Development of Global Heat and Freshwater Anomaly Analyses

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1. Project Summary

We perform analyses of ocean heat content and salinity distribution and their variability to assess the role of ocean heat and freshwater storage in climate change. These assessments include quantification of year-to-year global upper (0-750 m) ocean heat content changes and global ocean surface salinity changes for the annual NOAA-led *State of the Climate* report, published as a supplement to the *Bulletin of the American Meteorological Society* (BAMS). We also work to quantify errors in estimates of upper ocean heat content, and to reduce those errors as feasible. We are also making global assessments of decadal abyssal ocean warming and freshening. These analyses are important for estimating how fast and how much the earth will warm for a given time-series of atmospheric CO_2 concentration, and how much and how fast sea level will rise.

Understanding global climate variability requires knowledge of ocean temperature and salinity fields (or more precisely ocean heat and fresh water content). Accurate estimates of changes in distribution of ocean heat and fresh water content combined with analyses of how thermohaline (temperature-salinity) anomalies enter, circulate within, and leave the ocean are necessary to monitor and understand interannual to decadal changes in climate. Such fields and analyses help to verify climate models and improve their predictive skill. They also help to diagnose the components of sea level change (ocean temperature variations versus ocean mass variations) and radiative imbalance (net energy through the top of the atmosphere versus rate at which the oceans and rest of the earth warm).

This project is developing, updating, and analyzing global analyses of ocean temperature and salinity using quality-controlled compilations of in situ temperature and salinity data from CTD-equipped autonomous profiling floats (Argo), shipboard Conductivity-Temperature-Depth (CTD) instruments, eXpendable Bathy Thermographs (XBTs), moored buoys, and other sources. These data are used to estimate global ocean temperature and salinity fields, hence upper ocean heat and freshwater content variations, on annual time-scales. Historically, in situ data distributions are relatively sparse, especially before the advent of Argo. However, variations in

upper ocean heat content are closely related to variations in sea-surface height, which has been very well measured since 1993 by satellite altimeters. By exploiting this close relationship, we are able to quantify sampling errors inherent in estimating a global average of upper ocean heat content from an incomplete data set. We also exploit the relationship to improve maps of upper ocean heat content from in situ data by using the altimeter data with local correlation coefficients applied as a first guess at upper ocean heat content in poorly measured regions. We exploit recent Argo data to map salinity fields in recent years, helping to assess the roles of ocean salinity in diagnosing and forcing climate variability. Furthermore, we analyze deep ocean temperature changes as data become available, and assess their contributions to global ocean heat content and sea level budgets.

By providing analyses of ocean data this project helps NOAA to use and assess the effectiveness of the sustained ocean observing system for climate. We present some of our products in the NOAA-led annual *State of the Climate* report. Our customers include the climate modelers, the scientific climate community, and assessments such as those of the Intergovernmental Panel on Climate Change. The work is primarily carried out at NOAA's Pacific Marine Environmental Laboratory by the PMEL and JIMAR investigators, but in close consultation with the co-investigator at NASA's Jet Propulsion Laboratory.

2. Scientific and Observing System Accomplishments

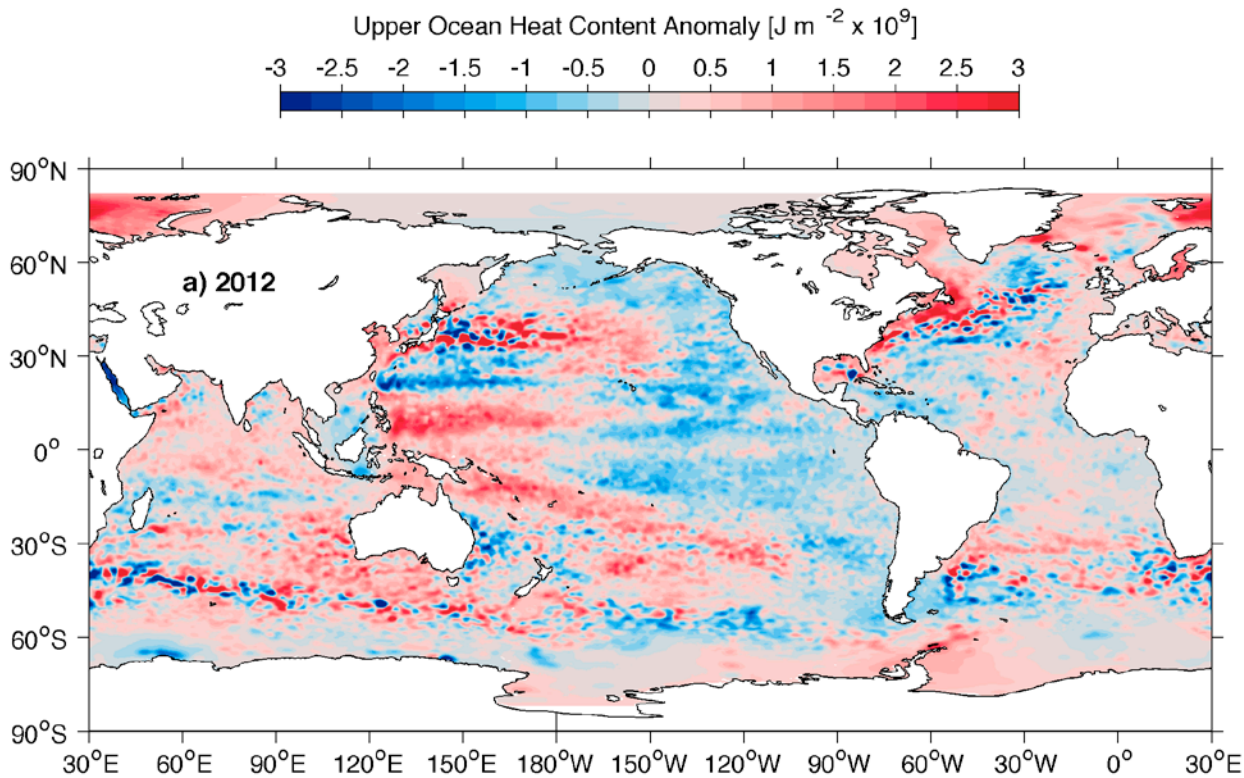

Figure 1. Combined satellite altimeter and in situ ocean temperature data upper (0 – 750 m) ocean heat content anomaly OHCA (J m^{-2}) map for 2012 analyzed following Willis et al. (2004), but relative to a 1993 – 2012 baseline. Figure after Johnson et al. (2013a).

In FY2013 we produced maps (e.g., Fig. 1) of annual upper (0-750 m) ocean heat content primarily for the ice-free portions of the globe from 1993 through 2012 that well resolve smaller (sub-gyre) scale spatial variability over shorter (year-to-year) time-scales. We discuss the results in the BAMS *State of the Climate in 2012* report (Johnson et al., 2013a). In brief, regional maps of heat content reflect changes in ocean circulation and these regional signals are an important component of local sea level rise. Prior to making these maps, we removed Argo float profile data with known potential serious pressure biases from our database, and applied published annual fall rate correction estimates for deep and shallow XBT probe data.

We also produced annual average maps of Sea-Surface Salinity (SSS) anomalies for the BAMS *State of the Climate in 2011* report (Johnson et al, 2013b). These maps (e.g., Fig. 2) reflect changes in ocean currents and the hydrological cycle (evaporation and precipitation) over the ocean.

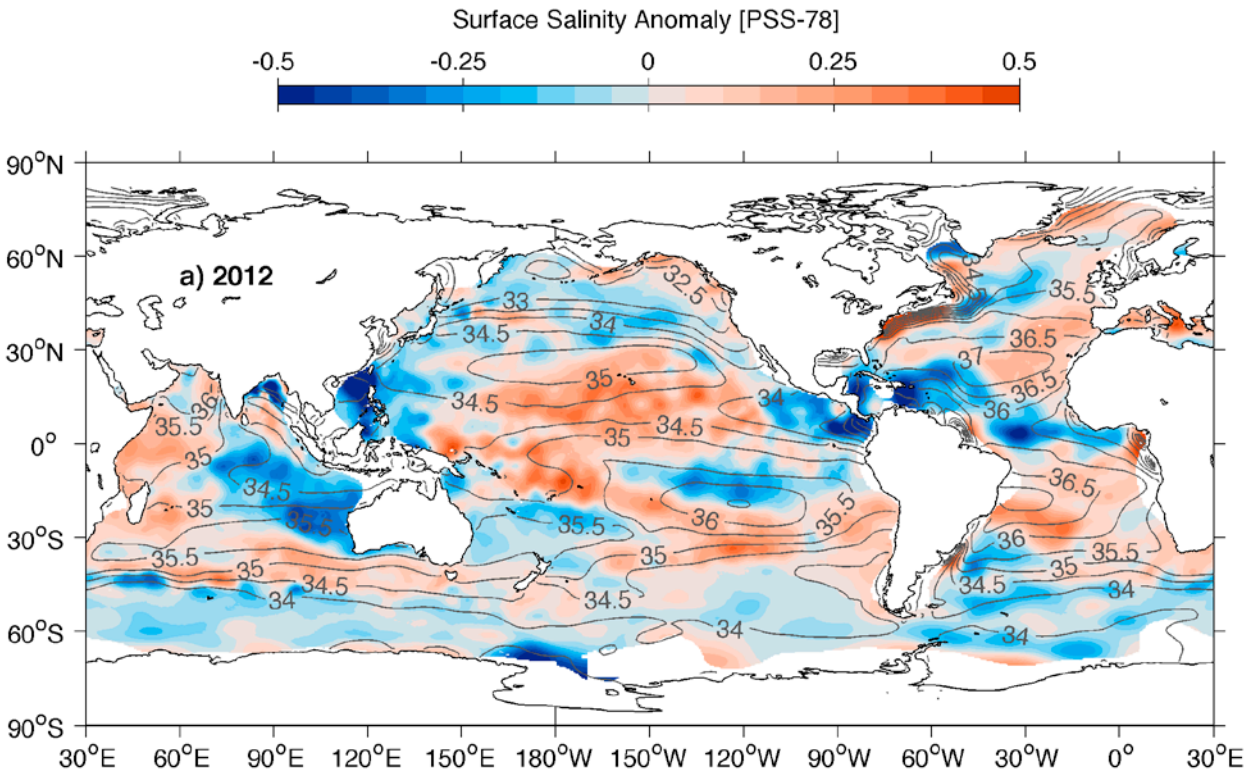

Figure 2. Map of the 2012 annual surface salinity anomaly estimated from Argo data [colors in PSS-78] with respect to a climatological salinity field from WOA 2001 [gray contours at 0.5 PSS-78 intervals]. White areas are too data-poor to map. While salinity is often reported in practical salinity units, or PSU, it is actually a dimensionless quantity reported on the 1978 Practical Salinity Scale, or PSS-78. Figure after Johnson et al. (2013b).

Global integrals of upper (0-700 m) ocean heat content anomalies from four different research groups (Fig. 3) are also discussed in the BAMS *State of the Climate in 2012* report (Johnson et al., 2013a). These curves show a substantial heat gain in the upper ocean over the past two decades. In fact, the oceans take up about 93% of the heat the Earth's climate system has been gaining over the past several decades, a key to diagnosing climate change.

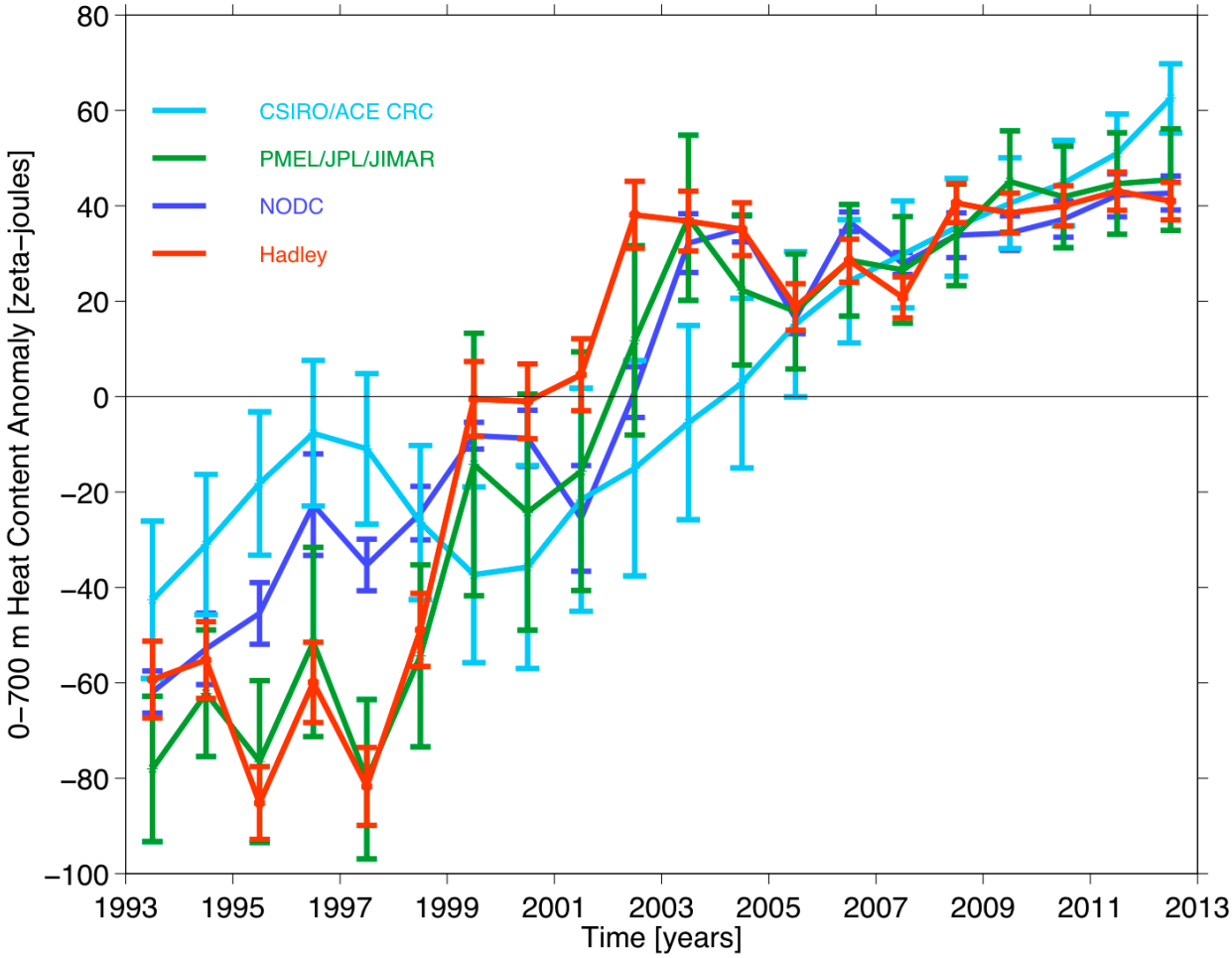

Figure 3. Time series of annual average global integrals of in situ estimates of upper (0 – 700 m) OHCA (10^{21} J, or ZJ) for 1993 – 2012 with standard errors of the mean. Details are discussed in Johnson et al. (2013a).

We have expanded our yearly ocean heat content anomaly estimates from 1993 back to 1950, and in five distinct depth layers (0–100, 100–300, 300–700, 700–900, and 900–1800 m). These depth layers are chosen based on historical in situ sampling patterns arising from instrument changes and large-scale oceanographic observation initiatives. We compute the global integral for each of these layers along with its sampling uncertainty. These anomalies are all relative to a new monthly 2005–2010 climatology based mostly on Argo data. The use of a monthly climatology generated over a relatively short, homogeneously and well-sampled time period is only possible because of Argo, but avoids all sorts of potential aliasing problems relative to using the seasonal mixed-era climatologies of the past. We submitted this work to a refereed scientific journal early in FY2013, and have revised it and resubmitted it after review.

In addition to the BAMS upper ocean heat content and sea surface salinity reports, we contributed a sidebar to the BAMS report on a slowdown in the northward flow of Antarctic Bottom Water since the 1980s (Johnson and Purkey, 2013). We also published several other manuscripts related to this project in the scientific literature, including papers on seasonal and decadal variations in ocean mass (Johnson and Chambers, 2013), an improved climatology of

surface currents from drifters (Lumpkin and Johnson, 2013), new estimates of climate response constrained by surface temperature and ocean heat content records (Otto et al., 2013), a global synthesis of Antarctic Bottom Water freshening during the 1990s and 2000s (Purkey and Johnson, 2012) that is featured in the Repeat Hydrography annual progress report, and a Monthly Isopycnal/Mixed-layer Ocean Climatology (MIMOC; Schmidtko et al., 2013) that is featured in the U.S. Argo consortium FY2013 annual progress report.

The project web page is http://oceans.pmel.noaa.gov/.
The web page for the MIMOC (Monthly Isopycnal/Mixed-layer Ocean Climatology) is http://www.pmel.noaa.gov/mimoc/.

3. Outreach and Education

Johnson served as a lead author for Chapter 3: Observations: Oceans for Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Intergovernmental Panel on Climate Change Fifth Assessment Report. He also currently advises a University of Washington School of Oceanography Graduate Student, Sarah Purkey, and an NRC Postdoctoral Research Fellow, Dr. Marion Meinvielle. On 31 July 2013, he gave a public lecture on "The Warming Ocean's Role in Climate" at the Nisqually Wildlife Refuge Summer Lecture Series to a full auditorium. The following are links to news stories reported in FY2013 regarding Argo or on various publications co-authored by Johnson which are related to this project:

Schultz, Colin (3 September 2013). New surface ocean current maps created from drifter data. *EOS-Transactions American Geophysical Union, Vol. 94, Issue 29, page 260*.
Abraham, John (28 August 2013). Global warming and oceans: what are the known unknowns?. *Climate Consensus - the 97%, hosted by The Guardian*.
Kennedy, Caitlyn (28 August 2013). Ocean Saltiness Provides Clues to Precipitation Patterns. *ClimateWatch Magazine*.
Kennedy, Caitlyn (30 July 2013). 2012 State of the Climate: Ocean Heat Content. *ClimateWatch Magazine*.
Schultz, Colin (16 July 2013). Decadal shifts in ocean basin mass detected in satellite observations. *EOS-Transactions American Geophysical Union, Vol. 94, Issue 36, page 320*.
Schultz, Colin (21 May 2013). A global map of the ocean's climate. *EOS-Transactions American Geophysical Union, Vol. 94, Issue 21, pages 196-197*.
Clarke, Sarah, and Katie Hamann (20 May 2013). New reports suggests global warming could be slower than first thought. *ABC News*.
Marshall, Michael (19 May 2013). A second chance to save the climate . *New Scientist*.
Harvey, Fiona (19 May 2013). Climate change: human disaster looms, claims new research. *The Guardian*.
McGrath, Matt (19 May 2013). Climate slowdown means extreme rates of warming 'not as likely'. *BBC News*.
Newton, Alicia (27 March 2013). Oceanography: Rise from below. *Nature Geoscience*.
Purkey, Sarah and Gregory Johnson (27 March 2013). Surprising Depth to Global Warming's Effects. *Live Science*.
Qiu, Jane (16 November 2012). Winds of Change. *Science*.

4. Publications and Reports

4.1. Publications by Principal Investigators

Published:

Abraham, J. P., M. Baringer, N. L. Bindoff, T. Boyer, L. J. Cheng, J. A. Church, J. L. Conroy, C. M. Domingues, J. T. Fasullo, J. Gilson, G. Goni, S. A. Good, J. M. Gorman, V. Gouretski, M. Ishii, G. C. Johnson, S. Kizu, J. M. Lyman, A. M. Macdonald, W. J. Minkowycz, S. E. Moffitt, M. D. Palmer, A. R. Piola, F. Reseghetti, K. Schuckmann, K. E. Trenberth, I. Velicogna, and J. K. Willis, 2013: A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. *Rev. Geophys. 51*, 450–483, doi: 10.1002/rog.20022.

Johnson, G.C ., and D. P. Chambers, 2013: Ocean bottom pressure seasonal cycles and decadal trends from GRACE Release-05: Ocean circulation implications. *J. Geophys. Res.*, **118**, doi: 10.1002/jgrc.20307.

Johnson, G. C., J. M. Lyman, G. S. E. Lagerloef, and H.-Y. Kao, 2013b: Sea surface salinity. In *State of the Climate in 2012*, Global Oceans. *Bull. Am. Meteorol. Soc.*, **94**, S57–S60. doi: 10.1175/2013BAMSStateoftheClimate.1.

Johnson, G. C., J. M. Lyman, J. K. Willis, S. Levitus, T. Boyer, J. Antonov, S. A. Good, C. M. Domingues, S. Wijffels, and N. Bindoff, 2013a: Ocean heat content. In *State of the Climate in 2012*, Global Oceans, *Bull. Am. Meteorol. Soc.*, **94**, S50–S53, doi:10.1175/2013BAMSStateoftheClimate.1.

Johnson, G. C., and S. G. Purkey, 2013: Slow-down of the lower, southern limb of the meridonal overturning circulation in recent decades. In *State of the Climate in 2012*, Global Oceans, *Bull. Am. Meteorol. Soc.*, **94**, S68–S69. doi:10.1175/2013BAMSStateoftheClimate.1.

Lumpkin, R., and G. C. Johnson, 2013: Global ocean surface velocities from drifters: Mean, variance, El Niño–Southern Oscillation response, and seasonal cycle. *J. Geophys. Res.*, **118**, 2992–3006, doi: 10.1002/jgrc.20210,

Otto, A., F. E. L. Otto, O. Boucher, J. Church, G. Hegerl, P. M. Forster, N. Gillett, J. Gregory, G. C. Johnson, R. Knutti, N. Lewis, U. Lohmann, J. Marotzke, G. Myhre, D. Shindell, B. Stevens, and M. R. Allen, 2013: Energy budget constraints on climate response. *Nature Geosci.*, **6**, 415–416, doi: 10.1038/ngeo1836.

Purkey, S. G., and G. C. Johnson, 2013: Antarctic Bottom Water warming and freshening: Contributions to sea level rise, ocean freshwater budgets, and global heat gain. *J. Climate*, **26**, 6105–6122, doi: 10.1175/JCLI-D-12-00834.1.

Schmidtko, S., G. C. Johnson, and J. M. Lyman, 2013: MIMOC: A global monthly isopycnal upper-ocean climatology with mixed layers. *J. Geophys. Res.*, **118**, 1658–1672, doi: 10.1002/jgrc.20122.

4.2. Other Relevant Publications

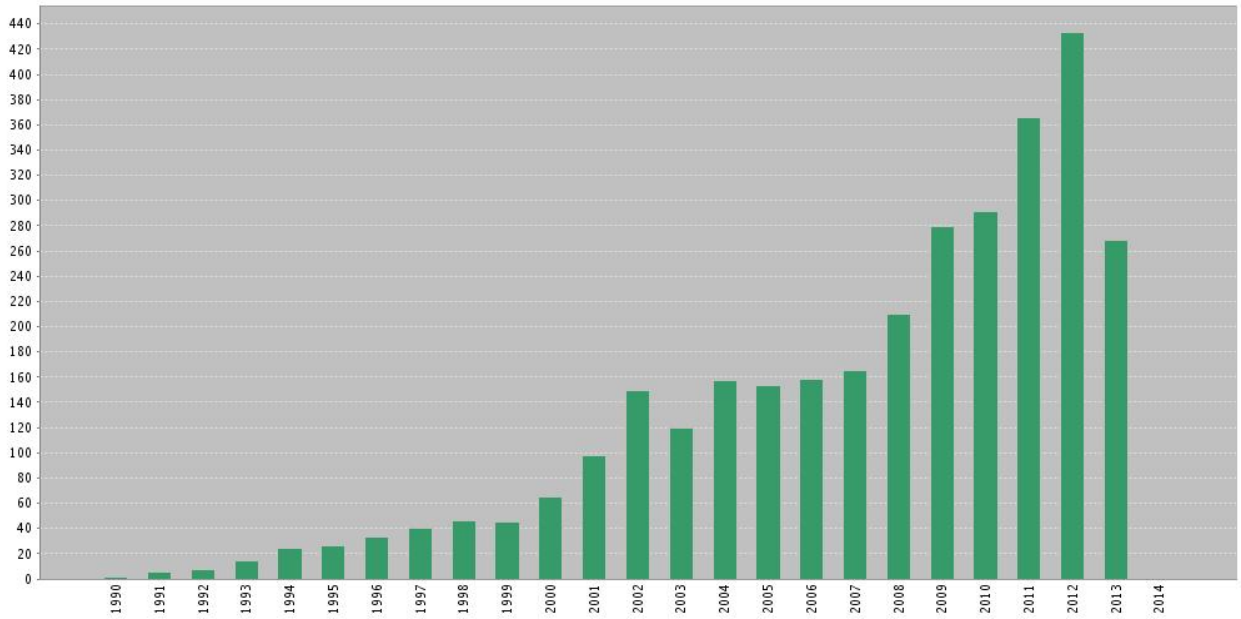

Figure 4: Citations per calendar year of G. C. Johnson's publications in the refereed scientific literature as of 21 October 2013 according to ISI Web of Science®, with 3154 total.

The work of this group is widely cited in the refereed scientific literature (e.g., Fig. 4). For instance, as of 21 October 2013 Purkey and Johnson (2010, *J. Climate*) had been cited at least 59 times and Lyman et al. (2010, *Nature*) at least 77 times.