oviduct. Secondary gymnovaries are found in salmonids and a few other teleosts.

Oogonia development in teleosts fish varies according to the group, and the determination of oogenesis dynamics allows the understanding of maturation and fertilization processes. Changes in the nucleus, ooplasm, and the surrounding layers characterize the oocyte maturation process.

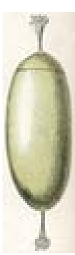
Postovulatory follicles are structures formed after oocyte release; they do not have endocrine function, present a wide irregular lumen, and are rapidly reabsorbed in a process involving the apoptosis of follicular cells. A degenerative process called follicular atresia reabsorbs vitellogenic oocytes not spawned. This process can also occur, but less frequently, in oocytes in other development stages.

Some fish are hermaphrodites, having both testes and ovaries either at different phases in their life cycle or, as in hamlets, have them simultaneously.

Reproductive method

Over 97% of all known fishes are oviparous, that is, the eggs develop outside the mother's body. Examples of oviparous fishes include salmon, goldfish, cichlids, tuna, and eels. In the majority of these species, fertilization takes place outside the mother's body, with the male and female fish shedding their gametes into the surrounding water. However, a few oviparous fishes practice internal fertilization, with the male using some sort of intromittent organ to deliver sperm into the genital opening of the female, most notably the oviparous sharks, such as the horn shark, and oviparous rays, such as skates. In these cases, the male is equipped with a pair of modified pelvic fins known as claspers.

Marine fish can produce high numbers of eggs which are often released into the open water column. The eggs have an average diameter of 1 millimetre (0.039 in).



Egg of lamprey

Egg of catshark (mermaids' purse)

Egg of bullhead shark

Egg of chimaera

An example of zooplankton

The newly hatched young of oviparous fish are called larvae. They are usually poorly formed, carry a large yolk sac (for nourishment) and are very different in appearance from juvenile and adult specimens. The larval period in oviparous fish is relatively short (usually only several weeks), and larvae rapidly grow and change appearance and structure (a process termed metamorphosis) to become juveniles. During this transition larvae must switch from their yolk sac to feeding on zooplankton prey, a process which depends on typically inadequate zooplankton density, starving many larvae.

In ovoviviparous fish the eggs develop inside the mother's body after internal fertilization but receive little or no nourishment directly from the mother, depending instead on the yolk. Each embryo develops in its own egg. Familiar examples of ovoviviparous fishes include guppies, angel sharks, and coelacanths.

Some species of fish are viviparous. In such species the mother retains the eggs and nourishes the embryos. Typically, viviparous fishes have a structure analogous to the placenta seen in mammals connecting the mother's blood supply with that of the embryo. Examples of viviparous fishes include the surf-perches, splitfins, and lemon shark. Some viviparous fishes exhibit oophagy, in which the developing embryos eat other eggs produced by the mother. This has been observed primarily among sharks, such as the shortfin mako and porbeagle, but is known for a few bony fish as well, such as the halfbeak *Nomorhamphus ebrardtii*. Intrauterine cannibalism is an even more unusual mode of vivipary, in which the largest embryos eat weaker and smaller siblings. This behavior is also most commonly found among sharks, such as the grey nurse shark, but has also been reported for *Nomorhamphus ebrardtii*.

Aquarists commonly refer to ovoviviparous and viviparous fishes as livebearers.

Immune system

Immune organs vary by type of fish. In the jawless fish (lampreys and hagfishes), true lymphoid organs are absent. These fish rely on regions of lymphoid tissue within other organs to produce immune cells. For example, erythrocytes, macrophages and plasma cells are produced in the anterior kidney (or pronephros) and some areas of the gut (where granulocytes mature.) They resemble primitive bone marrow in hagfish. Cartilaginous fish (sharks and rays) have a more advanced immune system. They have three specialized organs that are unique to chondrichthyes; the epigonal organs (lymphoid tissue similar to mammalian bone) that surround the gonads, the Leydig's organ within the walls of their esophagus, and a spiral valve in their intestine. These organs house typical immune cells (granulocytes, lymphocytes and plasma cells). They also possess an identifiable thymus and a well-developed spleen (their most important immune organ) where various lymphocytes, plasma cells and macrophages develop and are stored. Chondrostean fish (sturgeons, paddlefish and bichirs) possess a major site for the production of granulocytes within a mass that is associated with the meninges (membranes surrounding the central nervous system.) Their heart is frequently covered with tissue that contains lymphocytes, reticular cells and a small number of macrophages. The chondrostean kidney is an important hemopoietic organ; where erythrocytes, granulocytes, lymphocytes and macrophages develop.

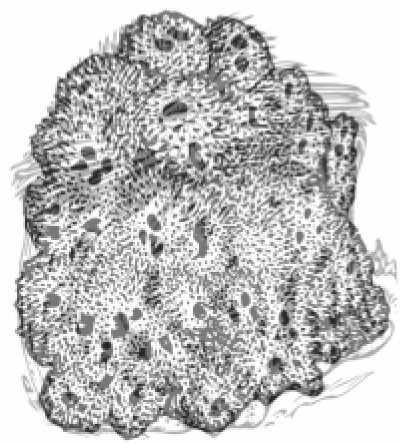
Like chondrostean fish, the major immune tissues of bony fish (or teleostei) include the kidney (especially the anterior kidney), which houses many different immune cells. In addition, teleost fish possess a thymus, spleen and scattered immune areas within mucosal tissues (e.g. in the skin, gills, gut and gonads). Much like the mammalian immune system, teleost erythrocytes, neutrophils and granulocytes are believed to reside in the spleen whereas lymphocytes are the major cell type found in the thymus. In 2006, a lymphatic system similar to that in mammals was described in one species of teleost fish, the zebrafish. Although not confirmed as yet, this system presumably will be where naive (unstimulated) T cells accumulate while waiting to encounter an antigen.

Diseases

Like other animals, fish suffer from diseases and parasites. To prevent disease they have a variety of defenses. *Non-specific* defenses include the skin and scales, as well as the mucus layer secreted by the epidermis that traps and inhibits the growth of microorganisms. If pathogens breach these defenses, fish can develop an inflammatory response that increases blood flow to the infected region and delivers white blood cells that attempt to destroy pathogens. Specific defenses respond to particular pathogens recognised by the fish's body, i.e., an immune response. In recent years, vaccines have become widely used in aquaculture and also with ornamental fish, for example furunculosis vaccines in farmed salmon and koi herpes virus in koi.

Some species use cleaner fish to remove external parasites. The best known of these are the Bluestreak cleaner wrasses of the genus *Labroides* found on coral reefs in the Indian and Pacific Oceans. These small fish maintain so-called "cleaning stations" where other fish congregate and perform specific movements to attract the attention of the cleaners. Cleaning behaviors have been observed in a number of fish groups, including an interesting case between two cichlids of the same genus, *Etroplus maculatus*, the cleaner, and the much larger *Etroplus suratensis*.

Evolution



Outdated evolutionary view of continual gradation

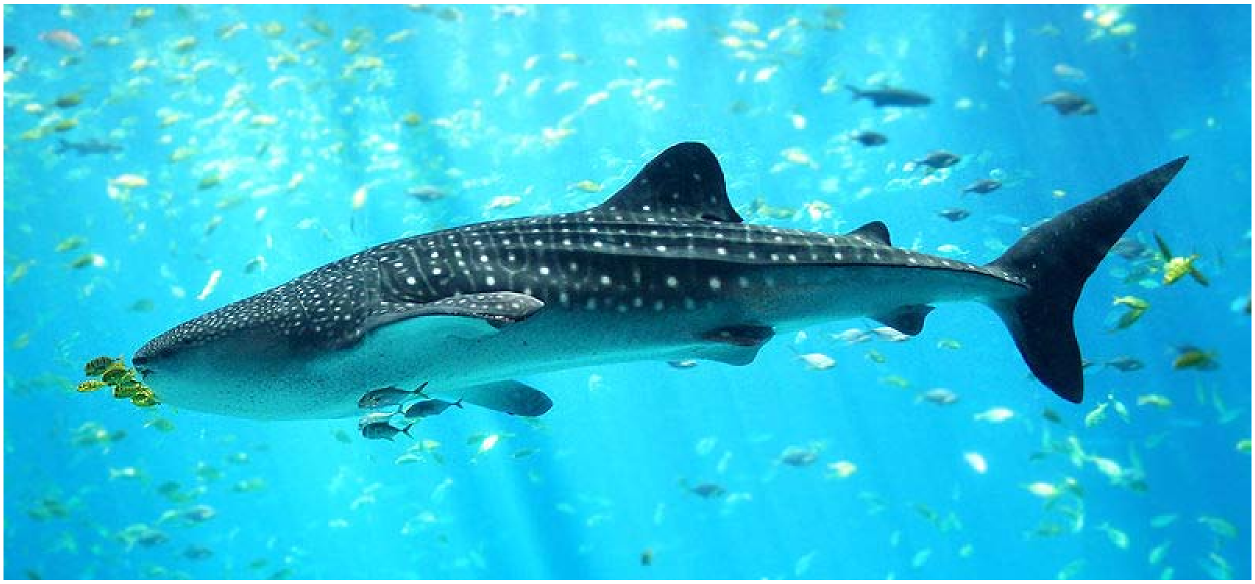
Dunkleosteus was a gigantic, 10 meter (33 ft) long prehistoric fish

Fish do not represent a monophyletic group, and therefore the "evolution of fish" is not studied as a single event.

Proliferation of fish was apparently due to the hinged jaw, because jawless fish left very few descendants. Lampreys may approximate pre-jawed fish. The first jaws are found in Placodermi fossils. It is unclear if the advantage of a hinged jaw is greater biting force, improved respiration, or a combination of factors.

Fish may have evolved from a creature similar to a coral-like Sea squirt, whose larvae resemble primitive fish in important ways. The first ancestors of fish may have kept the larval form into adulthood (as some sea squirts do today), although perhaps the reverse is the case.

Conservation



A Whale shark, the world's largest fish, is classified as Vulnerable

The 2006 IUCN Red List names 1,173 fish species that are threatened with extinction. Included are species such as Atlantic cod, Devil's Hole pupfish, coelacanths, and great white sharks. Because fish live underwater they are more difficult to study than terrestrial animals and plants, and information about fish populations is often lacking. However, freshwater fish seem particularly threatened because they often live in relatively small water bodies. For example, the Devil's Hole pupfish occupies only a single 3 by 6 metres (10 by 20 ft) pool.

Overfishing

Overfishing is a major threat to edible fishes such as cod and tuna. Overfishing eventually causes population (known as stock) collapse because the survivors cannot produce enough young to replace those removed. Such **commercial extinction** does not mean that the species is extinct, merely that it can no longer sustain a fishery.

One well-studied example of fishery collapse is the Pacific sardine *Sadinops sagax caerulues* fishery off the California coast. From a 1937 peak of 790,000 long tons (800,000 t) the catch steadily declined to only 24,000 long tons (24,000 t) in 1968, after which the fishery was no longer economically viable.

The main tension between fisheries science and the fishing industry is that the two groups have different views on the resiliency of fisheries to intensive fishing. In places such as Scotland, Newfoundland, and Alaska the fishing industry is a major employer, so governments are predisposed to support it. On the other hand, scientists and conservationists push for stringent protection, warning that many stocks could be wiped out within fifty years.

Habitat destruction

A key stress on both freshwater and marine ecosystems is habitat degradation including water pollution, the building of dams, removal of water for use by humans, and the introduction of exotic species. An example of a fish that has become endangered because of habitat change is the pallid sturgeon, a North American freshwater fish that lives in rivers damaged by human activity.

Exotic species

Introduction of non-native species has occurred in many habitats. One of the best studied examples is the introduction of Nile perch into Lake Victoria in the 1960s. Nile perch gradually exterminated the lake's 500 endemic cichlid species. Some of them survive now in captive breeding programmes, but others are probably extinct. Carp, snakeheads, tilapia, European perch, brown trout, rainbow trout, and sea lampreys are other examples of fish that have caused problems by being introduced into a lien environments.

Terminology

Fish or fishes

Though often used interchangeably, these words have different meanings. ***Fish*** is used either as singular noun or to describe a group of specimens from a single species. ***Fishes*** describes a group of different species.

Shoal or school

These goldband fusiliers are schooling because their swimming is synchronised

A random assemblage of fishes merely using some localised resource such as food or nesting sites is known simply as an ***aggregation***. When fish come together in an interactive, social grouping, then they may be forming either a *shoal* or a *school* depending on the degree of organisation. A ***shoal*** is a loosely organised group where each fish swims and forages independently but is attracted to other members of the group and adjusts its behaviour, such as swimming speed, so that it remains close to the other members of the group. ***Schools*** of fish are much more tightly organised, synchronising their swimming so that all fish move at the same speed and in the same direction. Shoaling and schooling behaviour is believed to provide a variety of advantages.

Examples:

- Cichlids congregating at lekking sites form an *aggregation*.
- Many minnows and characins form *shoals*.
- Anchovies, herrings, and silversides are classic examples of *schooling* fishes.

While school and shoal have different meanings within biology, they are often treated as synonyms by non-specialists, with speakers of British English using "shoal" to describe any grouping of fish, while speakers of American English often using "school" just as loosely.

Marine reptile

Sea turtle

Marine reptiles are reptiles which have become secondarily adapted for an aquatic or semi-aquatic life in a marine environment.

The earliest marine reptiles arose in the Permian period during the Paleozoic era. During the Mesozoic era, many groups of reptiles became adapted to life in the seas, including such familiar clades as the ichthyosaurs, plesiosaurs (these two orders were once thought united in the "Enalosauria", now known to be an unnatural group), placodonts, and mosasaurs.

After the mass extinction at the end of the Cretaceous period, marine reptiles were less numerous. Extant marine reptiles include marine iguanas, sea snakes, sea turtles, and some species of crocodiles.

Some marine reptiles, such as ichthyosaurs and mosasaurs, rarely ventured onto land and gave birth in the water. Others, such as sea turtles, and saltwater crocodiles, return to shore to lay their eggs. Some marine reptiles also occasionally rest and bask on land.

Seabird

The Sooty Tern is highly aerial and marine and will spend months flying at sea, returning to land only for breeding.

Seabirds (also known as **marine birds**) are birds that have adapted to life within the marine environment. While seabirds vary greatly in lifestyle, behaviour and physiology, they often exhibit striking convergent evolution, as the same environmental problems and feeding niches have resulted in similar adaptations. The first seabirds evolved in the Cretaceous period, and modern seabird families emerged in the Paleogene.

In general, seabirds live longer, breed later and have fewer young than other birds do, but they invest a great deal of time in their young. Most species nest in colonies, which can vary in size from a few dozen birds to millions. Many species are famous for undertaking long annual migrations, crossing the equator or circumnavigating the Earth in some cases. They feed both at the ocean's surface and below it, and even feed on each other. Seabirds can be highly pelagic, coastal, or in some cases spend a part of the year away from the sea entirely.

Seabirds and humans have a long history together: they have provided food to hunters, guided fishermen to fishing stocks and led sailors to land. Many species are currently threatened by human activities, and conservation efforts are under way.

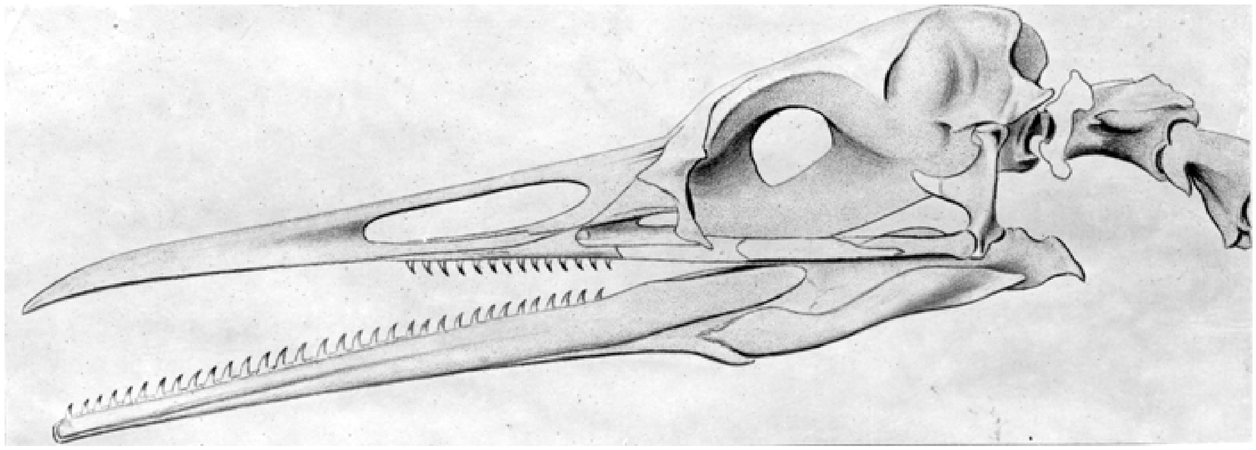
Classification of seabirds

There exists no single definition of which groups, families, and species are seabirds, and most definitions are in some way arbitrary. In the words of two seabird scientists, "The one common characteristic that all seabirds share is that they feed in saltwater; but, as seems to be true with any statement in biology, some do not." However, by convention all of the Sphenisciformes and Procellariiformes, all of the Pelecaniformes except the darters, and some of the Charadriiformes (the skuas, gulls, terns, auks and skimmers) are classified as seabirds. The phalaropes are usually included as well, since although they are waders ("shorebirds" in North America), two of the three species are oceanic for nine months of the year, crossing the equator to feed pelagically.

Loons and grebes, which nest on lakes but winter at sea, are usually categorized as water birds, not seabirds. Although there are a number of sea ducks in the family Anatidae which are truly marine in the winter, by convention they are usually excluded from the seabird grouping. Many waders (or shorebirds) and herons are also highly marine, living on the sea's edge (coast), but are also not treated as seabirds.

Evolution and fossil record

Seabirds, by virtue of living in a geologically depositional environment (that is, in the sea where sediments are readily laid down), are well represented in the fossil record. They are first known to occur in the Cretaceous Period, the earliest being the Hesperornithiformes, like *Hesperornis regalis*, a flightless loon-like seabird that dove in a fashion similar to grebes and loons (using its feet to move underwater) but had a beak filled with sharp teeth.



The Cretaceous seabird *Hesperornis*

While *Hesperornis* is not thought to have left descendants, the earliest modern seabirds also occurred in the Cretaceous, with a species called *Tytthostonyx glauconiticus*, which seems allied to the Procellariiformes and/or Pelecaniformes. In the Paleogene the seas were dominated by early Procellariidae, giant penguins and two extinct families, the Pelagornithidae and the Plotopteridae (a group of large seabirds that looked like the penguins). Modern genera began their wide radiation in the Miocene, although the genus *Puffinus* (which includes today's Manx Shearwater and Sooty Shearwater) might date back to the Oligocene. The highest diversity of seabirds apparently existed during the Late Miocene and the Pliocene. At the end of the latter, the oceanic food web had undergone a period of upheaval due to extinction of considerable numbers of marine species; subsequently, the spread of marine mammals seems to have prevented seabirds from reaching their erstwhile diversity.

Characteristics

Adaptations to life at sea

Seabirds have made numerous adaptations to living on and feeding in the sea. Wing morphology has been shaped by the niche an individual species or family has evolved, so that looking at a wing's shape and loading can tell a scientist about its life feeding behaviour. Longer wings and low wing loading are typical of more pelagic species, whilst diving species have shorter wings. Species such as the Wandering Albatross, which forage over huge areas of sea, have a reduced capacity for powered flight and are dependent on a type of gliding called dynamic soaring (where the wind deflected by waves provides lift) as well as slope soaring. Seabirds also almost always have webbed feet, to aid movement on the surface as well as assisting diving in some species. The Procellariiformes are unusual amongst birds in having a strong sense of smell, which is used to find widely distributed food in a vast ocean, and possibly to locate their colonies.

Salt glands are used by seabirds to deal with the salt they ingest by drinking and feeding (particularly on crustaceans), and to help them osmoregulate. The excretions from these glands (which are positioned in the head of the birds, emerging from the nasal cavity) are almost pure sodium chloride.

Cormorants, like this Double-Crested Cormorant, have plumage that is partly wettable, allowing them to dive without fighting buoyancy.

With the exception of the cormorants and some terns, and in common with most other birds, all seabirds have waterproof plumage. However, compared to land birds, they have far more feathers protecting their bodies. This dense plumage is better able to protect the bird from getting wet, and cold is kept out by a dense layer of down feathers. The cormorants possess a layer of unique feathers that retain a smaller layer of air (compared to other diving birds) but otherwise soak up water. This allows them to swim without fighting the buoyancy that retaining air in the feathers causes, yet retain enough air to prevent the bird losing excessive heat through contact with water.

The plumage of most seabirds is less colourful than that of land birds, restricted in the main to variations of black, white or grey. A few species sport colourful plumes (such as the tropicbirds or some penguins), but most of the colour in seabirds appears in the bills and legs. The plumage of seabirds is thought in many cases to be for camouflage, both defensive (the colour of US Navy battleships is the same as that of Antarctic Prions, and in both cases it reduces visibility at sea) and aggressive (the white underside possessed by many seabirds helps hide them from prey below).

Diet and feeding

Seabirds evolved to exploit different food resources in the world's seas and oceans, and to a great extent, their physiology and behaviour have been shaped by their diet. These evolutionary forces have often caused species in different families and even orders to evolve similar strategies and adaptations to the same problems, leading to remarkable convergent evolution, such as that between auks and penguins. There are four basic feeding strategies, or ecological guilds, for feeding at sea: surface feeding, pursuit diving, plunge diving, and predation of higher vertebrates; within these guilds there are multiple variations on the theme.

Surface feeding

Many seabirds feed on the ocean's surface, as the action of marine currents often concentrates food such as krill, forage fish, squid or other prey items within reach of a dipped head.

Wilson's Storm Petrels pattering on the water's surface

Surface feeding itself can be broken up into two different approaches, surface feeding while flying (for example as practiced by gadfly petrels, frigatebirds and storm-petrels), and surface feeding whilst swimming (examples of which are practiced by fulmars, gulls, many of the shearwaters and gadfly petrels). Surface feeders in flight include some of the most acrobatic of seabirds, which either snatch morsels from the water (as do frigate-birds and some terns), or "walk", pattering and hovering on the water's surface, as some of the storm-petrels do. Many of these do not ever land in the water, and some, such as the frigatebirds, have difficulty getting airborne again should they do so. Another seabird family that does not land while feeding is the skimmer, which has a unique fishing method: flying along the surface with the lower mandible in the water—this shuts automatically when the bill touches something in the water. The skimmer's bill reflects its unusual lifestyle, with the lower mandible uniquely being longer than the upper one.

Surface feeders that swim often have unique bills as well, adapted for their specific prey. Prions have special bills with filters called lamellae to filter out plankton from mouthfuls of water, and many albatrosses and petrels have hooked bills to snatch fast-moving prey. Gulls have more generalised bills that reflect their more opportunistic lifestyle.

Pursuit diving

The Chinstrap Penguin is a highly streamlined pursuit diver

Pursuit diving exerts greater pressures (both evolutionary and physiological) on seabirds, but the reward is a greater area in which to feed than is available to surface feeders. Propulsion underwater can be provided by wings (as used by penguins, auks, diving petrels, and some other species of petrel) or feet (as used by cormorants, grebes, loons and several types of fish-eating ducks). Wing-propelled divers are generally faster than foot-propelled divers. In both cases, the use of wings or feet for diving has limited their utility in other situations: loons and grebes walk with extreme difficulty (if at all), penguins cannot fly, and auks have sacrificed flight efficiency in favour of underwater diving. For example, the razorbill (an Atlantic auk) requires 64% more energy to fly than a petrel of equivalent size. Many shearwaters are intermediate between the two, having longer wings than typical wing-propelled divers but heavier wing loadings than the other surface-feeding procellariids, leaving them capable of diving to considerable depths while still being efficient long-distance travellers. The most impressive diving exhibited by shearwaters is found in the Short-tailed Shearwater, which has been recorded diving below 70 m. Some albatross species are also capable of some limited diving, with Light-mantled Sooty Albatrosses holding the record at 12 m. Of all the wing-propelled pursuit divers, the most efficient in the air are the albatrosses, and it is no coincidence that they are the poorest divers. This is the dominant guild in polar and subpolar environments, as it is energetically inefficient in warmer waters. With their poor flying ability, many wing-propelled pursuit divers are more limited in their foraging range than other guilds, especially during the breeding season when hungry chicks need regular feeding.

Plunge diving

Gannets, boobies, tropicbirds, some terns and Brown Pelicans all engage in plunge diving, taking fast moving prey by diving into the water from flight. Plunge diving allows birds to use the energy from the momentum of the dive to combat natural buoyancy (caused by air trapped in plumage), and thus uses less energy than the dedicated pursuit divers, allowing them to utilise more widely distributed food resources, for example, in impoverished tropical seas. In general, this is the most specialised method of hunting employed by seabirds; other non-specialists (such as gulls and skuas) may employ it but do so with less skill and from lower heights. In Brown Pelicans the skills of plunge diving take several years to fully develop—once mature, they can dive from 20 m (70 ft) above the water's surface, shifting the body before impact to avoid injury. It has been suggested that plunge divers are restricted in their hunting grounds to clear waters that afford a view of their prey from the air, and while they are the dominant guild in the tropics, the link between plunge diving and water clarity is inconclusive. Some plunge divers (as well as some surface feeders) are dependent on dolphins and tuna to push shoaling fish up towards the surface.

Kleptoparasitism, scavenging and predation

Some seabirds, like this South Polar Skua (left), will take the eggs of other birds. This skua is attempting to push an Adelie Penguin (right) off its nest.

This catch-all category refers to other seabird strategies that involve the next trophic level up. Kleptoparasites are seabirds that make a part of their living stealing food of other seabirds. Most famously, frigatebirds and skuas engage in this behaviour, although gulls, terns and other species will steal food opportunistically. The nocturnal nesting behaviour of some seabirds has been interpreted as arising due to pressure from this aerial piracy. Kleptoparasitism is not thought to play a significant part of the diet of any species, and is instead a supplement to food obtained by hunting. A study of Great Frigatebirds stealing from Masked Boobies estimated that the frigatebirds could at most obtain 40% of the food they needed, and on average obtained only 5%. Many species of gull will feed on seabird and sea mammal carrion when the opportunity arises, as will giant petrels. Some species of albatross also engage in scavenging: an analysis of regurgitated squid beaks has shown that many of the squid eaten are too large to have been caught alive, and include mid-water species likely to be beyond the reach of albatrosses. Some species will also feed on other seabirds; for example, gulls, skuas and giant petrels will often take eggs, chicks and even small adult seabirds from nesting colonies.

Life history

Seabirds' life histories are dramatically different from those of land birds. In general, they are K-selected, live much longer (anywhere between twenty and sixty years), delay breeding for longer (for up to ten years), and invest more effort into fewer young. Most species will only have one clutch a year, unless they lose the first (with a few exceptions, like the Cassin's Auklet), and many species (like the tubenoses and sulids), only one egg a year.

Northern Gannet pair "billing" during courtship; like all seabirds except the phalaropes they maintain a pair bond throughout the breeding season.

Care of young is protracted, extending for as long as six months, among the longest for birds. For example, once Common Guillemot chicks fledge, they remain with the male parent for several months at sea. The frigatebirds have the longest period of parental care of any bird, with the chicks fledging after four to six months and with continued assistance after that for up to fourteen months. Due to the extended period of care, breeding occurs every two years rather than annually for some species. This life-history strategy has probably evolved both in response to the challenges of living at sea (collecting widely scattered prey items), the frequency of breeding failures due to unfavourable marine conditions, and the relative lack of predation compared to that of land-living birds.

Because of the greater investment in raising the young and because foraging for food may occur far from the nest site, in all seabird species except the phalaropes, both parents participate in caring for the young, and pairs are typically at least seasonally monogamous. Many species, such as gulls, auks and penguins, retain the same mate for several seasons, and many petrel species mate for life. The albatrosses and procellariids which mate for life can take many years to form a pair bond before they breed, and the albatrosses have an elaborate breeding dance that is part of pair-bond formation.

Breeding and colonies

Common Murres breed on densely packed colonies on offshore rocks, islands and cliffs

Ninety-five per cent of seabirds are colonial, and seabird colonies are amongst the largest bird colonies in the world, providing one of Earth's great wildlife spectacles. Colonies of over a million birds have been recorded, both in the tropics (such as Kiritimati in the Pacific) and in the polar latitudes (as in Antarctica). Seabird colonies occur exclusively for the purpose of breeding; non-breeding birds will only collect together outside the breeding season in areas where prey species are densely aggregated.

Seabird colonies are highly variable. Individual nesting sites can be widely spaced, as in an albatross colony, or densely packed as with a murre colony. In most seabird colonies, several different species will nest on the same colony, often exhibiting some niche separation. Seabirds can nest in trees (if any are available), on the ground (with or without nests), on cliffs, in burrows under the ground and in rocky crevices. Competition can be strong both within species and between species, with aggressive species such as Sooty Terns pushing less dominant species out of the most desirable nesting spaces. The tropical Bonin Petrel nests during the winter to avoid competition with the more aggressive Wedge-tailed Shearwater. When the seasons overlap, the Wedge-tailed Shearwaters will kill young Bonin Petrels in order to use their burrows.

Many seabirds show remarkable site fidelity, returning to the same burrow, nest or site for many years, and they will defend that site from rivals with great vigour. This increases breeding success, provides a place for returning mates to reunite, and reduces the costs of prospecting for a new site. Young adults breeding for the first time usually return to their natal colony, and often nest close to where they hatched. This tendency, known as philopatry, is so strong that a study of Laysan Albatrosses found that the average distance between hatching site and the site where a bird established its own territory was 22 m; another study, this time on Cory's Shearwaters nesting near Corsica, found that of nine out of 61 male chicks that returned to breed at their natal colony bred in the burrow they were raised in, and two actually bred with their own mother.

Colonies are usually situated on islands, cliffs or headlands which land mammals have difficulty accessing. This is thought to provide protection to seabirds, which are often very clumsy on land. Coloniality often arises in types of bird which do not defend feeding territories (such as swifts, which have a very variable prey source); this may be a reason why it arises more frequently in seabirds. There are other possible advantages: colonies may act as information centres, where seabirds returning to the sea to forage can find out where prey is by studying returning individuals of the same species. There are disadvantages to colonial life, particularly the spread of disease. Colonies also attract the attention of predators, principally other birds, and many species attend their colonies nocturnally to avoid predation.

Migration

Pelicans flock flying over Havana Bay area. These birds come to Cuba every year from North America in the north hemisphere winter season.

Arctic Terns breed in the arctic and subarctic and winter in Antarctica

Like many birds, seabirds often migrate after the breeding season. Of these, the trip taken by the Arctic Tern is the farthest of any bird, crossing the equator in order to spend the Austral summer in Antarctica. Other species also undertake trans-equatorial trips, both from the north to the south, and from south to north. The population of Elegant Terns, which nest off Baja California, splits after the breeding season with some birds travelling north to the Central Coast of California and some travelling as far south as Peru and Chile to feed in the Humboldt Current. The Sooty Shearwater undertakes an annual migration cycle that rivals that of the Arctic Tern; birds that nest in New Zealand and Chile and spend the northern summer feeding in the North Pacific off Japan, Alaska and California, an annual round trip of 40,000 statute miles (64,000 km).

Other species also migrate shorter distances away from the breeding sites, their distribution at sea determined by the availability of food. If oceanic conditions are unsuitable, seabirds will emigrate to more productive areas, sometimes permanently if the bird is young. After fledging, juvenile birds often disperse further than adults, and to different areas, so are commonly sighted far from a species' normal range. Some species, such as the auks, do not have a concerted migration effort, but drift southwards as the winter approaches. Other species, such as some of the storm-petrels, diving petrels and cormorants, never disperse at all, staying near their breeding colonies year round.

Away from the sea

While the definition of seabirds suggests that the birds in question spend their lives on the ocean, many seabird families have many species that spend some or even most of their lives inland away from the sea. Most strikingly, many species breed many tens, hundreds or even thousands of miles inland. Some of these species still return to the ocean to feed; for example, the Snow Petrel, the nests of which have been found 480 km (300 miles) inland on the Antarctic mainland, are unlikely to find anything to eat around their breeding sites. The Marbled Murrelet nests inland in old growth forest, seeking huge conifers with large branches to nest on. Other species, such as the California Gull, nest and feed inland on lakes, and then move to the coasts in the winter. Some cormorant, pelican, gull and tern species have individuals that never visit the sea at all, spending their lives on lakes, rivers, swamps and, in the case of some of the gulls, cities and agricultural land. In these cases it is thought that these terrestrial or freshwater birds evolved from marine ancestors. Some seabirds, principally those that nest in tundra-like skuas and phalaropes, will migrate over land as well.

The more marine species, such as petrels, auks, and gannets, are more restricted in their habits, but are occasionally seen inland as vagrants. This most commonly happens to young inexperienced birds, but can happen in great numbers to exhausted adults after large storms, an event known as a *wreck*, where they provide prized sightings for birders.

Relationship with humans

Seabirds and fisheries

Seabirds have had a long association with both fisheries and sailors, and both have drawn benefits and disadvantages from the relationship.

Fishermen have traditionally used seabirds as indicators of both fish shoals, underwater banks that might indicate fish stocks, and of potential landfall. In fact, the known association of seabirds with land was instrumental in allowing the Polynesians to locate tiny landmasses in the Pacific. Seabirds have provided food for fishermen away from home, as well as bait. Famously, tethered cormorants have been used to catch fish directly. Indirectly, fisheries have also benefited from guano from colonies of seabirds acting as fertilizer for the surrounding seas.

Negative effects on fisheries are mostly restricted to raiding by birds on aquaculture, although long-lining fisheries also have to deal with bait stealing. There have been claims of prey depletion by seabirds of fishery stocks, and while there is some evidence of this, the effects of seabirds are considered smaller than that of marine mammals and predatory fish (like tuna).

Seabirds (mostly Northern Fulmars) flocking at a long-lining vessel

Some seabird species have benefited from fisheries, particularly from discarded fish and offal. These discards compose 30% of the food of seabirds in the North Sea, for example, and compose up to 70% of the total food of some seabird populations. This can have other impacts; for example, the spread of the Northern Fulmar through the United Kingdom is attributed in part to the availability of discards. Discards generally benefit surface feeders, such as gannets and petrels, to the detriment of pursuit divers like penguins.

Fisheries also have negative effects on seabirds, and these effects, particularly on the long-lived and slow-breeding albatrosses, are a source of increasing concern to conservationists. The bycatch of seabirds entangled in nets or hooked on fishing lines has had a big impact on seabird numbers; for example, an estimated 100,000 albatrosses are hooked and drown each year on tuna lines set out by long-line fisheries. Overall, many hundreds of thousands of birds are trapped and killed each year, a source of concern for some of the rarest species (for example, only about 2,000 Short-tailed Albatrosses are known to still exist). Seabirds are also thought to suffer when overfishing occurs.

Exploitation

The hunting of seabirds and the collecting of seabird eggs have contributed to the declines of many species, and the extinction of several, including the Great Auk and the Spectacled Cormorant. Seabirds have been hunted for food by coastal peoples throughout history—one of the earliest instances known is in southern Chile, where archaeological excavations in middens has shown hunting of albatrosses, cormorants and shearwaters from 5000 BP. This pressure has led to some species becoming extinct in many places; in particular, at least 20 species of an original 29 no longer breed on Easter Island. In the 19th century, the hunting of seabirds for fat deposits and feathers for the millinery trade reached industrial levels. Muttonbirding (harvesting shearwater chicks) developed as important industries in both New Zealand and Tasmania, and the name of one species, the Providence Petrel, is derived from its seemingly miraculous arrival on Norfolk Island where it provided a windfall for starving European settlers. In the Falkland Islands, hundreds of thousands of penguins were harvested for their oil each year. Seabird eggs have also long been an important source of food for sailors undertaking long sea voyages, as well as being taken when settlements grow in areas near a colony. Eggers from San Francisco took almost half a million eggs a year from the Farallon Islands in the mid-19th century, a period in the islands' history from which the seabird species are still recovering.

Both hunting and egging continue today, although not at the levels that occurred in the past, and generally in a more controlled manner. For example, the Māori of Stewart Island/Rakiura continue to harvest the chicks of the Sooty Shearwater as they have done for centuries, using traditional methods (called *kaitiakitanga*) to manage the harvest, but now work with the University of Otago in studying the populations. In Greenland, however, uncontrolled hunting is pushing many species into steep decline.

Other threats

Other human factors have led to declines and even extinctions in seabird populations, colonies and species. Of these, perhaps the most serious are introduced species. Seabirds, breeding predominantly on small isolated islands, have lost many predator defence behaviours. Feral cats are capable of taking seabirds as large as albatrosses, and many introduced rodents, such as the Pacific Rat, can take eggs hidden in burrows. Introduced goats, cattle, rabbits and other herbivores can lead to problems, particularly when species need vegetation to protect or shade their young. Disturbance of breeding colonies by humans is often a problem as well—visitors, even well-meaning tourists, can flush brooding adults off a colony leaving chicks and eggs vulnerable to predators.

This Crested Auklet was oiled in Alaska during the M/V Selendang Ayu spill of 2004

The build-up of toxins and pollutants in seabirds is also a concern. Seabirds, being apex predators, suffered from the ravages of DDT until it was banned; among other effects, DDT was implicated in embryo development problems and the skewed sex ratio of Western Gulls in southern California. Oil spills are also a threat to seabird species, as both a toxin and because the feathers of the birds become saturated by the oil, causing them to lose their waterproofing. Oil pollution threatens species with restricted ranges or already depressed populations.

Conservation

The threats faced by seabirds have not gone unnoticed by scientists or the conservation movement. As early as 1903, U.S. President Theodore Roosevelt was convinced of the need to declare Pelican Island in Florida a National Wildlife Refuge to protect the bird colonies (including the nesting Brown Pelicans), and in 1909 he protected the Farallon Islands. Today many important seabird colonies are given some measure of protection, from Heron Island in Australia to Triangle Island in British Columbia.

Island restoration techniques, pioneered by New Zealand, enable the removal of exotic invaders from increasingly large islands. Feral cats have been removed from Ascension Island, Arctic

Foxes from many islands in the Aleutian Islands, and rats from Campbell Island. The removal of these introduced species has led to increases in numbers of species under pressure and even the return of extirpated ones. After the removal of cats from Ascension Island, seabirds began to nest there again for the first time in over a hundred years.

Seabird mortality caused by long-line fisheries can be greatly reduced by techniques such as setting long-line bait at night, dying the bait blue, setting the bait underwater, increasing the amount of weight on lines and by using bird scarers, and their deployment is increasingly required by many national fishing fleets. The international ban on the use of drift nets has also helped reduce the mortality of seabirds and other marine wildlife.

One of the Millennium Projects in the UK was the Scottish Seabird Centre, near the important bird sanctuaries on Bass Rock, Fidra and the surrounding islands. The area is home to huge colonies of gannets, puffins, skuas and other seabirds. The centre allows visitors to watch live video from the islands as well as learn about the threats the birds face and how we can protect them, and has helped to significantly raise the profile of seabird conservation in the UK. Seabird tourism can provide income for coastal communities as well as raise the profile of seabird conservation. For example, the Northern Royal Albatross colony at Taiaroa Head in New Zealand attracts 40,000 visitors a year.

The plight of albatross and large seabirds, as well as other marine creatures, being taken as bycatch by long-line fisheries, has been addressed by a large number of non-governmental organizations (including BirdLife International, the American Bird Conservancy, and the Royal Society for the Protection of Birds). This led to the Agreement on the Conservation of Albatrosses and Petrels, a legally binding treaty designed to protect these threatened species, which has been ratified by eleven countries as of 2008 (namely Argentina, Australia, Chile, Ecuador, France, New Zealand, Norway, Peru, South Africa, Spain, and the United Kingdom).

Marine mammal

A Humpback whale (*Megaptera novaeangliae*), a member of order Cetacea

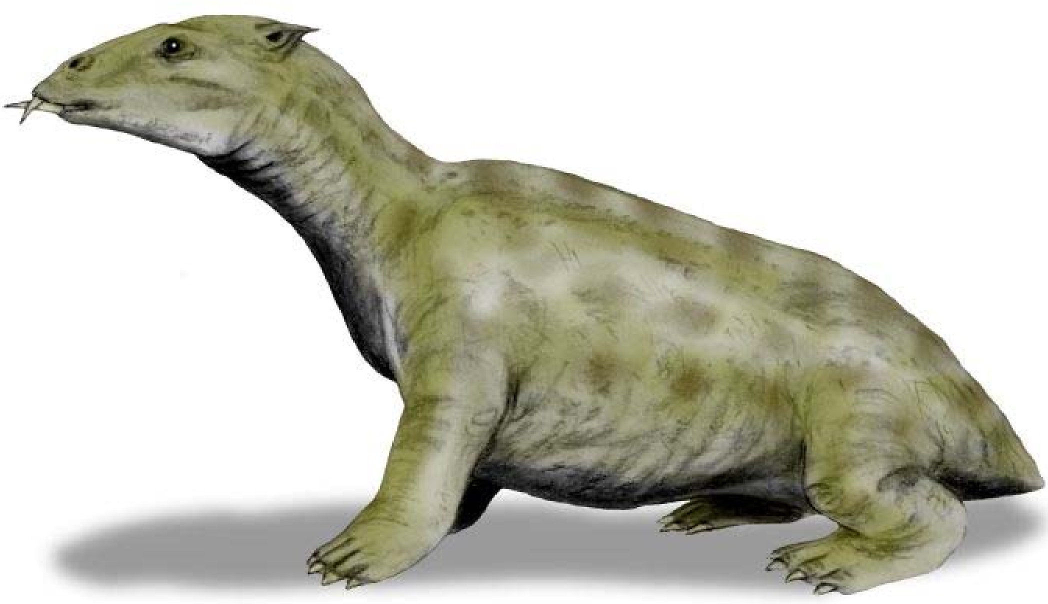
A Leopard seal (*Hydrurga leptonyx*), a member of suborder Pinnipedia of order Carnivora

A West Indian Manatee (*Trichechus manatus*), a member of order Sirenia

A Sea Otter (*Enhydra lutris*), a member of family Mustelidae

A Polar bear (*Ursus maritimus*), a member of family Ursidae

California sea lions, members of the family Otariidae



Desmostylus

Marine mammals are a diverse group of 120 species of mammal that are primarily ocean-dwelling or depend on the ocean for food. They include the cetaceans (whales, dolphins, and porpoises), the sirenians (manatees and dugong), the pinnipeds (true seals, eared seals and walrus), and several otters (the sea otter and marine otter). The polar bear, while not fully aquatic, is also usually considered a marine mammal because it lives on sea ice for most or all of the year.

Marine mammals evolved from land dwelling ancestors and share several adaptive features for life at sea such as generally large size, hydrodynamic body shapes, modified appendages and various thermoregulatory adaptations. Whales are the largest mammals ever. Different species are, however, adapted to marine life to varying degrees. The most fully adapted are the cetaceans and the sirenians, which cannot live on land.

Despite the fact that marine mammals are highly recognizable charismatic megafauna, many populations are vulnerable or endangered due to a history of commercial use for blubber, meat, ivory and fur. Most species are currently in protection from commercial use.

Groups

There are some 120 extant species of marine mammals, generally sub-divided into the five groups bold-faced below. Each group descended from a different land-based ancestor. The morphological similarities between these diverse groups are a result of convergent and parallel evolution. For example, although whales and seals have some similarities in shape, whales are more closely related to deer than they are to seals.

- **Order Sirenia**: Sirenians, belonging to Afrotheria, a group that includes elephants and hyraxes
    - family Trichechidae: manatees (3 species, however, only one is actually a marine mammal)
    - family Dugongidae: dugong (1 species)
- **Order Cetacea**: Cetaceans, belonging to Cetartiodactyla, a group that includes hippopotamuses, deer, and pigs.
    - Suborder Mysticeti: Baleen whales (14 or 15 species)
    - Suborder Odontoceti: Toothed whales (around 73 species)
- **Order Carnivora**,
    - **superfamily Pinnipedia**, belonging to Caniformia descended from a bear-like ancestor.
        - family Phocidae: true seals (around 20 species)
        - family Otariidae: eared seals (around 16 species)
        - family Odobenidae: walrus (1 species)
    - **family Mustelidae**, belonging to Caniformia and most closely related to other otters and weasels
        - sea otter (*Enhydra lutris*)
        - marine otter (*Lontra felina*)
    - **family Ursidae**, belonging to Caniformia

        - polar bear (*Ursus maritimus*), most closely related to other bears, particularly the brown bear
- **Order** Desmostylia
- **Order** Pilosa
    - *Thalassocnus*

Several groups of marine mammals existed in the past that are not alive today. In addition to the ancestors of the modern day whales, seals, and manatees, there existed desmostylians, cousins of the manatees, and *Kolponomos*, a genus of clam-eating marine bears not related to the modern polar bear.

Adaptations

Since mammals originally evolved on land, their spines are optimized for running, allowing for up-and-down but only little sideways motion. Therefore, marine mammals typically swim by moving their spine up and down. By contrast, fish normally swim by moving their spine sideways. For this reason, fish mostly have vertical caudal (tail) fins, while marine mammals have horizontal caudal fins.

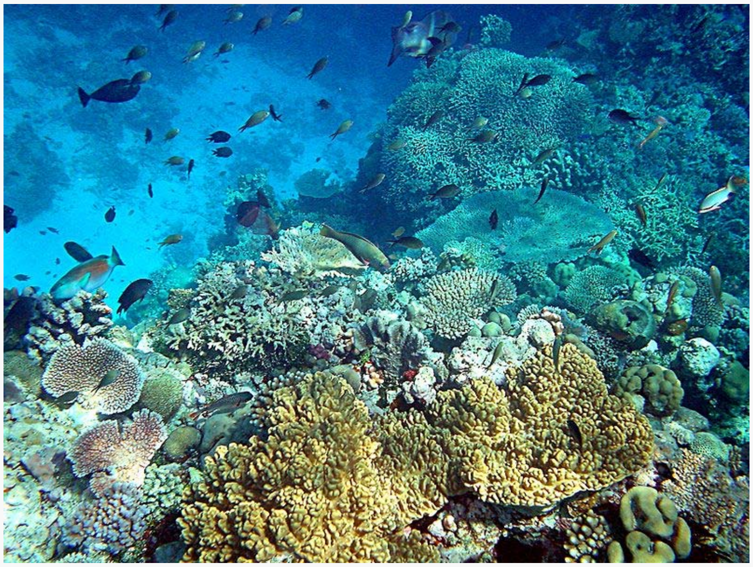
Some of the primary differences between marine mammals and other marine life are:

- Marine mammals breathe air, while most other marine animals extract oxygen from water.
- Marine mammals have hair. Cetaceans have little or no hair, usually a very few bristles retained around the head or mouth. All members of the Carnivora have a coat of fur or hair, but it is far thicker and more important for thermoregulation in sea otters and polar bears than in seals or sea lions. Thick layers of fur contribute to drag while swimming, and slow down a swimming mammal, giving it a disadvantage in speed.
- Marine mammals have thick layers of blubber used to insulate their bodies and prevent heat loss. Sea otters and polar bears are exceptions, relying more on fur and behavior to stave off hypothermia.
- Marine mammals give birth. Most marine mammals give birth to one calf or pup at a time.
- Marine mammals feed off milk as young. Maternal care is extremely important to the survival of offspring that need to develop a thick insulating layer of blubber. The milk from the mammary glands of marine mammals often exceeds 40-50% fat content to support the development of blubber.
- Marine mammals maintain a high internal body temperature. Unlike most other marine life, marine mammals carefully maintain a core temperature much higher than their environment. Blubber, thick coats of fur, bubbles of air between skin and water, countercurrent exchange, and behaviors such as hauling out, are all adaptations that aid marine mammals in retention of body heat.

The polar bear spends a large portion of its time in a marine environment, albeit a frozen one. When it does swim in the open sea it is extremely proficient and has been shown to cover 74 km in a day. For these reasons, some scientists regard it as a marine mammal.

Oceanic habitats

Ocean habitats



Corals and reef fish in Papua New Guinea

- Littoral zone
- Intertidal zone
- Estuaries
- Kelp forests
- Coral reefs
- Ocean banks
- Continental shelf
- Neritic zone
- Straits
- Pelagic zone
- Oceanic zone

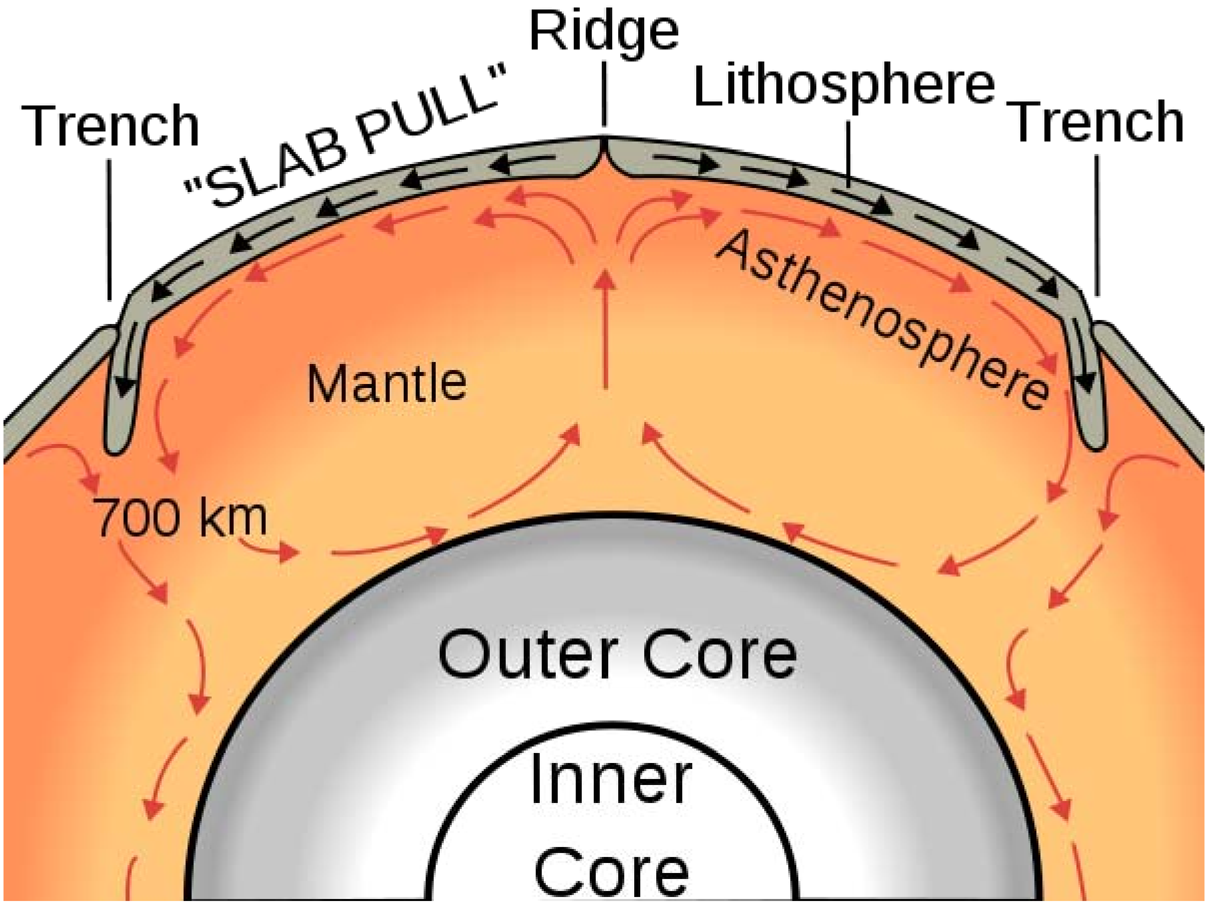
	Seamounts
	Hydrothermal vents
	Cold seeps
	Demersal zone
	Benthic zone

Reefs

Reefs comprise some of the densest and most diverse habitats in the world. The best-known types of reefs are tropical coral reefs which exist in most tropical waters; however, reefs can also exist in cold water. Reefs are built up by corals and other calcium-depositing animals, usually on top of a rocky outcrop on the ocean floor. Reefs can also grow on other surfaces, which has made it possible to create artificial reefs. Coral reefs also support a huge community of life, including the corals themselves, their symbiotic zooxanthellae, tropical fish and many other organisms.

Much attention in marine biology is focused on coral reefs and the El Niño weather phenomenon. In 1998, coral reefs experienced a "once in a thousand years" bleaching event, in which vast expanses of reefs across the Earth died because sea surface temperatures rose well above normal. Some reefs are recovering, but scientists say that 58% of the world's coral reefs are now endangered and predict that global warming could exacerbate this trend.

Oceanic trench



Oceanic crust is formed at an oceanic ridge, while the lithosphere is subducted back into the asthenosphere at trenches.

The **oceanic trenches** are hemispheric-scale long but narrow topographic depressions of the sea floor. They are also the deepest parts of the ocean floor.

Trenches define one of the most important natural boundaries on the Earth's solid surface: the one between two lithospheric plates. There are three types of lithospheric plate boundaries: divergent (where lithosphere and oceanic crust is created at mid-ocean ridges), convergent (where one lithospheric plate sinks beneath another and returns to the mantle), and transform (where two lithospheric plates slide past each other).

Trenches are a distinctive morphological feature of plate boundaries. Along convergent plate boundaries, plates move together at rates that vary from a few mm to over ten cm per year. A trench marks the position at which the flexed, subducting slab begins to descend beneath another lithospheric slab. Trenches are generally parallel to a volcanic island arc, and about 200 km from a volcanic arc. Oceanic trenches typically extend 3 to 4 km (1.9 to 2.5 mi) below the level of the surrounding oceanic floor. The greatest ocean depth to be sounded is in the Challenger Deep of the Mariana Trench, at a depth of 10,911 m (35,798 ft) below sea level. Oceanic lithosphere moves into trenches at a global rate of about a tenth of a square metre per second.

Geographic distribution

There are about 50,000 km of convergent plate margins, mostly around the Pacific Ocean—the reason for the reference "Pacific-type" margin—but they are also in the eastern Indian Ocean, with relatively short convergent margin segments in the Atlantic Ocean and in the Mediterranean Sea. Trenches are sometimes buried and lack bathymetric expression, but the fundamental structures that these represent mean that the great name should also be applied here. This applies to Cascadia, Makran, southern Lesser Antilles, and Calabrian trenches. Trenches along with volcanic arcs and zones of earthquakes that dip under the volcanic arc as deeply as 700 km are diagnostic of convergent plate boundaries and their deeper manifestations, subduction zones. Trenches are related to but distinguished from continental collision zones (like that between India and Asia to form the Himalaya), where continental crust enters the subduction zone. When buoyant continental crust enters a trench, subduction eventually stops and the convergent plate margin becomes a collision zone. Features analogous to trenches are associated with collisions zones; these are sediment-filled foredeeps referred to as peripheral foreland basins, such as that which the Ganges River and Tigris-Euphrates rivers flow along.

History of the term "trench"

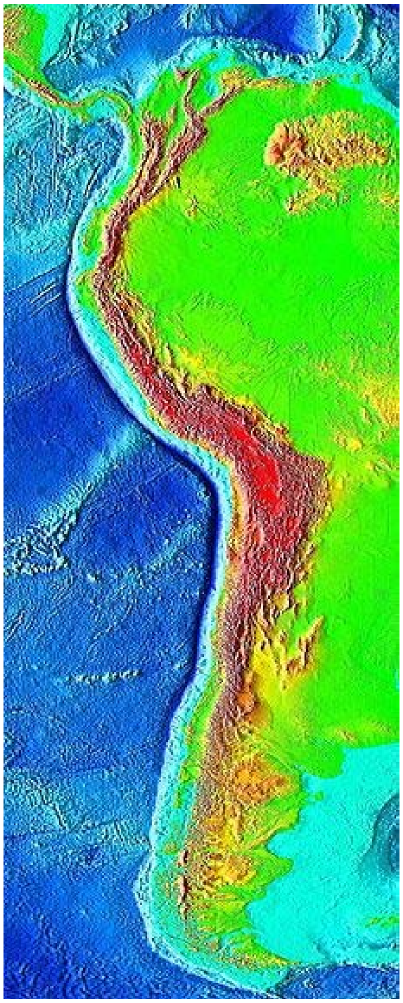
Trenches were not clearly defined until the late 1940s and 1950s. The bathymetry of the ocean was of no real interest until the late 19th and early 20th centuries, with the initial laying of Transatlantic telegraph cables on the seafloor between the continents. Even then the elongated bathymetric expression of trenches was not recognized until well into the 20th century. The term "trench" does not appear in Murray and Hjort's (1912) classic oceanography book. Instead they applied the term "deep" for the deepest parts of the ocean, such as Challenger Deep. Experiences from World War I battlefields emblazoned the concept of the trench warfare as an elongate depression defining an important boundary, so it was no surprise that the term "trench" was used to describe natural features in the early 1920s. The term was first used in a geologic context by Scofield two years after the war ended to describe a structurally-controlled depression in the Rocky Mountains. Johnstone, in his 1923 textbook *An Introduction to Oceanography* first used the term in its modern sense for any marked, elongate depression of the sea bottom.

During the 1920s and 1930s, Felix Andries Vening Meinesz developed a unique gravimeter that could measure gravity in the stable environment of a submarine and used it to measure gravity over trenches. His measurements revealed that trenches are sites of downwelling in the solid Earth. The concept of downwelling at trenches was characterized by Griggs in 1939 as the tectogene hypothesis, for which he developed an analogue model using a pair of rotating drums. World War II in the Pacific led to great improvements of bathymetry in especially the western and northern Pacific, and the linear nature of these deeps became clear. The rapid growth of deep sea research efforts, especially the widespread use of echosounders in the 1950s and 1960s confirmed the morphological utility of the term. The important trenches were identified, sampled, and their greatest depths sonically plumbed. The heroic phase of trench exploration culminated in the 1960 descent of the Bathyscaphe *Trieste*, which set an unbeatable world record by diving to the bottom of the Challenger Deep. Following Robert S. Dietz' and Harry Hess' articulation of the seafloor spreading hypothesis in the early 1960s and the plate tectonic revolution in the late 1960s the term "trench" has been redefined with plate tectonic as well as bathymetric connotations.

Trench rollback

Although trenches would seem to be positionally stable over time, it is hypothesized that some trenches, particularly those associated with subduction zones where two oceanic plates converge, retrograde, that is, they move backward into the plate which is subducting, akin to a backward-moving wave. This has been termed **trench rollback** (also **hinge rollback**). This is one explanation for the existence of back-arc basins.

Morphologic expression



The Peru-Chile Trench

Trenches are centerpieces of the distinctive physiography of a convergent plate margin. Transects across trenches yield asymmetric profiles, with relatively gentle (~5°) outer (seaward) slope and a steeper (~10–16°) inner (landward) slope. This asymmetry is due to the fact that the outer slope is defined by the top of the downgoing plate, which must bend as it starts its descent. The great thickness of the lithosphere requires that this bending be gentle. As the subducting plate approaches the trench, it is first bent upwards to form the outer trench swell, then descends to form the outer trench slope. The outer trench slope is disrupted by a set of subparallel normal faults which staircase the seafloor down to the trench. The plate boundary is defined by the trench axis itself. Beneath the inner trench wall, the two plates slide past each other along the subduction decollement, the seafloor intersection of which defines the trench location. The overriding plate contains volcanic arc (generally) and a forearc. The volcanic arc is caused by physical and chemical interactions between the subducted plate at depth and asthenospheric mantle associated with the overriding plate. The forearc lies between the trench and the volcanic arc. Forearcs have the lowest heatflow from the interior Earth because there is no asthenosphere (convecting mantle) between the forearc lithosphere and the cold subducting plate.

The inner trench wall marks the edge of the overriding plate and the outermost forearc. The forearc consists of igneous and metamorphic crust, and this crust acts as buttress to a growing accretionary prism (sediments scraped off the downgoing plate onto the inner trench wall, depending on how much sediment is supplied to the trench). If the flux of sediments is high, material will be transferred from the subducting plate to the overriding plate. In this case an accretionary prism grows and the location of the trench migrates progressively away from the volcanic arc over the life of the convergent margin. Convergent margins with growing accretionary prisms are called accretionary convergent margins and make up nearly half of all convergent margins. If the sediment flux is low, material will be transferred from the overriding plate to the subducting plate by a process of tectonic ablation known as subduction erosion and carried down the subduction zone. Forearcs undergoing subduction erosion typically expose igneous rocks. In this case, the location of the trench will migrate towards the magmatic arc over the life of the convergent margin. Convergent margins experiencing subduction erosion are called nonaccretionary convergent margins and comprise more than half of convergent plate boundaries. This is an oversimplification, because different parts of a convergent margin can experience sediment accretion and subduction erosion over its life.

The asymmetric profile across a trench reflects fundamental differences in materials and tectonic evolution. The outer trench wall and outer swell comprise seafloor that takes a few million years to move from where subduction-related deformation begins near the outer trench swell until sinking beneath the trench. In contrast, the inner trench wall is deformed by plate interactions for the entire life of the convergent margin. The forearc is continuously subjected to subduction-related earthquakes. This protracted deformation and shaking ensures that the inner trench slope is controlled by the angle of repose of whatever material it is composed of. Because they are composed of igneous rocks instead of deformed sediments, non-accretionary trenches have steeper inner walls than accretionary trenches.

Filled trenches

The composition of the inner trench slope and a first-order control on trench morphology is determined by sediment supply. Active accretionary prisms are common for trenches near continents where large rivers or glaciers reach the sea and supply great volumes of sediment which naturally flow to the trench. These filled trenches are confusing because in a plate tectonic sense they are indistinguishable from other convergent margins but lack the bathymetric expression of a trench. The Cascadia margin of the northwest USA is a filled trench, the result of sediments delivered by the rivers of the NW USA and SW Canada. The Lesser Antilles convergent margin shows the importance of proximity to sediment sources for trench morphology. In the south, near the mouth of the Orinoco River, there is no morphological trench and the forearc plus accretionary prism is almost 500 km wide. The accretionary prism is so large that it forms the islands of Barbados and Trinidad. Northward the forearc narrows, the accretionary prism disappears, and only north of 17°N the morphology of a trench is seen. In the extreme north, far away from sediment sources, the Puerto Rico Trench is over 8600 m deep and there is no active accretionary prism. A similar relationship between proximity to rivers, forearc width, and trench morphology can be observed from east to west along the Alaskan-Aleutian convergent margin. The convergent plate boundary offshore Alaska changes along its strike from a filled trench with broad forearc in the east (near the coastal rivers of Alaska) to a deep trench with narrow forearc in the west (offshore the Aleutian islands). Another example is the Makran convergent margin offshore Pakistan and Iran, which is a trench filled by sediments from the Tigris-Euphrates and Indus rivers. Thick accumulations of turbidites along a trench can be supplied by down-axis transport of sediments that enter the trench 1,000–2,000 km away, as is found for the Peru-Chile Trench south of Valparaíso and for the Aleutian Trench. Convergence rate can also be important for controlling trench depth, especially for trenches near continents, because slow convergence causes the capacity of the convergent margin to dispose of sediment to be exceeded.

There an evolution in trench morphology can be expected as oceans close and continents converge. While the ocean is wide, the trench may be far away from continental sources of sediment and so may be deep. As the continents approach each other, the trench may become filled with continental sediments and become shallower. A simple way to approximate when the transition from subduction to collision has occurred is when the plate boundary previously marked by a trench is filled enough to rise above sealevel.

Accretionary prisms and sediment transport

Accretionary prisms grow by frontal accretion, whereby sediments are scraped off, bulldozer-fashion, near the trench, or by underplating of subducted sediments and perhaps oceanic crust along the shallow parts of the subduction decollement. Frontal accretion over the life of a convergent margin results in younger sediments defining the outermost part of the accretionary prism and the oldest sediments defining the innermost portion. Older (inner) parts of the accretionary prism are much more lithified and have steeper structures than the younger (outer) parts. Underplating is difficult to detect in modern subduction zones but may be recorded in ancient accretionary prisms such as the Franciscan Group of California in the form of tectonic mélanges and duplex structures. Different modes of accretion are reflected in morphology of the inner slope of the trench, which generally shows three morphological provinces. The lower slope comprises imbricate thrust slices that form ridges. The mid slope may comprise a bench or terraces. The upper slope is smoother but may be cut by submarine canyons. Because accretionary convergent margins have high relief, are continuously deformed, and accommodate a large flux of sediments, they are vigorous systems of sediment dispersal and accumulation. Sediment transport is controlled by submarine landslides, debris flows, turbidity currents, and contourites. Submarine canyons transport sediment from beaches and rivers down the upper slope. These canyons form by channelized turbidites and generally lose definition with depth because continuous faulting disrupts the submarine channels. Sediments move down the inner trench wall via channels and a series of fault-controlled basins. The trench itself serves as an axis of sediment transport. If enough sediment moves to the trench, it may be completely filled so that turbidity currents are able to carry sediments well beyond the trench and may even surmount the outer swell. Sediments from the rivers of SW Canada and NW USA spill over where the Cascadia trench would be and cross the Juan de Fuca plate to reach the spreading ridge several hundred kilometres to the west.

The slope of the inner trench slope of an accretionary convergent margin reflects continuous adjustments to the thickness and width of the accretionary prism. The prism maintains a 'critical taper', established in conformance with Mohr-Coulomb Theory for the pertinent materials. A package of sediments scraped off the downgoing lithospheric plate will deform until it and the accretionary prism that it has been added to attain a critical taper (constant slope) geometry. Once critical taper is attained, the wedge slides stably along its basal decollement. Strain rate and hydrologic properties strongly influence the strength of the accretionary prism and thus the angle of critical taper. Fluid pore pressures modify rock strength and are important controls of critical taper angle. Low permeability and rapid convergence may result in pore pressures that exceed lithostatic pressure and a relatively weak accretionary prism with a shallowly tapered geometry, whereas high permeability and slow convergence result in lower pore pressure, stronger prisms, and steeper geometry.

The Hellenic trench system is unusual because this convergent margin subducts evaporites. The slope of the surface of the southern flank of the Mediterranean Ridge (its accretionary prism) is low, about 1°, which indicates very low shear stress on the decollement at the base of the wedge. Evaporites influence the critical taper of the accretionary complex, as their mechanical properties differ from those of siliciclastic sediments, and because of their effect upon fluid flow and fluid pressure, which control effective stress. In the 1970s, the linear deeps of the Hellenic trench south of Crete were interpreted to be similar to trenches at other subduction zones, but with the realization that the Mediterranean Ridge is an accretionary complex, it became apparent that the Hellenic trench is actually a starved forearc basin, and that the plate boundary lies south of the Mediterranean Ridge.

Water and biosphere

The volume of water escaping from within and beneath the forearc results in some of Earth's most dynamic and complex interactions between aqueous fluids and rocks. Most of this water is trapped in pores and fractures in the upper lithosphere and sediments of the subducting plate. The average forearc is underrun by a solid volume of oceanic sediment that is 400 m thick. This sediment enters the trench with 50-60% porosity. These sediments are progressively squeezed as they are subducted, reducing void space and forcing fluids out along the decollement and up into the overlying forearc, which may or may not have an accretionary prism. Sediments accreted to the forearc are another source of fluids. Water is also bound in hydrous minerals, especially clays and opal. Increasing pressure and temperature experienced by subducted materials converts the hydrous minerals to denser phases that contain progressively less structurally-bound water. Water released by dehydration accompanying phase transitions is another source of fluids introduced to the base of the overriding plate. These fluids may travel through the accretionary prism diffusely, via interconnected pore spaces in sediments, or may follow discrete channels along faults. Sites of venting may take the form of mud volcanoes or seeps and are often associated with chemosynthetic communities. Fluids escaping from the shallowest parts of a subduction zone may also escape along the plate boundary but have rarely been observed draining along the trench axis. All of these fluids are dominated by water but also contain dissolved ions and organic molecules, especially methane. Methane is often sequestered in an ice-like form (methane clathrate, also called gas hydrate) in the forearc. These are a potential energy source and can rapidly break down. Destabilization of gas hydrates has contributed to global warming in the past and will likely do so in the future.

Chemosynthetic communities thrive where cold fluids seep out of the forearc. Cold seep communities have been discovered in inner trench slopes down to depths of 6000 m in the western Pacific, especially around Japan, in the Eastern Pacific along North, Central and South America coasts from the Aleutian to the Peru-Chile trenches, on the Barbados prism, in the Mediterranean, and in the Indian Ocean along the Makran and Sunda convergent margins. These communities receive much less attention than the chemosynthetic communities associated with hydrothermal vents. Chemosynthetic communities are located in a variety of geological settings: above over-pressured sediments in accretionary prisms where fluids are expelled through mud volcanoes or ridges (Barbados, Nankai and Cascadia); along active erosive margins with faults; and along escarpments caused by debris slides (Japan trench, Peruvian margin). Surface seeps may be linked to massive hydrate deposits and destabilization (e.g. Cascadia margin). High concentrations of methane and sulfide in the fluids escaping from the seafloor are the principal energy sources for chemosynthesis.

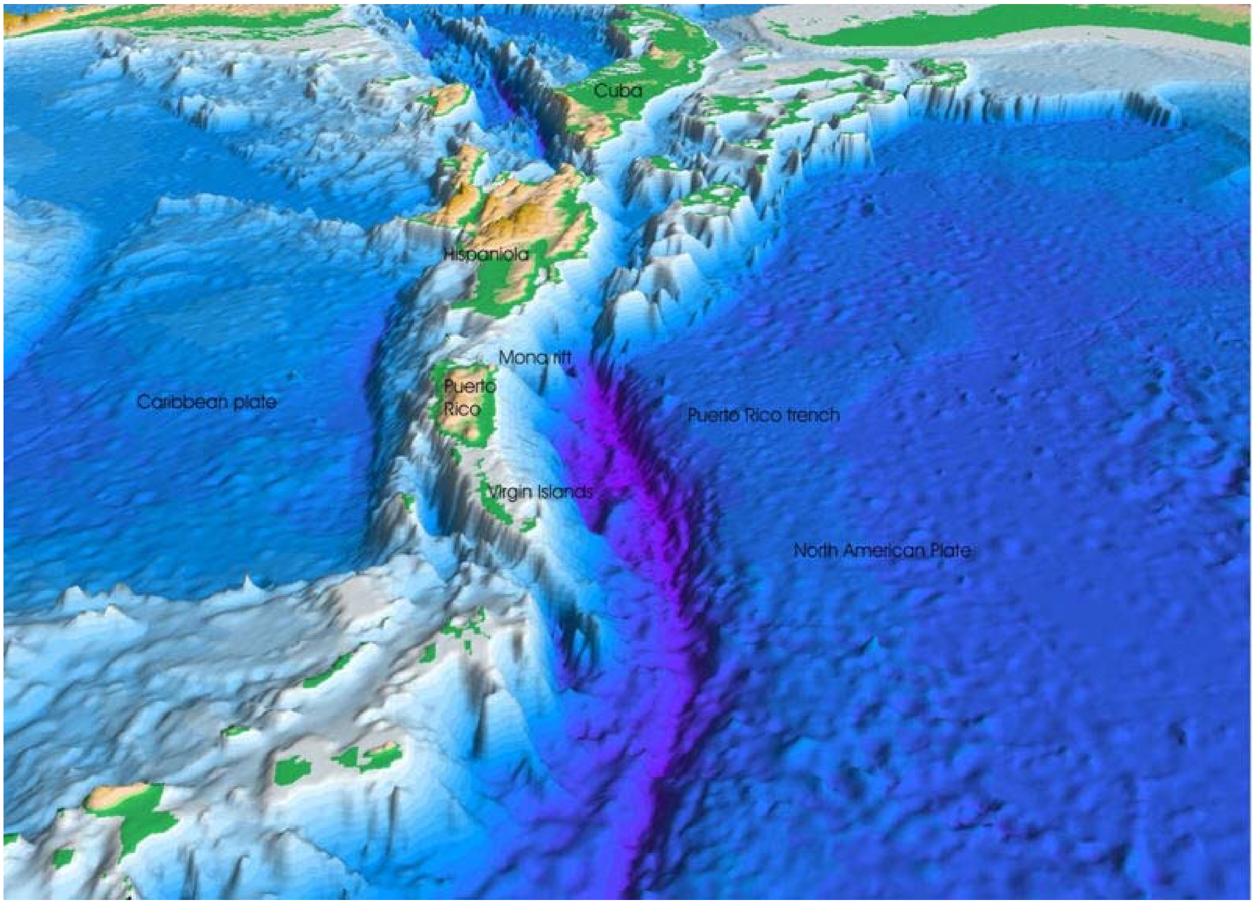
Empty trenches and subduction erosion

Trenches distant from an influx of continental sediments lack an accretionary prism, and the inner slope of such trenches is commonly composed of igneous or metamorphic rocks. Non-accretionary convergent margins are characteristic of (but not limited to) primitive arc systems. Primitive arc systems are those built on oceanic lithosphere, such as the Izu-Bonin-Mariana, Tonga-Kermadec, and Scotia (South Sandwich) arc systems. The inner trench slope of these convergent margins exposes the crust of the forearc, including basalt, gabbro, and serpentinized mantle peridotite. These exposures allow easy access to study the lower oceanic crust and upper mantle in place and provide a unique opportunity to study the magmatic products associated with the initiation of subduction zones. Most ophiolites probably originate in a forearc environment during the initiation of subduction, and this setting favors ophiolite emplacement during collision with blocks of thickened crust. Not all non-accretionary convergent margins are associated with primitive arcs. Trenches adjacent to continents where there is little influx of sediments carried by rivers, such as the central part of the Peru-Chile Trench, may also lack an accretionary prism.

Igneous basement of a nonaccretionary forearc may be continuously exposed by subduction erosion. This transfers material from the forearc to the subducting plate and can be accomplished by frontal erosion or basal erosion. Frontal erosion is most active in the wake of seamounts being subducted beneath the forearc. Subduction of large edifices (seamount tunneling) oversteepens the forearc, causing mass failures that carry debris towards and ultimately into the trench. This debris may be deposited in graben of the downgoing plate and subducted with it. In contrast, structures resulting from subduction erosion of the base of the forearc are difficult to recognize from seismic reflection profiles, so the possibility of basal erosion is difficult to confirm. Subduction erosion may also diminish a once-robust accretionary prism if the flux of sediments to the trench diminishes.

Nonaccretionary forearcs may also be the site of serpentine mud volcanoes. These form where fluids released from the downgoing plate percolate upwards and interact with cold mantle lithosphere of the forearc. Mantle peridotite is hydrated into serpentinite, which is much less dense than peridotite and so will rise diapirically when there is an opportunity to do so. Some nonaccretionary forearcs are subjected to strong extensional stresses, for example the Marianas, and this allows buoyant serpentinite to rise to the seafloor where they form serpentinite mud volcanoes. Chemosynthetic communities are also found on non-accretionary margins such as the Marianas, where they thrive on vents associated with serpentinite mud volcanoes.

Factors affecting trench depth



The Puerto Rico Trench

There are several factors that control the depth of trenches. The most important control is the supply of sediment, which fills the trench so that there is no bathymetric expression. It is therefore not surprising that the deepest trenches (deeper than 8,000 m) are all nonaccretionary. In contrast, all trenches with growing accretionary prisms are shallower than 8000 m. A second order control on trench depth is the age of the lithosphere at the time of subduction. Because oceanic lithosphere cools and thickens as it ages, it subsides. The older the seafloor, the deeper it lies and this determines a minimum depth from which seafloor begins its descent. This obvious correlation can be removed by looking at the relative depth, the difference between regional seafloor depth and maximum trench depth. Relative depth may be controlled by the age of the lithosphere at the trench, the convergence rate, and the dip of the subducted slab at intermediate depths. Finally, narrow slabs can sink and roll back more rapidly than broad plates, because it is easier for underlying asthenosphere to flow around the edges of the sinking plate. Such slabs may have steep dips at relatively shallow depths and so may be associated with unusually deep trenches, such as the Challenger Deep.

Open ocean

The open ocean is relatively unproductive because of a lack of nutrients, yet because it is so vast, in total it produces the most primary productivity. Much of the aphotic zone's energy is supplied by the open ocean in the form of detritus. The open ocean consists mostly of jellyfish and its predators such as the mola mola.

Intertidal and shore

Tide pools with sea stars and sea anemone in Santa Cruz, California

Intertidal zones, those areas close to shore, are constantly being exposed and covered by the ocean's tides. A huge array of life lives within this zone.

Shore habitats span from the upper intertidal zones to the area where land vegetation takes prominence. It can be underwater anywhere from daily to very infrequently. Many species here are scavengers, living off of sea life that is washed up on the shore. Many land animals also make much use of the shore and intertidal habitats. A subgroup of organisms in this habitat bores and grinds exposed rock through the process of bioerosion.

Distribution factors

An active research topic in marine biology is to discover and map the life cycles of various species and where they spend their time. Marine biologists study how the ocean currents, tides and many other oceanic factors affect ocean lifeforms, including their growth, distribution and well-being. This has only recently become technically feasible with advances in GPS and newer underwater visual devices.

Most ocean life breeds in specific places, nests or not in others, spends time as juveniles in still others, and in maturity in yet others. Scientists know little about where many species spend different parts of their life cycles. For example, it is still largely unknown where sea turtles and some sharks travel. Tracking devices do not work for some life forms, and the ocean is not friendly to technology. This is important to scientists and fishermen because they are discovering that by restricting commercial fishing in one small area they can have a large impact in maintaining a healthy fish population in a much larger area far away.

Chapter- 3

Chemical Oceanography, Marine Geology and Physical Oceanography

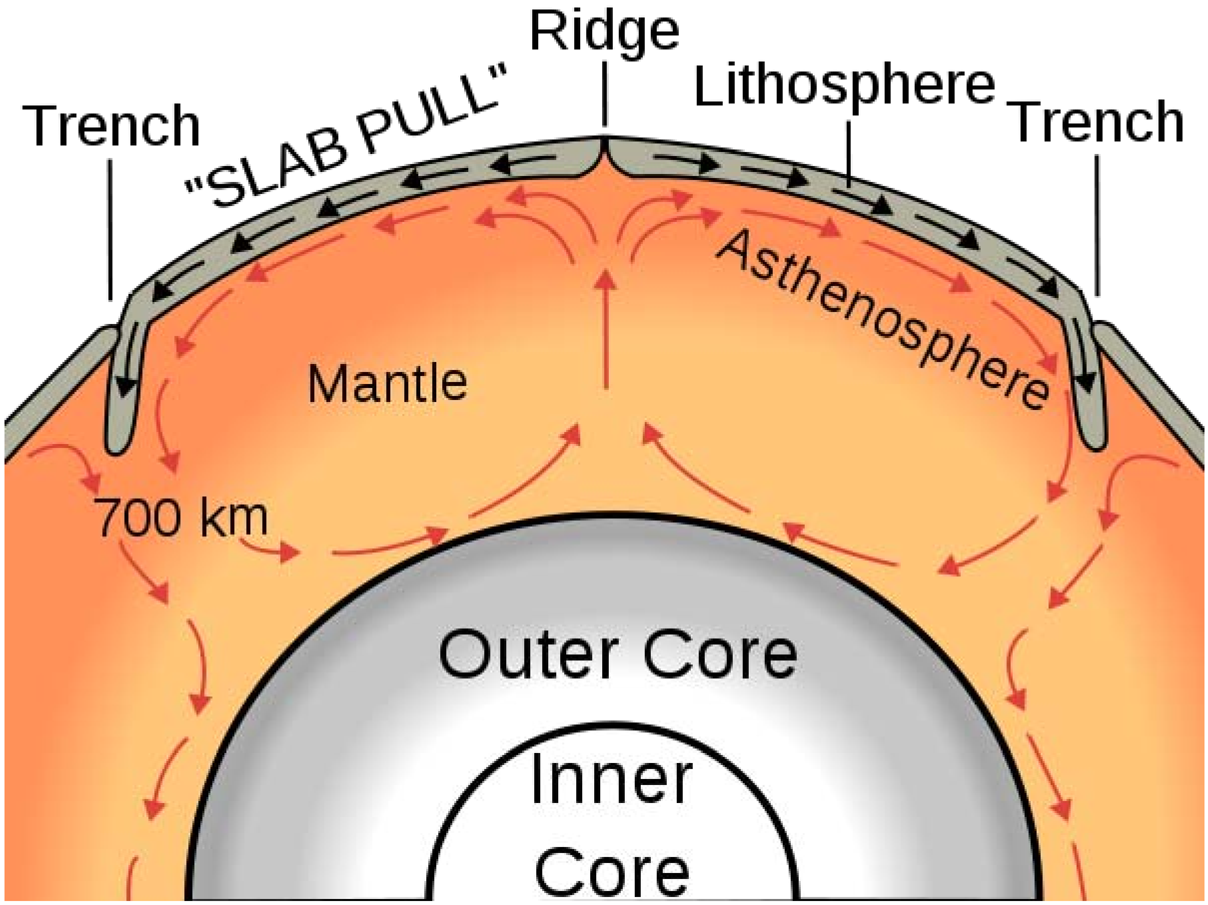
Chemical oceanography

Chemical oceanography is the study of ocean chemistry: the behavior of the chemical elements within the Earth's oceans. The ocean is unique in that it contains - in greater or lesser quantities - nearly every element in the periodic table.

Much of chemical oceanography describes the cycling of these elements both within the ocean and with the other spheres of the Earth system. These cycles are usually characterised as quantitative fluxes between constituent reservoirs defined within the ocean system and as residence times within the ocean. Of particular global and climatic significance are the cycles of the biologically active elements such as carbon, nitrogen, and phosphorus as well as those of some important trace elements such as iron.

Another important area of study in chemical oceanography is the behaviour of isotopes and how they can be used as tracers of past and present oceanographic and climatic processes. For example, the incidence of ^{18}O (the heavy isotope of oxygen) can be used as an indicator of polar ice sheet extent, and boron isotopes are key indicators of the pH and CO_2 content of oceans in the geologic past.

Marine geology

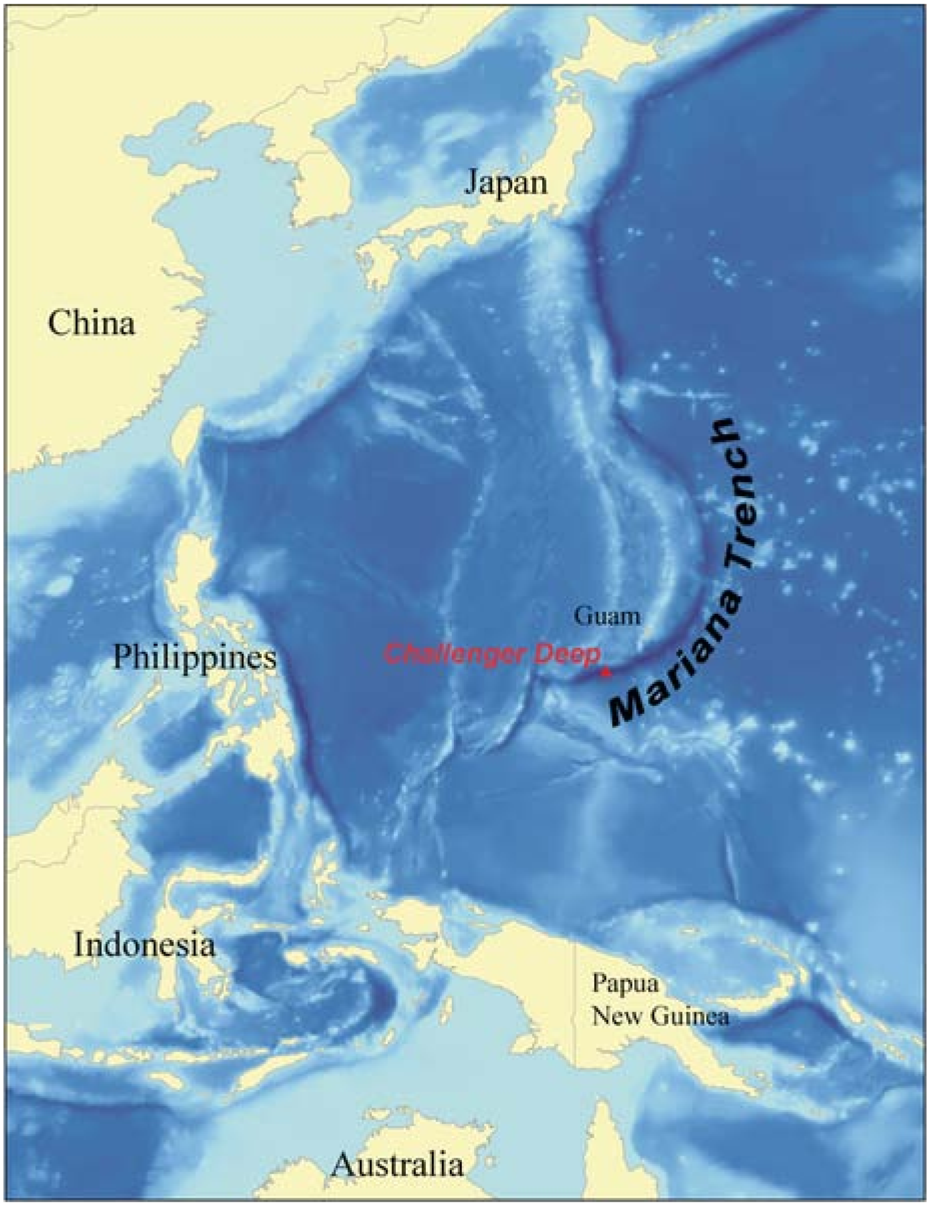


Oceanic crust is formed at an oceanic ridge, while the lithosphere is subducted back into the asthenosphere at trenches.

Marine geology involves geophysical, geochemical, sedimentological and paleontological investigations of the ocean floor and coastal margins. Marine geology has strong ties to physical oceanography and plate tectonics.

Marine geological studies were of extreme importance in providing the critical evidence for sea floor spreading and plate tectonics in the years following World War II. The deep ocean floor is the last essentially unexplored frontier and detailed mapping in support of both military (submarine) objectives and economic (petroleum and metal mining) objectives drives the research.

Overview



A trench forms at the boundary where two tectonic plates meet

The Ring of Fire around the Pacific Ocean with its attendant intense volcanism and seismic activity poses a major threat for disastrous earthquakes, tsunamis and volcanic eruptions. Any *early warning* systems for these disastrous events will require a more detailed understanding of marine geology of coastal and island arc environments.

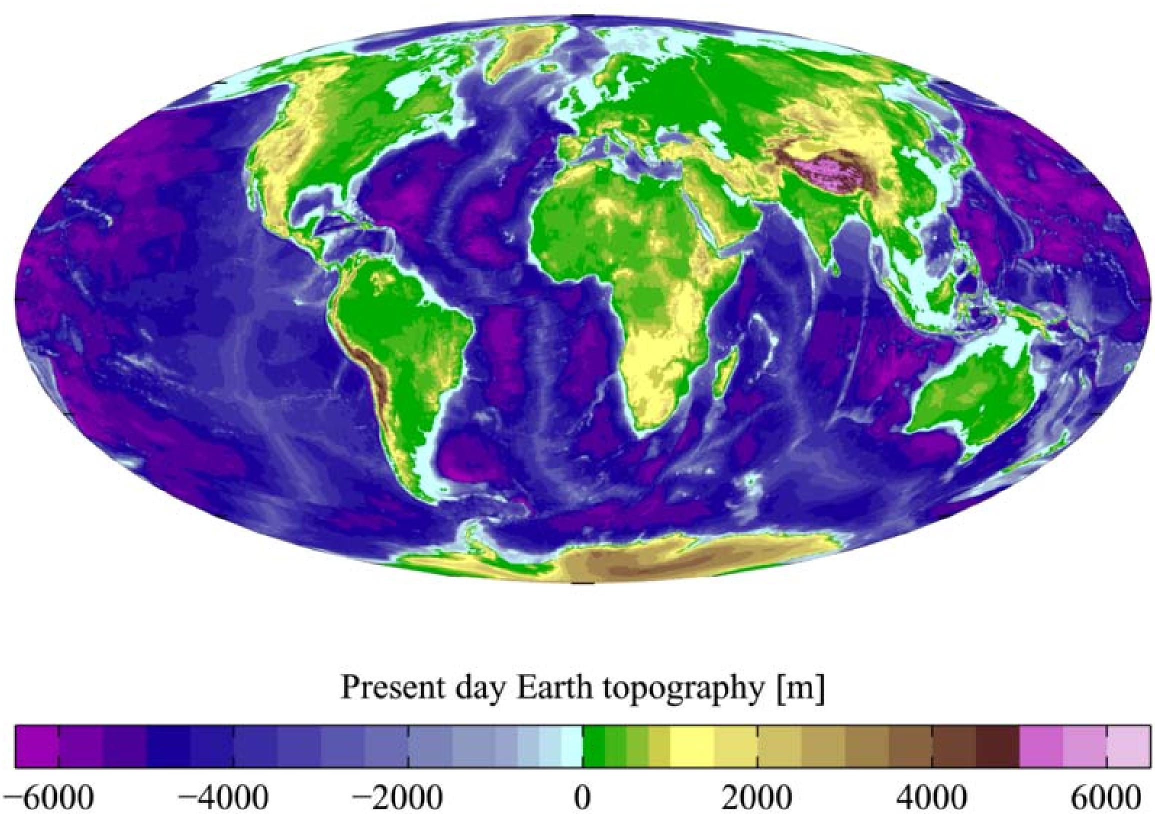
The study of littoral and deep sea sedimentation and the precipitation and dissolution rates of calcium carbonate in various marine environments has important implications for global climate change.

The discovery and continued study of mid-ocean rift zone volcanism and hydrothermal vents, first in the Red Sea and later along the East Pacific Rise and the Mid-Atlantic Ridge systems were and continue to be important areas of marine geological research. The extremophile organisms discovered living within and adjacent to those hydrothermal systems have had a pronounced impact on our understanding of life on Earth and potentially the origin of life within such an environment.

Oceanic trenches are hemispheric-scale long but narrow topographic depressions of the sea floor. They also are the deepest parts of the ocean floor.

The Mariana Trench (or Marianas Trench) is the deepest known submarine trench, and the deepest location in the Earth's crust itself. A subduction zone where the Pacific Plate is being subducted under the Philippine Sea Plate. The bottom of the trench is further below sea level than Mount Everest is above sea level.

Physical oceanography

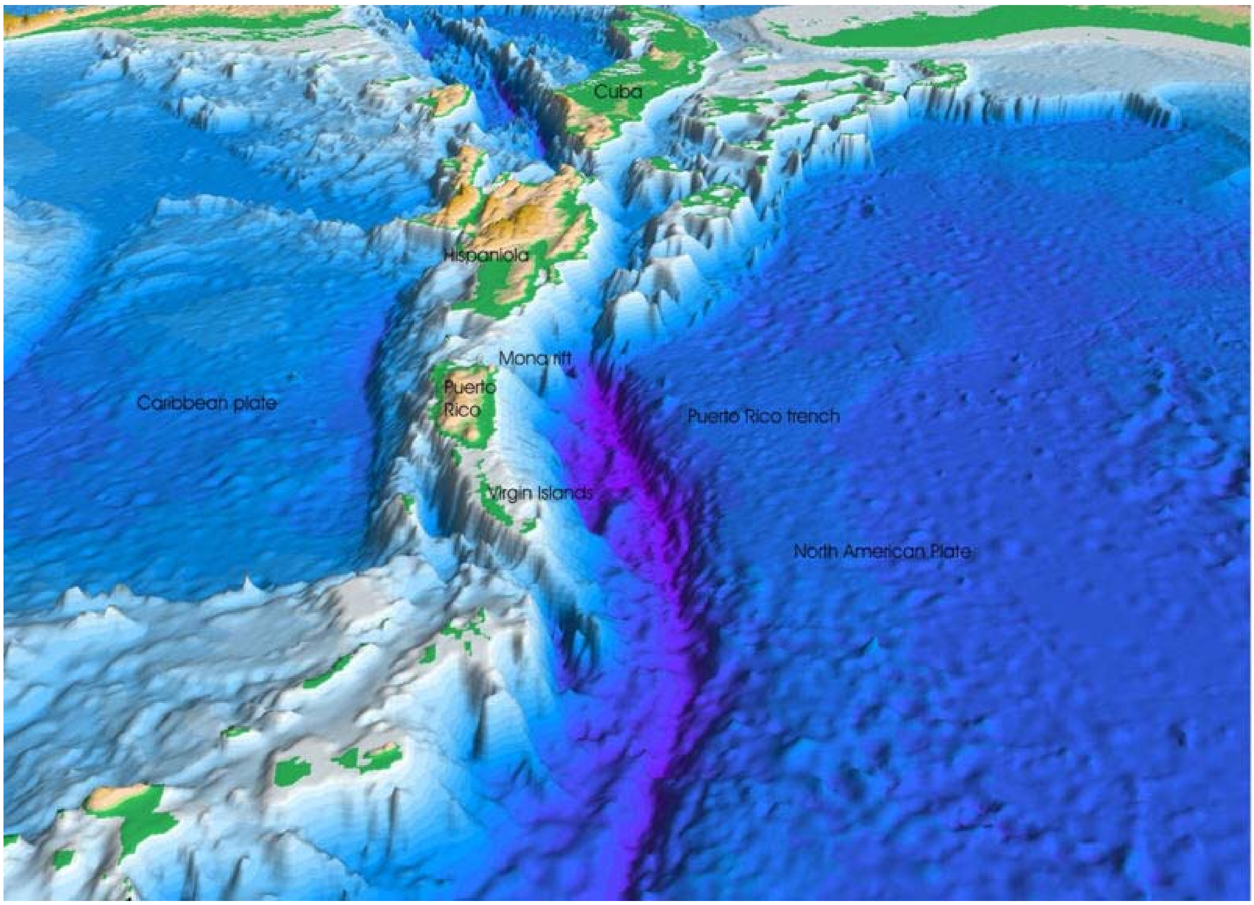


World ocean bathymetry

Physical oceanography is the study of physical conditions and physical processes within the ocean, especially the motions and physical properties of ocean waters.

Physical oceanography is one of several sub-domains into which oceanography is divided. Others include biological, chemical and geological oceanographies.

The physical setting



Perspective view of the sea floor of the Atlantic Ocean and the Caribbean Sea. The purple sea floor at the center of the view is the Puerto Rico Trench.

The pioneering oceanographer Matthew Maury said in 1855 *"Our planet is invested with two great oceans; one visible, the other invisible; one underfoot, the other overhead; one entirely envelopes it, the other covers about two thirds of its surface."* The fundamental role of the oceans in shaping Earth is acknowledged by ecologists, geologists, meteorologists, climatologists, geographers and others interested in the physical world. An Earth without oceans would truly be unrecognizable.

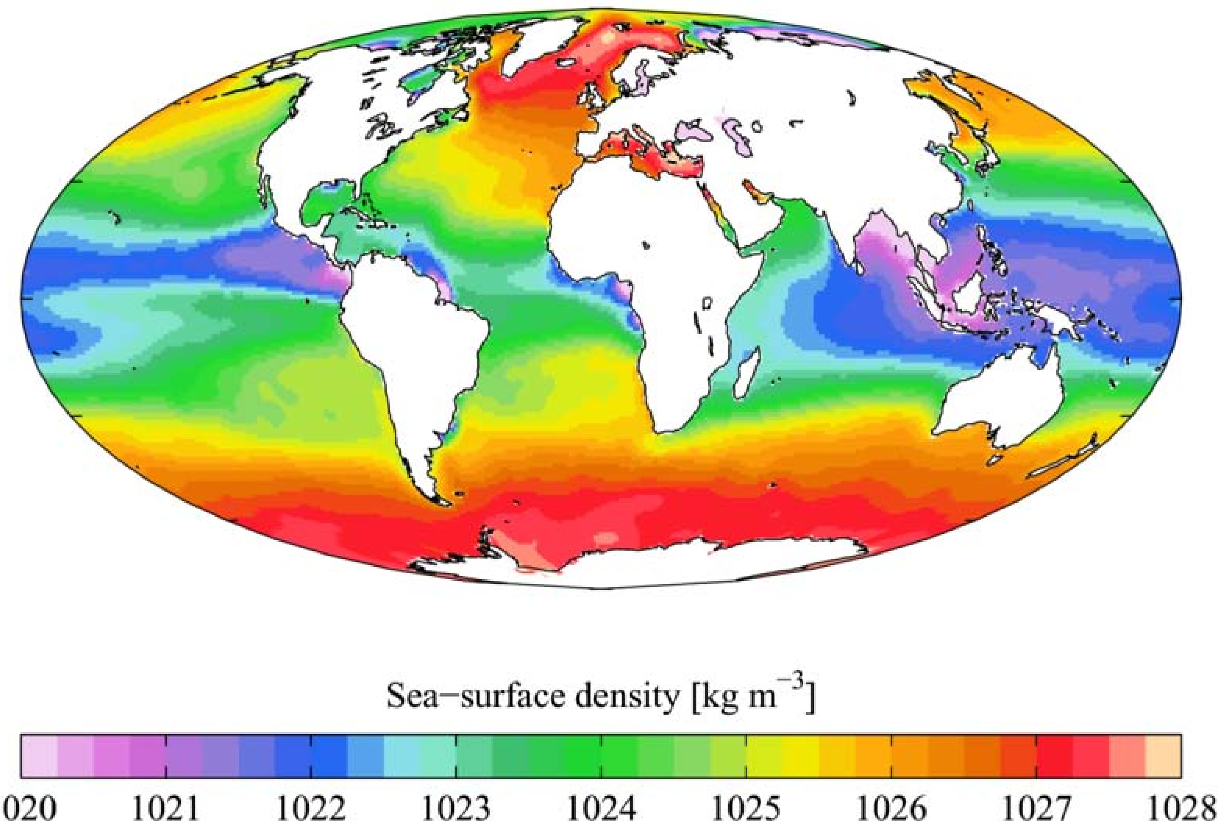
Roughly 97% of the planet's water is in its oceans, and the oceans are the source of the vast majority of water vapor that condenses in the atmosphere and falls as rain or snow on the continents. The tremendous heat capacity of the oceans moderates the planet's climate, and its absorption of various gases affects the composition of the atmosphere. The ocean's influence extends even to the composition of volcanic rocks through seafloor metamorphism, as well as to that of volcanic gases and magmas created at subduction zones.

The oceans are far deeper than the continents are tall; examination of the Earth's hypsographic curve shows that the average elevation of Earth's landmasses is only 840 metres (2,760 ft), while the ocean's average depth is 3,800 metres (12,500 ft). Though this apparent discrepancy is great, for both land and sea, the respective extremes such as mountains and trenches are rare.

Area, volume plus mean and maximum depths of oceans (excluding adjacent seas)

Body	**Area** ($10^6 km^2$)	**Volume** ($10^6 km^3$)	**Mean depth** (m)	**Maximum** (m)
Pacific Ocean	165.2	707.6	4282	-10911
Atlantic Ocean	82.4	323.6	3926	-8605
Indian Ocean	73.4	291.0	3963	-8047
Southern Ocean	20.3			-7235
Arctic Ocean	14.1		1038	
Caribbean Sea	2.8			-7686

Temperature, salinity and density



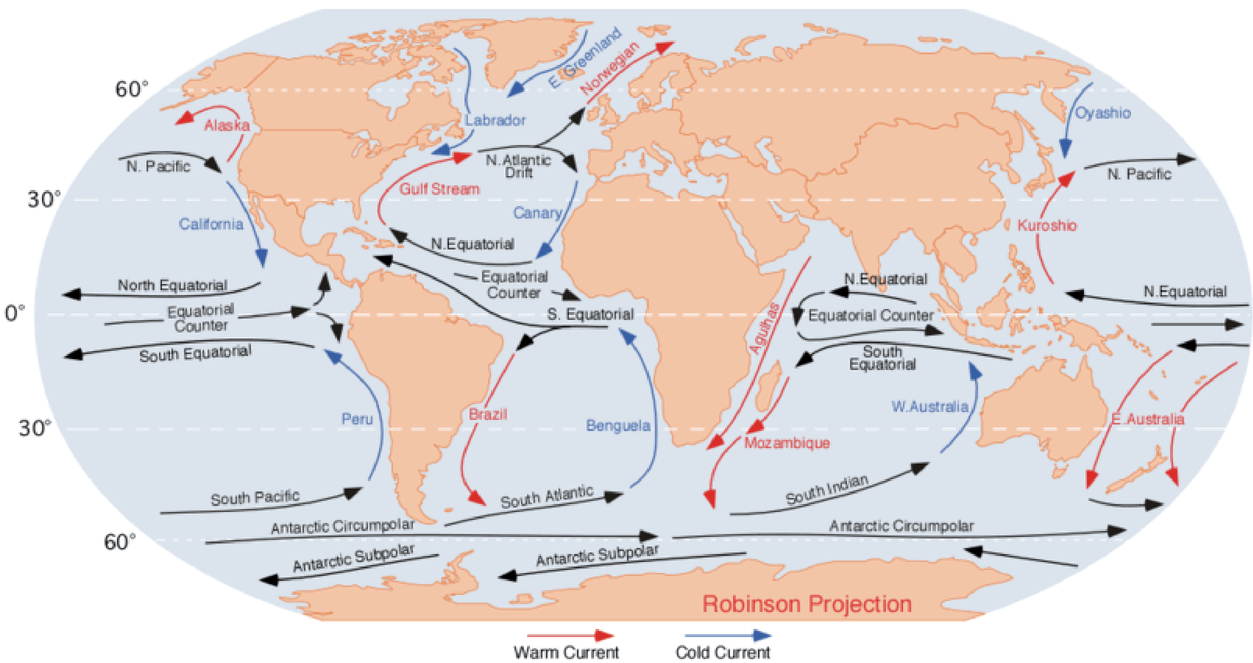
WOA surface density

Because the vast majority of the world ocean's volume is deep water, the mean temperature of seawater is low; roughly 75% of the ocean's volume has a temperature from 0° – 5°C (Pinet 1996). The same percentage falls in a salinity range between 34–35 ppt (3.4–3.5%) (Pinet 1996). There is still quite a bit of variation, however. Surface temperatures can range from below freezing near the poles to 35°C in restricted tropical seas, while salinity can vary from 10 to 41 ppt (1.0–4.1%).

The vertical structure of the temperature can be divided into three basic layers, a surface mixed layer, where gradients are low, a thermocline where gradients are high, and a poorly stratified abyss.

In terms of temperature, the ocean's layers are highly latitude-dependent; the thermocline is pronounced in the tropics, but nonexistent in polar waters (Marshak 2001). The halocline usually lies near the surface, where evaporation raises salinity in the tropics, or meltwater dilutes it in polar regions. These variations of salinity and temperature with depth change the density of the seawater, creating the pycnocline.

Ocean current

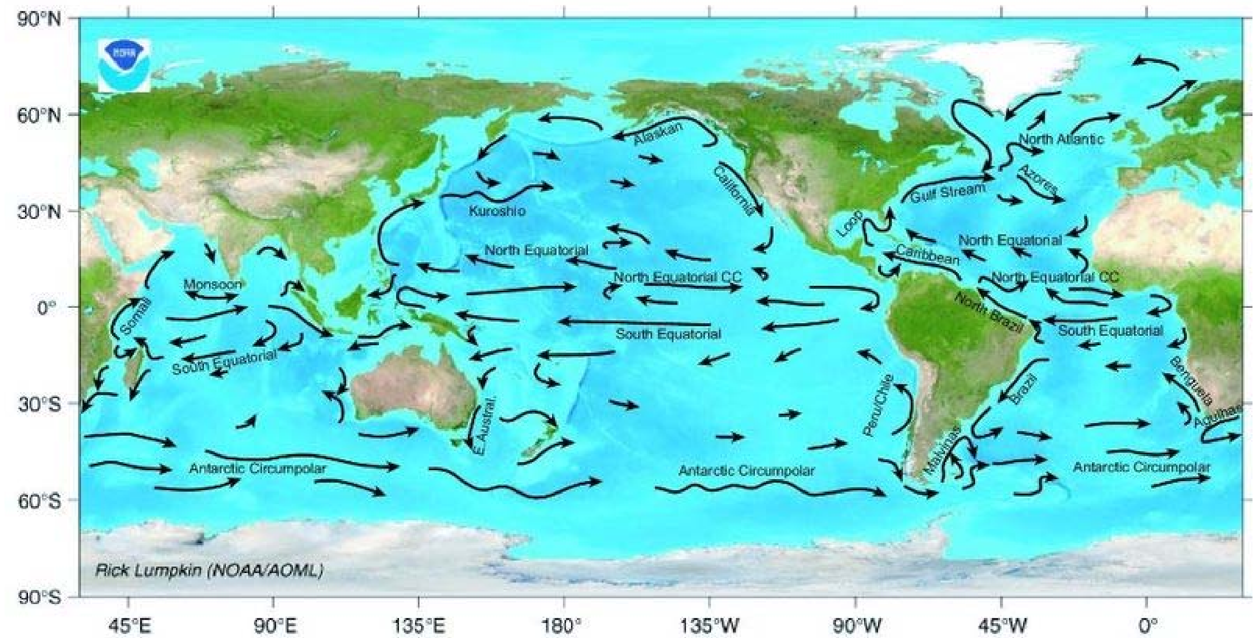


The ocean currents

An **ocean current** is a continuous, directed movement of ocean water generated by the forces acting upon this mean flow, such as breaking waves, wind, Coriolis force, temperature and salinity differences and tides caused by the gravitational pull of the Moon and the Sun. Depth contours, shoreline configurations and interaction with other currents influence a current's direction and strength.

Ocean currents can flow for great distances, and together they create the great flow of the global conveyor belt which plays a dominant part in determining the climate of many of the Earth's regions. Perhaps the most striking example is the Gulf Stream, which makes northwest Europe much more temperate than any other region at the same latitude. Another example is the Hawaiian Islands, where the climate is cooler (sub-tropical) than the tropical latitudes in which they are located, due to the effect of the California Current.

Function



Major ocean surface currents

Device to record ocean currents

Surface ocean currents are generally wind driven and develop their typical clockwise spirals in the northern hemisphere and counter-clockwise rotation in the southern hemisphere because of the imposed wind stresses. In wind driven currents, the Ekman spiral effect results in the currents flowing at an angle to the driving winds. The areas of surface ocean currents move somewhat with the seasons; this is most notable in equatorial currents.

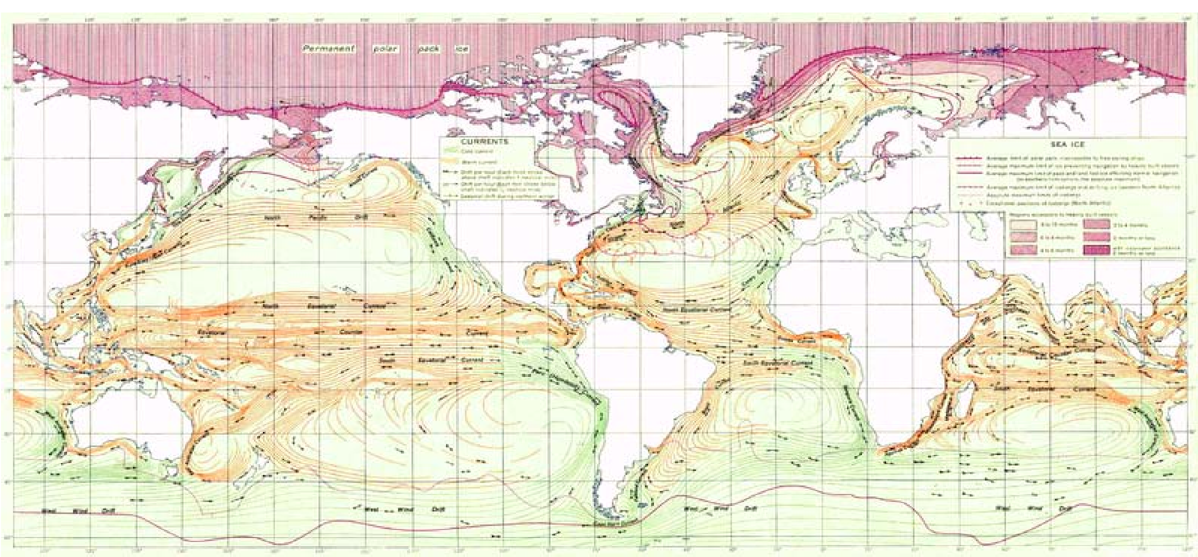
Ocean basins generally have a non-symmetric surface current, in that the eastern equatorward-flowing branch is broad and diffuse whereas the western poleward-flowing branch is very narrow. These western boundary currents (of which the gulf stream is an example) are a consequence of basic fluid dynamics.

Deep ocean currents are driven by density and temperature gradients. Thermohaline circulation, also known as the ocean's conveyor belt, refers to the deep ocean density-driven ocean basin currents. These currents, which flow under the surface of the ocean and are thus hidden from immediate detection, are called submarine rivers. These are currently being researched using a fleet of underwater robots called Argo. Upwelling and downwelling areas in the oceans are areas where significant vertical movement of ocean water is observed.

Surface currents make up about 10% of all the water in the ocean. Surface currents are generally restricted to the upper 400 m (1,300 ft) of the ocean. The movement of deep water in the ocean basins is by density driven forces and gravity. The density difference is a function of different temperatures and salinity. Deep waters sink into the deep ocean basins at high latitudes where the temperatures are cold enough to cause the density to increase.

Ocean currents are measured in Sverdrup (Sv), where 1Sv is equivalent to a volume flow rate of 1,000,000 m^3 (35,000,000 cu ft) per second.

Importance



A 1943 map of the world's ocean currents

Knowledge of surface ocean currents is essential in reducing costs of shipping, since they reduce fuel costs. In the sail-ship era knowledge was even more essential. A good example of this is the Agulhas current, which long prevented Portuguese sailors from reaching India. Even today, the round-the-world sailing competitors employ surface currents to their benefit. Ocean currents are also very important in the dispersal of many life forms. An example is the life-cycle of the eel.

Ocean currents are important in the study of marine debris, and vice versa. These currents also affect temperatures throughout the world. For example, the current that brings warm water up the north Atlantic to northwest Europe stops ice from forming by the shores, which would block ships from entering and exiting ports.

Coriolis effect

The Coriolis effect results in a deflection of fluid flows (to the right in the Northern Hemisphere and left in the Southern Hemisphere). Because the distance around the Earth decreases as one moves away from the equator, and because the Earth rotates in a counter clockwise direction as seen from the north pole, air and water masses are deflected to the east as they move from the equator to the poles, and to the west as they move from the poles to the equator. This has profound effects on the flow of the oceans. In particular it means the flow goes *around* high and low pressure systems, permitting them to persist for long periods of time. As a result, tiny variations in pressure can produce measurable currents. A slope of one part in one million in sea surface height, for example, will result in a current of 1 cm/s at mid-latitudes. The fact that the Coriolis effect is largest at the poles and weak at the equator results in sharp, relatively steady western boundary currents which are absent on eastern boundaries.

The Coriolis effect is also responsible for coastal upwelling as wind-driven currents tend to forced to the right of the winds in the Northern Hemisphere and to the left of the winds in the Southern Hemisphere. When winds blow either equatorward along an eastern ocean boundary or poleward along a western ocean boundary, water is driven away from the coasts (the so called Ekman transport), and denser water rises from below to replace it.

Ekman transport

Ekman Transport results in the net transport of surface water 90 degrees to the right of the wind in the Northern Hemisphere, and 90 degrees to the left of the wind in the Southern Hemisphere. As the wind blows across the surface of the ocean, it "grabs" onto a thin layer of the surface water. In turn, that thin sheet of water transfers motion energy to the thin layer of water under it, and so on. However, because of the Coriolis Effect, the direction of travel of the layers of water slowly move farther and farther to the right as they get deeper in the Northern Hemisphere, and to the left in the Southern Hemisphere. In most cases, the very bottom layer of water affected by the wind is at a depth of 100 m – 150 m and is traveling about 180 degrees, completely opposite of the direction that the wind is blowing. Overall, the net transport of water would be 90 degrees from the original direction of the wind.

Langmuir circulation

Langmuir circulation results in the occurrence of thin, visible stripes, called windrows on the surface of the ocean parallel to the direction that the wind is blowing. If the wind is blowing with more than 3 m s^{-1}, it can create parallel windrows alternating upwelling and downwelling about 5–300 m apart. These windrows are created by adjacent ovular water cells (extending to about 6 m (20 ft) deep) alternating rotating clockwise and counterclockwise. In the convergence zones debris, foam and seaweed accumulates, while at the divergencezones plankton are caught and carried to the surface. If there are many plankton in the divergencezone fish are often attracted to feed on them.

Ocean–atmosphere interface

Hurricane Isabel east of the Bahamas on 15 September 2003

At the ocean-atmosphere interface, the ocean and atmosphere exchange fluxes of heat, moisture and momentum.

Heat

The important heat terms at the surface are the sensible heat flux, the latent heat flux, the incoming solar radiation and the balance of long-wave (infrared) radiation. In general, the tropical oceans will tend to show a net gain of heat, and the polar oceans a net loss, the result of a net transfer of energy polewards in the oceans.

The oceans' large heat capacity moderates the climate of areas adjacent to the oceans, leading to a maritime climate at such locations. This can be a result of heat storage in summer and release in winter; or of transport of heat from warmer locations: a particularly notable example of this is Western Europe, which is heated at least in part by the north atlantic drift.

Momentum

Surface winds tend to be of order meters per second; ocean currents of order centimeters per second. Hence from the point of view of the atmosphere, the ocean can be considered effectively stationary; from the point of view of the ocean, the atmosphere imposes a significant wind stress on its surface, and this forces large-scale currents in the ocean.

Through the wind stress, the wind generates ocean surface waves; the longer waves have a phase velocity tending towards the wind speed. Momentum of the surface winds is transferred into the energy flux by the ocean surface waves. The increased roughness of the ocean surface, by the presence of the waves, changes the wind near the surface.

Moisture

The ocean can gain moisture from rainfall, or lose it through evaporation. Evaporative loss leaves the ocean saltier; the Mediterranean and Persian Gulf for example have strong evaporative loss; the resulting plume of dense salty water may be traced through the Straits of Gibraltar into the Atlantic Ocean. At one time, it was believed that evaporation/precipitation was a major driver of ocean currents; it is now known to be only a very minor factor.

Planetary waves

Kelvin Waves

A Kelvin wave is any progressive wave that is channeled between two boundaries or opposing forces (usually between the Coriolis force and a coastline or the equator). There are two types, coastal and equatorial. Kelvin waves are gravity driven and non-dispersive, meaning that the phase speed of the wave at any one frequency will equal the group speed of the wave energy for all frequencies. This means that Kelvin waves can retain their shape and direction over long periods of time. They are usually created by a sudden shift in the wind, such as the change of the trade winds at the beginning of the El Niño-Southern Oscillation.

Coastal Kelvin waves follow shorelines and will always propagate in a counterclockwise direction in the Northern hemisphere (with the shoreline to the right of the direction of travel) and clockwise in the Southern hemisphere.

Equatorial Kelvin waves propagate to the east in the Northern hemisphere and to the west in the Southern hemisphere, using the equator as a guide.

Kelvin waves are known to have very high speeds, typically around 2–3 meters per second. They have wavelengths of thousands of kilometers and amplitudes in the tens of meters.

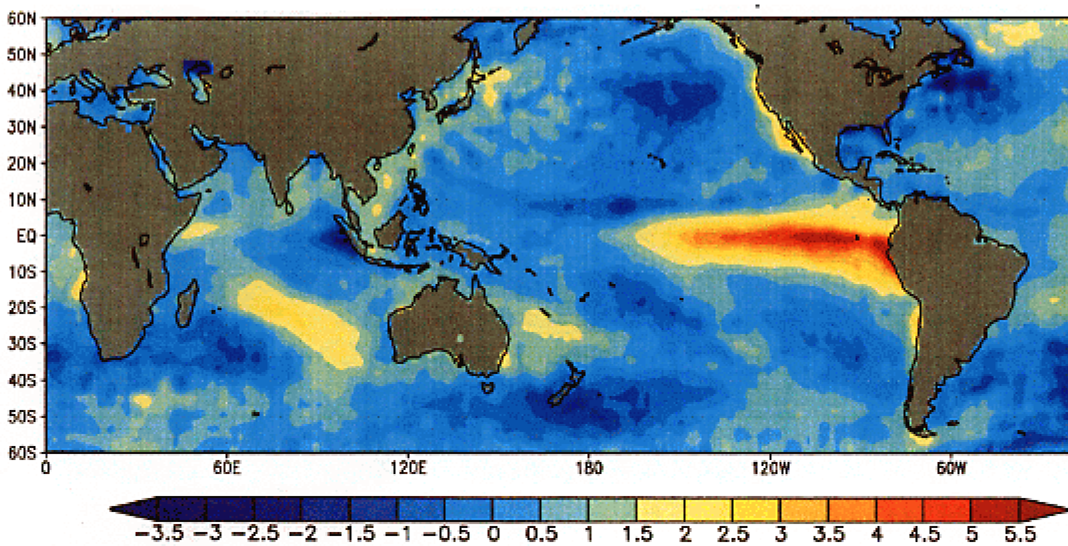
Rossby Waves

Rossby waves, or planetary waves are huge, slow waves generated in the troposphere by temperature differences between the ocean and the continents. Their major restoring force is the change in Coriolis force with latitude. Their wave amplitudes are usually in the tens of meters and very large wavelengths. They are usually found at low or mid latitudes

There are two types of Rossby waves, barotropic and baroclinic. Barotropic Rossby waves have the highest speeds and do not vary vertically. Baroclinic Rossby waves are much slower.

The special identifying feature of Rossby waves is that the phase velocity of each individual wave always has a westward component, but the group velocity can be in any direction. Usually the shorter Rossby waves have an eastward group velocity and the longer ones have a westward group velocity.

Climate variability



December 1997 chart of ocean surface temperature anomaly [°C] during the last strong El Niño

The interaction of ocean circulation, which serves as a type of heat pump, and biological effects such as the concentration of carbon dioxide can result in global climate changes on a time scale of decades. Known climate oscillations resulting from these interactions, include the Pacific decadal oscillation, North Atlantic oscillation, and Arctic oscillation. The oceanic process of thermohaline circulation is a significant component of heat redistribution across the globe, and changes in this circulation can have major impacts upon the climate.

La Niña–El Niño

Antarctic circumpolar wave

This is a coupled ocean/atmosphere wave that circles the Southern Ocean about every eight years. Since it is a wave-2 phenomenon (there are two peaks and two troughs in a latitude circle) at each fixed point in space a signal with a period of four years is seen. The wave moves eastward in the direction of the Antarctic Circumpolar Current.

Ocean currents

Among the most important ocean currents are the:

- Antarctic Circumpolar Current
- Deep ocean (density-driven)
- Western boundary currents
  - Gulf Stream
  - Kuroshio Current
  - Labrador Current
  - Oyashio Current
  - Agulhas Current
  - Brazil Current
  - East Australia Current
- Eastern Boundary currents
  - California Current
  - Canary Current
  - Peru Current
  - Benguela Current

Antarctic circumpolar

The ocean body surrounding the Antarctic is currently the only continuous body of water where there is a wide latitude band of open water. It interconnects the Atlantic, Pacific and Indian oceans, and provide an uninterrupted stretch for the prevailing westerly winds to significantly increase wave amplitudes. It is generally accepted that these prevailing winds are primarily responsible for the circumpolar current transport. This current is now thought to vary with time, possibly in an oscillatory manner.

Deep ocean

In the Norwegian Sea evaporative cooling is predominant, and the sinking water mass, the North Atlantic Deep Water (NADW), fills the basin and spills southwards through crevasses in the submarine sills that connect Greenland, Iceland and Britain. It then flows along the western boundary of the Atlantic with some part of the flow moving eastward along the equator and then poleward into the ocean basins. The NADW is entrained into the Circumpolar Current, and can be traced into the Indian and Pacific basins. Flow from the Arctic Ocean Basin into the Pacific, however, is blocked by the narrow shallows of the Bering Strait.

Western boundary

An idealised subtropical ocean basin forced by winds circling around a high pressure (anticyclonic) systems such as the Azores-Bermuda high develops a gyre circulation with slow steady flows towards the equator in the interior. As discussed by Henry Stommel, these flows are balanced in the region of the western boundary, where a thin fast polewards flow called a western boundary current develops. Flow in the real ocean is more complex, but the Gulf stream, Agulhas and Kuroshio are examples of such currents. They are narrow (approximately 100 km across) and fast (approximately 1.5 m/s).

Equatorwards western boundary currents occur in tropical and polar locations, e.g. the East Greenland and Labrador currents, in the Atlantic and the Oyashio. They are forced by winds circulation around low pressure (cyclonic)

Gulf stream

The Gulf Stream, together with its northern extension, North Atlantic Current, is a powerful, warm, and swift Atlantic ocean current that originates in the Gulf of Mexico, exits through the Strait of Florida, and follows the eastern coastlines of the United States and Newfoundland to the northeast before crossing the Atlantic Ocean.

Kuroshio

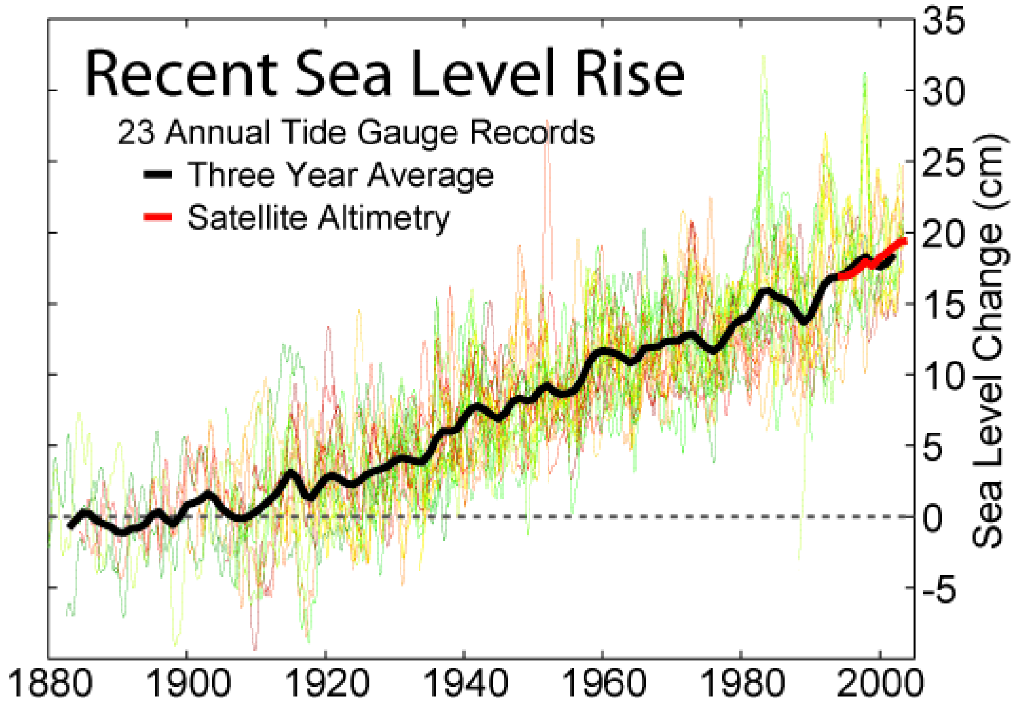
The Kuroshio Current is an ocean current found in the western Pacific Ocean off the east coast of Taiwan and flowing northeastward past Japan, where it merges with the easterly drift of the North Pacific Current. It is analogous to the Gulf Stream in the Atlantic Ocean, transporting warm, tropical water northward towards the polar region.

Heat flux

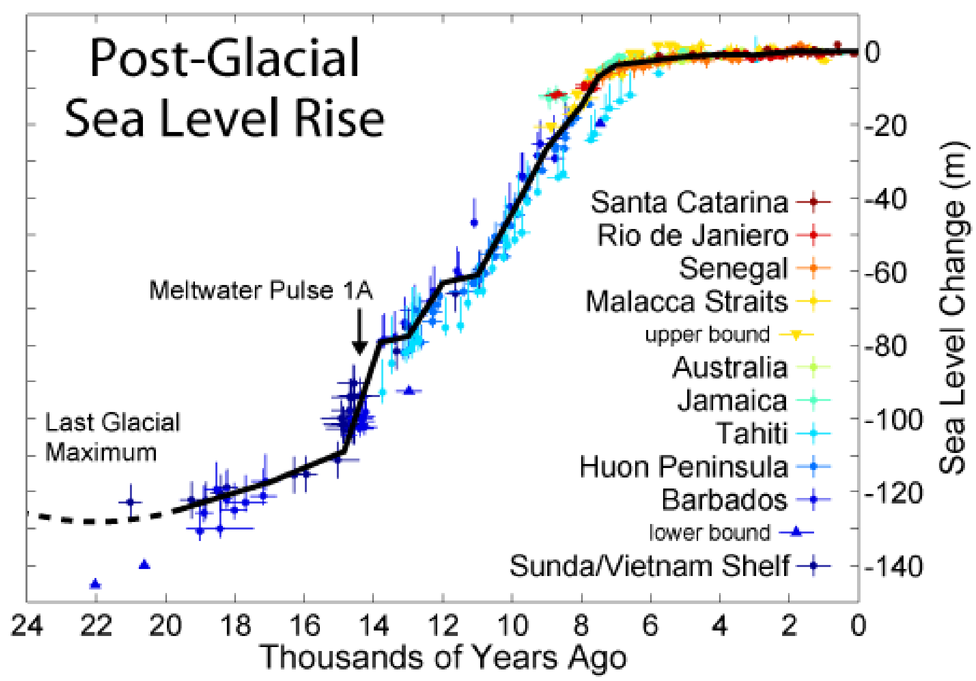
Heat storage

Heat storage and transfer in the ocean is very uneven.

Current sea level rise



Sea level measurements from 23 long tide gauge records in geologically stable environments show a rise of around 200 millimetres (8 inches) per century, or 2 mm/year.



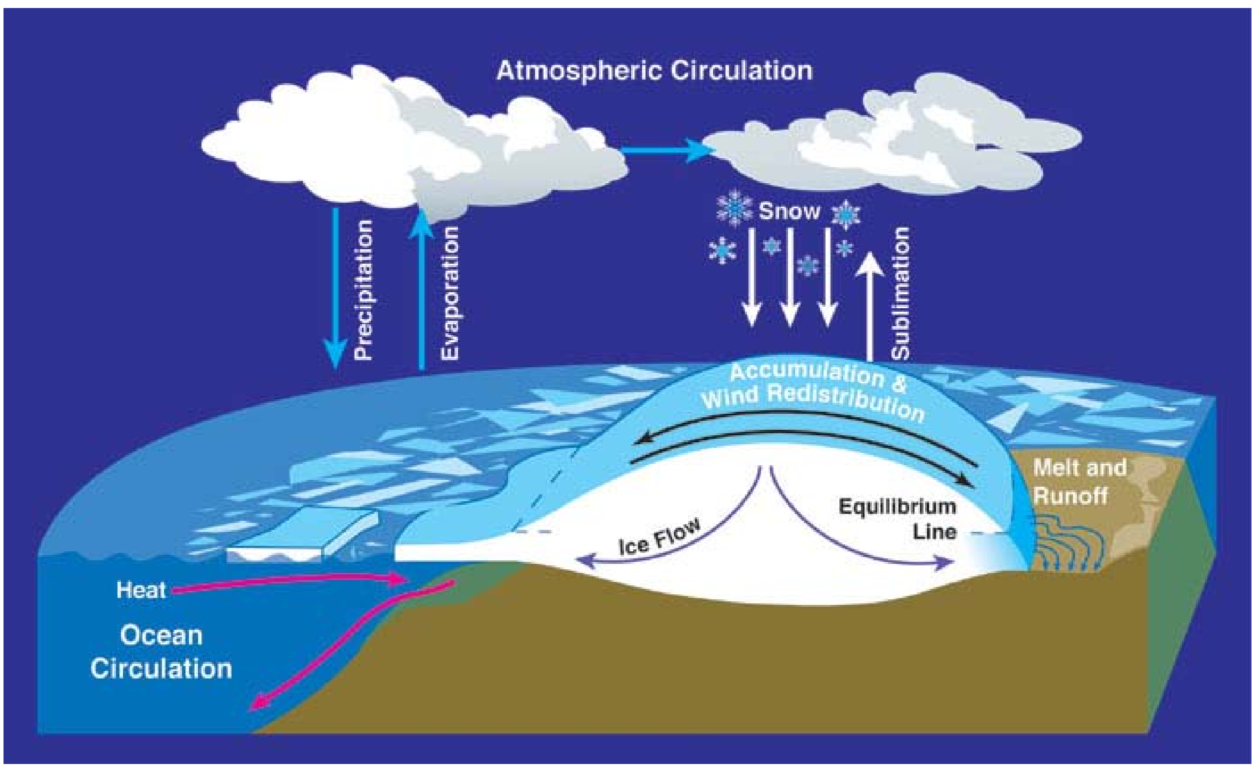
Changes in sea level since the end of the last glacial episode

Current sea level rise has occurred at a mean rate of 1.8 mm per year for the past century, and more recently, during the satellite era of sea level measurement, at rates estimated near 2.8 ± 0.4 to 3.1 ± 0.7 mm per year (1993–2003). Current sea level rise is due significantly to global warming, which will increase sea level over the coming century and longer periods. Increasing temperatures result in sea level rise by the thermal expansion of water and through the addition of water to the oceans from the melting of mountain glaciers, ice caps and ice sheets. At the end of the 20th century, thermal expansion and melting of land ice contributed roughly equally to sea level rise, while thermal expansion is expected to contribute more than half of the rise in the upcoming century.

Values for predicted sea level rise over the course of this century typically range from 90 to 880 mm, with a central value of 480 mm. Models of glacier mass balance (the difference between melting and accumulation of snow and ice on a glacier) give a theoretical maximum value for sea level rise in the current century of 2 metres (and a "more plausible" one of 0.8 metres), based on limitations on how quickly glaciers can melt.

Overview of sea-level change

Local and eustatic sea level



Water cycles between ocean, atmosphere, and glaciers

Local mean sea level (LMSL) is defined as the height of the sea with respect to a land benchmark, averaged over a period of time (such as a month or a year) long enough that fluctuations caused by waves and tides are smoothed out. One must adjust perceived changes in

LMSL to account for vertical movements of the land, which can be of the same order (mm/yr) as sea level changes. Some land movements occur because of isostatic adjustment of the mantle to the melting of ice sheets at the end of the last ice age. The weight of the ice sheet depresses the underlying land, and when the ice melts away the land slowly rebounds. Atmospheric pressure, ocean currents and local ocean temperature changes also can affect LMSL.

"Eustatic" change (as opposed to local change) results in an alteration to the global sea levels, such as changes in the volume of water in the world oceans or changes in the volume of an ocean basin.

Short term and periodic changes

There are many factors which can produce short-term (a few minutes to 18.6 years) changes in sea level.

Short-term (periodic) causes	Time scale (P = period)	Vertical effect
Periodic sea level changes		
Diurnal and semidiurnal astronomical tides	12–24 h P	0.2–10+ m
Long-period tides		
Rotational variations (Chandler wobble)	14 month P	
Lunar Node astronomical tides	18.613 year	
Meteorological and oceanographic fluctuations		
Atmospheric pressure	Hours to months	−0.7 to 1.3 m
Winds (storm surges)	1–5 days	Up to 5 m
Evaporation and precipitation (may also follow long-term pattern)	Days to weeks	
Ocean surface topography (changes in water density and currents)	Days to weeks	Up to 1 m
El Niño/southern oscillation	6 mo every 5–10 yr	Up to 0.6 m

Seasonal variations		
Seasonal water balance among oceans (Atlantic, Pacific, Indian)		
Seasonal variations in slope of water surface		
River runoff/floods	2 months	1 m
Seasonal water density changes (temperature and salinity)	6 months	0.2 m
Seiches		
Seiches (standing waves)	Minutes to hours	Up to 2 m
Earthquakes		
Tsunamis (generate catastrophic long-period waves)	Hours	Up to 10 m
Abrupt change in land level	Minutes	Up to 10 m

Longer term changes

Various factors affect the volume or mass of the ocean, leading to long-term changes in eustatic sea level. The two primary influences are temperature (because the density of water depends on temperature), and the mass of water locked up on land and sea as fresh water in rivers, lakes, glaciers, polar ice caps, and sea ice. Over much longer geological timescales, changes in the shape of the oceanic basins and in land/sea distribution will affect sea level.

Observational and modelling studies of mass loss from glaciers and ice caps indicate a contribution to sea-level rise of 0.2 to 0.4 mm/yr averaged over the 20th century.

Glaciers and ice caps

Each year about 8 mm (0.3 inch) of water from the entire surface of the oceans falls into the Antarctica and Greenland ice sheets as snowfall. If no ice returned to the oceans, sea level would drop 8 mm every year. To a first approximation, the same amount of water appeared to return to the ocean in icebergs and from ice melting at the edges. Scientists previously had estimated which is greater, ice going in or coming out, called the *mass balance*, important because it causes changes in global sea level. High-precision gravimetry from satellites in low-noise flight has since determined Greenland is losing millions of tons per year, in accordance with loss estimates from ground measurement. Some estimates range up to 240 km^3 per year in recent years.

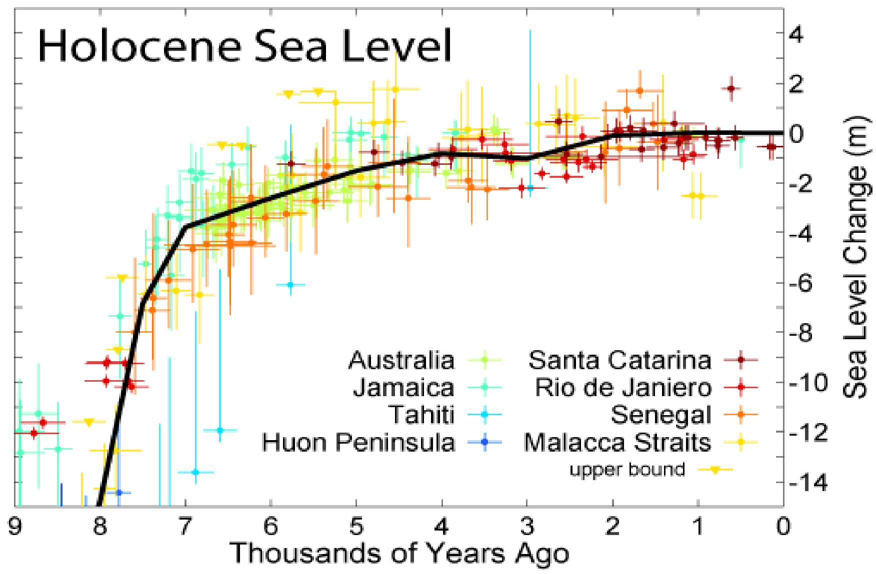
Ice shelves float on the surface of the sea and, if they melt, to first order they do not change sea level. Likewise, the melting of the northern polar ice cap which is composed of floating pack ice would not significantly contribute to rising sea levels. Because they are fresh, however, their melting would cause a very small increase in sea levels, so small that it is generally neglected. It can however be argued that if ice shelves melt it is a precursor to the melting of ice sheets on Greenland and Antarctica.

- If small glaciers and polar ice caps on the margins of Greenland and the Antarctic Peninsula melt, the projected rise in sea level will be around 0.5 m. Melting of the Greenland ice sheet would produce 7.2 m of sea-level rise, and melting of the Antarctic ice sheet would produce 61.1 m of sea level rise. The collapse of the grounded interior reservoir of the West Antarctic Ice Sheet would raise sea level by 5–6 m.
- The interior of the Greenland and Antarctic ice sheets has been (as of 2009) sufficiently high (and therefore cold) enough that direct melt there cannot cause them to melt in a time-frame less than several millennia; therefore it is likely that they will not, through melting of the interior, contribute significantly to sea level rise in the coming century. They can, however, do so through acceleration in flow and enhanced iceberg calving. Also, melt of the fringes of the ice caps could be significant, as could be sub-ice-shelf melting in Antarctica.
- Climate changes during the 20th century are estimated from modelling studies to have led to contributions of between –0.2 and 0.0 mm/yr from Antarctica (the results of increasing precipitation) and 0.0 to 0.1 mm/yr from Greenland (from changes in both precipitation and runoff).
- Estimates suggest that Greenland and Antarctica have contributed 0.0 to 0.5 mm/yr over the 20th century as a result of long-term adjustment to the end of the last ice age.

The current rise in sea level observed from tide gauges, of about 1.8 mm/yr, is within the estimate range from the combination of factors above but active research continues in this field. The terrestrial storage term, thought to be highly uncertain, is no longer positive, and shown to be quite large.

Since 1992 a number of satellites have been recording the change in sea level; they display an acceleration in the rate of sea level change, but they have not been operating for long enough to work out whether this is a real signal, or just an artefact of short-term variation.

Past changes in sea level



Changes in sea level during the last 9,000 years

The sedimentary record

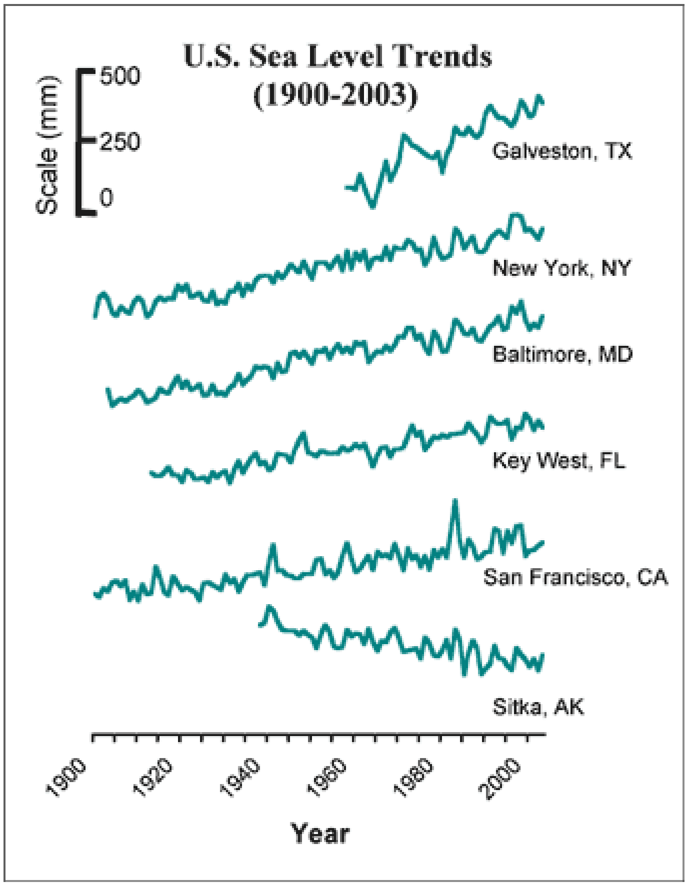
For generations, geologists have been trying to explain the obvious cyclicity of sedimentary deposits observed everywhere we look. The prevailing theories hold that this cyclicity primarily represents the response of depositional processes to the rise and fall of sea level. In the rock record, geologists see times when sea level was astoundingly low alternating with times when sea level was much higher than today, and these anomalies often appear worldwide. For instance, during the depths of the last ice age 18,000 years ago when hundreds of thousands of cubic miles of ice were stacked up on the continents as glaciers, sea level was 120 m (390 ft) lower, locations that today support coral reefs were left high and dry, and coastlines were miles farther basinward from the present-day coastline. It was during this time of very low sea level that there was a dry land connection between Asia and Alaska over which humans are believed to have migrated to North America.

However, for the past 6,000 years (many centuries before the first known written records), the world's sea level has been gradually approaching the level we see today. During the previous interglacial about 120,000 years ago, sea level was for a short time about 6 m higher than today, as evidenced by wave-cut notches along cliffs in the Bahamas. There are also Pleistocene coral reefs left stranded about 3 metres above today's sea level along the southwestern coastline of West Caicos Island in the West Indies. These once-submerged reefs and nearby paleo-beach deposits are silent testimony that sea level spent enough time at that higher level to allow the reefs to grow (exactly where this extra sea water came from—Antarctica or Greenland—has not yet been determined). Similar evidence of geologically recent sea level positions is abundant around the world.

Estimates

- The 2007 IPCC (Intergovernmental Panel on Climate Change) report suggested that sea levels would rise by between 190 mm (7.5 inches) and 590 mm by the end of this century.
- Sea-level rise estimates from satellite altimetry since 1992 (about 2.8 mm/yr) exceed those from tide gauges. It is unclear whether this represents an increase over the last decades, variability, or problems with satellite calibration.
- Church and White (2006) report an acceleration of SLR since 1870. This is a revision since 2001, when the TAR stated that measurements have detected no significant acceleration in the recent rate of sea level rise.
- Based on tide gauge data, the rate of global average sea level rise during the 20th century lies in the range 0.8 to 3.3 mm/yr, with an average rate of 1.8 mm/yr.
- Recent studies of Roman wells in Caesarea and of Roman *piscinae* in Italy indicate that sea level stayed fairly constant from a few hundred years AD to a few hundred years ago.
- Based on geological data, global average sea level may have risen at an average rate of about 0.5 mm/yr over the last 6,000 years and at an average rate of 0.1 to 0.2 mm/yr over the last 3,000 years.
- Since the Last Glacial Maximum about 20,000 years ago, sea level has risen by over 120 m (averaging 6 mm/yr) as a result of melting of major ice sheets. A rapid rise took place between 15,000 and 6,000 years ago at an average rate of 10 mm/yr which accounted for 90 m of the rise; thus in the period since 20,000 years BP (excluding the rapid rise from 15-6 kyr BP) the average rate was 3 mm/yr.
- A significant event was Meltwater pulse 1A (mwp-1A), when sea level rose approximately 20 m over a 500 year period about 14,200 years ago. This is a rate of about 40 mm/yr. Recent studies suggest the primary source was meltwater from the Antarctic, perhaps causing the south-to-north cold pulse marked by the Southern Hemisphere Huelmo/Mascardi Cold Reversal, which preceded the Northern Hemisphere Younger Dryas
- Relative sea level rise at specific locations is often 1–2 mm/yr greater or less than the global average. Along the US mid-Atlantic and Gulf Coasts, for example, sea level is rising approximately 3 mm/yr

U. S. Tide Gauge Measurements



U. S. Sea Level Trends 1900-2003

Tide gauges in the United States show considerable variation because some land areas are rising and some are sinking. For example, over the past 100 years, the rate of sea level rise varies from about an increase of 0.36 inches (9.1 mm) per year along the Louisiana Coast (due to land sinking), to a drop of a few inches per decade in parts of Alaska (due to post-glacial rebound). The rate of sea level rise increased during the 1993-2003 period compared with the longer-term average (1961–2003), although it is unclear whether the faster rate reflects a short-term variation or an increase in the long-term trend.

Amsterdam Sea Level Measurements

The longest running sea-level measurements are recorded at Amsterdam, in the Netherlands—part of which (about 25%) lies beneath sea level.

Australian Sea Level Change

The London Royal Society calculates net sea level rise in Australia at 1 mm/yr—an important result for the Southern Hemisphere. The National Tidal Center also graphs 32 gauges, some since 1880, for the entire coastline

Future sea level rise

In 2007, the Intergovernmental Panel on Climate Change's Fourth Assessment Report (AR4) predicted that by 2100, global warming will lead to a sea level rise of 180 to 590 mm, depending on which of six possible world scenarios comes to pass, and barring rapid dynamical changes in ice flow. More recent research, which has observed rapid declines in ice mass balance from both Greenland and Antarctica, finds that sea-level rise by 2100 is likely to be at least twice as large as that presented by IPCC AR4, with an upper limit of about two meters.

These sea level rises could lead to potentially catastrophic difficulties for shore-based communities in the next centuries: for example, many major cities such as London and New Orleans already need storm-surge defenses, and would need more if sea level rose, though they also face issues such as sinking land. Sea level rise could also displace many shore-based populations: for example it is estimated that a sea level rise of just 200 mm could create 740,000 homeless people in Nigeria. Maldives, Tuvalu, and other low-lying countries are among the areas that are at the highest level of risk. The UN's environmental panel has warned that, at current rates, sea level would be high enough to make the Maldives uninhabitable by 2100.

Future sea level rise, like the recent rise, is not expected to be globally uniform (details below). Some regions show a sea-level rise substantially more than the global average (in many cases of more than twice the average), and others a sea level fall. However, models disagree as to the likely pattern of sea level change.

In September 2008, the Delta Commission presided by Dutch politician Cees Veerman advised in a report that The Netherlands would need a massive new building program to strengthen the country's water defenses against the anticipated effects of global warming for the next 190 years. This commission was created in September 2007, after the damage caused by Hurricane Katrina prompted reflection and preparations. Those included drawing up worst-case plans for evacuations. The plan included more than €100 billion, or $144 billion, in new spending through the year 2100 to take measures, such as broadening coastal dunes and strengthening sea and river dikes.

The commission said the country must plan for a rise in the North Sea up to 4.25 feet (1.3 meters) by 2100, rather than the previously projected 30 inches (0.80 meters), and plan for a 6.5–13 foot rise by 2200.

Intergovernmental Panel on Climate Change results

The results from the IPCC Third Assessment Report (TAR) sea level chapter (convening authors John A. Church and Jonathan M. Gregory) are given below.

IPCC change factors 1990-2100	IS92a prediction	SRES prediction
Thermal expansion	110 to 430 mm	
Glaciers	10 to 230 mm (or 50 to 110 mm)	
Greenland ice	–20 to 90 mm	
Antarctic ice	–170 to 20 mm	
Terrestrial storage	–83 to 30 mm	
Ongoing contributions from ice sheets in response to past climate change	0 to 55 mm	
Thawing of permafrost	0 to 5 mm	
Deposition of sediment	not specified	
Total global-average sea level rise ***(IPCC result, not sum of above)***	**110 to 770 mm**	**90 to 880 mm (central value of 480 mm)**

The sum of these components indicates a rate of eustatic sea level rise (corresponding to a change in ocean volume) from 1910 to 1990 ranging from –0.8 to 2.2 mm/yr, with a central value of 0.7 mm/yr. The upper bound is close to the observational upper bound (2.0 mm/yr), but the central value is less than the observational lower bound (1.0 mm/yr), i.e., the sum of components is biased low compared to the observational estimates. The sum of components indicates an acceleration of only 0.2 (mm/yr)/century, with a range from –1.1 to +0.7 (mm/yr)/century, consistent with observational finding of no acceleration in sea level rise during the 20th century. The estimated rate of sea-level rise from anthropogenic climate change from 1910 to 1990 (from modeling studies of thermal expansion, glaciers and ice sheets) ranges from 0.3 to 0.8 mm/yr. It is very likely that 20th century warming has contributed significantly to the observed sea-level rise, through thermal expansion of sea water and widespread loss of land ice.

A common perception is that the rate of sea-level rise should have accelerated during the latter half of the 20th century, but tide gauge data for the 20th century show no significant acceleration. Estimates obtained are based on AOGCMs for the terms directly related to anthropogenic climate change in the 20th century, i.e., thermal expansion, ice sheets, glaciers and ice caps... The total computed rise indicates an acceleration of only 0.2 (mm/yr)/century, with a range from -1.1 to +0.7 (mm/yr)/century, consistent with observational finding of no acceleration in sea-level rise during the 20th century. The sum of terms not related to recent climate change is -1.1 to +0.9 mm/yr (i.e., excluding thermal expansion, glaciers and ice caps, and changes in the ice sheets due to 20th century climate change). This range is less than the observational lower bound of sea level rise. Hence it is very likely that these terms alone are an insufficient explanation, implying that 20th century climate change has made a contribution to 20th century sea level rise. Recent figures of human, terrestrial impoundment came too late for the 3rd Report, and would revise levels upward for much of the 20th century.

Uncertainties and criticisms regarding IPCC results

- Tide records with a rate of 180 mm/century going back to the 19th century show no measurable acceleration throughout the late 19th and first half of the 20th century. The IPCC attributes about 60 mm/century to melting and other eustatic processes, leaving a residual of 120 mm of 20th century rise to be accounted for. Global ocean temperatures by Levitus et al. are in accord with coupled ocean/atmosphere modelling of greenhouse warming, with heat-related change of 30 mm. Melting of polar ice sheets at the upper limit of the IPCC estimates could close the gap, but severe limits are imposed by the observed perturbations in Earth rotation. (Munk 2002)
- By the time of the IPCC TAR, attribution of sea-level changes had a large unexplained gap between direct and indirect estimates of global sea-level rise. Most direct estimates from tide gauges give 1.5–2.0 mm/yr, whereas indirect estimates based on the two processes responsible for global sea-level rise, namely mass and volume change, are significantly below this range. Estimates of the volume increase due to ocean warming give a rate of about 0.5 mm/yr and the rate due to mass increase, primarily from the melting of continental ice, is thought to be even smaller. One study confirmed tide gauge data is correct, and concluded there must be a continental source of 1.4 mm/yr of fresh water. (Miller 2004)
- From (Douglas 2002): "In the last dozen years, published values of 20th century GSL rise have ranged from 1.0 to 2.4 mm/yr. In its Third Assessment Report, the IPCC discusses this lack of consensus at length and is careful not to present a best estimate of 20th century GSL rise. By design, the panel presents a snapshot of published analysis over the previous decade or so and interprets the broad range of estimates as reflecting the uncertainty of our knowledge of GSL rise. We disagree with the IPCC interpretation. In our view, values much below 2 mm/yr are inconsistent with regional observations of sea-level rise and with the continuing physical response of Earth to the most recent episode of deglaciation."
- The strong 1997-1998 El Niño caused regional and global sea level variations, including a temporary global increase of perhaps 20 mm. The IPCC TAR's examination of satellite trends says *the major 1997/98 El Niño-Southern Oscillation (ENSO) event could bias the above estimates of sea-level rise and also indicate the difficulty of separating long-term trends from climatic variability*.

Glacier contribution

It is well known that glaciers are subject to surges in their rate of movement with consequent melting when they reach lower altitudes and/or the sea. The contributors to Annals of

Glaciology, Volume 36 (2003) discussed this phenomenon extensively and it appears that slow advance and rapid retreat have persisted *throughout the mid to late Holocene* in nearly all of Alaska's glaciers. Historical reports of surge occurrences in Iceland's glaciers go back several centuries. Thus rapid retreat can have several other causes than CO2 increase in the atmosphere.

The results from Dyurgerov show a sharp increase in the contribution of mountain and subpolar glaciers to sea level rise since 1996 (0.5 mm/yr) to 1998 (2 mm/yr) with an average of approx. 0.35 mm/yr since 1960.

Of interest also is Arendt et al., who estimate the contribution of Alaskan glaciers of 0.14±0.04 mm/yr between the mid 1950s to the mid 1990s increasing to 0.27 mm/yr in the middle and late 1990s.

Greenland contribution

Krabill *et al.* estimate a net contribution from Greenland to be at least 0.13 mm/yr in the 1990s. Joughin *et al.* have measured a doubling of the speed of Jakobshavn Isbræ between 1997 and 2003. This is Greenland's largest outlet glacier; it drains 6.5% of the ice sheet, and is thought to be responsible for increasing the rate of sea level rise by about 0.06 millimetres per year, or roughly 4% of the 20th century rate of sea level increase. In 2004, Rignot *et al.* estimated a contribution of 0.04±0.01 mm/yr to sea level rise from southeast Greenland.

Rignot and Kanagaratnam produced a comprehensive study and map of the outlet glaciers and basins of Greenland. They found widespread glacial acceleration below 66 N in 1996 which spread to 70 N by 2005; and that the ice sheet loss rate in that decade increased from 90 to 200 cubic km/yr; this corresponds to an extra 0.25 to 0.55 mm/yr of sea level rise.

In July 2005 it was reported that the Kangerdlugssuaq glacier, on Greenland's east coast, was moving towards the sea three times faster than a decade earlier. Kangerdlugssuaq is around 1,000 m thick, 7.2 km (4.5 miles) wide, and drains about 4% of the ice from the Greenland ice sheet. Measurements of Kangerdlugssuaq in 1988 and 1996 showed it moving at between 5 and 6 km/yr (3.1 to 3.7 miles/yr) (in 2005 it was moving at 14 km/yr [8.7 miles/yr]).

According to the 2004 Arctic Climate Impact Assessment, climate models project that local warming in Greenland will exceed 3° Celsius during this century. Also, ice sheet models project that such a warming would initiate the long-term melting of the ice sheet, leading to a complete melting of the Greenland ice sheet over several millennia, resulting in a global sea level rise of about seven metres.

Antarctic contribution

On the Antarctic continent itself, the large volume of ice present stores around 70 % of the world's fresh water. This ice sheet is constantly gaining ice from snowfall and losing ice through outflow to the sea. West Antarctica is currently experiencing a net outflow of glacial ice, which will increase global sea level over time. A review of the scientific studies looking at data from 1992 to 2006 suggested a net loss of around 50 Gigatonnes of ice per year was a reasonable estimate (around 0.14 mm of sea level rise), although significant acceleration of outflow glaciers in the Amundsen Sea Embayment could have more than doubled this figure for the year 2006.

East Antarctica is a cold region with a ground base above sea level and occupies most of the continent. This area is dominated by small accumulations of snowfall which becomes ice and thus eventually seaward glacial flows. The mass balance of the East Antarctic Ice Sheet as a whole is thought to be slightly positive (lowering sea level) or near to balance. However, increased ice outflow has been suggested in some regions.

Effects of snowline and permafrost

The snowline altitude is the altitude of the lowest elevation interval in which minimum annual snow cover exceeds 50%. This ranges from about 5,500 metres above sea-level at the equator down to sea-level at about 65° N&S latitude, depending on regional temperature amelioration effects. Permafrost then appears at sea-level and extends deeper below sea-level pole-wards. The depth of permafrost and the height of the ice-fields in both Greenland and Antarctica means that they are largely invulnerable to rapid melting. Greenland Summit is at 3,200 metres, where the average annual temperature is minus 32 °C. So even a projected 4 °C rise in temperature leaves it well below the melting point of ice. Frozen Ground 28, December 2004, has a very significant map of permafrost affected areas in the Arctic. The continuous permafrost zone includes all of Greenland, the North of Labrador, NW Territories, Alaska north of Fairbanks, and most of NE Siberia north of Mongolia and Kamchatka. Continental ice above permafrost is very unlikely to melt quickly. As most of the Greenland and Antarctic ice sheets lie above the snowline and/or base of the permafrost zone, they cannot melt in a timeframe much less than several millennia; therefore they are unlikely to contribute significantly to sea-level rise in the coming century.

Polar ice

The sea level will rise above its current level if more polar ice melts. However, compared to the heights of the ice ages, today there are very few continental ice sheets remaining to be melted. It is estimated that Antarctica, if fully melted, would contribute more than 60 metres of sea level rise, and Greenland would contribute more than 7 metres. Small glaciers and ice caps on the margins of Greenland and the Antarctic Peninsula might contribute about 0.5 metres. While the latter figure is much smaller than for Antarctica or Greenland it could occur relatively quickly (within the coming century) whereas melting of Greenland would be slow (perhaps 1,500 years to fully deglaciate at the fastest likely rate) and Antarctica even slower. However, this calculation does not account for the possibility that as meltwater flows under and lubricates the larger ice sheets, they could begin to move much more rapidly towards the sea.

In 2002, Rignot and Thomas found that the West Antarctic and Greenland ice sheets were losing mass, while the East Antarctic ice sheet was probably in balance (although they could not determine the sign of the mass balance for The East Antarctic ice sheet). Kwok and Comiso (*J. Climate*, v15, 487-501, 2002) also discovered that temperature and pressure anomalies around

West Antarctica and on the other side of the Antarctic Peninsula correlate with recent Southern Oscillation events.

In 2004 Rignot et al. estimated a contribution of 0.04±0.01 mm/yr to sea level rise from South East Greenland. In the same year, Thomas et al. found evidence of an accelerated contribution to sea level rise from West Antarctica. The data showed that the Amundsen Sea sector of the West Antarctic Ice Sheet was discharging 250 cubic kilometres of ice every year, which was 60% more than precipitation accumulation in the catchment areas. This alone was sufficient to raise sea level at 0.24 mm/yr. Further, thinning rates for the glaciers studied in 2002-2003 had increased over the values measured in the early 1990s. The bedrock underlying the glaciers was found to be hundreds of metres deeper than previously known, indicating exit routes for ice from further inland in the Byrd Subpolar Basin. Thus the West Antarctic ice sheet may not be as stable as has been supposed.

In 2005 it was reported that during 1992-2003, East Antarctica thickened at an average rate of about 18 mm/yr while West Antarctica showed an overall thinning of 9 mm/yr. associated with increased precipitation. A gain of this magnitude is enough to slow sea-level rise by 0.12±0.02 mm/yr.

Effects of sea level rise

Based on the projected increases stated above, the IPCC TAR WG II report notes that current and future climate change would be expected to have a number of impacts, particularly on coastal systems. Such impacts may include increased coastal erosion, higher storm-surge flooding, inhibition of primary production processes, more extensive coastal inundation, changes in surface water quality and groundwater characteristics, increased loss of property and coastal habitats, increased flood risk and potential loss of life, loss of nonmonetary cultural resources and values, impacts on agriculture and aquaculture through decline in soil and water quality, and loss of tourism, recreation, and transportation functions.

There is an implication that many of these impacts will be detrimental—especially for the three-quarters of the world's poor who depend on agriculture systems. The report does, however, note that owing to the great diversity of coastal environments; regional and local differences in projected relative sea level and climate changes; and differences in the resilience and adaptive capacity of ecosystems, sectors, and countries, the impacts will be highly variable in time and space.

Statistical data on the human impact of sea level rise is scarce. A study in the April, 2007 issue of *Environment and Urbanization* reports that 634 million people live in coastal areas within 30 feet (9.1 m) of sea level. The study also reported that about two thirds of the world's cities with over five million people are located in these low-lying coastal areas. The IPCC report of 2007 estimated that accelerated melting of the Himalayan ice caps and the resulting rise in sea levels would likely increase the severity of flooding in the short term during the rainy season and greatly magnify the impact of tidal storm surges during the cyclone season. A sea-level rise of just 400 mm in the Bay of Bengal would put 11 percent of the Bangladesh's coastal land underwater, creating 7 to 10 million climate refugees.

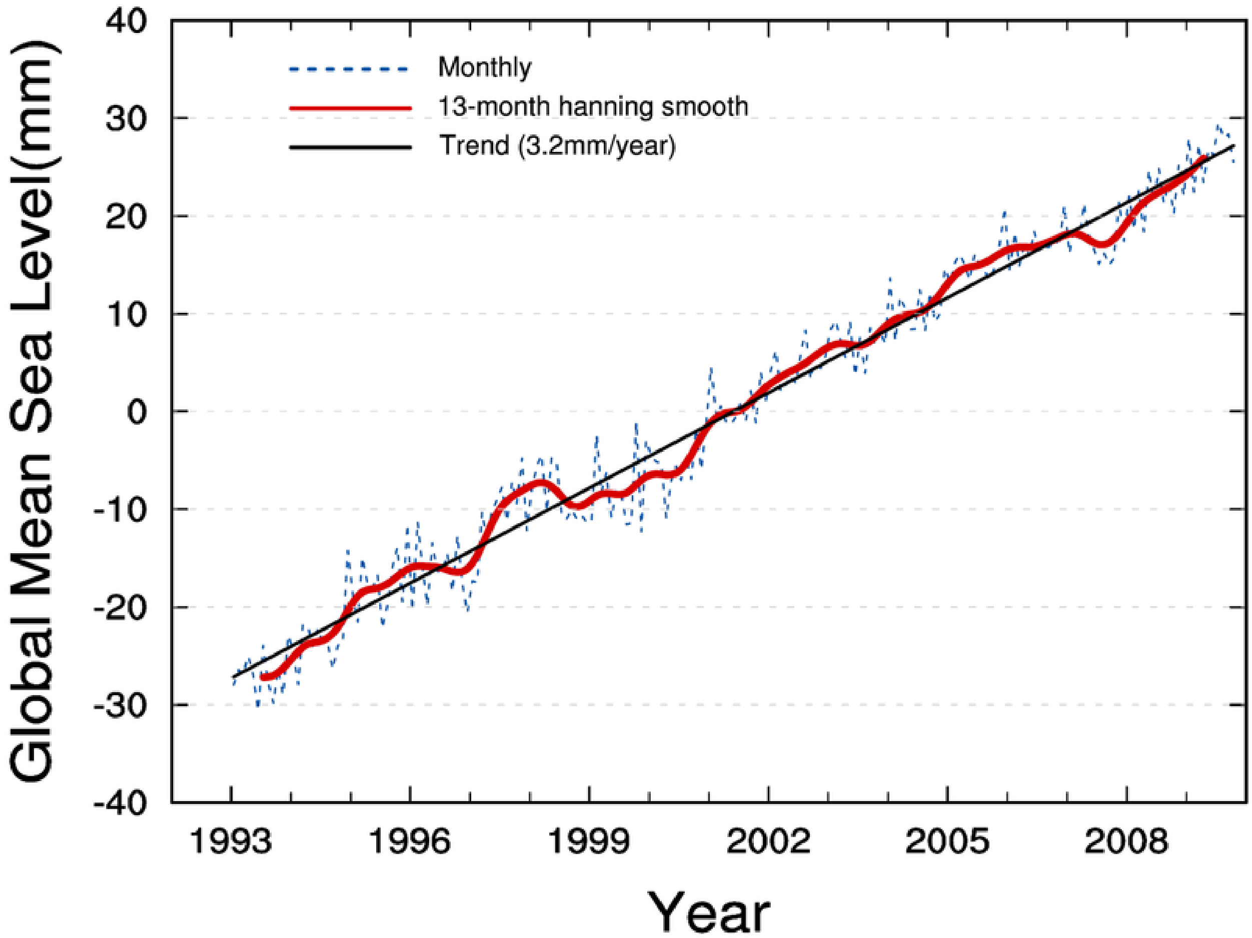
Island nations

IPCC assessments suggest that deltas and small island states are particularly vulnerable to sea level rise caused by both thermal expansion and ocean volume. Relative sea level rise (mostly caused by subsidence) is currently causing substantial loss of lands in some deltas. Sea level changes have not yet been conclusively proven to have directly resulted in environmental, humanitarian, or economic losses to small island states, but the IPCC and other bodies have found this a serious risk scenario in coming decades.

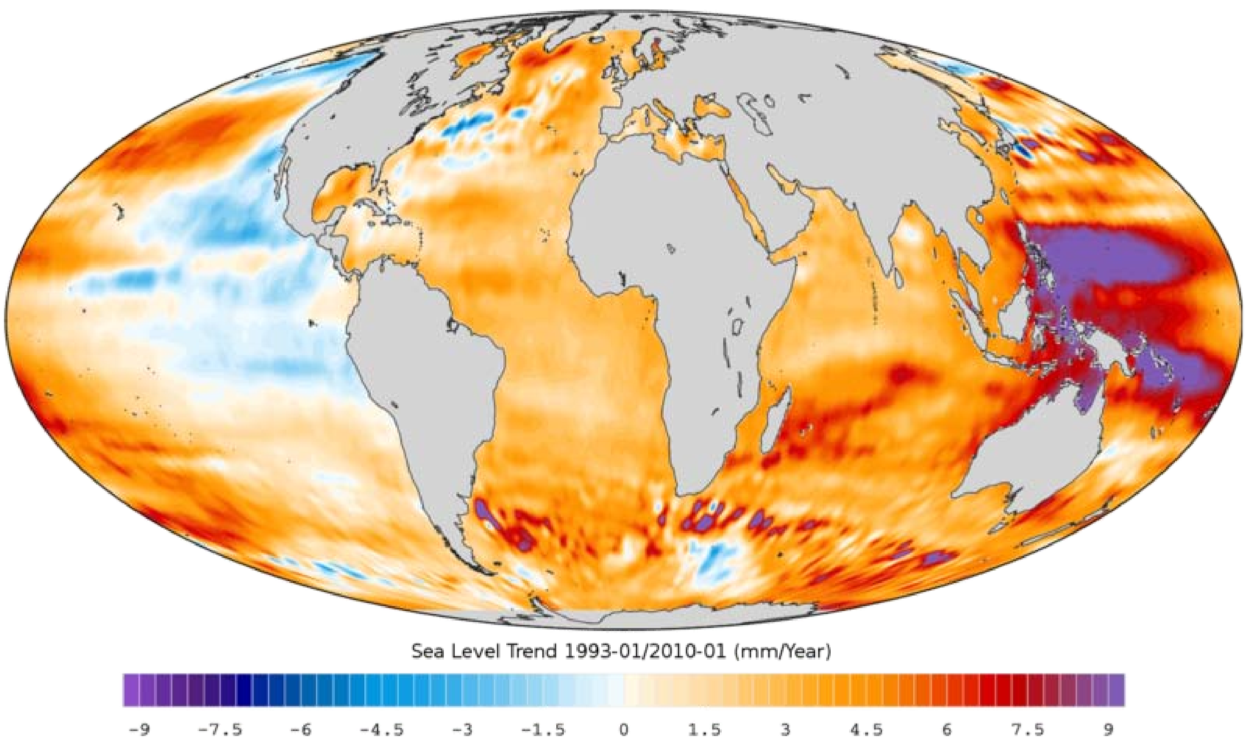
Many media reports have focused the island nations of the Pacific, notably the Polynesian islands of Tuvalu, which based on more severe flooding events in recent years, was thought to be "sinking" due to sea level rise. A scientific review in 2000 reported that based on University of Hawaii gauge data, Tuvalu had experienced a negligible increase in sea-level of 0.07 mm a year over the past two decades, and that ENSO had been a larger factor in Tuvalu's higher tides in recent years. A subsequent study by John Hunter from the University of Tasmania, however, adjusted for ENSO effects and the movement of the gauge (which was thought to be sinking). Hunter concluded that Tuvalu had been experiencing sea-level rise of about 1.2 mm per year. The recent more frequent flooding in Tuvalu may also be due to an erosional loss of land during and following the actions of 1997 cyclones Gavin, Hina, and Keli.

Numerous options have been proposed that would assist island nations to adapt to rising sea level.

Satellite sea level measurement



Satellite Measurement of Sea Level



1993-2010 Sea level trends from satellite altimetry

Sea level rise estimates from satellite altimetry are 3.1 ± 0.4 mm/yr for 1993-2003 (Leuliette et al. (2004)). This exceeds those from tide gauges. It is unclear whether this represents an increase over the last decades; variability; true differences between satellites and tide gauges; or problems with satellite calibration. Knowing the current altitude of a satellite which can measure sea level to a precision of about 20 millimetres (e.g. the Topex/Poseidon system) is primarily complicated by orbital decay and the difference between the assumed orbit and the earth geoid. This problem is partially corrected by regular re-calibration of satellite altimeters from land stations whose height from MSL is known by surveying. Over water, the height is calibrated from tide gauge data which is needed to correct for tides and atmospheric effects on sea level.

The IPCC predicts that by 2100, global warming will lead to a sea level rise of 110 to 880 mm.

Rapid variations

Tides

The **Bay of Fundy** is a bay located on the Atlantic coast of North America, on the northeast end of the Gulf of Maine between the provinces of New Brunswick and Nova Scotia.

The rise and fall of the oceans due to tidal effects is a key influence upon the coastal areas. Ocean tides on the planet Earth are created by the gravitational effects of the Sun and Moon. The tides produced by these two bodies are roughly comparable in magnitude, but the orbital motion of the Moon results in tidal patterns that vary over the course of a month.

The ebb and flow of the tides produce a cyclical current along the coast, and the strength of this current can be quite dramatic along narrow estuaries. Incoming tides can also produce a tidal bore along a river or narrow bay as the water flow against the current results in a wave on the surface.

Tide and Current (Wyban 1992) clearly illustrates the impact of these natural cycles on the lifestyle and livelihood of Native Hawaiians tending coastal fishponds. *Aia ke ola ka hana* meaning . . . *Life is in labor*.

Tidal resonance occurs in the Bay of Fundy since the time it takes for a large wave to travel from the mouth of the bay to the opposite end, then reflect and travel back to the mouth of the bay coincides with the timing between this repeating wave that is also reinforced by the tidal rhythm producing the world's highest tides.

As the surface tide oscillates over topography, such as submerged seamounts or ridges, it generates internal waves at the tidal frequency, which are known as internal tides.

Tsunamis

A series of surface waves can be generated due to large-scale displacement of the ocean water. These can be caused by sub-marine landslides, seafloor deformations due to earthquakes, or the impact of a large meteorite.

The waves can travel with a velocity of up to several hundred km/hour across the ocean surface, but in mid-ocean they are barely detectable with wavelengths spanning hundreds of kilometers.

Tsunamis, originally called tidal waves, were renamed because they are not related to the tides. They are regarded as shallow-water waves, or waves in water with a depth less than 1/20 their wavelength. Tsunamis have very large periods, high speeds, and great wave heights.

The primary impact of these waves is along the coastal shoreline, as large amounts of ocean water are cyclically propelled inland and then drawn out to sea. This can result in significant modifications to the coastline regions where the waves strike with sufficient energy.

The tsunami that occurred in Lituya Bay, Alaska on July 9, 1958 was 520 m (1,710 ft) high and is the biggest tsunami ever measured, almost 90 m (300 ft) taller than the Sears Tower in Chicago and about 110 m (360 ft) taller than the World Trade Center in New York.

Wind wave

North Pacific storm waves as seen from the NOAA M/V *Noble Star*, Winter 1989

Ocean waves

In fluid dynamics, **wind waves** or, more precisely, **wind-generated waves** are surface waves that occur on the free surface of oceans, seas, lakes, rivers, and canals or even on small puddles and ponds. They usually result from the wind blowing over a vast enough stretch of fluid surface. Some waves in the oceans can travel thousands of miles before reaching land. Wind waves range in size from small ripples to huge rogue waves. When directly being generated and affected by the local winds, a wind wave system is called a **wind sea**. After the wind ceases to blow, wind waves are called *swell*. Or, more generally, a swell consists of wind generated waves that are not — or hardly — affected by the local wind at that time. They have been generated elsewhere, or some time ago. Wind waves in the ocean are called **ocean surface waves**.

Tsunamis are a specific type of wave not caused by wind but by geological effects. In deep water, tsunamis are not visible because they are small in height and very long in wavelength. They may grow to devastating proportions at the coast due to reduced water depth.

Wave formation

NOAA ship *Delaware II* in bad weather on Georges Bank

The great majority of large breakers one observes on a beach result from distant winds. Five factors influence the formation of wind waves:

- Wind speed
- Distance of open water that the wind has blown over (called the *fetch*)
- Width of area affected by fetch
- Time duration the wind has blown over a given area
- Water depth

All of these factors work together to determine the size of wind waves. The greater each of the variables, the larger the waves. Waves are characterized by:

- Wave height (from trough to crest)
- Wavelength (from crest to crest)
- Wave period (time interval between arrival of consecutive crests at a stationary point)
- Wave propagation direction

Waves in a given area typically have a range of heights. For weather reporting and for scientific analysis of wind wave statistics, their characteristic height over a period of time is usually expressed as *significant wave height*. This figure represents an average height of the highest one-third of the waves in a given time period (usually chosen somewhere in the range from 20 minutes to twelve hours), or in a specific wave or storm system. Given the variability of wave height, the largest individual waves are likely to be about twice the reported significant wave height for a particular day or storm.

Types of wind waves

Three different types of wind waves develop over time:

- Capillary waves, or ripples
- Seas
- Swells

Ripples appear on smooth water when the wind blows, but will die quickly if the wind stops. The restoring force that allows them to propagate is surface tension. Seas are the larger-scale, often irregular motions that form under sustained winds. They tend to last much longer, even after the wind has died, and the restoring force that allows them to persist is gravity. As seas propagate away from their area of origin, they naturally separate according to their direction and wavelength. The regular wave motions formed in this way are known as swells.

Individual "rogue waves" (also called "freak waves", "monster waves", "killer waves", and "king waves") sometimes occur, up to heights near 30 meters, and being much higher than the other waves in the sea state. Such waves are distinct from tides, caused by the Moon and Sun's gravitational pull, tsunamis that are caused by underwater earthquakes or landslides, and waves generated by underwater explosions or the fall of meteorites — all having far longer wavelengths than wind waves.

Wave breaking

Big wave breaking

Surf in a rocky irregular bottom. Porto Covo, west coast of Portugal

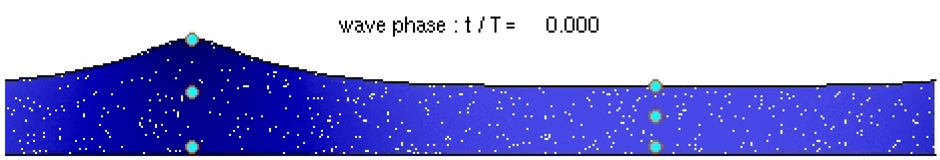
Some waves undergo a phenomenon called "breaking". A breaking wave is one whose base can no longer support its top, causing it to collapse. A wave breaks when it runs into shallow water, or when two wave systems oppose and combine forces. When the slope, or steepness ratio, of a wave is too great, breaking is inevitable.

Individual waves in deep water break when the wave steepness — the ratio of the wave height H to the wavelength λ — exceeds about 0.17, so for $H > 0.17\,\lambda$. In shallow water, with the water depth small compared to the wavelength, the individual waves break when their wave height H is larger than 0.8 times the water depth h, that is $H > 0.8\,h$. Waves can also break if the wind grows strong enough to blow the crest off the base of the wave.

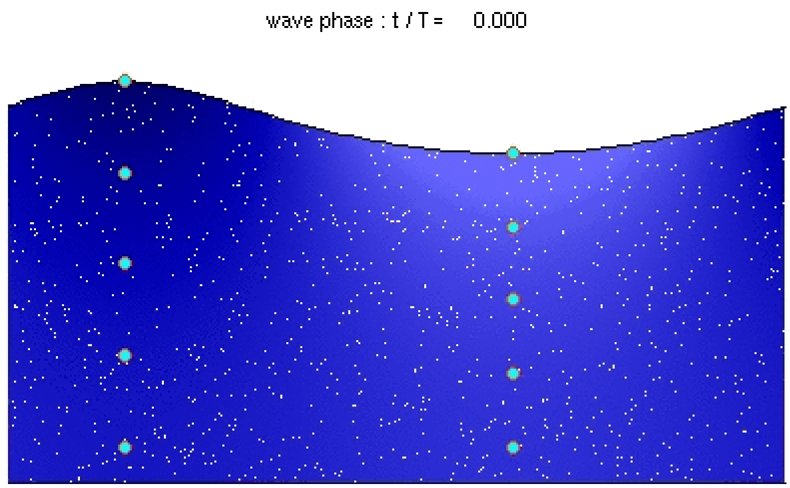
Three main types of breaking waves are identified by surfers or surf lifesavers. Their varying characteristics make them more or less suitable for surfing, and present different dangers.

- **Spilling**, or **rolling**: these are the safest waves on which to surf. They can be found in most areas with relatively flat shorelines. They are the most common type of shorebreak
- **Plunging**, or **dumping**: these break suddenly and can "dump" swimmers—pushing them to the bottom with great force. These are the preferred waves for experienced surfers. Strong offshore winds and long wave periods can cause dumpers. They are often found where there is a sudden rise in the sea floor, such as a reef or sandbar.
- **Surging**: these may never actually break as they approach the water's edge, as the water below them is very deep. They tend to form on steep shorelines. These waves can knock swimmers over and drag them back into deeper water.

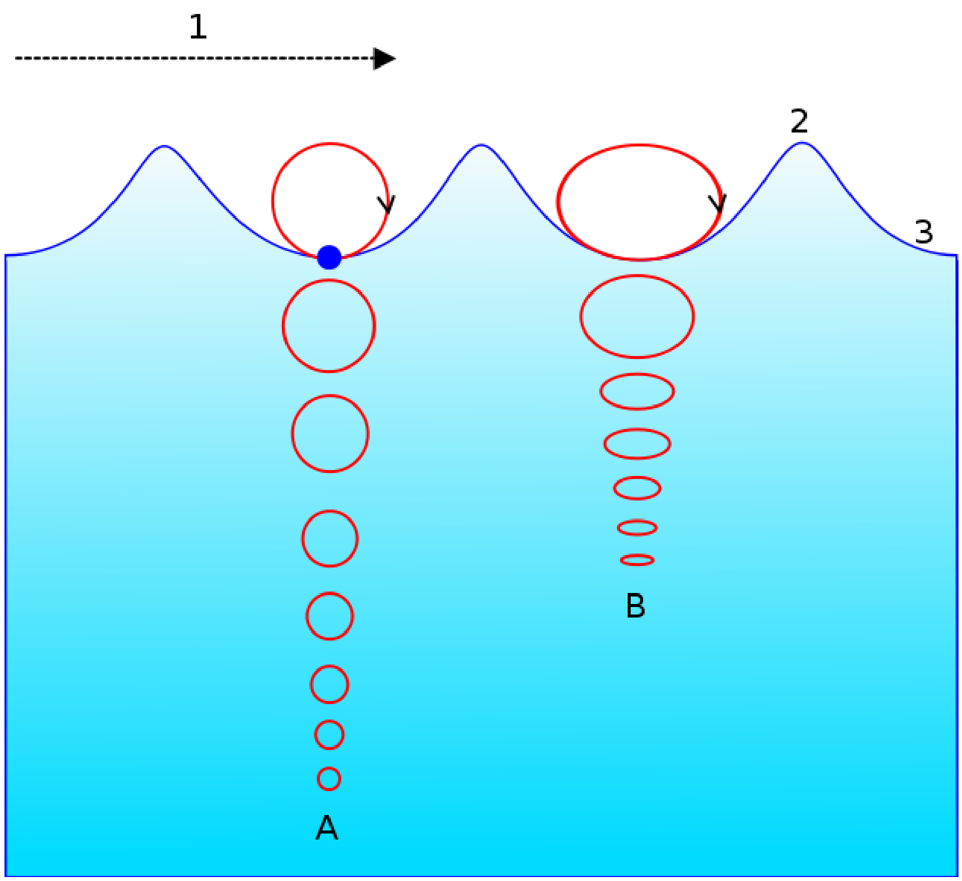
Science of waves



Shallow water wave



Deep water wave



Motion of a particle in a wind wave.
A = At deep water. The orbital motion of fluid particles decreases rapidly with increasing depth below the surface.
B = At shallow water (sea floor is now at B). The elliptical movement of a fluid particle flattens with decreasing depth.

1 = Propagation direction.
2 = Wave crest.
3 = Wave trough.

Wind waves are mechanical waves that propagate along the interface between water and air; the restoring force is provided by gravity, and so they are often referred to as surface gravity waves. As the wind blows, pressure and friction forces perturb the equilibrium of the water surface. These forces transfer energy from the air to the water, forming waves. In the case of monochromatic linear plane waves in deep water, particles near the surface move in circular paths, making wind waves a combination of longitudinal (back and forth) and transverse (up and down) wave motions. When waves propagate in shallow water, (where the depth is less than half the wavelength) the particle trajectories are compressed into ellipses.

As the wave amplitude (height) increases, the particle paths no longer form closed orbits; rather, after the passage of each crest, particles are displaced slightly from their previous positions, a phenomenon known as Stokes drift.

For intermediate and shallow water, the Boussinesq equations are applicable, combining frequency dispersion and nonlinear effects. And in very shallow water, the shallow water equations can be used.

As the depth below the free surface increases, the radius of the circular motion decreases. At a depth equal to half the wavelength λ, the orbital movement has decayed to less than 5% of its value at the surface. The phase speed of the surface wave (also called the celerity) is well approximated by

$$c = \sqrt{\frac{g\lambda}{2\pi}\tanh\left(\frac{2\pi d}{\lambda}\right)}$$

where

c = phase speed;
λ = wavelength;
d = water depth;
g = acceleration due to gravity at the Earth's surface.

In deep water, where $d \geq \frac{1}{2}\lambda$, so $\frac{2\pi d}{\lambda} \geq \pi$ and the hyperbolic tangent approaches 1, the speed c, in m/s, approximates $1.25\sqrt{\lambda}$, when λ is measured in meters. This expression tells us that waves of different wavelengths travel at different speeds. The fastest waves in a storm are the ones with the longest wavelength. As a result, after a storm, the first waves to arrive on the coast are the long–wavelength swells.

When several wave trains are present, as is always the case in nature, the waves form groups. In deep water the groups travel at a group velocity which is half of the phase speed. Following a single wave in a group one can see the wave appearing at the back of the group, growing and finally disappearing at the front of the group.

As the water depth *d* decreases towards the coast, this will have an effect: wave height changes due to wave shoaling and refraction. As the wave height increases, the wave may become unstable when the crest of the wave moves faster than the trough. This causes *surf*, a breaking of the waves.

The movement of wind waves can be captured by wave energy devices. The energy density (per unit area) of regular sinusoidal waves depends on the water density ρ, gravity acceleration *g* and the wave height *H* (which, for regular waves, is equal to twice the amplitude, *a*):

$$E = \frac{1}{8}\rho g H^2 = \frac{1}{2}\rho g a^2.$$

The velocity of propagation of this energy is the group velocity.

Wind wave models

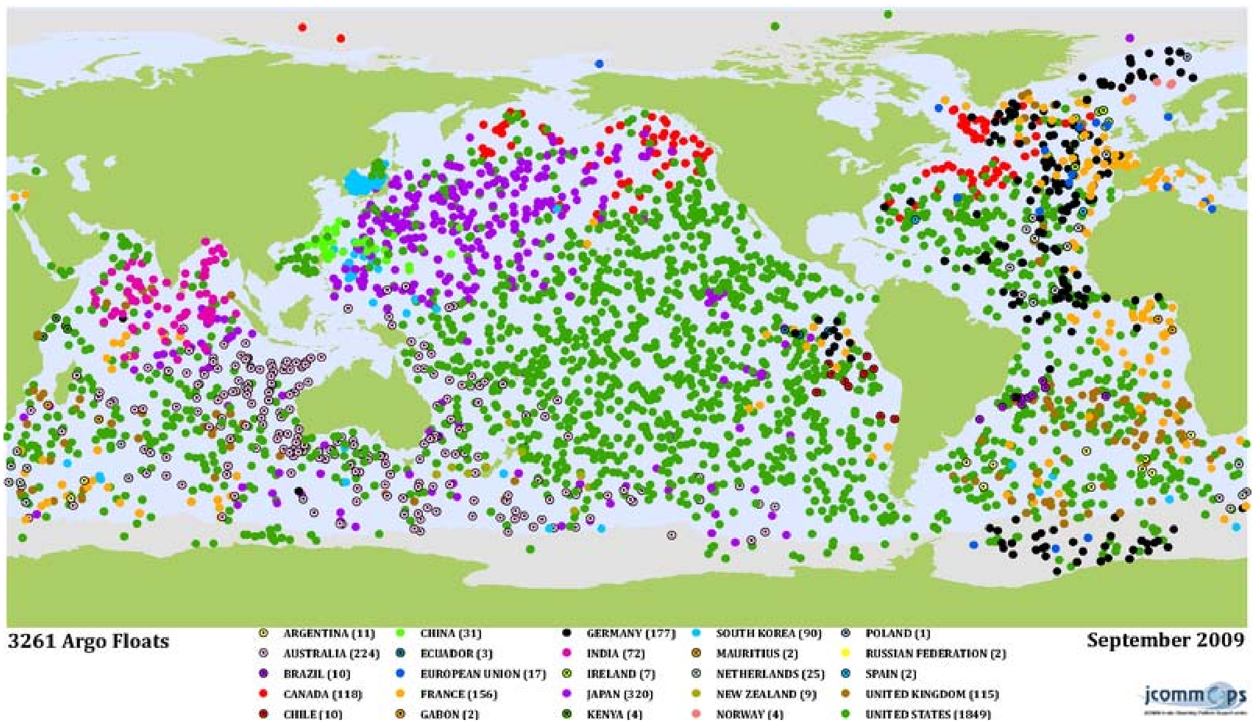
Surfers are very interested in the wave forecasts. There are many websites that provide predictions of the surf quality for the upcoming days and weeks. Wind wave models are driven by more general weather models that predict the winds and pressures over the oceans, seas and lakes.

Wind wave models are also an important part of examining the impact of shore protection and beach nourishment proposals. For many beach areas there is only *patchy information* about the wave climate, therefore estimating the effect of wind waves is important for managing littoral environments.

Chapter- 4

Argo

Argo is an observation system for the Earth's oceans that provides real-time data for use in climate, weather, oceanographic and fisheries research. Argo consists of a large collection of small, drifting oceanic robotic probes deployed worldwide. The probes float as deep as 2 km. Once every 10 days, the probes surface, measuring conductivity and temperature profiles to the surface. From these salinity and density can be calculated. The data are transmitted to scientists on shore via satellite. The data collected are freely available to everyone, without restrictions. The initial project goal was to deploy 3,000 probes, completed in November 2007.



Map of the Argo float network as of September 2009

International collaboration

The Argo program is a collaboration between 50 research and operational agencies from 26 countries, with the United States contributing over half the total funding (as of December 2004). Argo is a component of the Integrated Ocean Observing System.

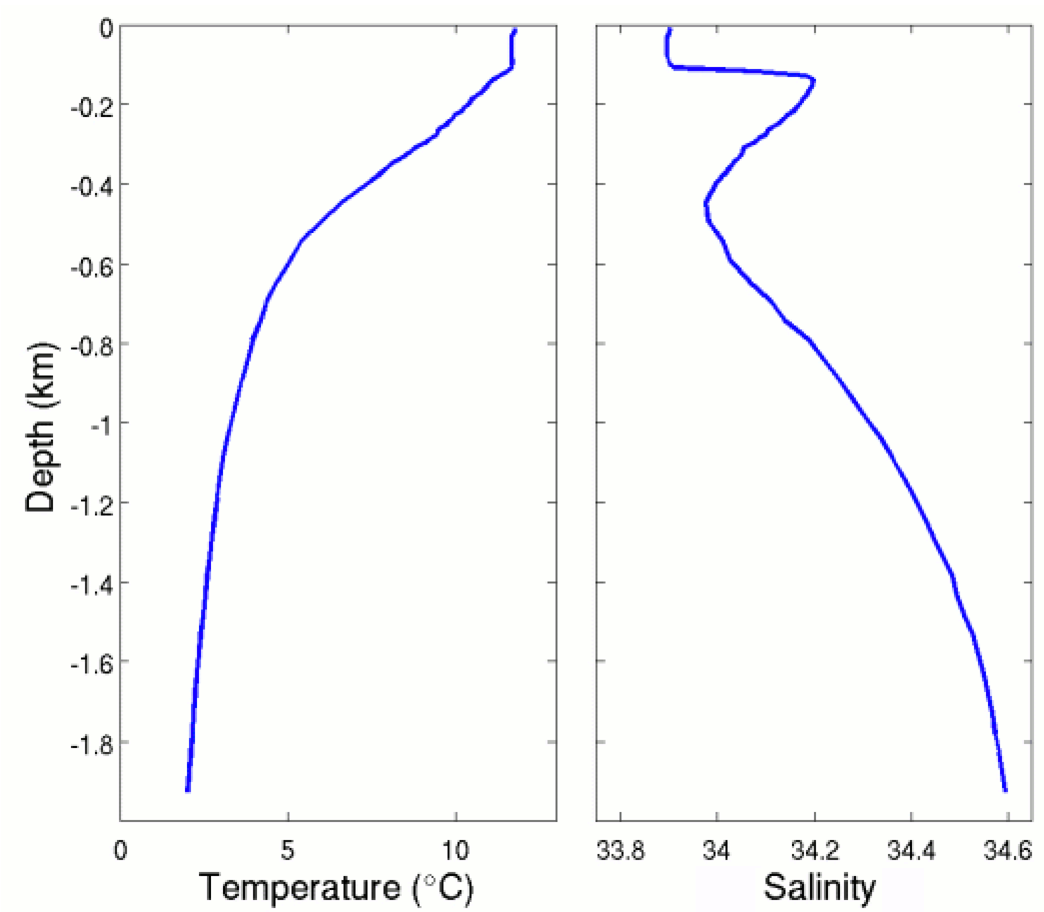
Float operation

The Argo program was designed to operate on the same 10-day duty cycle to match the existing satellite measurements of the ocean's sea surface. These satellites, called Topex/Poseidon and Jason 1, measure changes in the surface topography of the ocean. With such measurements, information about temperature, mass redistribution, or surface currents can be inferred. The Argo floats measure *subsurface* changes in temperature and salinity, hence the float measurements are complementary to the altimetry.

Argo is named after the Greek mythical ship Argo which Jason and the Argonauts use on their quest for the Golden Fleece. The name was chosen to emphasize the complementary relationship of the project with the Jason-1 satellite altimeter.

Although drifting floats had been deployed during the World Ocean Circulation Experiment in the 1990s, Argo floats began to be deployed in earnest in the early 2000s. The target number of 3000 deployed floats was reached during 2006–2007. The number of floats is continually changing as floats are lost or expire, while others are deployed. Nominally, some 750 floats are deployed each year to sustain the system. The floats have a nominal 300-km spacing, although the exact separations depend on the randomness of the float drift.

The Argo temperature and salinity measurements are yielding valuable information about the large-scale water properties and currents of the ocean, including the variability of these properties over time scales from seasonal to decadal.



Example profiles of temperature and salinity obtained from an Argo float in the central North Pacific (38.4°N, 155.3°W) on April 8, 2005.

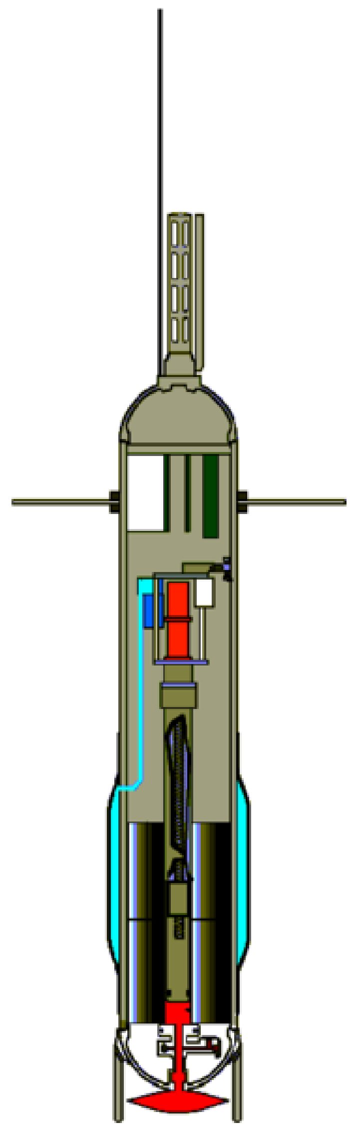
Profiling

Argo floats drift at a fixed pressure (usually around 1000 metres depth) for 10 days. After this period, within the relatively short time of around two hours, the floats move to a profiling pressure (usually 2000 metres deep) then rise, collecting instantaneous profiles of pressure, temperature, and salinity data on their way to the surface. Once at the surface, the floats remain there for under a day, transmitting the data collected via a satellite link back to a ground station and allowing the satellite to determine their surface drift. The floats then sink again and repeat their mission.

Data communication

Most of the floats use the Argos System of satellites to recover data, though a few are using the newer Iridium satellite constellation. The Iridium system offers significant advantages associated with the much faster data transfer. Since an Iridium float spends only 3 minutes at the sea surface, the opportunity to observe surface currents by tracking the movements of the floats is lost but the trajectories of the floats become more representative of the flow at their parking depth.

Float design



Cutaway diagram of an Argo float. The height of the float is about 2 m. The antenna and sensors are mounted at the top of the buoy.

A critical capability of an Argo float is its ability to rise and descend in the ocean on a programmed schedule. The floats do this by changing their effective density. The density of any object is given by its mass divided by its volume. The Argo float keeps its mass constant, but by altering its volume, it changes its density. To do this, a hydraulic piston is used to push mineral oil out of the float and expand a rubber bladder at the bottom end of the float. As the bladder expands, the float becomes less dense than seawater and rises to the surface. Upon finishing its tasks at the surface, the float withdraws the piston and descends again.

An increasing number of the floats also carry other sensors, such as for measuring dissolved oxygen.

The antenna for satellite communications is mounted at the top of the float. Once the float reaches the surface, the float is essentially a spar buoy, allowing the antenna to poke above the sea surface for communication. The ocean is saline, hence an electric conductor, so that radio communications from under the sea surface are difficult.

The nominal life span of an Argo float is five years. After the internal batteries expire, the floats are allowed to sink to the ocean floor or wash ashore.

Data access

Argo is unique among research programs in that the real-time data are freely offered to anyone. The data collected by the network are made available with no constraint on use of the data, and most data are available for download within 24 hours of a float measurement. Data can be downloaded over the world wide web from one of two global data servers (OPeNDAP servers).

Data format

Even though data are supplied by 24 national programs, all data are available in near real-time in a single format. Argo data are in the native import format of the Ocean DataView suite of programs. Ocean DataView (ODV) is freely available software created by Reiner Schlitzer that offers flexible ways of displaying oceanographic data. Data in other formats are also available, e.g., netCDF. A careful study of the manuals before starting to use the data is essential

Data results

It is not yet possible to use Argo data to detect global change signals.

Data results from year 2006 with undetected errors

The Argo Network has shown a continuous declining trend in ocean temperatures. The trend was overstated in media reports because of published data with undetected errors in year 2006. In March 2008, Josh Willis of NASA's Jet Propulsion Laboratory did report that the Argo system show no ocean warming since it started in 2003. "There has been a very slight cooling, but not anything really significant," Willis has stated. A lot of media has reported the uncorrected data results and even though the revised corrected data appeared in 2008, many articles and arguments still use and promote the uncorrected data results from 2006.

Data results from year 2008 and after

In an article from November 5, 2008, Josh Willis states that the world ocean actually has been warming since 2003 after removing Argo measurement errors from the data and adjusting the measured temperatures with a computer model his team developed.

Here is a graph with the 2008/2009 Argo network data included.