Development of Global Heat and Freshwater Anomaly Analyses

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Budget Summary
FY 2023: $215,000

Development of Global Heat and Freshwater Anomaly Analyses

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1. Project Summary

We perform, develop, update, and analyze global ocean temperature and salinity distributions and their variability to assess the roles of ocean heat and freshwater storage in climate, weather, and ecosystems. We use quality-controlled in situ ocean temperature data from Argo floats, research cruises, and a variety of other sources. We also analyze Argo salinity data to assess the roles of ocean salinity in diagnosing and forcing climate variability. We use measurements of variations of sea-surface height, sea-surface temperature, ocean mass, and top-of-the-atmosphere energy fluxes from satellites, which are closely related to variations in ocean temperature and salinity. We use these relationships to improve maps of upper ocean heat.

We quantify year-to-year global upper (0–700 m) to intermediate depth (700–2000 m) ocean heat content changes and global ocean surface salinity changes and present them in the annual NOAA-led *State of the Climate* report, published as a supplement to the *Bulletin of the American Meteorological Society* (BAMS). We edit the *Global Oceans* chapter of that report. We also work to quantify errors in estimates of ocean heat content, and to reduce those errors as feasible. We also periodically contribute to global assessments of decadal deep (> 2000 m) ocean warming and freshening, and assess their contributions to the global radiative imbalance (net energy transfer through the top of the atmosphere) and sea level budgets.

These analyses are important for estimating how fast and how much the earth will warm for a given time-line of atmospheric CO_2 concentration, how much and how fast sea level will rise, and how often Marine Heatwaves may occur. They are also related to changes in oxygen and nutrients, important for marine ecosystems and fisheries, as well as for improving weather and seasonal predictions. Analyses of how thermohaline (temperature-salinity) anomalies enter, circulate within, and leave the ocean are necessary to monitor and understand seasonal to decadal ocean variations that can affect weather, climate, and ecosystems. Such fields and analyses help to verify models and improve their predictive skill.

By performing these analyses this project helps NOAA to use and assess the effectiveness of the sustained ocean observing system for weather, climate, and even ecosystems. Our customers include oceanographers, meteorologists, climate modelers, the scientific community, and both national and international assessments. The work is primarily carried out at NOAA's Pacific Marine Environmental Laboratory by the PMEL and CIMAR investigators, in collaboration with scientists around the world.

2. Scientific and Observing System Accomplishments

In FY2023 we produced maps of annual upper (0–700 m) ocean heat content and sea surface salinity, as discussed in two sections of the Global Oceans chapter of the BAMS *State of the Climate in 2022* report (Johnson et al. 2023b, 2023c, respectively). We edited the Global Oceans chapter of that report and wrote the overview (Johnson and Lumpkin, 2023).

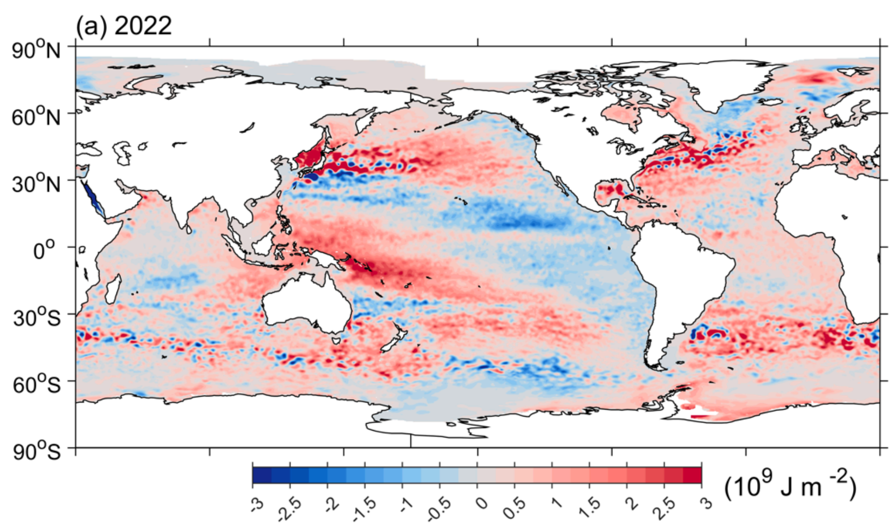

Figure 1. Combined satellite altimeter and in situ ocean temperature data upper (0 – 700 m) ocean heat content anomaly OHCA (J m^{-2}) map for 2022 analyzed following Willis et al. (2004), but relative to a 1993 – 2022 baseline. Figure after Johnson et al. (2023b).

Maps of upper ocean heat content (Fig. 1) for the ice-free portions of the globe from 1993 through 2021 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 2022* report (Johnson et al., 2023b). 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.

We also produced annual average maps of Sea-Surface Salinity (SSS) anomalies (Fig. 2) for the BAMS *State of the Climate in 2022* report (Johnson et al, 2023c). These maps reflect changes in ocean currents, ice melt, and the hydrological cycle (evaporation and precipitation) over the ocean.

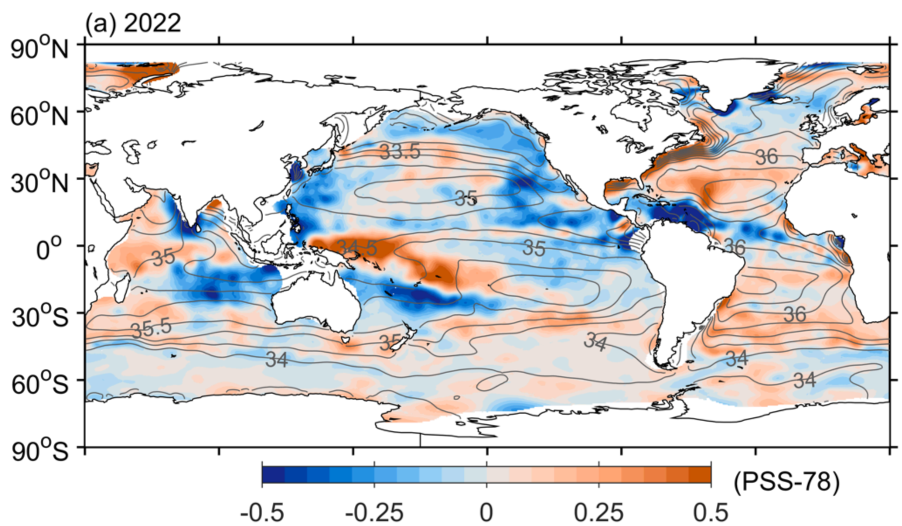

Figure 2. Map of the 2022 annual surface salinity anomaly estimated from Argo data [colors in PSS-78] with respect to a climatological salinity field from WOA 2013 [gray contours at 0.5 PSS-78 intervals]. White areas are too data-poor to map. While salinity is often reported in practical salinity units, or PSU, it is actually a dimensionless quantity reported on the 1978 Practical Salinity Scale, or PSS-78. Figure after Johnson et al. (2023c).

Global integrals of ocean heat content anomalies by five different research groups from around the world (Fig. 3) are also discussed in the BAMS *State of the Climate in 2022* report (Johnson et al., 2023b). These curves show a substantial heat gain in the ocean over the past two decades. The oceans take up about 90% of the heat the Earth's climate system has been gaining over the past several decades, a key to diagnosing climate change.

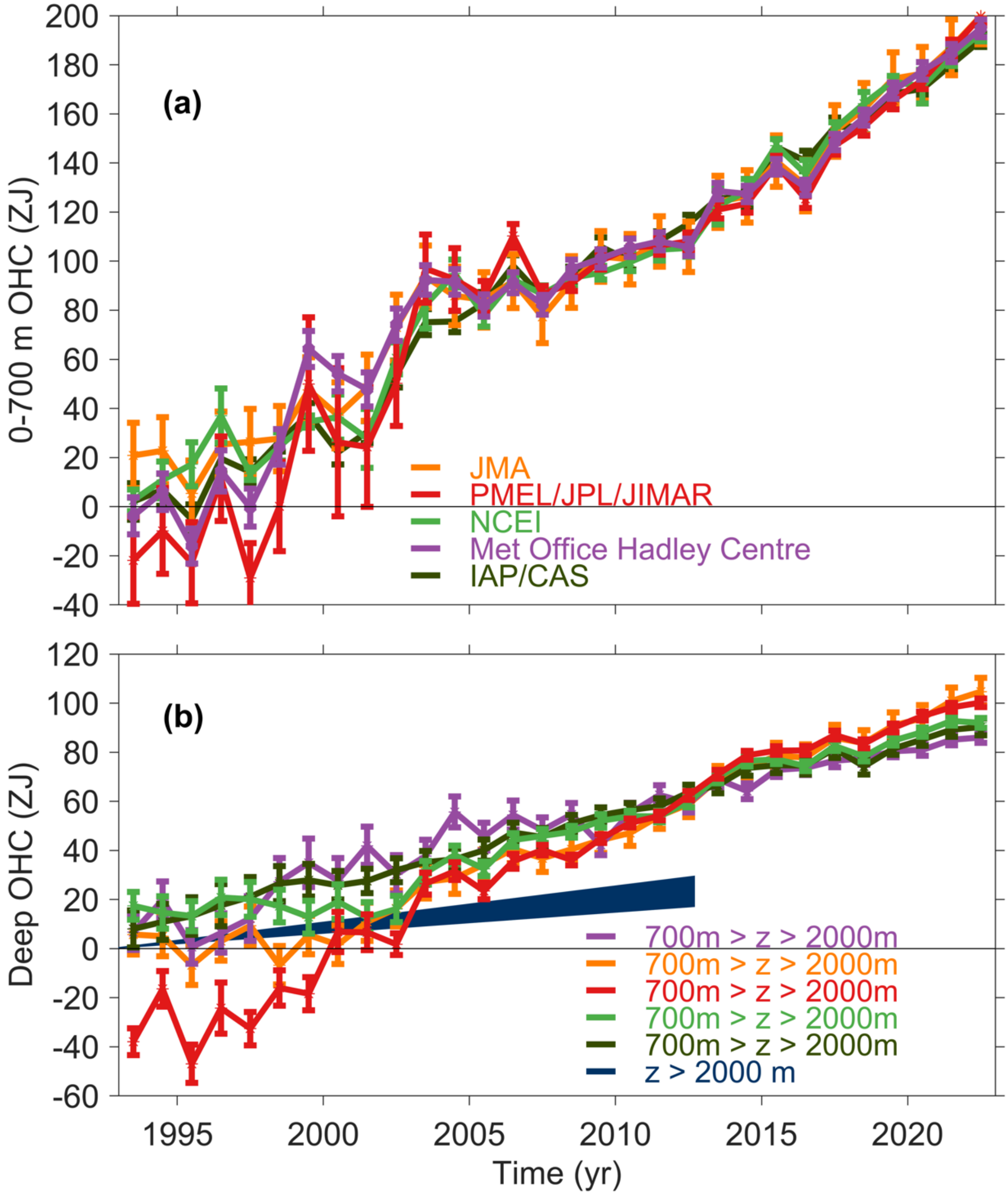

Figure 3. Time series of annual average global integrals of in situ estimates of OHCA (10^{21} J, or ZJ) for different depth ranges from 1993–2022 and the 1992–2011 trend for the deep (> 2000 m) ocean. Standard errors of the mean are shown for annual values and the deep trend. Details are discussed in Johnson et al. (2023b).

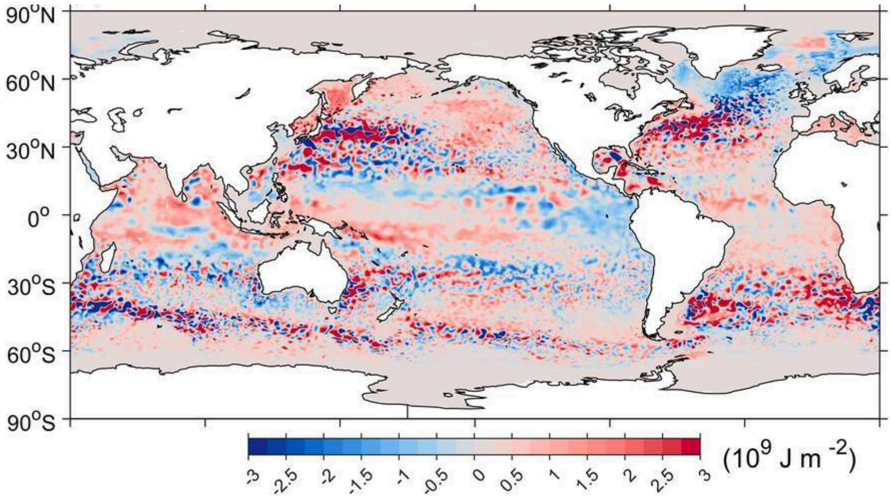

Figure 4. RFROM (Random Forest Regression Ocean Maps) Upper (0 – 700 m) ocean heat content anomaly OHCA (J m^{-2}) for week centered on 3 July 2020 relative to a 1993 – 2022 baseline analyzed following Lyman and Johnson (2023). Figure after Lyman and Johnson (2023).

In addition to writing the overview, heat content, and salinity sections (Johnson and Lumpkin, 2023, Johnson et al., 2023b; c) for the *Global Oceans* chapter of the *State of the Climate in 2021* report, Dr. G. Johnson co-edited the chapter, and contributed to the following six additional refereed scientific journal articles: An opinion piece calling for systematic measurements of deep ocean water properties (Heuzé et al., 2022). An observational analysis of the circulation and water property distributions of the Zapiola Gyre in the Argentine Basin using Deep Argo and historical shipboard CTD data (Johnson and King, 2023). An interdisciplinary analysis of the seasonal cycle of Energy flows within Earth's climate system (Johnson et al., 2023a) that benefited from a new set of ocean heat content maps described next. A new set of ocean heat content maps made at high accuracy and resolution (7 day × ¼° × ¼°) by using satellite data as predictors and in situ (mostly Argo data) for training a machine learning algorithm (Lyman and Johnson, 2023). This product, called RFROM (Random Forest Regression Ocean Maps) resolves eddies and fronts at much higher than is possible with in situ data alone from 1993 onwards (Figure 4). A call for a climate model intercomparison study using observations of Earth's recent historical energy imbalance made using satellite and in situ ocean data (Schmidt et al., 2023). And an updated observation-based assessment of Earth's energy imbalance (von Schuckmann et al., 2023).

The project web page is https://oceans.pmel.noaa.gov/. We also have pages for GOSML, our global ocean statistical mixed layer climatology (https://www.pmel.noaa.gov/gosml/), MIMOC, our monthly isopycal and mixed layer ocean climatology (https://www.pmel.noaa.gov/mimoc/), and RFROM, our new Random Forest Regression Ocean Maps (https://www.pmel.noaa.gov/rfrom/).

3. Outreach and Education

For outreach in FY2023 Dr. Johnson was quoted regarding Argo in an October 2022 *Haikai Magazine* story about autonomous ocean observing systems. He gave an adopt-a-float presentation to a Ballard High School science class with other members of the GO-BOP group in March 2023. He was interviewed by a Science magazine correspondent for an article on reductions of the global meridional overturning circulation in the Southern Ocean with a warming climate in April 2023. He was interviewed on ocean warming and ocean heat uptake by AP news, CNN (twice), Fox Weather, the LA Times, The Washington Post, and the NY Times between April and July 2023.

Dr. Johnson is also an Affiliate Professor at the UW School of Oceanography and most recently supervised Kimberly Gottschalk, who completed her Master's work in December 2021. He co-advised NOAA Lapenta Intern Sarah Packman (with Dr. Zacharay Erickson) and WHOI Summer Student Fellow Abir Sadman (with Dr. Alison Macdonald) in summer 2023. Both of them worked on scientific analyses using Argo data. He is a CICOES and a CIMAR Senior Fellow. He has just begun co-advising (with Drs. Andrea Fassbender and Alison Gray) a CICOES postdoctoral scholar, Dr. Jannes Koelling, in September 2023. Dr. Koelling's project also makes use of Argo data.

4. Publications and Reports

4.1. Publications by Principal Investigators

Published:

Heuzé, C., S. G. Purkey, and G. C. Johnson. 2022. It's High Time We Monitor the Deep Ocean. *Environmental Research Letters*, **17**, 121002, doi:10.1088/1748-9326/aca622.

Johnson, G. C., and B. A. King. 2023. Zapiola Gyre, Velocities and Mixing, New Argo Insights. *Journal of Geophysical Research*, **128**, e2023JC019893, doi:10.1029/2023JC019893.

Johnson, G. C., and R. Lumpkin. 2023. Overview. In State of the Climate in 2022, Global Oceans. *Bull. Am. Meteorol. Soc.*, **104**, *9*, S152–S153, doi:10.1175/BAMS-D-23-0072.2.

Johnson, G. C., F. Landerer, N. Loeb, J. M. Lyman, M. Mayer, A. L. S. Swann, and J. Zhang. 2023a. Closure of Earth's Global Seasonal Cycle of Energy Storage. *Surveys in Geophysics*, doi:10.1007/s10712-023-09797-6.

Johnson, G. C., J. M. Lyman, C. Atkison, T. Boyer, L. Cheng, J. Gilson, M. Ishii, R. Locarnini, A. Mishonov, S. G. Purkey, J. Reagan, and K. Sato. 2023b. Ocean heat content. In State of the Climate in 2023, Global Oceans. *Bull. Am. Meteorol. Soc.*, **104**, *9*, S159–S162, doi:10.1175/BAMS-D-23-0072.2.

Johnson, G. C., J. Reagan, J.M. Lyman, T. Boyer, C. Schmid, and R. Locarnini. 2023c. Salinity. In State of the Climate in 2022, Global Oceans. *Bull. Am. Meteorol. Soc.*, **104,** *9*, S163–S167, doi:10.1175/BAMS-D-23-0072.2.

Lyman, J. M. and G. C. Johnson. 2023. Global High-Resolution Random Forest Regression Maps of Ocean Heat Content Anomalies Using in Situ and Satellite Data. *Journal of Atmospheric and Oceanic Technology*, **40,** 575–586, doi:10.1175/JTECH-D-22-0058.1.

Schmidt, G. A., T. Andrews, S. E. Bauer, P. J. Durack, N. G. Loeb, V. Ramaswamy, N. P. Arnold, M. G. Bosilovich, J. Cole, L. W. Horowitz, G. C. Johnson, J. M. Lyman, B. Medeiros, T. Michibata, D. Olonscheck, D. Paynter, S. Priyam Raghuraman, M. Schulz, D. Takasuka, V. Tallapragada, P. C. Taylor, and T. Ziehn. 2023. CERESMIP: A climate modeling protocol to investigate recent trends in the Earth's Energy Imbalance. *Frontiers in Climate*, **5**:1202161, doi:10.3389/fclim.2023.1202161.

von Schuckmann, K., A. Minère, F. Gues, F. J. Cuesta Valero, G. Kirchengast, S. Adusumilli, F. Straneo, M. Ablain, R. P. Allan, P. M. Barker, H. Beltrami, A. Blazquez, T. Boyer, L. Cheng, J. Church, D. Desbruyeres, H. Dolman, C. M. Domingues, A. García-García, D. Giglio, J. E. Gilson, M. Gorfer, L. Haimberger, M. Z. Hakuba, S. Hendricks, S. Hosoda, G. C. Johnson, R. Killick, B. King, N. Kolodziejczyk, A. Korosov, G. Krinner, M. Kuusela, F. Landerer, M. Langer, T. Lavergne, I. Lawrence, Y. Li, J. Lyman, F. Marti, B. Marzeion, M. Mayer, A. H. MacDougall, T. McDougall, D. P. Monselesan, J. Nitzbon, I. Otosaka, J. Peng, S. Purkey, D. Roemmich, K. Sato, K. Sato, A. Savita, A. Schweiger, A. Shepherd, S. I. Seneviratne, L. Simons, D. A. Slater, T. Slater, A. K. Steiner, T. Suga, T. Szekely, W. Thiery, M.-L. Timmermans, I. Vanderkelen, S. E. Wjiffels, T. Wu, and M. Zemp. 2023. Heat stored in the Earth system 1960-2020: Where does the energy go? *Earth System Science Data*, **15**, 1675–1709, doi:10.5194/essd-15-1675-2023.

The project has satisfied NOAA's repository requirements for these publications.

5. Data and Publication Sharing

This project analyzes data and publishes the results in the refereed scientific literature. NOAA's Public Access to Research Results (PARR) requirements for those publications have been satisfied.