Progress Report

World Ocean Database Updates and Seasonal Estimates of Ocean Temperature, Salinity, Heat Content, and Steric Sea Level

Period of Activity: 01 October 2022 – 30 September 2023

Principal Investigator
Name Tim Boyer
Institute National Center for Environmental Information
Address 1315 East-West Highway
Silver Spring, MD 20910
Email:tim.boyer@noaa.gov
Tel:202-744-0271

Financial Contact
Name Susan Stevens
Institute National Center for Environmental Information
Address 151 Patton Avenue
Asheville, NC 28801

Email:susan.stevens@noaa.gov
Tel: (828) 271-4223

Signature Date

Signature Date

Budget Summary
FY 2022: Total Cost:
$440,000
Cost breakdown: Labor costs for Alexey Mishonov, Alexandra Grodsky, Jim

Beauchamp, at the Cooperative Institute for Satellite Earth System Studies (CISESS) at the University of Maryland, College Park, MD and cloud computing costs at the University of Colorado

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Tim Boyer
National Center for Environmental Information (NCEI), Silver Spring, MD

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1. Project Summary

The World Ocean Database (WOD) is the world's most extensive collection of uniformly formatted, quality controlled, subsurface ocean profile data available without restriction. Profile data are measurements at multiple depths from the ocean surface to the ocean bottom at a single geographic location during a finite time period – the time it takes to lower and raise the measuring instrumentation. Singly, profiles can provide a snapshot of oceanographic conditions at one location at one time. Combined with other available profiles over discrete time intervals, a view of regional and even global changes in the ocean can emerge. Programs such as Argo profiling floats and Ship of Opportunity (SOOP) expendable bathythermographs (XBTs) have sophisticated deployment, data retrieval, and quality control procedures in place across the globe. WOD incorporates these data with historical and recent oceanographic cruise data, preserving the quality control flags set by these programs along with WOD quality flags, providing a uniform format and delivery system for all data. Using temperature and salinity measurements, ocean heat content and salt content changes are calculated against baseline long-term means, utilizing WOD for both the baseline mean and the discrete time period differences (anomalies) from the mean. Ocean heat content is an important component of the Earth's energy budget, ameliorating to some extent the imbalance between incoming solar radiation and outgoing heat radiation, while ocean salt and freshwater content is important for understanding the global water cycle, including melting of continental glaciers. Time series products include one-degree global fields of temperature anomalies, salinity anomalies at various depths down to 2000 m, ocean heat content, mean temperature and salinity anomalies, and thermosteric (temperature dependent), halosteric (salinity dependent), and total steric (temperature + salinity dependent) sea level change for the top 700 m and 2000m of the global ocean, as well as integrated global ocean heat and steric sea level change. These time series products are the culmination of the global ocean observing system and are used extensively for oceanographic, environmental, and climate research. Further, this project enables scientific research to better constrain uncertainties in the calculations of these variables, error statistics, and improvements in technique. Scientific research on improved quality control of data and communication with projects, such as Argo, which are integral to the continued monitoring of ocean heat and freshwater content changes are also important components of the project.

2. Scientific and Observing System Accomplishments

This section should be written as a narrative that summarizes accomplishments in FY 2021. Please include responses to the following bullets, recognizing that you may not have information for the entire list:

- The WOD was updated four times in FY23: November, 2022, January, 2023, May, 2023, and August, 2023. WOD is available through https://www.ncei.noaa.gov/products/world-ocean-database. The updates to WOD included 259,650 casts from the period July 1, 2022 through June 30, 2023, which included 162,509 Argo casts (cycles), 21,138 casts (daily means in this case) from the tropical moored buoy arrays and OceanSITES moored buoys, and 66,488 casts from the Global Temperature and Salinity Profile Project (GTSPP). GTSPP is an international project dedicated to aggregating all near-real time profile data from the Global Telecommunications System (GTS) of the World Meteorological Organization (WMO). Near-real time refers to reports which are available within 48 hours of measurement. Argo and the tropical moored buoy data are also available in near-real time from their respective Data Assembly Centers. GTSPP includes casts from the Ship of Opportunity Program (SOOP) Expendable Bathythermograph (XBT) network, instrumented pinnipeds, gliders, and ship-based Conductivity-Depth-Temperature (CTD) instruments. All near-real time data were put through WOD quality control procedures in addition to the quality control performed by the originators. The near-real time data streams represent data from a number of NOAA investments: Argo, TAO (Pacific), PIRATA (Atlantic), RAMA (Indian) moored buoy arrays, SOOP XBTs. While each of these projects has its own quality control procedures and distribution systems, incorporation into the WOD provides a wider audience, a uniform format, and an extra layer of quality control in addition to the originators own quality control flags. This quality control is unique in that it is specifically geared to tracking down data which may be high quality measurements, but are outliers compared to historical data and in the computations of heat and salt content.

- In addition to the near-real time data sources. 198,868 delayed-mode oceanographic casts were added to the WOD. Delayed-mode casts are those which are not available within 48 hours of measurement or replacements for the near-real time data, often at higher resolution and with additional quality control and calibration. These casts were taken in many years from 2000 to 2020. While this project is not primarily concerned with historical data, older casts can be very helpful in understanding the previous state of the ocean for comparison with the present state to understand long-term change. While the Argo program, and to a lesser extent the tropical moored buoy arrays and SOOP, are the main source of oceanographic profile data for monitoring heat and salt, there are areas of the ocean for which other data sources can augment, or in some cases, be the sole source of subsurface temperature and salinity information. These areas include the high Arctic, shelf regions, the Indonesian Throughflow, and Southern Ocean under-ice regions. Further, many of the data added to the WOD represent significant investment from

NOAA and other U.S. sources and making them readily accessible through WOD increases their utility. Finally, some of these data represent adjusted, calibrated, and/or higher resolution versions of previous near-real-time data, replacing existing data with higher quality versions. Some of the main sources for the non-real time (delayed-mode) data are the CLIVAR and Carbon Hydrographic Data Office (CCHDO – global coverage), NOAA Northeast Fisheries Science Center (NEFSC, US Atlantic shelf), the Woods Hole Ice-Tethered Profiler Program, the International Council for the Exploration of the Seas (ICES, international contribution, mainly eastern Atlantic) and the OceanSITES research moored buoys. Further, international data exchanges through official and unofficial agreements carried out routinely by NCEI add more data to the WOD.

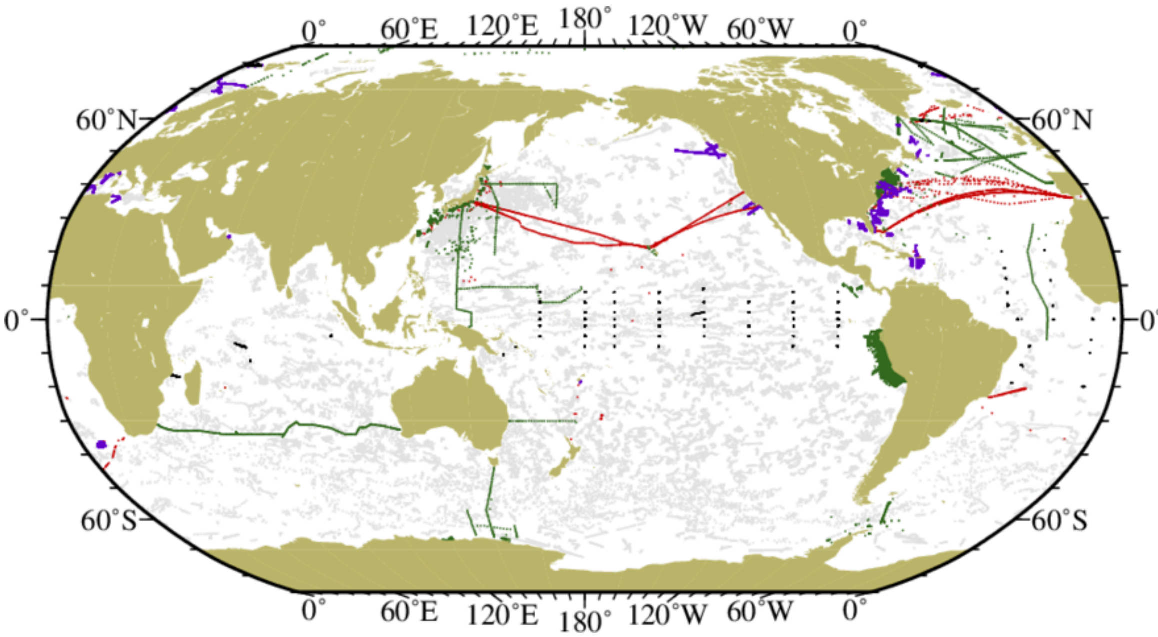

Figure 1: Data added to WOD in FY23 from sources other than near-real time – measurements representing 20+ year period January, 2000 – June 30, 2023, including bottle and CTD casts (dark green), glider cycles (purple), moored buoy daily means (black), and delayed-mode Argo cycles (grey).

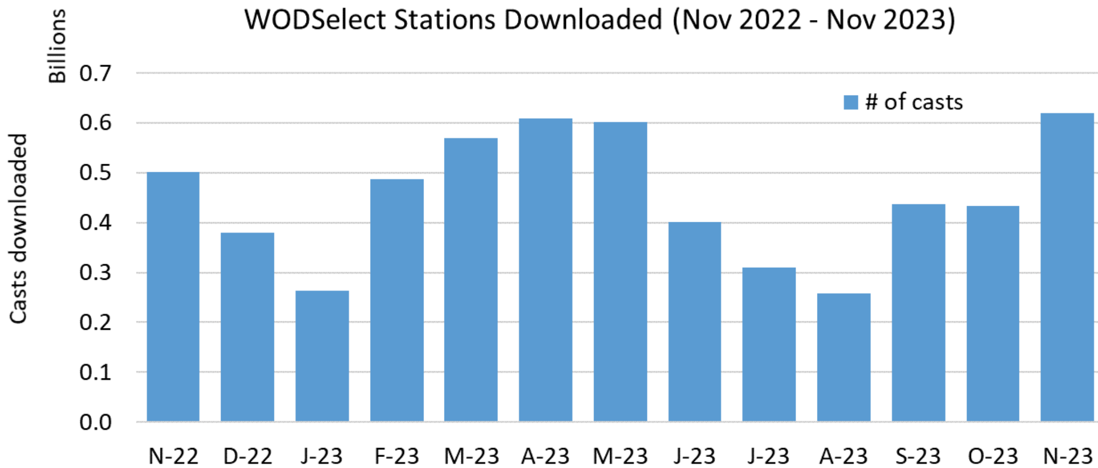

Figure 2 Oceanographic Casts downloaded from and unique downloaders using WODselect from Nov 2022 to Nov 2023.

It is difficult to present statistics on the utility of WOD for research, as it can be downloaded from NCEI in a number of forms (sorted by year, sorted by geographic area – 10 degree squares) as well as subset through the WODselect tool. Further, other international databases such as EN4 use WOD as a major data source, and so WOD data are disseminated (with different quality control flags and formats) through many secondary sources. To give some idea of the utility of WOD, **Figure 2** shows the number of casts downloaded through WODselect subsetting tool by month for November, 2022 to November, 2023. For perspective, there are approximately 18.8 million casts (collocated profiles of oceanographic variables) in the entire WOD, so 200 million (.2 billion) casts downloaded is more than 10 times the entire database. Some users download the entire WOD through WODselect, while others subset just a few hundred or a few thousand casts. There were 2,001 new unique users who downloaded from WODselect in FY23 in addition to downloads from some of the 29,134 previous users of WODselect. Many more used WODselect as a tool to inventory oceanographic data without downloading their subsets. As stated above, WODselect is just one of a number of ways to access WOD data through NCEI and other sources.

- The Global Ocean Heat and Salt Content Dataset was updated four times in FY23, in the same months as the WOD (see above). Data and figures are available at https://www.ncei.noaa.gov/access/global-ocean-heat-content/. The four quarterly updates consist of seasonal temperature anomalies at 26 discrete levels from the surface to 2000 m depth, salinity anomalies at the same discrete levels, seasonal integrals of heat content for the upper 700 m (**Figure 3**) and 2000m, seasonal averages of thermosteric, halosteric, and total steric sea level change for the upper 700m and upper 2000m, and seasonal averages of temperature and salinity anomaly for the upper 100m, upper 700m and upper 2000m. All fields are on one-degree latitude/longitude grids and include error statistics. In addition, global integrals of ocean heat content (in Joules) and global averages of thermosteric, halosteric, and total steric sea level change (in millimeters), and global average temperature and salinity change were calculated and made available. In FY23, yearly (2022) and pentadal (2018-2022) fields were also calculated for all above noted variables. Calculating these fields involved significant quality control of the underlying data, quality control information which was fed back into the WOD.

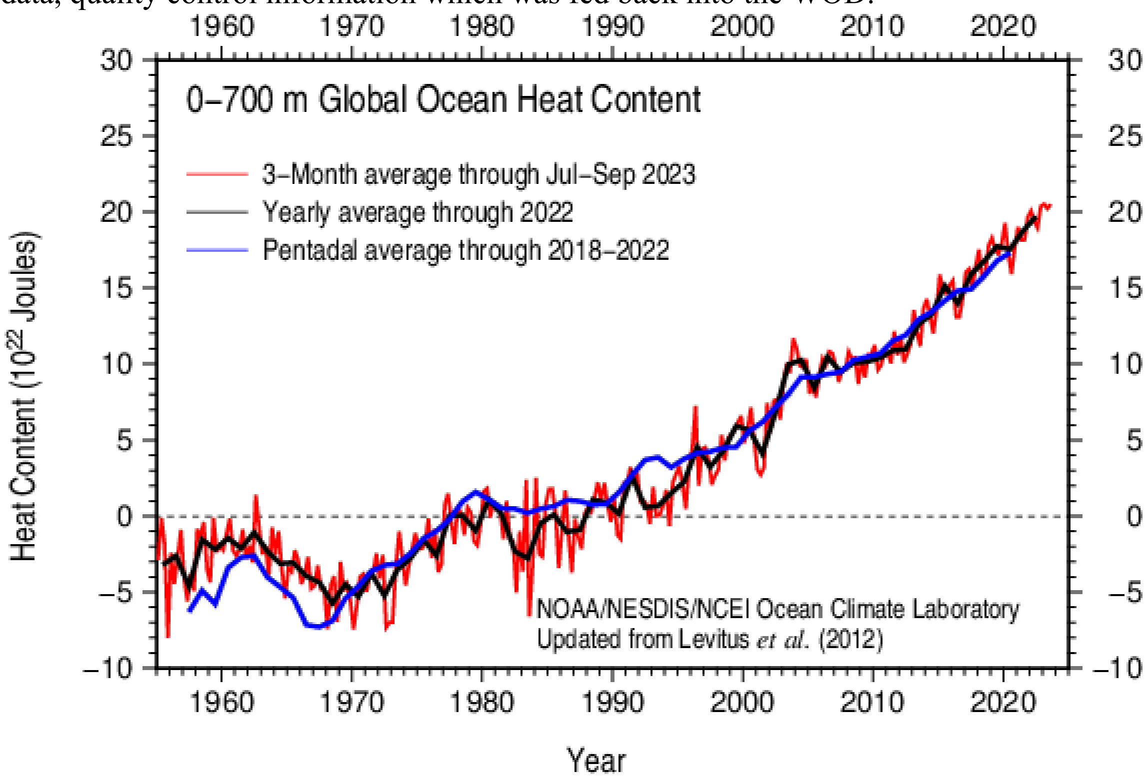

Figure 3 Ocean heat content change (0-700m) from in situ profile data from https://www.ncei.noaa.gov/access/global-ocean-heat-content/

- A continued emphasis was placed this year on developing an understanding and utilization of calculated salinity content (and freshwater content) anomaly fields. In partnership with NOAAs National Center for Environmental Prediction (NCEP), routines were previously developed for blending the sea surface salinity anomaly fields calculated under the WOD project and Aquarius, SMOS, and SMAP satellite fields of sea surface salinity (Xie *et al.*, 2014). Fields of monthly sea surface salinity have been generated routinely using WOD algorithms and GTSPP near-real time data and sent to NCEP by the 4th of each month for blending. The blended fields are then used for medium to long-term climate prediction The results are used directly in the NCEP Monthly Climate Forecast briefing. Procedures are also in place to provide five day composite SSS gridded fields from Argo and GTSPP sources to NCEP. This new system is still in the test phase but could greatly enhance SSS use in NCEP climate forecast models

- C. Paver heads a project with NOAAs Office of Marine and Aviation Operations (OMAO) to ensure that all data taken on NOAA ships will be sent to NCEI, archived, and, where appropriate, uploaded to the WOD. This project has reached the stage in which all CTD data can be submitted directly from NOAA ships to the archive. Once all ships are participating, this will enhance the data available from near-real time sources in the WOD. This is part of a concerted effort by our project to ensure that all NOAA subsurface profile data are available through the WOD.

- J. Reagan has made available the climatological mean fields of mixed-layer depth (Figure 4), the necessary step to adding mixed-layer depth change as an available climate change variable. Ocean heat content in the mixed layer, as well as changes to the mixed layer depth will be added as climate indices.

- J. Reagan was first author on the subsurface salinity section of the Bulletin of the American Meteorological Society (BAMS) State of the Climate 2021, which was published in 2022. The subsurface section of the State of the Climate utilized all available salinity data for the year 2020 from the WOD.

- T. Boyer, R. Locarnini, A. Mishonov, J. Reagan were co-authors on the ocean heat content section of the Bulletin of the American Meteorological Society (BAMS) State of the Climate 2021, which was published in 2022. The NCEI contribution to the ocean heat content section of the State of the Climate utilized all available temperature data for the year 2021 from the WOD.

Publications and reports

(see below under publications including primary investigator)

3. Outreach and Education

- The Global Ocean Heat Content is one of the climate variables available through NOAAs climate.gov website dashboard. This brings our work from this project to the main public access point of NOAA for climate change information. The Global Ocean Heat Content field calculated from WOD is an official Climate Data Record (CDR). A CDR must pass rigorous algorithm and procedural tests, including public availability of all software used in computation. This ensures the transparency and repeatability of the calculations

- WOD help desk (OCLhelp@noaa.gov, OCL= Ocean Climate Lab) answered numerous questions from users from the elementary school through graduate school level and from the general public regarding oceanographic profile data, ocean heat and salt content, and climate change in general. The help desk also generated custom figures and special format data sets for users.

- T. Boyer is co-lead with Benoit Meyssignac an effort by the World Climate Research Program (WCRP) Global Energy and Water Cycle Exchanges Project (GEWEX) Data and Analysis Panel (GDAP) to quantify uncertainty in the estimates of Earth's Energy Imbalance (EEI) with an emphasis on ocean heat content. GEWEX held a workshop in Frascati, Italy in May, 2023 at which uncertainties in ocean heat content from various methods – in situ temperature profiles, satellite (altimeter for sea level, gravimeter for mass balance), and reanalyses. Contributions to two papers on global and regional ocean heat budgets and Earth's Energy Imbalance were direct results of this workshop and a previous workshop from FY22.

- A major thrust in FY23 was the direct availability of the WOD and Argo data from the Global Data Assembly Center (GDAC) in the cloud, facilitating greater incorporation into available tools for a more equitable distribution of ocean profile data and information generated from these profiles. Significant progress was made in devising a system by which archived Argo data are available by cycle instead of in a monthly saved full set compressed file.

4. Publications and Reports

4.1. Publications including Principal Investigators

- Blunden, J., T. Boyer, and E. Bartow-Gillies, Eds., 2023: "State of the Climate in 2022". Bull. Amer. Meteor. Soc., 104 (9), Si–S501 https://doi.org/10.1175/2023BAMSStateoftheClimate.1.
- Boyer, T., and Coauthors, 2023: Effects of the Pandemic on Observing the Global Ocean. *Bull. Amer. Meteor. Soc.*, **104**, E389–E410, https://doi.org/10.1175/BAMS-D-21-0210.1.
- Cheng, L., Abraham, J., Trenberth, K.E. *et al.* Another Year of Record Heat for the Oceans. *Adv. Atmos. Sci.* **40**, 963–974 (2023). https://doi.org/10.1007/s00376-023-2385-2
- Forster, P. M., Smith, C. J., Walsh, T., Lamb, W. F., Lamboll, R., Hauser, M., Ribes, A., Rosen, D., Gillett, N., Palmer, M. D., Rogelj, J., von Schuckmann, K., Seneviratne, S. I., Trewin, B., Zhang, X., Allen, M., Andrew, R., Birt, A., Borger, A., Boyer, T., Broersma, J. A., Cheng, L., Dentener, F., Friedlingstein, P., Gutiérrez, J. M., Gütschow, J., Hall, B., Ishii, M., Jenkins, S., Lan, X., Lee, J.-Y., Morice, C., Kadow, C., Kennedy, J., Killick, R., Minx, J. C., Naik, V., Peters, G. P., Pirani, A., Pongratz, J., Schleussner, C.-F., Szopa, S., Thorne, P., Rohde, R., Rojas Corradi, M., Schumacher, D., Vose, R., Zickfeld, K., Masson-Delmotte, V., and Zhai, P.: Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence, Earth Syst. Sci. Data, 15, 2295–2327, https://doi.org/10.5194/essd-15-2295-2023, 2023.
- Gouretski, V., L. Cheng, and T. Boyer, 2022: On the Consistency of the Bottle and CTD Profile Data. *J. Atmos. Oceanic Technol.*, **39**, 1869–1887, https://doi.org/10.1175/JTECH-D-22-0004.1.
- Johnson, G. C., J. M. Lyman, C. Atkinson, T. Boyer, L. Cheng, J. Gilson, M. Ishii, R. Locarnini, A. Mishonov, S. G. Purkey, J. Reagan, and K. Sato (2023): Ocean heat content. In State of the Climate in 2022, Global Oceans. Bull. Am. Meteorol. Soc., 104(9), S159-162, https://doi.org/10.1175/BAMS-D-23-0076.2.
- Reagan, J., T. Boyer, C. Schmid, and R. Locarnini (2023): Subsurface Salinity. In State of the Climate in 2022, Global Oceans. Bull. Am. Meteorol. Soc., 104(9), S165-167, https://doi.org/10.1175/BAMS-D-23-0076.2.
- von Schuckmann, K., Minière, A., Gues, F., Cuesta-Valero, F. J., Kirchengast, G., Adusumilli, S., Straneo, F., Ablain, M., Allan, R. P., Barker, P. M., Beltrami, H., Blazquez, A., Boyer, T., Cheng, L., Church, J., Desbruyeres, D., Dolman, H., Domingues, C. M., García-García, A., Giglio, D., Gilson, J. E., Gorfer, M., Haimberger, L., Hakuba, M. Z., Hendricks, S., Hosoda, S., Johnson, G. C., Killick, R., King, B., Kolodziejczyk,

N., Korosov, A., Krinner, G., Kuusela, M., Landerer, F. W., Langer, M., Lavergne, T., Lawrence, I., Li, Y., Lyman, J., Marti, F., Marzeion, B., Mayer, M., MacDougall, A. H., McDougall, T., Monselesan, D. P., Nitzbon, J., Otosaka, I., Peng, J., Purkey, S., Roemmich, D., Sato, K., Sato, K., Savita, A., Schweiger, A., Shepherd, A., Seneviratne, S. I., Simons, L., Slater, D. A., Slater, T., Steiner, A. K., Suga, T., Szekely, T., Thiery, W., Timmermans, M.-L., Vanderkelen, I., Wjiffels, S. E., Wu, T., and Zemp, M.: Heat stored in the Earth system 1960–2020: where does the energy go?, Earth Syst. Sci. Data, 15, 1675–1709, https://doi.org/10.5194/essd-15-1675-2023, 2023.

- Wang, Z., T. Boyer, J. Reagan, and P. Hogan, 2023: Upper-Oceanic Warming in the Gulf of Mexico between 1950 and 2020. *J. Climate*, **36**, 2721–2734, https://doi.org/10.1175/JCLI-D-22-0409.1.

4.2. Other Relevant Publications

The publications resulting from the work involved in this project have been cited numerous times, demonstrating the utility of the work for scientific research

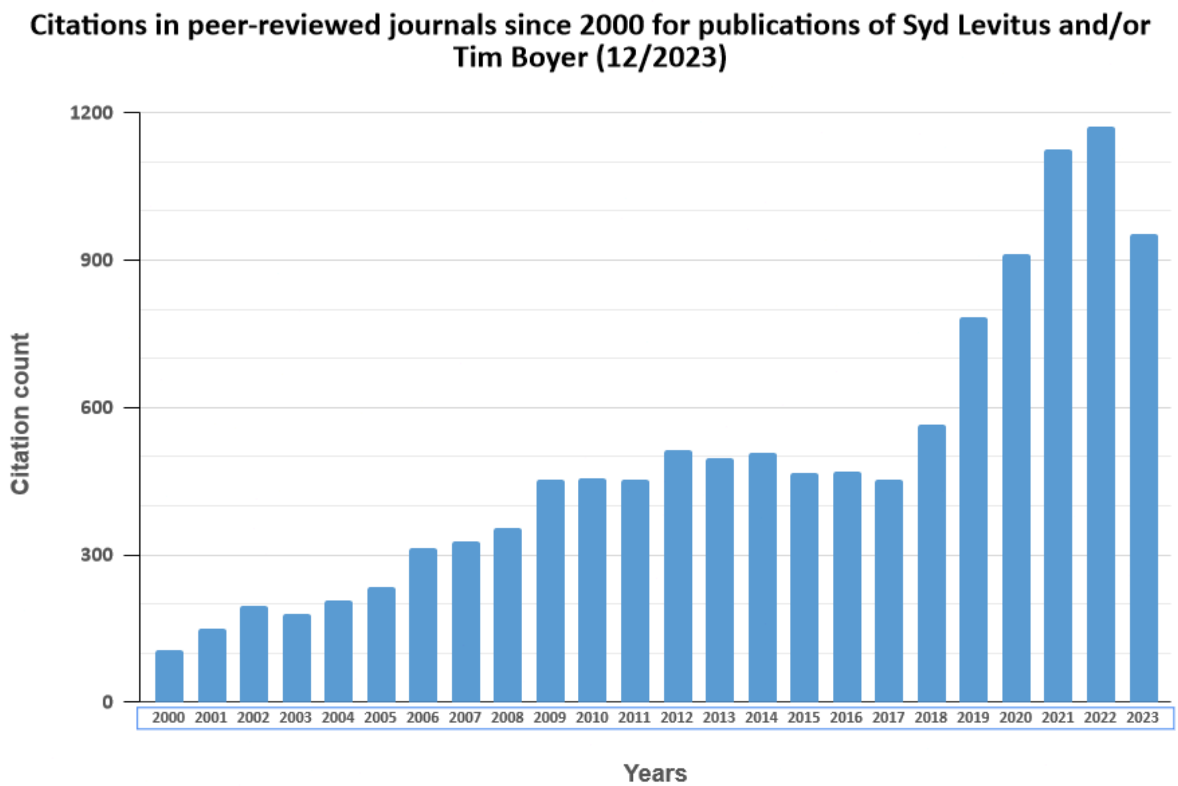

Figure 4: Citations in peer-reviewed journals since 2000 for publications with Syd Levitus and or Tim Boyer as lead or co-author (not including State of the Climate contributions).

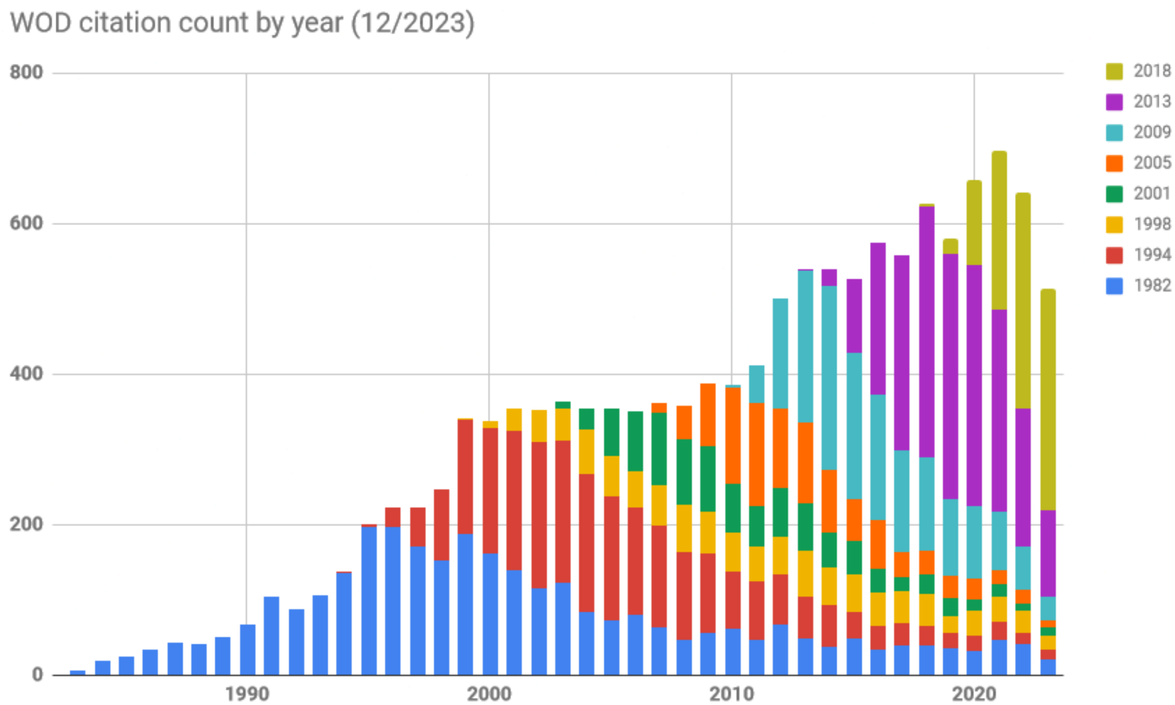

Figure 5: Citations of Levitus climatological Atlas (1982) and World Ocean Database/Atlases (1994, 1998, 2001, 2005, 2009, 2013, 2018) 1984 through Dec. 2023.

As of Dec 18, 2022, there are 900+ citations for Levitus and/or Boyer in calendar year 2023 (**Figure 4**) in addition to 500+ citations of the WOD and resultant World Ocean Atlases (**Figure 5**).

5. Data and Publication Sharing

All data and products from this project are archived and made public upon release at NCEI.

6. Project Highlight Slides