

2j. Oceanographic Data

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Symbols

c	speed of sound, vapor pressure, speed of gravity wave
c_p	specific heat at constant pressure
g	acceleration of gravity
h	water depth, mean celestial longitude of sun
k	thermal conductivity
L	wavelength of gravity wave
n	refractive index
p	pressure, mean celestial longitude of lunar perigee
s	mean celestial longitude of moon
T	absolute temperature, hour angle of mean sun
v	specific volume
η	dynamic viscosity
κ	thermal diffusivity
ν	kinematic viscosity
ρ	density

2j-1. General. Oceanography is a composite of the marine aspects of science and engineering plus descriptive elements to incorporate spatial and temporal changes. This unusual grouping of disciplines has evolved special marine philosophies and experimental techniques that constitute much of the oceanographic profession.¹⁻³ This summary is primarily concerned with physical oceanography.

The great interconnected bodies of water constitute the world ocean. Although the salinity at the mouth of large rivers may approach zero, the salinity and density of the vast majority of ocean water is close to 35 parts per thousand of salt by weight and 1.030 g/cc density, or about 2.5 per cent greater density than that of fresh water at the same pressure.

Ocean currents are driven partly by the wind and partly as the working fluid of a great heat engine warmed near the equator and cooled near the poles. In the winter, and particularly in cold winters, high-latitude water cools and sinks to the bottom

¹ R. Fairbridge, "Encyclopedia of Oceanography," Reinhold Book Corporation, New York, 1966.

² G. Dietrich, "General Oceanography," Interscience Publishers, a division of John Wiley & Sons, Inc., New York, 1963.

³ M. N. Hill, ed., "The Sea: Ideas and Observations on Progress in the Study of the Seas": vol. 1, "Physical Oceanography"; vol. 2, "Composition of Sea Water"; vol. 3, "The Earth beneath the Sea: History"; vol. 4 (to be published in 1971); Interscience Publishers, a division of John Wiley & Sons, Inc., New York and London, 1962, 1963.

where it slowly moves to warmer latitudes, mixing and rising as it goes. Water currents result from a combination of wind- and gravity-driven tidal oscillation and different-sized mixing eddies as modified by the earth's rotation.¹

About half the ocean surface is warmer than 20°C—the upper limit of temperature being about 32°C in tropical regions, and the lower limit for liquid sea water the melting point -2°C. The temperature of sea ice ranges from 0°C down to something like -50°C.

Warm water is confined to the upper layers. For example, water deeper than 1 km is less than 10°C, and water deeper than 2 km is less than 4°C. (This excludes an interesting phenomenon recently found in the Red Sea where a few small bottom depressions are filled with very saline dense water reaching 56°C and 1.10 g/cc.) Typical temperature and salinity distributions appear in references, particularly those summing up major surveys.² Nontropical enclosed seas with shallow entrances to the open sea, such as the Mediterranean, have annual thermal patterns and circulatory systems intermediate between oceans and lakes. In drawing analogies to more familiar phenomena and professions, it seems reasonable to say:

1. Transoceanic depth profiles are remarkably similar to transcontinental elevation profiles.

2. The low compressibility, low thermal expansion, and high heat capacity of sea water result in a relatively more homogeneous and sluggish environment in the ocean than in the atmosphere.

3. Water masses in the ocean can be likened to air masses in the air and produce underwater weather that is remarkably similar to atmospheric weather, except that velocities are only 0.1 to 0.01 times as fast, with correspondingly longer time constants. However, except near the poles, the north-south-oriented continents block water currents from going around the world. This blocking effect plus Coriolis effects produces several major current systems such as the Gulf Stream.³

2j-2. Depth. Most of the surface of the earth's crust occurs at two prevailing levels, as shown by Table 2j-1. The higher of these levels is the continental platform, embracing the lower land and the submerged continental shelf out to depths of about 200 m. The lower oceanic platform lies about 5 km below the continental platform. The mean level of the crust's surface is 2.43 km below sea level, and the mean depth of the sea is 4.75 km.

The ocean floor appears to be more rugged than the dry land in both large-scale features^{4,5} and small-scale features. The increased ruggedness results from less underwater weathering plus the buoyant effect on sediments and rock. Sedimentation is important at sea, and large flat areas may have slopes less than one in a thousand. Islands, seamounts, and submarine ridges rise from the oceanic platform, and about a dozen trenches extend below. The continental slopes between are frequently steep and cut by submarine canyons extending out from shore.

A more recent paper⁶ has a recent and diversified breakdown of depths of the ocean in terms of both ocean areas and geologic provinces. Table 2j-2 gives one such breakdown.

¹ H. Stommel, "The Gulf Stream: a Physical and Dynamical Description," University of California Press, Berkeley, 1965.

² F. C. Fuglister, "Atlantic Ocean Atlas: Temperature and Salinity Profiles and Data," from the International Geophysical Year of 1957-1958, Woods Hole Oceanographic Institution, Woods Hole, Mass., 1960.

³ Stommel, *op. cit.*

⁴ Hill, *op. cit.*

⁵ P. H. Kuenen, "Marine Geology." John Wiley & Sons, Inc., New York, 1950; J. T. Wilson, "The Development and Structure of the Crust," pp. 138-214 in "The Earth as a Planet," J. P. Kuiper, ed., University of Chicago Press, Chicago, 1954.

⁶ H. W. Menard and S. M. Smith, "Hypsometry of Ocean Basin Provinces," *J. Geophys. Research* 71, 18, 4305 Sept. 15, 1966).

TABLE 2j-1. AREAS OF EARTH'S CRUST CLASSED ACCORDING TO HEIGHT OR DEPTH FROM SEA LEVEL. AFTER MEINARDUS*

<i>Proportion in interval</i>		<i>Proportion above</i>	
	[Highest land †	8.85 km (314 mb †)]	
Land above 5 km.....	0.1%	5 km (540 mb).....	0.1%
Land 4-5 km.....	0.4%	4 km (616 mb).....	0.5%
Land 3-4 km.....	1.1%	3 km (701 mb).....	1.6%
Land 2-3 km.....	2.2%	2 km (795 mb).....	3.8%
Land 1-2 km.....	4.5%	1 km (899 mb).....	8.3%
Land 0-1 km.....	20.8%	0 km (1,013 mb).....	29.1%
Ocean 0-1 km.....	8.5%	1 km (1,010 decibars ‡).....	37.6%
Ocean 1-2 km.....	2.9%	2 km (2,024 decibars).....	40.5%
Ocean 2-3 km.....	4.7%	3 km (3,045 decibars).....	45.2%
Ocean 3-4 km.....	14.1%	4 km (4,069 decibars).....	59.3%
Ocean 4-5 km.....	23.9%	5 km (5,098 decibars).....	83.2%
Ocean 5-6 km.....	16.0%	6 km (6,132 decibars).....	99.2%
Ocean 6-7 km.....	0.7%	7 km (7,169 decibars).....	99.9%
Ocean below 7 km.....	0.1%		
	[Greatest depth §	10.86 km (11,216 decibars)]	

* Wilhelm Meinardus, Die bathygraphische Kurve des Tiefseebodens und die hypsographische Kurve der Erdkruste (Tabelle 6), *Ann. Hydrogr. mar. Meteor.* 70, 225-244 (1942).

† Mt. Everest.

‡ Pressure according to NACA standard atmosphere. See, e.g., Smithsonian Meteorological Tables, 6th ed., *Smithsonian Misc. Collections* 114 (1951).

§ Sea pressure in water at 0°C, salinity 35 per mille, gravity at sea level being 9.8 m/sec². From Vilhelm Bjerknes, *Hydrographic Tables, Carnegie Inst. Wash. Publ.* 88, 1A-36A (1910).

¶ Marianas Trench, adjacent to Mariana Islands, Pacific Ocean. Soundings from H.M. Survey Ship *Challenger* in 1951. T. F. Gaskell, J. C. Swallow, and G. S. Ritchie, *Further Notes on the Greatest Oceanic Sounding and the Topography of the Marianas Trench, Deep Sea Research* 1 60-63 (1953).

TABLE 2j-2. DEPTH DISTRIBUTION OF WORLD OCEAN

Depth, km	Area, %	Cumulative area, %
0-0.2	7.49	7.49
0.2-1	4.42	11.91
1-2	4.38	16.29
2-3	8.50	24.79
3-4	20.94	45.73
4-5	31.69	77.42
5-6	21.20	98.62
6-7	1.23	99.85
7-8	0.10	99.96
8-9	0.03	99.99
9-10	0.01	100.00
10-11	0.00	100.00

2j-3. Properties of Sea Water. Because ocean currents are generated and maintained by very small differences in density of different water masses, much effort has been devoted to learning the relationships between temperature, pressure, salinity, and electrical conductivity in sea water. For many years salinity was generally determined by chemically titrating small samples of water. In the open ocean where horizontal and vertical gradients are low, water temperatures were hopefully measured to 0.02°C and salinities to 0.02 part per thousand, and densities were computed to about 2×10^{-5} . Since about 1960, electrical conductivity has gradually been replacing chemical titration, being much faster and more accurate in the field. This has resulted in oceanographers emphasizing conductivity measurements, although they still express total salt content in terms of salinity through the use of tables.

Recent studies and reports¹⁻³ on the physical properties of sea water have helped quantify and clarify many of the relations involved.

Pressure. Pressures in a standard atmosphere and ocean are included in parentheses in Table 2j-1. For the ocean, the quantity tabulated is sea pressure; the total pressure is sea pressure plus atmospheric pressure (10 decibars). The units are defined by

$$10^6 \text{ dynes/cm}^2 = \text{bar} = 10 \text{ decibars} = 10^3 \text{ mb}$$

Composition. Sea water, not including the suspended particles (inorganic matter, living organisms, and organic detritus), is a solution of a large number of constituents, which may be divided into four groups: water, major solids, minor solids (and liquids), and gases. The major solids are those which have appreciable influence on density. The minor solids compose only some 0.025 per cent of the total solids in typical sea water.

The major solids are composed of salts that are almost completely ionized, the proportions by mass being as follows:⁴

Na ⁺	30.61%	Cl ⁻	55.04%	H ₂ BO ₃	0.07%
Mg ⁺⁺	3.69	SO ₄ ⁻	7.08		
Ca ⁺⁺	1.16	HCO ₃ ⁻	0.41		
K ⁺	1.10	Br ⁻	0.19		
Sr ⁺⁺	0.04				

These proportions have been found to be highly constant throughout the ocean except where the water is nearly fresh (the salt in river water is very different from sea salt). Hence to a remarkable degree the measurement of the concentration of any of the major solids in sea water permits the calculation of the concentration of total solids. The abundance of the elements in sea water is presented in detail in Table 2j-3.

The constituent commonly measured (by chemical titration) is the sum of the halide ions (Cl⁻, Br⁻, I⁻). The quantity *chlorinity* is approximately the ratio, by mass, of halides to total sample of sea water, but for the precise technical definition

¹ Physical and Chemical Properties of Sea Water, report of 1958 Easton, Md., Conference, *Natl. Acad. Sci.-Natl. Research Council Publ.* 600.

² N. P. Fofonoff, Physical Properties of Sea Water, in M. N. Hill, *op. cit.*, vol. 1, 1962. (Summary of physical relationships.)

³ Handbook of Oceanographic Tables, U.S. Naval Oceanographic Office Spec. Publ. 68, 1966.

⁴ H. U. Sverdrup, M. W. Johnson, and R. H. Fleming, "The Oceans, Their Physics, Chemistry, and General Biology," Table 33, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1942.

TABLE 2j-3. ABUNDANCE OF THE ELEMENTS IN SEA WATER*

Element	$\mu\text{g/liter}$	Principal dissolved species	Element	$\mu\text{g/liter}$	Principal dissolved species
H	1.1×10^3	H ₂ O	Ru		
He	7×10^{-3}	He gas	Rh		
Li	1.7×10^2	Li ⁺	Pd		
Be	6×10^{-4}		Ag	0.3	Ag ⁺
B	4.5×10^3	B(OH) ₃ , B(OH) ₄ ⁻	Cd	0.1	Cd ⁺⁺
C	2.8×10^4	HCO ₃ ⁻ , CO ₃ ²⁻	In	<20	
C(org)	1×10^2		Sn	0.8	
N	1.5×10^4	N ₂ gas	Sb	0.3	
N	6.7×10^2	NO ₃	Te		
O	8.8×10^3	H ₂ O	I	60	IO ₃ ⁻ , I ⁻
O	6×10^3	O ₂	Xe	5×10^{-2}	Xe gas
O	1.8×10^6	SO ₄ ²⁻	Cs	0.3	Cs ⁺
F	1.3×10^3	F ⁻	Ba	20	Ba ⁺⁺
Ne	0.12	Ne gas	La	3×10^{-3}	La(OH) ₃ ⁰
Na	1.1×10^7	Na ⁺	Ce	1×10^{-3}	Ce(OH) ₃ ⁰
Mg	1.3×10^6	Mg ⁺⁺	Pr	0.6×10^{-3}	Pr(OH) ₃ ⁰
Al	1		Nd	3×10^{-3}	Nd(OH) ₃ ⁰
Si	3×10^3	Si(OH) ₄ , SiO(OH) ₃ ⁻	Sm	0.5×10^{-3}	Sm(OH) ₃ ⁰
P	90	HPO ₄ ²⁻ , H ₂ PO ₄ ⁻ , PO ₄ ³⁻	Eu	0.1×10^{-3}	Eu(OH) ₃ ⁰
S	9.0×10^3	SO ₄ ²⁻	Gd	0.7×10^{-3}	Gd(OH) ₃ ⁰
Cl	1.9×10^7	Cl ⁻	Tb	1.4×10^{-3}	Tb(OH) ₃ ⁰
Ar	4.5×10^2	Ar gas	Dy	0.9×10^{-3}	Dy(OH) ₃ ⁰
K	3.9×10^5	K ⁺	Ho	0.2×10^{-3}	Ho(OH) ₃ ⁰
Ca	4.1×10^5	Ca ⁺⁺	Er	0.9×10^{-3}	Er(OH) ₃ ⁰
Sc	$<4 \times 10^{-3}$	Sc(OH) ₃	Tm	0.2×10^{-3}	Tm(OH) ₃ ⁰
Ti	1	Ti(OH) ₄	Yb	0.8×10^{-3}	Yb(OH) ₃ ⁰
V	2	VO ₂ (OH) ₂ ⁻	Lu	0.1×10^{-3}	Lu(OH) ₃ ⁰
Cr	0.5	CrO ₄ ²⁻ , Cr ³⁺	Hf	$<8 \times 10^{-3}$	
Mn	2	Mn ⁺⁺	Ta	$<3 \times 10^{-3}$	
Fe	3		W	0.1	WO ₄ ²⁻
Co	0.4	Co ⁺⁺	Re		
Ni	7	Ni ⁺⁺	Os		
Cu	3	Cu ⁺⁺	Ir		
Zn	10	Zn ⁺⁺	Pt		
Ga	3×10^{-2}		Au	1×10^{-2}	AuCl ₂ ⁻
Ge	7×10^{-2}	Ge(OH) ₄	Hg	0.2	HgCl ₄ ²⁻ , HgCl ₂ ⁰
As	2.6	HAsO ₄ ²⁻ , H ₂ AsO ₄ ⁻	Tl	<0.1	Tl ⁺
Se	9×10^{-2}	SeO ₄ ²⁻	Pb	0.03	PbCl ₂ ⁻ , PbCl ⁺ , Pb ⁺⁺
Br	6.7×10^4	Br ⁻	Bi	0.02	
Kr	0.2	Kr gas	Po		
Rb	1.2×10^2	Rb ⁺	At		
Sr	8×10^3	Sr ⁺⁺	Rn	6×10^{-13}	
Y	1×10^{-3}	Y(OH) ₃ ⁰	Ra	1×10^{-7}	Ra ⁺⁺
Zr	3×10^{-3}		Ac		
Nb	0.01		Th	$<5 \times 10^{-4}$	Th(OH) ₄
Mo	10	MoO ₄ ²⁻	Pa	Check	
			U	3	UO ₂ (CO ₃) ₂ ⁴⁻

* A. H. Seymour, ed., "Radioactivity in the Marine Environment," National Academy of Sciences-National Research Council, Washington, D.C. (to be published in 1971).

the reader is referred elsewhere.¹ Similarly, *salinity* is approximately the ratio of total solids to total sample of sea water, but the definition² used in practice is the one given by the empirical formula

$$\text{Salinity} = 0.00003 + 1.805 \times \text{chlorinity} \quad (2j-1)$$

Both chlorinity and salinity are customarily expressed in per mille, meaning 10^{-3} .

The salinity of most water in the open ocean lies between 33 and 37 per mille, and 35 per mille is often chosen as standard.

Because the major solids are uniform in composition, the density and some other physical properties of sea water depend on only three variables: temperature, salinity, and pressure. Some of these properties at a pressure of 1 atm are shown in Fig. 2j-1.

Density and Melting Point. Density at 1 atm is shown in Fig. 2j-1a.³ The effect of pressure on the density of sea water of salinity 35 per mille at temperature 0°C is as follows:

Sea pressure, decibars	0	2,000	4,000	6,000	8,000	10,000
Density, g/ml	1.02813	1.03748	1.04640	1.05495	1.06315	1.07104

Water that is more saline or warmer is less compressible.

The temperature of maximum density, shown for 1 atm on the graph, decreases as pressure increases. For pure water at 1 atm the decrease is 2.22°C per thousand decibars.⁴

The melting point decreases with increasing salinity or pressure. The melting-point depression at 1 atm equals 56.90°C times the salinity according to Miyake⁵ and is shown as the dotted line on the graphs. The decrease with pressure for pure water at 1 atm is 0.742°C per thousand decibars.⁶

Many tables and other aids have been prepared for the routine calculation of density and specific volume of sea water. A selection follows.

References on Calculation of Density and Specific Volume of Sea Water

Density at a Pressure of 1 Atm

- Knudsen, Martin: "Hydrographical Tables," Copenhagen, 63 pp., 1901. (Range -2 to 33°C , salinity 2 to 41 per mille.) Part of Knudsen's can be replaced with the following more detailed tables: Matthews, D. J.: "Tables for the Determination of the Density of Seawater under Normal Pressure, σ_t ," Andr. Fred. Høst & Fils, Copenhagen, 56 pp., 1932.
- Kalle, Kurt, und Hermann Thorade: Tabellen und Tafeln für die Dichte des Seewassers (σ_t), *Arch. deut. Seewarte Marineobs.* **60** (2), 49 pp. (1940). (Range -2 to 30°C , salinity 0 to 41.5 per mille.)
- Ennis, C. C.: Note on Computation of Density of Sea Water and on Corrections for Deep-sea Reversing Thermometers, *Carnegie Inst. Wash. Publ.* **545A**, 23-45 (1944). (Range -2 to 30°C , salinity 34 to 36 per mille.)

¹ E.g., Sverdrup et al., *op. cit.*, p. 52.

² Bjørn Helland-Hansen, J. P. Jacobsen, and T. G. Thompson, Chemical Methods and Units, *Publ. sci. Ass. Océanogr. phys.* **9**, 28 (1948).

³ Martin Knudsen, "Hydrographical Tables," Copenhagen, 1901; N. E. Dorsey, "Properties of Ordinary Water Substance," Reinhold Book Corporation, New York, 1940. For more recent work see M. S. Newton and G. C. Kennedy, An Experimental Study of the P-V-T-S Relations of Sea Water, *J. Marine Research* **23**, 89-103 (1965).

⁴ Dorsey, *op. cit.*, p. 275.

⁵ Yasuo Miyake, Chemical Studies of the Western Pacific Ocean, III, Freezing Point, Osmotic Pressure, Boiling Point and Vapour Pressure of Sea Water, *Bull. Chem. Soc. Japan* **14**, 58-62 (1939).

⁶ Dorsey, *op. cit.*, Table 267.

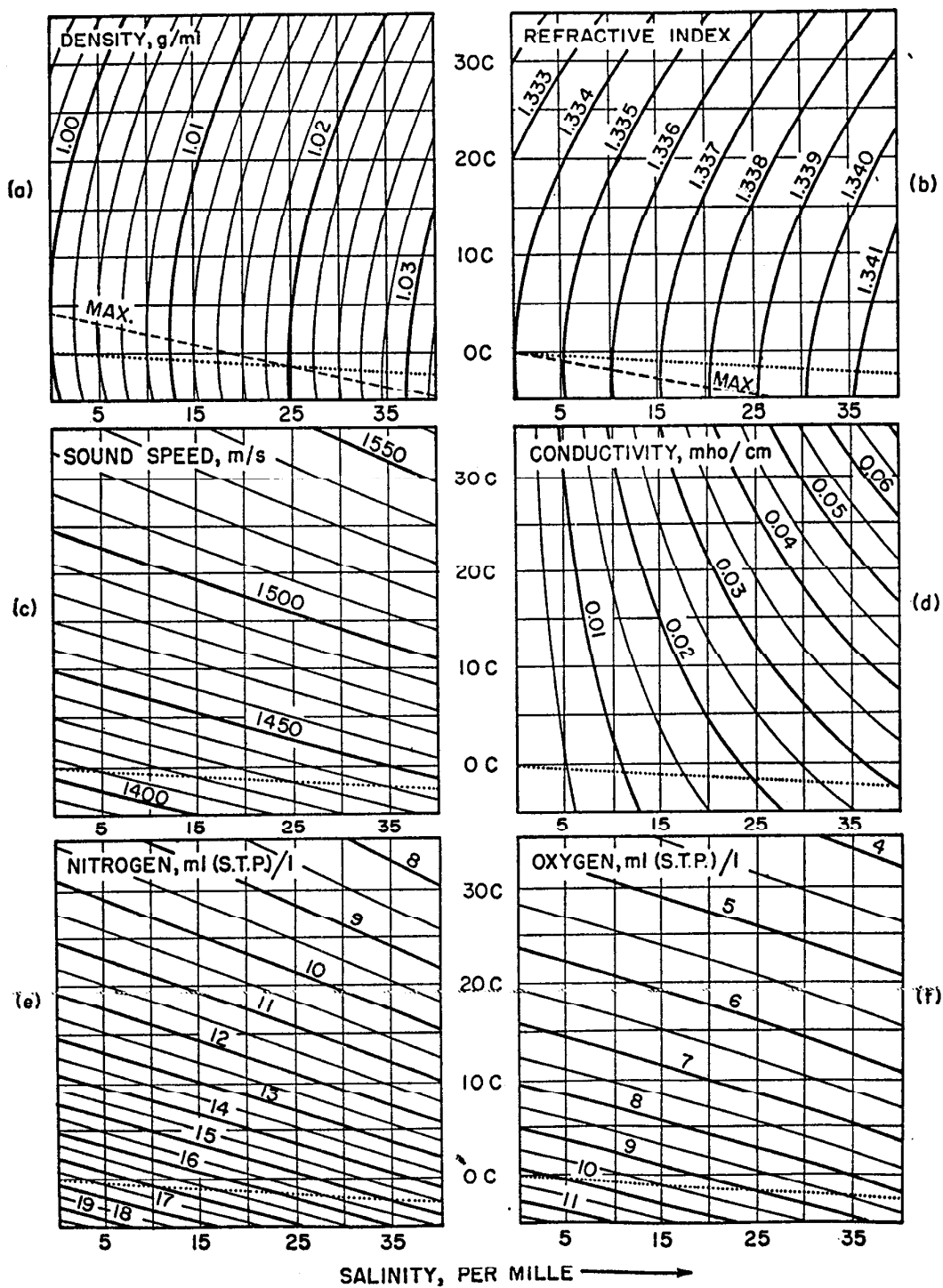


FIG. 2j-1. Temperature-salinity diagrams for sea water at 1 atm pressure: (a) density, (b) refractive index for sodium light (0.5893 micron) relative to air, (c) sound speed, (d) conductivity, (e) concentration of nitrogen in equilibrium with 1 atm (1,013.25 mb) of air saturated with aqueous vapor, (f) concentration of oxygen under same equilibrium conditions. Freezing point is shown by dotted line; values below it pertain to undercooled water.

- LaFond E. C.: Processing Oceanographic Data (Table X), U.S. Navy Hydrographic Office, H. O. Pub. 614, 1951. (Range -2 to 30°C , salinity 30 to 48 per mille.)
- U.S. Navy Hydrographic Office: "Tables for Sea Water Density," H. O. Pub. 615, 265 pp., 1952 (range -2 to 30°C , salinity 0 to 40 per mille). Recomputed from same empirical formulas as preceding tables but expressed to one more decimal place (10^{-6} g/ml) and tabulated for each 0.01°C of temperature argument.
- Bein, Willy: Physikalische und chemische Konstanten des Meerwassers (pp. 102-103), *Veröffentl. Inst. Meeresk. Univ. Berlin*, neue Folge, A, **28**, 36-190 (1935). The arguments are temperature (0, 1, . . . , 40°C) and the ratio of density at 17.5°C to density of pure water at 17.5°C (1.000, 1.002, . . . , 1.032). This table is based on Bein's own measurements, the most recent. Argument converted to salinity by G. Dietrich, Landolt-Börnstein Zahlenwerte und Funktionen, *Ozeanographie*, 6 Auflage, **3**, 428 (1952). (Temperature 0, 1, . . . , 32°C , salinity 0, 5, . . . , 40 per mille.)

Specific Volume at a Pressure of 1 Atm

LaFond, above, Table V. (Range -2 to 30°C , salinity 21 to 38 per mille.)

Density at Greater Pressures

Ekman, V. W.: Tables for Sea Water under Pressure, *Publ. Circ. Cons. int. Explor. Mer* **49**, 48 pp., 1910. [The arguments are density at 1 atm and 0°C , pressure (0 to 10,000 decibars), and temperature.]

Specific Volume at Greater Pressures

- Bjerknes, Vilhelm: Hydrographic Tables, *Carnegie Inst. Wash. Publ.* **88**, 1A-36A (1910). (Range -2 to 30°C , salinity 0 to 40 per mille, 0 to 10,000 decibars.)
- Subow, N. N., S. W. Brujewicz, and W. W. Shoulejkin: "Oceanographical Tables," Moscow, 208 pp., 1931.
- Matthews, D. J.: "Tables for Calculating the Specific Volume of Seawater under Pressure," Andr. Fred. Høst & Fils, Copenhagen, 67 pp., 1938. [The arguments are density at 1 atm, pressure (0 to 12,000 decibars), and temperature.]
- Sverdrup, H. U., M. W. Johnson, and R. H. Fleming: "The Oceans," Appendix, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1942. [The arguments are density at 1 atm, pressure (0 to 10,000 decibars), temperature, and salinity.]
- LaFond, above, Tables IV-VII. (Range -2 to 30°C , salinity 21 to 38 per mille, 0 to 10,000 decibars.)
- Crease, J.: The Specific Volume of Sea Water under Pressure as Determined by Recent Measurements of Sound Velocity, *Deep Sea Research* **9**, 209-213 (1962).

Viscosity. Viscosity of sea water varies only a few per cent over the range of temperatures, salinities, and pressures encountered in the ocean, increasing with salinity and with temperature. With pressure it decreases at shallow depths; but at pressures comparable to ocean depths and depending upon temperature and salinity, it begins to increase.¹

Sound Speed. The graph of sound speed in Fig. 2j-1c is based on the work of Del Grosso.² More work is summarized in Eq. (2j-2) due to W. D. Wilson.³

$$V = 1449.22 + \Delta V_T + \Delta V_P + \Delta V_S + \Delta V_{STP} \quad (2j-2)$$

$$\text{where } \Delta V_T = 4.6233T - 5.4585 \times 10^{-2}T^2 + 2.822 \times 10^{-4}T^3 - 5.07 \times 10^{-7}T^4$$

$$\Delta V_P = 1.60518 \times 10^{-1}P + 1.0279 \times 10^{-5}P^2 + 3.451 \times 10^{-9}P^3$$

$$- 3.503 \times 10^{-12}P^4$$

$$\Delta V_S = 1.391(S - 35) - 7.8 \times 10^{-2}(S - 35)^2$$

$$\Delta V_{STP} = (S - 35)(-1.197 \times 10^{-2}T + 2.61 \times 10^{-4}P - 1.96 \times 10^{-7}P^2$$

$$- 2.09 \times 10^{-6}PT) + P(-2.796 \times 10^{-4}T + 1.3302 \times 10^{-5}T^2$$

$$- 6.644 \times 10^{-8}T^3) + P^2(-2.391 \times 10^{-7}T + 9.286 \times 10^{-10}T^2)$$

$$- 1.745 \times 10^{-10}P^3T$$

¹ R. A. Horne and D. S. Johnson, The Viscosity of Compressed Sea Water, *J. Geophys. Research* **71**, 22, (November, 1966).

² V. A. Del Grosso, The Velocity of Sound in Sea Water at Zero Depth, *Naval Research Lab. Rept.* 4002, 39 pp., 1952.

³ W. D. Wilson, Speed of Sound in Sea Water as a Function of Temperature, Pressure, and Salinity, *J. Acoust. Soc. Am.*, **32**, 6 (June, 1960).

TABLE 2j-4. CORRECTION TO BE ADDED TO $V_0 = 1449.22$ M/SEC TO ACCOUNT FOR CHANGES IN TEMPERATURE
(T in °C, ΔV_T in m/sec)

T	ΔV_T	T	ΔV_T
-3	-14.37	13	51.48
-2	-9.47	14	54.78
-1	-4.68	15	58.00
0	0.00	16	61.12
0	0.00	17	64.17
1	4.57	18	67.13
2	9.03	19	70.01
3	13.39	20	72.81
4	17.64	21	75.53
5	21.79	22	78.18
6	25.84	23	80.75
7	29.78	24	83.25
8	33.64	25	85.68
9	37.39	26	88.04
10	41.05	27	90.32
11	44.62	28	92.54
12	48.10	29	94.69
		30	96.78

TABLE 2j-5. CORRECTION TO $V_0 = 1449.22$ M/SEC TO ACCOUNT FOR CHANGES IN PRESSURE
(P in kg/cm², ΔV_P in m/sec)

P	ΔV_P	P	ΔV_P
0*	500	83.04
100	16.16	600	100.30
200	32.54	700	117.74
300	49.15	800	135.33
400	65.98	900	153.01

* At atmospheric pressure, $P = 1.0332$ kg/cm², $\Delta V_P = 0.16$ m/sec.

For greater pressures, Matthews¹ and Kuwahara² have computed the sound speed c from $c^2 = (d\rho/dp)_s$, which is the adiabatic change of pressure with density and can be expressed in terms of known properties (isothermal compressibility, thermal expansion, specific heat, temperature, and specific volume).

¹ D. J. Matthews, "Tables of the Velocity of Sound in Pure Water and Sea Water for Use in Echo-sounding and Sound-ranging," 2d ed., H. D. 282, Hydrographic Department, Admiralty, London, 52 pp., 1939. (Range -2 to 30°C, salinity 0 to 41 per mille, depth 0 to 10,900 m.)

² Susumu Kuwahara, The Velocity of Sound in Sea Water and Calculation of the Velocity for Use in Sonic Sounding, *Japan. J. Astron. Geophys.* 16, 1-17 (1938). (Tables for range -2 to 30°C, salinity 30 to 40 per mille, pressure 0 to 10,000 decibars.) Kuwahara's tables are reproduced and extended in salinity down to 21 per mille by E. C. LaFond, "Processing Oceanographic Data," Table XIV, U.S. Navy Hydrographic Office, H.O. Pub. 614, 1951.

TABLE 2j-6. CORRECTION TO $V_0 = 1449.22$ M/SEC TO ACCOUNT FOR CHANGES IN SALINITY
(S in parts per thousand, ΔV_S in m/sec)

S	ΔV_S
33	-3.09
34	-1.47
35	0.00
36	1.31
37	2.47

Additional ΔV_{TPS} tables correct for simultaneous changes in T , P , and S .

The transmission of sound in the sea can be very complex, and a large literature exists¹ on this subject.

Refractive Index. For given wavelength, temperature, and pressure the relation between refractive index and salinity is very nearly linear. The graph of refractive index for sodium light in Fig. 2j-1b is based on the formulas of Utterback et al.² The formulas have been adjusted slightly to agree at zero chlorinity with the measurements of Tilton and Taylor.³ Measurements by Bein⁴ give values higher than those of Utterback et al. by as much as 0.00012. The effect of pressure is roughly such that, if n is refractive index and ρ is density, $(n - 1)/\rho$ is constant for given temperature, salinity, and wavelength.⁵

Dissolved Nitrogen and Oxygen. The two principal atmospheric gases are differently distributed in the ocean. Because nitrogen is highly inert, its concentration is determined entirely by contact with the atmosphere. Oxygen is both released and consumed by biological processes, so that its concentration is much more variable. Right at the sea surface, there is equilibrium between the two phases; the nitrogen and oxygen in the liquid phase depend on their partial pressures in the gaseous phase, while the partial pressure of aqueous vapor depends on the salinity of the liquid phase (see below).

Figures 2j-1e and f show the concentrations of nitrogen and oxygen in equilibrium with saturated air at a pressure of 1 atm. For a given temperature, solubility decreases linearly with increasing salinity. The nitrogen graph has been calculated from Fox's⁶ table for pure water and from Rakestraw and Emmel's⁷ data for sea

¹ C. F. Officer, "Introduction to the Theory of Sound Transmission," McGraw-Hill Book Company, New York, 1958; R. J. Urick, "Principles of Underwater Sound for Engineers," McGraw-Hill Book Company, New York, 1967; L. M. Brekhovskikh, "Waves in Layered Media," Academic Press, Inc., New York, 1960.

² C. L. Utterback, T. G. Thompson, and B. D. Thomas, Refractivity-Chlorinity-Temperature Relationships of Ocean Waters, *J. Cons. int. Explor. Mer* **9**, 35-38 (1934). (Table for 0, 5, . . . , 25°C, chlorinity 1, 2, . . . , 22 per mille.)

³ L. W. Tilton and J. K. Taylor, Refractive Index and Dispersion of Distilled Water for Visible Radiation, at Temperatures 0 to 60°C, *Natl. Bur. Standards J. Research* **20**, 419-477 (1938).

⁴ Willy Bein, Physikalische und chemische Konstanten des Meerwassers, *Veröffentl. Inst. Meeresk. Univ. Berlin*, neue Folge, A, **28**, 162 (1935).

⁵ Dorsey, *op. cit.*, Table 144.

⁶ C. J. J. Fox, On the Coefficients of Absorption of Nitrogen and Oxygen in Distilled Water and Sea-water, and of Atmospheric Carbonic Acid in Sea-water, *Trans. Faraday Soc.* **5**, 68-87 (1909). (Table 1 gives nitrogen dissolved in pure water from 1 atm of pure nitrogen for 0, 1, . . . , 50°C.)

⁷ N. W. Rakestraw and V. M. Emmel, The Solubility of Nitrogen and Argon in Sea Water, *J. Phys. Chem.* **42**, 1211-1215 (1938). (Table 2 gives nitrogen dissolved in sea water from 1 atm of saturated air for 0, 1, . . . , 28°C, chlorinity 15, 16, . . . , 21 per mille.) A personal communication from Dr. Rakestraw states that all values pertain to air saturated with aqueous vapor. Data in Table 1 used in present work.

water. The oxygen graph is based on Fox's¹ table. For temperatures below 0°C and for part of the high-temperature areas, the graphs depend on extrapolation.

The equilibrium concentration of dissolved nitrogen or oxygen is proportional to its partial pressure in the gaseous phase (Henry's law) up to several atmospheres. As the partial pressure increases to 1,000 atm, however, the concentration attains only about half the value given by simple proportionality.² Sea water has not been studied at pressures greater than 1 atm.

Carbon dioxide in the ocean is in dynamic balance with that in the atmosphere and represents the overwhelming majority in the air-water system. The CO₂ residence time is longer than for most gases.³

Vapor Pressure. The vapor-pressure lowering of an aqueous solution is related to the melting-point depression. At the melting point of the solution the vapor pressure is the same as the vapor pressure of ice.

Let e be the vapor pressure of sea water of given salinity and temperature, and let e_0 be the vapor pressure of pure water at the same temperature. Then

$$\frac{e_0 - e}{e_0} = 0.537 \times \text{salinity} \quad (2j-3)$$

so the vapor pressure for salinity 35 per mille is 98.12 per cent of that for pure water. This formula by Witting⁴ is satisfactory for the range of conditions occurring at the natural ocean surface, but for greater salinity or higher temperature the results of recent measurements should be consulted.⁵

Latent Heats and Specific Heat. The latent heats of fusion and vaporization are practically the same for sea water as for pure water.

The specific heat at constant pressure depends on salinity as follows at 17.5°C and 1 atm:⁶

Salinity, per mille . . .	0	5	10	15	20	25	30	35	40
c_p , cal g ⁻¹ °C ⁻¹	1.000	0.982	0.968	0.958	0.951	0.945	0.939	0.932	0.926

The changes with temperature and pressure have not been measured. The effect of pressure can be computed by use of the thermodynamic formula

$$\left(\frac{dc_p}{dp}\right)_T = -T \left(\frac{d^2v}{dT^2}\right)_p \quad (2j-4)$$

¹C. J. J. Fox, On the Coefficients of Absorption of the Atmospheric Gases in Distilled Water and Sea Water, pt. I, Nitrogen and Oxygen, *Publ. Circ. Cons. int. Explor. Mer* 41, 23 pp. (1907). (Table 11 gives oxygen dissolved in sea water from 1 atm of dry air at -2, -1, . . . , 30°C, chlorinity 0, 1, . . . , 20 per mille.) Table reproduced by K. Kalle, "Landolt-Börnstein Zahlenwerte und Funktionen," 6th ed., vol. 3, p. 478, 1952.

²Dorsey, *op. cit.*, Table 233.

³G. Skirrow, The Dissolved Gases—Carbon Dioxide, chap. 7 in "The Sea: Ideas and Observations on Progress in the Study of the Seas," vol. 2, "Composition of Sea Water," M. N. Hill, ed., Interscience Publishers, a division of John Wiley & Sons, Inc., New York and London, 1962.

⁴Rolf Witting, Untersuchungen zur Kenntnis der Wasserbewegungen und der Wassermischung in den Finland umgebenden Meeren, I, *Finnländische Hydrographisch-biologische Untersuchungen* 2, 173 (1908).

⁵A. B. Arons and C. F. Kientzler, Vapor Pressure of Sea-salt Solutions, *Trans. Am. Geophys. Union* 35, 722-728 (1954).

⁶Otto Krümmel, "Handbuch der Ozeanographie," vol. 1, p. 279, Stuttgart, 1907.

where v is specific volume and T is absolute temperature. The following values of the decrease in specific heat at 0°C and salinity 35 per mille are from Ekman's¹ table:

Sea pressure, decibars.....	0	2,000	4,000	6,000	8,000	10,000
$(c_p)_{0 \text{ decibars}} - c_p$, cal g ⁻¹ °C ⁻¹	0	0.0159	0.0291	0.0401	0.0492	0.0566

Adiabatic Temperature Change. This quantity is computed from the thermodynamic formula

$$\left(\frac{dT}{dp}\right)_s = \frac{T}{c_p} \left(\frac{dv}{dT}\right)_p \quad (2j-5)$$

The following values for 0°C and salinity 35 per mille are converted from Ekman's paper:

Sea pressure, decibars.....	0	2,000	4,000	6,000	8,000	10,000
$(dT/dp)_s$, °C/1,000 decibars.....	0.035	0.072	0.104	0.133	0.159	0.181

Transport Phenomena. The values for a pressure of 1 atm are assembled in Table 2j-7. Measurements with sea water are restricted to viscosity; the other properties tabulated under sea water are from measurements with sodium chloride solutions. The diffusivities of nitrogen and oxygen are especially uncertain and may be incorrect by as much as 15 per cent.

Dynamic and kinematic viscosities and thermal conductivity change linearly with salinity. In contrast, both thermal diffusivity (associated with specific heat) and diffusivity of sodium chloride go through minima at salinities less than 35 per mille.

For pure water, pressure increasing to 10,000 decibars has a nonlinear effect on the dynamic viscosity, which decreases at 0°C by 8 per cent and increases at 30°C by 5 per cent.² The thermal conductivity at 30°C increases linearly with pressure and becomes 6 per cent greater at 10,000 decibars.³

2j-4. Gravity Waves. Wave Speed. Most of the ocean is stabilized by a downward increase of density, so that *internal waves* as well as *surface waves* are common. Only surface waves are discussed here.

Let L be wavelength, T be period, and c be wave speed. Then $L = Tc$. Let h be the depth of water (undisturbed surface to bottom) and g be gravity.

For a uniform train of long-crested sinusoidal waves of small amplitude in an ideal liquid of uniform depth, in general⁴

$$c^2 = \frac{gL}{2\pi} \tanh 2\pi \frac{h}{L} \quad (2j-6)$$

For $h/L \gg 1$, *deep-water waves*, the general formula reduces to $c^2 = gL/2\pi$, and the group speed equals half the wave speed. For $h/L \ll 1$, *shallow-water waves*, $c^2 = gh$, and group speed equals wave speed (there is no dispersion, and any waveform of small amplitude is propagated unchanged at this speed). Within 5 per cent, sufficient accuracy for many problems, the deep-water formula holds if $h/L \sim h/L_0 > \frac{1}{3}$ and the shallow-water formula holds if $h/L < \frac{1}{11}$ or $h/L_0 < \frac{1}{2.2}$; L_0 is defined below.

Change in depth along wave rays changes the speed and length of sufficiently long waves. Near shore, therefore, waves often experience refraction and accompanying

¹ V. W. Ekman, Der adiabatische Temperaturgradient im Meere, *Ann. Hydrogr. mar. Meteor.* **42**, 340-344 (1914).

² Dorsey, *op. cit.*, Table 86.

³ *Ibid.*, Table 131.

⁴ See, e.g., C. A. Coulson, "Waves," 6th ed., Oliver & Boyd, Ltd., Edinburgh, 1952.

TABLE 2j-7. TRANSPORT PHENOMENA IN WATER AT A PRESSURE OF 1 ATM

Name, symbol, units	Pure water		Sea water, salinity 35 per mille	
	0°C	20°C	0°C	20°C
Dynamic viscosity, η , g cm ⁻¹ sec ⁻¹ = poise...	0.01787 ^a	0.01009 ^b	0.01877 ^a	0.01075 ^a
Thermal conductivity, k , watt cm ⁻¹ °C ⁻¹ ...	0.00566 ^c	0.00599 ^c	0.00563 ^c	0.00596 ^c
Kinematic viscosity, $\nu = \eta/\rho$, cm ² sec ⁻¹ ...	0.01787	0.01004	0.01826	0.01049
Thermal diffusivity, ^d $\kappa = k/c_p\rho$, cm ² sec ⁻¹ ...	0.00134	0.00143	0.00139	0.00149
Diffusivity, D , cm ² sec ⁻¹ :				
NaCl.....	0.0000074 ^e	0.0000141 ^f	0.0000068 ^e	0.0000129 ^f
N ₂	0.0000106 ^g	0.0000169 ^g		
O ₂		0.000021 ^h		
Prandtl number, $N_P = \nu/\kappa$	13.3	7.0	13.1	7.0

^a Yasuo Miyake and Masami Koizumi, The Measurement of the Viscosity Coefficient of Sea Water, *J. Marine Research* 7, 63-66 (1948). Values taken from their Table I and reduced by 0.00007 poise to agree with Swindells et al. (Table III presents smoothed values for 0, 1, . . . , 30°C, chlorinity 0, 1, . . . , 20 per mille.)

^b J. F. Swindells, J. R. Coe, Jr., and T. B. Godfrey, Absolute Viscosity of Water at 20°C, *Natl. Bur. Standards J. Research*, 48, 1-31 (1952).

^c L. Riedel, Die Wärmeleitfähigkeit von wässrigen Lösungen starker Elektrolyte, *Chem.-Ing.-Technik* 23, 59-64 (1951).

^d Thermal diffusivity is also called thermometric conductivity.

^e Values for 0°C calculated from those at 20°C by use of temperature coefficient of L. W. Öholm, Über die Hydrodiffusion der Elektrolyte, *Z. physik. Chem.* 50, 309-349 (1904).

^f A. R. Gordon, The Diffusion Constant of an Electrolyte, and Its Relation to Concentration, *J. Chem. Phys.* 5, 522-526 (1937). Gordon used measurements by B. W. Clack, On the Study of Diffusion in Liquids by an Optical Method, *Proc. Phys. Soc. (London)* 36, 313-335 (1924). R. H. Stokes, The Diffusion Coefficients of Eight Uni-univalent Electrolytes in Aqueous Solution at 25°, *J. Am. Chem. Soc.* 72, 2243-2247 (1950).

^g Gustav Tammann und Vitus Jeasen, Über die Diffusionskoeffizienten von Gasen in Wasser und ihre Temperaturabhängigkeit, *Z. anorg. Chem.* 179, 125-144 (1929).

^h Tor Carlson, The Diffusion of Oxygen in Water, *J. Am. Chem. Soc.* 33, 1027-1032 (1911); I. M. Kolthoff and C. S. Miller, The Reduction of Oxygen at the Dropping Mercury Electrode, *J. Am. Chem. Soc.* 63, 1013-1017 (1941); H. A. Laitinen and I. M. Kolthoff, Voltammetry with Stationary Microelectrodes of Platinum Wire, *J. Phys. Chem.* 45, 1061-1079 (1941).

convergence and divergence. Such phenomena are conveniently treated by relating the speed and length of waves of any given period to the speed and length for the same period in deep water, c_0 and L_0 . As $T = L/c = L_0/c_0$ and $c^2 = gL_0/2\pi$, (2j-6) may be written^{1,2}

$$\frac{c}{c_0} = \frac{L}{L_0} = \tanh 2\pi \frac{h}{L_0} \frac{L_0}{L} \tag{2j-7}$$

Functions of h/L_0 have been presented in an extensive table,³ from which the following values are extracted:

h/L_0	0	0.001	0.01	0.02	0.05	0.1	0.2	0.3	0.4	0.5	1
$c/c_0 = L/L_0$	0	0.0792	0.2480	0.3470	0.5310	0.7093	0.8884	0.9611	0.9877	0.9964	1.0000

These elementary results are not suitable for direct application to the irregular aperiodic waves in areas of generation by wind.

¹ G. Neuman and W. Pierson, "Principles of Physical Oceanography," Prentice-Hall, Inc., Englewood Cliffs, N.J., 1966.

² J. J. Stoker, "Water Waves—Mathematical Theory and Applications," Interscience Publishers, Inc., New York, 1957.

³ U.S. Department of the Army, Corps of Engineers, *Bulletin of the Beach Erosion Board*, Special Issue 2, Appendix D 1953.

TABLE 2j-8. SELECTED TIDAL CONSTITUENTS

Symbol	Name	Argument	Period	Speed, degrees per hour	Relative coefficient of equilibrium tide
Sa	Solar annual	h	1.0 year	0.0411	0.012
Ssa	Solar semiannual	$2h$	0.5 year	0.0821	0.073
Mm	Lunar monthly	$s - p$	27.55 day	0.5444	0.083
Mf	Lunar fortnightly	$2s$	13.66 day	1.0980	0.156
K_1	Lunisolar declinational diurnal	$T + h - 90^\circ$	23.93 hr	15.0411	0.531
O_1	Lunar declinational diurnal	$T + h - 2s + 90^\circ$	25.82 hr	13.9430	0.377
P_1	Solar declinational diurnal	$T - h + 90^\circ$	24.07 hr	14.9589	0.176
Q_1	Lunar diurnal	$T + h - 3s + p + 90^\circ$	26.87 hr	13.3987	0.072
M_2	Principal lunar semi-diurnal	$2T + 2h - 2s$	12.42 hr	28.9841	0.908
S_2	Principal solar semi-diurnal	$2T$	12.00 hr	30.0000	0.423
N_2	Larger lunar elliptic semidiurnal	$2T + 2h - 3s + p$	12.66 hr	28.4397	0.174
K_2	Lunisolar declinational semidiurnal	$2T + 2h$	11.97 hr	30.0821	0.115

*Tidal Constituents*¹ The gravitational fluctuations that produce tides can be resolved into harmonic constituents. Some are listed in Table 2j-8, their periods being determined by the constant rates of change of four angles:

T = hour angle of mean sun (increasing by $15^\circ/\text{hr}$)

h = mean celestial longitude of sun (increasing by $0.0411^\circ/\text{hr}$)

s = mean celestial longitude of moon (increasing by $0.5490^\circ/\text{hr}$)

p = mean celestial longitude of lunar perigee (increasing by $0.0046^\circ/\text{hr}$)

Ocean Engineering. Increased activity at sea has brought a wide variety of engineers into the marine field. Recent books on ocean engineering provide useful information, tables, and references. The following are examples:

Brahtz, John F., ed. "Ocean Engineering, Systems Planning and Design," John Wiley & Sons, Inc., New York, 1968.

Handbook of Oceanographic Tables, U.S. Naval Oceanographic Office Spec. Publ. 68, 1966.

Myers, John J., ed.-in-chief: "Handbook of Ocean and Underwater Engineering," McGraw-Hill Book Company, New York, 1969.

Urick, Robert J.: "Principles of Underwater Sound for Engineers," McGraw-Hill Book Company, New York, 1967.

¹ Paul Schureman, "Manual of Harmonic Analysis and Prediction of Tides," U.S. Coast and Geodetic Survey, Special Publication 98, rev. ed., 1940; A. T. Doodson and H. D. Warburg, "Admiralty Manual of Tides," H.M. Stationery Office, London, 1941.