USEFUL LOOKUP ITEMS

Some physical, chemical, biological and geological ocean data

I, Units used; II, Aspects of Chemistry; III, Outline of Systematics; IV, Geologic Time Scale; V, Topographic Statistics

Appendix I: Units used in the ocean sciences

Distance

m, meter; picometer (1/trillion m); nanometer (1/billion m); micrometer (1/million m); millimeter (1/1000 m); centimeter (1/100 m); decimeter (1/10 m); kilometer (1000 m); inch (2.54 cm); foot (30.48 cm); fathom (6 foot, 1.8288 m); yard (1/2 fathom); mile (1.61 km); nautical mile (1.852 km; 1 min. of latitude at 45º of lat.)

Volume

liter (33.814 U.S. fluid ounces; volume of 1 kg of water); cubic meter (1000 liter); milliliter (1 ml; 1 cubic cm; 0.001 liter); cubic inch (16.387 cm^3); gallon (U.S.) (3.7854 liter); quart (0.95 l)

Time

s, second; pico- to milli-second, see distance for meaning of prefix terms; minute (60 s); hour (60 min); solar day (24 hrs); astronomical day (0.9973 solar days); lunar month (29.53 days); year (mean solar year, 365.2564 solar days; 31,558,150 seconds)

Velocity (distance per time)

cm/s (1 knot is 51.444 cm/s), kph (27.78 cm/s; 1 kn is 1.852 kph), mph (1 kn is 1 naut.mile/h), m/s (3.6 kph; 1.944 knot)

Temperature

centigrade (or Celsius or Kelvin); Fahrenheit (1.8 centigrades; zero Celsius at 32ºF)

Mass

gram (mass of 1 ml of water; 1/1000 kg; 1/million ton); mg (1/1000 g); µg (1/million g); metric ton (1 t = 1000 kg = 2205 lb)

Transport (volume per time)

sverdrup (1 sv = 1 million cubic meters per second)

Energy and Power

calorie (gram) (energy to raise 1 ml of water by 1 degree centigrade); watt (1 joule/s; 860 g-cal/hour); horsepower (0.7457 watt)

Irradiance: watts per square meter

Pressure (force per area)

atmosphere (1.0332 kg/cm^2); bar (0.9869233 atm); $lb/inch^2$ (14.22 $lb/inch^2$ = 1 kg/cm^2)

Concentration

grams per liter; mg/liter (milligrams per liter, parts per million); moles per liter (or gram-atom per liter, number of molecules or atoms per liter in terms of the ratio of mass over molecular weight; unity denotes Avogadro's number)

Sound Intensity and Frequency

decibel, a measure of the ratio of power densities, on a logarithmic scale, whereby the intensity of interest is compared to a standard. In air, faint whispers are near 40 decibels, the average human voice is 60, a leaf blower is 100 (for the operator) and exposure above 115 is considered hazardous. In water, numbers for equivalent intensity levels are higher by 62 db, because of differences in reference level and in transmission efficiency.

hertz, (Hz, cycles per second); pitch of sound; important in communication and orientation and echo hunting (acoustic biology), and in acoustic exploration (including seismic exploration); infrasound (low frequency, <20 Hz) carries over long distances; ultrasound (high frequency, >20 kilo-Hz) is useful in resolving small objects (such as swim-bladders); typical range of hearing in fishes (response to noise) ca. 100 to 1000 Hz, but varies greatly depending on species (some respond to ultrasound); in baleen whales ca. 10 to 1000 Hz; in dolphins ca. 100 to 100,000 Hz. [Maximum sensitivity in humans ca. 2000 Hz.] Typical frequency in seismic exploration, 100 to 1000 Hz.

Sources (other than acoustics)**:** C. Emiliani, 1992, *Planet Earth – Cosmology, Geology, and the Evolution of Life and Environment,* Cambridge University Press, Cambridge New York, 719pp.; acoustics: various sources, scientific literature, also see articles on ocean acoustics in Steele, J. H., S. A. Thorpe and K. K. Turekian (eds.) 2001, *Encyclopedia of Ocean Sciences*, 6 vols., Academic Press, San Diego, 3399pp.

Appendix II: Aspects of Ocean Chemistry

Composition of Seawater

Seawater is a solution of various **salts**, with about 96.5% water. The content of salt in seawater is called the “salinity;” it is normally near 3.5% (by weight, given as 35 permil). The salinity is commonly measured by determining the conductivity of seawater (while correcting for the temperature effect). The salt is present as “ions;” that is, charged molecules. The ions are surrounded by water molecules (which have dipole nature; that is, a negative and a positive pole). Thus, they do not readily combine to make salt, which explains the fact that water is of all natural liquids the best solvent.

The **major ions** in seawater are the following (numbers are percent of total weight of the salt in seawater): chloride (Cl^-, 55.04), sodium (Na^+, 30.61), sulfate ($SO_4^=$, 7.68), magnesium (Mg^{++}, 3.69), calcium (Ca^{++}, 1.16), potassium (K^+, 1.10), bicarbonate (HCO_3^-, 0.41) [sum, 99.69%]. The next four components are bromide, boric acid, strontium, and fluoride. The first four are entirely dominant (97%); the main constituent of the salt formed when evaporating seawater is the familiar table salt. On the whole, the composition of seawater reflects the solubility of the substances involved, which are abundant in crustal rocks (sodium, magnesium, calcium, potassium) and in volcanic emissions (chlorine, sulfur, carbon). Long-term control of the composition of seawater involves reaction of volcanic gases with the continental crust (chemical weathering), deposition of enormous salt bodies through geologic time, and reactions of seawater with hot basalt in volcanically active regions.

Seawater contains dissolved **gases**, such as nitrogen (N_2), oxygen (O_2), Argon (Ar) and carbon dioxide (CO_2). In the case of **carbon dioxide**, there is a reaction with the water, which generates a number of molecules, including ions (H_2CO_3, HCO_3^{-}, $CO_3^{=}$). This greatly enhances the ability of the water to hold carbon dioxide in solution, which results in the fact that the ocean holds the bulk of the combined ocean-and-atmosphere mass of carbon. Of the three species, the **bicarbonate** (HCO_3^{-}) is greatly dominant at the pH values (concentration of hydrogen ions, acidity) found in the ocean (slightly basic, **pH near 8**). High alkalinity (high carbonate-ion content) enhances carbon dioxide uptake by seawater. Precipitation of solid carbonate lowers the alkalinity, while dissolution of solid carbonate increases it. When seawater takes up additional carbon dioxide, carbonate is converted to bicarbonate, and the pH drops somewhat. This process is currently driven by the ongoing increase in carbon dioxide in the atmosphere and referred to as “acidification”. As the concentration of carbonate ion drops, the ability of seawater to take up carbon dioxide decreases.

Limiting Nutrients in Ocean Productivity

In most of the surface waters of the ocean, wherever there is sufficient light for photosynthesis, the concentrations of **nitrate** (NO_3^{-}), **phosphate** (PO_4^{-3}), and **silicate** (H_4SiO_4) are extremely low, these species having been removed by precipitation within photosynthesizing organisms and an associated “rain” of particles toward deeper waters. The ratio of the elements N and P, during such removal and regardless of concentrations, stays approximately constant (reflecting the mixture of phytoplankton using them); this is the so-called **Redfield ratio**, and is near a value of 16. The ratio of Si to the other two nutrients varies considerably, which is of great interest. Silicate is crucially important in the growth of diatoms (the ratio of Si to C in diatoms approaching unity); it is used in making the glass shells of the siliceous phytoplankton. Since diatoms are at the base of short food chains, silicate supply governs the distribution and abundance of high-energy apex consumers (such as marine mammals: no silicate, long food chains, little food for apex consumers at the top level).

Nutrients are remineralized below the sunlit zone by bacteria-facilitated processes involving oxygen; thus, the amount of oxygen in deep waters is important in the recycling of nutrients, as is the rate of replacement of deep waters (thermohaline circulation). Typical concentrations of **phosphate** in the ocean vary between 0.1 and 3.0 micro-moles per liter (µg-atoms/l) with values below 2.0 common in the deep Atlantic, and values greater than 2.0 common in the deep Pacific. **Nitrate** concentrations are 16 times greater by number of molecules (Redfield ratio). There has been much discussion about which is the “true” limiting factor, nitrate or phosphate. Most oceanographers concerned with this problem agree that nitrate (along with other bio-available nitrogen species such as nitrite and ammonia) are limiting on the short time scales considered by biologists, while phosphate abundance controls the overall productivity of the sea on geologic time scales (millennia).

Iron is one of the more abundant elements in the crust (4.3% in the continental crust, making the Earth look yellowish-brown from space) and indeed in the solar system (it makes Mars look reddish). It is of very low abundance in seawater, but abundant in the sediment. It is intimately involved in biological processes, mainly because of its ability to readily change its oxidation state (**ferric and ferrous iron**) but also in other contexts of biochemical reactions. Being in short supply in the oxidized uppermost waters of the sea, **iron is a limiting nutrient**, a fact that has been verified by experiment. Iron is also involved in the productivity of the ocean through the adsorption of **phosphate** on freshly precipitated iron species within the uppermost sediment, especially in continental margins. The intimate connection of iron to the sulfur cycle (precipitation of iron sulfide) links the **sulfur** cycle to ocean production, as well. Besides iron there are other trace elements that are necessary to life processes, including manganese, zinc, cobalt, molybdenum, and others. Controls on their cycling differ, but commonly involve microbe-dominated reactions with **oxygen** and **sulfur** at the seafloor.

Composition of Vent Water

Reactions of seawater with hot basalt within hydrothermal cells provide important controls on the chemistry of the sea. The **removal of sulfate and magnesium** is central, as well as the addition of **hydrogen ions** (acidity) and of **calcium** and **silicate**. **Iron** and **manganese** are delivered in large amounts, but in the present **oxygen**-rich environment in the deep sea these are rapidly precipitated, making ferromanganese concretions and crusts. Thus, the chemistry of seawater is not much affected.

Sources: P.K. Weyl, 1970, *Oceanography – An Introduction to the Marine Environment*, John Wiley & Sons, New York London Toronto, 535pp.; National Oceanic and Atmospheric Administration (U.S. Department of Commerce); H.U. Sverdrup, M.W. Johnson, and R.H. Fleming, 1942. *The Oceans - Their Physics, Chemistry and General Biology*. Prentice Hall, Englewood Cliffs, N.J., 1087pp.; P.G. Falkowski (ed.) 1980, *Primary Productivity in the Sea*, Plenum Press, New York and London, 531pp.; L.A. Codispoti, 1989, *Phosphorus vs. nitrogen limitation of new and export production,* in W.H. Berger, V.S. Smetacek and G. Wefer (eds.) *Productivity of the Ocean: Present and Past,* John Wiley & Sons, Chichester New York Singapore, pp. 377-394; R.R. Haese, 2000, *The reactivity of iron*, in H.D. Schulz and M. Zabel (eds.) *Marine Geochemistry,* Springer-Verlag Berlin Heidelberg New York, pp. 233-261; Steele, J. H., S. A. Thorpe and K. K. Turekian (eds.) 2001, *Encyclopedia of Ocean Sciences*, 6 vols., Academic Press, San Diego, 3399pp.; C.L. van Dover, 2000, *The Ecology of Deep-Sea Hydrothermal Vents,* Princeton University Press, Princeton, N.J., 424pp.

Appendix III: Overview of major groups of important marine organisms

Single-celled organisms ("microbes")

Autotrophs (synthesizing)

Prokaryotes: "blue-green algae" (*Prochlorococcus,* cyanobacteria); methanogens (archaea) (bacteria and archaea are kingdoms)

Eukaryotes: coccolithophorids, "nannofossils" (Haptophyta); dinoflagellates (Pyrrhophyta); diatoms, silicoflagellates (Chrysophyta) (Haptophyta, Pyrrhophyta, Chrysophyta are "divisions" of the "plant" kingdom)

Heterotrophs (using pre-existing organic matter)

Prokaryotes: sulfate-reducing bacteria, nitrate-reducing bacteria, methane-oxidizing bacteria, fermenting bacteria, organic-matter oxidizing bacteria

Eukaryotes: foraminifera (rhizopods); radiolarians (actinopods); tintinnids (ciliophora) (single-celled heterotrophic eukaryotes are "protozoans" if excluding forms with chlorophyll, otherwise "protists" on the level of kingdom)

Multicellular organisms (plants, animals, fungi)

Autotrophs (using light and carbon dioxide)

Giant kelp (*Macrocystis*), elkhorn kelp (*Pelagophycus*), *Fucus, Alaria, Sargassum* (brown algae, Phaeophyta); calcareous green algae (*Halimeda, Penicillus,* Chlorophyta); coralline and encrusting algae (*Lithothamnium, Lithophyllum,* Rhodophyta); "sea grasses" (*Zostera*, *Phyllospadix, Thalassia,* marine angiosperms); mangrove (*Rhizophora, Laguncularia, Avicennia*), salt-marsh halophytes: cordgrass and pickleweed (*Spartina, Salicornia*) (terrestrial angiosperms, Spermatophyta)

Heterotrophs (consuming pre-existing organic matter)

Fungi (decomposers of organic matter, or living in association with marine macroalgae or with animals, commonly as infectious parasites)

Animals (invertebrates, numerous phyla, major phyla: sponges, cnidarians, mollusks, annelids, arthropods, echinoderms; vertebrates, a subdivision of the phylum chordates) (see below)

Major marine animal phyla

Porifera, sponges, organization of flagellated cells, structure of support for the cells with canals and chambers, no mouth or digestive cavity, skeletal elements: "spicules."

Cnidaria, animals with stinging cells: jellyfish, stony corals, gorgonians, sea pens, sea anemones, hydroids.

Ctenophores, comb jellies (a small group but with common representatives).

Platyhelmintes, flatworms and flukes, thousands of species**.**

Nematoda, nematode worms, thousands of species.

Mollusca, mollusks (thousands of species): gastropods (prosobranch and opisthobranch forms, thousands of species each, with and without shell), bivalves (mussels, scallops, cockles, clams, geoducks; thousands of species), cephalopods (squids, octopods, cuttlefish, ammonites Ω), chitons, scaphopods, etc.

Annelida, segmented worms (thousands of species): polychaetes (scale worms, paddleworms, fireworms, ragworms, lugworms, sabellarid worms, terebellid worms, sabellid fan worms, serpulid fan worms, etc.

Pogonophora, giant tube worms (few species but spectacular).

Arthropoda, arthropods (thousands of species, jointed-limb animals): copepods (thousands, calanoid, harpacticoid, etc., also parasitic forms), isopods (thousands), amphipods (thousands), decapods (thousands, crabs, shrimps, lobsters), cumacea (hundreds), euphausids (few, but important as krill), pycnogonids (hundreds, sea spiders), ostracods (thousands, mussel shrimps), cirripeds (hundreds, barnacles), etc.; some break this super-phylum into several phyla (crustaceans, chelicerates, uniramians, tardigrades and pentastomids); the largest animal class (insects, uniramians) only has a few water striders in the sea; trilobites and eurypterid sea scorpions are extinct, the horseshoe crab (related to eurypterids) is still extant.

Bryozoa, moss animals, sea mats (thousands of species), colonies of small individuals (zooids) with a tentacled crown, mouth and anus, branching and encrusting forms, common in the intertidal zone.

Brachiopoda, lampshells (hundreds of species, common benthic organism, extensive fossil record) organism with a bivalve shell on a stalk (pedicle) and an internal bilateral tentacle crown (lophophore).

Chaetognatha, arrow worms (few species, but abundant in the plankton).

Echinodermata, echinoderms (thousands of species, spiny-skinned animals, benthic when adult): Starfishes, brittle stars and basket stars (asterozoans), sea lilies and feather stars (crinozoans), sea urchins and sea cucumbers (echinozoans), and many extinct forms.

Hemichordata, acorn worms and pterobranchs (few species, but important in an evolutionary context, connecting chordates to their distant relatives, the echinoderms and other groups).

Chordata, animals with a dorsal nerve chord (thousands of species): urochordates (sea squirts, salps, planktonic tunicates), cephalochordates (lancelets), vertebrates (mainly fishes, also reptiles, mammals, birds) (see below); the relationship between sea squirts and vertebrates is best seen in the "tadpole" larvae of the sea squirts (the sac-like sessile adults do not resemble vertebrates), the fish-like lancelet is built much like a squirt larva and stays mobile throughout its life

Vertebrates, jawless fishes (hagfish and lampreys), cartilaginous fishes, bony fishes and tetrapods (amphibians [freshwater], reptiles and birds, mammals); fishes have thousands of species, tetrapods have a few hundred within the marine realm (being mostly terrestrial). Some biologists include the tetrapods in a subclass with the lobe-finned fishes, that is, with the bony fishes. About half of all vertebrates are fishes, and there are about 24,000 species, of which 60 percent are marine. The largest fish is the whale shark *Rhincodon typus.* Giant sturgeons can reach an age of more than 100 years. Fishes have a remarkable range of adaptations to different environments. Some fishes, adapted to freezing waters in polar regions, have antifreeze in their blood. Others have adapted to hot springs and soda lakes, with rather high temperatures. Some have life cycles involving both the sea and freshwater (e.g., salmon and some eels). Some marine fishes can readily move out of water (e.g., mudskippers). Some can fly, while others (on land) can survive long periods of drought, burrowing into the ground. The following list only mentions major groups and is not comprehensive.

Agnatha, jawless fishes (few species, hagfishes and lampreys, sea lamprey: *Petromyzon marinus*); the two groups placed here are not closely related.

Hagfishes, predators and scavengers (can twist the body into a knot to gain leverage in penetrating live or dead prey), eel-like, several blood-pumping organs are present, no paired fins, no eyes (but light-sensitive skin patches in places), highly developed sense of smell, with tentacles around the mouth, rasping teeth on the tongue only, defend themselves by extruding large amounts of slime that clogs the gills of potential predators.

Lampreys, predators (some attack larger fishes attaching to their sides or bellies, some feed only as larvae on smaller invertebrates), circular sucking mouth ringed with teeth that open access to the body of the prey, eel-like, no paired fins, with a pair of large eyes (and a light-sensitive pineal organ on top of the head), seven gill slits; lampreys breed in fresh water, but some spend their life at sea, as adults.

Chondrichtyes, fishes with a cartilaginous skeleton, lacking a swim-bladder, and with multiple gill slits. The skin is covered by denticles (rather than scales). Fertilization is internal, and eggs are few and large, while live births prevail in pelagic forms. The young look like small adults (no larvae as in bony fishes).

Sharks and rays, hundreds of species in twelve orders for sharks and one order for skates and rays; **sharks** have five gill slits (some have 6 or 7), a strong sense of smell; some sharks can sense very weak electric fields; teeth are replaced in rows (commonly there are hundreds of them in the mouth at any one time); they have a highly developed lateral line system for picking up vibrations and pressure fluctuations; sharks are found throughout the water column in all parts of the ocean where there is sufficient food; the largest fishes are plankton–eating sharks (Whale shark, Basking shark), while fish- (and meat-) eating predators (Great white shark, Tiger shark) overlap in size with the largest bony fishes (marlin, sturgeon); the Mako shark is among the fastest fish extant (clocked at 60 mph; perhaps matched by swordfish); **skates and rays** basically are flattened sharks, adapted for life in contact with the sea floor, where they feed on mollusks and crustaceans and other benthic organisms using button-like teeth for crushing, except for a few (like the plankton-eating Manta ray, some of which reach giant proportions) that opted for the open sea; their pectoral fins are modified to make wings; some ("sawfish") have a modified head, carrying a "saw" with sharp teeth, which is used to slash prey and to defend against larger attackers; some rays are capable to produce electric shock. There are hundreds of species of rays.

Chimaeras, "ratfish," few species, all marine; somewhat similar to sharks and rays, living in cold water and at depth, slow swimming, bottom-hugging, teeth fused into a solid beak, modified breathing apparatus (relative to sharks).

Osteichthyes, fishes with a bony skeleton, with an immense range of adaptations to various environments in the sea and on land; containing two major groups: the lobe-finned fishes (with lungfishes and coelacanths) and the ray-finned fishes (the great majority of fishes populating the sea and freshwater bodies); characteristic properties (with some exceptions): true scales on the skin, a protective structure for the gills, and movable rays in the fins and the tail. Swimbladders are common. Reproduction commonly involves a large number of eggs, and fertilization is external. (Exceptions exist.) In many species there is a larval stage, linked to dispersion.

Lungfishes, few species, habitat is freshwater in drought-prone areas. Closest living relatives of tetrapods, among the fishes.

Coelacanths, one genus only, *Latimeria*, a marine fish, rarely caught. Large eggs, few in number; swim-bladder filled with fat.

Ray-finned fishes, an enormously large group, including the modern teleosts that dominate the scene throughout the Tertiary.

Sturgeons, bony fishes with a shark-like tail, less than 50 species, largest freshwater fishes, some live at sea when adult; millions of eggs ("caviar"); stocks greatly reduced from overfishing.

Teleosts, ray-finned fishes, thousands of species, two-thirds marine. Some important types of teleosts are eels and tarpons, herring-like fishes (herring, sardine, alewife, shad, anchovy, pilchard, sprat), salmons and argentines ("herring smelt"), codfishes and hakes and grenadiers and anglerfishes (including frogfishes and batfishes, and many deep-sea species), clingfishes, bristle mouth and dragonfishes and viperfishes (deep-sea fishes with luminous organs), lizard fishes and lanternfishes (the latter with hundreds of species in the deeper waters of all oceans), catfishes and carp-like fishes (thousands of species with some marine representation), needlefishes and flying fishes and silversides (including the familiar grunion), flashlight fishes and squirrel fishes, pipefishes and shrimp fishes and seahorses (male brood pouch), zebrafishes and scorpionfishes (poison spines), gurnards and sculpins, sea basses, remoras (modified dorsal fin for attaching to free ride), jacks, dolphin fishes, snappers, drums, butterfly fishes, ribbonfishes (including the oarfish) and moonfishes, angelfishes, damselfishes, parrotfishes (fused beak-like teeth for biting coral, grinding teeth in the throat), clownfishes, wrasses, eelpouts, icefishes (with antifreeze in the blood), stargazers, blennies, dragonets, gobies, surgeonfishes, tunas and mackerels (built for speed), billfishes (including the fast-swimming marlins, sailfishes and swordfish), barracudas, flatfishes (hundreds of species, including soles and flounders; some change their colors to match the sea floor on which they rest), triggerfishes, pufferfishes, boxfishes, sunfishes and porcupine fishes.

Tetrapods, four-legged vertebrates; in essence, lobe-finned fishes adapted to a life without water (that is, breathing air), as most clearly seen in reptiles and the closely related birds and mammals. In most amphibians, the ancestral water-link is maintained through breeding and larval development within fresh water. The crab-eating frog *Rana cancrivora* inhabits mangrove swamps in southeastern Asia. In marine reptiles, birds and mammals, there is a return to the water in cases. This shift is completed in whales, and is partially completed in seals and penguins. It is most clearly seen happening at present in sea otters (which have closely related weasel cousins on land) and polar bears (which have terrestrial congeners). Marine turtles, crocodiles and penguins continue to lay their eggs on land; a behavioral reminder of their terrestrial ancestry.

Reptiles, close to 100 marine species, with sea snakes dominant, followed by sea turtles. **Sea snakes,** leg-less reptiles with a flattened tail for swimming, e.g., the yellow-bellied sea snake (*Pelamis platurus,* the most abundant of reptiles, a relative of the cobra); some sea snakes lay eggs, others give live birth. **Sea turtles,** reptiles that make a shell from horny shields (except the Leatherback turtle, *Dermochelys coriacea*, which is covered by leathery skin). Representatives are: Loggerhead turtle, Ridley turtle, Flatback turtle, Green turtle, and Hawksbill turtle. Some turtles apparently have an internal magnetic compass useful in guiding migration. There are two species of (optionally) marine crocodiles (American crocodile: *Crocodylus acutus*; Indo-Pacific crocodile: *Crocodylus porosus*, the largest living reptile) and one of marine lizard (marine iguana, *Amblyrhynchus cristatus*) that feeds on algae in the Galapagos Islands.

Birds, warm-blooded egg-laying tetrapods resembling reptiles but bearing feathers; several hundred marine species. Most seabirds are capable of flight, except for penguins (cold southern waters) and some representatives of cormorants. Prominent among strictly marine birds are albatrosses, shearwaters and petrels, storm-petrels and diving-petrels, tropic-birds, gannets and boobies, frigatebirds, and auks (habitat: cold northern waters, with the familiar guillemots, murres and puffins). Among cormorants and pelicans there are some species that are found with freshwater bodies. Some ducks and geese find food in saltwater lagoons. Skuas (jaegers), gulls, and terns are mainly marine, although some species prefer freshwater. Many freshwater birds can be observed along the seashore feeding, depending on the season. In terms of number of species, the most diverse are petrels and shearwaters, then gulls, then terns, then cormorants and shags, then auks. There are 17 species of penguins; the most abundant are the species of the genus *Pygoscelis* (Adélie, Chinstrap, Gentoo), whose members are counted in the millions. Shearwaters, albatrosses and terns, among other birds, undertake extensive migrations involving thousands of miles.

Mammals, warm-blooded tetrapods bearing live offspring that developed *in utero*, and which feed on their mother's milk. Marine forms include whales, pinnipeds, seacows and otters, all of which are able to hold their breath to procure food below the sea surface.

Whales, a diverse group of marine mammals that spend their entire lives at sea, from birth to mating to death, and whose members have a fish-like appearance. There are fewer than 100 species. The common ancestors (archaeocetes, e.g. *Pakicetus*) were terrestrial and lived in the earliest Tertiary, at the edge of land and water (Paleocene), in a life style reminiscent of the modern hippo (which is in fact an extant relative of the cetacean ancestor). There are two major groupings: whales bearing teeth (**Odontoceti**) and whales bearing baleen (**Mysticeti**). Baleen whales evolved from teeth-bearing ancestors in the middle of the Tertiary (Oligocene), as a result of the appearance of high-production upwelling areas with high plankton density, on a planet with cooling polar regions. The baleen is used to filter the water for food. The odontocetes contain the following major groups: delphinids (e.g., *Delphinus,* common dolphin, *Orcinus,* killer whale; *Tursiops,* bottle-nosed dolphin); monodontids (beluga and narwhal); phocoenids (porpoises); physeterids (sperm whales); "platanistids" (various types of river dolphins); ziphiids (beaked whales and bottlenose whales). The largest predatory diving mammals are in this group (sperm whale, *Physeter*). Toothed whales use echo-location to "see" using sound when submerged; they have an unusually large brain (compared with other tetrapods) for processing acoustic signals; they also communicate using such signals. The mysticetes contain the following major groups: balaenids (bowhead and right whales, *Balaena*), rorquals (*Balaenoptera* (Blue Whale, Fin Whale, Minke, Sei, Bryde's; *Megaptera*, Humpback Whale), Gray Whales (*Esrichtius*) and Pygmy Right Whale (*Caperea* in the family Neobalaenidae)). The largest animals on Earth (Blue Whale, Fin Whale) are mysticetes. Large size is an asset when storing energy for long migrations and when nursing without feeding. In cold waters, large size is good for preserving heat.

Pinnipeds, four-legged marine carnivore mammals that feed at sea and breed on shore (or on ice); comprising the "true" seals (**Phocidae,** about 20 species of northern and southern seals, with the greatest abundance in the Antarctic lobodonts, which group contains the krill-eating seal, *Lobodon carcinophagus*, with a population estimated at > 10 million), the "eared" seals (**Otariidae,** fewer than 20 species of sea lions and fur seals) and the walrus (**Odobenidae,** one species). Phocids rely on blubber for insulation; otarids have a thick fur. Phocids are the better divers, some can go without air for more than an hour, and Weddell Seals and Elephant Seals have been observed to reach great depths (hundreds of meters, and even exceeding a mile in *Mirounga*). Terrestrial ancestors of pinnipeds existed in the late Oligocene; they were related to ancient types of dogs, bears, and weasels. It is not clear whether the last common ancestor was aquatic or terrestrial.

Sea Cows (sirenians) are fully aquatic mammals feeding on plants; there are three species, one of which lives in the Amazon river system; dugongs (tropical Indo-Pacific) are marine; manatees (tropical Atlantic) are at home in coastal waters including associated estuaries. The large Steller's sea cow (a cold-water species in the North Pacific) was hunted to extinction in the 18th century. As in whales, there are no hind limbs, and there is a fluke for propulsion. Movement is comparatively sluggish. The terrestrial ancestor of sirenians lived in the earliest Tertiary (Paleocene). It was related to elephants.

Sea Otter, *Enhydra lutris*, a fully marine mammal, living in coastal waters of the North Pacific and feeding on sea urchins, mollusks and crabs; closely related to river otters, carnivores of the weasel group. Pups are born at sea. Little is known about the habits of a coastal otter hunting in the waters off Peru and Chile, the Marine Otter.

Sources: B.B. Joergensen, 2000, *Bacteria and marine biogeochemistry,* in: H.D. Schulz and M. Zabel (eds.) *Marine Geochemistry,* Springer-Verlag Berlin Heidelberg New York, pp. 173-207; E.Y. Dawson, 1966, *Marine Botany*, Holt, Rinehart, Winston, New York Chicago London, 371pp.; G. Waller (ed.) 1996, *SeaLife, a Complete Guide to the Marine Environment*, Smithsonian Institution Press, Washington, D.C., 504pp.; K. Banister and A. Campbell (eds.) 1985, *The Encyclopedia of Aquatic Life*, Facts on File, Inc., New York, 349pp.

Appendix IV: Geologic Time Scale

Major subdivisions of the geologic time scale

PERIOD	START	DURATION	REMARKS
QUATERNARY	**1.8**	**1.8**	Ice age cycles; *Homo* spp.
NEOGENE	**23.3**	**21.5**	Antarctic ice shield expansion
PALEOGENE	**65**	**41.7**	Circumpolar Current established
CRETACEOUS	**146**	**81**	Giant marine lizards, diving birds
JURASSIC	**208**	**64**	Ichthyosaurs, Ammonites abundant
TRIASSIC	**250**	**42**	N America separating from Africa
PERMIAN	**295**	**45**	Ice ages; great extinction at end
CARBONIFEROUS	**360**	**65**	Extensive coal formations
DEVONIAN	**412**	**42**	Fishes thrive; first amphibians
SILURIAN	**445**	**33**	First bony fishes
ORDOVICIAN	**490**	**45**	First corals, first jawless fishes
CAMBRIAN	**550**	**60**	Sudden expansion of shelled fossils
PRECAMBRIAN	**>550**	**~3000**	Poor fossil record; low oxygen

AGE OF EARTH 4.6 billion years

Major subdivisions of the Cretaceous period

STAGE	START	DURATION	REMARKS
MAASTRICHTIAN	**71**	**6**	Major extinctions at end of Maastr.
CAMPANIAN	**83**	**12**	Cooling trend
SANTONIAN	**86**	**3**	Magnetically quiet zone ends
CONIACIAN	**89**	**3**	Mid-Cretaceous warm time ends
TURONIAN	**94**	**5**	Changes in deep circulation
CENOMANIAN	**100**	**6**	Radiation of plankton (starts in Alb.)
ALBIAN	**112**	**12**	Volcanism, high CO_2, warm peak
APTIAN	**125**	**13**	Anoxia spreads, high extinction rates
BARREMIAN	**130**	**5**	Sea level rises; magnetic. quiet z. on
HAUTERIVIAN	**136**	**6**	South Atlantic opens
VALANGINIAN	**140**	**4**	Circum-tropical sea: Tethys dominant
BERRIASIAN	**146**	**6**	North Atlantic keeps expanding

Major subdivisions of the Cenozoic (Paleogene & Neogene periods)

AGE	START	DURATION	REMARKS
HOLOCENE	**0.012**	**0.012**	Agriculture, iron age
PLEISTOCENE	**1.8**	**1.8**	Ice age cycles
LATE PLIOCENE	**3.0**	**1.2**	Onset of northern ice ages
MIDDLE PLIOCENE	**3.4**	**0.4**	Uplift of Himalayas
EARLY PLIOCENE	**5.2**	**1.8**	Closing of Panama Isthmus
LATE MIOCENE	**12**	**6.8**	NADW production; Mediterranean dry
MIDDLE MIOCENE	**16**	**4**	Expansion of southern ice sheets
EARLY MIOCENE	**23**	**7**	Radiation of plankton; Tethys closes
LATE OLIGOCENE	**29**	**6**	Cold deep water; baleen whales
EARLY OLIGOCENE	**34**	**5**	Major cooling; low production ocean
LATE EOCENE	**40**	**6**	Major shift in deep-sea sediment type
MIDDLE EOCENE	**49**	**9**	High marine diversity; Tethyan seas
EARLY EOCENE	**56**	**7**	Plankton radiation
LATE PALEOCENE	**61**	**5**	End-of-Paleocene warm peak
EARLY PALEOCENE	**65**	**4**	Recovery from K/T extinctions

Sources: C. Emiliani, 1992, *Planet Earth – Cosmology, Geology, and the Evolution of Life and Environment,* Cambridge University Press, Cambridge New York, 719pp.; H.M. Bolli, J.B. Saunders, K. Perch-Nielsen, 1985, *Plankton stratigraphy*, Cambridge University Press, Cambridge New York Sydney, 1032pp.; B. McGowran, 2005, *Biostratigraphy – Microfossils and Geologic Time*, Cambridge University Press, Cambridge New York, Sao Paulo, 459pp.; F.M. Gradstein and J.G. Ogg, 2004, Geologic time scale 2004 – why, how, and where next! Lethaia, 37, 175-181; W.H. Berger and J.C. Crowell (eds.) 1982, *Climate in Earth History*, National Academy Press, Washington, D.C., 198pp.; X. LePichon et al., 1988, *Report of the Second Conference on Scientific Ocean Drilling <Cosod II>*, European Science Foundation, Strasbourg, 142pp.; K. Becker et al., 2002, *Achievements and Opportunities of Scientific Ocean Drilling*, Joides Journal 28 (1, Special Issue), Joint Oceanographic Institutions for Deep Earth Sampling.

Appendix V: Topographic Statistics

Earth's size and surface

Latitude (^{o})	Northern Hemisphere		Southern Hemisphere	
	% of total area	% water	% of total area	% water
0-5	4.34	78.6	4.34	75.9
5-10	4.31	75.7	4.31	76.9
10-15	4.24	76.5	4.24	79.6
15-20	4.15	70.8	4.15	76.4
20-25	4.02	65.2	4.02	75.4
25-30	3.86	59.6	3.86	78.4
30-35	3.68	57.7	3.68	84.2
35-40	3.46	56.8	3.46	93.4
40-45	3.22	51.2	3.22	96.4
45-50	2.96	43.8	2.96	97.5
50-55	2.665	40.7	2.665	98.5
55-60	2.355	45.0	2.355	99.9
60-65	2.025	31.2	2.025	99.7
65-70	1.68	28.7	1.68	79.5
70-75	1.32	65.5	1.32	38.6
75-80	0.95	77.1	0.95	10.7
80-85	0.575	85.2	0.575	0.0
85-90	0.19	100.0	0.19	0.0
Total	50	60.7	50	80.9

All oceans and seas: 361.059 million square km, 70.8%
All land: 148.892 million square km, 29.2%

Area, volume, and mean depth of ocean basins and some seas

Geographic unit	Area (million km^2)	Volume (million km^3)	Mean depth (m)
Atlantic Ocean	82.44	323.6	3926
with adjacent seas	106.46	354.7	3332
Pacific Ocean	165.25	707.6	4282
with adjacent seas	179.68	723.7	4028
Indian Ocean	73.44	291.0	3963
with adjacent seas	74.92	291.9	3897
Arctic Ocean	14.09	17.0	1205
Caribbean & Gulf Mx	4.32	9.57	2216
Mediterr. & Black S.	2.97	4.24	1429
Hudson Bay	1.23	0.16	128
Bering Sea	2.27	0.69	1437
Okhotsk Sea	1.53	3.26	838
Japan Sea	1.01	1.36	1350
East China Sea	1.25	0.24	188
All oceans and seas	361.06	1370.32	3795

Area of depth zones in the oceans (in percent, reflecting benthic habitat)

Depth zone (m)	Atlantic Ocean	Pacific Ocean	Indian Ocn	All oceans
0-200	13.3	5.7	4.2	7.6
200-1000	7.1	3.1	3.1	4.3
1000-2000	5.3	3.9	3.4	4.2
2000-3000	8.8	5.2	7.4	6.8
3000-4000	18.5	18.5	24.0	19.6
4000-5000	25.8	35.2	38.1	33.0
5000-6000	20.6	26.6	19.4	23.3
6000-7000	0.6	1.6	0.4	1.1
>7000	<.1	0.2	<0.1	0.1

Greatest depths in the ocean basins and some seas

(All values approximate because of uncertainties in estimating sound velocity; sources commonly disagree. Also note that rough estimates measured in steps of hundreds of meters can acquire spurious precision when converted to feet.)

Pacific Ocean: Marianas Trench (Challenger Deep), 10,915 m (35,810 ft); Tonga Trench, 10,850 m (35,600 ft); Kuril-Kamchatka Trench, 10,500 m (34,400 ft); Philippine Trench (near Cape Johnson Deep), 10,200 m (33,500 ft); Kermadec Trench, 10,050 (33,000 ft); Japan Trench (Ramapo Deep), 9700 m (32,000 ft); New Hebrides Trench, 9165 m (30,070 ft); Peru-Chile Trench, 8055 m (26430 ft); Aleutian Trench, ca. 7700 m (25,000 ft); Middle America Trench, 6660 m (21,900 ft)
Atlantic Ocean: Puerto Rico Trench, 8,400 m (27,600 ft); South Sandwich Trench, 9,300 m (30, 500 ft)
Indian Ocean: Java Trench, 7,450 m (24,440 ft)
Arctic Ocean: Pole Abyssal Plain, 4,660 m (15,300 ft)
Caribbean Sea: Cayman Trench, 7680 m (25,200 ft)
Mediterranean: Hellenic Trough, 5090 m (16,700 ft)

Sources: H.U. Sverdrup, M.W. Johnson, and R.H. Fleming, 1942. *The Oceans - Their Physics, Chemistry and General Biology*. Prentice Hall, Englewood Cliffs, N.J., 1087pp.; J.F. Luhr, 2003, *Earth*, Smithsonian Institution, DK Publishing, New York, 520pp.; M. Leier (ed.) 2001, *World Atlas of the Oceans*, Firefly Books, Buffalo, New York, 264pp.; M. Bramwell (ed.) 1977, *The Rand McNally Atlas of the Oceans*, Rand McNally, New York, 208pp.; R.L. Fisher and H.H. Hess, 1963, *Trenches*, in M.N. Hill (ed.) *The Sea,* vol. 3, John Wiley & Sons, New York London, pp. 411-436; Puerto Rico Trench *fide* U. ten Brink.

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