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Citation: The Journal of the Acoustical Society of America **56**, 1084 (1974); doi: 10.1121/1.1903388
View online: https://doi.org/10.1121/1.1903388
View Table of Contents: https://asa.scitation.org/toc/jas/56/4
Published by the Acoustical Society of America

New equation for the speed of sound in natural waters (with comparisons to other equations)

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(Received 20 May 1974)

A new equation for the speed of sound in sea water has been developed with validity not only for realistic combinations of the parameters salinity, temperature, and pressure, but with extension to pure water as well. This new equation, referred to as NRL II, has a standard deviation of 0.05 m/sec. Tables are presented comparing calculations using this new model to each of eight earlier equations. Graphs are also included indicating approximate corrections that could be applied to existing sound speed profiles, but it is recommended that such profiles be recalculated and new ones obtained according to NRL II.

Subject Classification: 30.25.

An earlier article[1] promised a sea water sound-speed table which was also valid for pure water. E. R. Anderson of NUC obtained such a combined equation by adding pure-water values calculated from the NRL pure-water equation to the set of sea-water data. The pure-water points were calculated for the same nominal temperatures used for the sea-water data and were included with the same weight as the replicate sea-water data, e.g., they were added at 5° intervals from 0° to 30 °C and given a weight of five each.

The new equation, henceforth referred to as NRL II, is:

$$C_{STP} = C_{000} + \Delta C_T + \Delta C_S + \Delta C_P + \Delta C_{STP} ,$$

where

$$C_{000} = 1402.392$$

$$\Delta C_T = 0.501109398873\times 10^{1} T - 0.550946843172\times 10^{-1} T^2 + 0.221535969240\times 10^{-3} T^3 ,$$

$$\Delta C_S = 0.132952290781\times 10^{1} S + 0.128955756844\times 10^{-3} S^2 ,$$

$$\Delta C_P = 0.156059257041\times 10^{0} P + 0.244998688441\times 10^{-4} P^2 - 0.883392332513\times 10^{-8} P^3 ,$$

$$\begin{aligned}\Delta C_{STP} = &- 0.127562783426\times 10^{-1} TS \\ &+ 0.635191613389\times 10^{-2} TP \\ &+ 0.265484716608\times 10^{-7} T^2P^2 \\ &- 0.159349479045\times 10^{-5} TP^2 \\ &+ 0.522116437235\times 10^{-9} TP^3 \\ &- 0.438031096213\times 10^{-6} T^3P \\ &- 0.161674495909\times 10^{-8} S^2P^2 \\ &+ 0.968403156410\times 10^{-4} T^2S \\ &+ 0.485639620015\times 10^{-5} TS^2P \\ &- 0.340597039004\times 10^{-3} TSP ,\end{aligned}$$

and where again T is in degrees Celsius, S is in parts per thousand, and P is in kilograms per square centimeter gauge.

The same reference promised also tables of differences from existing equations and these are presented herein. Tables I and II are for variable temperature and salinity parameter with pressure equaling 0 kg/cm² in Tables I, and 20 kg/cm in Tables II. The tables have been prepared with attention to realistic triads of S, T, and P, so the salinity parameter considered in Tables I is 29, 35, and 41 ppt but only 33, 35, and 37 in Tables II. The temperatures considered range from 0° to 35 °C.

Tables III and IV are for variable salinity and temperature parameter. Here salinity ranges from 29 to 43 ppt with the temperature parameter 0°, 10°, 20°, and 30 °C. In Tables III the pressure is fixed at 0 kg/cm² gauge. A single elevated pressure could not be considered for Tables IV without violating reality so the S, T, P are, respectively: S, 0, 50 for Table IV(a); S, 10, 20 for Table IV(b); S, 20, 10 for Table IV(c); and S, 30, 1 for Table IV(d).

Tables V and VI are for variable pressure with salinity parameter. Pressure ranges from 0 to 1000 kg/cm² gauge but the salinity parameter is again restricted by reality to 33, 35, and 37 ppt. Temperature is fixed at 0 °C for Tables V and at 5 °C for Tables VI.

The rows in the bodies of the tables show the differences between the NRL II equation and each of eight previously reported sound speed equations, in the form of corrections, if you will, to the latter. NRL I is the previous NRL equation.[2] WI and WII refer to the first[3] and second[4] Wilson equations, respectively. F and P/W is the stepwise regression fit to selected points of Wilson's first data set by Fry and Pugh[5] after they had determined the incompatibility of his two sets of data. A/W is the regression fit obtained by Anderson[6] to Wilson's two data sets combined with a third data set of Wilson's,[7] but after Anderson had deleted all unrealistic data points as well as all Wilson's pure-water data (questioning their validity) and had also "adjusted" three of Wilson's reported salinities. M/K is the equation fit by Mackenzie[8] to the tables of Kuwahara.[9] K and F refer to the formula appearing in "Fundamentals of Acoustics" and referred to as "a simplification of more com-

TABLE I. Sound-speed differences of previous equations (identified in text) from NRL II. Temperature variable with salinity parameter equal to (a) 29, (b) 35, (c) 41 ppt, and pressure fixed at 0 kg/cm^2 gauge.

				(a) S, T, P = 29, T, 0				
	29, 0, 0	29, 5, 0	29, 10, 0	29, 15, 0	29, 20, 0	29, 25, 0	29, 30, 0	29, 35, 0
NRL II–NRL I	0.085	0.031	0.047	0.066	0.053	0.002	−0.060	−0.078
NRL II–W I	2.826	2.608	2.463	2.356	2.263	2.164	2.047	1.909
NRL II–W II	0.079	−0.051	−0.277	−0.418	−0.411	−0.314	−0.305	−0.681
NRL II–F & P/W	19.469	19.406	19.378	19.354	19.305	19.203	19.018	18.721
NRL II–A/W	−0.089	−0.147	−0.166	−0.163	−0.154	−0.152	−0.174	−0.235
NRL II–M/K	3.404	3.144	2.951	2.802	2.671	2.533	2.366	2.142
NRL II–K & F	0.397	0.300	0.281	0.280	0.238	0.096	−0.205	−0.723
NRL II–L II/W	−0.057	−0.082	−0.253	−0.409	−0.416	−0.249	−0.059	−0.253
				(b) S, T, P = 35, T, 0				
	35, 0, 0	35, 5, 0	35, 10, 0	35, 15, 0	35, 20, 0	35, 25, 0	35, 30, 0	35, 35, 0
NRL II–NRL I	0.022	−0.045	−0.022	0.018	0.029	−0.001	−0.056	−0.086
NRL II–W I	−0.303	−0.530	−0.655	−0.712	−0.728	−0.720	−0.700	−0.673
NRL II–W II	−0.222	−0.383	−0.611	−0.725	−0.663	−0.481	−0.359	−0.593
NRL II–F & P/W	−0.380	−0.451	−0.459	−0.433	−0.403	−0.397	−0.444	−0.575
NRL II–A/W	−0.414	−0.454	−0.458	−0.442	−0.420	−0.407	−0.419	−0.471
NRL II–M/K	3.583	3.268	3.035	2.859	2.716	2.580	2.428	2.234
NRL II–K & F	0.083	−0.021	−0.019	0.029	0.066	0.032	−0.131	−0.483
NRL II–L II/W	−0.257	−0.349	−0.559	−0.725	−0.714	−0.499	−0.231	−0.320
				(c) S, T, P = 41, T, 0				
	41, 0, 0	41, 5, 0	41, 10, 0	41, 15, 0	41, 20, 0	41, 25, 0	41, 30, 0	41, 35, 0
NRL II–NRL I	−0.032	−0.091	−0.039	0.042	0.099	0.110	0.084	0.062
NRL II–W I	2.194	1.957	1.852	1.844	1.907	2.022	2.178	2.371
NRL II–W II	−0.636	−0.827	−1.058	−1.145	−1.027	−0.761	−0.526	−0.618
NRL II–F & P/W	−20.221	−20.299	−20.286	−20.211	−20.101	−19.987	−19.898	−19.862
NRL II–A/W	−0.894	−0.918	−0.907	−0.876	−0.841	−0.818	−0.820	−0.864
NRL II–M/K	3.783	3.413	3.139	2.937	2.781	2.646	2.510	2.346
NRL II–K & F	−0.221	−0.333	−0.311	−0.212	−0.096	−0.022	−0.049	−0.234
NRL II–L II/W	−0.555	−0.715	−0.965	−1.141	−1.110	−0.847	−0.503	−0.485

TABLE II. Sound-speed differences of previous equations (identified in text) from NRL II. Temperature variable with salinity parameter equal to (a) 33, (b) 35, (c) 37 ppt, and pressure fixed at 20 kg/cm^2 gauge.

				(a) S, T, P = 33, T, 20			
	33, 0, 20	33, 5, 20	33, 10, 20	33, 15, 20	33, 20, 20	33, 25, 20	33, 30, 20
NRL II–NRL I	0.035	−0.009	0.010	0.042	0.068	0.098	0.174
NRL II–W I	0.041	−0.126	−0.219	−0.277	−0.332	−0.409	−0.525
NRL II–W II	−0.186	−0.285	−0.476	−0.583	−0.552	−0.448	−0.456
NRL II–F & P/W	0.045	0.008	0.004	−0.002	−0.045	−0.162	−0.388
NRL II–A/W	−0.312	−0.335	−0.331	−0.328	−0.350	−0.425	−0.577
NRL II–M/K	3.131	2.872	2.691	2.547	2.397	2.194	1.894
NRL II–K & F	0.007	−0.058	−0.034	0.016	0.025	−0.073	−0.342
NRL II–L II/W	−0.253	−0.285	−0.451	−0.596	−0.593	−0.421	−0.240
				(b) S, T, P = 35, T, 20			
	35, 0, 20	35, 5, 20	35, 10, 20	35, 15, 20	35, 20, 20	35, 25, 20	35, 30, 20
NRL II–NRL I	0.015	−0.034	−0.016	0.016	0.041	0.066	0.131
NRL II–W I	−0.387	−0.559	−0.647	−0.690	−0.721	−0.764	−0.836
NRL II–W II	−0.302	−0.414	−0.607	−0.707	−0.660	−0.530	−0.502
NRL II–F & P/W	−0.427	−0.469	−0.467	−0.458	−0.477	−0.560	−0.743
NRL II–A/W	−0.438	−0.458	−0.452	−0.447	−0.468	−0.541	−0.694
NRL II–M/K	3.180	2.901	2.706	2.553	2.399	2.199	1.906
NRL II–K & F	−0.096	−0.166	−0.137	−0.073	−0.040	−0.103	−0.329
NRL II–L II/W	−0.331	−0.388	−0.570	−0.720	−0.713	−0.527	−0.322
				(c) S, T, P = 37, T, 20			
	37, 0, 20	37, 5, 20	37, 10, 20	37, 15, 20	37, 20, 20	37, 25, 20	37, 30, 20
NRL II–NRL I	−0.004	−0.052	−0.029	0.010	0.039	0.066	0.126
NRL II–W I	−0.191	−0.363	−0.442	−0.466	−0.469	−0.474	−0.499
NRL II–W II	−0.431	−0.550	−0.742	−0.832	−0.764	−0.605	−0.537
NRL II–F & P/W	−0.897	−0.940	−0.930	−0.902	−0.893	−0.939	−1.074
NRL II–A/W	−0.581	−0.594	−0.582	−0.571	−0.587	−0.656	−0.805
NRL II–M/K	3.231	2.936	2.731	2.573	2.419	2.225	1.944
NRL II–K &F	−0.199	−0.270	−0.232	−0.149	−0.088	−0.114	−0.291
NRL II–L II/W	−0.419	−0.497	−0.689	−0.841	−0.825	−0.622	−0.390

TABLE III. Sound-speed differences of previous equations (identified in text) from NRL II. Salinity variable with temperature parameter equal to (a) 0 °C, (b) 10 °C, (c) 20 °C, (d) 30 °C, and pressure fixed at 0 kg/cm^2 gauge.

(a) S, T, P = S, 0, 0

	0, 0, 0	29, 0, 0	31, 0, 0	33, 0, 0	35, 0, 0	37, 0, 0	39, 0, 0	41, 0, 0	43, 0, 0
NRL II–NRL I	0.523	0.085	0.063	0.042	0.022	0.003	−0.015	−0.032	−0.048
NRL II–W I	97.251	2.826	1.158	0.115	−0.303	−0.096	0.737	2.194	4.276
NRL II–W II	−0.054	0.079	−0.009	−0.110	−0.222	−0.348	−0.485	−0.636	−0.799
NRL II–F & P/W	4110.578	19.469	5.171	0.091	−0.380	−0.851	−5.928	−20.221	−48.336
NRL II–A/W	−0.721	−0.089	−0.180	−0.288	−0.414	−0.556	−0.716	−0.894	−1.088
NRL II–M/K	2.821	3.404	3.462	3.521	3.583	3.647	3.714	3.783	3.854
NRL II–K & F	2.042	0.397	0.291	0.187	0.083	−0.019	−0.120	−0.221	−0.320
NRL II–L II/W	−0.486	−0.057	−0.113	−0.179	−0.257	−0.345	−0.444	−0.555	−0.676

(b) S, T, P = S, 10, 0

	0, 10, 0	29, 10, 0	31, 10, 0	33, 10, 0	35, 10, 0	37, 10, 0	39, 10, 0	41, 10, 0	43, 10, 0
NRL II–NRL I	0.868	0.047	0.019	−0.044	−0.022	−0.033	−0.039	−0.039	−0.032
NRL II–W I	96.833	2.463	0.798	−0.241	−0.655	−0.445	0.391	1.852	3.938
NRL II–W II	−0.250	−0.277	−0.376	−0.487	−0.611	−0.748	−0.896	−1.058	−1.232
NRL II–F & P/W	4110.425	19.378	5.084	0.008	−0.459	−0.925	−5.998	−20.286	−48.397
NRL II–A/W	−0.952	−0.166	−0.246	−0.344	−0.458	−0.591	−0.740	−0.907	−1.091
NRL II–M/K	2.828	2.951	2.977	3.005	3.035	3.068	3.102	3.139	3.178
NRL II–K & F	1.865	0.281	0.180	0.080	−0.019	−0.118	−0.215	−0.311	−0.406
NRL II–L II/W	−0.162	−0.253	−0.344	−0.446	−0.559	−0.684	−0.819	−0.965	−1.122

(c) S, T, P = S, 20, 0

	0, 20, 0	29, 20, 0	31, 20, 0	33, 20, 0	35, 20, 0	37, 20, 0	39, 20, 0	41, 20, 0	43, 20, 0
NRL II–NRL I	1.016	0.053	0.035	0.027	0.029	0.041	0.064	0.099	0.145
NRL II–W I	96.019	2.263	0.641	−0.356	−0.728	−0.474	0.404	1.907	4.035
NRL II–W II	−0.780	−0.411	−0.482	−0.566	−0.663	−0.771	−0.893	−1.027	−1.173
NRL II–F & P/W	4109.730	19.305	5.055	0.022	−0.403	−0.826	−5.856	−20.101	−48.169
NRL II–A/W	−1.067	−0.154	−0.225	−0.314	−0.420	−0.543	−0.683	−0.841	−1.017
NRL II–M/K	2.737	2.671	2.683	2.698	2.716	2.735	2.757	2.781	2.807
NRL II–K & F	1.198	0.238	0.179	0.122	0.066	0.011	−0.043	−0.096	−0.149
NRL II–L II/W	−0.369	−0.416	−0.505	−0.604	−0.714	−0.835	−0.967	−1.110	−1.265

(d) S, T, P = S, 30, 0

	0, 30, 0	29, 30, 0	31, 30, 0	33, 30, 0	35, 30, 0	37, 30, 0	39, 30, 0	41, 30, 0	43, 30, 0
NRL II–NRL I	1.126	−0.060	−0.072	−0.071	−0.056	−0.025	0.021	0.084	0.164
NRL II–W I	94.626	2.047	0.506	−0.410	−0.700	−0.366	0.594	2.178	4.387
NRL II–W II	−1.629	−0.305	−0.311	−0.329	−0.359	−0.402	−0.458	−0.526	−0.607
NRL II–F & P/W	4108.258	19.018	4.850	−0.102	−0.444	−0.786	−5.734	−19.898	−47.884
NRL II–A/W	−1.188	−0.174	−0.238	−0.320	−0.419	−0.535	−0.669	−0.820	−0.988
NRL II–M/K	2.349	2.366	2.384	2.405	2.428	2.453	2.480	2.510	2.542
NRL II–K & F	−0.429	−0.205	−0.181	−0.157	−0.131	−0.105	−0.077	−0.049	−0.019
NRL II–L II/W	−0.616	−0.059	−0.105	−0.163	−0.231	−0.311	−0.401	−0.503	−0.615

TABLE IV. Sound-speed differences of previous equations (identified in text) from NRL II. Salinity variable with temperature parameter equal to °C and pressure fixed at kg/cm^2 gauge: (a) 0 °C–50, (b) 10 °C–20, (c) 20 °C–10, (d) 30 °C–1 kg/cm^2.

(a) S, T, P = S, 0, 50

	0, 0, 50	29, 0, 50	31, 0, 50	33, 0, 50	35, 0, 50	37, 0, 50	39, 0, 50	41, 0, 50	43, 0, 50
NRL II–NRL I	0.485	0.066	0.045	0.025	0.006	−0.012	−0.029	−0.045	−0.060
NRL II–W I	97.499	2.708	1.015	−0.054	−0.498	−0.316	0.490	1.922	3.978
NRL II–W II	−0.109	−0.081	−0.177	−0.285	−0.405	−0.538	−0.683	−0.841	−1.012
NRL II–F & P/W	4110.476	19.364	5.066	−0.015	−0.487	−0.958	−6.036	−20.329	−48.445
NRL II–A/W	−0.774	−0.145	−0.237	−0.345	−0.471	−0.614	−0.775	−0.953	−1.148
NRL II–M/K	2.392	2.529	2.555	2.584	2.615	2.648	2.683	2.721	2.760
NRL II–K & F	1.637	−0.012	−0.118	−0.223	−0.327	−0.429	−0.531	−0.632	−0.732
NRL II–L II/W	0.244	−0.199	−0.269	−0.345	−0.426	−0.512	−0.603	−0.699	−0.801

TABLE IV. (*Continued*)

					(b) S, T, P = S, 10, 20				
	0, 10, 20	29, 10, 20	31, 10, 20	33, 10, 20	35, 10, 20	37, 10, 20	39, 10, 20	41, 10, 20	43, 10, 20
NRL II–NRL I	2.153	0.103	0.050	0.010	−0.016	−0.029	−0.029	−0.014	0.015
NRL II–W I	98.202	2.536	0.842	−0.219	−0.647	−0.442	0.396	1.866	3.970
NRL II–W II	1.002	−0.228	−0.349	−0.476	−0.607	−0.742	−0.883	−1.028	−1.178
NRL II–F & P/W	4111.612	19.405	5.092	0.004	−0.467	−0.930	−5.992	−20.261	−48.345
NRL II–A/W	0.279	−0.119	−0.220	−0.331	−0.452	−0.582	−0.722	−0.871	−1.030
NRL II–M/K	3.890	2.692	2.687	2.691	2.706	2.731	2.766	2.811	2.866
NRL II–K & F	2.943	0.200	0.079	−0.034	−0.137	−0.232	−0.317	−0.394	−0.463
NRL II–L II/W	1.380	−0.217	−0.334	−0.451	−0.570	−0.689	−0.810	−0.931	−1.053
					(c) S, T, P = S, 20, 10				
	0, 20, 10	29, 20, 10	31, 20, 10	33, 20, 10	35, 20, 10	37, 20, 10	39, 20, 10	41, 20, 10	43, 20, 10
NRL II–NRL I	2.398	0.125	0.078	0.047	0.035	0.040	0.064	0.107	0.170
NRL II–W I	97.293	2.316	0.670	−0.343	−0.724	−0.471	0.414	1.932	4.083
NRL II–W II	0.443	−0.368	−0.461	−0.558	−0.661	−0.767	−0.879	−0.995	−1.116
NRL II–F & P/W	4110.887	19.303	5.033	−0.012	−0.440	−0.860	−5.878	−20.104	−48.145
NRL II–A/W	0.133	−0.137	−0.229	−0.332	−0.443	−0.565	−0.696	−0.836	−0.986
NRL II–M/K	3.828	2.556	2.546	2.546	2.556	2.575	2.605	2.645	2.695
NRL II–K & F	2.339	0.220	0.142	0.073	0.012	−0.039	−0.082	−0.116	−0.141
NRL II–L II/W	1.005	−0.374	−0.485	−0.598	−0.713	−0.830	−0.949	−1.070	−1.193
					(d) S, T, P = S, 30, 1				
	0, 30, 1	29, 30, 1	31, 30, 1	33, 30, 1	35, 30, 1	37, 30, 1	39, 30, 1	41, 30, 1	43, 30, 1
NRL II–NRL I	1.356	−0.039	−0.056	−0.059	−0.046	−0.018	0.028	0.091	0.173
NRL II–W I	94.805	2.047	0.503	−0.415	−0.707	−0.372	0.588	2.175	4.388
NRL II–W II	−1.454	−0.306	−0.315	−0.335	−0.366	−0.409	−0.463	−0.529	−0.605
NRL II–F & P/W	4108.422	19.008	4.837	−0.116	−0.459	−0.800	−5.747	−19.908	−47.890
NRL II–A/W	−1.018	−0.182	−0.249	−0.333	−0.433	−0.549	−0.681	−0.829	0.994
NRL II–M/K	2.500	2.344	2.360	2.379	2.401	2.427	2.456	2.489	2.525
NRL II–K & F	−0.260	−0.209	−0.189	−0.166	−0.141	−0.114	−0.085	−0.053	−0.020
NRL II–L II/W	−0.424	−0.057	−0.107	−0.167	−0.236	−0.315	−0.403	−0.501	−0.609

TABLE V. Sound-speed differences of previous equations (identified in text) from NRL II. Pressure variable with salinity parameter equal to (a) 33, (b) 35, (c) 37 ppt, and temperature fixed at 0 °C.

				(a) S, T, P = 33, 0, P				
	33, 0, 0	33, 0, 1	33, 0, 10	33, 0, 20	33, 0, 50	33, 0, 100	33, 0, 500	33, 0, 1000
NRL II–NRL I	0.042	0.042	0.038	0.035	0.025	0.010	−0.038	0.024
NRL II–W I	0.115	0.111	0.077	0.041	−0.054	−0.172	−0.165	−0.553
NRL II–W II	−0.110	−0.114	−0.149	−0.186	−0.285	−0.408	−0.432	−0.970
NRL II–F & P/W	0.091	0.088	0.067	0.045	−0.015	−0.093	−0.267	−0.703
NRL II–A/W	−0.288	−0.289	−0.300	−0.312	−0.345	−0.393	−0.621	−1.478
NRL II–M/K	3.521	3.501	3.323	3.131	2.584	1.774	−0.511	5.145
NRL II–K & F	0.187	0.177	0.094	0.007	−0.223	−0.505	0.986	8.379
NRL II–K II/W	−0.179	−0.183	−0.217	−0.253	−0.345	−0.457	−0.419	−0.892
				(b) S, T, P = 35, 0, P				
	35, 0, 0	35, 0, 1	35, 0, 10	35, 0, 20	35, 0, 50	35, 0, 100	35, 0, 500	35, 0, 1000
NRL II–NRL I	0.022	0.022	0.018	0.015	0.006	−0.006	−0.005	0.003
NRL II–W I	−0.303	−0.307	−0.346	−0.387	−0.498	−0.640	−0.800	−1.320
NRL II–W II	−0.222	−0.227	−0.263	−0.302	−0.405	−0.535	−0.612	−1.197
NRL II–F & P/W	−0.380	−0.383	−0.404	−0.427	−0.487	−0.566	−0.793	−1.394
NRL II–A/W	−0.414	−0.415	−0.426	−0.438	−0.471	−0.520	−0.751	−1.421
NRL II–M/K	3.583	3.563	3.379	3.180	2.615	1.777	−0.617	5.171
NRL II–K & F	0.083	0.074	−0.009	−0.096	−0.327	−0.611	0.828	8.056
NRL II–L II/W	−0.257	−0.261	−0.295	−0.331	−0.426	−0.543	−0.580	−1.246
				(c) S, T, P = 37, 0, P				
	37, 0, 0	37, 0, 1	37, 0, 10	37, 0, 20	37, 0, 50	37, 0, 100	37, 0, 500	37, 0, 1000
NRL II–NRL I	0.003	0.003	−0.001	−0.004	−0.012	−0.021	0.026	−0.030
NRL II–W I	−0.096	−0.101	−0.144	−0.191	−0.316	−0.484	−0.814	−1.475
NRL II–W II	−0.348	−0.352	−0.390	−0.431	−0.538	−0.676	−0.807	−1.450
NRL II–F & P/W	−0.851	−0.853	−0.875	−0.897	−0.958	−1.039	−1.322	−2.097
NRL II–A/W	−0.556	−0.558	−0.569	−0.581	−0.614	−0.664	−0.902	−1.395
NRL II–M/K	3.647	3.626	3.437	3.231	2.648	1.782	−0.723	5.187
NRL II–K & F	−0.019	−0.029	−0.111	−0.199	−0.429	−0.715	0.667	7.720
NRL II–L II/W	−0.345	−0.349	−0.383	−0.419	−0.512	−0.628	−0.698	−1.510

TABLE VI. Sound-speed differences of previous equations (identified in text) from NRL II. Pressure variable with salinity parameter equal to (a) 33, (b) 35, (c) 37 ppt, and temperature fixed at 5 °C.

	(a) S, T, P = 33, 5, P							
	33, 5, 0	33, 5, 1	33, 5, 10	33, 5, 20	33, 5, 50	33, 5, 100	33, 5, 500	33, 5, 1000
NRL II–NRL I	−0.023	−0.022	−0.016	−0.009	0.010	0.034	0.031	−0.001
NRL II–W I	−0.109	−0.110	−0.118	−0.126	−0.143	−0.154	0.016	−0.419
NRL II–W II	−0.260	−0.261	−0.273	−0.285	−0.315	−0.346	−0.309	−0.920
NRL II–F & P/W	0.023	0.022	0.015	0.008	−0.011	−0.033	−0.127	−0.251
NRL II–A/W	−0.334	−0.334	−0.335	−0.335	−0.337	−0.344	−0.507	−0.808
NRL II–M/K	3.225	3.207	3.046	2.872	2.374	1.629	−0.725	4.398
NRL II–K & F	0.085	0.078	0.012	−0.058	−0.245	−0.482	0.360	5.533
NRL II–L II/W	−0.249	−0.251	−0.268	−0.285	−0.328	−0.373	−0.296	−0.898
	(b) S, T, P = 35, 5, P							
	35, 5, 0	35, 5, 1	35, 5, 10	35, 5, 20	35, 5, 50	35, 5, 100	35, 5, 500	35, 5, 1000
NRL II–NRL I	−0.045	−0.045	−0.040	−0.034	−0.020	0.000	0.017	−0.036
NRL II–W I	−0.530	−0.532	−0.545	−0.559	−0.594	−0.633	−0.663	−1.272
NRL II–W II	−0.383	−0.385	−0.399	−0.414	−0.451	−0.495	−0.551	−1.261
NRL II–F & P/W	−0.451	−0.452	−0.460	−0.469	−0.491	−0.520	−0.708	−1.048
NRL II–A/W	−0.454	−0.454	−0.456	−0.458	−0.465	−0.480	−0.704	−0.891
NRL II–M/K	3.268	3.250	3.083	2.901	2.383	1.605	−0.891	4.322
NRL II–K & F	−0.021	−0.029	−0.096	−0.166	−0.356	−0.601	0.147	5.104
NRL II–L II/W	−0.349	−0.351	−0.370	−0.388	−0.437	−0.492	−0.532	−1.379
	(c) S, T, P = 37, 5, P							
	37, 5, 0	37, 5, 1	37, 5, 10	37, 5, 20	37, 5, 50	37, 5, 100	37, 5, 500	37, 5, 1000
NRL II–NRL I	−0.064	−0.063	−0.058	−0.052	−0.036	−0.011	0.100	0.114
NRL II–W I	−0.326	−0.328	−0.345	−0.363	−0.410	−0.469	−0.624	−1.318
NRL II–W II	−0.519	−0.520	−0.535	−0.550	−0.590	−0.636	−0.712	−1.434
NRL II–F & P/W	−0.924	−0.925	−0.933	−0.940	−0.960	−0.986	−1.194	−1.663
NRL II–A/W	−0.591	−0.591	−0.593	−0.594	−0.600	−0.615	−0.825	−0.810
NRL II–M/K	3.314	3.295	3.123	2.936	2.403	1.603	−0.961	4.430
NRL II–K & F	−0.126	−0.134	−0.200	−0.270	−0.458	−0.699	0.029	4.857
NRL II–L II/W	−0.460	−0.462	−0.479	−0.497	−0.541	−0.590	−0.627	−1.575

plicated equations." L II/W is an equation developed by Leroy[10] to fit the combined Wilson data except for the deletion of all unrealistic points and the substitution of Greenspan and Tschiegg's[11] pure-water data (at atmospheric pressure only) for Wilson's. The original 1952 NRL sea-water sound-speed equation[12] has not been included in the comparisons since it did not present a pressure or depth coefficient, although it was tempting to add a simple Kuwahara-type[13] depth term like 0.0181D (cf. the 0.017D of Kinsler and Frey), since even this first equation based on laboratory measurements appears to be as adequate[14] as the later equations.

The first row in the tables is included not only to indicate the excellent agreement between values calculated for common parameters by use of either NRL I or NRL II, but to substantiate that no prejudice accrues to comparison of the other equations with the newer NRL one which also fits pure water.

Perhaps the most striking observation obtained from a perusal of Tables I and II (temperature variable) is that most of the other equations agree as well if not better with the newest NRL equation as do the two Wilson equations. This is particularly startling when considering the relatively simple K and F equation. Of course, the M/K equation has been known to be in error since the 1952 NRL report, but it is interesting to sub-

TABLE VII. Sound-speed differences of previous equations (identified in text) from NRL II. Temperature variable with salinity parameter equal to 0 ppt and pressure fixed at 0 kg/cm^2 gauge.

	S, T, P = 0, T, 0							
	0,0,0	0,5,0	0,10,0	0,15,0	0,20,0	0,25,0	0,30,0	0,35,0
NRL II–NRL I	0.523	0.711	0.868	0.968	1.016	1.047	1.126	1.350
NRL II–W I	97.251	97.076	96.833	96.490	96.019	95.401	94.626	93.689
NRL II–W II	−0.054	−0.034	−0.250	−0.519	−0.780	−1.091	−1.629	−2.691
NRL II–F&P/W	4110.578	4110.555	4110.425	4110.160	4109.730	4109.105	4108.258	4107.158
NRL II–A/W	−0.721	−0.858	−0.952	−1.016	−1.067	−1.119	−1.188	−1.289
NRL II–M/K	2.821	2.825	2.828	2.807	2.737	2.592	2.349	1.982
NRL II–K&F	2.042	1.985	1.865	1.622	1.198	0.534	−0.429	−1.750
NRL II–L II/W	−0.486	−0.180	−0.162	−0.270	−0.369	−0.434	−0.616	−1.324

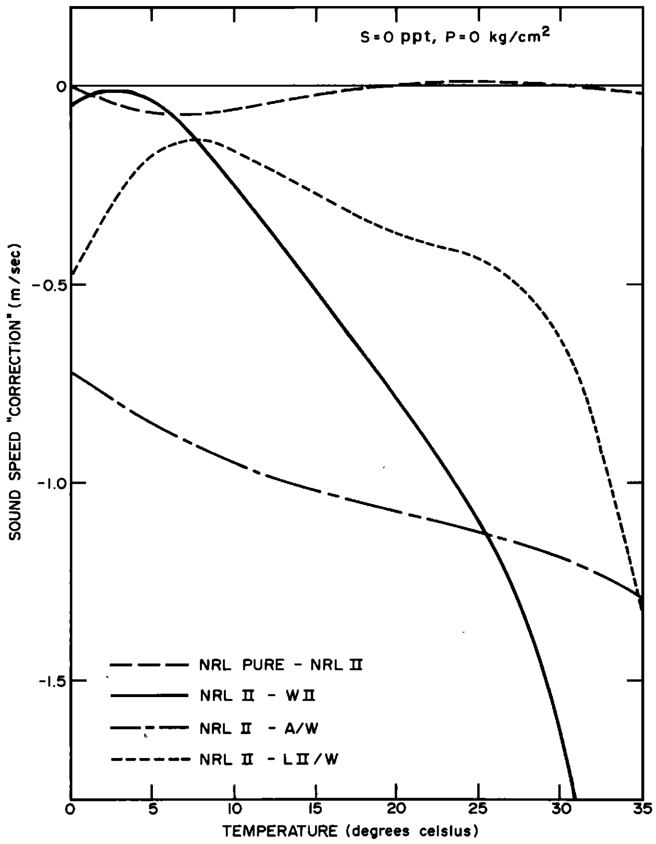

FIG. 1. Deviations of pure-water sound-speed calculations based on other equations (identified in text) from NRL II with temperature variable and pressure fixed at 0 kg/cm^2 gauge.

tract 3 m/sec from the tabulated values as had been recommended then. If this is done it is remarkable how all rows converge with the exception, of course, of the first and the F and P/W equation for which latter salinities as low as 29‰ are admittedly outside the range of fit. Of course, most of them are based on Wilson data and manipulations thereof.

A similar perusal of Tables III and IV for salinity variable discloses the same features noted for the temperature variable tables. That is, many of the simpler equations again agree at least as well as the Wilson equations with the newest NRL II. Again, the good agreement of the simple K and F equation is remarked upon as well as the validity of the 3-m/sec correction to the Kuwahara tables fit by M/K. The invalidity of the W I and F and P/W equations for both low and high salinities is also noted.

Tables V and VI for pressure variable again indicate that there is little to choose from among the non-NRL equations up to intermediate pressures, assuming the 3-m/sec correction is made to M/K. But at higher realistic pressures all the other equations exhibit large differences from the NRL equations. Somewhat interesting are the several instances where the differences appear to decrease, most likely in demonstration of the possible cancellation of opposing errors.

Table VII is a comparison of values calculated by the several equations of the speed of sound in pure water at atmospheric pressure as a function of temperature. It must be noted that the NRL I equation was not modeled to fit pure water any more than was W I, F and P/W, M/K, and K/F. But W II and A/W did include Wilson pure-water data and L II/W included Greenspan and Tschiegg pure-water data. A plot of the deviations of the latter from NRL II is given in Fig. 1. Included in this same figure is a comparison of the results predicted from NRL II with those from the NRL pure-water equation[15] to indicate the lack of bias in making the comparisons with NRL II.

Figures 2, 3, and 4 are plots of the differences between NRL II and W II for the three respective basic variations: temperature variable with salinity parameter, salinity variable with temperature parameter, and pressure variable with salinity parameter. Differences between NRL I and NRL II are again given for the reasons previously mentioned. Figure 2 demonstrates that the difference between the equations as a function of temperature is itself salinity dependent (and vice versa). It is thus not possible to prepare a simple graph or table for a temperature correction alone to calculations based on the W II equation, which has been used by the National Oceanographic Data Center (NODC) to prepare sound-speed profile data for over 300 000 oceanographic casts.[16] Most of the temperature variation in the ocean occurs at relatively shallow depths (low pressure) so

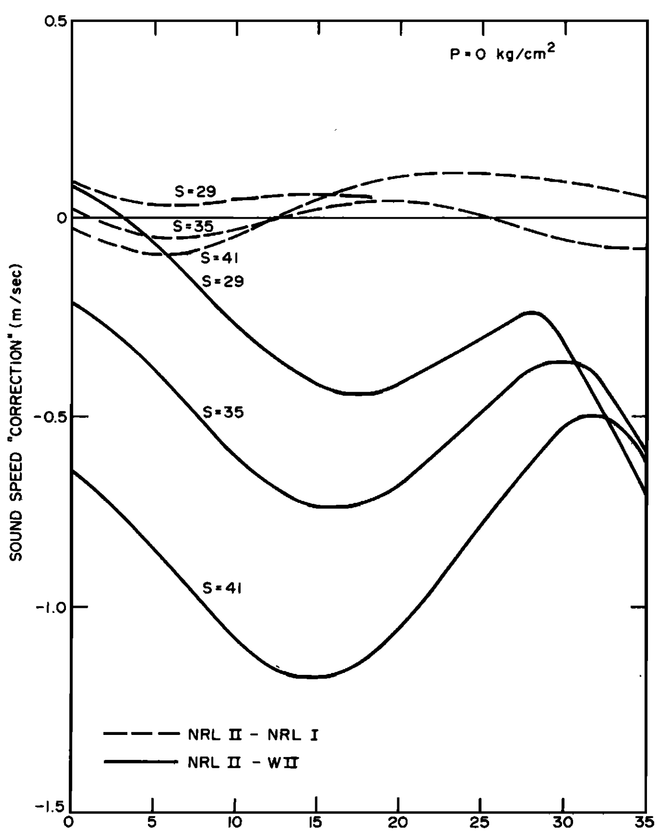

FIG. 2. Deviations of sea-water sound-speed calculations based on other equations (identified in text) from NRL II with temperature variable, salinity parameter, and pressure fixed at 0 kg/cm^2 gauge.

the surface differences in Fig. 2 serve to indicate the real differences expected. As stated previously, the corrections calculated for a pressure of 20 kg/cm^2 (195 m for standard water) display the same trend and may be obtained from Tables II.

The salinity correction in Fig. 3 is seen to be a function of temperature, although the parametric dependence is not as smooth as the salinity effect on the temperature correction noted in Fig. 2. These corrections, of course, are designed to take full advantage of the estimated accuracy of the NRL equations, which have standard deviations of 0.05 m/sec. But if an error, in the real sense, of ±0.3 m/sec could be tolerated, it is possible to draw an average, indeed a straight line, on Fig. 3 and apply it as a salinity correction to W II, which would then vary from about −0.2 m/sec to −1.0 m/sec. Similarly, if the indicated 35 ppt correction to W II on Fig. 2 were applied indiscriminately to all appropriate salinities, the error could be kept to within ±0.3 m/sec if corrections ranging from −0.2 m/sec to −0.7 m/sec were used.

The pressure correction to W II in Fig. 4 could also be approximated by a straight line indicating corrections ranging from about −0.3 m/sec to −1.2 m/sec, with the resultant error maintained within ±0.3 m/sec.

Thus, to an accuracy of ±0.3 m/sec, relatively simple corrections not exceeding 1.2 m/sec could be applied

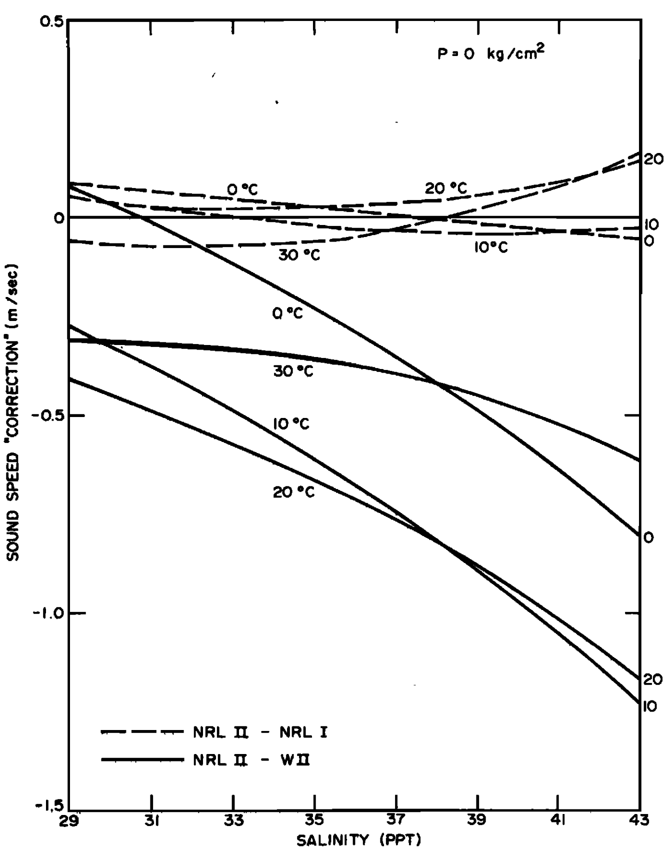

FIG. 3. Deviations of sea-water sound-speed calculations based on other equations (identified in text) from NRL II with salinity variable, temperature parameter, and pressure fixed at 0 kg/cm^2 gauge.

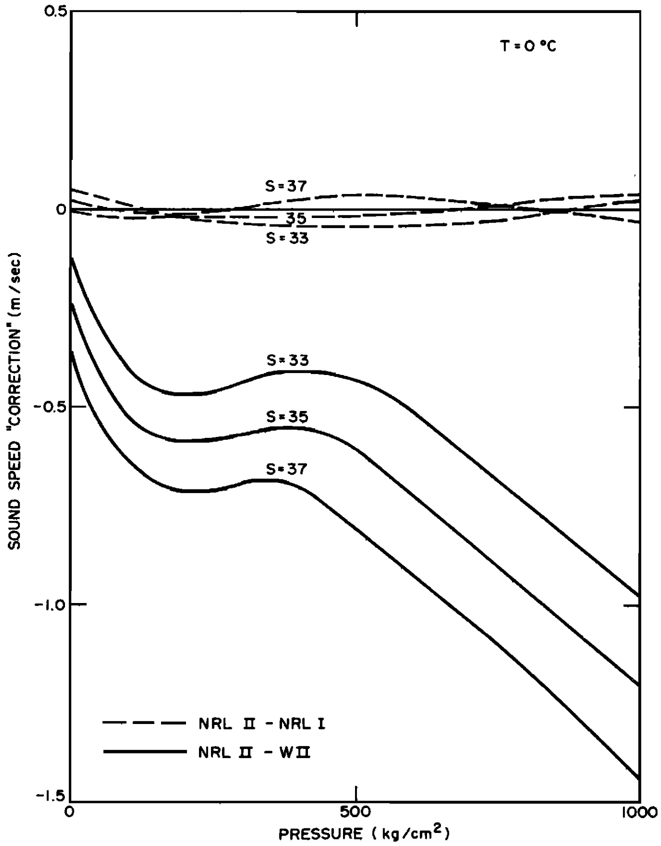

FIG. 4. Deviations of sea-water sound-speed calculations based on other equations (identified in text) from NRL II with pressure variable, salinity parameter, and temperature fixed at 0 °C.

to sound-speed calculations based on the W II equation (this would not apply to pure water); this should be considered a temporary expedient only, since it would not appear that difficult to recalculate the profiles from the same S and T data used for the Wilson-based sound-speed profiles. But the major reason for treating these simplified corrections as an expedient is the many occasions for which sound-speed differences are of greater importance than the actual speeds. For these situations even the application of the actual corrections tabulated or graphed herein would probably not suffice. And surely any more elegant form of correction would approach in complexity the complete recalculation of sound speeds by the NRL equation. Thus, it is earnestly hoped that the data bank of sound-speed profiles may soon be recalculated according to the NRL II model.

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