John Wahr

June 22, 1951–November 11, 2015
Elected to the NAS, 2012

A Biographical Memoir by Jerry Mitrovica, Isabella Velicogna, and Shijie Zhong

Figure 1 John Wahr.

John Wahr was a pre-eminent geophysicist whose influential work spanned solid-earth science, planetary science, and geodesy. During his career, he was the recipient of numerous awards, including the James B. Macelwane (1985) and Charles A. Whitten (2006) Medals of the American Geophysical Union (AGU) and the Vening Meinesz Medal (2004) of the European Geosciences Union. He was elected to the National Academy of Sciences in 2012. Moreover, in honor of his stature in the field and his many seminal contributions to the geosciences, the Geodesy Section of the American Geophysical Union renamed its award for junior scientists the John Wahr Early Career Award.

John was born on June 22, 1951, in Ann Arbor, Michigan, and grew up in Midland, Michigan. He graduated from the University of Michigan with honors in both mathematics and physics in 1973. He married Ann Carol Brady, also from Midland, in September 1974. John pursued graduate studies in the Department of Physics at the University of Colorado, obtaining his Ph.D. in December 1979 with a thesis focused on Earth's tidal motion and advised by Martin Smith. In January 1980, John and Ann moved to Princeton, where he took up a postdoctoral fellowship in both the Department of Geological and Geophysical Sciences at Princeton University and in the Geophysical Fluid Dynamics Laboratory. John returned to the University of Colorado in 1983 as an assistant professor in the Department of Physics—a first in the field of geophysics—and a fellow of the Cooperative Institute for Research in Environmental Sciences. He remained a faculty member at the University of Colorado to the end of his life.

John's early work, for which he was ultimately awarded the Macelwane Medal, was concerned with extending existing theoretical treatments of Earth's tides and rotation. This is a classic area of geophysical research, dating to the nineteenth century and involving contributions from George Darwin, William Thomson (Lord Kelvin), A. E. H. Love, Toshi Shida, William Farrell, and Walter Munk, among other notable scientists. In 1981, John published two seminal articles that remain standard references in modern tidal and nutation theory.[1,2] These studies were the first to incorporate the effects

Figure 2 John on a summer backpacking trip to Titcomb Basin in the Wind River Range, Wyoming.

of rotation and elliptical material stratification in the Earth's mantle on solid-Earth body tides and the Earth's forced nutations. The latter has been incorporated in the standard forced nutation model adopted by the International Astronomical Union. At the center of this work was a powerful new normal-mode formulism developed to efficiently compute the generalized response of a rotating, elastically deformable Earth to tidal forcings. Further extensions of the theory have been developed by John and others to consider a range of additional Earth model complexities, including anelasticity and lateral variations in elastic structure.

In the late 1980s, John's work turned to studies of glacial isostatic adjustment (GIA), the ongoing, viscoelastic response of the Earth to the Plio-Pleistocene ice age cycles. His first contribution highlighted an unappreciated but important feedback between Earth rotation and ice age sea level change.[3] Viscoelastic deformation of the Earth and movement of mass between ice sheets and oceans perturb the inertia tensor of the planet and drive solid-body rotation with respect to the spin axis, and this "true polar wander" will, in turn, perturb global sea level. This rotational feedback into sea level is now incorporated in all modern analyses of ice age sea level change and is particularly important in the analysis of Holocene sea level curves in low latitudes. Later work on GIA by John led to several major contributions, including the first study quantifying the sensitivity of ice age observables to three-dimensional variations in mantle viscosity[4] and a new, far more accurate normal-mode approach for computing ice age true polar wander.[5]

In the 1990s, John's work moved energetically toward climate and geodesy, and with his students he next examined the effects of mountain glacier melting and both oceanic and atmospheric loading on Earth's gravitational field, sea level change, and crustal deformation.[6,7] His dual insights into both ice age and modern climate motivated him to solve a problem that was vexing geoscientists: in geodetic studies of gravity changes and crustal deformation in polar regions, how can one correct for the ongoing, contaminating impacts of GIA to isolate the signal associated with modern ice melting? John and his graduate students resolved this important conundrum by demonstrating that the two modern geodetic sets can be combined to isolate the viscoelastic GIA signal.[8] This remarkably elegant study served as a precursor to efforts that preoccupied the second half of John's career and transformed studies of modern climate through space-based geodetic observations of the Earth's glaciological and hydrological system. This would be John's foundational work on the interpretation of the Earth's time-varying gravity field measured by the NASA and the German Space Center (DLR)'s Gravity Recovery and Climate Experiment (GRACE) mission from its very inception in 1990s.[9]

Geophysicists recognized in the early 1990s that space geodesy using satellite technology could measure not only Earth's static gravity field but also the time-dependent gravity field related to seasonal variations in atmospheric mass and long-term GIA-related mass redistribution.[10] But because of the high altitude of existing satellite systems (such as LAGEOS, which orbits at an altitude of 6,000 kilometers) and limitations in tracking satellite locations, the time-varying gravity field could then only be measured at very long-wavelengths or, equivalently, at large length scales. In 1990s, John was among a group of geophysicists that proposed the GRACE mission, which was ultimately approved by NASA and DLR.[9] The mission involves twin satellites, with a microwave ranging connection between them, flying in a low-Earth orbit of hundreds of kilometer of altitude and continuously measuring the Earth's gravity field at unprecedent spatial resolution and precision. John served as one of the principal intellectual forces behind the GRACE mission, and his early prediction of the performance of satellite system in detecting changes in land hydrology and ocean mass presaged the enormous impact that GRACE has had in elucidating the many responses of the Earth system in a progressively warming climate.[11]

The tandem GRACE satellites were launched in 2002, marking the beginning of two decades of exciting discoveries that have made it one of NASA's most successful scientific missions. After launch, John and his many collaborators examined the first results related to polar ice sheets, glaciers, land hydrology, and the ocean, and they developed state-of-the-art analysis methodologies and error models for the data.[12] The major discoveries that followed are too many to list here but consider these three representative examples. John derived the first estimates of glacial mass loss in Antarctica and Greenland and demonstrated in subsequent studies that the major ice sheets are losing mass at an accelerating pace.[13,14] Next, he provided the first comprehensive estimates of mass loss from mountain glaciers and ice caps and concluded that the net rate of global ice mass loss, including the polar ice sheets, was mm/year, in units of equivalent global mean sea level rise, from 2003 to 2010.[15] Finally, John detected massive groundwater loss of km^3 due to large scale and long-term agriculture irrigation in Northern India from 2002 to 2008, a region home to about 600 million people.[16] This body of work, and his intellectual leadership, helped establish momentum for time-variable gravity missions beyond GRACE, including the GRACE Follow-On mission, launched in 2018, and the future GRACE Continuity mission to be launched in the coming decade.

Even as his work on GRACE gravity measurements occupied a significant amount of his time, John continued to explore a wide range of geophysical and planetary science topics. These include using measurements of Europa's tides to constrain the thickness of its icy shell,[17] analyzing GNSS-based surveying of horizontal crustal motion to locate sources of deformation,[18] and constraining changes in Alaskan permafrost using InSAR measurements.[19] He also continued his string of important GIA studies, for example, investigating the impact of lateral variations in mantle viscosity on ongoing GIA-driven crustal motion in Antarctica,[20] and using the GRACE measurements of long-term rate of gravity change in North America to place constraints on mantle viscosity.[21]

In addition to his illustrious career as a research scientist, John was an outstanding teacher and mentor, teaching physics from freshman introductory level to graduate level, and mentoring a large number of graduate students and post-doctoral scholars, always with the patience and humility that were the defining elements of his character. He also collaborated with many junior scientists from around the world, including from Europe, India, China, and Japan, who made the pilgrimage to Colorado to visit and learn from him. John loved music, especially opera, a passion he exercised while attending the annual meeting of the European Geoscience Union held in Vienna, albeit with a less formal attire than those around him. He played many musical instruments, including the piano, trumpet—which he learned as an undergraduate student in the University of Michigan marching band—and loved to play bluegrass and folk music on the banjo and guitar.

John had a lifelong passion and love for outdoor adventures and nature that were instilled in him by his parents, shared with Ann, and passed on to his children, Katie and Andrew. He had an abiding love of the Rocky Mountains. He was a passionate hiker, backpacker, cross-country skier, and road biker. John climbed every named peak in Rocky Mountain National Park and the Indian Peaks, and he would often leave home in the morning, climb four local peaks (South Boulder Peak, Bear Peak, Green Mountain, and Flagstaff), and return in time for lunch. He and his family would enjoy extensive backpacking trips in the summer and winter throughout Colorado, Wyoming, and Utah. For his often lone, week-long cross-country ski trips in the wilderness of Wyoming, John would dig snow caves to sleep in evenings and re-use those same caves on the way back. On the final day of the 2013 international workshop on polar ice sheets in Ilulissat, Greenland, John headed outdoors to hike a sector of the Greenland ice sheet together with a small group of somewhat hesitant junior colleagues. With the Sun circling in the sky all day long with no sunset, the group hiked for nearly twenty hours, returning only shortly before the bus departed for the airport. His love of nature and passion for science were seamless.

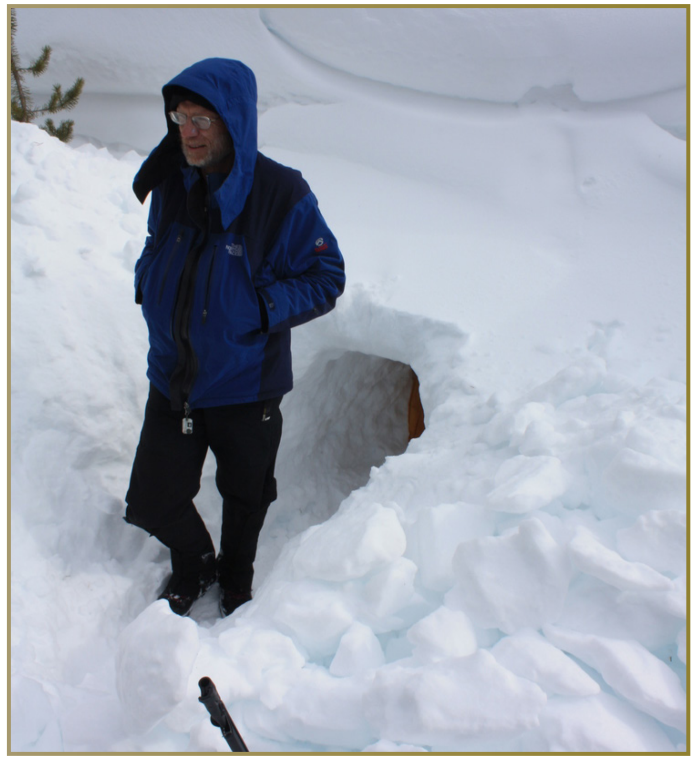

Figure 3 John outside a snow cave that he dug to sleep on a winter cross-country ski trip in Wyoming.

John passed away on November 11, 2015, in Boulder, Colorado. We miss him. For us, and many of his collaborators, interactions with John became highlights of our professional career and his friendship gave us an optimistic sense that brilliance and deep humanity could so easily and graciously coexist.

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References

1 Wahr, J. M. 1981a. Body tides on an elliptical, rotating, elastic and oceanless Earth. *Geophys. J. Int.* 64:677–703.

2 Wahr, J. M. 1981b. The forced nutations of an elliptical, rotating, elastic and oceanless Earth. *Geophys. J. Int.* 64:705–727.

3 Han, D. Z., and J. Wahr. 1989. *Post-Glacial Rebound Analysis for a Rotating Earth.* Slow Deformation and Transmission of Stress in the Earth, Vol. 49. Washington, D.C.: American Geophysical Union.

4 Paulson, A., S. J. Zhong, and J. Wahr. 2007. Inference of mantle viscosity from GRACE and relative sea level data. *Geophys. J. Int.* 171:497–508.

5 Mitrovica, J. X., and J. Wahr. 2011. Ice age Earth rotation. *Annu. Rev. Earth Planet. Sci.* 39:577–616.

6 Trupin, A. S., M. F. Meier, and J. M. Wahr, 1992, The effect of melting glaciers on the Earth's rotation and gravitational field: 1965-1984. *Geophys. J. Int.* 108:1–15.

7 Van Dam, T. M., et al. 1997. Predictions of crustal deformation and of geoid and sea level variability caused by oceanic and atmospheric loading. *Geophys. J. Int.* 129:507–517.

8 Wahr, J., D.Z. Han, and A. Trupin. 1995. Predictions of vertical uplift caused by changing polar ice volumes on a viscoelastic Earth. *Geophys. Res. Lett.* 22:977–980.

9 Dickey, J. O., et al. 1997. *Satellite Gravity and the Geosphere: Contributions to the Study of the Solid Earth and Its Fluid Envelopes.* National Research Council Report. Washington, D.C.: National Academies Press.

10 Yoder, C. F., et al. 1983. Secular variations of Earth's gravitational harmonic J_2 coefficient from Lageos and the non-tidal acceleration of Earth rotation. *Nature* 303:757–762.

11 Wahr, J., M. Molenaar, and F. Bryan. 1998. Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. *J. Geophys. Res. Solid Earth* 103:30205–30229.

12 Wahr, J., S. Swenson, and I. Velicogna. 2006. Accuracy of GRACE mass estimates. *Geophys. Res. Lett.* 33:L06401.

13 Velicogna, I., and J. Wahr. 2006a. Acceleration of Greenland ice mass loss in spring 2004. *Nature* 443:329–331.

14 Velicogna, I., and J. Wahr. 2006b. Measurements of time-variable gravity show mass loss in Antarctica. *Science* 311:1754–1756.

15 Jacob, T., et al. 2012. Recent contributions of glaciers and ice caps to sea level rise. *Nature* 482:514–518.

16 Tiwari, V. M., J. Wahr, and S. Swenson. 2009. Dwindling groundwater resources in northern India, from satellite gravity observations. *Geophys. Res. Lett.* 36:L18401.

17 Wahr, J. M., et al. 2006. Tides on Europa, and the thickness of Europa's icy shell. *J. Geophys. Res. Planets* 111:E12005.

18 Wahr, J., et al. 2013. The use of GPS horizontals for loading studies, with applications to northern California and southeast Greenland, *J. Geophys. Res. Solid Earth* 118:1795–1806.

19 Liu, L., T. Zhang, and J. Wahr. 2010. InSAR measurements of surface deformation over permafrost on the North Slope of Alaska. *J. Geophys. Res. Earth Surface* 115:F03023.

20 Geruo, A., J. Wahr, and S. J. Zhong. 2013. Computations of the viscoelastic response of a 3-D compressible Earth to surface loading: An application to glacial isostatic adjustment in Antarctica and Canada. *Geophys. J. Int.* 192:557–557.

21 Paulson, A., S. J. Zhong, and J. Wahr. 2007, Inference of mantle viscosity from GRACE and relative sea level data, *Geophys. J. Int.* 171, 497-5082007.