Marine Geodesy, 35:379–388, 2012

ISSN: 0149-0419 print / 1521-060X online
DOI: 10.1080/01490419.2012.709476

Area of the Ocean

J. GRAHAM COGLEY

Department of Geography, Trent University, Peterborough, Ontario, Canada

The area of the ocean, as derived from a new analysis of two digital data sets, is near to 362.5 Mm^2 *(1Mm*^{2} *=* 10^6 *km*^{2}*). The decimal digit is meaningful: uncertainty is about* ±*0.1 Mm*^{2} *or* ±*0.03%. Although it is impractical to quantify their dominant errors precisely, the ocean areas presented in both of the canonical sources are significantly more uncertain. The often-quoted figure of 361 Mm*^{2} *probably derives from the work of Kossinna in 1921 and represents the ocean without the ice shelves and floating glacier tongues, which have an area at present of 1.561 Mm*^{2}*. The often-quoted figure of 362 Mm*^{2} *probably derives from the work of Menard and Smith in 1966 and includes the ice shelves, as it should for the purpose of converting masses of cryospheric or terrestrial water to sea-level equivalent units. However, when Kossinna's estimate is corrected by adding the ice shelves, the two canonical estimates are seen to be inconsistent. The discrepancy implies that measurement errors are much larger than estimated in one source or in both, but Kossinna's estimate, when corrected, agrees much more closely with the modern digital estimates than does the Menard-Smith estimate.*

Keywords Ocean area, sea level, sea-level rise, sea-level equivalent

1. Introduction

The area of the ocean is a fundamental quantity in many earth-scientific contexts. For example, sea-level equivalents are convenient units, representing changes in the mass of the ocean as volumes distributed uniformly over the ocean surface. The conversion, neglecting complications such as isostatic readjustment to changing patterns of water loading, yields the sea-level equivalent $M/(\rho_w S_O)$ of the mass of water M. Here ρ_w is the mean density of the water, assumed constant here, and S_O the area of the ocean.

Different works of reference give different estimates of S_O, most often either 361 Mm^2 or 362 Mm^2 (1Mm^2 = 10^6 km^2 = 10^{12} m^2). These areas are usually stated without attribution or explanation, and are therefore difficult to trace to any authoritative source. The aims of this paper are to determine the provenance and reliability of the two numbers, to explain the small difference between them, and to investigate whether ocean area might be determinable with more than three digits of precision. Towards the latter aim, S_O is calculated here from two modern sources of information.

"Modern" simply means "relying on digital sources of shoreline or topographic data." The maps from which the digital data derive are all paper products that were compiled over some decades during the middle to late 20th century. This statement holds in some degree even for the digital elevation model of the Shuttle Radar Topography Mission (SRTM),

Received 3 July 2011; accepted 11 June 2012.
Address correspondence to J. Graham Cogley, Trent University, Department of Geography, 1600 West Bank Drive, Peterborough, Ontario, K9J 7B8, Canada. E-mail: gcogley@trentu.ca

which is tied to ocean heights measured by concurrent satellite altimetry but also relies on older information from the SRTM Water Body Data set (Farr et al. 2007).

The following section describes preparatory corrections that need to be applied to some estimates of ocean area. Section 3 assesses earlier measurements of ocean area. Section 4 describes two new measurements that are reported for the first time here. Section 5 is a further discussion of sources of uncertainty, and a summary concludes the paper.

2. Corrective Calculations

Ocean areas are calculated on the authalic sphere of a particular ellipsoid, that is, on a sphere with the same surface area as the ellipsoid. Comparisons are only precise when made on the same authalic sphere. To eliminate this purely geometric ambiguity, estimates from different ellipsoids must be transposed to a reference ellipsoid by multiplying by the square of the ratio of the radii (Table 1). When the WGS84 ellipsoid is the reference, as in the calculations below, estimates of S_O change by up to 0.1 Mm^2.

For purposes such as the calculation of sea-level equivalents, S_O must include the ice shelves. The best estimate of the area occupied by ice shelves in Antarctica is that of the Antarctic Digital Database, 1.555 Mm^2 (Fox and Cooper 1994; ADD Consortium 2000). Fox and Cooper describe their measurement uncertainty only as "less than 3%," or $\pm$0.047 Mm^2. A more realistic estimate may be the repeatability of measured lengths, which they give as $\pm$0.2%; this translates to $\pm$0.003 Mm^2, which is negligible. Some earlier measurements should probably be corrected for the retreat of ice-shelf calving fronts and grounding lines that has gone on during the 20th century, but this would require re-measurement of the original charts. A small correction is made here, however, for ice shelves and floating glacier tongues in the Northern Hemisphere. Their total extent has not been compiled but, drawing on regional sources (Hagen et al. 1993; Thomas 2004; Rignot and Steffen 2008; Dowdeswell et al. 2010; Seroussi et al. 2011) and on measurements on Canadian maps, the total extent in the mid to late 20th century is estimated here to be not less than 0.006 Mm^2. Estimates of S_O that exclude the ice shelves can therefore be corrected by adding a total of 1.561 Mm^2, with a random uncertainty of $\pm$0.047 Mm^2.

Table 1
Some ellipsoids in use in the 20th century

Ellipsoid	R_E (m)[a]	Difference of scale (ppm)[b]	S_E (Mm^2)[c]	$S_{WGS84} - S_E$ (Mm^2)[d]
Bessel	6370289.5	−225	509.951	0.115
Clarke 1866, NAD27	6370997.2	−3	510.064	0.002
Clarke 1880	6371002.7	−1	510.065	0.001
Helmert-Hayford	6371227.7	69	510.101	−0.035
Krasovskiy	6371116.1	34	510.083	−0.017
WGS84, GRS80	6371007.2	0	510.066	0.000

[a]Authalic radius.
[b]Scale difference is $10^6 \times [(R_E/R_{WGS84})^2 - 1]$.
[c]Area of authalic sphere.
[d]Differences in ocean area due solely to the choice of a different ellipsoid are about 0.7 times this quantity.

The GSHHS vector data set (version 1.11) of Wessel and Smith (1996) affords the opportunity to estimate a correction for omission of islets from source maps. When the number of GSHHS polygons of area *s* is plotted against *s* on a log-log plot (Figure 1; see also Wessel and Smith 1996), a clear deficit appears at sizes less than about 0.5 km^2. Assuming that the islets obey the logarithmic law evidenced by the larger landmasses in Figure 1, and thus that the deficit is due entirely to omission of islets from the maps, I extrapolated a linear regression to estimate a missing-islet correction of 0.011 Mm^2.

One of the earlier estimates discussed below, in section 3, lumps land below sea level together with the ocean. The extent of this "ocean" (including the Caspian Sea), obtained from the GLOBE data set (Hastings and Dunbar 1999) with an additional 0.012 Mm^2 to account for GLOBE's omission of the Eyre depression in Australia, is 0.759 Mm^2.

3. Previous Estimates

Kossinna (1921) measured areas by counting squares on equiareal maps at a scale of 1:40 million that were published in 1912. They did not distinguish the ice shelves from grounded

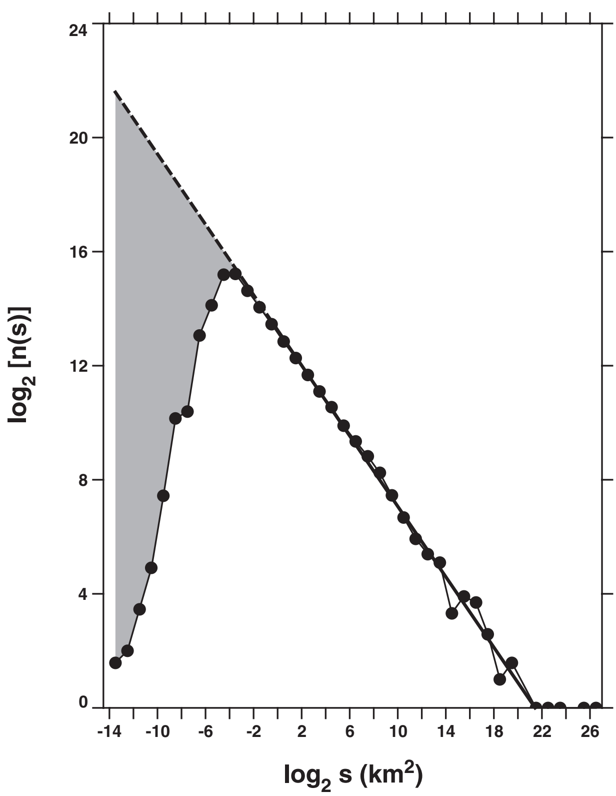

Figure 1. Connected solid dots: number of landmasses $n(s)$ in GSHHS (Wessel and Smith 1996) as a function of landmass area s. On the horizontal axis, –14.5 is the base-2 logarithm of 3×10^{-11} Mm^2 (about 30 m^2) and 26.5 is the base-2 logarithm of 134.2 Mm^2. Dashed line: extrapolation of the best fit (solid line) of number to size in the range of $\log_2 s$ from –1 (0.5 km^2) to 21 (2.097 Mm^2). The missing-islet correction (see text) is represented by the shaded region between the connected dots and the dashed line.

ice, the geography of ice-shelf grounding lines being little known at the time. The map datum was the Bessel ellipsoid. Kossinna's 1 × 1 mm grid gave a spatial resolution of the order of 1600 km^2, and results were recorded to the nearest 0.1 mm^2. He accumulated the areas of 1 km depth intervals within 5° × 5° geographical rectangles. The count for each interval was expressed as a fraction of the separately measured count for the geographical rectangle, the true area of the latter being known by trigonometry. Differences between the 5° × 5° count and the sum of depth-interval counts were typically 0.5–2.0%. In the GSHHS vector data set of Wessel and Smith (1996), ocean shorelines are found in 900 of the 5° × 5° rectangles. If all of their errors are independent and equal to a nominal ±1%, with no contribution from the other 1692 rectangles, the standard error of Kossinna's estimate of S_O is ±0.121 Mm^2. (In a sampling context the standard error is representable as the standard deviation of the observations divided by the square root of the number of independent observations. More generally, it estimates the standard deviation of an observed quantity considered as an estimator of the true quantity. In some fields the standard error is called the standard deviation.)

Kossinna (1933) retabulated the measurements of Kossinna (1921). His newer estimate of S_O, 361.160 Mm^2, differs from the older only by a switch to the Helmert-Hayford ellipsoid (Table 1). Fairbridge (1968) presents Kossinna's 1933 tabulation more accessibly.

Menard and Smith (1966) measured bathymetric charts with planimeters. They included the waters beneath Antarctic ice shelves. Chart scales ranged from 1:2,259,000 down to 1:25 million. Different planimeter scale factors were adopted for each rectangle in a 10° × 10° grid. Menard and Smith suggested that errors in these scale factors were of the order of ±0.2% or less, while tests of instrumental and operator errors by repeated measurement gave a range of ±0.32%. Taking one half of each of these percentages and adding in quadrature implies a standard error of about ±0.2%. By analogy with the error model constructed above for Kossinna's S_O, the errors from the 367 shoreline-containing 10° × 10° rectangles, if they were independent, would amount to ±0.036 Mm^2. As for Kossinna's estimate, this reconstructed error may be too optimistic, as discussed in Section 5.

Korzun et al. (1974) and Shiklomanov and Sokolov (1983) give the area of the ocean as 361.3 Mm^2. This number derives from Frolov (1971), who worked with bathymetric charts from the Soviet Ministry of Defense. His correction for the areal distortion of the Mercator projection, described by Maling (1989), is said to introduce no uncertainty. The charts ranged in scale from 1:500,000 down to 1:10 million, and are assumed here to have been drawn with the Krasovskiy ellipsoid as datum. Frolov does not provide enough information about methods for an estimate of uncertainty to be practical. Nor does he mention the ice shelves, although it seems certain that they were excluded.

Charette and Smith (2010) calculated ocean volume with the topographic and bathymetric data set SRTM30_PLUS (Becker et al. 2009), which has a resolution of 30 arc seconds, or about 1 km at the Equator, and treats the ice shelves as land. Charette and Smith relied on the SRTM digital elevation model, and so their ocean area is presumed here to have the WGS84 ellipsoid as datum. They derived the uncertainty of their S_O estimate from the number of grid cells with positive elevation that were adjacent to cells with negative elevation. Because their main concern was with ocean volume, they treated the ice shelves and land below sea level as negligible. As shown in Section 2, it is essential to correct both of these assumptions when the main concern is ocean area. Therefore both corrections appear in Table 2, which summarizes all the original reports of ocean area, together with the necessary corrections and the resulting final estimates of S_O. When appropriate, the uncertainty of the final estimate includes the uncertainty in ice-shelf area.

Table 2
Area of the ocean in the 20th century[a]

Source	Original	Corrections				S_O[f]
		Ellipsoid[b]	Shelves[c]	Islets[d]	Dry land[e]	
Kossinna (1921)	361.059	+0.081	+1.561	0.000	0.000	362.701 ± 0.130
Menard and Smith (1966)	362.033	−0.025	0.000	0.000	0.000	362.008 ± 0.036
Frolov (1971)	361.302	−0.038	+1.561	0.000	0.000	362.825
Charette and Smith (2010)	361.841	0.000	+1.561	0.000	−0.759	362.643 ± 0.148
This study (GLOBE)	362.523	0.000	0.000	−0.011	0.000	362.512 ± 0.080
This study (GSHHS)	361.001	0.000	+1.561	−0.011	0.000	362.551 ± 0.057

[a]All areas in Mm^2.
[b]Transposition from the authalic sphere of the source ellipsoid to that of the WGS84 ellipsoid.
[c]Addition of ice shelves and floating glacier tongues.
[d]Correction for unmapped small landmasses.
[e]Removal of dry land and inland water bodies below sea level.
[f]Final corrected estimate with formal standard error as obtained in the text, including uncertainty in the ice-shelf correction when appropriate.

4. New Estimates

All of the calculations in this section are done on the authalic sphere of the WGS84 ellipsoid.

GLOBE

GLOBE is the Global Land One-kilometer Base Elevation digital elevation model (Hastings and Dunbar 1999). It consists of land-surface elevations at a spatial resolution of 30 arc seconds, or roughly 1 km, and treats the ice shelves, with grounding lines derived from the Antarctic Digital Database, as part of the ocean. The missing-islet correction of Section 2 is applied to GLOBE because it adjusts a defect of the source maps, which are of roughly the same vintage as those on which the correction is based.

Internal information is lacking for an estimate of uncertainty in GLOBE. Working with a data set of coarser resolution, Cogley (2003) presented evidence that errors in surface-cover extents are ±(6–8)% of the area of the geographical rectangle to which they pertain. I assume therefore that the probability that each GLOBE shoreline cell has been identified incorrectly is 8%, a shoreline cell being an ocean cell with at least one of its eight neighbours represented as land. If these probabilities are independent, and if other cells contribute no uncertainty, the standard error of S_O from GLOBE is ±0.080 Mm^2.

GSHHS

GSHHS, a collection of vector data, is the Global Self-consistent, Hierarchical, High-resolution Shoreline database (Wessel and Smith 1996). Most of the GSHHS landmass shorelines come from the World Vector Shoreline (Soluri and Woodson 1990), compiled originally as a raster with a cell size of 3 arc seconds (93 m or less). The highest of several available resolutions gives a typical spacing between points of about 200 m. For measurements of landmass area, the authalic latitude was calculated from the geographic latitude of each point following Snyder (1982). GSHHS treats the ice shelves as land.

There is no explicit information on the positional accuracy of the GSHHS shorelines. I chose ±20 m, or 10% of the typical distance between points, for the uncertainty of position in the direction perpendicular to the shoreline. Multiplying this error, assumed to be random, by the total perimeter length of GSHHS landmass polygons, 1.65×10^6 km, results in an estimate of ±0.033 Mm^2 for the GSHHS uncertainty in S_O.

Spherical-trigonometric algorithms for the computation of area become inaccurate for very small polygons. I used a different, somewhat slower algorithm to compute the areas of the 110 598 GSHHS polygons (out of 180 508) having 10 vertices or fewer. Each polygon was transformed to a Lambert azimuthal equal-area projection centred at its centroid, and measured in the projected coordinates. This cartesian algorithm uses no inverse trigonometric functions, which are the source of most of the inaccuracy in the spherical computations. Root-mean-square differences between the algorithms exceeded 1% and 10% for cartesian areas less than 0.5 km^2 and 0.008 km^2 respectively. However the total area of the 110 598 polygons was 91 423.3 km^2 by spherical trigonometry and only 0.5 km^2 less in projected coordinates. Numerical error can thus be neglected.

5. Discussion

Unattributed values of 361 Mm^2 for the area of the ocean appear to derive from Kossinna (1921), while values of 362 Mm^2 are probably from Menard and Smith (1966). It has not been noticed, however, that these numbers are not just different, but inconsistent (Figure 2). After correction, the two sources differ by nearly 0.7 Mm^2 or about 0.2%, which is well in excess of the formal errors in Table 2.

Sea-level rise over the 40–50 years between the source surveys is in the wrong direction to account for the inconsistency. New discoveries, first mapped in publications of the 1950s and 1960s and thus known to Menard and Smith but not to Kossinna, will surely not be a negligible factor. For example, Kossinna was unable to allow for Prince Charles Island and its neighbors, which occupy 0.012 Mm^2 west of Baffin Island, because they were not discovered until 1948.

It is likely, however, that the true error in both estimates of S_O is governed by spatial resolution. Kossinna's 1-mm grid squares represent about 1600 km^2 at the Equator. Islands of this size and smaller, if not omitted from the maps altogether, must introduce random uncertainty because of inability to estimate their sizes accurately. From the same analysis of GSHHS that led to the missing-islet correction of section 2, the total area of islands smaller than Kossinna's recording unit, 0.1 $mm^2 \equiv 160$ km^2, is 0.252 Mm^2. Similarly, the vernier unit of the planimeters used by Menard and Smith (1966) represents, at a typical map scale of 1:9 million estimated from their Table 1, an area of about 500 km^2. The total area of islands smaller than 500 km^2 is 0.417 Mm^2, and the repeatability of the measurements was apparently several vernier units.

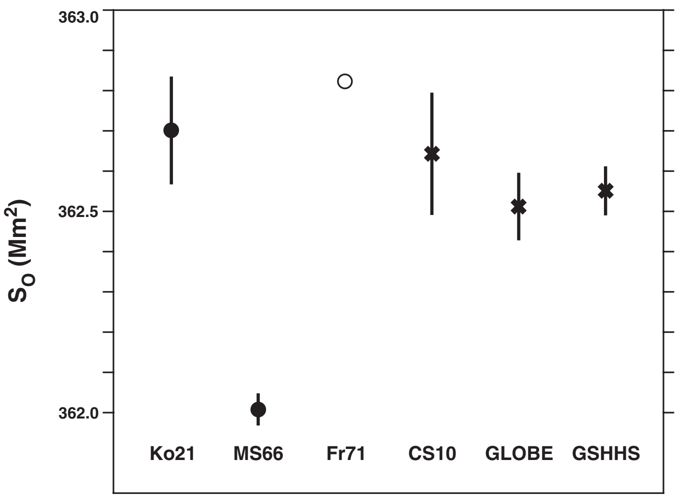

Figure 2. Area of the ocean according to various sources, but as corrected in the present work. Ko21: Kossinna (1921); MS66: Menard and Smith (1966); Fr71: Frolov (1971); CS10: Charette and Smith (2010); GLOBE, GSHHS: this study. Vertical lines represent ±1 formal standard error, estimated as described in the text. Circles: older analogue measurements on maps. Crosses: recent digital measurements.

Thus, although this small-island uncertainty cannot be quantified, the formal standard errors reconstructed here and presented in Table 2 are likely to be too small. Real standard errors of a few tenths of 1 Mm^2 are indicated for both of the canonical estimates of S_O. Even at this level of uncertainty, the two estimates may differ significantly. Considering that Kossinna's estimate agrees more closely with the other estimates (Figure 2), an alternative explanation is that most of the difference is due to additional unexplained errors in the Menard-Smith measurement. For example, their procedure does not appear to conform to the "minimum measurement routine" prescribed for planimetry by Maling (1989), which includes multiple clockwise and counterclockwise measurements of every polygon.

The method of Frolov (1971), probably planimetry or counting squares but in either case analogue rather than digital, was presumably subject to errors similar to those of Kossinna and of Menard and Smith.

Impressive as these early, very laborious studies are, they also had the aim of calculating the volume or mean depth of the ocean, in which context substantial missing-islet and small-island errors are of little consequence. Sea level is more than 4 km higher than the mode of the oceanic hypsometric curve, and errors in S_O of a few tenths of 1 Mm^2 make no perceptible difference to estimates of volume. They are more significant, however, when area is in question rather than volume.

The new digitally derived estimates in Table 2 have better resolution than the earlier estimates: about 1 km for GLOBE and about 0.2 km for GSHHS. If resolution is the best source of information on uncertainty, then GSHHS yields the best estimate of the area of the ocean. In fact, however, even the errors of the new estimates are incomplete. Their true errors may be dominated by errors of interpretation, such as mistaken treatment of estuaries and lagoons, that cannot be assessed, and by real but unquantified changes during the mapping period due to migration of the grounding lines of glaciers, volcanic eruptions, uplift and subsidence, landslides, sedimentation, and a variety of human activities including dredging and reclamation. It is also true that for both new estimates the uncertainties derived in Section 4 rest on numbers that, though plausible, are constrained only loosely by measurements.

Global-average sea-level rise over the mapping period may contribute moderately to uncertainty. Assume that the maps are an unfocussed representation of a period of half a century, during which sea level rose by about $\delta z = 0.08$ m (Bindoff et al. 2007). Then the resulting expansion of the ocean is $\delta S_O \approx p\ \delta z/\tan\theta$, where $p = 1.65 \times 10^6$ km is the length of the shoreline from GSHHS, θ is a typical but unknown shoreline slope, and one half of δS_O is an appropriate rough estimate of uncertainty. If the unknown slope were 0.1°, say, then the uncertainty due to sea-level rise over the mapping period would be ±0.038 Mm^2. It would be about ten times greater if θ were 0.01° and ten times less if it were 1.0°. Unfortunately θ cannot be estimated usefully with the present materials, which have horizontal resolution of ∼1 km. The expected shoreline encroachment for a sea-level rise of 0.04 m is ∼23 m for a slope of 0.1° or ∼230 m for a slope of 0.01°.

The adjusted S_O from Charette and Smith (2010) is greater than the GLOBE and GSHHS estimates, both of which lie within the Charette-Smith confidence region. However, the Charette-Smith estimate falls outside both of the new confidence regions. The unquantified errors discussed above, for example sea-level rise between the ill-defined mapping era and 2000, the date of the Shuttle Radar Topography Mission, may account for some of the difference. Alternatively, or as well, SRTM30_PLUS may omit an undue number of small landmasses, or it may be compromised by the tendency of the SRTM digital elevation model to confuse shorelines and the outlines of data voids, as documented for example by ISciences LLC (http://www.terraviva.net/datasolutions/projects_coastlines.html). These possibilities are outside the present scope, and remain to be investigated.

6. Summary

The area of the ocean as estimated here is near to 362.5 Mm^2, and its uncertainty is of the order of ±0.1 Mm^2. The uncertainty will be less if the unquantifiable errors are small but may be greater if the 0.10–0.13 Mm^2 disagreement between Charette and Smith (2010) and the new measurements presented here remains unexplained.

There are no current earth-scientific problems in which the area of the ocean is a significant contributor to uncertainty. Even the error in the often-seen figure of 361 Mm^2, which represents the ocean without the ice shelves and is about 0.4% less than the best estimate, will be small in many investigations. On the other hand, there is no reason not to use the number that is correct for the context. When the aim is to calculate sea-level equivalents, the larger number $S_O = 362.5$ Mm^2, which treats the ice shelves as part of the ocean, is correct, and it appears to be accurate to about three parts in ten thousand. It should replace the often-seen figure of 362 Mm^2, which is the outcome of a less accurate analysis.

Acknowledgements

I thank the anonymous reviewers for careful comments.

References

ADD Consortium, 2000. *Antarctic digital database, Version 3.0. Database, manual and bibliography*. Cambridge, British Antarctic Survey, Mapping and Geographic Information Centre. Working Group on Geodesy and Geographic Information, Scientific Committee on Antarctic Research. Version 4.1. http://www.add.scar.org:8080/add/index.jsp

Becker, J. J., D. T. Sandwell, W. H. F. Smith, J. Braud, B. Binder, J. Depner, D. Fabre, J. Factor, S. Ingalls, S.-H. Kim, R. Ladner, K. Marks, S. Nelson, A. Pharaoh, R. Trimmer, J. von Rosenberg, G. Wallace, and P. Weatherall, 2009. Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS. *Marine Geodesy* 32(4):355–371.

Bindoff, N. L., J. Willebrand, V. Artale, A. Cazenave, J. M. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C. K. Shum, L. D. Talley, and A. S. Unnikrishnan, 2007. Observations: Oceanic climate change and sea level. In eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, *Climate change 2007: The physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 387–432. Cambridge: Cambridge University Press.

Charette, M. A., and W. H. F. Smith, 2010. The volume of Earth's ocean. *Oceanography* 23(2):112–114.

Cogley, J. G. 2003. GGHYDRO—Global hydrographic data, Release 2.3. *Trent Technical Note 2003–1*. Peterborough: Department of Geography, Trent University. http://www.trentu.ca/geography/glaciology/glaciology.htm

Dowdeswell, J. A., E. K. Dowdeswell, M. Williams, and A. F. Glazovskii, 2010. The glaciology of the Russian High Arctic from Landsat imagery. In eds. R. S. Williams, Jr., and J. G. Ferrigno, *Satellite image atlas of glaciers of the world: Glaciers of Asia*. U.S. Geological Survey Professional Paper 1386-F, 94–125.

Fairbridge, R. W. 1968. Continents and oceans—statistics of area, volume and relief. In ed. R. W. Fairbridge, *Encyclopedia of geomorphology* (pp. 177–186). New York: Reinhold.

Farr, T. G., P. A. Rosen, E. Caro, R. Crippen, R. Duren, S. Ensley, M. Kobrick, M. Paller, E. Rodriguez, L. Roth, D. Seal, S. Shaffer, J. Shimada, J. Umland, M. Werner, M. Oskin, D. Burbank, and D. Alsdorf, 2007. The shuttle radar topography mission. *Reviews of Geophysics* 45(2):RG2004. doi: 10.1029/2005RG000183.

Fox, A. J., and A. P. R. Cooper, 1994. Measured properties of the Antarctic ice sheet derived from the SCAR Antarctic digital database. *Polar Record* 30(174):201–206.

Frolov, Yu. S. 1971. Novye fundamental'nye dannye po morfometrii mirovogo okeana [New fundamental data for morphometry of the world ocean]. *Vestnik Leningradskogo Gosudarstvennoe Universiteta, Geologiya—Geografiya* 6(1):85–90.

Hagen, J.-O., O. Liestøl, E. Roland, and T. Jørgensen, 1993. *Glacier Atlas of Svalbard and Jan Mayen*. Meddelelser No. 129, Norsk Polarinstitutt, Oslo.

Hastings, D. A., and P. K. Dunbar, eds. 1999. Global land one-kilometer base elevation (GLOBE). *Key to Geophysical Records Documentation No. 34*, Digital Elevation Model, Version 1.0. Boulder, CO: National Oceanic and Atmospheric Administration, National Geophysical Data Center.

Korzun, V. I., M. I. Budyko, K. P. Voskresenskiy, G. P. Kalinin, A. A. Konoplyantsev, E. S. Korotkevich, P. S. Kuzin, and M. I. Lvovich, eds. 1974. *Mirovoi vodnyi balans i vodnye resursy zemli*. Trans. & ed. R. L. Nace (1978), as *World water balance and water resources of the Earth*. Paris: UNESCO.

Kossinna, E. 1933. Die Erdoberfläche. In ed. B. Gutenberg, *Handbuch der Geophysik*, 2:869–954. Berlin: Gebrüder Borntraeger.

Kossinna, E. 1921. *Die Tiefen des Weltmeeres*. Veröffentlichungen des Instituts für Meereskunde, 9. Berlin: E. S. Mittler and Son.

Maling, D. H. 1989. *Measurements from maps*. Oxford: Pergamon Press.

Menard, H. W., and S. M. Smith, 1966. Hypsometry of ocean basin provinces. *Journal of Geophysical Research* 71(18):4305–4325.

Rignot, E., and K. Steffen, 2008. Channelized bottom melting and stability of floating ice shelves. *Geophysical Research Letters* 35:L02503. doi: 10.1029/2007GL031765.

Seroussi, H., M. Morlighem, E. Rignot, E. Larour, D. Aubry, H. Ben Dhia, and S.S. Kristensen, 2011. Ice flux divergence anomalies on 79north Glacier, Greenland. *Geophysical Research Letters* 38:L09501. doi: 10.1029/2011GL047338.

Shiklomanov, I. A., and A. A. Sokolov, 1983. Methodological basis of world water balance investigation and computation. *International Association of Hydrological Sciences Publications* 148:77–92.

Snyder, J. P. 1982. *Map projections used by the U.S. Geological Survey*. Bulletin 1532. Reston, VA: U.S. Geological Survey.

Soluri, E. A., and V. A. Woodson, 1990. World Vector Shoreline. *International Hydrographic Review* 47(1):27–35.

Thomas, R. H. 2004. Force-perturbation analysis of recent thinning and acceleration of Jakobshavn Isbrae, Greenland. *Journal of Glaciology* 50(168):57–66.

Wessel, P., and W. H. F. Smith, 1996. A global, self-consistent, hierarchical, high-resolution shoreline database. *Journal of Geophysical Research* 101(B4):8741–8743.