



THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

# Oceanography

[Subscribe](#) | [Join TOS](#)

Search

> Oceanography > Issues > Archive > Volume 24, Number 2

About

[View Issues](#)

Subscribe

Order Back Issues

Author Guidelines

Permissions

Advertising

Change of Address

Contact Us

Magazine Home

TOS Home

2011, *Oceanography* 24(2):80–93, <http://dx.doi.org/10.5670/oceanog.2011.29>

## Nineteenth and Twentieth Century Changes in Sea Level

[Authors](#) | [Abstract](#) | [Full Article](#) | [Citation](#) | [References](#)

---

### Authors

[Philip L. Woodworth](#) | National Oceanography Centre, Liverpool, UK

[W. Roland Gehrels](#) | School of Geography, Earth and Environmental Sciences at the University of Plymouth, UK

[R. Steven Nerem](#) | Colorado Center for Astrodynamics Research, and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA

[Top](#)

---

## Abstract

Following the Last Glacial Maximum (25,000–20,000 years ago), sea level rose at rates on the order of several tens of millimeters per year at times, and increased overall by over 130 m. However, melting of the great ice sheets was largely complete by 6,000 years ago, and it is believed that sea level did not rise significantly again until recently. The rates of sea level change during the last few centuries and in recent decades can be measured in units of millimeters per year and are particularly important in understanding present-day climate change. We now have a range of techniques with which sea level changes can be measured and thus studied more intensively than before, as a global average and in each region. This article introduces each of the main data sets and presents the primary research findings. It is hoped that a greater understanding of the reasons for past observed sea level change, discussed elsewhere in this issue, will lead to better estimation of the changes likely to occur in the future.

[Top](#)

---

## Full Article

[Download 1.49 MB pdf.](#)

[Top](#)

---

## Citation

Woodworth, P.L., W.R. Gehrels, and R.S. Nerem. 2011. Nineteenth and twentieth century changes in sea level. *Oceanography* 24(2):80–93, <http://dx.doi.org/10.5670/oceanog.2011.29>.

[Top](#)

---

## References

Bindoff, N., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, and others. 2007. Observations: Oceanic climate change and sea level. Chapter 5 in *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, and M. Manning, eds, Cambridge University Press, Cambridge, United Kingdom.

Bouin, M.N., and G. Wöppelmann. 2010. Land motion estimates from GPS at tide gauges: A geophysical evaluation. *Geophysical Journal International* 180:193–209. [[CrossRef](#)]

Cazenave, A., D.P. Chambers, P. Cipollini, L.L. Fu, J.W. Hurrell, M. Merrifield, R.S. Nerem, H.P. Plag, C.K. Shum, and J. Willis. 2010. Sea level: Regional and global trends. In *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society*, vol. 1. Venice, Italy, September 21–25, 2009, J. Hall, D.E. Harrison, and D. Stammer, eds, European Space Agency Publication WPP-306.

Chambers, D.P., J. Wahr, and R.S. Nerem. 2004. Preliminary observations of global ocean mass variations with GRACE. *Geophysical Research Letters* 31, L13310. [[CrossRef](#)]

Chen, J.L., C.R. Wilson, B.D. Tapley, D.D. Blankenship, and E.R. Ivins. 2007. Patagonia Icefield melting observed by Gravity Recovery and Climate Experiment (GRACE). *Geophysical Research Letters* 34, L22501. [[CrossRef](#)]

Church, J.A., J.M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M.T. Nhuan, D. Qin, and P.L. Woodworth. 2001. Changes in sea level. Pp. 639–694 in *Climate Change 2001: The Scientific Basis*. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell, and C.I. Johnson, eds, Cambridge University Press, Cambridge, UK.

Church, J.A., and N.J. White. 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* 33, L01602. [\[CrossRef\]](#)

Church, J.A., and N.J. White. 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics* 32, . [\[CrossRef\]](#)

Church, J.A., D. Roemmich, C.M. Domingues, J.K. Willis, N.J. White, J.E. Gilson, D. Stammer, A. Köhl, D.P. Chambers, F.W. Landerer, and others. 2010. Ocean temperature and salinity contributions to global and regional sea-level change. Chapter 6 in *Understanding Sea-Level Rise and Variability*. J.A. Church, P.L. Woodworth, T. Aarup and W.S. Wilson, eds, Wiley-Blackwell, London, UK.

Church, J.A., N.J. White, R. Coleman, K. Lambeck, and J.X. Mitrovica. 2004. Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. *Journal of Climate* 17:2,609–2,625. [\[CrossRef\]](#)

Donnelly, J.P., P. Cleary, P. Newby, and R. Ettinger. 2004. Coupling instrumental and geological records of sea-level change: Evidence from southern New England of an increase in the rate of sea-level rise in the late 19th century. *Geophysical Research Letters* 31, L05203. [\[CrossRef\]](#)

Douglas, B.C. 1991. Global sea level rise. *Journal of Geophysical Research* 96(C4):6,981–6,992. [\[CrossRef\]](#)

Douglas, B.C. 1997. Global sea level rise: A redetermination. *Surveys in Geophysics* 18:279–292. [\[CrossRef\]](#)

Douglas, B.C. 2008. Concerning evidence for fingerprints of glacial melting. *Journal of Coastal Research* 24(2B):218–227. [\[CrossRef\]](#)

Emery, K.O., and D.G. Aubrey. 1991. *Sea Levels, Land Levels, and Tide Gauges*. Springer-Verlag, New York, NY, 237 pp.

Engelhart, S.E., B.P. Horton, and A.C. Kemp. 2011. Holocene sea level changes along the United States' Atlantic Coast. *Oceanography* 24(2):70–79. [\[CrossRef\]](#)

Gehrels, W.R., J.R. Kirby, A. Prokoph, R.M. Newnham, E.P. Achterberg, E.H. Evans, S. Black, and D.B. Scott. 2005. Onset of recent rapid sea-level rise in the western Atlantic Ocean. *Quaternary Science Reviews* 24:2,083–2,100. [\[CrossRef\]](#)

Gehrels, W.R., B.W. Hayward, R.M. Newnham, and K.E. Southall. 2008. A 20th century sea-level acceleration in New Zealand. *Geophysical Research Letters* 35, L02717. [\[CrossRef\]](#)

Gehrels, W.R., W.A. Marshall, M.J. Gehrels, G. Larsen, J.R. Kirby, J. Eiriksson, J. Heinemeier, and T. Shimmield. 2006. Rapid sea-level rise in the North Atlantic Ocean since the first half of the 19th century. *The Holocene* 16:948–964. [\[CrossRef\]](#)

Holgate, S.J., and P.L. Woodworth. 2004. Evidence for enhanced coastal sea level rise during the 1990s. *Geophysical Research Letters* 31, L07305. [\[CrossRef\]](#)

Jevrejeva, S., A. Grinsted, J.C. Moore, and S.J. Holgate. 2006. Nonlinear trends and multiyear cycles in sea level records. *Journal of Geophysical Research* 111, C09012. [\[CrossRef\]](#)

Kemp, A.C., B.P. Horton, S.J. Culver, D.R. Corbett, O. van de Plassche, W.R. Gehrels, B.C. Douglas, and A.C. Parnell. 2009. Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States). *Geology* 37:1,035–1,038. [\[CrossRef\]](#)

Leorri, E., and A. Cearreta. 2009. Anthropocene versus Holocene relative sea-level rise rates in the southern Bay of Biscay. *Geogaceta* 46:127–130.

Leorri, E., B.P. Horton, and A. Cearreta. 2008. Development of a foraminifera-based transfer function in the Basque marshes, N. Spain: Implications for sea-level studies in the Bay of Biscay. *Marine Geology* 251:60–74. [\[CrossRef\]](#)

Leuliette, E., and L. Miller. 2009. Closing the sea level budget with altimetry, Argo and GRACE. *Geophysical Research Letters* 36, L04608. [\[CrossRef\]](#)

Leuliette, E.W., and J.K. Willis. 2011. Balancing the sea level budget. *Oceanography* 24(2):122–129. [\[CrossRef\]](#)

Llovel, W., M. Becker, A. Cazenave, S. Jevrejeva, R. Alkama, B. Decharme, H. Douville, M. Ablain, and B. Beckley. 2011. Terrestrial waters and sea level variations on interannual time scale. *Global and Planetary Change* 75:76–82. [\[CrossRef\]](#)

Lowe, J.A., P.L. Woodworth, T. Knutson, R.E. McDonald, K. McInnes, K. Woht, H. Von Storch, J. Wolf, V. Swail, N. Bernier, and others. 2010. Past and future changes in extreme sea levels and waves. Chapter 11 in *Understanding Sea-Level Rise and Variability*. J.A. Church, P.L. Woodworth, T. Aarup, and W.S. Wilson, eds, Wiley-Blackwell, London, UK.

Luthcke, S.B., A.A. Arendt, D.D. Rowlands, J.J. McCarthy, and C.F. Larsen. 2008. Recent glacier mass changes in the Gulf of Alaska region from GRACE mascon solutions. *Journal of Glaciology* 54:767–777. [\[CrossRef\]](#)

Luthcke, S.B., H.J. Zwally, W. Abdalati, D.D. Rowlands, R.D. Ray, R.S. Nerem, F.G. Lemoine, J.J. McCarthy, and D.S. Chinn. 2006. Recent Greenland ice mass loss by drainage system from satellite gravity observations. *Science*

- Marshall, W.A., W.R. Gehrels, M.H. Garnett, S.P.H.T. Freeman, C. Maden, and S. Xu. 2007. The use of 'bomb spike' calibration and high-precision AMS  $^{14}\text{C}$  analyses to date salt-marsh sediments deposited during the past three centuries. *Quaternary Research* 68:325–337. [[CrossRef](#)]
- Maul, G.A., and D.M. Martin. 1993. Sea level rise at Key West, Florida, 1846–1992: America's longest instrument record? *Geophysical Research Letters* 20(18):1,955–1,958. [[CrossRef](#)]
- Menéndez, M., and P.L. Woodworth. 2010. Changes in extreme high water levels based on a quasi-global tide-gauge dataset. *Journal of Geophysical Research* 115, C10011. [[CrossRef](#)]
- Merrifield, M.A., S.T. Merrifield, and G.T. Mitchum. 2009. An anomalous recent acceleration of global sea level rise. *Journal of Climate* 22:5,772–5,781. [[CrossRef](#)]
- Miller, L., and B.C. Douglas. 2007. Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise. *Geophysical Research Letters* 34, L16602. [[CrossRef](#)]
- Mitchum, G.T. 2000. An improved calibration of satellite altimetric heights using tide gauge sea levels with adjustment for land motion. *Marine Geodesy* 23:145–166. [[CrossRef](#)]
- Mitchum, G.T., R.S. Nerem, M.A. Merrifield, and W.R. Gehrels. 2010. Modern sea-level-change estimates. Chapter 5 in *Understanding Sea-Level Rise and Variability*. J.A. Church, P.L. Woodworth, T. Aarup, and W.S. Wilson, eds, Wiley-Blackwell, London, UK.
- Mitrovica, J.X., M.E. Tamisiea, J.L. Davis, and G.A. Milne. 2001. Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature* 409:1,026–1,029. [[CrossRef](#)]
- Mitrovica, J.X., M.E. Tamisiea, E.R. Ivins, L.L.A. Vermeersen, G.A. Milne, and K. Lambeck. 2010. Surface mass loading on a dynamic Earth: Complexity and contamination in the geodetic analysis of global sea-level trends. Chapter 10 in *Understanding Sea-Level Rise and Variability*. J.A. Church, P.L. Woodworth, T. Aarup, and W.S. Wilson, eds, Wiley-Blackwell, London, UK.
- Moray, R. 1665. Considerations and enquiries concerning tides; Likewise for a further search into Dr. Wallis's newly publish't hypothesis. *Philosophical Transactions of the Royal Society of London* 1:298–301, <http://dx.doi.org/10.1098/rstl.1665.0113>. [[CrossRef](#)]
- Morison, J., J. Wahr, R. Kwok, and C. Peralta-Ferriz. 2007. Recent trends in Arctic Ocean mass distribution revealed by GRACE. *Geophysical Research Letters* 34, L07602. [[CrossRef](#)]
- Nerem, R.S., D.P. Chambers, C. Choe, and G.T. Mitchum. 2010. Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Marine Geodesy* 33:435–446. [[CrossRef](#)]
- Nerem, R.S., D.P. Chambers, E.W. Leuliette, G.T. Mitchum, and B.S. Giese. 1999. Variations in global mean sea level associated with the 1997–1998 ENSO event: Implications for measuring long term sea level change. *Geophysical Research Letters* 26:3,005–3,008. [[CrossRef](#)]
- Palmer, H.R. 1831. Description of a graphical register of tides and winds. *Philosophical Transactions of the Royal Society of London* 121:209–213. [[CrossRef](#)]
- Peltier, W.R. 2001. Global glacial isostatic adjustment. Pp. 65–95 in *Sea Level Rise: History and Consequences*. B.C. Douglas, M.S. Kearney and S.P. Leatherman, eds, Academic Press, San Diego. [[CrossRef](#)]
- Prandi, P., A. Cazenave, and M. Becker. 2009. Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993–2007. *Geophysical Research Letters* 36, L05602. [[CrossRef](#)]
- Rodell, M., I. Velicogna, and J.S. Famiglietti. 2009. Satellite-based estimates of groundwater depletion in India. *Nature* 460:999–1,002. [[CrossRef](#)]
- Sturges, W., and B.C. Douglas. In press. Wind effects on estimates of sea-level rise. *Journal of Geophysical Research*. [[CrossRef](#)]
- Tamisiea, M.E., and J.X. Mitrovica. 2011. The moving boundaries of sea level change: Understanding the origins of geographic variability. *Oceanography* 24(2):24–39. [[CrossRef](#)]
- Tiwari, V.M., J. Wahr, and S. Swenson. 2009. Dwindling groundwater resources in northern India, from satellite gravity observations. *Geophysical Research Letters* 36, L18401. [[CrossRef](#)]
- Velicogna, I. 2009. Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophysical Research Letters* 36, L19503. [[CrossRef](#)]
- White, N.J., J.A. Church, and J.M. Gregory. 2005. Coastal and global averaged sea level rise for 1950 to 2000.

Willis, J.K., D.P. Chambers, C-Y. Kup, and C.K. Shum. 2010. Global sea level rise. *Oceanography* 23(4):26–35. [[CrossRef](#)]

Willis, J.K., D.P. Chambers, and R.S. Nerem. 2008. Assessing the globally averaged sea level budget on seasonal to interannual timescales. *Journal of Geophysical Research* 113, C06015. [[CrossRef](#)]

Wilson, W.S., W. Abdalati, D. Alsdorf, J. Benveniste, H. Bonekamp, J.G. Cogley, M.R. Drinkwater, L-L. Fu, R. Gross, B.J. Haines, and others. 2010. Observing systems needed to address sea-level rise and variability. Chapter 12 in *Understanding Sea-Level Rise and Variability*. A. Church, P.L. Woodworth, T. Aarup, and W.S. Wilson, eds, Wiley-Blackwell, London, UK.

Woodworth, P.L., and R. Player. 2003. The Permanent Service for Mean Sea Level: An update to the 21st century. *Journal of Coastal Research* 19:287–295.

Woodworth, P.L., M. Menéndez, and W.R. Gehrels. 2011. Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels. *Surveys in Geophysics*. [[CrossRef](#)]

Woodworth, P.L., N. Pouvreau, and G. Wöppelmann. 2010. The gyre-scale circulation of the North Atlantic and sea level at Brest. *Ocean Science* 6:185–190. [[CrossRef](#)]

Woodworth, P.L., N.J. White, S. Jevrejeva, S.J. Holgate, J.A. Church, and W.R. Gehrels. 2009. Evidence for the accelerations of sea level on multi-decade and century timescales. *International Journal of Climatology* 29:777–789. [[CrossRef](#)]

[Top](#)