

BACK MATTER



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GLOSSARY

absolute density | The mass per unit volume of a substance (usually expressed as grams per cubic centimeter). Compare to relative density.

absorption spectrum, absorptionspectra | Wavelengths of electromagnetic energy that substances can absorb and convert to heat. Absorption spectra are plotted as the relative efficiency of absorption versus wavelength. Compare emission spectrum.

abyssal fan | Fan-shaped sediment accumulation spreading out and decreasing in thickness from a point of large sediment input. Abyssal fans are located usually off the mouth of a river or at the foot of a submarine canyon.

abyssal hill | Sediment-covered volcanic peak that rises less than 1 km above the deep-ocean floor.

abyssal plain | Flat seafloor extending seaward from the base of the continental slope and continental rise or from the seaward edge of an oceanic trench.

abyssal zone | Benthic environment between 4000 and 6000 m depth.

acid rain | Rain with acidity higher than normal because of dissolved gaseous emissions of industry and automobiles, notably sulfur compounds.

acidification | An increase of hydrogen ion concentration to make a solution more acidic or less alkaline. In ocean acidification refers to the addition of anthropogenic carbon dioxide to the oceans that reduces the pH and renders calcium carbonate more soluble.

acoustic | Pertaining to sound.

adiabatic expansion | Expansion of a gas without the addition of external heat. Adiabatic expansion causes the temperature of the gas to decrease. Adiabatic compression causes the temperature of the gas to increase.

adsorption, adsorbed | Attraction and adhesion of ions to a solid surface.

aerobic | In the presence of oxygen.

algae, alga | Simple single-celled or many-celled photosynthetic organisms that have no root, stem, or leaf systems.

algal ridge | Irregular ridge located on the wave-exposed seaward edge of many coral reefs. The ridge is composed largely of encrusting algae.

alkalinity, alkaline | The opposite of acidity. Measure of the degree to which the concentration of hydroxyl ions (OH⁻) is greater than the concentration of hydrogen ions (H⁺) in a solution. Seawater is slightly alkaline.

amino acids | Members of a group of compounds that combine in varied proportions to form proteins.

amoebas | Microscopic single-celled animals that move by making continuous protrusions of the body and that feed by engulfing bits of food.

amphidromic system | Tide wave that rotates around an ocean basin during one tidal period. An amphidromic system rotates around an amphidromic point (a node) at which the tidal range is zero.

amphipods | Members of an order of the subphylum Crustacea, phylum Arthropoda, that includes laterally compressed species such as the "sand hoppers."

amplitude | Vertical distance from the mean level of a wave (the still sea surface for an ocean wave) to the crest or to the trough. A wave's amplitude equals one-half of the wave height.

anadromous | Pertaining to species of fishes that are spawned in freshwater, migrate to the ocean to live until they reach maturity, then return to freshwater to spawn. Compare catadromous.

anaerobic | In the absence of oxygen.

anemones | Multicelled animals of the class Anthozoa, phylum Cnidaria. There are both single and colonial polypoid forms.

angle of approach | The angle of incidence is important in refraction.

angle of incidence | Angle between a wave front (usually an electromagnetic wave) or a wave ray and the plane of an interface that it meets.

anion | Negatively charged ion. Compare to cation.

annelids | Members of the phylum Annelida. Elongated segmented worms.

anoxia, anoxic | Total absence of dissolved or free molecular oxygen.

anthropogenic | Produced by humans and their activities.

antinode | The part of a standing wave where the vertical motion is at a maximum. Compare to node.

aphotic zone | The part of the ocean in which light is insufficient for phototrophy (which includes photosynthesis). The aphotic zone comprises all the oceans below about 1000 m in areas where ocean water is clear and extends to shallower depths in more turbid waters. Compare to photic zone.

aragonite | A mineral form of calcium carbonate. Aragonite is less common than calcite, but it comprises shells of many pteropod species.

archaea, archaean, archeal | Microorganisms of the domain Archaea (previously called Archaeobacteria) that belong to an ancient group of organisms that are separate from bacteria and from which eukaryotes (multicelled organisms) may have evolved. Many archaeal species are chemosynthetic and live in extreme environments.

aspect ratio | Index of the propulsive efficiency of a fish species that is obtained by dividing the square of the height of the caudal fin by the area of the caudal fin.

assimilative capacity | Maximum rate at which a particular segment of the environment or ocean can accommodate the input of a substance. The term usually applies to anthropogenic waste materials.

asteroid | Rocky object orbiting the sun. An asteroid is smaller than a planet. Most asteroids are found in a belt between the orbits of Mars and Jupiter, but some have orbits that take them close to the sun and across the orbits of the planets.

asthenosphere | Plastic or partially molten layer of the Earth's upper mantle upon which the continents "float." The asthenosphere varies in thickness, with its upper boundary at depths of 10 km or more and its lower boundary at depths as great as 800 km.

atoll | Ring-shaped coral reef that grows upward from a submerged volcanic peak and encloses a lagoon. Atolls may support low-lying islands composed of coral debris. Compare barrier reef and fringing reef.

autotrophs, autotrophic | Algae, bacteria, archaea, or plants that can synthesize organic compounds from inorganic nutrients by phototrophy or chemosynthesis. Compare to heterotrophs.

back-arc basin | Generally shallow sea created on the non-subducting plate at an oceanic convergent plate boundary where the subduction is fast enough to stretch the edge of the nonsubducting plate. The back-arc basin lies behind the volcanic island arc. Also called "back-island basin."

backscatter, backscattered | The portion of the light or sound randomly reflected off particles suspended in a fluid that is scattered back in the general direction of the light or sound source. Compare to scatter.

backshore | Inner portion of the shore that is landward of the mean spring-tide high-water line. Waves act on the backshore only during exceptionally high tides and severe storms. Compare to foreshore.

backwash | Water flowing down a beach after the swash of one wave has stopped and before the swash of the next wave arrives.

bacteria,bacterium,bacterial | Microscopic single-celled organisms that comprise one of the three recognized biological domains. Other than cyanobacteria, most bacteria species are autotrophs and decomposers, and most are parasitic. They reproduce by cell division.

baleen | Horny material consisting of numerous plates with fringed edges that grows down from the upper jaw of plankton-feeding whales. Baleen is used to filter (strain) the plankton food from the water.

bar-built estuary | Shallow estuary (lagoon) separated from the open ocean by a bar such as a barrier island. Water in bar-built estuaries is usually well mixed vertically.

barnacles | Members of an order of the subphylum Crustacea, phylum Arthropoda, that attach to the substrate, secrete a protective covering of calcareous plates, and strain food particles from the water with a weblike structure.

barrier island | Long, narrow island built of wave-transported sand, separated from the mainland by a usually shallow lagoon.

barrier reef | Coral reef that parallels the shore but is separated from the landmass by open water. Compare to fringing reef and atoll.

basalt,basaltic | Dark-colored volcanic rock, rich in iron, magnesium, and calcium, characteristic of the oceanic crust.

bathyal zone | Benthic environment from 200 to 2000 m depth.

bathymetry, bathymetric | Seafloor mapping; the study of landform features beneath the water surface. A bathymetric map gives the depth contours of the seafloor.

baymouth bar | Shallow bar, usually of sand, that extends partially or completely across the mouth of a bay.

beach | Sand- or sediment-covered zone between the seaward limit of permanent vegetation and the mean low-water line. Beaches sometimes include the seafloor from the mean low-water line to the surf zone.

benthic | Pertaining to the seafloor, or to organisms that live on or in the seafloor.

benthos | Organisms that live on or in the ocean bottom.

berm | Nearly horizontal portion of a beach backshore at the seaward edge of which the beach slopes abruptly seaward. Compare to scarp.

binning | The process of grouping DNA sequences from the same organism together from a mixed sample

bioaccumulation,bioaccumulate | Process by which dissolved chemicals are taken up by organisms until the concentrations in the tissues are at equilibrium with those in the solution. See CC18.

bioassay | Test in which organisms are exposed to different concentrations of a substance to determine the concentration at which the substance is toxic to that species. See CC18.

bioavailable | Existing in a chemical form that is suitable for uptake by organisms.

biochemical | Pertaining to the synthesis, conversion, use, and decomposition of organic chemicals in the life processes of organisms.

biodegradable | Capable of being decomposed by organisms in the environment. The term generally refers to decomposition to harmless substances.

biodiversity | Poorly defined term that refers to a combination of genetic diversity, species diversity, ecosystem diversity, and physiological diversity within a community or ecosystem. See CC17.

biogenous | Pertaining to material of a biological origin. Usually applied to sediments in which the hard-part remains of organisms (e.g., diatom tests, radiolarian shells) constitute a high proportion of the grains. Compare to cosmogenous, hydrogenous, and lithogenous.

biogeochemical cycle | Transfers of compounds among the living and nonliving components of an ecosystem.

bioinformatics | The use of computer and software programming to analyze biological data, especially when large amounts of data are involved like in genome sequencing. See CC19

bioluminescent, bioluminescence | Light-producing. Referring to organisms that use chemical reactions to produce light.

biomagnification, biomagnify | Process by which dissolved chemicals are taken up by organisms and continuously accumulated to higher concentrations throughout the life cycle. Tissue concentrations are not in equilibrium with concentrations in the surrounding environment. See CC18.

biomass | The total amount of living matter, expressed in units of weight in the entire water column per unit area of water surface, or weight per unit of water volume.

biome | Any defined area or volume of the environment that is characterized chiefly by the dominant species present and the prevailing physical and chemical environmental conditions (e.g., tropical rain forest, or kelp forest, or tundra).

biota | All living organisms in a given ecosystem, including archaea, bacteria, protists, fungi, algae, plants, and animals.

bioturbation | Reworking (churning and mixing) of sediments by organisms that burrow in them.

bloom | Very dense aggregation of phytoplankton, resulting from a rapid rate of reproduction.

blubber | Outer fat layer of whales.

bottom trawling | A widely used fishing technique where a net is dragged across the sea floor to catch bottom dwelling species.

brackish | Pertaining to water that is a mixture of freshwater and seawater and has a low salinity.

breakwater | Artificial structure constructed in the ocean to protect a shore from the action of ocean waves.

brine | Water that has a higher salinity (generally much higher) than normal seawater.

brittle stars | Organisms of the class Ophiuroidea, phylum Echinodermata, that have long, slender arms covered in bristles attached to a small central disk.

bulkhead | Structure constructed to separate land and water areas at the shoreline and designed to reduce earth slides and slumps or to lessen wave erosion at the base of a cliff.

buoyancy, buoyant | Ability of an object to float (or rise through a fluid) that results from a density difference between the object and the fluid in which it is immersed.

bycatch | Fishes and other marine animals caught in fishers' nets that are not the target of the fishing. Bycatch is generally thrown overboard as waste.

calcareous, calcium carbonate | Composed of or containing calcium carbonate.

calcite | The most common mineral form of calcium carbonate. Compare to aragonite.

caldera | Crater in a volcano, usually at the center, created by an explosion or collapse of the volcanic cone.

calorie | Obsolete unit of heat energy defined as the amount of heat needed to raise the temperature of 1 g of water by 1°C.

capillary wave | Small ocean wave that has a wavelength less than 1.5 cm. The primary restoring force for capillary waves is surface tension.

carbonate compensation depth, CCD | Depth below which all calcium carbonate particles falling from above are dissolved before they can be incorporated in the sediments.

carcinogens, carcinogenic | Compounds that cause cancer in animals. Compare to mutagens and teratogens.

carnivores, carnivorous | Animals that depend solely on other animals for their food supply. Compare herbivores and omnivores.

cartilaginous | Pertaining to vertebrate animals that have skeletons made of cartilage, a tough elastic tissue.

catadromous | Pertaining to species of fishes that are spawned at sea, migrate to a freshwater stream or lake where they live until they reach maturity, then return to sea to spawn. Compare to anadromous.

cation | Positively charged ion. Compare to anion.

CC1 | Density and Layering in Fluids: Water in the oceans is arranged in layers according to the water density. Many movements of ocean water masses are driven by differences in water density.

CC2 | Isostasy, Eustasy, and Sea Level: Earth's crust floats on the asthenosphere, rising and falling isostatically as climate-driven temperature or mass changes alter its density, affecting local sea levels. Sea levels also change eustatically worldwide due to fluctuations in ocean temperature or shifts in continental ice volume. Eustatic changes occur synchronously and more rapidly than isostatic changes.

CC3 | Convection and Convection Cells: Fluids heated from below, like Earth's mantle, oceans, or atmosphere, rise as their density decreases. Upon cooling at higher levels, they become denser and sink. This creates convection cells in which material rises in upwelling zones, spreads, cools, and descends in downwelling zones.

CC4 | Particle Size, Sinking, Deposition, and Resuspension: Suspended particles in water or air sink at rates based on size, with larger particles descending faster. While high currents or winds can resuspend deposited material, large particles are typically harder to lift, though cohesive fine particles also resist resuspension. These dynamics primarily dictate the grain size of local sediments.

CC5 | Transfer and Storage of Heat by Water: Water's thermal properties are vital for climate regulation. Its high heat capacity enables oceans to store and release vast amounts of thermal energy while maintaining stable temperatures. High latent heat of vaporization enables heat transport via vapor, while the latent heat of fusion allows ice to buffer climate extremes in high latitudes.

CC6 | Salinity, Temperature, Pressure, and Water Density: Sea water density is controlled by temperature, salinity, and, to a lesser extent, pressure. Density is higher at lower temperatures, higher salinities, and higher pressures. Movements of water below the ocean's surface layer are driven primarily by density differences.

Appendix 1 - Units and Conversion Factors

Wherever possible, this text uses metric units of measurement. The metric system of measurement is used by all major countries but the United States, and it is the universal system used by all scientists. At present, an additional process is under way directed toward using only those metric units that are standard units approved in the International System of units (SI units). However, some of these standard units are unfamiliar even to many scientists, so they are not yet universally used. SI units are used in this text if they are generally in wide usage. In some instances where nonstandard units are much more widely used in the United States, the nonstandard units are used in this text. Over time, there will likely be a migration to the universal and exclusive use of SI units. The SI unit system has only seven base units from which all other units are derived (derived units are combinations of the base units). Tables listing the base units of the SI system, some derived SI units, and all of the units used in this text are included in this appendix. Some conversion factors to relate the SI units and other metric units to other units commonly used in the United States are also included.

The scientific community almost universally uses exponential notation for numbers. Exponential notation is explained in Chapter 1 and is used throughout this text. This appendix includes a table ("Exponential Notation and the Decimal System") for converting exponential numbers to their nonexponential equivalents. To multiply numbers expressed exponentially, add the exponents (superscript numbers). For example, $10^{-1} \times 10^3 = 10^2$ (one-tenth of 1000 is equal to 100). To divide, subtract the exponents. The "SI Base Units" table also lists the common terms used to identify certain exponent values. For example, 1000 is equivalent to 10^3 , or 1×10^3 , and 1000 can be expressed as "one thousand," while other units can be prefixed by "kilo-" to express one thousand of the units; for example, 1 kilogram is equal to 1000 grams.

Note that the naming system for large and small numbers is different in different parts of the world. In many non-English-speaking countries (and formerly in England), the term billion does not mean 10^9 . Instead, in this alternate system billion is 10^{12} and trillion is 10^{18} . This is one reason why it is always better to use exponential notation for large or small numbers.

SI Base Units

SI Base Units

Parameter	Unit	Symbol
Length	meter	m
Mass	gram	g
Time	second	s
Electrical current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole ^a	mol
Luminous intensity	candela	cd

^a1 mol is equal to the molecular weight in grams

Examples of Derived SI Units

Derived SI Units

Derived Quantity	Name	Symbol
Area	square meter	m ²
Volume	cubic meter	m ³

Derived Quantity	Name	Symbol
Speed, velocity	meter per second	$\text{m}\cdot\text{s}^{-1}$
Acceleration	meter per second squared	$\text{m}\cdot\text{s}^{-2}$
Mass density	kilogram per cubic meter	$\text{kg}\cdot\text{m}^{-3}$
Specific volume	cubic meter per kilogram	$\text{m}^3\cdot\text{kg}^{-1}$
Current density	ampere per square meter	$\text{A}\cdot\text{m}^{-2}$
Magnetic field strength	ampere per meter	$\text{A}\cdot\text{m}^{-1}$
Amount-of-substance concentration	mole per cubic meter	$\text{mol}\cdot\text{m}^{-3}$
Luminance	candela per square meter	$\text{cd}\cdot\text{m}^{-2}$
Mass fraction	kilogram per kilogram, which may be represented by the number 1	$\text{kg}\cdot\text{kg}^{-1} = 1$

SI Derived Units with Special Names and Symbols

Special Names and Symbols

Derived Quantity	Name	Symbol	Expression in Terms of Other SI Units
Plane angle	radian	rad	—
Frequency	hertz	Hz	—
Force	newton	N	—
Pressure, stress	pascal	Pa	$\text{N}\cdot\text{m}^{-2}$
Energy, work, quantity of heat	joule	J	$\text{N}\cdot\text{m}$
Power, radiant flux	watt	W	$\text{J}\cdot\text{s}$
Celsius temperature	degree Celsius	$^{\circ}\text{C}$	—
Luminous flux	lumen	lm	$\text{cd}\cdot\text{sr}$
Illuminance	lux	lx	$\text{lm}\cdot\text{m}^{-2}$
Activity (of a radionuclide)	becquerel	Bq	—

For ease of understanding and convenience, a few SI derived units have been given special names and symbols. These are some that are relevant to this text.

Exponential Notation and the Decimal System

Exponential Notation

Value	Exponential Expression	Name	Prefix
1,000,000,000,000	10^{12}	1 trillion	tera-
1,000,000,000	10^9	1 billion	giga-
1,000,000	10^6	1 million	mega-

Value	Exponential Expression	Name	Prefix
1,000	10^3	1 thousand	kilo-
100	10^2	1 hundred	centa-
10	10^1	ten	deca-
1	10^0	one	uni-
0.1	10^{-1}	1 tenth	deci-
0.01	10^{-2}	1 hundredth	centi-
0.001	10^{-3}	1 thousandth	milli-
0.000,001	10^{-6}	1 millionth	micro-
0.000,000,001	10^{-9}	1 billionth	nano-
0.000,000,000,001	10^{-12}	1 trillionth	pico-

Conversions between Basic Units of Length, Mass, and Time

Length

1 kilometer = 1000 meters (m)
 1 meter = 100 centimeters (cm)
 1 centimeter = 10 millimeters (mm)
 1 millimeter = 10 micrometers (mm)
 1 micrometer = 10 nanometers (nm)

Mass

1 tonne (metric ton) = 1000 kilograms (kg)
 1 kilogram = 1000 grams (g)
 1 gram = 10 milligrams (mg)
 1 milligram = 10 micrograms (mg)
 1 microgram = 10 nanograms (ng)
 1 nanogram = 10 picograms (pg)

Time

1 hour = 3600 seconds (s)

Units of Measurement Used in this Text

- Length/distance
 - meter (m) — SI base unit**
 - millimeter (mm)
 - centimeter (cm)
 - kilometer (km)
 - foot (ft.) — *obsolete nonmetric unit*
 - nautical mile (n.m.) — *equals 1.853 km (1.15 statute mi.) or 1 min (1/60 of a degree) of longitude*
- Mass
 - kilogram (kg) — SI base unit**
 - gram (g)
 - milligram (mg)
 - microgram (mg)

- tonne (t) — *metric ton, equal to 10³ kg*
- Time
 - **second (s) — SI base unit**
 - year (yr)
 - day (day)
 - hour (h)
 - minute (min)
- Area
 - meter squared (m²) — *derived SI unit*
 - centimeter squared (cm²)
 - kilometer squared (km²)
- Volume
 - meter cubed, cubic meters (m³) — *derived SI unit*
 - centimeter cubed (cm³)
 - kilometer cubed (km³)
 - liter (l) — *equals 10 cm³, so 1 m³ = 1000 l*
- Pressure
 - pascal (Pa) — *derived SI unit (not used in this text)*
 - kilogram per centimeter squared (kg · cm⁻²) — *equals 9.56 × 10⁶ Pa*
 - atmosphere (atm) — *equals 1.03 kg · cm⁻²*
- Mass density (absolute density)
 - kilogram per cubic meter (kg · m⁻³) — *derived SI unit*
 - gram per cubic centimeter (g · cm⁻³)
- Speed/velocity
 - meters per second (m · s⁻¹) — *derived SI unit*
 - centimeters per second (cm · s⁻¹)
 - kilometers per hour (km · h⁻¹) — *1 km · h⁻¹ = 0.28 m · s⁻¹ = 28 cm · s⁻¹*
 - kilometers per day (km · day⁻¹)
- Acceleration
 - meters per second per second (m · s⁻²) — *derived SI unit*
- Temperature
 - degrees Celsius (°C)
- Energy and related unites
 - joule (J) — *derived SI unit*
 - joule per meter squared (J · m⁻²) — *used as measure of wave energy*
 - joule per gram (J · g⁻¹) — *used as measure of latent heat*
 - joule per gram per degree Celsius (J · g⁻¹ · °C⁻¹) — *used as measure of heat capacity*
 - calorie (cal) — *obsolete measure of energy*
 - calories per gram (cal · g⁻¹) — *obsolete, used as measure of latent heat*
 - calories per gram per degree Celsius (cal · g⁻¹ · °C⁻¹) — *obsolete, used as measure of heat capacity*
- Concentration
 - mole per cubic meter (mol · m³) — *derived SI unit (not used in this text)*
 - milligram per kilogram (mg · kg⁻¹)
 - microgram per kilogram (mg · kg⁻¹)
 - Notes:
 - *Concentrations are expressed as mass of dissolved (or constituent) substance in one unit mass of the solution (or combined mixture)*
 - *1 mol is defined as the molecular weight of a substance expressed in grams. To convert concentration in mg · kg⁻¹ to mol · m⁻³, divide by the molecular weight of the dissolved substance (or constituent); then divide by the solution (or mixture) density in kg · m³ and multiply by 1000*
- Miscellaneous

- grams per year ($\text{g} \cdot \text{yr}^{-1}$) — *mass transport rate*
- cubic meters per second ($\text{m}^3 \cdot \text{s}^{-1}$) — *volume transport rate*
- practical salinity unit — *dimensionless ratio; no abbreviation, but sometimes listed as PSU*
- millions of years ago (mya) — *millions of years before the present date*
- before the common era (BCE) — *number of years before the year 1 of the Christian calendar, equivalent to BC*
- the common era (CE) — *number of years after the year 1 of the Christian calendar, equivalent to AD*

Additional Conversations: Metric to Other Units

Length

$$1 \text{ km} = 0.62 \text{ mi.}$$

$$1 \text{ km} = 0.54 \text{ n.m.}$$

$$1 \text{ km} = 1093 \text{ yard}$$

$$1 \text{ m} = 39.4 \text{ in.}$$

$$1 \text{ m} = 3.28 \text{ ft.}$$

$$1 \text{ cm} = 0.394 \text{ in.}$$

Mass

$$1 \text{ kg} = 2.2 \text{ lb}$$

$$1 \text{ t} = 2205 \text{ lb}$$

$$1 \text{ t} = 1.10 \text{ U.S. tons}$$

$$1 \text{ g} = 0.035 \text{ ounce}$$

Area

$$1 \text{ km}^2 = 0.386 \text{ mi.}^2$$

$$1 \text{ km}^2 = 247.1 \text{ acres}$$

$$1 \text{ m}^2 = 10.7 \text{ ft.}^2$$

$$1 \text{ cm}^2 = 0.155 \text{ in.}^2$$

Volume

$$1 \text{ m}^3 = 25.3 \text{ ft.}^3$$

$$1 \text{ m}^3 = 264 \text{ U.S. gallons}$$

$$1 \text{ cm}^3 = 0.061 \text{ in.}^3$$

$$1 \text{ l} = 2.12 \text{ pints}$$

Pressure

$$1 \text{ kg} \cdot \text{cm}^{-2} = 14.2 \text{ lb} \cdot \text{in.}^{-2}$$

$$1 \text{ kg} \cdot \text{cm}^{-2} = 0.97 \text{ atm}$$

$$1 \text{ kg} \cdot \text{cm}^{-2} = 956 \text{ millibars}$$

$$1 \text{ kg} \cdot \text{cm}^{-2} = 0.956 \text{ bar}$$

$$1 \text{ kg} \cdot \text{cm}^{-2} = 956,000 \text{ Pa}$$

$$1 \text{ kg} \cdot \text{cm}^{-2} = 29.0 \text{ in. of mercury at } 0^{\circ}\text{C}$$

$$1 \text{ kg} \cdot \text{cm}^{-2} = 737 \text{ mm of mercury at } 0^{\circ}\text{C}$$

Speed

$$1 \text{ km} \cdot \text{h}^{-1} = 0.62 \text{ mi.} \cdot \text{h}$$

$$1 \text{ km} \cdot \text{h}^{-1} = 0.54 \text{ knot}$$

$$1 \text{ cm} \cdot \text{s}^{-1} = 1.97 \text{ ft.} \cdot \text{min}^{-1}$$

$$1 \text{ cm} \cdot \text{s}^{-1} = 0.033 \text{ ft.} \cdot \text{s}^{-1}$$

Temperature

$$0^{\circ}\text{C} = 32^{\circ}\text{F}$$

$$10^{\circ}\text{C} = 50^{\circ}\text{F}$$

$$20^{\circ}\text{C} = 68^{\circ}\text{F}$$

$$30^{\circ}\text{C} = 86^{\circ}\text{F}$$

$$40^{\circ}\text{C} = 104^{\circ}\text{F}$$

$$100^{\circ}\text{C} = 212^{\circ}\text{F}$$

Appendix 2 - Dimensions of Earth and Ocean

The Earth

Earth's Dimensions

Space	Distance (km)
Radius at equator	6,378
Radius at poles	6,357
Average radius	6,371
Circumference at equator	40,077

Areas of Land and Oceans

Earth's Areas

Space	Area (km ²)
Land (29.22% of total)	149,000,000
Oceans and seas (70.78%)	361,000,000
Pacific Ocean (marginal seas included)	180,000,000
Atlantic Ocean (marginal seas included)	107,000,000
Indian Ocean (marginal seas included)	74,000,000
Ice sheets and glaciers	15,600,000
Land plus continental shelf	177,400,000
Land in the Northern Hemisphere	100,200,000
Ocean in the Northern Hemisphere	154,800,000
Land in the Southern Hemisphere	48,700,000
Ocean in the Southern Hemisphere	206,300,000

Percentage of Ocean Area Occupied by Ocean Provinces

Area of Earth's Ocean Features

Space	Percentage
Continental shelf and slope	15.30%
Continental rise	5.3%
Abyssal seafloor	41.80%
Volcanoes and volcanic ridges	3.1%
Oceanic ridges and rises	32.70%
Trenches	1.7%

Density and Mass of Earth's Spheres

Earth's Density and Mass

Space	Average Thickness or Radius (km)	Mean Density ($\text{g} \cdot \text{cm}^{-3}$)
Atmosphere	—	—
Oceans and seas	3.8	1.03
Ice sheets and glaciers	1.6	0.9
Continental crust (includes continental shelves)	35	2.8
Oceanic crust (excludes continental shelves)	8	2.9
Mantle	2881	4.53
Core	3473	10.7

Elevations and Depths

Earth's Highs and Lows

Space	Distance (m)
Average elevation of land	840
Average depth of oceans	3,800
Average depth of Pacific Ocean (marginal seas excluded)	3,940
Average depth of Atlantic Ocean (marginal seas excluded)	3,310
Average depth of Indian Ocean (marginal seas excluded)	3,840
Highest elevation of land (Mount Everest)	8,848
Greatest depth of oceans (Mariana Trench)	11,035

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Appendix 3 - Classification of Marine Organisms

Understanding life on the Earth and how this life has evolved and may evolve in the future in response to human influences requires that we understand the differences between the many forms of life on the Earth, and how and why the differences have developed. Fundamental to such studies is taxonomy, the classification of organisms to express their relationship to each other.

One fundamental concept of taxonomy is that organisms can be identified as belonging to a species. The definition of a species is generally accepted to be a population of organisms whose members interbreed under natural conditions and produce fertile offspring that are reproductively isolated from other such groups. A new definition based on genetics, the composition of DNA, may be developed in the future. The current definition has generally worked well, although there are difficulties, for example, when two populations that are capable of interbreeding are geographically separated and do not interbreed. In some such cases, scientists disagree as to whether these separate populations are of the same species or are different enough to be considered separate species. Populations of king salmon that breed in different rivers along the coasts of the United States and Canada are an example. Other difficulties arise because the members of a single species may look very different. For example, bulldogs, terriers, and poodles all belong to the same species. Conversely, organisms that appear to be very similar may belong to different species; red squirrels and gray squirrels are an example.

Millions of species on the Earth have been identified and studied, and certainly many more millions remain to be found, particularly in tropical rainforests and coral reefs. Species are arranged in a hierarchical classification similar to a human family tree. Taxonomists have established a series of levels for this hierarchy, from species at the bottom to kingdom, which was the top level until recent years, when a new top level—domain—was added. This new top level became needed when archaea were discovered. Initially placed in a kingdom along with bacteria, archaea were subsequently found to be entirely different from bacteria. In fact, archaea are different enough that they do not fit into any of the five kingdoms that were previously recognized and that are still listed in many texts. Although the new top level (domain) is not yet universally accepted, the generally accepted classification now identifies three such domains:

Three Domains of Living Organisms

- **Domain Bacteria – Most of the Known Prokaryotes**
 - *Although it is clear that the bacteria need to be separated into kingdoms, they are not well enough studied for this to have been done yet. At present, they are separated into five phyla.*
 - Phylum Proteobacteria: Nitrogen-fixing bacteria
 - Phylum Cyanobacteria: Photosynthetic bacteria (formerly blue-green algae)
 - Phylum Eubacteria: True gram-positive bacteria
 - Phylum Spirochetes: Spiral bacteria
 - Phylum Chlamydiae: Intracellular parasites
- **Domain Archaea – Prokaryotes of Extreme Environments**
 - Kingdom Crenarchaeota: Thermophiles
 - Kingdom Euryarchaeota: Methanogens and halophiles
 - Kingdom Korarchaeota: Some hot-springs microbes
- **Domain Eukarya – Eukaryotic Cells**
 - Protista (Informal Group): Single-celled organisms that have a nucleus and other internal structure in the cell (e.g., diatoms, dinoflagellates, foraminifera, radiolaria, marine algae, seaweeds)
 - Kingdom Fungi: Multicelled organisms that are not able to photosynthesize (or chemosynthesize)
 - Kingdom Plantae (or Metaphyta): Multicelled photosynthetic autotrophs (e.g., kelp)
 - Kingdom Animalia (or Metazoa): Multicelled heterotrophs (invertebrates and vertebrates)

Viruses have traditionally been considered to be non-living (since they cannot reproduce without a host). However, this view is now changing, and viruses may soon be recognized as life. In addition, there is now evidence that viruses may have preceded all of the other existing kingdoms, that they stand somewhere at the base of the tree of life, and may have evolved into cellular organisms. Some may even have devolved from a member of the 3 domains, losing (as no longer necessary) their prior cellular structure and ability to breed without a host, two of the characteristics recognized as generally defining life. As a result, it is likely that viruses will have to be found a place within the taxonomic hierarchy. Whether this will require reorganization of the 3 Domain structure shown in the table above to include a new Domain, a new Kingdom or lower order, or even a new classification level above Domain is not yet clear.

The taxonomic hierarchy generally has nine levels, although sometimes one or another level is omitted, sometimes intermediate levels are added within the hierarchy, and there is, as yet, no universal agreement on the use of the top level domains. The major levels in the hierarchy are as follows:

Domain

Kingdom

Phylum

Subphylum

Class

Order

Family

Genus

Species

The principal phyla and classes to which all common marine species belong, and some examples of each type are listed at the end of this appendix.

Scientific names of organisms are important for many reasons, one of which is that common names are often confusing. For example, the common name “red snapper” is used in the Gulf of Mexico for the species *Lutjanus campechanus*. In the Pacific Ocean the same common name, “red snapper,” is used for at least three different species (*Lutjanus bohar*, *Lutjanus malabaricus*, and *Lutjanus gibbus*) that are related but very different from one another. This difference does not matter to the local populations who eat these fishes (indeed, when you order red snapper in a restaurant, you may be served any one of many species that may not even be snappers). However, scientists must be able to distinguish them in the literature, and they do so by using scientific names.

The scientific names given to species always consist of two parts: a genus name followed by a species name. For example, mussels are classified as follows:

- **Domain:** Eukarya
- **Kingdom:** Animalia (Metazoa)
- **Phylum:** Mollusca
- **Class:** Bivalvia
- **Order:** Mytiloida
- **Superfamily:** Mytilacea (this is good example of an intermediate level used in the taxonomic hierarchy for only some orders)
- **Family:** Mytilidae
- **Genus:** *Mytilus*

The common blue mussel of the east coast of North America is *Mytilus edulis*, and a different species, *Mytilus californianus*, is present only on the west coast.

These and other scientific names may seem complicated, but they are either Latin or Greek words modified to explain something that the taxonomist considers important in identifying the organism. For example, “*Mytilus*” is derived from the Greek word for sea mussels, “*californianus*” expresses that this species is present only on the West Coast; and “*edulis*” means “edible,” a suitable term for this species that is so good to eat. Similarly, the genus name *Sargassum* is applied to species of algae present in the Sargasso Sea, and *Enterococcus* is the genus name for species of bacteria (“-coccus”) that are present in vertebrate intestines (“*Entero-*”).

Scientific names can be complicated and sometimes obscure, but in general, they follow an internationally accepted set of rules. Note that the convention is to use italics for scientific names and to capitalize the genus name only. In addition, shortening the genus name is acceptable when clear. For example, this text refers to mussels as *M. edulis* and *M. californianus* after the full names have been used once. There are other conventions as well. For example, “*sp.*” after the genus name refers to a single species of the genus whose species name is not known, and “*spp.*” after the genus name indicates that all (or many) of the

species of that genus are being referred to (e.g., “*Mytilus sp.*” refers to an unstated or unknown species of mussel, and “*Mytilus spp.*” refers to all or any species of mussel). The “*sp.*” and “*spp.*” are often omitted, as is done for simplicity in many cases in this text. Sometimes the genus name is followed by abbreviations such as “*cf.*” and “*aff.*” The first of these abbreviations (“*cf.*”) means that the genus listed is thought to be correct and that the species is very similar to the species identified by the name following the genus name and “*cf.*” but there are enough differences to lead the investigator to believe that this may turn out to be a new, but very closely related, species or a subspecies. The second abbreviation (“*aff.*”) means that the species is very similar to the species identified by the name following the genus name and “*aff.*” but it is sufficiently different that it is most likely an undescribed species similar to the one named.

Taxonomic Classification

Phyla that have no members in the marine environment, as well as phyla in which all species are extinct, are omitted from the following list. The list includes general descriptions of members of each classification and, in some cases, examples of common species and a listing of figures in this text that show a photograph of a member of this classification. The classification presented is not accepted by all taxonomists. Classifications, including the distinctions between phyla, continually change as more is learned.

Domain Archaea. Organisms that have no nucleus, predominantly single-celled. Occur primarily in extreme environments.

Kingdom Crenarchaeota. Thermophiles.

Kingdom Euryarchaeota. Methanogens and halophiles.

Kingdom Korarchaeota. Some hot-springs microbes.

Domain Bacteria. Organisms that have no nucleus, predominantly single-celled.

Phylum Proteobacteria. Nitrogen-fixing bacteria.

Phylum Cyanobacteria. Photosynthetic bacteria (formerly blue-green algae).

Phylum Eubacteria. True gram-positive bacteria.

Phylum Spirochetes. Spiral bacteria.

Phylum Chlamydiae. Intracellular parasites.

Domain Eukarya, Protista (Informal). Organisms with a nucleus confined by a membrane, predominantly single-celled. This group may eventually be broken up and reclassified.

Phylum Chrysophyta. Diatoms (Figs. 6-6; 12-16a), coccolithophores (Figs. 6-7; 12-16c), silicoflagellates.

Phylum Pyrrophyta. Autotrophic dinoflagellates (Fig. 12-16b), zooxanthellae.

Phylum Chlorophyta. Green algae (Fig. 13-4a,d; 15-13f).

Phylum Phaeophyta. Brown algae (Fig. 13-4a). Kelps (Figs. 12-4a,b; 15.3a,c; 15-7c), Sargassum (Figs. 15-8; 15-15), and others.

Phylum Rhodophyta. Red algae (Fig. 13-4a,b,e).

Phylum Zoomastigophora. Flagellated protozoa, including heterotrophic dinoflagellates.

Phylum Sarcodina. Amoebas and relatives, including foraminifera (Figs. 6-8a; 12-19d) and radiolaria (Figs. 6-9; 12-19e).

Phylum Ciliophora. Protozoa with cilia.

Domain Eukarya, Kingdom Fungi. Fungi, lichens.

Phylum Mycophyta. Marine fungi are primarily benthic decomposers. Marine lichens are primarily intertidal.

Domain Eukarya, Kingdom Plantae (Metaphyta). Autotrophic multicelled plants.

Phylum Tracheophyta. Plants with roots, stems, leaves, and special cells that transport nutrients and water.

Class Angiospermae. Flowering plants with seeds contained in a closed seedpod. Turtle grass (*Thalassia*; Fig. 14-12b), marsh grasses (*Spartina*; Fig. 14-12c).

Domain Eukarya, Kingdom Animalia (Metazoa). Multicelled heterotrophs (animals).

Phylum Placozoa. Amoeba-like multicelled animals.

Phylum Mesozoa. Wormlike parasites of cephalopods.

Phylum Porifera. Sponges (Fig. 14-28m).

Phylum Cnidaria (Coelenterata). Jellies and related organisms, all of which have stinging cells.

Class Hydrozoa. Polypoid colonial animals, most with a medusa-like stage. Includes Portuguese man-of-war (Fig. 12-20d).

Class Scyphozoa. Jellies with no (or reduced) polyp stage in life cycle. Medusa stage dominates (Fig. 12-20a,b).

Class Anthozoa. Zooanthids (Fig. 14-8h), anemones (Figs. 14-6c; 14-8g,i; 14-20a; 14-35a; 15-9b), sea pens (Fig. 14-6a,b), and corals (Figs. 13-12; 14-8a-f; 14-28a; 15-5e,f; 15-7; 15-9a) that have only a polypoid body form.

Phylum Ctenophora. Comb jellies (Fig. 12-20d), “sea gooseberries.” Predatory, predominantly planktonic.

Phylum Platyhelminthes. Flatworms, flukes, tapeworms. Many are parasitic; many others are free-living predators.

Phylum Nemertea. Ribbon worms. Benthic and pelagic.

Phylum Gnathostomulida. Microscopic, wormlike, meiofaunal (small organisms that live in the spaces between sediment grains).

Phylum Gastrotricha. Microscopic, ciliated, meiofaunal.

Phylum Rotifera. Ciliated, less than about 2 mm long. Most species freshwater. Planktonic or epibenthic.

Phylum Kinorhyncha. Small, spiny, segmented worms; meiofaunal.

Phylum Acanthocephala. Spiny-headed worms. All are intestinal parasites of vertebrates.

Phylum Entoprocta. Small polyplike suspension feeders.

Phylum Nematoda. Roundworms. Most are 1 to 3 mm; marine species are infaunal.

Phylum Bryozoa. Small moss animals that form encrusting or branching colonies on the seafloor.

Phylum Phoronida. Suspension-feeding tube worms. Infaunal; inhabit shallow and temperate sediments.

Phylum Brachiopoda. Lamp shells. Bivalve animals that superficially resemble clams. Mostly deep-water.

Phylum Mollusca. Soft-bodied animals with a mantle and muscular foot. Most species secrete a calcium carbonate shell.

Class Monoplacophora. Limpetlike shells, segmented bodies, abyssal only.

Class Polyplacophora. Chitons (Fig. 15-13d). Oval, flattened body covered by eight overlapping plates.

Class Aplacophora. Worm-shaped mollusks; soft-sediment infauna.

Class Gastropoda. Snails (Figs. 14-3b; 14-19b; 14-28h; 15-13a), limpets (Fig. 15-13b), abalones, pteropods (Figs. 6-8b; 14-3a), nudibranchs (Figs. 3-1c; 14-11c,d; 14-28d-g; 15-9f), and many others (Figs. 14-11b; 14-19c; 14-34s).

Class Bivalvia. Clams (Fig. 14-35d), scallops, oysters (Fig. 14-7b), mussels (Figs. 14-7a; 15-13e; 15-14). Bivalves (shell with two fitted segments). Mostly filter-feeding.

Class Scaphopoda. Tusk shells. Soft-sediment infauna.

Class Cephalopoda. Squid (Figs. 12-24a, 14-28i), octopi (Figs. 12-1, 14-18e; 15-18), cuttlefish (Figs. 12-24b-d, 14-1; 14-28j), *Nautilus* (Figs. 12-24e,f). No external shell except in *Nautilus* sp.

Phylum Priapulida. Small, wormlike, subtidal.

Phylum Sipuncula. Peanut worms, benthic, exclusively marine.

Phylum Echiura. Spoon worms. Spoon-shaped proboscis. Infaunal or live under rocks.

Phylum Annelida. Segmented worms. Mostly benthic. Includes feather duster worms (Fig. 14-6d), scale worms (Fig. 14-34r), and Christmas tree worms (Figs. 14-10c,d).

Phylum Tardigrada. Meiofaunal. Eight-legged. Can hibernate for long periods.

Phylum Pentastoma. Tongue worms. Parasites of vertebrates.

Phylum Pogonophora. Tube-dwelling worms with no digestive system. Absorb food through body wall. All species are marine. Mostly deep-water (Fig. 15-20b).

Phylum Echinodermata. Spiny-skinned animals. Most are benthic epifaunal or infaunal.

Class Asteroidea. Sea stars (Figs. 12-21c; 15-5b, 15-9e).

Class Ophiuroidea. Brittle stars, basket stars (Fig. 14-33e).

Class Echinoidea. Sea urchins (Figs. 14-10b; 14-11a; 14-18d; 14-35b; 15-5c; 15-10b), sand dollars (Fig. 15-5d), sea biscuits.

Class Holothuroidea. Sea cucumbers (Figs. 14-10a; 14-28l; 15-5a).

Class Crinoidea. Sea lilies and feather stars (Figs. 14-16a,b; 14-34g).

Phylum Chaetognatha. Arrowworms, stiff-bodied, mostly planktonic.

Phylum Hemichordata. Unsegmented infauna with primitive nerve cord. Acorn worms. All marine.

Phylum Arthropoda. Jointed, legged animals with segmented body covered by an exoskeleton.

Subphylum Crustacea. Copepods (Figs. 12-19a, 14-32a), krill (Fig. 14-2a), barnacles (Figs. 14-7c,d; 15-13c), amphipods, shrimp (Figs. 14-2b,c; 14-16a,b,j-l; 14-18a; 14-34h-q; 14-35c,e; 15-9d), lobster, crabs (Figs. 12-21a; 14-16f,g; 14-18c; 14-34a-e; 14-35a,b; 15-9c; 15-13g), euphausiids (Figs. 12-19b; 14-2a), isopods (Fig. 14-32b,c).

Subphylum Chelicerata. Horseshoe crabs, sea spiders.

Subphylum Uniramia. Insects. Only five species of a single genus are present in the ocean.

Phylum Chordata. Animals with a nerve cord and gills, gill slits, or lungs.

Subphylum Urochordata. Tunicates (Fig. 14-9), sea squirts, salps (Fig. 12-20e; 14-4).

Subphylum Cephalochordata. Lancelets, Amphioxus. Found in coarse temperate and tropical sediments.

Subphylum Vertebrata. Spinal column of vertebrae, internal skeleton, brain.

Class Agnatha. Jawless fishes. Cartilaginous skeletons. Lampreys, hagfishes.

Class Chondrichthyes. Cartilaginous skeletons. Rays (Fig. 12-23f,h,i), sharks (Fig. 12-23a-e,g; 14-25e), skates, sawfishes, chimeras.

Class Osteichthyes. Bony fishes (Figs. 12-22; 14-13d; 14-14; 14-15; 14-16c-e,h,i; 14-17; 14-18b; 14-19a,d-f; 14-20b-f; 14-21; 14-22; 14-23; 14-24; 14-25a-d; 14-26; 14-27; 14-28b,c,k,n; 14-32; 14-34f,g; 14-35c; 15-7; 15-9g).

Class Amphibia. No marine species, but one species (Asian mud frog) is known to tolerate marine water. Frogs, toads, salamanders.

Class Reptilia. Turtles (Figs. 12-28a,b; 14-12d), sea snakes (Fig. 12-28c,d). One species of iguana (Fig. 12-28e,f) and one species of crocodile are marine.

Class Aves. Birds (Figs. 12-29; 16-9b). Many species live on and feed in the ocean, but all must return to land to breed.

Class Mammalia. Warm-blooded animals that have mammary glands and hair, bear live young.

Order Cetacea. Whales (Fig. 12-25a-d), porpoises, dolphins (Fig. 12-25e).

Order Sirenia. Sea cows. Manatee (Fig. 12-26), dugong.

Order Carnivora. Marine species in two suborders.

Suborder Pinnipedia. Seals (Figs. 12-27a,b; 15-16; 16-9a), sea lions (Fig. 12-27c), walrus (Fig. 12-27d).

Suborder Fissipedia. Sea otters (Figs. 12-27e; 15-10a).

Order Primates. Primates. Apes, human beings. Only one species is known to tolerate marine water—surfers, swimmers, scuba divers.

The phyla Porifera, Cnidaria, Platyhelminthes, Nematoda, Mollusca, Arthropoda, Arthropoda, and Chordata each have more than 10,000 known member species. The phyla Cyanobacteria, Chrysophyta, Pyrrophyta, Chlorophyta, Phaeophyta, Rhodophyta, Zoomastigophora, Sarcodina, Ciliophora, Mycophyta, and Echinodermata each have between approximately 1000 and 10,000 known member species. All other phyla listed have fewer than about 1000 known species. However, it is estimated that there may be between 1 and 10 million species in the oceans, of which only a few hundreds of thousands have yet been identified.

Appendix 4 - Milestones in the History of Ocean Study

4000 BCE Egyptians developed shipbuilding and ocean piloting capabilities, as well as trading on the Nile.

3800 BCE First maps showing water (river charts).

3000 BCE Evidence for seafaring between China and Taiwan that may have spurred colonization of the tropical Pacific Ocean islands by the Polynesians.

2000-500 BCE The Polynesians voyaged across the Pacific Ocean and settled all the major islands, first inhabiting Tonga, Samoa, ca. 1000 BCE. Micronesian stick chart used.

1200-850 BCE Phoenicians explored entire Mediterranean Sea and sailed into the Atlantic to West Africa and to Cornwall, England for trading.

900 BCE Greeks first use the term *okeanos*, a mythical god, to describe the great river that flowed in a circle around the Earth and the root of the present word ocean.

800 BCE First graphic aids to marine navigation.

600 BCE The Greek Pythagoreans assumed a spherical Earth.

Thales of Miletus, a Greek natural philosopher, developed the origin of science as we define it today and he is alleged to have written a book on navigation.

450 BCE The Greek Herodotus compiled a map of the known world centered on the Mediterranean region.

325 BCE The Greek Pytheas explored the coasts of England, Norway, and perhaps Iceland. He developed a means of determining latitude from the angular distance of the North Star and proposed a connection between the phases of the moon and the tides.

The Greek philosopher, Aristotle, published *Meteorologica*, which described the geography of the Greek world, and *Historia Animalium* the first known treatise on marine biology—a catalog of marine organisms.

300 BCE Library founded at Alexandria by Alexander the Great, which served as the repository for scrolls from ships and land caravans; for the next 600 years, it was a maritime studies center, fostering advances in science, celestial navigation by a variety of Greek and Egyptian scholars.

276-192 BCE The Greek Eratosthenes, a scholar and librarian at Alexandria, calculated the circumference of a spherical Earth with remarkable accuracy using trigonometry noting the specific angle of sunlight that occurred at Alexandria and Syene (now called Aswan), Egypt. He also invented latitude and longitude lines based on landmarks.

127 BCE Hipparchus of Nicaea, a Greek mathematician, developed a 360 degree system and arranged latitude and longitude in regular grid by degrees.

54 BCE - 30 CE The Roman Seneca devised the hydrologic cycle to show that, despite the inflow of river water, the level of the ocean remained stable because of evaporation.

1st century CE Chinese invent first compass.

150 CE The Greek-Egyptian scientist, Claudius Ptolemy, added minutes and seconds to the latitude-longitude system and compiled a map of the Roman World, but erred in estimating Earth's circumference, which remained uncorrected for hundreds of years.

415 CE The Alexandrian library with an estimated 700,000 scrolls destroyed and the last librarian, Hypatia, murdered by religious mob; Earth considered flat again.

673-735 CE The English monk Bede published *De Temporum Ratione*, which discussed the lunar control of the tides and

recognized monthly tidal variations and the effect of wind drag on tidal height.

780 Viking raids begin.

800-1000 Hawaii colonized by Polynesians

950-1250 Medieval Warm Period

982 Eric the Red, a Norse chieftain, completed the first transatlantic voyage, reaching present-day Baffin Island, Canada.

995 Leif Ericson, son of Eric the Red, established the settlement of Vinland in what is now Newfoundland, Canada.

1000 Norwegian colonies established in North America

1050 The astrolabe, a navigation instrument used to measure the height of celestial bodies above the horizon, first arrived in Europe from the East.

1400-1900 The Little Ice Age.

1405 Admiral Cheng Ho, the commander of the Treasure Fleet of the Dragon Throne began his voyages for Emperor Chu Ti, ultimately ruling the South Pacific and Indian Ocean until 1433.

1420 Prince Henry the Navigator, of Portugal, founded a naval observatory and the first school for teaching navigation, astronomy, and cartography.

1452-1519 Leonardo da Vinci, the famous Italian scientist, observed, recorded and interpreted characteristics of currents and waves and noted that fossils in Italian mountains implied that sea level had been higher in the ancient past.

1492 Christopher Columbus rediscovered North America, sailing to the islands of the West Indies.

1497-1499 Vasco da Gama, a Portuguese navigator, journeyed to India by sea by rounding the Cape of Good Hope with four ships, thereby establishing the first all water trade route between Europe and India.

1500 The Portuguese navigator and explorer, Pedro Alvares Cabral, traveled westward in search of a route to India, but reached and explored Brazil.

1513 Juan Ponce de Leon described the swift and powerful Florida Current.

1513-1518 Vasco de Nunez de Balboa crossed the Isthmus of Panama and sailed in the Pacific Ocean.

1515 Peter Martyr proposed an origin for the Gulf Stream.

1519-1522 Ferdinand Magellan embarked on the first circumnavigation of the globe; the crew led by Sebastian del Cano completed the voyage. On the voyage, the Pacific Ocean was named.

1569 Gerardus Mercator, the Flemish mapmaker, constructed a map projection of the world that was adapted to navigational charts.

1605 Bishop Resen of Copenhagen drew the first map of the Gulf Stream.

1609 Hugo Grotius, a Dutch legal scholar, published *Mare Liberum*, the foundation for all modern law of the sea.

1674 The British scientist Robert Boyle investigated the relation among temperature, salinity, and pressure of seawater with depth and reported his findings in *Observations and Experiments on the Saltiness of the Sea*.

1687 Sir Isaac Newton published *Principia Mathematica*, which includes an explanation of the operation of gravity and that tides are the result of gravitational attraction of the moon and sun.

1714 Gabriel D. Fahrenheit invents a temperature scale.

1725 Count Luigi Marsigli from Bologna, Italy compiled *Histoire Physique de la Mer*, the first book pertaining entirely to

oceanography, examining the geological formation of ocean basins along with the marine life that lived in the sea.

1733 English clockmaker John Harrison invented the first of his five accurate and durable nautical chronometers for determining longitude at sea.

1735 George Hadley proposed an explanation for the trade wind regime that involved a consideration of the Earth's rotation.

1740 Leonhard Euler, noted Swiss mathematician, developed an approximation of the three-body problem to calculate the magnitude of the lunar and solar attractive forces that generate ocean tides.

1742 Anders Celsius invents a temperature scale.

1758 Carolus Linnaeus publishes 10th edition of *Systema Naturae*, formalizing biological nomenclature.

1760 John Harrison invented the Number Four chronometer in his quest to solve the longitude problem.

Joseph Black proposed the concept of specific heat.

1768-1775 Captain James Cook commanded three major ocean voyages gathering extensive data on 1776-1780 geography, geology, biota, currents, tides, and water temperatures of all of the principal oceans.

1769 or 1770 The American scientist, Benjamin Franklin, published the first chart of the Gulf Stream (by Folger), which was used by ships to cross the North Atlantic Ocean faster.

1779 James Cook died in Hawaii.

1802 Nathaniel Bowditch of Massachusetts published the *New American Practical Navigator*, a navigational resource that continues to be revised and published to this day.

1805 Admiral Sir Francis Beaufort of the Royal Navy developed his 12-category wind force scale to aid mariners estimate wind speed; this scale was later modified.

1807 President Thomas Jefferson mandated coastal charting of the entire United States and established the U.S. Coast and Geodetic Survey, now known as the National Geodetic Survey.

1811 British chemist Sir Humphry Davy made the first gas hydrates in his laboratory.

1817-1818 Sir John Ross ventured into the Arctic Ocean to explore Baffin Island, where he sounded the bottom successfully (took the first deep-water and sediment samples) and recovered starfish and mud worms from a depth of 1.8 km.

1820 Alexander Marcet, a London physician, noted that the proportion of the chemical ingredients in seawater is unvarying in all ocean basins.

1831-1836 The epic five-year journey of Charles Darwin aboard the British research ship HMS *Beagle* led to a theory of atoll formation and later the theory of evolution by natural selection.

1835 Gaspard-Gustav de Coriolis, a French mathematician, published the first papers on an object's horizontal motion across the surface of the rotating Earth.

1836 William Henry Harvey, an Irish botanist, devised a taxonomy of seaweeds.

1838-1842 Departure of the United States Exploring Expedition led by Lieutenant Charles Wilkes on the flagship *Vincennes*. Six vessels mapping coastal areas, collected specimens.

1839-1843 Sir James Clark Ross led an expedition to Antarctica, recovering samples of deep-sea benthos down to a depth of 4.9 km.

1841, 1854 Sir Edward Forbes published *The History of British Star-Fishes* (1841) and then his *Distribution of Marine Life* (1854), in which he argued that sea life cannot exist below a depth of about 600 m (the so called azoic hypothesis).

1847 Hans Christian Oersted observed plankton.

1851 The first telegraph cable was laid across the Straits of Dover, stimulating new technologies to protect, raise and lower cables to the sea floor.

1853 The first international conference convened in Brussels by Lt. Matthew Fontaine Maury, USN for the purpose of establishing a uniform means of meteorological observations at sea.

1855 Matthew Fontaine Maury, USN compiled and standardized the wind and current data recorded in U.S. ship logs and summarized his findings in *The Physical Geography of the Sea*, credited as the first textbook of modern oceanography.

1859 Darwin's *Origin of Species* published.

1865 Fr. Pietro Angelo Secchi, a papal scientific advisor, perfected the Secchi disc for determination of the transparency of Mediterranean Sea water to sunlight.

1868-1870 Charles Wyville Thomson, aboard HMS *Lightning* and HMS *Porcupine*, made the first series of deep-sea temperature measurements and collected marine organisms from great depths, disproving Forbes' azoic hypothesis.

1870s William Ferrel, an American meteorologist, drew attention to the deflecting effect of the Earth's rotation on ocean currents (the Coriolis Effect).

1871 The U.S. Fish Commission was established with a modern laboratory at Woods Hole, MA.

1872-1876 Lead by Charles Wyville Thomson, HMS *Challenger* conducted worldwide scientific expeditions, collecting data and specimens that were later analyzed in the more than 50 volumes of the *Challenger Reports*.

1873 Charles Wyville Thomson published a general oceanography book called the *Depths of the Sea*.

1877-1880 Alexander Agassiz, an American naturalist, founded the first U.S. marine station, the Anderson School of Natural History, on Penikese Island, Buzzards Bay, MA.

1880 William Dittmar determined major salts in seawater.

1884-1901 USS *Albatross* was designed and constructed specifically to conduct scientific research at sea and undertook numerous oceanographic cruises.

1880s Development of the civil time zones and the ultimate specification of the Greenwich Mean Time (GMT) as the world-wide reference.

1888 The Marine Biological Laboratory was established at Woods Hole, MA.

1890 Alfred Thayer Mahan completed *The Influence of Sea Power upon History*.

1891 Sir John Murray and Alphonse Renard classified marine sediments.

1893 Discovery of Maunder sunspot minimum by astronomer E. Walter Maunder.

1893-1896 The Norwegian Fridtjof Nansen, while aboard the *Fram*, studied the circulation pattern of the Arctic Ocean and confirmed that a northern continent did not exist.

1900 On 8 September, a hurricane storm surge struck Galveston, TX. More than 8000 people died, mostly by drowning, in the most deadly natural disaster in U.S. history.

1902 Danish scientists with government backing established the International Council for the Exploration of the Sea (ICES) to investigate oceanographic conditions that affect North Atlantic fisheries. Council representatives were from Great Britain, Germany, Sweden, Norway, Denmark, Holland, and the Soviet Union.

1903 The Friday Harbor Oceanographic Laboratory was established at the University of Washington in Seattle.

The Laboratory that became the Scripps Institution of Biological Research, and later the Scripps Institution of Oceanography, was founded in San Diego, CA.

1905 Marconi perfected wireless telegraphy, which became important for communication on the ocean.

The Swedish oceanographer, V.W. Ekman, published his classic work on the cause of the spiral nature of wind driven ocean currents near the surface.

1906 The first Sonar type listening device was invented by Lewis Nixon in order to detect icebergs.

Prince Albert I of Monaco established the Musée Océanographique.

1907 Bertram Boltwood calculated age of Earth by radioactive decay.

1911 Roald Amundsen was first at South Pole.

1912 Following the sinking of the *Titanic*, the International Ice Patrol was formed to monitor icebergs.

German meteorologist Alfred Wegener proposed his theory of continental drift.

1912 Scripps Institution allied with the University of California.

1918 Vilhelm Bjerknes and colleagues at the Bergen (Norway) school formulated theories of air masses, atmospheric fronts, and midlatitude storm systems.

1921 International Hydrographic Bureau founded.

1924 Discovery of the Southern Oscillation by Sir Gilbert Walker.

1925-1927 A German expedition aboard the research vessel *Meteor* studied the physical oceanography of the Atlantic Ocean, using an echo sounder extensively for the first time.

1929 British geologist Arthur Holmes proposed that convection in Earth's mantle was the driving force for continental drift. This explanation was revived in the 1960s by Harry Hess and Robert S. Dietz.

1930 The Woods Hole Oceanographic Institution was established on the southwestern shore of Cape Cod, MA.

1931 *Atlantis* launched.

1932 The International Whaling Commission was organized to collect data on whale species and to enforce voluntary regulations on whaling.

1937 *E.W. Scripps* launched.

1938 Serbian astronomer Milutin Milankovitch began work on his astronomical theory of the Ice Age.

1942 Harald Sverdrup, Richard Fleming, and Martin Johnson published the first modern oceanographic reference text, *The Oceans*, which is still consulted today.

1943 Jacques Cousteau and Emile Gagnan invented the scuba regulator and tank combination, the "aqualung" for diving underwater.

1946 On 1 April, a tsunami destroyed most of the waterfront of Hilo, Hawaii causing 159 deaths.

1949 Maurice Ewing formed the Lamont (later changed to Lamont Doherty) Geological Observatory at Columbia University in New York.

1957 Systematic monitoring of atmospheric carbon dioxide levels began at the Mauna Loa Observatory, Hawaii, under the direction of Charles D. Keeling.

1957-1958 The International Geophysical Year (IGY) was organized as an international effort to coordinate geophysical

investigations of the Earth, including the ocean.

1958 The first U.S. nuclear submarine, USS *Nautilus*, also made the first submerged transit of the Arctic ice pack, passing the geographic North Pole.

1959 Antarctic Treaty System adopted by 12 nations.

1959-1965 The International Indian Ocean Expedition was established under United Nations auspices to intensively investigate Indian Ocean oceanography.

1960 The bathyscaphe *Trieste* carrying Jacques Piccard and Don Walsh reached the bottom of the deepest (Mariana) trench (10,912 m, or 35,800 ft).

1960s Jacob Bjerknes developed concept of teleconnections involving El Niño events and the Southern Oscillation.

1962 Rachel Carson's book *Silent Spring* initiated the U.S. environmental movement.

1963 F.J. Vine and D.H. Matthews of Cambridge University interpreted sea floor magnetic field anomaly patterns in support of sea floor spreading.

1964 *Alvin*, the world's first deep-ocean research submersible was launched.

On 28 March, a tsunami struck the Seward, Alaska area, claiming more than 100 lives.

1965 Discovery of a natural deposit of methane hydrates under permafrost in Siberia.

1966 The U.S. Congress adopted the Sea Grant College and Programs Act to provide nonmilitary funding for marine science education and research.

1968 *Glomar Challenger* returns first deep-sea cores, indicating the age of the Earth's crust. The cores support theories of plate tectonics.

The U.S. National Science Foundation organized the Deep Sea Drilling project (DSDP) to core through the sediments and crust of the ocean bottom.

1969 Santa Barbara, CA, oil well blowout captured national attention.

Stratton Commission developed the first national ocean policy for the U.S.

1970 The U.S. government created the National Oceanic and Atmospheric Administration (NOAA) to oversee and coordinate government activities related to oceanography and meteorology.

Completion of the Aswan High Dam on the Nile River.

1970s The United Nations initiated the International Decade of Ocean Exploration (IDOE) to improve scientific knowledge of the ocean.

Saffir-Simpson Hurricane Intensity Scale rated hurricanes from 1 to 5 corresponding to increasing intensity. It was revised in 2010 and is now known as the Saffir Simpson Hurricane Wind Scale.

1970 John Tuzo Wilson, a Canadian geologist, proposed a cyclic model of tectonic revolution.

1971 Jason Morgan of Princeton University proposed hotspot volcanism.

1972 The Geochemical Ocean Sections Study (GEOSECS) was organized to study seawater chemistry, ocean circulation and mixing, and the biogeochemical recycling of chemical substances.

Marine Mammal Protection Act established a moratorium on the hunting of marine mammals in U.S. waters and by U.S. citizens on the high seas (reauthorized in 1994).

Provisions of the 1972 Marine Protection, Research and Sanctuaries Act authorized the President to designate national marine

sanctuaries in coastal waters of the continental shelf and in the Great Lakes (reauthorized in 2000).

1972 London Dumping Convention banned the discharge of waste from land into the ocean by ships or aircraft.

Coastal Zone Management Act passed into law whereby the federal government assists coastal states in managing and protecting coastal resources.

1973 U.S. Endangered Species Act became law.

1974 Project FAMOUS (French-American Mid-Ocean Undersea Study) mapped and sampled the Mid-Atlantic Ridge, a zone of seafloor spreading.

1974 F.S. Rowland and M.J. Molina first warned of the threat of CFCs to the stratospheric ozone shield.

1975 Sinking, on 10 November, of the ore carrier Edmund Fitzgerald on Lake Superior with the loss of her 29-member crew.

1976 Scientists discover indications of Milankovitch cycles in deep-sea sediment cores.

Magnuson-Stevens Fisheries and Conservation Act established fishery councils to manage the fishery resources in each region of the nation.

1977 The submersible *Alvin* finds hydrothermal vents in the Galápagos rift.

1978 *Seasat-A*, the first satellite dedicated to the remote sensing of the ocean, was launched.

Coastal Zone Color Scanner (CZCS) flown aboard NASA's Nimbus-7 satellite.

1979 NOAA's SLOSH numerical model developed to predict the location and height of a storm surge.

1981 The Burgess Shale declared a UNESCO World Heritage Site.

1982 The UN Convention on the Law of the Sea established, which granted jurisdiction over an exclusive economic zone (EEZ) to 151 coastal nations.

1983 The Chesapeake Bay Program became the nation's largest federal-state environmental restoration project; the nation's first estuary selected for restoration and protection.

1985 The scientific research vessel *JOIDES Resolution* replaced *Glomar Challenger* in Deep Sea Drilling Project.

Tropical Ocean-Global Atmosphere (TOGA) commenced a 10-year experiment in the equatorial Pacific, with the deployment of the TOGA Tropical Atmosphere Ocean (TAO) Array.

R. D. Ballard located wreck of *Titanic*.

1986 Moratorium on commercial whaling issued by the International Whaling Commission (IWC).

1987 Joint Global Ocean Flux Study (JGOSS) founded to assess processes controlling carbon fluxes.

1988 The Intergovernmental Panel on Climate Change (IPCC) formed by the World Meteorological Organization and the UN Environmental Programme to evaluate the state of climate science as the basis for policy action.

Heinrich layers first described by German researcher Hartmut Heinrich. Sediment released to the floor of the North Atlantic during the melting of fleets of ice bergs.

1989 On 24 March, the supertanker *Exxon Valdez* ran aground on a reef in Prince William Sound, Alaska, producing the 2nd largest oil spill in U.S. history.

1990 The *JOIDES Resolution* retrieved a sediment sample estimated to be 170 million years old.

1991 JOI researchers bore to a depth of 2 km (1.24 mi) beneath the seafloor near the Galápagos Islands.

The NOAA National Weather Service Forecast Office in Miami, FL, began to issue outlooks for rip currents.

1992 The U.S.-French *TOPEX/Poseidon* satellite launched to monitor global ocean topography.

The Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) was conducted in western Pacific.

1993 Beginning of a series of ocean iron fertilization experiments.

1994 The Law of the Sea Treaty entered into force.

1995 *Keiko*, a small remotely controlled Japanese submersible, sets a new depth record, reaching 10,978 m (36,008 ft) in the Challenger Deep.

1998 UN declared the “Year of the Oceans” to increase awareness of the importance of the ocean.

Galileo spacecraft found possible evidence of an ocean on Jupiter’s moon Europa.

Scientists from 30 nations began deploying Argo profiling floats in the world ocean.

2000 Beginning of 10-year international project, *Census of Marine Life*.

2004 On 26 December, tsunami originated off the west coast of Sumatra, Indonesia; death toll is estimated at 227,900.

U.S. Commission on Ocean Policy made recommendations for a new national ocean policy.

2005 On 28 August, Hurricane Katrina struck the Gulf coast of Louisiana and Mississippi. At least 1500 people lost their lives in the most destructive hurricane in U.S. history.

2007-09 Fourth International Polar Year (IPY).

2007 Modern Japanese drill ship, *Chikyu*, became fully operational.

Argo array is completed with over 3000 active profiling floats deployed in the world ocean.

2008 The U.S.-French Jason-2 satellite launched to continue monitoring global ocean topography.

2009 IceBridge, a six-year NASA mission, begins the largest airborne survey of polar ice.

2010 An explosion on 20 April at the Deepwater Horizon drilling platform, leased by BP, releases almost 5 million barrels of oil into the Gulf of Mexico before it is capped in mid-July.

The Census of Marine Life completes a decade of ocean life research.

The National Ocean Council is established by Executive Order.

2011 On 11 March, a tsunami originates off the east coast of Japan with a death toll of 15,093 in Japan and 9,093 persons missing.

2020 Discovery of microbial life deep within Earth’s crust beneath ocean sediments.

2026 The UN High Seas Treaty, formally known as the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement, officially enters into force in January.

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