Progress Report
SIO High Resolution XBT Transects

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Budget Summary
FY 2023: $1,037,000

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1. Project Summary

The unique role of the SIO High Resolution Expendable Bathythermograph (HR-XBT) Program in the global ocean observing system is in providing boundary-to-boundary repeating transects of temperature and geostrophic currents over the upper 800 m. Boundary current mass and heat transports are critical elements in the global circulation and heat budget. The Scripps HR-XBT Network was initiated over 30-years ago in 1986 along a commercial shipping route between New Zealand and Fiji and now includes lines in the Pacific, Indian and Southern Oceans (Figure 1). Each transect is repeated nominally on a quarterly basis with XBT probe spacing at 50 km or less in the ocean interior and as fine as 10 km in boundary currents. All HR-XBT data are made available without restriction in near real-time and delayed-mode versions.
Specific scientific objectives of the SIO HR-XBT program are to:

- Determine the long-term mean and the spatial and temporal statistics of variability of temperature, geostrophic velocity and circulation in the top 800 m of the ocean.
- Identify permanent boundary currents and fronts, describe their persistence and recurrence and their relation to large-scale transports.
- Provide appropriate *in situ* data (together with Argo profiling floats, ocean gliders, tropical moorings, air-sea flux measurements, sea level etc.) for testing ocean and ocean-atmosphere models.

The primary societal benefits of the HR-XBT data are in research and education (including 10 PhD theses completed to date and two underway). The multi-decadal HR-XBT time series are used to understand the role of upper ocean circulation and variability in the mass and heat balances and in air-sea interaction. This knowledge is applied in global and regional models for understanding and predicting economic and human impacts. Interactions in the ocean-atmosphere system are responsible for extreme weather events, for extended periods of drought or flooding, and for regional and global sea level rise; therefore, they are important in

assessing risks to coastlines and coastal infrastructure. Ocean temperature and circulation are also primary factors influencing marine ecosystems, and their systematic observation is essential for ecosystem management. The HR-XBT network is presently the main element of the global ocean observing system to provide systematically repeating observations in the boundary currents that fully resolve these important circulation features.

2. Scientific and Observing System Accomplishments

HR-XBT Observing System Performance Measures and Notable Achievements:
During FY2023, the SIO HR-XBT program has made solid progress on all milestones detailed as part of the Work Plan. The most notable observing system accomplishment is the successful undertaking of XBT transects. We continue to actively collaborate with major partners in the SIO HR-XBT network including NOAA/AOML (Atlantic), CSIRO Australia (SW Pacific, Southern and Indian Oceans), NZOI New Zealand (SW Pacific), LEGOS France (Southern Ocean) and NSF Polar Research (AX22). Many of these international partners are primarily responsible for the transects, with the partner providing logistics, coordination and most of the XBT probes.

- **The zonal crossing of the North Pacific Ocean** (PX40, PX37). PX40 (Honolulu to Yokohama) samples the Kuroshio and interior subtropical gyre. It was carried out 3 times; all onboard the Tallahassee in November 2022, and March and July 2023. PX37S (Los Angeles – Honolulu) samples the California Current System, it was carried out 4 times onboard Horizon Enterprise in October 2022, and January, May, and September 2023. PX37 (San Francisco to Honolulu) also sampling the California Current System was carried out 3 times onboard Horizon Enterprise in October 2022, and January and May 2023.
- **The western boundary region of the South Indian Ocean** (IX21 Durban – Mauritius) sampling the Agulhas and the western boundary region near Madagascar was carried out 2 times the Santa Ines in January and June 2023.
- **The meridional crossing of the Central Pacific Ocean** (PX06/13, New Zealand – Fiji / New Zealand - California) sampling the East Auckland Current and the zonal tropical Pacific current system. PX06 was carried out 1 time in August 2023 onboard the Capitaine Baret. PX13 was carried out 2 times; June and August 2023, both onboard the ANL Warrnambool.
- **The meridional crossing of the Western Pacific Ocean** (PX05, Brisbane – Solomon Sea – Yokohama), crossing the East Australian Current, Solomon Sea, and Kuroshio, was carried not carried out.
- **The meridional crossing of Drake Passage** (AX22, Punta Arenas, Chile – Palmer Station, Antarctica), crossing the Antarctic Circumpolar Current, was carried out 4 times: October and November 2022 and January and April 2023, both onboard the LM Gould.
- **Other short transects and collaborative support for partners.** Routes PX30, PX34, and IX28 in the southwestern Pacific are carried out collaboratively with CSIRO, who typically sample 3 to 5 transects per year on PX30 and PX34 and 6 to 8 transects per year on IX28. CSIRO has primary responsibility for these transects, providing logistics, coordination, and most of the XBT probes.

Transects collected and XBTs deployed	Transects	Total XBTs	Good profiles
1. Zonal crossing of the North Pacific	3 PX40, 4 PX37S, 3 PX37	1249	1236
2. Western boundary of the South Indian	2 IX21	187	185
3. Meridional crossing of the Central Pacific	2 PX13, 1 PX06	550	544
4. Meridional crossing of Drake Passage	4 AX22	263	239
5. Other short transects/collaborations	See text	1041	1041
Totals		3290	3245

Table 1: Summary of FY23 transects, total XBTs dropped, and good temperature profiles. The high proportion of good-to-total XBTs (> 98%) is due to mounting of an automatic XBT launcher on the stern of the ships, rather than conventional hand-launching from the ship's bridge.

Performance Measures:

Data Availability: We report annually to the OceanObs Ship Observations Team (SOT). In calendar year Jan 2022 - Dec 2022 the number of BUFR messages on the GTS reported by SIO was 3290. That is, 100% of all XBTs deployed as part of the SIO HR-XBT appeared on the GTS within 24 hours during calendar year 2022. The processed data for each transect can be found on the SIO High Resolution XBT/XCTD Network Site is http://www-hrx.ucsd.edu/ Thus, we have successfully addressed this Performance Measure. See Section 5 for further details.

Contributions to Models/Data Products: The SIO HR-XBT data continues to be assimilated into multiple ocean state estimates, including several using the Estimating the Circulation and Climate of the Ocean (ECCO) framework, based on the MIT GCM and its adjoint model. The assimilation of XBT data into the global ECCO models (http://www.ecco.ucsd.edu/index.html), including the California Current System State Estimate (CASE), the Tropical Pacific Ocean State Estimate (TPOSE), the Northwest Pacific State Estimate (NWPac), the Australian BRAN2020 model and the Southern Ocean State Estimate (SOSE), enable a better understanding of ocean circulation and its variability. Thus, we have successfully addressed this Performance Measure.

In addition, all SIO HR-XBT data is included in the regularly updated NCEI Ocean Heat Content estimate that provides scientific researchers with a high-quality Climate Data Record (CDR) and is used in publications such as Cheng et al (2022).

Publication Metrics: During the FY2023, we have directly contributed to 2 refereed publications that were authored/co-authored by the PIs. In addition, over 90 papers have attributed the use of HR-XBT data during calendar year 2022. Further details are provided in Section 4. Thus, we have successfully addressed this Performance Measure.

Scientific Advances and Highlights:

Scientific highlights in FY2023 include the analysis of HR-XBT data in the PhD studies of SIO graduate students Dr. Manuel Gutierrez-Villanueva, MS student Ms. Scarlett Hensen, BSc (Honours) student Ms. Clea Welch and BS undergraduate Mr Junnan Yan (See Section 3). PI Sprintall also contributed to scientific papers that employed and acknowledged the SIO XBT data sets.

Although the westerly winds that drive the Antarctic Circumpolar Current (ACC) have increased over the past several decades, the ACC response remains an open question. The unique 15-year time series of concurrent upper-ocean temperature, salinity, and ocean velocity across Drake Passage is used to estimate trends in the transport and properties in the upper 760 m depth. Although the net Drake Passage transport relative to 760 m shows insignificant acceleration, the Subantarctic and Polar Frontal jets have accelerated while the currents located between the fronts have decelerated over the last 15 years. These opposing trends explain the lack of a trend in the net transport integrated across Drake Passage. The results suggest that the acceleration of the frontal jets results from an increase in the mesoscale eddy activity due to buoyancy changes in the fronts, consistent with an eddy saturation state. This study formed the final chapter of Manuel's PhD thesis.

MS student Ms. Scarlett Hensen studied the variability in the Solomon Sea using data sampled by SIO XBT transect PX05. UCSD undergraduate student Mr Junnan Yan is used XBT data sampled by PX37 and PX37S to understand the drivers of marine heat waves in the California Current system. University of Cape Town BSc (Honours) student Clea Welch studied marine heat waves in the Agulhas Current using data from the IX21 XBT transect.

The Nature review paper published in Communications Earth & Environment (Chidichimo et al., 2023) highlights new knowledge developed during the last 10 years on the role and contribution of South Atlantic variability, including its inter-basin linkage through Drake Passage, to the Atlantic Meridional Overturning Circulation. The paper included a review of knowledge gained about the Drake Passage linkage from the XBT transects.

Naturally-occurring tropical Pacific variations at timescales of 7-70 years—Tropical Pacific Decadal Variability (TPDV)—describes basin-scale sea surface temperature (SST), sea level pressure and heat content anomalies. In the Nature review, Capotondi et al (2023), several mechanisms are proposed to explain TPDV, which can originate through oceanic processes, atmospheric processes, or as an ENSO residual. The analysis includes data from the global observing system, including the HRX data.

The PIs, their students and postdocs also participated in and presented work related to the SIO HR-XBT transects at numerous conferences during FY2023 (see Section 4).

Finally, during FY2023, we also participated and served as chairs and committee members in international planning groups and in science workshops (e.g. JCOMM SOT Meetings (Sprintall, Parks); committee member and interim chair of the GOOS OOPC Boundary Currents and Shelf

Sea Interactions Task Team (Sprintall); co-chair of the CLIVAR Global Synthesis and Observations panel (Zilberman); and committee member of the Global Temperature-Salinity Profile Program (GTSPP) (Sprintall). SIO HR-XBT Manager Ms. Justine Parks is the vice-chair of the Ship of Opportunity Program Implementation Panel (SOOPIP). Ms. Parks organized the SOOP activities as part of the SOT-12 Workshop held in Melbourne, May 2023. Part of Ms. Parks duties include development of a Standards and Best Practices (SBPs) for the SOOP Vessel Recruiting Best Practices that was endorsed by GOOS and successfully underwent community review.

Essential Ocean Variables (EOVs):
Through its global collection of the EOV surface and subsurface temperature observations, the SIO HR-XBT data directly address the GOMO priorities to provide information about the state of the world's ocean and its regional variations to address important societal needs related to the Earth's climate. The HR-XBT profile data provide the near-surface temperature structure and the geostrophic current flowing across the repeatedly sampled routes, with spatial resolution of 10-15 km in boundary current regions. HR-XBT observations of temperature and geostrophic velocity are also used to estimate seasonal to decadal variability in the meridional transport of heat across ocean-spanning transects, including the large contributions of boundary currents to the ocean-wide heat transport.

Website: http://www.hrx.ucsd.edu/

Challenges Affecting Progress:
The primary challenge for the HR-XBT Program in general is the increasingly transient nature of ships and routing in the commercial shipping industry, and the increase in size of container ships leading to a reduction in ocean-crossing routes. Like other observing systems, our HR-XBT network has been challenged during FY2023. The newest challenge is the hesitancy of some in the commercial shipping industry to resume cooperation with the program since the COVID pandemic exposed the lack of company-wide policies on these activities. Our priority is to sustain long time-series transects, particularly those including boundary currents.

Finally, there continues to be little funding to support scientific analysis directly by the PIs or their students, however we expect that the HR-XBT data will continue to be employed by other scientists and in model forecasts. Our students are currently funded through separate funding opportunities such as external fellowships from other agencies.

3. Outreach and Education

The Scripps HR-XBT Operations Manager and the ship-riders perform key outreach functions in relation to the shipping industry. While at sea, they inform shipping company managers and ships crews of the objectives and results of the HR-XBT program to promote the ongoing partnership of the research community with the commercial shipping industry. Through these outreach efforts as well as articles published in shipping industry trade magazines, we inform management and crews of the need for their assistance in climate change research and the value of their contributions.

SIO XBT Network program manager Ms. Justine Parks and Systems Analyst Lisa Lehmann (retired 30 June 2023) have contributed to the successful management and distribution of the XBT shipboard data at the SIO High Resolution XBT/XCTD Network Site (http://www-hrx.ucsd.edu/) where XBT cruise tracks and along track temperature/depth cross-sections are displayed. The XBT data are also available from the NOAA NCEI site: https://www.nodc.noaa.gov/OC5/SELECT/dbsearch/dbsearch.html

The Scripps HR-XBT Program has made strong contributions to education by serving as a source of data for PhD and Master's theses and for research by post-doctoral investigators. To date, 12 completed PhD theses have used Scripps HR-XBT data as a primary dataset in studies of time-varying ocean circulation, global ocean heat content, water mass formation, and ocean heat transport. The use of the HR-XBT dataset in student and postdoctoral research is indicative of the increasing value of ocean observations that are sustained over a long period of time.

SIO PhD graduate student Manuel Gutierrez Villanueva (co-advised by PI Sprintall) used the 20-year Drake Passage AX22 HR-XBT data and concurrent underway ADCP velocity data to understand the eddy energy distribution within Drake Passage and its relationship to topographic features, ACC fronts, and wind and buoyancy forcing. Manuel successfully defended his PhD thesis, "Dynamics of the Southern Ocean in Drake Passage from Observations" in September 2022. He is currently doing a postdoc at SIO. UCSD Masters student Scarlett Hensen (co-advised by PIs Sprintall and Zilberman) examined variability in the Solomon Sea from PX05 data. Scarlett successfully defended her Masters thesis in June 2023. She is currently an education specialist at the Laguna Ocean Foundation. UCSD undergraduate student Junnan Yan (co-advised by PIs Sprintall and Zilberman) studied marine heat waves in the California Current using data from PX37 combined with remotely sensed data sets. Mr. Yan graduated in Spring 2023 and is currently enrolled in a PhD program at University of Rhode Island. Finally, Ms. Clea Welch, a BSc (Honors) student at University of Cape Town (co-advised by Sprintall), studied marine heat waves in the Agulhas Current using data from IX2. Ms. Welch is currently applying for graduate schools, including Scripps.

4. Publications and Reports

4.1. Publications by Principal Investigators

The following publications have used and acknowledged the HR-XBT data sets and are provided annually to the PARR through CIMEC.

Published

Capotondi, A., S. McGregor, M. J. McPhaden, S. Cravatte, N. J. Holbrook, Y. Imada, S. C. Sanchez, ***J. Sprintall***, M. F. Stuecker, C. C. Ummenhofer, M. Zeller, R. Farneti, G. Graffino, S. Hu, K. B. Karnauskas, Y. Kosaka, F. Kucharski, M. Mayer, B. Qiu, A. Santoso, A. S. Taschetto, F. Wang, X. Zhang, R. M. Holmes, J-J Luo, N. Maher, C. Martinez-Villalobos, S. Stevenson, A. Sullivan, P. van Rensch, T. Xu (2023). Mechanisms of tropical Pacific decadal variability. *Nature Reviews Earth and Environment,* https://doi.org/10.1038/s43017-023-00486-x.

Chidichimo, M. P., Perez, R. C., Speich, S., Kersale, M., ***Sprintall, J.,*** Dong, S., Lamont, T., Sato, O. T., Chereskin, T. K., Hummels, R., and Schmid, C. Energetic overturning flows, dynamic interocean exchanges, and ocean warming observed in the South Atlantic, *Commun Earth Environ* **4**, 10 (2023). https://doi.org/10.1038/s43247-022-00644-x

Conferences:
Gutierrez-Villanueva, M. O. 2022. Southern Ocean Dynamics in Drake Passage from Observations. Physical Oceanography Dissertations Symposium (PODS) XII*,* October 2022, Honolulu, HI.

Gutierrez-Villanueva, M. O., T. K Chereskin and J. Sprintall, 2023. Has the net Drake Passage transport accelerated over the last 15 years in response to increased wind over the ACC? Presented at the *XBT Science Meeting,* May 2023, Melbourne, Australia.

Gutierrez-Villanueva, M. O., T. K. Chereskin, and J. Sprintall, 2023. Has the net Drake Passage transport accelerated over the last 15 years in response to the increased wind over the Antarctic Circumpolar Current? Presented at the 2nd US-SCAR Antarctic Science Meeting June 2023 (virtual).

Thesis:
Gutierrez-Villanueva, M.O. Dynamics of the Southern Ocean in Drake Passage from Observations, 2022. PhD thesis, University of California, San Diego.

4.2 Other Relevant Publications

A bibliography of publications using XBT data is maintained on the XBT Science Page, http://www.aoml.noaa.gov/phod/goos/xbtscience/bibliography.php. The bibliography contains 96 research papers in 2022 alone. Some particularly relevant publications that use the SIO HR-XBT data include:

Cheng, L., Foster, G., Hausfather, Z., Trenberth, K.E., and Abraham, J. (2022). Improved Quantification of the Rate of Ocean Warming. Journal of Climate, 35(14), 4827-4840, doi: 10.1175/JCLI-D-21-0895.1
George, J.V., and Anilkumar, N. (2022). High-frequency noise and depth error associated with the XCTD/XBT profiles in the Indian Ocean sector of Southern Ocean and southwestern tropical Indian Ocean. Journal of Earth System Science, 131, 47, doi: 10.1007/s12040-021-01789-7
Haddad, S., Killick, R.E., Palmer, M.D., Webb, M.J., Prudden, R., Capponi, F., and Adams, S.V. (2022). Improved Infilling of Missing Metadata from Expendable Bathythermographs (XBTs) Using Multiple Machine Learning Methods. Journal of Atmospheric and Oceanic Technology, 39(9), 1367-1385, doi: 10.1175/JTECH-D-21-0117.1.

5. Data and Publication Sharing

All HR-XBT data follow the NOAA PARR mandate and are available without restriction in near real-time and delayed-mode versions. Real-time data are available from the Global Temperature-Salinity Profile Program (GTSPP) http://www.nodc.noaa.gov/GTSPP/, while the delayed mode dataset is archived and distributed by the National Center for Environmental Information (NCEI) and can also be accessed in transect mode from http://www-hrx.ucsd.edu.

a) Near real-time data are transmitted from the ship by the Scripps ship-rider using iridium on the NOAA/SEAS System, following quick visual inspection, and distributed via the Global Telecommunications System.

b) The real-time data are freely available via the internet from the Global Temperature-Salinity Profile Program (GTSPP) http://www.nodc.noaa.gov/GTSPP/ .

c) The delayed mode dataset, produced by expert examination of all profiles and statistical comparison to adjacent profiles and to previous profiles along the same track, is made available in transect form at http://www-hrx.ucsd.edu. Most transects are made available within a week or two of collection.

d) The HR-XBT dataset is archived and distributed by the NCEI. We transmit delayed-mode data to NCEI on an annual basis.

e) The HR-XBT data can be accessed at http://www-hrx.ucsd.edu. In addition, our data manager also responds to requests (e.g. for high vertical resolution data, or for specific collections of transects). The web site acknowledges NOAA support.

f) We have successfully retrieved HR-XBT data recently from the program web site.

A data flow chart for the HR-XBT program can be found at http://www-hrx.ucsd.edu/data_management.html and data quality control procedures are consistent with those described in NODC's GTSPP Data Quality Control manuals: http://www.nodc.noaa.gov/GTSPP/document/qcmans/index.html

Our primary users are scientists, numerical modelers and students for research and educational purposes.

6. Project Highlight Slides

Two slides are included that highlight the recent network contribution and science activities using the SIO HR-XBT data.