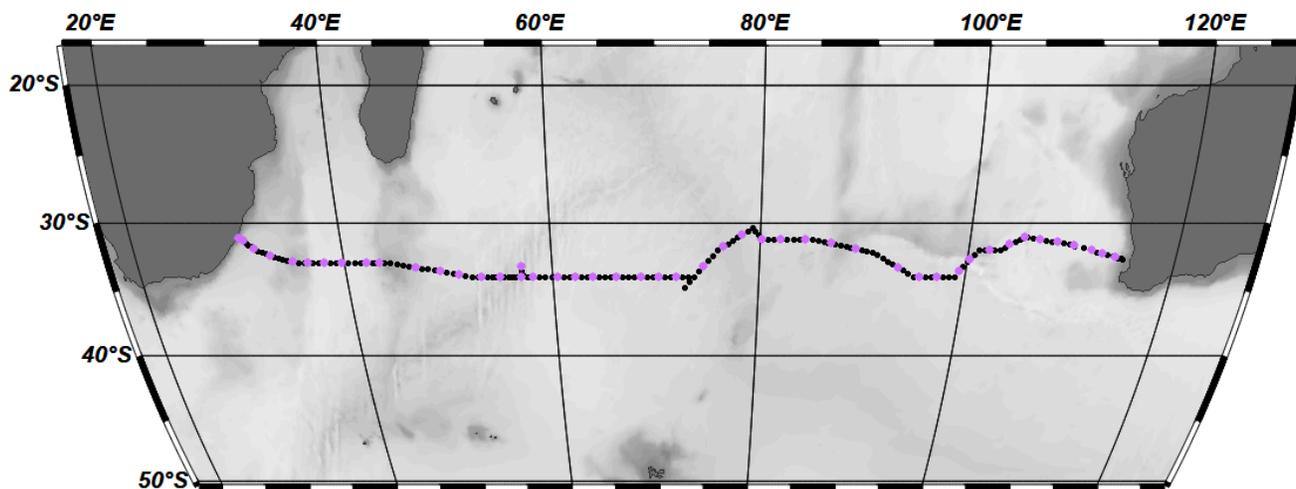




**Cruise Report for the  
I05\_2023 US GO-SHIP Cruise**  
*Updated 09/29/2023*

**Prepared by: Brendan Carter with contributions from Kay McMonigal and the I05 science party**



*Station map for I05\_2023 with stations marked in black and Bio-GO-SHIP casts superimposed in purple*

<i>Section Name</i>	I05
Expocode	33RR20230722
Occupation Name	I05_2023
UNOLS designation	RR2308
Chief Scientist	Brendan Carter
Co-Chief Scientist	Kay McMonigal
Dates	07/22/2023 to 09/14/2023 (55 DAS)
Ports of call	Fremantle, Australia to Cape Town, South Africa
Stations occupied	196, with 195 “bottle” casts and 50 “bio” stations
Equipment deployed	15 floats and 22 drifters

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## 1 Abstract

This report details the 2023 occupation of the I05 hydrographic section aboard the University-National Oceanographic Laboratory System (UNOLS) vessel the *R/V Roger Revelle* conducted as part of the United States contribution to the Global Ocean Ship-based Hydrographic Investigations Program (US GO-SHIP). This project was successful in its mission to reoccupy the I05 hydrographic section (Fig. 1) while deploying floats and drifters, collecting underway measurements, collecting full-depth profiles of sensor measurements, and collecting up-to-36 bottle samples per station for discrete chemical analyses. These measurements are used to quantify long-timescale (decadal+) changes in ocean heat, carbon, and freshwater content, as well as to detect changes in ocean circulation and biogeochemistry. US GO-SHIP nominally aims to conduct station work at 30 nautical-mile spacing with enhanced resolution over areas of high bathymetric variability. This planned spacing was achieved in full excepting two stations spaced by approximately 45 nautical miles. This cruise was delayed from an originally scheduled reoccupation of 2019 due to a variety of logistical concerns. This cruise represents the culmination of a successful decade of repeated hydrographic measurements and addresses a significant temporal observational gap in the GO-SHIP record of oceanographic changes.



\* Most images in this document have been saved at low resolution to minimize file size to permit downloading this file while at sea. Higher resolution images may be available upon request.

## 2 Contents

1	Abstract.....	1
2	Contents.....	1
3	Involvement.....	3
3.1	Participating Institutions.....	3
3.2	Leg 1 Science Party.....	4
3.3	Programs and PIs.....	4
4	Program and Project Overview.....	5
4.1	The I05 section and its history.....	6
5	The 2023 I05 reoccupation.....	7
5.1	Challenges.....	8
5.2	Changes from prior I05 cruises.....	9
5.3	Cruise narrative.....	16
5.4	Station timing.....	17
6	Water sampling package.....	19
7	Underway Data Acquisition.....	21
7.1	SADCP.....	22
7.2	Underway seawater $p\text{CO}_2$ .....	23
7.3	EK80 (fish finder).....	26
8	Casts and Niskins.....	27
		1

8.1	Bottle depth schemes.....	27
8.2	Bottom bottle.....	28
8.3	Bottle Sampling.....	29
9	Sub-project reports.....	30
9.1	CTD and sensor package measurements .....	30
9.2	LADCP.....	39
9.3	Chipods.....	41
9.4	Chlorofluorocarbon (CFC), Sulfur Hexafluoride (SF <sub>6</sub> ), and Nitrous Oxide (N <sub>2</sub> O).....	42
9.5	Bottle Oxygen Analysis.....	45
9.6	Dissolved inorganic carbon (DIC).....	47
9.7	Discrete total scale pH (pH <sub>T</sub> ).....	50
9.8	Total titration seawater alkalinity (A <sub>T</sub> ) .....	52
9.9	Dissolved organic matter (DOM or DOC and TDN) .....	54
9.10	Dissolved organic phosphorous.....	56
9.11	Discrete/bottle salinity.....	57
9.12	Nutrients .....	58
9.13	Isotopes of nitrate .....	63
9.14	Isotopes of H <sub>2</sub> O .....	65
9.15	Float and drifter deployments.....	66
9.16	Bio GO-SHIP .....	70
10	Appendices .....	71
10.1	Appendix 1: Cruise narrative.....	71
10.2	Appendix 2: Station timing .....	92

\* Many images in this document have been saved at low resolution to minimize file size. Higher resolution images may be available upon request.

### 3 Involvement



#### 3.1 Participating Institutions

Abbreviation Full name

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APL	Applied Physics Laboratory
AOML	Atlantic Ocean and Meteorological Laboratory
CICOES	Cooperative Institute for Climate, Ocean, and Ecosystem Sciences
CSUS	California State University, Sacramento
INCOIS	Indian National Center for Ocean Information Services
NCPOR	National Centre for Polar and Ocean Research
PMEL	Pacific Marine Environmental Laboratory
Princeton	Princeton University
Rutgers	Rutgers, The State University of New Jersey
RSMAS	Rosenstiel School of Marine and Atmospheric Science/University of Miami
SIO	Scripps Institution of Oceanography/University of California at San Diego
UAF	University of Alaska, Fairbanks
UCT	University of Cape Town
UCI	University of California, Irvine
UCSD	University of California, San Diego
UCA	Universidad de Cádiz
UH	University of Hawai'i
UMa	University of Maine
UMi	University of Miami
UNH	University of New Hampshire
USC	University of South Carolina
UW	University of Washington, Seattle
WHOI	Woods Hole Oceanographic Institute

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### 3.2 Leg 1 Science Party

Primary Task	Name	Affiliation	Additional Tasks (or expanded tasks)
Chief Scientist	Brendan Carter	UW/PMEL	<i>Deployments</i>
Co-Chief Scientist	Kay McMonigal	UAF	<i>Deployments, Blogs</i>
CTD processing	Alan Smith	SIO	<i>Salts</i>
Salinity/CTD	Jessica McLaughlin	AOML	<i>Deployments</i>
Salinity	John Calderwood	AOML	<i>ET</i>
CTD watch stander	Alexis Merk	UM	
CTD watch stander	Jomphol Lamoontkit	UH	
CTD watch stander	Kirsten Petzer	UCT	
CTD watch stander	Nirmala J. Nair	NCPOR	
CTD watch stander	Steven Akin	RSMAS	<i>Outreach</i>
Dissolved O <sub>2</sub>	Elisa Aitoro	SIO	<i>Bottle data synthesis</i>
Dissolved O <sub>2</sub>	Robert Freiberger	SIO	
ODF lead	Susan Becker	SIO	<i>Nutrients</i>
Nutrients	Tania Lueng	SIO	
DIC lead	Andrew Collins	PMEL	<i>Underway pCO<sub>2</sub></i>
DIC	Charles Featherstone	AOML	
CFCs/SF <sub>6</sub> lead	Mark Warner	UW	<i>N<sub>2</sub>O lead</i>
CFCs/SF <sub>6</sub>	Carol Gonzalez	CICOES	<i>N<sub>2</sub>O</i>
CFCs/SF <sub>6</sub>	Maggie Gaspar	USC-alum.	<i>N<sub>2</sub>O</i>
Total Alkalinity	Daniela Nestory	SIO	<i>Total alkalinity/pH<sub>T</sub> lead</i>
Total Alkalinity	Sara Gray	SIO	
pH <sub>T</sub>	Abigail Tinari	SIO	
pH <sub>T</sub>	Eva Capilla Garcia	UCA-alum.	
Bio. GO-SHIP	Yi Liu	UCI	<i>(POCN, POP, eDNA, HPLC)</i>
Bio. GO-SHIP	Nataly Pineda	UCI	<i>(POCN, POP, eDNA, HPLC)</i>
DOC	Jaeden Hansen	CalPoly	
LADCP	Lydia Pinard	UNH	<i>DOP</i>
Deployments	Aur�lie Moulin	UW/APL	<i>(Floats, Drifters, Adopt-a-float)</i>
Research Technician	Royhon Agostine	UCSD	
Ship. Tech. Support	Maya Thompson	UCSD	

### 3.3 Programs and PIs

Program	PI	Institution	E-mail
Bathymetry	Brendan Carter	UW/PMEL	brendan.carter@noaa.gov
CFCs/SF <sub>6</sub> /N <sub>2</sub> O	Mark Warner	UW	warnar@uw.edu
Chipods	Jonathan Nash	OSU	nash.coas@gmail.com
CTD	Lynne Talley	SIO	ltalley@ucsd.edu
Dissolved Oxygen	Susan Becker	SIO	sbecker@ucsd.edu

DOC	Craig Carlson	UCSB	craig_carlson@ucsb.edu
Drifters (DWSBD)	Suresh Kumar	INCOIS	sureshkumar@incois.gov.in
Drifters (NOAA)	Shaun Dolk	AOML	shaun.dolk@noaa.gov
Drifters (NOAA)	Rick Lumpkin	AOML	rick.lumpkin@noaa.gov
eDNA	Adam Martiny	UCI	amartiny@uci.edu
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Floats (BGC/SOCCOM)	Lynne Talley	SIO	ltalley@ucsd.edu
Floats (EM APEX)	James Girton	UW	girton@uw.edu
Flour./backscatter	Oscar Schofield	Rutgers	oscar@marine.rutgers.edu
H <sub>2</sub> O isotopes	Amy Wagner	CSUS	amy.wagner@csus.edu
HPLC	Adam Martiny	UCI	amartiny@uci.edu
LADCP	Andreas Thurnherr	LDEO	ant@ldeo.columbia.edu
Nitrate/nitrite isotopes	Dario Marconi	Princeton	dmarconi@princeton.edu
Nitrate/nitrite isotopes	Daniel Sigman	Princeton	sigman@princeton.edu
Nutrients	Susan Becker	SIO	sbecker@ucsd.edu
Particulate Organic CN	Adam Martiny	UCI	amartiny@uci.edu
Particulate Organic P	Adam Martiny	UCI	amartiny@uci.edu
Salinity	Susan Becker	SIO	sbecker@ucsd.edu
Shipboard ADCP	Jules Hummon	UH	hummon@hawaii.edu
Total Alkalinity/pH <sub>T</sub>	Andrew Dickson	SIO	adickson@ucsd.edu
Total CO <sub>2</sub> (DIC)	Richard Feely	PMEL	richard.a.feely@noaa.gov
Total CO <sub>2</sub> (DIC)	Rik Wanninkhof	AOML	Rik.Wanninkhof@noaa.gov
Transmissometer	Adam Martiny	UCI	amartiny@uci.edu
Underway pCO <sub>2</sub>	Simone Alin	PMEL	simone.r.alin@noaa.gov
Underway TSG	Brendan Carter	UW/PMEL	brendan.carter@noaa.gov

#### 4 Program and Project Overview

The Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) seeks to document ocean changes from one decade to the next. This program makes reference-quality measurements of seawater chemistry, heat, and freshwater content from the ocean surface to the seafloor along specified lines that cross all major ocean basins. Earlier programs under the Joint Global Ocean Flux Study (JGOFS), World Ocean Circulation Experiment (WOCE), and Climate Variability (CLIVAR) have provided approximately decadal observations on hydrographic lines, including the I05 line which was the focus of this research cruise.

Key uses for GO-SHIP data include:

- Model calibration and validation
- Carbon system studies including the inference of the anthropogenic carbon content of seawater
- Heat and freshwater storage and flux changes
- Deep and shallow water mass and ventilation studies
- Calibration of autonomous sensors

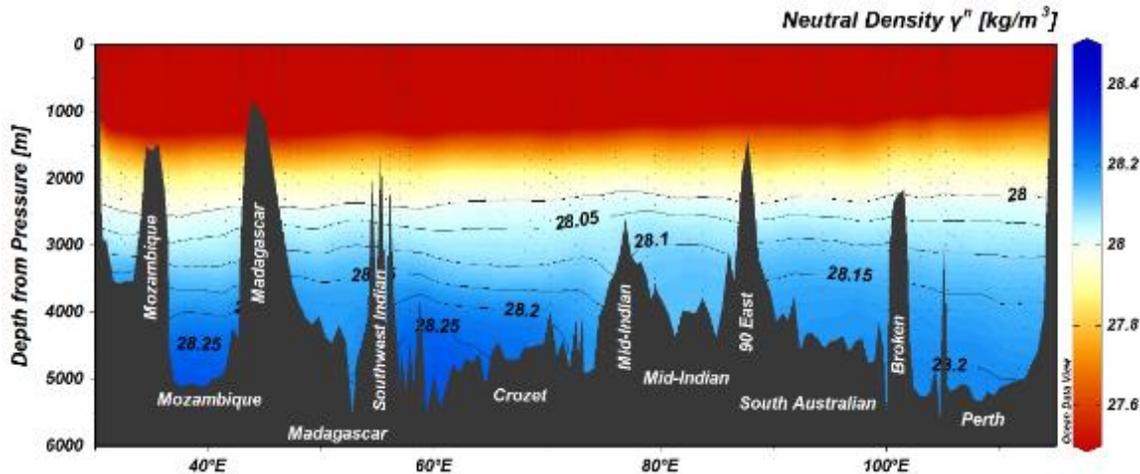
This is the first I05 occupation to collect that metagenomic information and particulate organic carbon measurements. This latter effort is through the new Bio. GO-SHIP program, and these measurements will provide the foundation for future studies examining how ocean biology is shifting in response to global changes.

The specific objectives of this cruise were as follows:

- Re-occupy this line spanning from Australia to South Africa at the nominal 30 nautical mile resolution
- As timing allows, repeat stations dedicated to obtaining higher resolution measurements while crossing important bathymetric features such as deep ocean ridges
- As timing allows, conduct a second cast dedicated to biological measurements at select stations throughout the line
- Deploy:
  - 7 EM Apex (“SQUID” floats, Sampling QUantitative Internal-wave Distribution) that measure temperature, salinity, velocity, ocean turbulence, and diffusivity
  - 8 floats (through the SOCCOM and GO-BGC programs) that measure biogeochemical properties in addition to measuring the temperature and salinity of seawater
  - 12 Directional Wave Spectra Barometric Drifters from the Indian National Centre for Ocean Information Services (INCOIS) and
  - 10 drifters from NOAA’s AOML laboratory

These objectives were met in full on this cruise aside from ~45 nautical mile spacing between two pairs of stations. These two station spacings were extended due to time, current, and weather constraints.

#### 4.1 The I05 section and its history



*A section showing the highly variable bathymetry of the I05 section and the various named topographic features crossed during the cruise. Ridges and plateaus are labeled vertically while basins are labeled horizontally. The small black dots indicate the bottle measurement locations in 2009.*

The I05 line crosses the Indian Ocean zonally at approximately 32° S, but the exact latitude of the section varies across the basin to allow the track to measure deep ocean basins while minimizing meridional deviations of the transect. It is one of the longer lines that is traditionally measured by GO-SHIP in one continuous research cruise, and the ideal station density is high due to the many rapid changes in bathymetric depth. The line crosses the Leeuwin Current adjacent to Australia—the only poleward flowing subtropical eastern boundary current—passes

over the complex and rugged topography of the southern Indian Ocean, and finishes by crossing the highly energetic Agulhas Current near South Africa. The 14-year gap prior to I05\_2023 is currently one of the longest gaps for the lines slated to be reoccupied by US teams, and this area has therefore become a critical knowledge gap for our understanding of global and regional ocean heat, carbon, and freshwater change. This reoccupation addresses that gap. The cruise was jointly funded by the National Science Foundation division for Ocean Sciences and the National Oceanographic and Atmospheric Administration's Global Ocean Monitoring and Observations division.

The I05 line was first occupied in earnest by scientists on the *RRS Charles Darwin* in 1987, though this cruise did not collect the full suite of “core” measurements that are characteristic of a GO-SHIP cruise. The line was partially reoccupied by scientists on the *R/V Knorr* in 1995, and another segment of the line was reoccupied by this vessel later the same year. In 2000, a cruise aboard the *R/V Franklin* reoccupied the easternmost portion of the I05 line. The *RRS Charles Darwin* reoccupied the full line in 2002. Most recently, the *R/V Roger Revelle* measured the line in 2009. The I05\_2023 cruise now marks the return of the *R/V Roger Revelle* after a 14-year gap without measurements. One notable difference is that this cruise will be conducted from east to west due whereas past complete occupations were conducted from west to east. These repeated hydrographic measurements—and the measurements collected by US GO-SHIP and its predecessor programs—provide one of the most accurate and enduring records of change in the world oceans and on Earth, and the I05 cruise is a central section for a crucial ocean basin.

## 5 The 2023 I05 reoccupation

Pre-cruise preparations went mostly to plan.

- Shipments were scheduled and arrived at the *R/V Roger Revelle* as planned and on time.
- Clearances to conduct work within the exclusive economic zones of Australia and South Africa were required for the I05\_2023 section, and both were requested according to specified timetables and the expedition was granted full clearance for the proposed activities by both nations.
- All participants were able to secure the necessary visas and paperwork for participation and travel through the two host nations, though there were some closer calls and situations of varying complexity for non-US participants.
- This cruise was planned during a period in which the COVID-19 prevention protocols were continuously evolving. Ultimately, vaccination status was not a barrier to participation and we did not have a mandated quarantine period before embarkation, though frequent communication regarding COVID-19 status was needed.
- Two science party members had to withdraw from participation due to personal concerns in the later stages of cruise planning. In one instance, a volunteer replacement was able to secure the needed travel documentation. In the other instance, a member of the watch stander team proved willing and able to fill the missing role.

Ultimately, the cruise successfully departed as planned from Fremantle on 7/22/2023 with a full complement of scientific and ship's crew aboard.

Once at sea, the I05\_2023 cruise was highly successful at carrying out its planned research due to the hard work of all aboard, the professionalism and competence of the scientific crew and the crew of the *R/V Roger Revelle*, the excellent condition of the *Revelle* and her scientific equipment, and the clear communication maintained by

all involved. The flawless condition of the winch and the deployment head aided the efficiency of the cruise, and deployments were efficiently and safely conducted by a single person each operating the winch, in the bridge, at the console, and on deck. In total, more than 780 km of wire was spooled out at 196 stations over 55 days at sea, counting the 38 separate casts for biological parameters.

Strong academic/student participation was instrumental to the success of this cruise with one “LADCP,” one “CFC,” one “float and drifter,” and six “CTD” watch standers. The larger-than-average number of watch standers allowed people to take on additional tasks as needed, to fill in for missing personnel (as noted earlier), to spell one another, and better engage in the science being conducted on board. Budgeting berths for more than the usual 4 CTD watch standers also allowed us to accept participants from nations that border the study region (South Africa and India) and from other partner nations that contribute to the international GO-SHIP effort. Several watch standers conducted personal research projects using GO-SHIP data collected at sea. One watch stander coordinated an informal outreach effort that, while initially unplanned, ended up reaching several hundred K-12 students spanning a region from Tennessee through Texas.

## 5.1 Challenges

The primary challenges faced by the cruise were due to the weather. This occupation took place in the austral winter and saw periods of rough weather at various points during the cruise. The first weeks saw several storm and strong current events while crossing the Leeuwin current and the Perth Basin. During one such storm, a large wave struck the transient tracer van on the port aft deck, causing a door to buckle inwards, flooding the van with saltwater, and tripping the electrical breaker. Transient tracer PI Warner led a (miraculous) recovery effort that moved his equipment into the Hydro Lab. They remained there for the rest of the cruise. Several stations worth of transient tracer information was not collected during this rebuild. Also, the station (13) immediately prior to the wave event was only sampled with the rosette package to shallow depth before being retrieved due to strong winds and an adverse (inboard) wire angle. To compensate, the next station (14) was moved to the midpoint between two adjoining stations (12 and 15), resulting in two successive full chemistry station spacings of ~45 nautical miles. Several other strong storm events led to shorter delays and a storm event on station 14 stopped operations for nearly a day. Ultimately, excellent efficiency and luck with weather throughout the middle portion of the cruise enabled the planned work to be completed essentially in full despite these delays. The strong Agulhas Current caused us to sample while drifting along-current for the last ~5 stations on the cruise. We began these stations about 1 nautical mile up-current and ended about 1 nautical mile down current. The last planned station was completed with only a handful of hours before the break-off deadline, and it was deemed the extra hours might be useful in transit due to the expectation of up to ~40 knot headwinds and 22' waves for the first 36 hours of the transit.

We also had several minor and typical issues with scientific equipment that were unrelated to the weather. In most cases this resulted in a slight decrease in the sampling resolution of the associated measurements while the situation was resolved. In one case, a critical piece of equipment failed for one of the analytical teams, but electrical engineer Shaun was able to quickly restore the equipment to working order before significant samples were omitted.

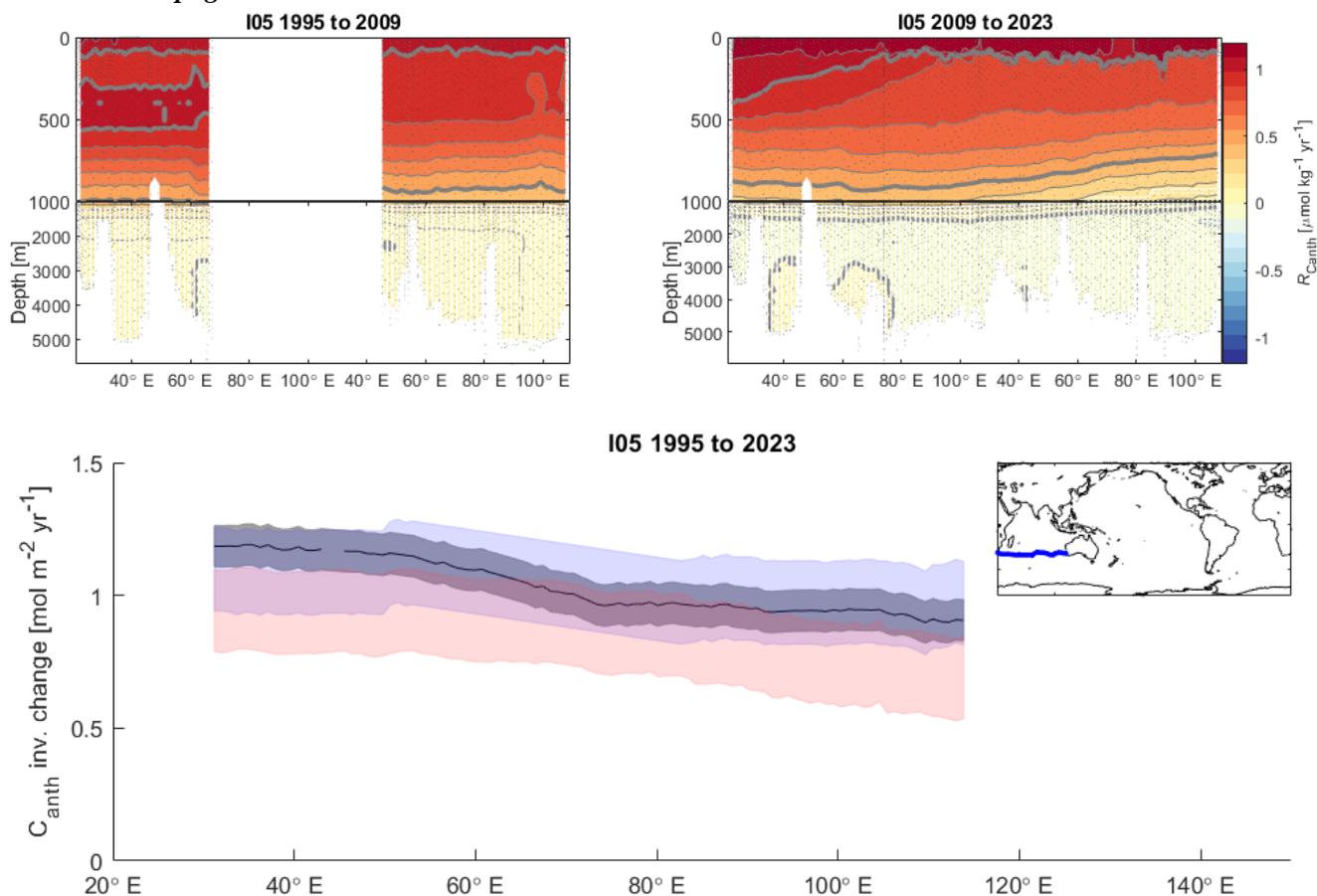
We had no significant delays associated with the mechanical functioning of the *R/V Roger Revelle* or her equipment. The issues that did arise at sea were expertly and efficiently handled by the ship's crew.

The *R/V Roger Revelle* was berthed at a secure port facility south of Fremantle due to the need for a land crane during mobilization, and this presented some small barriers to ship access that were resolved through patience and relentless communication.

## 5.2 Changes from prior I05 cruises

Three preliminary analyses were conducted on the data while at sea to assess changes relative to prior I05 cruises: (1) anthropogenic carbon accumulation rates ( $R_{\text{C}_{\text{anth}}}$ ) were computed using the CAREER method of Carter et al. (2019), (2) CTD profiles were compared in deep ocean basins to quantify deep ocean heat content increases, and (3) interpolated bottle measurement differences were calculated between the 2023 occupation and the 2009 occupation. It should be reiterated that all these analyses are preliminary and subject to change as the data are quality controlled. Nevertheless, these analyses seem to show several familiar and, by now expected, patterns:

### 5.2.1 Anthropogenic carbon accumulation rate



Anthropogenic carbon accumulation rates (top) for two decadal comparisons and column inventory increase rates (bottom) for both the 1995 to 2009 comparison (blue) and the 2009 to 2023 comparisons. A slight, but non-statistically significant slowdown in accumulation can be seen when comparing the blue and red bands.

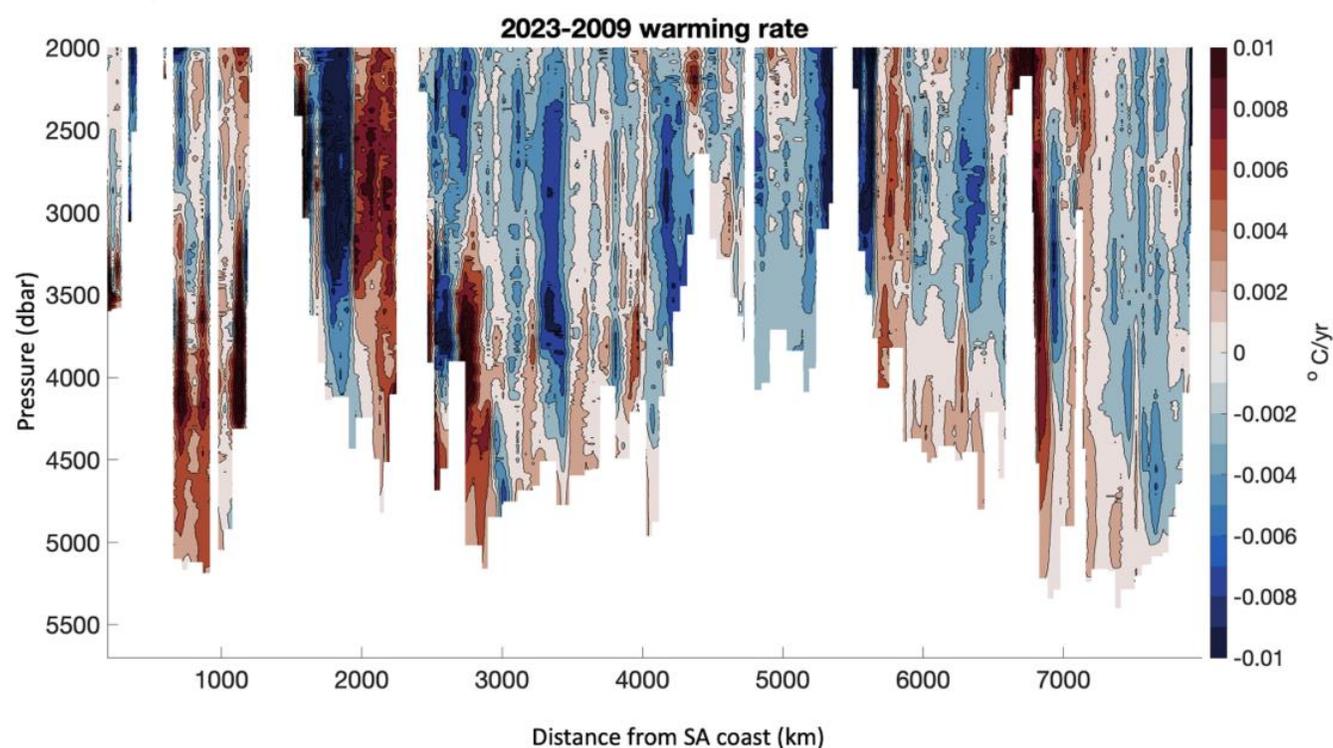
Strong accumulation continues in the upper 1000 m of the water column consistent with continued accumulation in Antarctic Intermediate and Subantarctic Mode waters at high latitude and advection of these signals northward

at depth along the I05 section. While there is an indication that the accumulation rate slowed in the recent decade, the decrease is not statistically significant from this section alone. It is yet to be determined whether the decrease is significant relative to the *increase* in accumulation rate that would be expected from the null-hypothesis assumption of transient steady state with an accelerating atmospheric anthropogenic carbon accumulation.

### 5.2.1.1 References

Carter, Brendan R., et al. "Pacific anthropogenic carbon between 1991 and 2017." *Global Biogeochemical Cycles* 33.5 (2019): 597-617.

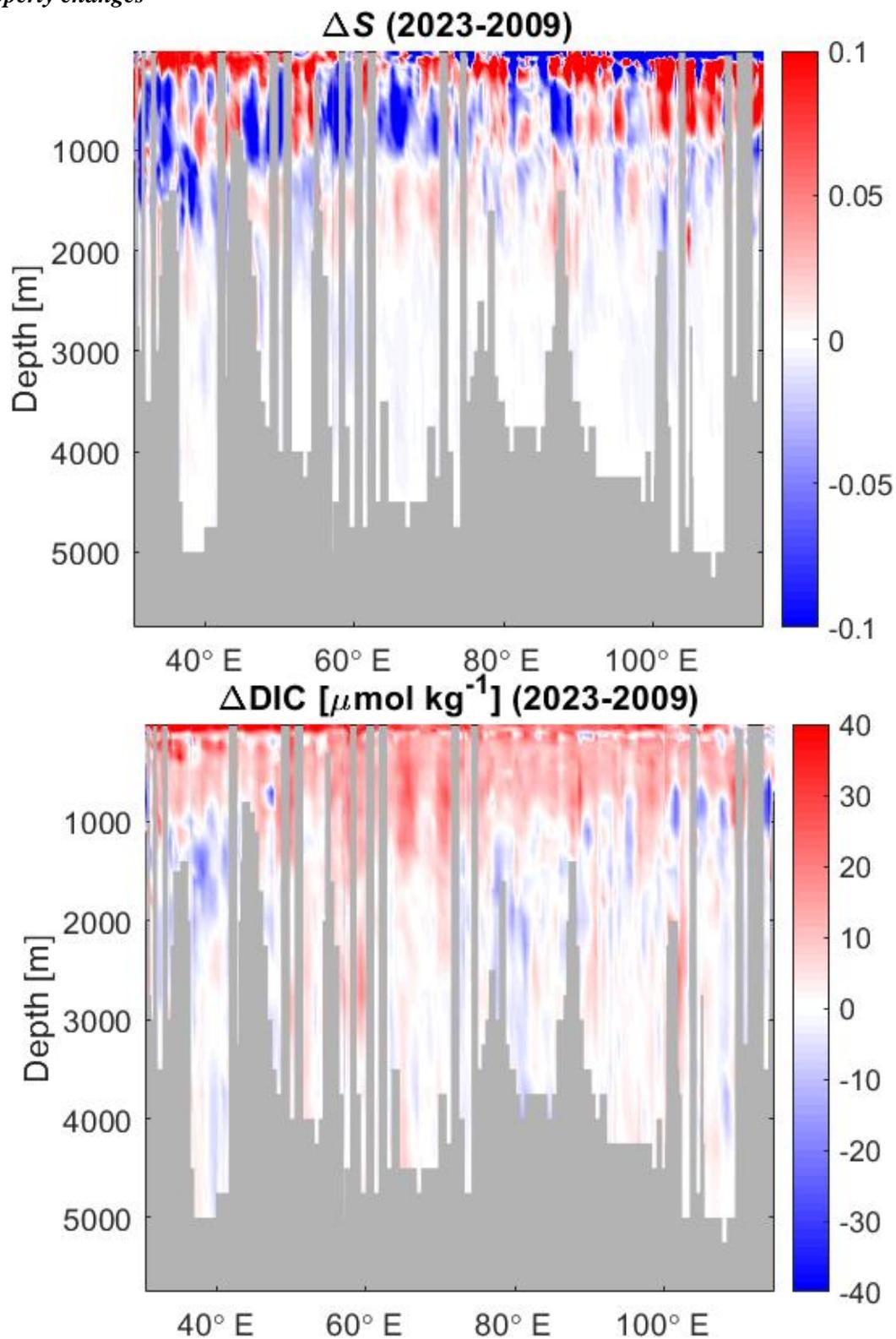
### 5.2.2 Deep ocean heat increases

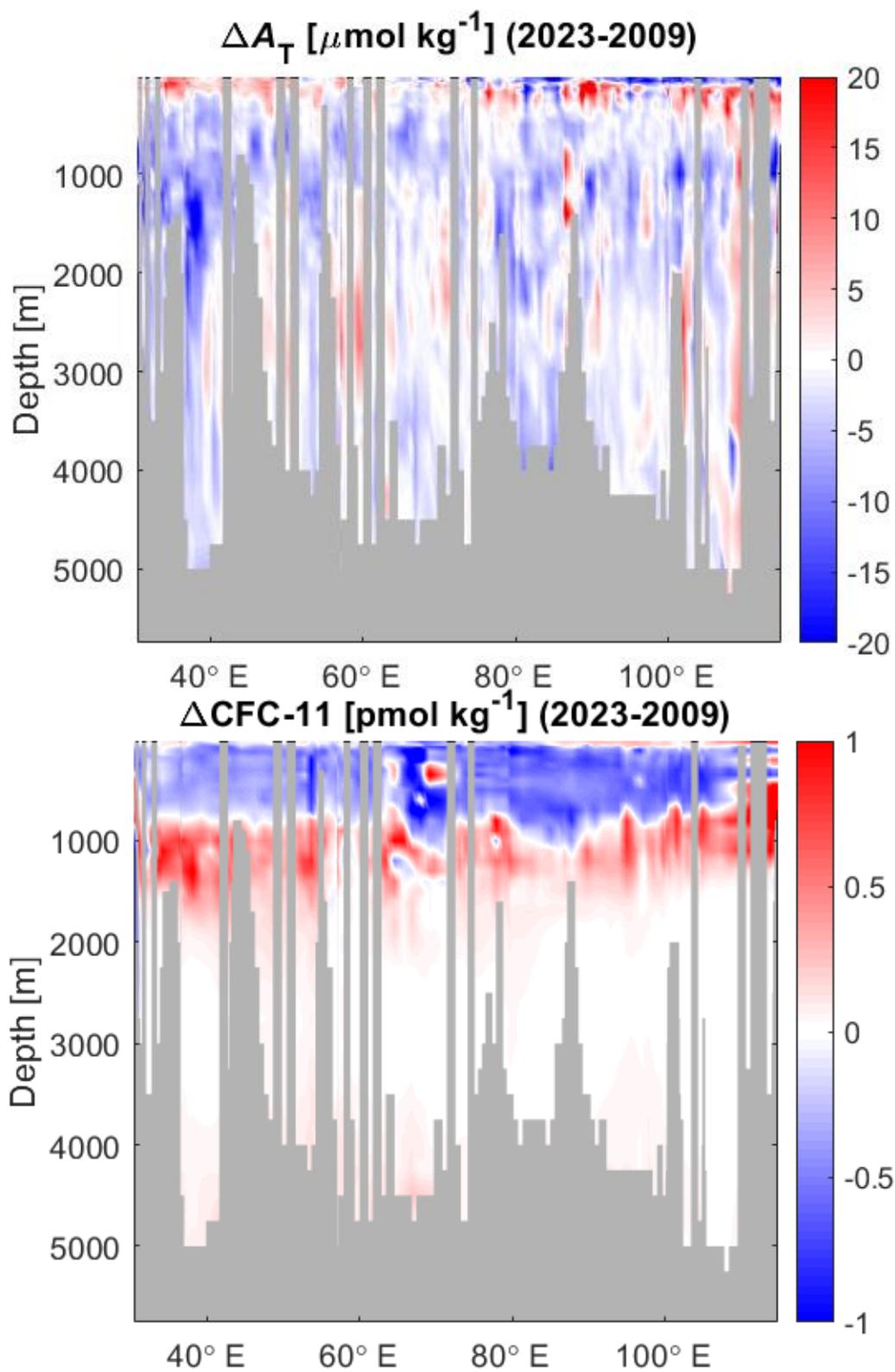


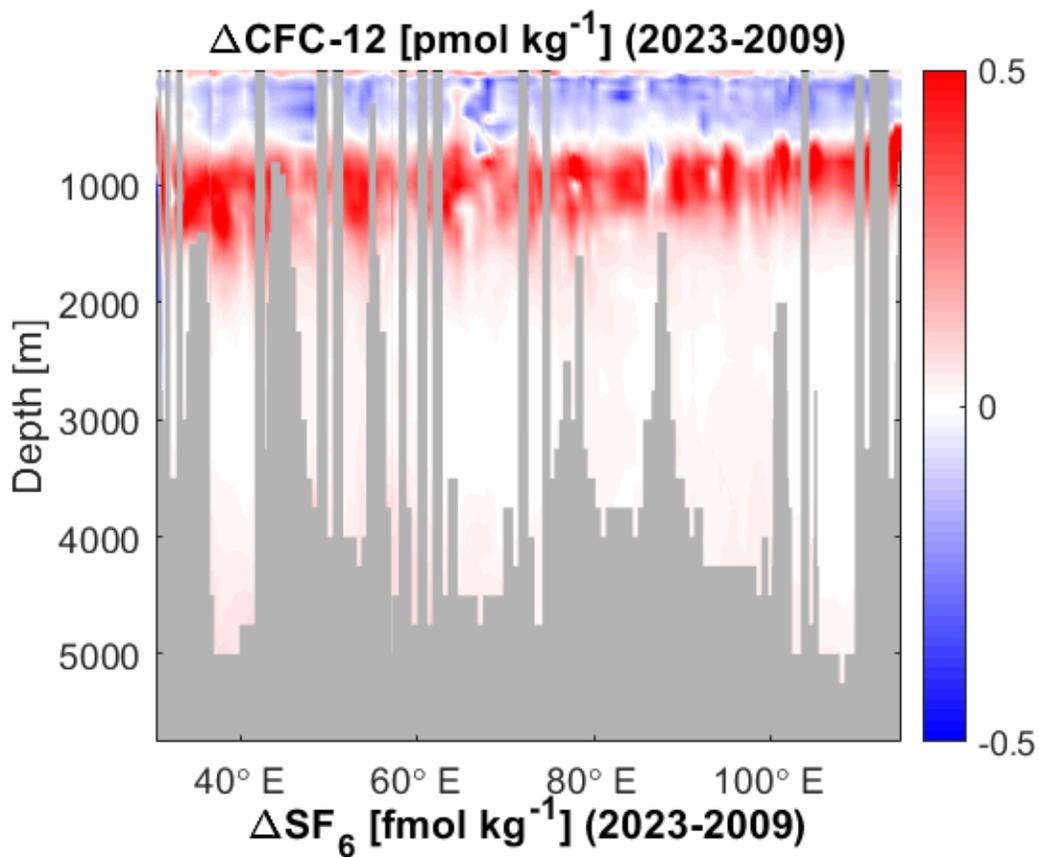
*Temperature changes relative to 2009.*

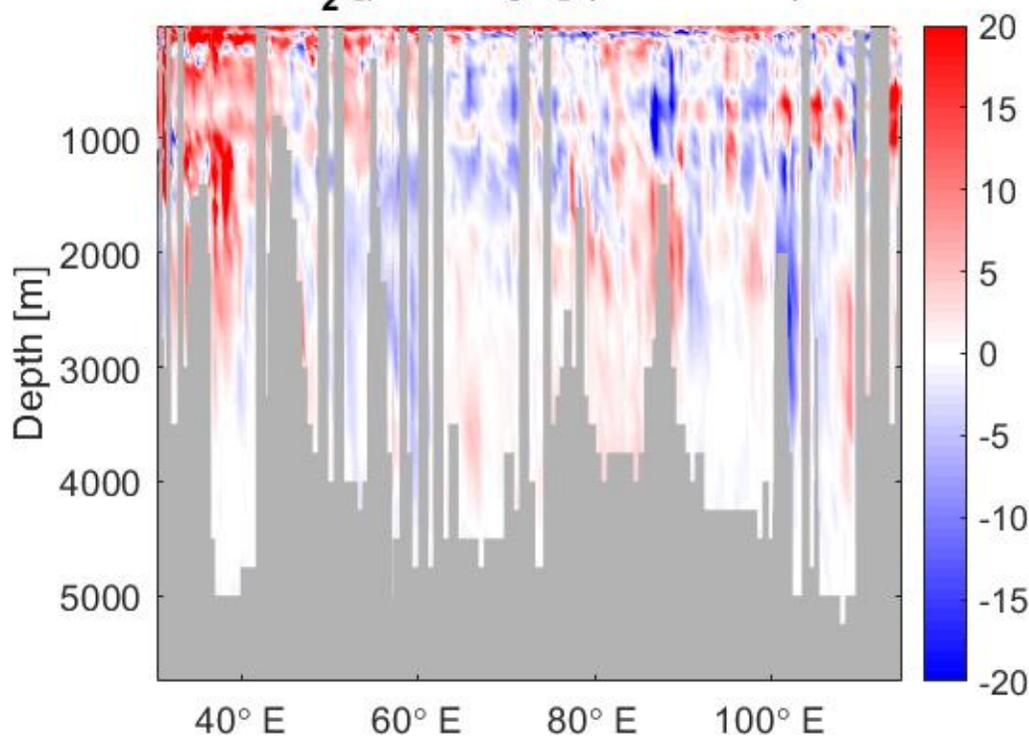
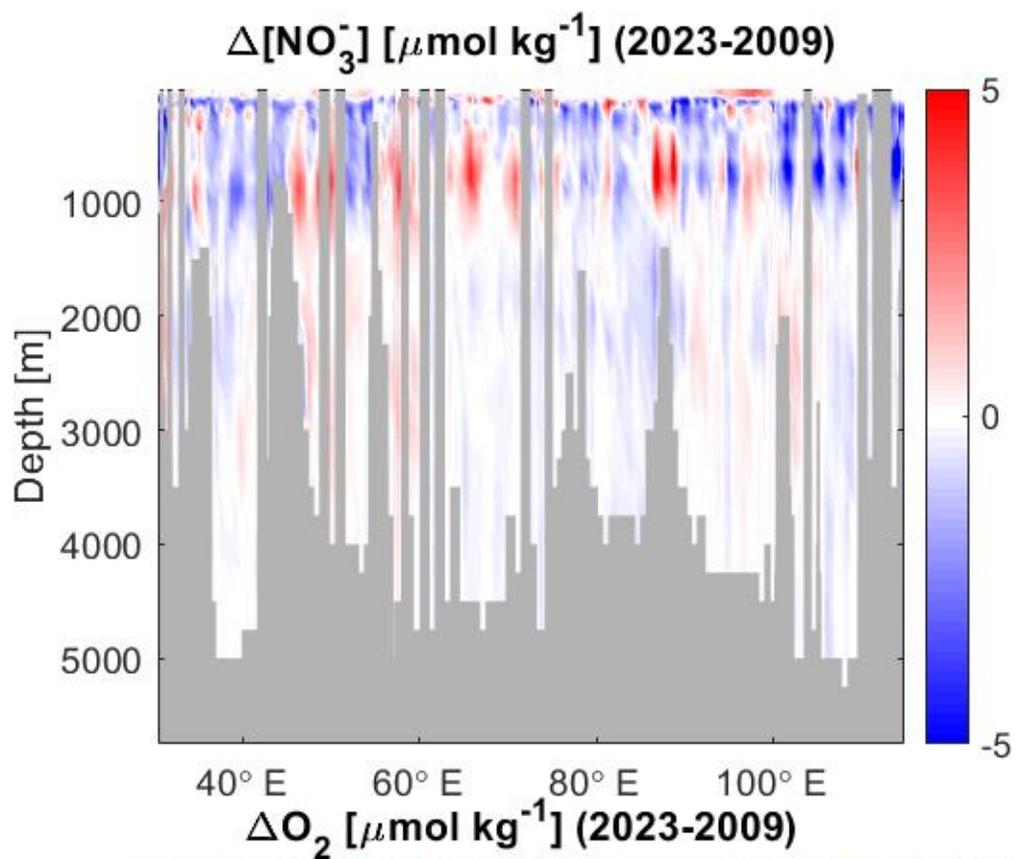
Preliminary analysis comparing temperature from this hydrographic section to the same stations in 2009 shows an overall deep warming. This warming varies spatially, with the fastest warming in the Mozambique Basin. Dipoles of warming and cooling occur in several locations, such as the Madagascar Basin, near the Southwest Indian Ridge, and east of the Broken Ridge. These may be indicative of shifts in the deep circulation. Cooling is evident in the Perth Basin and near the Ninety East Ridge

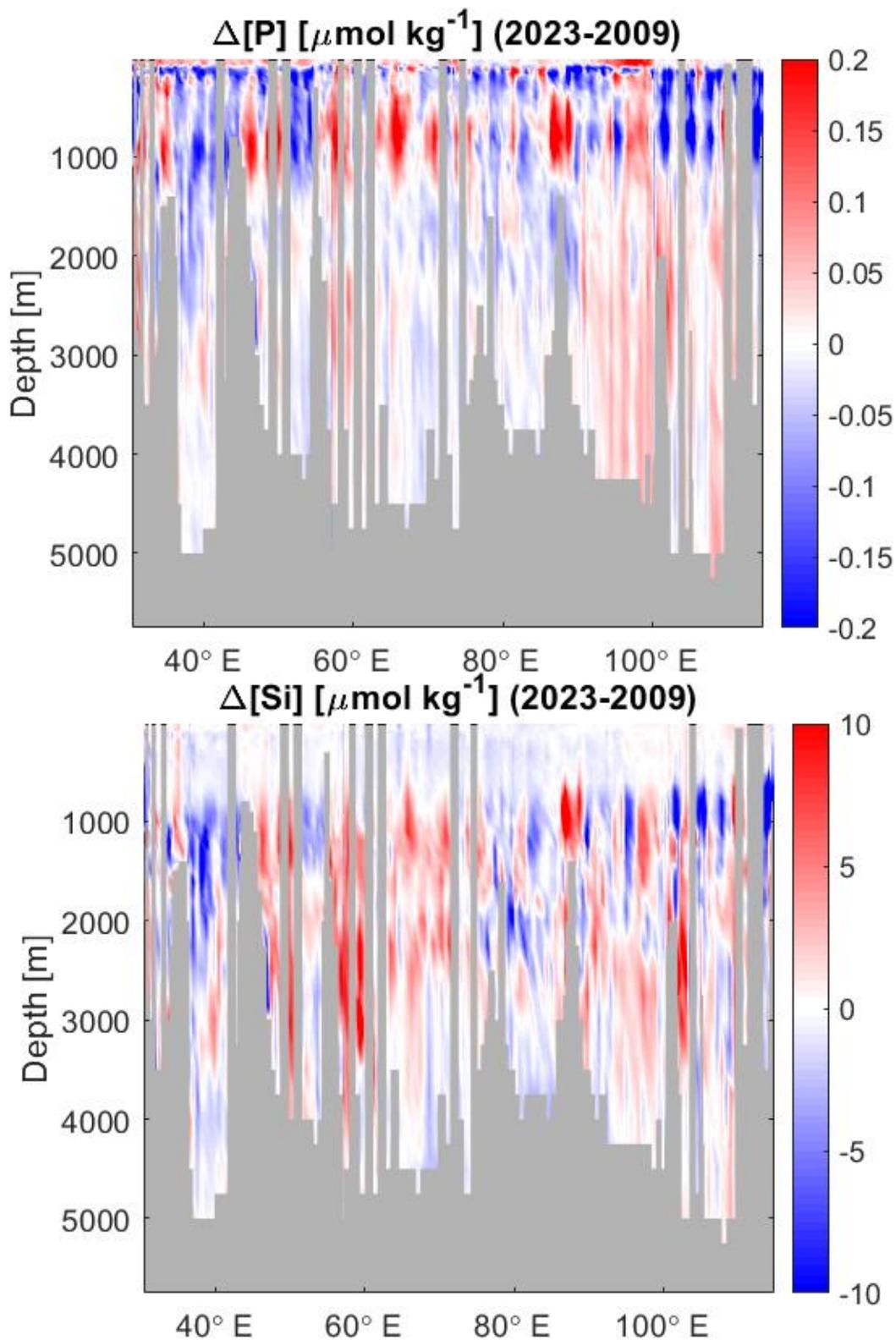
### 5.2.3 Property changes











Compared to the previous decade measurements, the most dramatic changes are found in the measurements of seawater variables with direct anthropogenic contributions: DIC, CFC-11, CFC-12, and SF<sub>6</sub>. Of these, annually

averaged SF<sub>6</sub> and CO<sub>2</sub> have increased monotonically in recent decades, and the chemical distributions have increased sharply in recent years throughout the upper water column. With DIC, the increase is complicated by large competing natural variations, whereas the natural variations in SF<sub>6</sub> are small and limited to shifts from physical circulation variability. Both CFC-11 and CFC-12 reached maximum atmospheric concentrations in the 90s, so these tracers are still increasing in water masses that were ventilated, on average, 30 or more years prior, including the intermediate water masses found near 1000 m depth. However, the concentrations are now decreasing in the most recently-ventilated water masses consistent with the falling atmospheric concentration. There is an indication that upper thermocline salinity has decreased in the western portion of the gyre and increased in the eastern portion, and A<sub>T</sub>, which is similarly controlled primarily by freshwater cycling, follows similar patterns with considerable natural variability. The nutrient increases show patchiness consistent with natural biogeochemical variability. It can be seen that similar patches are found in several nutrients, DIC, and O<sub>2</sub>, and this shows the strong explanatory power of the nutrient measurements when accounting for variations in other measurable seawater properties. Silicate shows less patchiness in the surface depths, though this is likely simply because the silicate contents of seawater are low at these depths in both decades.

### **5.3 Cruise narrative**

#### **5.3.1 Weekly updates**

A compilation of ~weekly updates on cruise life and progress is provided as Appendix 1.

#### **5.3.2 Student perspective**

I started the I05 cruise track on the Roger Revelle with a big question: what is next? I have just completed my Masters in physical oceanography and now I must decide what all Masters students must decide, am I going to get a PhD or start working? Starting my life as a CTD watch-stander, I have been on a cruise before but not one as scientifically extensive and as long, so naturally I was nervous about what to expect. Over the first two weeks I came to my first conclusion, working at sea is incredible. I got to meet new people from counties I have never visited before, the views really can't be beat by any other job and collecting data, while on a 12-hour shift can be tiring, is really enjoyable. Over weeks 3 to 4, I started to work on my science project and while I have worked on surface temperature, temperature throughout the water column is a whole different ball game. I realized how much there is still to learn about the ocean and just for my own knowledge of the ocean. I also realized I didn't bring enough snacks. Somewhere in-between weeks 5 and 6 I came to my final conclusion; I can definitely do this my whole life. Working on the ship the last few weeks I have learned so much more about oceanography and myself. While my next step isn't exactly planned out, I now know for sure that I want to contribute to the ever-growing knowledge of the ocean. I want to work with amazing people at sea and hopefully I will get to work with the people from the I05 2023 cruise again.

- Kirsten Petzer

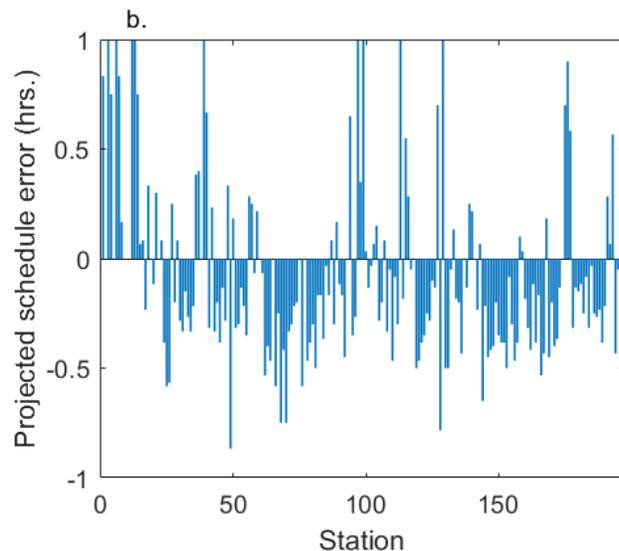
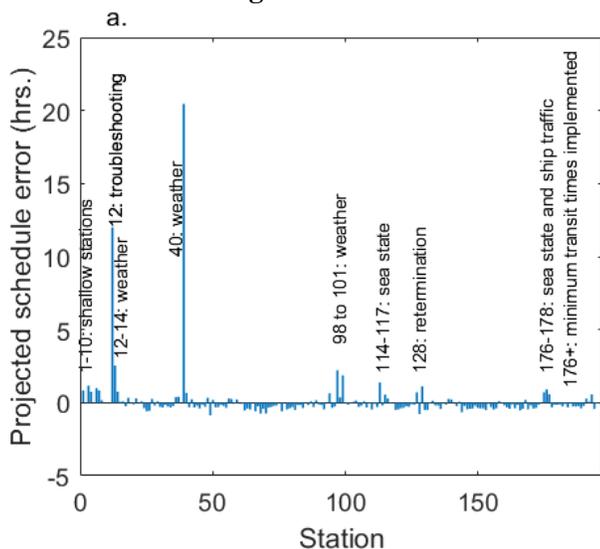
#### **5.3.3 Outreach talks**

Watch stander Steven Akin mentioned being on a research cruise on social media and was contacted about giving a remote outreach talk to elementary school children from the *R/V Roger Revelle*. Initially, all were apprehensive about the strength of the internet and his ability to give the talk without compromising his ability to perform his duties as a watch standers, but initial experimentation showed that the internet could provide the needed bandwidth in the early hours local time which coincided with business hours in the USA. Word of this outreach talk spread on social media and Steven was soon being contacted by many families and schools about possible

repeated conversations. It was found that he could schedule these talks in the hours before his shift so they were again attempted. Participants reported that the outreach calls were rewarding, and we view these talks as a significant boon for the public mission of the cruise. However, while some efforts were made to build consensus about these outreach talks, more should be done in advance of future cruises if a program like this would be desirable aboard. It is recommended to ensure that the STS, the Captain, and the port Captain all provide consent, and that cruise participants are made aware of the videocalls in advance and accommodations are made for individuals who do not wish to appear in the backgrounds. Ultimately, this was done for the videocalls on this cruise, though consensus was built late in several instances and it would be better had this all been done in advance of mobilization. Mostly, we note that this is an exciting new possibility in an age with strong remote internet connectivity. A table of these talks follows with personal information omitted.

Date (EST)	Location	School	# of Kids	Means of Contact
08.18 @ 2000	?	N/A	3	FB Messenger
08.21 @ 1200	Rogersville, MO	N/A	2	FB Messenger
08.22 @ 1210	Fruitvale, TX	Fruitvale Elementary, 6th Grade	15	personal email
08.24 @ 2200	?	N/A	4	personal email
08.25 @ 1130	Cleveland, TN	Walker Valley High School	1	personal email
08.28 @ 1200	Austin, TX	N/A	2	FB Messenger
08.29 @ 1015	Cleveland, TN	Walker Valley High School	15	personal email
08.31 @ 2100	Olive Branch, MS	N/A	1	FB Messenger
09.01 @ 1300	?	N/A	3	FB Messenger
09.04 @ 1200	?	N/A	2	FB Messenger
09.05 @ 1500	Austin, TX	N/A	2	FB Messenger
09.06 @ 1300	Eden, NC	Holmes Middle, 8th Grade	~150	personal email
09.07 @ 1200	Charleston, TN	Charleston Elementary School	~15	personal email
09.08 @ 1500	Cleveland, TN		~10	FB Messenger
09.12 @ 0900	Fort Worth, TX	Private, in-home tutor	6	FB Messenger

#### 5.4 Station timing



A bar plot of the difference between the actual time required for each station compared to the projected time required with positive numbers indicating that the station took longer than projected.

A full schedule for station work on leg 1 is provided as Appendix 2.

The I05\_2023 cruise was able to move consistently faster than projections, though the small number of large positive deviations from our projected station timings show the situations where unplanned (but not unexpected) mechanical or weather delays required significant time. We attribute most of the beaten projections (negative numbers in the figure above) to the efficient work of those aboard and the quick transits by the *R/V Roger Revelle* when in fair weather.

For most of the cruise, transit speeds (*s*) in nautical miles per hour (nmph) were projected from the *distance* between stations in nautical miles as:

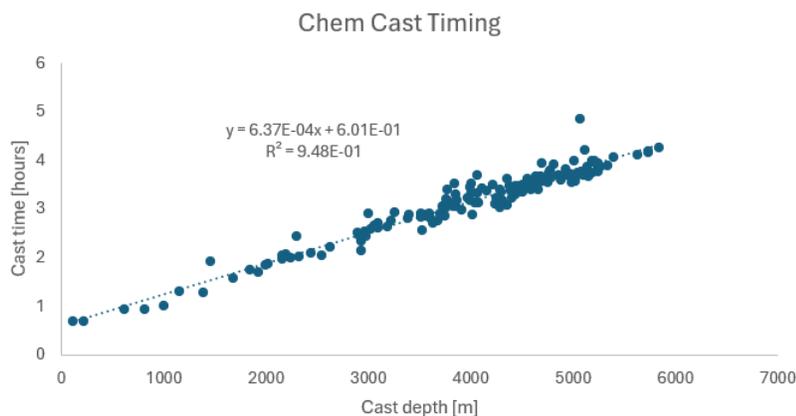
$$s = \frac{11.5(\text{nmph}) * \text{distance}}{5 + \text{distance}}$$

These speeds are intended to account for acceleration/deceleration as well as orienting the vessel and deploying the CTD rosette packages within the transit time budget. We note that the projections for the final ~20 stations were overridden with longer projected transit times of 2-3 hours when crossing the Agulhas or subsurface ridges/plateaus that required close station spacing. The intention with this change was to allow samplers time to fully sample the rosette and to analyze their samples before collecting additional seawater. This allowance was not made at the start of the cruise despite similarly proximal stations, which accounts for some of the early positive offsets. The actual transit speed varied with the sea state, but the *R/V Roger Revelle* averaged slightly faster than these projected transit speeds.

Initially the projected time required for a cast was estimated using an ad hoc function from another cruise with a different setup. Approximately 1/3<sup>rd</sup> of the way through the cruise the projections were updated to use an empirical fit to the maximum cast *depth* in meters based on the work performed to that point:

$$t = 0.0006352 \text{ (hours/m)} * (\text{depth}) + 0.6126 \text{ hours}$$

This projection can be updated for the full I05 cruise using the following fit:



*Time required for each cast as a function of the depth of the cast. This figure excludes several outliers and all biological casts except 6 that were combined with the chemistry casts on the same stations.*

The biological (bio) casts to 1000 m were provisionally budgeted 1 hour per station. Unlike the budget for the chemistry (chem) casts, this budget includes the length of time required to sample the rosette and prepare it for redeployment, as it is not possible to get underway before conducting the second cast. In practice, the bio casts required longer than projected. The first bio casts took longer than 2 hours from the time of the first deployment to the time of the subsequent deployment, counting the cast, securing the package, and sampling the bottles. However, all involved rapidly gained efficiency and the package started being secured in place rather than moved into the staging bay (as sea state was rarely a concern when sampling on station). After station 50 these casts required an average of 1.3 hours from the time when the first cast started to when the second cast started. In 12 instances, the 36 position rosette allowed the 4-11 Niskins needed for the bio cast to be collected simultaneously with the chem casts. In one instance, 4 samples were collected during the chem cast and a separate surface cast collected the balance of the needed seawater. These “combo-casts” were done where possible without significant loss of sampling resolution. This typically occurred in shallow water or when sampling proximal sets of stations over bathymetric changes where surface water resolution was deemed less important than resolving deep ocean features.

## 6 Water sampling package

Satellite communications via HiSeasNet using service from FleetExpress (FleetBroadband and Global Express) and Sealink Plus (Iridium CERTUS and Sealink Premium).

Rosette/CTD/LADCP casts were performed with a package consisting of a 36-bottle rosette frame (SIO/STS), a 36-place carousel (SBE32), and 36 10.0L Bullister bottles (SIO/STS) with an absolute volume of 10.4L. Underwater electronic components consisted of a Sea-Bird Electronics SBE9plus CTD with dual pumps (SBE5T), dual temperature (SBE3plus), dual conductivity (SBE4C), dissolved oxygen (SBE43), transmissometer (Wetlabs), fluorometer (Wetlabs FLRTD), altimeter (Valeport VA500) and an optical oxygen sensor (RINKO). An SBE35RT reference temperature sensor was connected to the SBE32 carousel and recorded a temperature for each bottle closure. The sea cable armor was used for ground (return). Power to the SBE9plus CTD (and CTD sensors), SBE32 carousel, and auxiliary sensors was provided through the sea cable from the SBE11plus deck unit in the main lab.

All sensor data looked good throughout the duration of the cruise except for the primary conductivity sensor (SN 1879). During the cast, the sensor was notably shifting baselines, presumably due to a cracked cell. This was swapped out with SBE4C SN 2319 which remained the primary sensor until the end of the cruise. The sensor serial numbers, calibration dates, and A/D channel are listed below.

<b>Sensor &amp; Serial Number</b>	<b>Cal. Date</b>	<b>A/D Channel</b>
9plus SN 0569	12/10/2021	
3plus SN 2166 (primary)	6/29/2023	
3plus SN 4953 (secondary)	6/29/2023	
4C SN 1879 (primary – removed)	6/9/2023	
4C SN 2319 (primary)	5/31/2023	
4C SN 3023 (secondary)	6/1/2023	
5T SN 1881	11/16/2022	
5T SN 1890	11/1/2022	
35RT SN 0011	7/7/2023	
43 SN 0197	6/6/2023	Aux4, V6
Transmissometer SN 1769	5/4/2023	Aux1 (low order), V0

Alt. VA500 SN 53821  
RINKO SN 0297  
FLRTD SN 4334

1/28/2016 Aux3, V4  
8/24/2022 Aux2, V2 & V3  
1/7/2022 Aux1 (high order), V1

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All electronics, with the exception of 2/3 of the Chipods were mounted below the carousel. The SBE9plus was mounted into its cage mount and attached to the bottom of the rosette frame across grid bars in the center of the rosette. The SBE4C conductivity, SBE3plus temperature, and SBE43 dissolved oxygen sensors and their respective pumps and tubing were assembled as recommended by SBE on the CTD cage. The transmissometer was mounted horizontally, and the fluorometer, altimeter, and RINKO were mounted vertically along the bottom of the rosette frame. Both the upward-looking and the downward-looking ADCP's were mounted vertically on one side of the frame between the bottles and the CTD. The ADCP battery pack was located on the opposite side of the center grid bars, mounted on the bottom of the frame. In front of the battery pack, the transmissometer was mounted along a Unistrut on the bottom frame.

The rosette system was suspended from a UNOLS-standard three-conductor 0.322" electro-mechanical sea cable. The sea cable underwent 2 full mechanical terminations during I05 (after station 012/02 and after station 127/01), as well as an additional electrical retermination after station 097/01. The 012/02 retermination was prompted by modulo errors causing 2 aborted casts. The first attempt to resolve the problems was an electrical retermination after the first cast and when that failed the slip ring connecting to the CAST6 winch was replaced and a full retermination was conducted. The 127/01 retermination was done as preventive maintenance to ensure the cable was in good working condition and free of kinks. Kinks in the EM cable are a result of the shock loading on sheaves at shallow depths during launch and recovery. The electrical retermination at station 097/01 was due to modulo errors which were resolved with the retermination. R/V Revelle's CAST6 winch and deployment system was used for all stations.

The CTD watchstanders prepared the rosette 15-30 minutes prior to each cast. The bottles were cocked and all spigots, vents, and lanyards were checked for proper orientation. LADCP technician would check for LADCP battery charge, prepare instruments for data acquisition, and disconnect cables. The Marine Technician would check the sea state ~15 minutes prior to station arrival and decide if conditions were acceptable for bringing out the rosette. The rosette was moved from the sampling bay out to the starboard side of the deck using Revelle's tugger-driven cart (requiring the use of 2 air tuggers in tandem). Once on deck, sea cable slack was pulled up by the winch operator and the docking head was brought out.

The CTD was powered-up and the data acquisition system started from the computer lab when directed by the marine technician from the deck. The rosette was unstrapped from the air-powered cart. The winch operator was directed by the deck watch leader to raise the package. Squirt boom and rosette were extended outboard, and the package was quickly lowered into the water. At the surface, the technician told the winch operator to "zero" the wire out and lower the rosette to 10 meters, where it was held until the console operators determined that all sensors had turned on. The winch operator was then directed to bring the package back to the surface and to begin the descent. Each rosette cast was lowered to within 10 meters of the bottom, using the altimeter, winch wireout, and CTD depth to determine the distance. One cast (128/01) was lowered to 6000db, the pressure limit of some of the package instrumentation.

For each upcast, the winch operator was directed to stop the winch at some number (between 10 and 36) of standard sampling depths. These standard depths were staggered at every station based on a Matlab code derived

by the Chief Scientist. To ensure the package shed wake had dissipated, the CTD console operator waited 30 seconds prior to tripping sample bottles. Before moving to the next consecutive trip depth, an additional 15-second pause was observed. The marine technician directed the package to the surface for the last bottle trip. Recovering the package at the end of the deployment was essentially the reverse of launching. Once the rosette was on deck, the console operator terminated the data acquisition, turned off the deck unit, and assisted with rosette sampling. The rosette was secured on the cart and moved into the aft hanger for sampling. The bottles and rosette were examined before samples were taken, and anything unusual was noted on the sample log. Routine CTD maintenance included flushing the conductivity and oxygen sensors with freshwater between casts to maintain sensor stability and rinsing the rest of the sensors (including the carousel) with freshwater as well.

Rosette maintenance was performed on a regular basis. Caps, spigots, and o-rings were inspected for leaks. Occasional reorientation of the bottles was required to ensure proper firing and sampling. Lanyards were replaced as needed. No bottle repairs were necessary for this cruise. Within the first week of deploying the package, bottle 4 was replaced due to a slow vacuum leak that was unaffected by o-ring, spigot, and vent swaps. The new bottle 4 exhibited slow leak symptoms in the last few casts but changing o-rings did not solve the issue. As the casts were shallower and all 36 bottles were not being fired, bottle 4 was skipped for the final few casts. Bottle 36 was also replaced around station 100, due to contamination that was seen in the CFC data after sampling (possible grease from the CAST6 extension).

## 7 Underway Data Acquisition

In addition to the measurements with dedicated sub-reports below, measurements were collected as possible from all ship's systems aboard the *R/V Roger Revelle* throughout the cruise. These systems include:

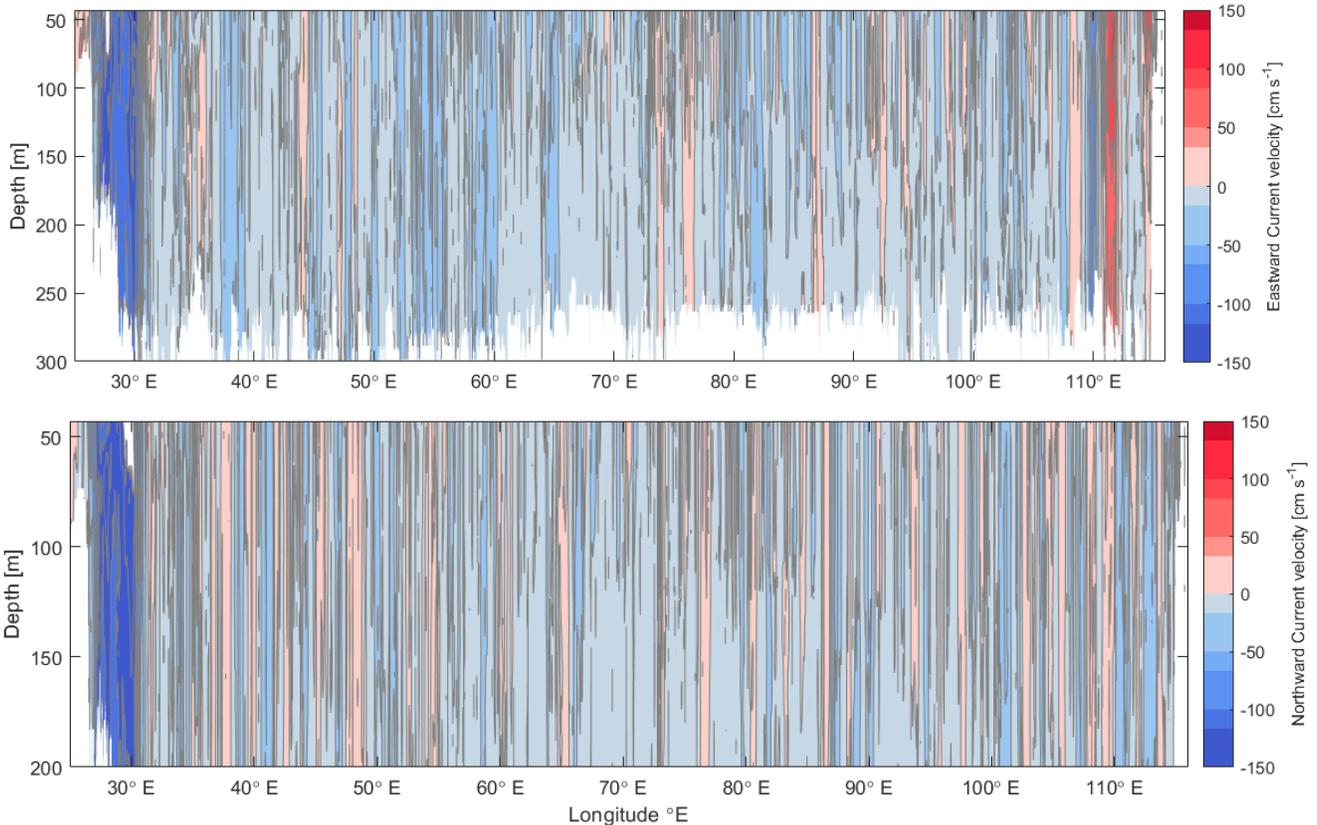
- Acoustic Doppler Current Profiler
  - RD Instruments Ocean Surveyor 75 kHz
  - RD Instruments Narrowband 150 kHz
  - RD Instruments Mariner Workhorse 300 kHz (portable)
  - UHDAS digital data acquisition system
- Multibeam mapping systems
  - Shallow water ( 20 to 1,000 meters)
    - Manufacturer/Model: Kongsberg EM712
    - 40 to 100 kHz 140-degree swath bathymetry and backscatter, with midwater imaging capability
  - Deep water (1,000 to 11,000 meters)
    - Manufacturer/Model: Kongsberg EM124
    - 12 kHz 150-degree swath bathymetry and backscatter, with midwater imaging capability
- Motion reference units
  - Manufacturer/Model: Kongsberg Seapath 330+
  - Fiber-optic gyroscope inertial navigation system
  - Manufacturer/Model: Ixblue Phins III
  - Ring laser gyrocompass & motion sensor
- Expendable bathythermograph (XBT) (3 deployed within the Agulhas Current on I05\_2023)
  - Manufacturer/Model: Turo Devil
  - Variety of probes for different depths / ship speeds

- Gravimeter
  - Manufacturer/Model: Bell BGM-3
- Hydrographic Doppler Sonar System
  - Manufacturer/Model: Scripps Institution of Oceanography / Pinkel HDSS
  - 50/140 kHz
  - Profiles to depth of 1,000 m with 15 m depth resolution
- Magnetometer (not used in I05\_2023)
  - Manufacturer/Model: Marine Magnetic SeaSpy
  - Towed Overhauser magnetic field sensor
- Sub-Bottom Profiler
  - Manufacturer/Model: Knudsen 3260 CHIRP
  - 3.5 / 12 kHz
  - Hull-mounted chirp deep-water subbottom echosounder
- Acoustic Synchronization Unit (not used on I05\_2023)
  - Manufacturer/Model: Kongsberg K-Sync
- Acoustic Navigation System
  - Manufacturer/Model: Kongsberg HiPAP 352P-MGC
  - Ultra short baseline positioning system
- Underway Data System
  - Meteorological sensor suite
  - Circulating uncontaminated seawater system
  - Sea surface water physical properties
- Shipboard Network
  - Wired and wireless networks in all labs and staterooms.
- Digital Data Archive
  - Linux rackmount servers with multiple terabyte RAID arrays
- $p\text{CO}_2$  system (see sub report)
  - Manufacturer/Model: General Oceanics
  - Underway  $p\text{CO}_2$  measuring system
- Ocean State Monitoring System
  - Manufacturer/Model: Rutter / WaMoS II
  - Underway X-band radar surface wave sensing system

These data are uploaded to the Rolling Deck Repository according to predetermined timetables by *R/V Roger Revelle* personnel. Please begin your search for these data at that repository and then contact the chief scientist if you have any difficulty finding the data you need. We note there were several data outages when routine operations and maintenance required that sensor suites be shut down, though, generally, these ship systems functioned well throughout the cruise.

## 7.1 SADCP

PI: Jules Hummon (UH)



*Eastwest (top) and Northsouth (bottom) current velocity from the shipboard ADCP. The Agulhas and Leeuwin currents are visible on either boundary of the section.*

LADCP data will be transmitted to PI Jules Hummon.

## 7.2 Underway seawater $p\text{CO}_2$

PI: Simone R. Alin (PMEL)

Shipboard personnel: Andrew Collins (UW/CICOES and PMEL)

### Data Collection

The partial pressure of  $\text{CO}_2$  ( $p\text{CO}_2$ ) in the surface ocean was measured throughout the duration of this expedition with a General Oceanics 8050 underway system. Uncontaminated seawater was continuously passed ( $\sim 2.7$  l/min) through a chamber where the seawater concentration of dissolved  $\text{CO}_2$  was equilibrated with an overlying headspace gas. The  $\text{CO}_2$  mole fraction of this headspace gas ( $x\text{CO}_2$ ) was measured approximately every three minutes via a non-dispersive infrared analyzer (Licor 7000). Roughly every three hours, the system measured four gas standards with known  $\text{CO}_2$  concentrations certified by the NOAA Earth Science Research Laboratory in Boulder, CO ranging from  $\sim 300 - 900$  ppm  $\text{CO}_2$ . Additionally, a tank of 99.9995% ultra-high purity nitrogen gas was measured as a baseline 0%  $\text{CO}_2$  standard. Following measurements of standard gases, six measurements of atmospheric  $x\text{CO}_2$  were made of air supplied through tubing fastened to the ships mast. Twice a day, the infrared analyzer was calibrated via a zero and span routine using the nitrogen gas and the highest concentration (818.3

ppm) CO<sub>2</sub> standard. In addition to measurements of seawater  $x\text{CO}_2$ , atmospheric  $x\text{CO}_2$ , and standard gases, several variables were monitored to evaluate system performance (e.g. gas and water flow rates, pump speeds, equilibrators pressures, etc). For more detail on the general design of this underway  $p\text{CO}_2$  system, see Pierrot et. al (2009).

A Seabird (SBE) 38 temperature sensor located at the ships seawater intake provided measurements of *in situ* seawater temperature, while a SBE 45 thermosalinograph monitored temperature and salinity in the bow of the ship before the seawater reached the  $p\text{CO}_2$  system. A Seabird SBE 43 membrane-based dissolved oxygen sensor plumbed upstream of the  $p\text{CO}_2$  system water supply measured dissolved oxygen (DO) continuously. Additionally, a WETLABS WS3S Wetstar fluorometer was also plumbed upstream for fluorometry measurements.

For the first seventeen days of data collection, the system was supplied by seawater from the ships bow intake. During this period, it appeared that there may have been some significant changes to seawater temperature and salinity (and therefore measured  $p\text{CO}_2$ ) when the ship stopped for CTD casts compared to when it was in underway transit. For this reason, we decided to switch from the bow intake to the seachest intake to supply the  $p\text{CO}_2$  system with seawater. A more thorough evaluation of a potential localized influence on SST, SSS, and ship speed will be performed at a later date. The seachest was used for the remainder of the cruise. A more detailed description of the bow- vs. seachest-intake sources, as well as serial numbers and gas standard concentrations can be found in S1.

### 7.2.1 Data return and system performance

A preliminary round of processing was performed on this dataset using Matlab routines developed by Denis Pierrot of the Atlantic Oceanic and Meteorological Lab in Miami, FL. Overall, the system performed very well, with only one instance where a prolonged loss of data occurred due to insufficient water flow. During this preliminary round of data processing, over 99% of the 25,733 measurements of seawater surface  $p\text{CO}_2$  collected by the underway system were considered high quality.

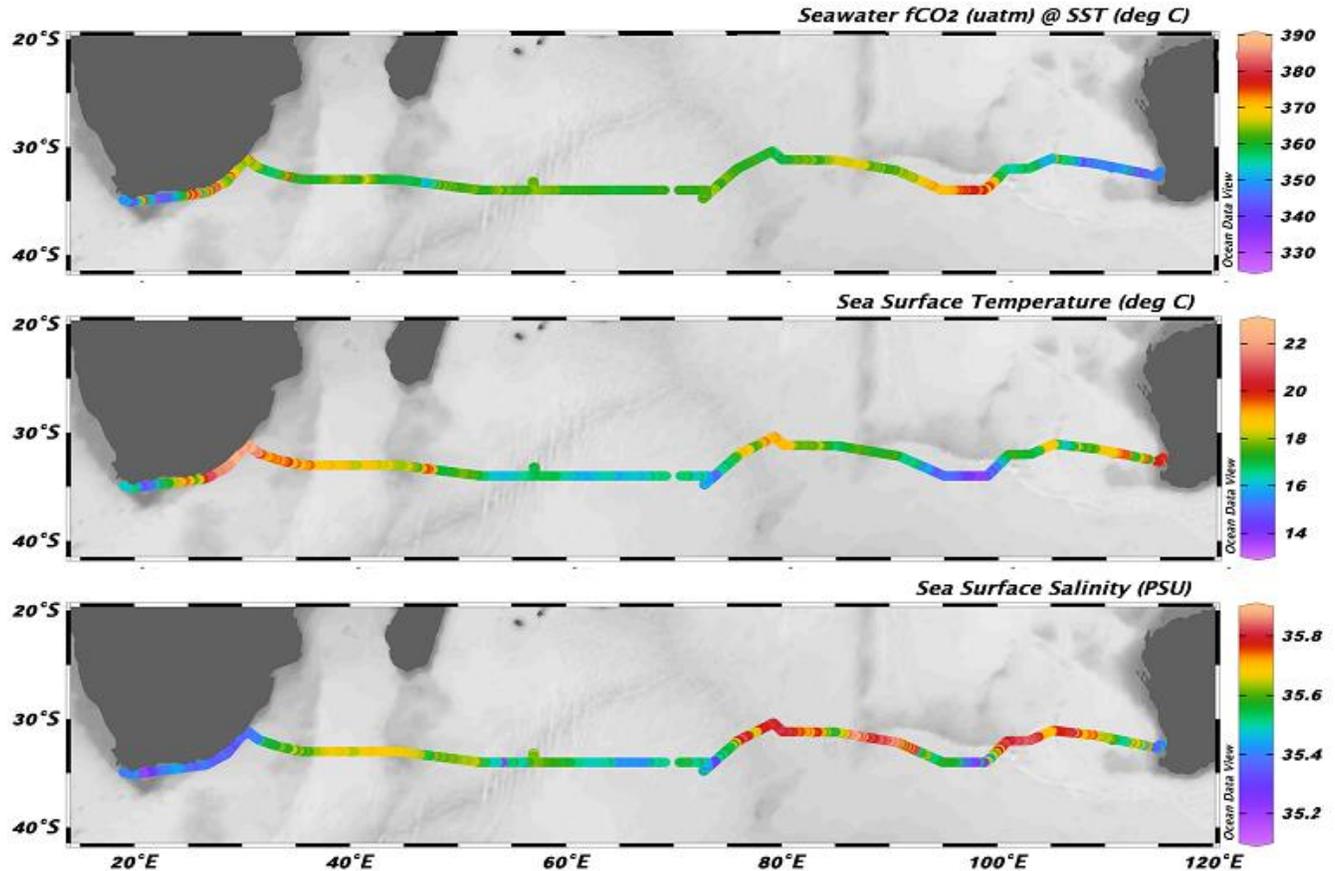
In one brief (~ 3 hr) instance, seawater flow was accidentally turned off to the underway system, resulting in data loss for that period. In another instance, an issue with the ships SBE 38 intake temperature sensor resulted in nearly three days of data loss. As such, in the preliminary data analysis, an average offset between intake temperature and equilibrator temperature (Estimated intake temperature=measured equilibrator temperature-0.13° C) was substituted for intake temperature during this data dropout. A more thorough reconstruction will be done on these data at a later date, and these data will likely be assigned a quality flag of 3. In several (~30) instances, sporadic data loss occurred when the ships data transmission dropped, resulting in the loss of position, temperature, salinity, etc data for the associated  $p\text{CO}_2$  measurements. These measurements will be merged with the  $p\text{CO}_2$  dataset during the next round of processing. Of the 2,587 measurements of atmospheric  $p\text{CO}_2$  measurements made during the cruise, 88 were assigned a WOCE quality flag of 4 (i.e. bad quality) on account of contamination from the ships stack gas. Measurements of gas standards were within 1% of their certified value throughout the duration of the expedition.

Preliminary review of collected data suggest that the main control on the surface seawater  $p\text{CO}_2$  was SST (Figure 1), with little clear evidence of strong biological influence at this time. However, a closer examination of these controls will occur during subsequent data review when combined with underway dissolved oxygen and fluorometry data.

This dataset should be considered preliminary; additional quality control and quality assurance is needed before these data can be considered final. This dataset will be submitted to the [SOCAT](#) and [NCEI](#) public databases.

### 7.2.2 References

Pierrot, D., Neill, C., Sullivan, K., Castle, R., Wanninkhof, R.W., Lüger, H., Johannessen, T., Olsen, A., Feely, R.A., Cosca, C.E.; 2009. Recommendations for autonomous underway pCO<sub>2</sub> measuring systems and data-reduction routines. *Deep-Sea Research II* 56 (2009) 512–522



Spatial distribution of relevant parameters (fCO<sub>2</sub> [ppm], sea surface temperature [SST, °C], sea surface salinity [PSU]) measured by the underway pCO<sub>2</sub> system during the 2023 GO-SHIP I05 research expedition.

### 7.2.3 S1. Supplementary Information

Notes on seawater source and data (from GO-SHIP 2022 P02 Research Expedition cruise report; Julian Herndon)

The pCO<sub>2</sub> system on this cruise was installed in the Hydrolab. The *R/V Revelle* has three separate but related sources of uncontaminated underway seawater. The first (#1) is fairly typical of AGOR-24 sister ships like the *R/V Brown* and the *R/V Thompson* with an intake at the bow that feeds all the labs. The second (#2) is sourced from the engine room sea-chest and is plumbed into the rest of the ship via a “T” in the system in the Hydrolab. This system has a baffle/diaphragm pump to supply intake water for biologists concerned about damage to the organisms by the centrifugal pump used for system #1. This (system #1) is the system that was used on this cruise. The residence time of water in the engine room sea-chest is believed, by the Chief Engineer, to be less than a minute given the large volume of water taken from it to cool the engines. There is no antifouling system

installed in this engine room sea-chest. The third (#3) system is an isolated/standalone flow-through at the bow, but separate from #1 at the bow. System #3 has a TSG45 and SBE38, downstream and upstream respectively, of the centrifugal pump. System #3 takes water in at the bow thruster and dumps it out over the side a few feet away. This was an installation done in drydock to get around the modifications associated with installing the new bow thruster during the mid-life refurbishment. The result is that the intake seawater temperature for system #1 and #2 comes from the independent system #3. Salinity can be sourced either from system #3 or a separate TSG45 installed in the Hydrolab that is fed by either system #1 or #2. System #1 (bow intake) does NOT have its own intake temperature probe. System #2 (engine room sea-chest) does NOT have an intake temperature probe. The  $p\text{CO}_2$  system in the Hydrolab received water from system #2, intake temperature from system #3 and salinity data from the TSG45 in the Hydrolab, which measured salinity (along with temperature) of the source water from the sea-chest once it reached the Hydrolab. The  $p\text{CO}_2$  received water from a “T” before the sea-chest water was de-bubbled and subsequently fed to the TSG45. To facilitate data processing and future troubleshooting of the *Revelle*  $p\text{CO}_2$  system, the column headings for data in the  $p\text{CO}_2$  files sourced from the ship are identified in Table #2. Serial numbers and additional details for the instruments in table #2 are in a separate excel file and will be reported as part of the metadata for  $p\text{CO}_2$  data submitted from this cruise.

Standard	Concentration (ppm)	Tank Serial Numbers
1	0.0	Praxair 5.0 Ultra High Purity N <sub>2</sub>
2	256.69	JB03786
3	401.1	JB03891
4	621.27	JB03864
5	818.3	JB04076

Table 1: Standard gases for the GO-SHIP I05 2023 cruise underway  $p\text{CO}_2$  system.

Column Header	Instrument	Seawater System	Location
TSGF1	SW flow meter	3	Bow
TSGT2	TSG45 temperature	2 and 3	Hydrolab
TSGS2	TSG45 salinity	2 and 3	Hydrolab
TSGF2	SW flow meter to TSG45	2 and 3	Hydrolab
PCO2F	SW flow meter to $p\text{CO}_2$	2 and 3	Hydrolab
SST	SBE 38 temperature	3	Bow
AT	RM Young temperature	MET	56' above MWL*
BP	RM Young barometer	MET	56' above MWL*
HDG	Konsberg GPS		
SOG	Speed over ground		

Table 2:  $p\text{CO}_2$  system ship supplied data column headers for the GO-SHIP I05 2023 cruise underway  $p\text{CO}_2$  system. \*MWL = mean water level.

### 7.3 EK80 (fish finder)

We collected underway EK80 data as Level 3 measurements on this cruise. Compared to physical observations, the low resolution in measuring biological properties has been the bottleneck for unraveling mechanisms underlying large-scale variations and predicting future changes in ecosystem

dynamics. By incorporating multifrequency echosounders as a part of the GO-SHIP observations, we can develop an understanding of the link between physical changes in global oceans with *quantitative* estimates of abundance and distributions of zooplankton and micronekton expanding the scope of Bio-GO-SHIP project to higher trophic levels. Furthermore, active acoustic techniques can be exploited to understand physical oceanography such as fronts, turbulence, internal waves and tides, ocean stratification, and mixing.

We tested the interference between shipboard ADCPs and echosounders (i.e., cross-talks) before the cruise started. We confirmed that simultaneous operations of ADCP and EK80s kept the quality of ADCP data which are Level 1 measurements on the GO-SHIP program. EK80 data were collected throughout the cruise. Some interference was noted with the HDSS and this system was disabled whenever possible given operational constraints.

## 8 Casts and Niskins

### 8.1 Bottle depth schemes

During pre-cruise planning, it became clear that most traditional combinations of repeating 3 depth schemes would lead to consistently-missed depths for parts of the water column due to the rapid changes in the bathymetry of the I05 section. Of many possibilities considered, this was the best outcome:

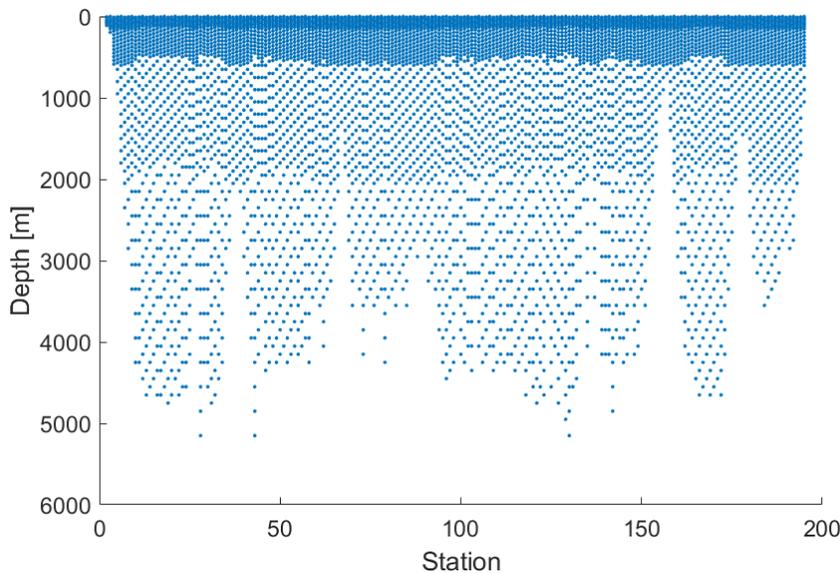


Figure XXXX. The best projection of many obtained from a traditional 3-set scheme.

Even in this projection there were several areas where depths were routinely missed. It was therefore attempted to create a function that would select depths automatically based upon a weighting function that set the desired sample density vs. depth and then maximized the weighted distance from samples on previous stations and from samples on the current station. This also allowed the sampling scheme to be updated semi-automatically to fill in depths left by miss-tripped bottles or other mishaps that prevented a viable sample. The depth distribution was weighting was approximately based on the distribution used for I05\_2009, but with smoother transitions. The final sample distribution is provided.

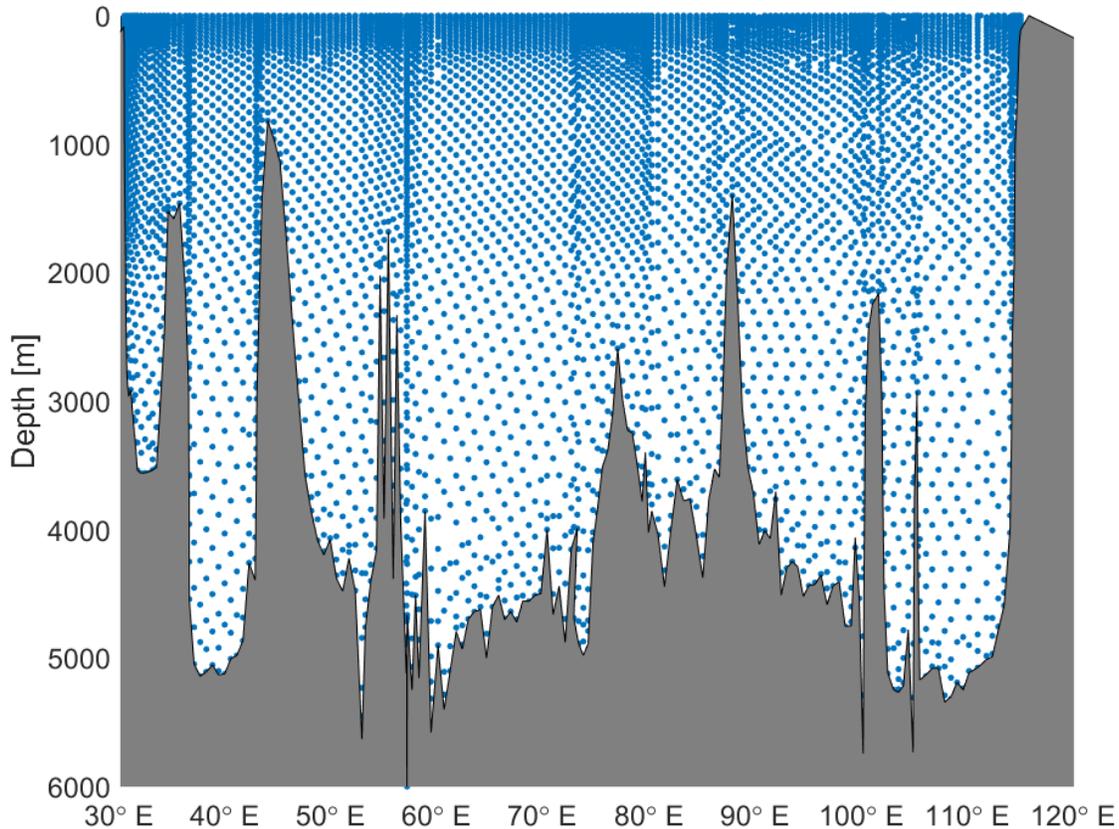


Figure XXXX. The sample distribution on I05.

At the outset of the cruise (i.e., on the right of Figure XXXX), the custom function was written to choose depths that were maximally distant from depths sampled on the previous two stations, with excess sample density reserved for the deepest ~10% of the cast. However, this optimization created a zig-zag pattern that created unnecessarily large gaps in the sample distribution. Thus, shortly after the 90° E Ridge crossing, the sample scheme was altered to avoid only depths from the previous station, and a slight preference was added to avoid the shallower depths relative to avoiding the deeper depths to ensure that the depths sampled did not repeat every other station. After ~60° E a final term was added to ensure a preference for regular (weighted) spacing with depth. This depth selection function was then used for the rest of the cruise with modifications only to account for the unique demands of certain bio and float deployment stations. The oxygen minima observed on this cruise were broad and flat and no optimization was required to ensure that these minima were routinely sampled. The vertical weighting function was left unchanged for the duration of the cruise, so the relative distribution should remain the same for both the early and later portions of the cruise, despite the change in the scheme.

## 8.2 Bottom bottle

With the exception of 2 stations, all rosette casts were lowered to within 8-12 meters of the bottom using the altimeter on the CTD-rosette package and the deepest bottle sample was collected at this depth. The two exceptions came on stations where bottom currents seemingly prevented the package from sinking to the desired depth. In one instance, 15 m of additional payout brought the package no closer to the ocean floor, so the cast was declared complete at ~20 m altitude from the ocean floor. In most cases, a second bottle was used to split the

difference between the deepest sample and the next optimized sample above. However, this difference splitting was varied to avoid excessively repeating the same depth at subsequent stations.

### 8.3 Bottle Sampling

At the end of each rosette deployment water samples were drawn from the bottles in the following order:

- Chlorofluorocarbons (CFCs) /N<sub>2</sub>O /SF<sub>6</sub>
- Dissolved O<sub>2</sub>
- Dissolved Inorganic Carbon (DIC)
- Total scale pH (pH<sub>T</sub>)
- Total titration seawater alkalinity (TAlk)
- Dissolved Organic Carbon / Total Dissolved Nitrogen (DOC/TDN)
- Dissolved Organic Phosphorous
- Nutrients
- Salinity
- Isotopes of nitrate
- Isotopes of H<sub>2</sub>O

The sample order was not strictly enforced after DOP. The order of the other samples collected was verified at the time of collection by a designated "sample cop." The log kept by the sample cop noted any sampling problems, the temperature of the water as measured by the dissolved oxygen sampler, and any issues with the Niskins (e.g. leaky valves and lanyards caught in end-caps).

#### 8.3.1 Bottle Data Processing

#### 8.3.2 Collected Samples

**Table I05 Samples Collected and/or Analyzed On-Board**

Samples Analyzed On-Board	Samples Collected (Not Analyzed)
Chlorofluorocarbons (CFCs)/SF <sub>6</sub> /N <sub>2</sub> O	DOC / TDN
Dissolved O <sub>2</sub>	HPLC
Total CO <sub>2</sub> (DIC)	NO <sub>3</sub> isotopes
Total Alkalinity/pH <sub>T</sub>	H <sub>2</sub> O isotopes
Nutrients	NO <sub>2</sub> isotopes
Salinity	eDNA
	POCN
	POP

## 9 Sub-project reports

### 9.1 CTD and sensor package measurements

PIs

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#### 9.1.1 CTDO and Bottle Data Acquisition

The CTD data acquisition system consisted of an SBE 11*plus* V2 deck unit and a networked PC workstation running Windows 10. Sea-Bird SeaSave V7 version 7.26.7.121 software was used for data acquisition and to close bottles on the rosette.

CTD deployments were initiated by the console watch operators (CWO) once the ship was positioned on each station. The watch maintained a detailed cast log for each attempted cast, to record each bottle fired, as well as any problems encountered.

CTD data acquisition was begun with the rosette on deck. Deck crew deployed the rosette and immediately lowered it to 10 meters. The CTD sensor pumps were configured to start 10 seconds after the primary conductivity cell detects salt water. The CWO checked the CTD data for proper sensor operation, waited for sensors to stabilize, and instructed the winch operator to bring the package back to the surface. Deck crew determined the surface depth based on their judgement of weather and sea state. The winch was then instructed to lower the package to the initial target wire-out at no more than 60 m/min after 100 m depending on depth, sea-cable tension, and the sea state.

The CWO monitored the progress of the deployment and quality of the CTD data through interactive graphics and operational displays. The altimeter channel, CTD pressure, wire-out and center multi-beam depth were all monitored to determine the distance of the package from the bottom. The winch was directed to slow decent rate to 30 m/min 100 m from the bottom, and 20 m/min 50 m from the bottom. The bottom of the CTD cast was usually to within 10 meters of the bottom determined by altimeter data. For each full upcast, the winch operator was directed to stop the winch at up to 36 predetermined wire lengths. The CWO allowed 30 seconds at each stop prior to closing the sample bottle. An additional 15 seconds were allowed before moving to the next planned depth for the SBE35RT to record bottle temperatures averaged from 13 samples. After the last bottle was closed, the CWO directed the deck crew to recover the rosette.

Once the rosette was out of the water and on deck, the CWO terminated the data acquisition, turned off the deck unit and assisted with rosette sampling. The CWOs filled out a console log for every deployment of the CTD to record depth metadata when bottles were fired. A sample log was filled out when the rosette returned on deck, recording the depths where bottles were fired and correspondence between analytical samples drawn. The bottles and rosette were examined before samples were drawn. The CTD sensors were rinsed after every cast using syringes of fresh water connected to Tygon tubing. The tubing was left on the CTD between casts, with the temperature and conductivity sensors immersed in fresh water.

Each bottle on the rosette had a unique serial number, independent of the bottle position on the rosette. If a Niskin bottle was replaced, the new bottle was tracked within a new rosette configuration.

Any abnormalities were noted on the sample log, stored in the cruise database and reported in the section 9.1.8.

### **9.1.2 CTDO Data Processing**

Shipboard CTD data processing was performed after deployment. Sea-Bird SeaSoft V2 Data Processing software was used to generate bottle summary files and bin-averaged converted files in 1 Hz, 1, dbar, 2 dbar bins for immediate use aboard the ship following the cast. An additional converted raw file was generated with parameters specified by the LADCP group for their use.

Raw CTD data were manually fit and quality controlled using SIO/ODF CTD processing software *ctdcal* v. 0.1.4 running on a Macintosh system. CTD data at bottle stops were extracted to create a 2 decibar downcast pressure series. The pressure series data set was submitted for CTD data distribution after corrections outlined in the following sections were applied.

A total of 195 CTD stations were occupied including one test station. A total of 232 casts were processed.

CTD data were examined at the completion of each cast for clean corrected sensor response and any calibration shifts. As bottle salinity and oxygen results became available, they were used to refine conductivity and oxygen sensor calibrations.

Temperature, salinity and dissolved oxygen comparisons were made between upcasts and downcasts, as well as between groups of adjacent deployments. Vertical sections of measured and derived properties from sensor data were checked for consistency.

For BIO-GOSHIP casts where ODF subsampling was not performed, fit coefficients were obtained from the subsequent cast, which in most cases occurred on the same station.

Issues that directly impacted CTD analysis are described in this report. Issues that affected bottle closures are detailed in the Underwater Sampling Package section of this report. Temperature, conductivity and oxygen sensor issues are detailed in the subsections below.

### **9.1.3 Pressure Analysis**

CTD pressure was provided by an SBE *9plus* profiling CTD unit. Serial number 0569 was used for the duration of the cruise with no performance issues noted.

Laboratory calibrations of CTD pressure sensors were performed prior to the cruise. Dates of laboratory calibration are recorded on the underway sampling package table and calibration documents are provided in the section 9.1.8.

The lab calibration coefficients provided on the calibration report were used to convert raw sensor frequency to pressure. Initial SIO pressure lab calibration coefficients were entered into SeaSave configurations and applied to cast data during acquisition. Additionally, a cast-by-cast offset was applied to the converted pressures during subsequent processing with *ctdcal*. These offsets were determined from on-deck pressure data recorded at the start and end of each cast.

For casts 03301 and 13602, *ctdcal* was unable to detect a starting pressure.

	Start Pressure	End Pressure
<b>Min</b>	-0.17	-0.36
<b>Max</b>	0.82	3.05
<b>Mean</b>	0.43	0.19

*On-deck pressure averages ranged from -0.17 to 0.82 dbar before the cast, and -0.36 to 3.05 dbar after the cast. The pressure offset varied from -0.78 to 2.56, with a mean value of -0.24 dbar.*

#### 9.1.4 Temperature Analysis

CTD temperature was provided by primary and secondary SBE 3*plus* temperature sensor units. Serial number 2166 was used on the primary CTD channel, and serial number 4953 was used on the secondary channel. Both were used for the duration of the cruise with no performance issues noted. Reference temperatures were provided by an SBE35RT Digital Reversing Thermometer. Serial number 0011 was used for the duration of the cruise with no performance issues noted.

Laboratory calibrations of temperature sensors were performed prior to the cruise at the SIO Calibration Facility. Dates of laboratory calibration are recorded on the underway sampling package table and calibration documents are provided in the section 9.1.8.

The pre-cruise laboratory calibration coefficients were used to convert SBE3*plus* frequency to ITS-90 temperature. Additional shipboard calibrations were performed to correct systematic sensor bias. Two independent metrics of calibration accuracy were used to determine sensor bias. At each bottle closure, the primary and secondary temperature were compared with each other and with a SBE35RT reference temperature sensor.

The SBE35RT Digital Reversing Thermometer is an internally-recording temperature sensor that operates independently of the CTD. The SBE35RT was located equidistant between the two SBE3*plus* temperature sensors. The SBE35RT is triggered by the SBE32 carousel in response to a bottle closure. According to the manufacturer's specifications, the typical stability is 0.001°C/year. The SBE35RT was set to internally average 13 samples, which is approximately a 15 second period.

The SBE3*plus* sensor typically exhibits a consistent well-modeled response, which is second-order with respect to pressure and second-order with respect to temperature:

$$T_{cor} = T + cp2P^2 + cp1P + ct2T^2 + ct1T + c0$$

Fit coefficients are shown in the following tables.

station	cp2	cp1	ct2	ct1	c0

all	0.e+0	-3.6871e-7	0.e+0	0.e+0	-1.0973e-4
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Table #-2 Primary temperature (T1) coefficients.

station	cp2	cp1	ct2	ct1	c0
all	0.e+0	-1.8527e-7	0.e+0	0.e+0	6.0537e-4

Table #-3 Secondary temperature (T2) coefficients.

The 95% confidence limits for the mean low-gradient (values  $-0.002\text{ }^{\circ}\text{C} \leq T1-T2 \leq 0.002\text{ }^{\circ}\text{C}$ ) differences are  $\pm 0.00685\text{ }^{\circ}\text{C}$  for SBE35RT-T1,  $\pm 0.00682\text{ }^{\circ}\text{C}$  for SBE35RT-T2 and  $\pm 0.00141\text{ }^{\circ}\text{C}$  for T1-T2. The 95% confidence limits for the deep temperature residuals (where pressure  $\geq 2000$  dbar) are  $\pm 0.00123\text{ }^{\circ}\text{C}$  for SBE35RT-T1,  $\pm 0.00138\text{ }^{\circ}\text{C}$  for SBE35RT-T2 and  $\pm 0.00109\text{ }^{\circ}\text{C}$  for T1-T2.

Issues affecting SBE35RT reference temperature data were:

- On casts where multiple bottles were sampled at a single depth, insufficient time was sometimes given for the sensor to complete burst sampling and averaging before closing the next bottle, resulting in no reference temperature recorded for some bottles.
- On several occasions, internal recorder memory was exceeded, resulting in incomplete or no samples recorded for some casts. Casts with incomplete reference samples were 03701, 08601, 14901, 15901 and 18701. Casts with no reference samples were 15001, 15101, 15102, 15201, 16001, 16101 and 16201.

### 9.1.5 Conductivity Analysis

CTD conductivity was provided by primary and secondary SBE 4C conductivity sensor units. Serial numbers 1879 and 2319 were used on the primary CTD channel, and serial number 3023 was used on the secondary channel. Issues with the primary sensor are detailed later in this section.

Laboratory calibrations of conductivity sensors were performed prior to the cruise at the Sea-Bird calibration facility. Dates of laboratory calibration are recorded on the underway sampling package table and calibration documents are provided in the section 9.1.8.

The pre-cruise laboratory calibration coefficients were used to convert SBE 4C frequency to mS/cm. Additional shipboard calibrations were performed to correct sensor bias. Corrections for both pressure and temperature sensors were finalized before analyzing conductivity differences. Two independent metrics of calibration accuracy were examined. At each bottle closure, the primary and secondary conductivity were compared with each other. Each sensor was also compared to conductivity calculated from bottle sample salinities using CTD pressure and temperature.

The differences between primary and secondary temperature sensors were used as filtering criteria to reduce the contamination of conductivity comparisons by package wake. The coherence of this relationship is shown in the following figures.

The SBE 4C sensor typically exhibits a predictable modeled response. Offsets for each sensor were determined using CBottle - CCTD differences in a deeper pressure range (900 or more dbars). After conductivity offsets were applied to all casts, response to pressure, temperature and conductivity were examined for each conductivity sensor. The response model is second-order with respect to pressure, second-order with respect to temperature, and second-order with respect to conductivity:

$$C_{cor} = C + cp2P^2 + cp1P + ct2T^2 + ct1T + cc2C^2 + cc1C + \text{Offset}$$

Fit coefficients are shown in the following tables.

station	cp2	cp1	ct2	ct1	cc2	cc1	c0
1-27	0.e+0	-3.1914e-7	0.e+0	0.e+0	0.e+0	0.e+0	1.3474e-3
28-196	0.e+0	-6.9892e-7	0.e+0	0.e+0	0.e+0	-1.0116e-4	2.8013e-3

Table #.4 Primary conductivity (C1) coefficients.

station	cp2	cp1	ct2	ct1	cc2	cc1	c0
1-27	0.e+0	-4.6206e-7	0.e+0	0.e+0	0.e+0	0.e+0	1.4525e-4
28-196	0.e+0	-5.1074e-7	0.e+0	1.2137e-4	0.e+0	0.e+0	7.2692e-4

Table #.5 Secondary conductivity (C2) coefficients.

Salinity residuals after applying shipboard P/T/C corrections are summarized in the following figures. Only CTD and bottle salinity data with acceptable quality codes are included in the differences. Quality codes and comments are published in section 9.1.8 of this report.

The 95% confidence limits for the mean low-gradient (values  $-0.002 \text{ oC} \leq T1 - T2 \leq 0.002 \text{ oC}$ ) differences are  $\pm 0.00834 \text{ mPSU}$  for salinity-C1SAL,  $\pm 0.00513 \text{ mPSU}$  for salinity-C2SAL and  $\pm 0.0128 \text{ mPSU}$  for C1SAL-C2SAL. The 95% confidence limits for the deep salinity residuals (where pressure  $\geq 2000 \text{ dbar}$ ) are  $\pm 0.01574 \text{ mPSU}$  for salinity-C1SAL,  $\pm 0.00173 \text{ mPSU}$  for salinity-C2SAL and  $\pm 0.01568 \text{ mPSU}$  for C1SAL-C2SAL.

Issues affecting SBE 4C salinity data were:

- The primary conductivity sensor, serial number 1879, experienced a progressive cell failure over the course of about 4 casts, resulting in sporadic punctuated offsets in the data. Affected casts were 02401, 02501, 02601 and 02701. The sensor was replaced with serial number 2319 for cast 02801 and was used without issue for the remainder of the cruise.

#### 9.1.6 CTD Dissolved Oxygen (SBE 43)

A Sea-Bird SBE 43 oxygen sensor installed on the CTD primary T-C channel provided one of two sources of dissolved oxygen data. Serial number 0197 was used for the duration of the cruise with no performance issues noted.

Laboratory calibrations of the dissolved oxygen sensors were performed prior to the cruise at the SBE calibration facility.

The pre-cruise laboratory calibration coefficients were used to convert SBE 43 frequency to  $\mu\text{mol/kg}$  oxygen values for acquisition only. Additional shipboard fitting was performed to correct for the sensor's non-linear response and for calibration drift over the course of the cruise. Corrections for pressure, temperature, and conductivity sensors were finalized before analyzing dissolved oxygen data. Corrections for hysteresis are applied following Sea-Bird Application Note 64-3. The SBE 43 sensor data were compared to dissolved oxygen bottle samples by matching the downcast CTD data to the upcast bottle stop locations along isopycnal surfaces. CTD dissolved oxygen was then calculated using Clark Cell MPOD oxygen sensor response model for Beckman/SensorMedics and SBE 43 dissolved oxygen sensors. The residual differences of bottle values versus CTD dissolved oxygen values are minimized by optimizing the PMEL DO sensor response model coefficients using the BFGS non-linear least-squares fitting procedure.

The general form of the PMEL DO sensor response model equation for Clark cells follows Brown and Morrison [Mill82] and Owens [Owen85]. Dissolved oxygen concentration is then calculated:

$$O_2 = Soc \cdot (V + Voff + \tau_{20} \cdot e^{(D1 \cdot p + D2 \cdot (T - 20))}) \cdot dV/dt \cdot O_{sat} \cdot e^{T_{cor} \cdot T} \cdot e^{[(E \cdot p)/(273.15 + T)]}$$

Where:

- V is oxygen voltage (V)
- D1 and D2 are (fixed) SBE calibration coefficients
- T is corrected CTD temperature ( $^{\circ}\text{C}$ )
- p is corrected CTD pressure (dbar)
- dV/dt is the time-derivative of voltage (V/s)
- O<sub>sat</sub> is oxygen saturation
- Soc, Voff,  $\tau_{20}$ , T<sub>corr</sub>, and E are fit coefficients

All stations were fit together to get an initial coefficient estimate. Stations were then fit individually to refine the coefficients as the membrane does not deform the same way with each cast. If the individual cast's coefficients yielded worse residuals, they were reverted to the original group fit coefficients.

Table #-6: SBE 43 group fit coefficients. Coefficients were further refined station-by-station.

	Soc	Voffset	Tau20	Tcorr	E
ox0	7.394e-1	-7.7283e-1	1.07e+0	-3.2260e-3	4.0156e-2

The 95% confidence limits of 1.76 ( $\mu\text{mol/kg}$ ) for all acceptable (flag 2) dissolved oxygen bottle data values and 1.32 ( $\mu\text{mol/kg}$ ) for deep dissolved oxygen values are only presented as general indicators of the goodness of fit. CLIVAR GO-SHIP standards for CTD dissolved oxygen data are < 1% accuracy against on-board Winkler titrated dissolved oxygen lab measurements.

Issues affecting SBE 43 oxygen data were:

- Because the primary conductivity sensor is integral to SBE 43 measurements, oxygen data were also impacted by the failure of that sensor on casts 02401, 02501, 02601 and 02701.

### 9.1.7 CTD Dissolved Oxygen (RINKO III)

A JFE Advantech Co., LTD RINKO III (ARO-CAV) provided the second of two sources of dissolved oxygen data. Serial number 0297 was used for the duration of the cruise with no performance issues noted.

RINKO data are reported as primary CTD oxygen for all stations.

A two-point calibration was performed prior and after deployment on the rosette. These calibrations produced sets of coefficients (G and H) to adjust factory calibration of dissolved oxygen raw voltage. The calibrations also provided an assessment of foil degradation over the course of the cruise. As per the manufacturer's recommendation, 100% saturation points were obtained by bubbling ambient air through an air stone into a stirred beaker of tap water for 30 minutes, removing the air stone, then submersing the powered RINKO. Zero point calibrations also followed manufacturer recommendations, using a sodium sulfite solution (25g in 500mL deionized water). Dissolved oxygen raw voltage (DO<sub>out</sub>), atmospheric pressure, and solution temperature were recorded for calculation of new oxygen sensor coefficients (G and H). Temperature was obtained from the RINKO sensor using factory temperature coefficients.

RINKO raw voltage data were acquired, converted to oxygen saturation, and then multiplied by the oxygen solubility to give values in  $\mu\text{mol/kg}$ . The resulting data were then fitted using the equations developed by [Uchida08]:

$$[O_2] = (V_0/V_c - 1)/K_{sv}$$

$$K_{sv} = c_0 + c_1T + c_2T^2, V_0 = 1 + d_0T, V_c = d_1 + d_2V_r$$

where:

- T is temperature ( $^{\circ}\text{C}$ )
- $V_r$  is raw voltage (V)
- $V_0$  is voltage at zero  $\text{O}_2$  (V)
- $c_0, c_1, c_2, d_0, d_1, d_2$  are calibration coefficients

Oxygen is further corrected for pressure effects:

$$[O_2]_c = [O_2](1 + cpP/1000)^{1/3}$$

where:

- P is pressure (dbar)
- cp is pressure compensation coefficient

Salinity corrections are applied per [GarciaGordon1992]:

$$[O_2]_{sc} = [O_2]_c \exp[S(B_0 + B_1TS + B_2TS^2 + B_3TS^3) + C_0S^2]$$

where:

- TS is scaled temperature ( $TS = \ln[(298.15 - T)/(273.15 + T)]$ )
- B0, B1, B2, B3, C0 are solubility coefficients

All stations were fit together to get an initial coefficient estimate. Stations were then fit in groups of similar profiles to get a further refined estimate. Individual casts were then fit to remove the noticeable time drift in coefficients. If an individual cast's coefficients yielded worse residuals, they were reverted to the original group fit coefficients.

Table #-7: Rinko group fit coefficients. Coefficients were further refined station-by-station.

station	c0	c1	c2	d0	d1	d2	cp
1-5	1.8929e+0	5.5793e-2	1.2727e-3	1.2137e-2	-1.9183e-1	3.0795e-1	9.7138e-2
6-60	1.8916e+0	3.4644e-2	8.7843e-4	3.1458e-3	-1.9040e-1	3.0632e-1	1.0584e-1
61-90	1.8869e+0	6.7975e-2	1.3636e-3	1.1097e-2	-2.2519e-1	3.2199e-1	8.8185e-2
91-196	1.8974e+0	-1.0599e-2	4.7598e-4	-1.0954e-2	-1.6406e-1	2.9399e-1	9.9375e-2

The 95% confidence limits of 1.11 ( $\mu\text{mol/kg}$ ) for all acceptable (flag 2) dissolved oxygen bottle data values and 0.47 ( $\mu\text{mol/kg}$ ) for deep dissolved oxygen values are only presented as general indicators of the goodness of fit. CLIVAR GO-SHIP standards for CTD dissolved oxygen data are < 1% accuracy against on board Winkler titrated dissolved oxygen lab measurements.

No performance issues were noted with the RINKO III sensor.

### 9.1.8 CTD and sensor measurements appendix

#### 9.1.8.1 Bottle Comments

In addition to the individual bottle comments detailed below, there were some issues which affected many or all bottle samples of several casts.

Data from casts 01002 and 01101 showed a marked offset from both primary and secondary CTD data. As both casts were processed together in the same salinometer run, it is assumed that a configuration error during the run was responsible for the offset. The offset was not noted on any subsequent processing runs. Data from these casts are reported, but are flagged and excluded from fitting analysis.

Samples from cast 13801, bottles 18-28 and cast 14601, bottles 20-34 were processed with the salinometer suppression knob on the incorrect setting, resulting in an offset in measurements. To avoid loss of these data, a constant 0.1 PSU was added to compensate for the error. The resulting values were within expected tolerances of derived CTD salinities and are thus retained and used for fitting analysis.

On cast 10301, bottle 12 was fired for test purposes.

#### sssc, btl, param, flag, notes

- 00701, 09, salt, 4, (+0.4280) residual out of range
- 00801, 14, salt, 4, (+1.0141) residual out of range
- 00801, 27, salt, 4, (-1.9553) residual out of range
- 00901, 26, salt, 4, (-1.9586) residual out of range

- 00901, 27, salt, 4, (-1.9667) residual out of range
- 00901, 28, salt, 4, (-1.9552) residual out of range
- 01802, 10, salt, 3, (+0.0038) residual out of range 5 attempted measurements on salinometer
- 01802, 13, salt, 4, (+0.3332) residual out of range
- 02001, 32, salt, 3, (+0.0189) 7 attempted measurements on salinometer
- 03201, 32, salt, 3, (+0.0234) residual out of range 7 attempted measurements on salinometer
- 03501, 29, salt, 3, (+0.0074) 5 attempted measurements on salinometer
- 03801, 30, salt, 4, (-0.2207) residual out of range
- 04401, 14, salt, 3, (+0.0077) residual out of range 5 attempted measurements on salinometer
- 04501, 10, salt, 3, (+0.0045) residual out of range 5 attempted measurements on salinometer
- 05101, 13, salt, 4, (+0.2088) residual out of range
- 05201, 13, salt, 4, (+0.0991) residual out of range
- 05701, 26, salt, 4, (-1.9527) residual out of range
- 05901, 32, salt, 3, (+0.0110) 5 attempted measurements on salinometer
- 06801, 01, salt, 3, (+0.0048) 5 attempted measurements on salinometer
- 07201, 28, salt, 4, (-0.1767) residual out of range
- 07302, 23, salt, 4, (+0.0679) residual out of range
- 07702, 13, salt, 4, (-0.0489) residual out of range
- 07801, 31, salt, 4, (-0.0548) residual out of range
- 08502, 31, salt, 4, (+0.1022) residual out of range
- 09302, 34, salt, 4, (+0.4087) residual out of range
- 09302, 34, salt, 4, (+0.4087) residual out of range
- 09302, 35, salt, 4, (+0.4087) residual out of range
- 10002, 13, salt, 4, (+0.0398) residual out of range
- 10302, 30, salt, 3, (+0.0108) 5 attempted measurements on salinometer
- 10302, 34, salt, 4, (-0.2212) residual out of range
- 10602, 28, salt, 3, (-0.0130) sample bottle partially filled
- 10602, 32, salt, 3, (+0.0783) sample bottle partially filled
- 11402, 11, salt, 4, (+0.0245) residual out of range
- 11402, 27, salt, 4, (+0.4111) residual out of range
- 11402, 28, salt, 4, (+0.4152) residual out of range
- 12402, 18, salt, 4, (+0.0966) residual out of range
- 13401, 14, salt, 4, (-0.0658) residual out of range
- 15102, 13, salt, 4, (+0.0240) residual out of range
- 15201, 13, salt, 4, (+0.1495) residual out of range
- 16401, 02, salt, 4, (-0.1927) residual out of range
- 16602, 02, salt, 4, (+0.0473) residual out of range
- 17201, 02, salt, 4, (-0.0352) residual out of range
- 18001, 23, salt, 4, (+0.0481) residual out of range
- 18001, 24, salt, 4, (+0.0273) residual out of range
- 18001, 25, salt, 4, (+0.0546) residual out of range
- 18001, 27, salt, 4, (+0.0233) residual out of range

- 18001, 28, salt, 4, (+0.0234) residual out of range
- 18001, 29, salt, 4, (-0.0292) residual out of range
- 18101, 20, salt, 4, (-1.9595) residual out of range
- 18602, 31, salt, 4, (+0.1222) residual out of range

### 9.1.9 References

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## 9.2 LADCP

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### 9.2.1 Data Acquisition and QC

In order to collect full-depth profiles of horizontal and vertical ocean velocity, two Acoustic Doppler Current Profilers (ADCPs), one facing upward (uplooker, UL) and the other downward (downlooker, DL), as well as a Deep Sea Power And Light rechargeable 48V battery and cables were installed on the CTD rosette. This lowered ADCP (LADCP) system was provided by the Lamont-Doherty Earth Observatory (LDEO). The LADCP system is self-contained, requiring on-deck cable connections to charge the battery and for communicating with the acquisition computer. The battery charger was affixed to an elevated cable run in the CTD bay and connected, via a waterproof power switch, to an outdoor extension power cable connected to vessel power inside the wet lab. The LADCP data acquisition computer, a Mac Mini, as well as two bench-top power supplies for the ADCPs connected to two waterproof power switches were installed on a bench in the same lab.

Between casts the LADCP system in the CTD bay was left unpowered, with the battery connected to the (usually powered) battery charger, and the two deck cables leading to the data acquisition computer also connected, but with the bench top power supplies turned off. No standard dummy plugs were shipped with the LADCP gear to protect the male battery connector pins on the rosette. To remedy this, a dummy plug for use on deck only was fabricated by the PI during pre-cruise training in port using a ring of plastic, electrical tape, sealant, and electrical grease. Unfortunately, as detailed below, this improvised dummy did not work as intended and caused corrosion of a connector, requiring fabrication of a new cable during the cruise.

A few minutes before the CTD rosette was moved out of the hangar for deployment, the charger was turned off, the battery was disconnected from the charger and connected to the ADCPs on the rosette, and the now free dummy was used to dummy up the battery charger. Then data acquisition was started on the computer in the wet

lab using a set of operator scripts created by the PI. After verifying that the data from the previous cast had been fully downloaded and backed up, the old data files were deleted from the instruments, before these were programmed to acquire data for the new cast. The two ADCPs on the rosette used synchronized pings and they followed a staggered ping rate alternating between 1.3 and 1.6 seconds, which is designed to mitigate contamination from acoustic reflection from the sea bed. With the instruments pinging the rosette was disconnected from the LADCP deck cables, and all four ends were dummied up. The loose cables on the rosette were secured with orange Velcro strap to prevent whiplashing during the casts. The same type of Velcro strap was also used to attach some of the permanently installed LADCP cables to the rosettes in an attempt to minimize plastic waste (zip ties). Once everything was set up, the CTD operator and the ResTech were notified that the LADCP system was ready for deployment. Deployment information was logged on LADCP log sheets once the rosette had entered the water.

After recovery of the CTD the Velcro straps securing the dummied pigtail ends to the rosette were removed, the connectors were rinsed with fresh water, the dummy plugs were removed and the ADCPs on the rosette were connected to the deck cables. The battery was then disconnected from the rosette cable and the connectors were washed with isopropyl alcohol. Once the connectors were dry, they were connected to the charger, with the dummy being switched from charger to the rosette in the process. Any hanging cables were attached with Velcro to the top of the CTD rosette. After turning on the two bench-top power supplies, LADCP data acquisition was stopped from the acquisition computer and the data download was initiated.

After the data from the cast had finished downloading (after about 20 minutes for deep casts, 5 minutes for bio casts), the bench top power supplies were turned off with power toggle switches. Then the data files, one for each the UL and DL, were checked by integrating the measured vertical velocities in time, which yields estimates for the maximum depth ( $z_{max}$ ) and the end depth ( $z_{end}$ ) of the profile, both of which were recorded on the log sheet. Occasionally, after the battery was fully charged (usually about an hour after charging was initiated, as indicated by LEDs on the charger) the charger was disconnected from power in the wet lab and the time was noted on the log sheet. The battery was more often left on the charger in trickle-charge mode, however.

Communication between the acquisition computer and the ADCPs was handled by the “acquire2” set of software scripts, implemented as a set of UNIX shell commands designed to minimize the possibility of operator errors.

During the night watch, the LADCP data were processed when time allowed. Processing was done for horizontal velocity using the LDEO\_IX processing software and for vertical velocity using the LADCP\_w processing software, both installed on the acquisition computer. In addition, Thurnherr performed in-lab processing daily and notes were exchanged between Thurnherr and Pinard. CTD .cnv data were obtained from the ship’s shared drive and processed into 1 and 6 Hz formats using the LADCP\_w processing software. In addition to the  $z_{end}$  and  $z_{max}$  processing diagnostics, LADCP data quality was monitored by creating section plots. A more comprehensive post-cruise LADCP QC will be carried out by Thurnherr in his lab before submission of the I05 data to the archives and the public.

### **9.2.2 Instrumentation**

Three 300kHz Teledyne RDI Workhorse Monitor ADCPs (S/N12243, S/N12734, S/N150) were used throughout I05. For a majority of the cruise the downward-facing ADCP, or DL, was the primary device and the upward-

facing ADCP, or UL, was the secondary device. Throughout the cruise, ADCPs were replaced several times to diagnose three separate faults affecting the LADCP system (see below for details). The changes to the instrumentation carried out during trouble shooting are detailed in Table 1.

Two Deep Sea Power And Light rechargeable 48V battery (S/N 01223 and S/N 02126) were used during the cruise. For stations 001.01-029.01 S/N 01223 was used. It was replaced during an attempt to diagnose data anomalies. For stations 029.02-123.01 S/N 02126 was used. After station 123.01, S/N 01223 was used. This was due to accumulation of hydrogen within the S/N 02126 battery related to the practice of leaving the battery connected to the charger during surface intervals.

Both the ADCPs and the Deep Sea Power and Light rechargeable batteries were replaced several times during the cruise, always during trouble shooting of communications problems between the ADCPs and the acquisition computer, and between the two ADCPs installed on the rosette. With hindsight, there were five underlying hardware problems that occurred during I05. The first was the inadequate binding of the battery to the CTD rosette. During station 41, when the rosette was removed from the water the battery was seen hanging off the side of the rosette by the star cable. It was secured with additional ratchet straps for the remainder of the cruise and fortunately after testing, the battery functioned as normal. Next was the corrosion of the pins on the battery cable. Since there was no dummy plug supplied for the connector of the battery-to-star cable adapter, a supplementary plug was crafted. This plug, however, was not watertight, and every time the Niskin bottles were emptied after sampling, the powered battery cable pins were soaked in seawater. This resulted in visible corrosion, which was suspected to be the cause of the communications problems. To remedy this, a new battery cable was fabricated from available spares, and a pin drying/cleaning protocol was implemented for the battery cable for the remainder of the cruise. This did not solve the communications problems, which were soon traced to an intermittent fault in the star cable installed on the rosette, the second hardware problem. After replacing the star cable, the system worked reliably for several dozen profiles. Then, after profile 121.01 the data could not be downloaded from the instruments during several attempts. Eventually (after several days), the fault was traced to the long deck cable connecting the acquisition computer to the DL instrument on the rosette, but diagnosis of this problem was greatly complicated by two compounding factors: 1) The cable fault was intermittent making the diagnostic test results ambiguous. For example, one test consisted in using the (bad) cable to connect to the UL instrument. Since this worked without a hitch, the DL instrument was suspected and swapped with the spare, but this did not eliminate the communications problems. 2) At some stage during the trouble shooting the DL instrument on the rosette failed as well. The combination of two simultaneous hardware problems, one of which was intermittent, was exceedingly difficult to trouble shoot. At one stage, replacement of the USB-to-serial adapter of the DL connection appeared to solve the problems, but they soon returned. Once the underlying problem was finally determined to be the downward-facing ADCP's deck cable, the cable was replaced. Additional testing then revealed the fault in the downlooker, which was replaced on station 140. Afterwards the system worked well again for the remainder of the cruise.

### **9.3 Chipods**

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Seagoing personnel: Aurélie Moulin

### 9.3.1 Overview

Chipods are instrument packages that measure turbulence in the ocean. Specifically, they are used to compute turbulent diffusivity of heat ( $K$ ) which is inferred from measuring dissipation rate of temperature variance ( $\chi$ ) combined with a shipboard CTD. Chipods are self-contained, robust and record temperature and derivative signals from FP07 thermistors at 100 Hz; they also record sensor motion at the same sampling rate. Details of the measurement and methods for processing  $\chi$  can be found in [Moum\_and\_Nash2009]. In an effort to expand the global coverage of deep ocean turbulence measurements, the ocean mixing group at Oregon State University has supported chipod measurements on all of the major global repeat hydrography cruises since December 2013.

### 9.3.2 System Configuration and Sampling

Three chipods were mounted on the rosette (Figure 1) to measure temperature ( $T$ ), its time derivative ( $dT/dt$ ), and  $x$  and  $z$  (horizontal and vertical) accelerations at a sampling rate of 100 Hz. Two chipods were oriented such that their sensors pointed upward. The third one was pointed downward.

The up-looking sensors (SN2014, SN2027) were positioned higher than the Niskin bottles on the rosette in order to avoid measuring turbulence generated by flow around the rosette and/or its wake while its profiling speed oscillates as a result of swell-induced ship-heave. The down-looking sensor (SN2017) was positioned as far from the frame as possible and as close to the leading edge of the rosette during descent as possible to avoid measuring turbulence generated by the rosette frame and lowered ADCP.

The chipods continuously recorded data at all stations, from 1 to 196, without interruptions.



*Mounting of the three CTD-chipods onto the rosette for I05.*

## 9.4 Chlorofluorocarbon (CFC), Sulfur Hexafluoride ( $SF_6$ ), and Nitrous Oxide ( $N_2O$ )

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Note that N<sub>2</sub>O measurements are a Level 3 measurement (per US GO-SHIP designation). The concentrations were measured on the same water samples collected for the Level 1 CFC/SF<sub>6</sub> measurements. The N<sub>2</sub>O analysis is still under development. Please contact the PI for any use of these data.

Samples for the analysis of dissolved CFC-11, CFC-12, SF<sub>6</sub>, and N<sub>2</sub>O were collected from approximately 3200 of the Niskin water samples during the expedition. When taken, water samples for tracer analysis were the first samples drawn from the 10-liter bottles. Care was taken to co-ordinate the sampling of the tracers with other samples to minimize the time between the initial opening of each bottle and the completion of sample drawing. In most cases, dissolved oxygen, partial pressure of CO<sub>2</sub>, dissolved inorganic carbon, and pH samples were collected within several minutes of the initial opening of each bottle. To minimize contact with air, the tracer samples were collected from the Niskin bottle petcock into 250-cc ground glass syringes through plastic 3-way stopcocks. The syringes were stored in the dark at 3.5° - 6° C until 45-60 minutes before analysis to reduce the degassing and bubble formation in the sample. At that time, they were transferred to a water bath at approximately 35° C to warm the samples prior to analysis in order to increase the stripping efficiency.

Concentrations of CFC-11, CFC-12, SF<sub>6</sub>, and N<sub>2</sub>O in air samples, seawater and gas standards were measured by shipboard electron capture gas chromatography (EC-GC). This system from the University of Washington was located in a portable laboratory on the fantail. Samples were introduced into the EC-GC via a purge and trap system. Approximately 200-ml water samples were purged with nitrogen and the compounds of interest were trapped on a Porapak Q/Carboxen 1000/Molecular Sieve 5A trap cooled by an immersion bath to >-60°C. During the purging of the sample (6 minutes at 170 ml min<sup>-1</sup> flow), the gas stream was stripped of any water vapor via a Nafion trap in line with an ascarite/magnesium perchlorate dessicant tube prior to transfer to the trap. The trap was then isolated and heated by direct resistance to 175°C. The desorbed contents of the trap were back-flushed and transferred onto the analytical pre-columns. The first precolumn was a 40-cm length of 1/8-in tubing packed with 80/100 mesh Porasil B. This precolumn was used to separate the CFC-11 from the other gases. The second pre-column was 13 cm of 1/8-in tubing packed with 80/100 mesh molecular sieve 5A. This pre-column separated the N<sub>2</sub>O from CFC-12 and SF<sub>6</sub>. Three analytical columns in three gas chromatographs with electron capture detectors were used in the analysis. CFC-11 was separated from other compounds (e.g. CFC-113 and CCl<sub>4</sub>) by a column consisting of 36 cm of Porasil B and 150 cm of Carbograph 1AC maintained at 80°C. CFC-12 and SF<sub>6</sub> were analyzed using a column consisting of 2.33 m of molecular sieve 5A and 1.5 m of Carbograph 1AC maintained at 90°C. The analytical column for N<sub>2</sub>O was 30 cm of molecular sieve 5A in a 120°C oven. The carrier gas for this column was instrumental grade P-5 gas (95% Ar / 5% CH<sub>4</sub>) that was directed onto the second precolumn and into the third column for the N<sub>2</sub>O analyses. The detectors for the CFC-11, and for CFC-12 and SF<sub>6</sub> analyses were operated at 300°C. The detector for N<sub>2</sub>O was maintained at 320 °C.

The analytical system was calibrated frequently using a standard gas of known gas composition. Gas sample loops of known volume were thoroughly flushed with standard gas and injected into the system. The temperature and pressure were recorded so that the amount of gas injected could be calculated. CFC concentrations in air and seawater samples were determined by fitting their chromatographic peak areas to multi-point calibration curves, generated by injecting multiple sample loops of gas from a working standard (UW WRS 32399) into the analytical instrument. A full range of calibration points were run at the beginning and end of the cruise, as well as during long transits/weather delays when possible. The procedures used to transfer the standard gas to the trap, precolumns, main chromatographic columns and EC detectors were similar to those used for analyzing water

samples. Single injections of a fixed volume of standard gas at one atmosphere were run much more frequently (at intervals of 2 hours) to monitor short-term changes in detector sensitivity. Air samples and system blanks (injections of loops of CFC-free gas) were injected and analyzed in a similar manner. The typical analysis time for samples was 748 sec.

For atmospheric sampling, an ~100 meter length of 3/8-in OD Dekaron tubing was run from the laboratory to the bow of the ship. A flow of air was drawn through this line to the main laboratory using an Air Cadet pump. The air was compressed in the pump, with the downstream pressure held at ~1.5 atm. using a back-pressure regulator. A tee allowed a flow ( $100 \text{ ml min}^{-1}$ ) of the compressed air to be directed to the gas sample valves of the CFC/SF<sub>6</sub>/N<sub>2</sub>O analytical system, while the bulk flow of the air ( $>7 \text{ l min}^{-1}$ ) was vented through the back-pressure regulator. Air samples were generally analyzed when the relative wind direction was within 50 degrees of the bow of the ship to reduce the possibility of shipboard contamination. The pump was run for approximately 30 minutes prior to analysis to insure that the air inlet lines and pump were thoroughly flushed. After the analytical system was moved into the Hydro Lab, it was another 30 days before the airline was rerouted into the ship. The average atmospheric concentrations determined during the cruise (from sets of 3 or 4 measurements analyzed when possible) were  $216.3 \pm 2.7$  parts per trillion (ppt) for CFC-11,  $486.2 \pm 0.5$  ppt for CFC-12,  $11.0 \pm 0.5$  ppt for SF<sub>6</sub>, and  $333.0 \pm 5.0$  parts per billion for N<sub>2</sub>O.

Concentrations of the CFCs in air, seawater samples and gas standards are reported relative to the SIO98 calibration scale (Prinn et. al., 2000). Concentrations in air and standard gas are reported in units of mole fraction in dry gas, and are typically in the parts per trillion (ppt) range for CFCs and SF<sub>6</sub> and parts per billion (ppb) for N<sub>2</sub>O. Dissolved CFC concentrations are given in units of picomoles per kilogram seawater ( $\text{pmol kg}^{-1}$ ), SF<sub>6</sub> in femtomoles per kilogram seawater ( $\text{fmol kg}^{-1}$ ), and N<sub>2</sub>O in nanomoles per kilogram seawater ( $\text{nmol kg}^{-1}$ ). Estimated limit of detection is  $1 \text{ fmol kg}^{-1}$  for CFC-11,  $1 \text{ fmol kg}^{-1}$  for CFC-12 and  $0.02 \text{ fmol kg}^{-1}$  for SF<sub>6</sub>.

The efficiency of the purging process was evaluated by re-stripping water samples and comparing the residual concentrations to initial values. These re-strip values were less than 1% for CFC-11 and essentially zero for CFC-12 and SF<sub>6</sub>. Based on the re-strips of numerous samples where the stripper blank was low and relatively constant, the mean values for N<sub>2</sub>O were approximately 5-10% during the cruise.

On this expedition, based on the analysis of 80 duplicate samples (i.e. two syringe samples collected from the same Niskin), we estimate precisions (1 standard deviation) to be the larger of 0.92% or  $0.003 \text{ pmol kg}^{-1}$  for CFC-12 measurements,  $0.025 \text{ fmol kg}^{-1}$  or 1.98% for SF<sub>6</sub>, and 0.85% or  $0.095 \text{ nmol kg}^{-1}$  for N<sub>2</sub>O. When the CFC-11 analysis was good (flag =2), the precisions are estimated to be 1.65% or  $0.004 \text{ pmol kg}^{-1}$ .

#### 9.4.1 *The Great Wave*

The major event that affected the tracer analysis was the destruction of one of the man-doors of the 20-ft portable laboratory and flooding of the lab by a large wave that came over the port side of the ship just prior to midnight of July 26th during analysis of samples from Station 12. With assistance from the crew and the science party, the bulk of the contents of the lab were relocated to the hydro lab on the *R/V Roger Revelle*. It took approximately two days to reassemble the analytical system and get it back to routine operations. There are no tracer data from Stations 13-16.

We were fortunate that one of the three immersion coolers, which were stored on the floor of the van, survived the flood and was still operable. The one which was being utilized was shorted and not salvageable. In spite of rinsing the interior of the second, its compressors would not start. The third immersion cooler ran continuously for 40 days, before it was turned off to change the fluids in the cooling dewar. It did not immediately restart so Station 168 was not sampled. After sitting idle for 4 hours, it did begin cooling again.

#### **9.4.2 Trap Replacement**

As we restarted the analyses after the flood, it became clear that the trap had been overheated at some point and a new trap was assembled. Several samples from Station 19 were affected by the bad trap and flagged as 4.

#### **9.4.3 CFC-11 Issues**

The CFC-11 chromatography was strongly affected by both a large peak whose retention was 10-15 seconds after that of CFC-11 and a transient contamination issue. As both CFC-11 and the second compound were higher in near surface waters, the separation between them became impossible to integrate and numerous samples are labelled as 3 or 4 depending upon the separation.

The other contaminant had the effect of broadening the peaks and affecting retention times. It also persisted through efforts to heat the column to 90 C for short time periods (1 hour). It took a multi-day bake at 120 C to remove the compound from the column used for CFC-11 analyses, Data from Stations 54-61 and from Station 97-100 have been flagged as bad.

#### **9.4.4 CFC-12 and SF<sub>6</sub> Baseline**

The ECD used to detect SF<sub>6</sub> and CFC-12 was very sensitive to pressure changes, such that rough seas had a strong effect on the precision of the measurements – especially for small peaks at low concentrations of SF<sub>6</sub>. Further data processing needs to be completed to identify how this affected the detection limits from station to station.

#### **9.4.5 References**

Prinn, R. G., Weiss, R.F., Fraser, P.J., Simmonds, P.G., Cunnold, D.M., Alyea, F.N., O'Doherty, S., Salameh, P., Miller, B.R., Huang, J., Wang, R.H.J., Hartley, D.E., Harth, C., Steele, L.P., Sturrock, G., Midgley, P.M., McCulloch, A., 2000. A history of chemically and radiatively important gases in air deduced from ALE/GAGE/AGAGE. *Journal of Geophysical Research*, 105, 17,751-17,792

### **9.5 Bottle Oxygen Analysis**

PIs: Todd Martz (SIO) and Susan Becker (SIO)

Shipboard personnel: Elisa Aitoro (SIO) and Robert “Ben” Freiberger (SIO)

#### **9.5.1 Equipment and Techniques**

Dissolved oxygen analyses were performed with an SIO/ODF-designed automated oxygen titrator using photometric end-point detection based on the absorption of 365nm wavelength ultra-violet light.

The titration of the samples and the data logging were controlled by PC LabView software. Thiosulfate was dispensed by a Dosimat 665 buret driver fitted with a 1.0 ml burette.

ODF used a whole-bottle modified-Winkler titration following the technique of Carpenter [Carpenter1965]\_ with modifications by [Culberson1991]\_ but with higher concentrations of potassium iodate standard (~0.012 N), and thiosulfate solution (~55 g/L).

Pre-made liquid potassium iodate standards and reagent/distilled water blanks were run every day (approximately every 3-4 stations), with samples analysed within 24 hours of the last standard.

### **9.5.2 Sampling and Data Processing**

A total of 6340 oxygen samples were collected, all of which were niskin samples.

Niskin samples were collected soon after the rosette was secured on deck, either from fresh niskins or immediately following CFC sampling.

Nominal 125 mL volume-calibrated biological oxygen demand (BOD) flasks were rinsed 3 times with minimal agitation using a silicone draw tube, then filled and allowed to overflow for at least 3 flask volumes, ensuring no bubbles remained. Pickling reagents MnCl<sub>2</sub> and NaI/NaOH (1 mL of each) were added via bottle-top dispensers to fix samples before stoppering. Flasks were shaken twice (10-12 inversions) to assure thorough dispersion of the precipitate - once immediately after drawing and then again after 30-60 minutes.

Sample draw temperatures, measured with an electronic resistance temperature detector (RTD) embedded in the draw tube, were used to calculate umol/kg concentrations, and as a diagnostic check of bottle integrity.

Niskin samples were analysed within 2-12 hours of collection, and the data incorporated into the cruise database.

Thiosulfate normalities were calculated for each standardisation and corrected to 20°C. The 20°C thiosulfate normalities and blanks were plotted versus time and were reviewed for possible problems, and were subsequently determined to be stable enough that no smoothing was required.

### **9.5.3 Volumetric Calibration**

Oxygen flask volumes were determined gravimetrically with degassed deionised water to determine flask volumes at ODF's chemistry laboratory. This is done once before using flasks for the first time and periodically thereafter when a suspect volume is detected. The 10 mL Dosimat buret used to dispense standard iodate solution was calibrated using the same method.

### **9.5.4 Standards**

Liquid potassium iodate standards were prepared in 6 L batches and bottled in sterile glass bottles at ODF's chemistry laboratory prior to the expedition. The normality of the liquid standard was determined by calculation from weight. The standard was supplied by Alfa Aesar and has a reported purity of 99.4-100.4%. All other reagents were "reagent grade" and were tested for levels of oxidising and reducing impurities prior to use.

### **9.5.5 Narrative**

- The oxygen analytical rig was setup in the main lab of the *R/V Roger Revelle*.
- Batches of reagents were prepared as needed during the cruise.
- No major analytical issues were encountered.
- A few high end points occurred and were corrected for.
- Only one sample was lost due to a LabView error.

- The Dosimat base used to deliver liquid potassium iodate standard malfunctioned after station 11 and was replaced with a spare unit.
- The analytical computer would freeze occasionally, but never while doing analysis.
- The thiosulfate stability was considered in 6 batches and showed remarkable stability throughout the entire cruise.
- No trends were observed or corrected for.
- No data updates are expected.

### 9.5.6 References

.. [Carpenter1965] Carpenter, J. H., “The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method,” *Limnology and Oceanography*, 10, pp. 141-143 (1965).

.. [Culberson1991] Culberson, C. H., Knapp, G., Stalcup, M., Williams, R. T., and Zemlyak, F., “A comparison of methods for the determination of dissolved oxygen in seawater,” Report WHPO 91-2, WOCE Hydrographic Programme Office (Aug 1991).

## 9.6 Dissolved inorganic carbon (DIC)

**PIs:** Richard A. Feely (NOAA-PMEL) & Rik Wanninkhof (NOAA-AOML)

**Technicians:** Andrew Collins (NOAA-PMEL) & Charles Featherstone (NOAA-AOML)

### 9.6.1 Sample collection:

Samples for DIC measurements were drawn (according to procedures outlined in the PICES Special Publication, *Guide to Best Practices for Ocean CO<sub>2</sub> Measurements*) from Bullister style niskin bottles into ~310ml borosilicate glass flasks using platinum-cured silicone tubing. The flasks were rinsed once and filled from the bottom with care not to entrain any bubbles, overflowing by at least one-half volume. The sample tube was pinched off and withdrawn, creating a 6ml headspace and 0.12 ml of saturated HgCl<sub>2</sub> solution was added as a preservative. The sample bottles were then sealed with glass stoppers lightly covered with Apiezon-L grease. DIC samples were collected from a variety of depths with approximately 9% of these samples collected as duplicates.

### 9.6.2 Equipment:

The analysis was done by coulometry with two analytical systems (PMEL1 and PMEL2) used simultaneously on the cruise. Each system consisted of a coulometer (50150 UIC Inc) coupled with a Dissolved Inorganic Carbon Extractor (DICE). The DICE system was developed by Esa Peltola and Denis Pierrot of NOAA/AOML and Dana Greeley of NOAA/PMEL to modernize a carbon extractor called SOMMA (Johnson et al. 1985, 1987, 1993, and 1999; Johnson 1992). The two DICE systems were set up in a seagoing container modified for use as a shipboard laboratory on the aft main working deck of the *R/V Roger Revelle*.

### 9.6.3 DIC Analysis

In coulometric analysis of DIC, all carbonate species are converted to CO<sub>2</sub> by addition of excess hydrogen ion (acid) to the seawater sample, and the evolved CO<sub>2</sub> is swept into the titration cell of the coulometer with CO<sub>2</sub> free dry air or compressed nitrogen where it reacts quantitatively with a proprietary reagent based on ethanolamine to generate hydrogen ions. In this process, the solution changes from blue to colorless, triggering a current through the cell and causing coulometric generation of OH<sup>-</sup> ions at the anode. The OH<sup>-</sup> ions react with the H<sup>+</sup> and the solution turns blue again. A beam of light is shone through the solution, and a photometric detector at the opposite side of the cell senses the change in transmission. Once the percent transmission reaches its original value, the

coulometric titration is stopped, and the amount of CO<sub>2</sub> that enters the cell is determined by integrating the total change during the titration.

#### **9.6.4 DIC Calculation**

The amount of CO<sub>2</sub> injected was calculated according to the 2007 PICES Special Publication. Each DICE instrument has a modified SBE45 salinity sensor, but all DIC values were recalculated to a molar weight ( $\mu\text{mol kg}^{-1}$ ) using density obtained from the CTDs salinity.

The DIC values were corrected for dilution resulting from the addition of 0.12 ml of saturated HgCl<sub>2</sub> used for sample preservation. The correction factor used for this dilution is 1.000397. A correction was also applied for the offset from the Certified Reference Material (CRM). This additive correction was applied for each cell using the value of the CRM obtained at the beginning of the cell. The coulometer cell solution was replaced after 24-28 mg of carbon was titrated, typically after 10-12 hours of continuous use. The blanks (background noise per cell) averaged 27.6 and 28.3 counts on DICE 1 and DICE 2, respectively.

#### **9.6.5 Calibration, Accuracy, and Precision:**

The stability of each coulometer cell solution was confirmed three different ways: Gas loops were always run at the beginning and usually at the end of each cell; CRMs supplied by Dr. A. Dickson of Scripps Institution of Oceanography (SIO), were measured near the beginning; and Duplicate samples were run throughout the life of the cell solution.

Each coulometer was calibrated by injecting aliquots of pure CO<sub>2</sub> (99.999%), as a standard, by means of an 8-port valve (*Wilke et al., 1993*) outfitted with two calibrated sample loops of different sizes (~1ml and ~2ml). The instruments were each separately calibrated at the beginning of each cell with a minimum of two sets of these gas loop injections; and when time allowed at the end of each cell to ensure no drift during the life of the cell.

The accuracy of the DICE measurement is determined with the use of CRMs consisting of filtered and UV irradiated seawater, supplied by Dr. A. Dickson of SIO. The CRM accuracy is determined manometrically on land at SIO, and the DIC data reported have been corrected to the certified values (DIC = 2021.55  $\mu\text{mol kg}^{-1}$ ; salinity = 33.4230 PSU) for CRM batch 206. The summary table below<sup>1</sup> lists information for the CRMs.

The precision of the two DICE systems can be demonstrated via the replicate samples. Approximately 6% of the total niskins sampled during the cruise were duplicates taken as a check of our precision. These replicate samples were interspersed throughout the station analysis for quality assurance and integrity of the coulometer cell solutions. The average absolute difference from the mean of these replicates was 0.86  $\mu\text{mol kg}^{-1}$ ; no systematic differences between the replicates were observed<sup>2</sup>.

#### **9.6.6 Summary**

The overall performance of the analytical equipment was good for most of the cruise. A few minor equipment problems were encountered, but none wound up compromising the overall quality of the data we collected. Just prior to sailing to begin the cruise, we noticed that the temperature for the gas loops that are used for gas calibrations were not being read by the DICE 1 software. We eventually decided to use an average calibration factor based on data from the 2022 GO-SHIP P02 cruise in order to allow time to evaluate the problem further and avoid the risk of escalating problems by working with complicated wiring in rough seas. The manually-entered average calibration factor yielded highly accurate CRM readings, so we proceeded with this method for the first 40 stations of the cruise. Several attempts to remedy the problem were unsuccessful, until the replacement

of the small gas loop thermistor yielded temperature readings by the software. Later in the cruise, we replaced a faulty drain valve and float switch, which had caused ~10 samples to be flagged “bad” on account of insufficient pipette volumes being dispensed to the stripper for titration.

As is standard operating procedure, the pipette calibrations will be repeated upon return to shore. During the 2022 GO-SHIP P02 occupation, higher than usual background noise (i.e. blanks) were suspected to be on account of extra noise due to the new bow thruster the *R/V Roger Revelle* had installed during the mid-life refit and the need for all thrusters (Z-drive included) to be calibrated so they work as a team. This extra instrument noise was less apparent during the 2023 I05 cruise.

Including the duplicates, 5,016 samples were analyzed for dissolved inorganic carbon during this expedition. Assuming that ~8% of total niskins tripped during this cruise were used for biological analysis, DIC was analyzed for approximately 73% of the niskins made available to us. The DIC data reported to the database directly from the ship are to be considered preliminary until a more thorough quality assurance can be completed shore side.

### 9.6.7 Calibration data during this cruise

SYSTEM	Average Gas Loop Cal Factor	Pipette Volume	Duplicate <sup>2</sup>
PMEL1	1.00809	27.4847 ml	0.76
PMEL2	1.00427	26.4014 ml	0.98

CRM Info <sup>1</sup>	PMEL1			PMEL2		
Batch - Cert.	Average	<i>n</i>	Std. Dev.	Average	<i>n</i>	Std. Dev.
206 – 2021.55	2024.24	91	2.09	2018.42	98	2.11

### 9.6.8 References

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## 9.7 Discrete total scale pH (pH<sub>T</sub>)

PI: Dr. Andrew Dickson (SIO)

Technicians:

- Daniela Nestory (SIO)
- Abigail Tinari (SIO)
- Eva Capilla-Garcia (SIO)

### 9.7.1 Analysis

pH<sub>T</sub> was measured spectrophotometrically on the total hydrogen scale using an Agilent 8453 spectrophotometer and in accordance with the methods outlined by Carter et al, 2013. A Kloehn V6 syringe pump was used to autonomously fill, mix, and dispense sample through the custom 10cm flow-through jacketed cell. A Thermo Fisher Isotemp recirculating water bath was used to maintain the cell temperature at 25.0°C during analyses, and a YSI 4600 precision thermometer and probe were used to monitor and record the temperature of each sample during the spectrophotometric measurements. Purified meta-cresol purple (mCP) was the indicator used to measure the absorbance of light measured at two different wavelengths (434 nm, 578 nm) corresponding to the maximum absorbance peaks for the acidic and basic forms of the indicator dye. A baseline absorbance was also measured and subtracted from these wavelengths. The baseline absorbance was determined by averaging the absorbances from 725-735nm. The ratio of the absorbances was then used to calculate pH on the total scale using the equations outlined in Liu et al., 2011. The salinity data used was obtained from the salinity analysis conducted on board.

Reagents:

The mCP indicator dye was made up to a concentration of approximately 2.0mM and a total ionic strength of 0.7 M. A total of four dye batches were used during I05. The pH<sub>T</sub> of these batches was adjusted with 0.1 mol kg<sup>-1</sup> solutions of HCl and NaOH (in 0.6 mol kg<sup>-1</sup> NaCl background) to approximately 7.80, measured with a pH meter calibrated with NBS buffers. The indicator was obtained from Dr. Robert Byrne at the University of Southern Florida and was purified using the flash chromatography technique described by Patsavas et al., 2013.

### 9.7.2 Data Processing

An indicator dye is itself an acid-base system that can change the pH of the seawater to which it is added. Therefore it is important to estimate and correct for this perturbation to the seawater's pH for each batch of dye used during the cruise. To determine this correction, multiple bottles from each station were measured twice, once with a single addition of indicator dye and once with a double addition of indicator dye. The measured absorbance ratio (R) and an isosbestic absorbance  $A_{iso}$  were determined for each measurement, where:

$$R = \frac{A_{578} - A_{base}}{A_{434} - A_{base}}$$

and

$$R = A_{488} - A_{base}$$

The change in R for a given change in  $A_{iso}$ ,  $\Delta R/\Delta A_{iso}$ , was then plotted against the measured R-value for the normal amount of dye and fitted with a linear regression. From this fit the slope and y-intercept (b and a respectively) are determined by:

$$\frac{\Delta R}{\Delta A_{iso}} = bR + a$$

From this the corrected ratio  $R'$  corresponding to the measured absorbance ratio if no indicator dye were present can be determined by:

$$R' = R - A_{iso}(bR + a)$$

### 9.7.3 Sample Collection

Samples were collected in 250 mL Pyrex glass bottles and sealed using butyl rubber stoppers held in place by aluminum-crimped caps. Each bottle was rinsed two times and allowed to overflow by one half additional bottle volume. Prior to sealing, each sample was given a 1% headspace and 0.1 mL of 50% saturated mercuric chloride solution was added to each sample for preservation. Samples were collected only from niskin bottles that were also being sampled for both total alkalinity and dissolved inorganic carbon to completely characterize the carbon system. Additionally, duplicate samples were collected from all stations for quality control purposes. The typical sample scheme was as follows: A full collection every 5 stations (36 niskins), a half collection every 5 stations (16 niskins), and partial collections (27 niskins) on the stations in-between.

### 9.7.4 Problems and Troubleshooting

We experienced several problems with both Kloehn V6 syringe pumps throughout the cruise. Firstly, one of two pumps showed signs of electrical damage during station 26. Upon startup, the pump blinked intermittently and was not communicating with the computer. The pump was replaced with a spare.

Not long after, around station 95, we received error messages describing a blockage in the valve of our spare pump. After removing the syringe from the pump body, we found a small piece of Teflon tape blocking the inlet between the syringe and the valve. A few samples were lost between 95–97 during troubleshooting.

Finally, the spare pump suddenly stopped working and showed similar electrical errors to the original pump that failed around station 26. The electrician aboard the *R/V Roger Revelle* (Shaun Morris) diagnosed the issues in

both pumps. The original pump had corrosion on the various areas of circuit boards. The spare pump had an overheating chip associated with the syringe pump motor. Shaun was able to solder a replacement chip sourced from the original pump.

### **9.7.5 Standardization/Results**

The precision of the data was assessed from measurements of duplicate analyses and certified reference material (CRM) Batch 207 (provided by Dr. Andrew Dickson, UCSD). To evaluate the reproducibility of the alkalinity system, two duplicate samples (two samples from one niskin bottle) were collected on each cast, except for casts with fewer than 18 niskins, in which one duplicate sample was collected. CRMs were measured at the beginning and ending of each day. The precision statistics for I05 are:

Duplicate precision	$\pm 0.0009$ (n = 306 pairs)
CRM Batch 207	$7.7908 \pm 0.0019$ (n = 94)

4602 pH values were submitted for I05.

Additional corrections will need to be performed and these data should be considered preliminary until a more thorough analysis of the data can take place on shore.

### **9.7.6 References**

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## **9.8 Total titration seawater alkalinity ( $A_T$ )**

PIs: Andrew G. Dickson (SIO)

Technicians

- Daniela Nestory (SIO)
- Sara Gray (SIO)
- Abigail Tinari (SIO)

### **9.8.1 Parameter definition**

The total alkalinity of sea water is defined as the number of moles of hydrogen ion equivalent to the excess of proton acceptors (bases formed from weak acids with a dissociation constant  $K < 10E-4.5$  at 25°C and zero ionic strength) over proton donors (acids with  $K > 10E-4.5$ ) in 1 kilogram of sample.

### **9.8.2 Total Alkalinity Measurement System**

Sample Delivery System:

Samples are dispensed using a Sample Delivery System (SDS) which has been calibrated for volume in the lab prior to the cruise. Its volume is confirmed immediately before use at sea to ensure a consistent volume will be delivered for each sample. The SDS consists of a volumetric pipette, various relay valves, an air pump, and is controlled by a program in LabVIEW 2012.

Before attaching a sample bottle to the SDS, the volumetric pipette is cleared of any residual solution. The pipette is then rinsed and filled with the sample. The sample overflows and time is allowed for the sample temperature to equilibrate.

The sample bottle temperature is measured using a DirecTemp thermistor probe inserted into the sample bottle and the volumetric pipette temperature is measured using a DirecTemp surface probe placed directly on the pipette. These temperature measurements, along with the bottle salinity, are used to convert the sample volume to mass for analysis.

Samples are delivered into a 250-mL water-jacketed open cell for titration analysis. While one sample is undergoing titration, a second sample is prepared with the SDS and equilibrated to 20°C for analysis.

### **9.8.3 Open-Cell Titration:**

The total alkalinity is measured through an open-cell titration with a dilute hydrochloric acid titrant of known concentration. A Metrohm 876 Dosimat Plus is used for all standardized hydrochloric acid additions.

An initial aliquot of approximately 2.3-2.4 mL of standardized hydrochloric acid (~0.1M HCl in ~0.6M NaCl solution) is first delivered and the sample is stirred for 5 minutes while air is bubbled into at a rate of 200 scc/m to remove any liberated carbon dioxide gas.

After equilibration, ~19 aliquots of 0.035 ml are added. Between the pH range of 3.5 to 3.0, the progress of the titration is monitored using a pH glass electrode/reference electrode cell, and the total alkalinity is computed from the titrant volume and e.m.f. measurements using a non-linear least-squares approach (Dickson, 2007).

A Thermo Scientific Isotemp water bath is connected to the water-jacketed open cell to maintain a cell temperature of approximately 20°C. An Agilent 34970A Data Acquisition/Switch Unit with a 34901A multiplexer is used to read the voltage measurements from the electrode and monitor the temperatures from the sample, acid, and room.

The calculations for this procedure are performed automatically using LabVIEW 2012.

### **9.8.4 Sample Collection**

Alkalinity samples are drawn using silicone tubing connected to the niskin bottle and collected into 250 mL Pyrex bottles. The sample bottles and Teflon-sleeved glass stoppers were rinsed at least twice before the final filling. A headspace of approximately 3 mL was removed and 0.1 mL of 50% saturated mercuric chloride solution was added to each sample for preservation. The samples were equilibrated prior to analysis at approximately 20°C using a Thermo Scientific Isotemp water bath.

Samples for total alkalinity were taken at all stations where a core cast was completed.

Alkalinity samples were collected from each niskin where DIC and pH were collected, to completely characterize the CO<sub>2</sub> system. The typical sample scheme was as follows: A full collection every 5 stations (36 niskins), a half collection every 5 stations (16 niskins), and partial collections (27 niskins) on the stations in-between.

To evaluate the reproducibility of the alkalinity system, 2 duplicate samples (two separate alkalinity bottles) were collected on each cast, except for casts with fewer than 18 bottles, in which 1 duplicate sample was collected.

### **9.8.5 Problems and Troubleshooting**

The primary SDS system used from stations 1–20 was producing high CRM values ( $\sim 1.5 \mu\text{mol kg}^{-1}$ ). The cause of the offset is not obvious but may be due to shifting of system parts after calibration in our land-based laboratory. The SDS system was replaced with a spare.

### **9.8.6 Quality Control**

Certified Reference Material (CRMs) and duplicate samples (two bottles collected from one niskin) were used to quality check the functioning of the total alkalinity system throughout the cruise.

Dickson laboratory Certified Reference Material (CRM) Batches 206 and 207 were used to determine the accuracy of the total alkalinity analyses. The total alkalinity certified values for these batches are:

- Batch 206:  $2193.88 \pm 0.76 \mu\text{mol/kg}$  (36; 16)
- Batch 207:  $2199.32 \pm 0.79 \mu\text{mol/kg}$  (33; 16)

The cited uncertainties represent the standard deviation. Figures in parentheses are the number of analyses made (total number of analyses; number of separate bottles analyzed).

A CRM sample was analyzed at a minimum frequency of once per every 20 runs, but more often once per every 15 runs. Because total alkalinity is not affected by gas-exchange, brand new CRM bottles were reserved for pH and DIC analysis. These pre-opened bottles were subsequently used for alkalinity analysis. 242 reference material samples were analyzed during I05. The average measured total alkalinity value for each batch is:

- Batch 206:  $2193.70 \pm 1.30 \mu\text{mol/kg}$  (222; 125)
- Batch 207:  $2198.60 \pm 1.54 \mu\text{mol/kg}$  (152; 88)

Duplicate samples were also used to check the reproducibility of the system. The pooled standard deviation of duplicate samples is given below.

Duplicate precision:  $\pm 1.02 \mu\text{mol kg}^{-1}$  (n = 318 pairs)

4602 total alkalinity values were submitted for I05.

Further dilution corrections need to be applied to this data back onshore, therefore, this data is to be considered preliminary.

## **9.9 Dissolved organic matter (DOM or DOC and TDN)**

PI: Craig Carlson, UCSB

Analysts: Keri Opalk, Elisa Halewood (UCSB)

Shipboard personnel: Jaden Hansen (UCSB)

Total Stations (Samples): 98 full depth (3,324)

### **9.9.1 Project goals**

The goal of the DOM project is to provide high resolution, long term monitoring of DOC/TDN distribution throughout the water column, in order to help better understand biogeochemical cycling in global oceans. For 2023 the Carlson Lab at UCSB will evaluate dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) concentrations along the US GO-SHIP I05 transect (114°E to 30°E along ~32°S).

### **9.9.2 Sampling Plan**

Over the course of the I05 cruise, DOC/TDN was sampled at every other station in conjunction with DIC, Alkalinity, and pH. For these, DOM was sampled from 36 unique Niskins ranging the full depth of the water column, with two duplicates randomly selected for a total of 38 samples collected per cast. In addition, at intermediate stations where DOM was not collected for the full depth profile a single surface sample was collected to increase surface resolution across this section.

*As of 9/10/23: DOM was sampled at full profile frequency at 98 stations of the total 196 stations, and another 93 single surface samples were collected. In total 3,324 individual DOC samples have been collected to date.*

### **9.9.3 Sampling details**

DOC samples were passed through an inline filter holding a combusted GF/F filter attached directly to the Niskin for samples above 500 m of each cast. This was done to eliminate particles larger than 0.7  $\mu\text{m}$  from the sample. Samples from deeper depths were not filtered. Previous work has demonstrated that there is no resolvable difference between filtered and unfiltered samples in waters below the upper 500 m at the  $\mu\text{mol kg}^{-1}$  resolution.

To avoid contamination, nitrile gloves were used when handling all sampling equipment and clean lab surfaces were used for processing samples. After each station, all equipment used for sampling was rinsed with 5-10% hydrochloric acid and MilliQ water in preparation for the following station. All samples were rinsed 3 times with ~5 mL of seawater and collected into 40 mL glass EPA vials.

Sample vials were prepared in advance for this cruise by combusting at 450°C for 4 hours to remove any organic matter. Vial caps were cleaned by soaking in 10% hydrochloric acid, followed by a soak in Nanopure water overnight, followed by a 3 times rinse with Nanopure water and left out to dry. Samples were fixed with 50  $\mu\text{L}$  of 4N hydrochloric acid and stored upright in well-sealed pelican coolers at room temperature on board (for I05 this was the forward hold). Samples were never frozen. Samples will be shipped back to UCSB for analysis via high temperature combustion on Shimadzu TOC-V or TOC L analyzers.

### **9.9.4 Standard Operating procedure for DOM analyses (Carlson Lab, UCSB)**

DOC samples will be analyzed via high temperature combustion using a Shimadzu TOC-V or Shimadzu TOC-L in a shore based laboratory at the University of California, Santa Barbara. The operating conditions of the Shimadzu TOC-V have been slightly modified from the manufacturer's model system. These methods have been added to the [GO SHIP Practices collection](#) and are fully detailed in [Halewood et. al, 2022](#), and previously [[Carlson 2010](#), [Hansell 2005](#), [Hansell 1998](#)].

Final results are reported in units of  $\mu\text{mol kg}^{-1}$ . Where possible direct measures of sample salinity and analytical temperature are used to calculate average seawater density. In practice we have found that applying an average seawater density of  $1.027 \text{ kg m}^{-3}$  to open ocean water column DOM samples, compared to direct measure of sample density results in a difference of less than  $0.01 \mu\text{mol kg}^{-1}$  (i.e., less than analytical resolution). However, when salinity and an average analytical lab temperature are available or in regions where salinity varies strongly, a more accurate density correction is determined and applied for each sample. Each parameter includes a field for quality control flags.

### **9.9.5 References**

Halewood E, Opalk K, Custals L, Carey M, Hansell D.A. and Carlson, C.A. (2022) Determination of dissolved organic carbon and total dissolved nitrogen in seawater using High Temperature Combustion Analysis. *Front. Mar. Sci.* 9:1061646. doi: 10.3389/fmars.2022.1061646.

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### **9.10 Dissolved organic phosphorous**

PI: Dr. Robert Letscher (University of New Hampshire)

Seagoing personnel: Lydia Pinard (University of New Hampshire)

#### **9.10.1 Data Acquisition and QC**

Seawater filtered through a 47 mm GF/F filter was collected in 40 mL EPA glass vials, acidified to  $\text{pH} < 2$  with HCl acid, and stored refrigerated until analysis. A total of 1 vial was collected from 6-10 unique Niskins from the upper 250 m. Target depths were: 5, 25, 50, 75, 125, 250 meters. One station was sampled per day between the hours of 24:00-12:00 local time. 41 stations were sampled, with a total of 298 water samples collected. At the end of the cruise, chilled samples were transported in a large cooler with ice packs and picked up by DHL for transport back to UNH where samples will be analyzed by Letscher.

During the first 3 stations: 029, 037, and 042, the GF/F filters ripped. After station 139, samples were collected without wearing gloves as the ship had run out. After station 164, seawater was no longer filtered, as the supply of filters had run out. All samples were acidified to  $\text{pH} < 2$  with HCl acid and stored refrigerated until analysis.

### **9.10.2 Analysis**

Dissolved organic phosphorus (DOP) will be calculated by difference from independent measurements of total dissolved phosphorus (TDP) and soluble reactive phosphorus (SRP). The latter is determined at sea by the nutrient analysts aboard the *R/V Roger Revelle* using the colorimetric method with molybdenum blue. TDP is measured following a digestion with an acidic potassium persulfate reagent with the subsequent solution measured for SRP using the same colorimetric method. TDP analyses will be performed at the University of New Hampshire (USA) in the laboratory of Dr. Robert Letscher on a SEAL Analytical AQ300 Discrete Analyzer system. Data analyses are expected to be completed by the autumn of 2024.

### **9.11 Discrete/bottle salinity**

Technicians: John Calderwood (SIO) and Jessica McLaughlin (SIO)

Samplers: Jessica McLaughlin, Steven Akin, Nirmala J. Nair, Jomphol Lamoonkit, Kirsten Petzer, Alexis Merk, Tania Leung, Brendan Carter,

#### **9.11.1 Equipment and techniques**

Two Guildline Autosals were on board and operational, SIO-owned 8400A S/N 57-526 and 8400A S/N 55-654. S/N 57-526 was used for all salinity measurements during this cruise. The salinity analysis was run in the ship's Climate Controlled Chamber, a refrigerator, port and amidships between the Computer Lab and Bioanalytical Lab. The chamber temperature varied between about 21 and 24 degrees Celsius around 3 times each hour, with an average (based on measuring temperatures of items in the chamber) of about 22.5°C. IAPSO Standard Seawater Batch P166 was used for all calibrations: K15 = 0.99987, Practical salinity = 34.995, expiration 2025-04-06. A LabView program developed by Carl Mattson was used for monitoring temperatures, logging data, and prompting the operator. Salinity analyses were performed after samples had equilibrated to a laboratory temperature of 23°C, 8 hours or more after collection. Samples were placed under fans to speed their acclimatization to the set room temperature. The salinometer was standardized for each group of samples analyzed (up to 3 casts, or up to 108 samples) using two bottles of standard seawater: one at the beginning and one at the end of each set of measurements. For each calibration standard and sample reading, the salinometer cell was initially flushed at least 2 times before a set of conductivity ratio readings was recorded. Standardization conductivity offsets did not exceed 0.00005 mS/cm for all casts. Between runs, the water from the last standard was left in the cell.

#### **9.11.2 Sampling & Data Processing**

The salinity samples were collected in 200 ml Kimax high-alumina borosilicate bottles that had been rinsed at least three times with sample water prior to filling. The bottles were sealed with plastic insert thimbles and Nalgene screw caps. This assembly provides very low container dissolution and sample evaporation. Prior to sample collection, inserts were inspected for proper fit, and loose inserts were replaced to ensure an airtight seal. Laboratory temperature was also monitored electronically throughout the cruise. PSS-78 salinity [UNESCO1981] was calculated for each sample from the measured conductivity ratios. The offset between the initial standard seawater value and its reference value was applied to each sample. Then the difference (if any) between the initial and final vials of standard seawater was applied to each sample as a function of elapsed run time. The corrected salinity data was then incorporated into the cruise database. 6340 salinity samples were collected and run during I05, using approximately 194 bottles of standard seawater. There were 2 crates (62 total samples) of samples run at the beginning of the cruise that had been collected from CTD casts done during the transit from Goa, India to Fremantle, Australia. These were used for training salinity analysts but are not included in the data for RR2308.

### **9.11.3 Problems**

10 sample bottles were broken or chipped during this cruise, and all were replaced during sampling. During various points of the cruise, it was noted that some sample bottles had red algae growing in them. To clean the bottles, they were rinsed with acid (10% HCl) and then rinsed with fresh water prior to being added back into the crates for sampling. To help with cell filling, capillary tubes were carefully cleaned with MilliQ, followed by air, once during the cruise, to help with cell filling.

Within the first 24 stations, the climate-controlled chamber lost temperature control 3 times due to a bad valve in the condenser line. Engineers from the ship's crew worked to fix this issue and the room maintained its after their work.

Towards the last 3 weeks of the cruise, the air temperature probe connected to LabView began to show some extremely unrealistic values (air temperatures between 500-1200 degrees Celsius). The air temperature probe that is used is old and both the connection prongs and the contacts in the electronics are oxidized. To combat unrealistic readings the prongs were cleaned which worked temporarily but continuous upkeep was unrealistic because of the placement. In tandem with the external temperature probes throughout the chamber, the temperature range between 21 and 24 degrees Celsius was maintained.

## **9.12 Nutrients**

Technicians

Susan Becker: Scripps Institution of Oceanography

Tania Leung: Scripps Institution of Oceanography

### **9.12.1 Summary of Analysis**

- 6342 samples from 196 CTD stations
- The cruise started with new pump tubes and they were changed 3 times, before stations 055, 114, and 148.
- 7 sets of Primary/Secondary mixed standards and 3 sets of primary Nitrite standards were made up over the course of the cruise.
- The cadmium column efficiency was checked periodically and ranged between 80%-100%.

### **9.12.2 Equipment and Techniques**

Nutrient analyses (phosphate, silicate, nitrate+nitrite, and nitrite) were performed on a Seal Analytical continuous-flow AutoAnalyzer 3 (AA3). The methods used are described by Gordon et al [Gordon1992], Hager et al. [Hager1972], and Atlas et al. [Atlas1971]. Details of modification of analytical methods used in this cruise are also compatible with the methods described in the nutrient section of the updated GO-SHIP repeat hydrography manual (Becker et al., 2019, [Becker 2019]).

### **9.12.3 Nitrate/Nitrite Analysis**

A modification of the Armstrong et al. (1967) [Armstrong1967] procedure was used for the analysis of nitrate and nitrite. For nitrate analysis, a seawater sample was passed through a cadmium column where the nitrate was reduced to nitrite. This nitrite was then diazotized with sulfanilamide and coupled with N-(1-naphthyl)-ethylenediamine to form a red dye. The sample was then passed through a 10mm flowcell and absorbance measured at 520nm. The procedure was the same for the nitrite analysis but without the cadmium column.

Reagents:

#### Sulfanilamide

- Dissolve 10g sulfanilamide in 1.2N HCl and bring to 1 liter volume.
- Add 2 drops of 30% Brij-35 surfactant.
- Store at room temperature in a dark poly bottle.
- Note: 30% Brij-35 is 30% Brij-35 dissolved in 100 mL DIW.

#### N-(1-Naphthyl)-ethylenediamine dihydrochloride (N-1-N)

- Dissolve 1g N-1-N in DIW, bring to 1 liter volume.
- Add 2 drops 30% Brij-35 surfactant.
- Store at room temperature in a dark poly bottle.
- Discard if the solution turns dark reddish brown.

#### Imidazole Buffer

- Dissolve 13.6g imidazole in ~3.8 liters DIW.
- Stir for at least 30 minutes to completely dissolve.
- Add 60 ml of CuSO<sub>4</sub> + NH<sub>4</sub>Cl mix (see below).
- Add 4 30% Brij-35 surfactant.
- Let sit overnight before proceeding.
- Using a calibrated pH meter, adjust to pH of 7.83-7.85 with 10% (1.2N) HCl (about 10 ml of acid, depending on exact strength).
- Bring final solution to 4L with DIW.
- Store at room temperature.

#### NH<sub>4</sub>Cl + CuSO<sub>4</sub> mix

- Dissolve 2g cupric sulfate in DIW, bring to 100 ml volume (2%).
- Dissolve 250g ammonium chloride in DIW, bring to 11 liter volume.
- Add 5ml of 2% CuSO<sub>4</sub> solution to this NH<sub>4</sub>Cl stock.
- This should last many months.

#### 9.12.4 Phosphate Analysis

Ortho-Phosphate was analyzed using a modification of the Bernhardt and Wilhelms (1967) [Bernhardt1967]\_ method. Acidified ammonium molybdate was added to a seawater sample to produce phosphomolybdic acid, which was then reduced to phosphomolybdous acid (a blue compound) following the addition of dihydrazine sulfate. The sample was passed through a 10mm flowcell and absorbance measured at 820nm.

Reagents:

#### Ammonium Molybdate H<sub>2</sub>SO<sub>4</sub> sol'n

- Pour 420 ml of DIW into a 2 liter Ehrlenmeyer flask or beaker, place this flask or beaker into an ice bath.

- SLOWLY add 330 ml of conc H<sub>2</sub>SO<sub>4</sub>.
- This solution gets VERY HOT!!
- Cool in the ice bath.
- Make up as much as necessary in the above proportions.
- Dissolve 27g ammonium molybdate in 250ml of DIW.
- Bring to 1 liter volume with the cooled sulfuric acid sol'n.
- Add 3 drops of 15% DDS surfactant.
- Store in a dark poly bottle.

#### Dihydrazine Sulfate

- Dissolve 6.4g dihydrazine sulfate in DIW, bring to 1 liter volume and refrigerate.

#### 9.12.5 Silicate Analysis

Silicate was analyzed using the basic method of Armstrong et al. (1967). Acidified ammonium molybdate was added to a seawater sample to produce silicomolybdic acid which was then reduced to silicomolybdous acid (a blue compound) following the addition of stannous chloride. The sample was passed through a 10mm flowcell and measured at 660nm.

#### Reagents:

##### Tartaric Acid

- Dissolve 200g tartaric acid in DW and bring to 1 liter volume.
- Store at room temperature in a poly bottle.
- Ammonium Molybdate
- Dissolve 10.8g Ammonium Molybdate Tetrahydrate in 1000ml dilute H<sub>2</sub>SO<sub>4</sub>.
- (Dilute H<sub>2</sub>SO<sub>4</sub> = 2.8ml conc H<sub>2</sub>SO<sub>4</sub> or 6.4ml of H<sub>2</sub>SO<sub>4</sub> diluted for PO<sub>4</sub> moly per liter DW) (dissolve powder, then add H<sub>2</sub>SO<sub>4</sub>)
- Add 3-5 drops 15% SDS surfactant per liter of solution.

##### Stannous Chloride

- stock: (as needed)
- Dissolve 40g of stannous chloride in 100 ml 5N HCl.
- Refrigerate in a poly bottle.

#### Notes:

- Minimize oxygen introduction by swirling rather than shaking the solution.
- Discard if a white solution (oxychloride) forms.
- working: (every 24 hours)
- Bring 5 ml of stannous chloride stock to 200 ml final volume with 1.2N HCl.
- Make up daily - refrigerate when not in use in a dark poly bottle.

### 9.12.6 Sampling

Nutrient samples were drawn into 30 ml polypropylene screw-capped centrifuge tubes. The tubes and caps were cleaned with 10% HCl and rinsed 2-3 times with sample before filling. Samples were analyzed within 4 hours after sample collection, allowing sufficient time for all samples to reach room temperature. The centrifuge tubes fit directly onto the sampler.

### 9.12.7 Data Collection and Processing

Data collection and processing was done with the software provided with the instrument from Seal Analytical (AACE). After each run, the charts were reviewed for any problems during the run, any blank was subtracted, and final concentrations (micro moles/liter) were calculated, based on a linear curve fit. Once the run was reviewed and concentrations calculated a text file was created. That text file was reviewed for possible problems and then converted to another text file with only sample identifiers and nutrient concentrations that was merged with other bottle data.

### 9.12.8 Standards and Glassware Calibration

Primary standards for silicate ( $\text{Na}_2\text{SiF}_6$ ), nitrate ( $\text{KNO}_3$ ), nitrite ( $\text{NaNO}_2$ ), and phosphate ( $\text{KH}_2\text{PO}_4$ ) were obtained from Johnson Matthey Chemical Co. and/or Fisher Scientific. The supplier reports purities of >98%, 99.999%, 97%, and 99.999 respectively. All glass volumetric flasks and pipettes were gravimetrically calibrated prior to the cruise. The primary standards were dried and weighed out to 0.1mg prior to the cruise. The exact weight was noted for future reference. When primary standards were made, the flask volume at 20C, the weight of the powder, and the temperature of the solution were used to buoyancy-correct the weight, calculate the exact concentration of the solution, and determine how much of the primary was needed for the desired concentrations of secondary standard. The new standards were compared to the old before use.

All the reagent solutions, primary and secondary standards were made with fresh distilled deionized water (DIW). Standardizations were performed at the beginning of each group of analyses with working standards prepared every 12-16 hours from a secondary. Working standards were made up in low nutrient seawater (LNSW). Multiple batches of LNSW were used on the cruise. The first batch of LNSW was treated in the lab. The water was re-circulated for ~8 hours through a 0.2 micron filter, passed a UV lamp and through a second 0.2 micron filter. The actual concentration of nutrients in this water was empirically determined during the standardization calculations.

The concentrations in micro-moles per liter of the working standards used were:

Standard number	Nitrate and nitrite	Phosphate	Silicate	NO <sub>2</sub>
0	0.0	0.0	0.0	0.0
3	15.50	1.2	60	0.50
5	31.00	2.4	120	1.00
7	46.50	3.6	180	1.50

### 9.12.9 Quality Control

All final data was reported in micro-moles/kg.  $[\text{NO}_3]$ ,  $[\text{PO}_4]$ , and  $[\text{NO}_2]$  were reported to two decimal places and SIL to one. Accuracy is based on the quality of the standards the levels are:

Nitrate                    0.05  $\mu\text{M}$

Phosphate	0.004 $\mu\text{M}$
Silicate	2-4 $\mu\text{M}$
NO <sub>2</sub>	0.05 $\mu\text{M}$

Reference materials for nutrients in seawater (RMNS) were used as a check sample run with every station. The RMNS preparation, verification, and suggested protocol for use of the material are described by [Aoyama2006]\_ [Aoyama2007]\_, [Aoyama2008]\_, Sato [Sato2010]\_ and Becker et al. [Becker 2019]. RMNS batch CM was used on this cruise, with each bottle being used for all runs in one day before being discarded and a new one opened.

Data are tabulated below.

Parameter	Concentration ( $\mu\text{mol kg}^{-1}$ )	Stddev	Assigned concentration ( $\mu\text{mol kg}^{-1}$ )
Nitrate	33.12	0.17	33.2
Phosphate	2.4	0.02	2.38
Silicate	100.	0.49	100.5
NO <sub>2</sub>	0.020	0.005	0.02

#### **9.12.10 Analytical Problems**

There were issues with columns losing efficiency quickly at the start of the cruise. These issues were resolved by cleaning, treating and repacking new columns. There were no other analytical errors.

#### **9.12.11 References**

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### **9.13 Isotopes of nitrate**

PIs: Dario Marconi and Daniel Sigman

Shipboard personnel: Kirsten Petzer and Steven Akin

#### **9.13.1 Sampling procedure**

The samples were collected 1x60ml for each depth with 1 replicate (2x60ml) shallower than 300 m (which would usually be the last 6 bottles per cast). The stations were chosen with 2.4-2.5° difference of longitude in between stations. Except for station 191 which was added because there were extra bottles and we thought a station at the core of the Agulhas Current could be beneficial.

Before filling the bottle, the sample bottle was rinsed three times with 10mls of sample water. The bottle was capped, inverted, and shook, with the rinse water discarded by pouring over the cap to wet the cap threads. The bottles were then filled to shoulder and capped. After sampling, the samples were stored in a freezer in the main lab, unless the sample box was not filled. If the box was not filled yet, then the samples were stored in an alternative box in a freezer in the hydro lab. No gloves were worn, and samples were all frozen after being sampled.

#### **9.13.2 Issues to note:**

- Station 11 - bottle 4 and 17 that was leaking

- Station 42 - bottle 33 was fired at the previous depth by accident
- Station 56 - bottle 13 did not fire.
- Station 166 - suspected bottle 2 mis-tripped based on sampled parameters
- Station 196 – bottle 4 is leaking so instead of swapping bottles on last station we fired bottles 4 and 5 at the same depth. Only 5 was sampled.

Station	Depth [m]	Niskin B. total	Sample #	Notes
5	1924	24	1-30	
11	4990	36	31-72	B. 4 & 17 was leaking
16	5248	36	73-114	
20	4970	36	115-156	
26	3746	16	157-176	
32	5115	36	177-219	
42	5743	36	220-260	No bottle 33
47	4405	36	261-302	

Station	Depth [m]	Niskin B. total	Sample #	Notes
52	4437	36	303-345	
56	4301	36	346-387	Bottle 13 did not fire
61	4117	36	388-429	
66	1391	22	430-457	
71	3766	36	458-499	
75	3776	36	500-541	
79	4041	36	542-583	
85	3194	34	584-623	
90	3388	35	624-664	
96	4887	36	665-706	
101	4440	36	707-748	
106	4559	36	749-790	
110	4702	36	791-832	
114	4621	36	833-874	
118	4793	36	875-916	
123	3814	36	917-958	
131	5088	36	959-1000	
137	2023	26	1001-1032	
142	4475	36	1033-1074	
146	4036	36	1075-1116	
151	2998	33	1117-1155	
155	962	20	1156-1181	
161	4392	36	1182-1223	
166	5118	36	1124-1265	Suspected B2 mis-tripped

170	5136	36	1266-1307	
177	1582	27	1308-1337	Bio and chem cast
183	3551	35	1338-1378	
191	2800	32	1379-1416	Extra station
196	231	11	1416-1432	(B4 will not be sampled)

### 9.13.3 Processing

The samples will be returned frozen to the United States where samples will be analyzed in the Geosciences Department of Princeton University. The “denitrifier method” will be used for isotopic analyses (Casciotti et al., 2002; Sigman et al., 2001). The nitrate and nitrite within the samples will be converted to N<sub>2</sub>O gas, and the N and O isotope ratios of this N<sub>2</sub>O will be measured on an isotope ratio mass spectrometer subsequent to on-line N<sub>2</sub>O extraction, purification, cryogenic concentration, and gas chromatography (McIlvin and Casciotti, 2011; Weigand et al., 2016). The samples will be analyzed at the rate of about 80 samples per week. After receiving the samples, the analyses (including replicates) should be completed within 8 to 12 months.

### 9.13.4 References:

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## 9.14 Isotopes of H<sub>2</sub>O

PI: Amy Wagner

Shipboard personnel: Jomphol Lamoonkit and Nirmala J. Nair

### 9.14.1 Sampling procedure

The oxygen isotope samples were taken by Jomphol Lamoonkit (day shift) and Nirmala J Nair (night shift). The sampler per station can be found on the sample logs.

The bottles were filled by a Niskin tube (silicone tube) and allowed to overflow 2 to 3 times as per instructed. The caps were screwed securely and wrapped with electrical tape in the clockwise direction. Extra ~10% of the samples were collected for duplication. Samplers switched to duct tape after the electrical tape ran out.

### 9.14.2 Seawater isotope analyses via OA-ICOS

The development and improvement of laser-based gas analyzers based on off-axis integrated cavity output spectroscopy (OA-ICOS) and cavity ring-down spectroscopy (CRDS) over recent decades has provided an opportunity for relatively low-cost, high-precision  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  measurements of natural waters to be analyzed

without the time, expense and overhead of traditional isotope ratio mass spectrometry (IRMS) (e.g. Lis et al., 2008; Maruyama et al., 2013; Walker et al., 2016). Seawater  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  measurements will be made using a Los Gatos Research (LGR) Liquid Water Isotope Analyzer (LWIA-24d), which utilizes OA-ICOS, at the Sacramento State WAGS Lab (Wagner Aquatic Geochemistry and Spectroscopy). A sub-set of coordinating samples (up to 25%) will be run at Rutgers on a Picarro L2130-i with 107 position autosampler. These will be used for instrument inter-comparison as well as to reduce the load on the Sacramento State instruments, if needed.

Samples will be run with 10% replication and in duplicate where possible. To minimize noise associated with salt build up in the injection port, a freshwater rinse will be performed after every seawater sample and before intra-run standards. Each sample will be the result of at least eight injections, with the first two injections being discarded out of an abundance of caution to avoid carryover between samples. Oxygen and hydrogen isotope ratios are reported as the per mil (‰) deviation of the  $^{18}\text{O}/^{16}\text{O}$  ratio and  $^2\text{H}/^1\text{H}$  ratio of the sample from that of Vienna Standard Mean Ocean Water (VSMOW; Coplen, 1994). The OA-ICOS methodology has shown to be successful analyzing seawater samples from the CROCCA-2s Indian Ocean cruise (Courser et al., 2020; Glaubke et al., in review) with a precision of  $\pm 0.15\text{‰}$  (1 SD) for  $\delta^{18}\text{O}$  and  $\pm 1.0\text{‰}$  (1 SD) for  $\delta^2\text{H}$ .

At optimum performance and efficiency, throughput for OA-ICOS theoretically could be as many as 20 seawater samples in a 24-hour period. Based on experience from a summer undergraduate research program at Sacramento State to analyze seawater samples from GEOTRACES GP17-OCE, we have found when the measurement and analysis of the samples was part of an undergraduate student research program, the throughput was more realistically about 40-50 samples per week. Given these considerations, we plan to hire a graduate student to oversee lab work and scheduling, perform routine instrumental maintenance, and perform QA/QC of the data to optimize throughput efficiency.

We expect to begin analysis of the samples early 2024 and it to take approximately 18 months to complete (late 2025 estimated completion of data collection and final submission of the dataset).

## **9.15 Float and drifter deployments**

PIs: varied, see below

Shipboard personnel: Aurélie Moulin (amoulin@uw.edu)

Several sets of autonomous profiling floats and drifters were deployed on I05. The specifics are detailed below. All deployments were successful and all assets are transmitting data. Communication with all PIs were consistent and outstanding throughout the cruise.

### ***9.15.1 SOCCOM and GO-BGC biogeochemical (BGC) Argo floats***

Eight BGC Argo floats were deployed in water depth  $> 3000\text{m}$ . The floats were supplied by the SOCCOM (Southern Ocean Carbon and Climate Observations and Modeling) and GO-BGC (Global Ocean Biogeochemistry Array) programs (NSF OPP-1936222 and OCE-1946578). Each float carries sensors for temperature, salinity, dissolved oxygen, nitrate, pH, fluorescence (Chl), and backscatter. One is a full 6-sensor BGC float, also measuring irradiance (OCR). The floats follow the Argo profiling protocol of parking at 1000 m, and profiling from 2000 m to the surface every 10 days. All sensor data are calibrated, quality-controlled, and made available through the Argo GDAC, and through links from the SOCCOM (<https://socc.com.princeton.edu/>) and GO-BGC (<https://www.go-bgc.org/>) websites.

Each float was sponsored by a school through the GO-BGC and SOCCOM Adopt-a-Float programs. PIs: Stephen Riser (UW, [riser@uw.edu](mailto:riser@uw.edu)), Ken Johnson (MBARI, [johnson@mbari.org](mailto:johnson@mbari.org)), Lynne Talley (UCSD, [ltalley@ucsd.edu](mailto:ltalley@ucsd.edu)) for the floats, and George Matsumoto (MBARI, [mage@mbari.org](mailto:mage@mbari.org)) for Adopt-a-Float. Float details and deployment locations are listed in Table 1.

Deployment of BGC floats on GO-SHIP cruises is especially useful because of the coincident reference quality measurements of oxygen, nutrients, and carbon parameters, which are used to validate the SOCCOM and GO-BGC sensor calibrations. Collection of HPLC and POC samples was added to US GO-SHIP I05 for similar validation of the float optical measurements.

Float	Lat °S	Lon °E	Station number	UW Float ID	WMO Float ID	Comments	School sponsor	Deployment Date, Time UTC
1	-32.517613	114.120900	007	22213	2903854	GOBGC	The Exceleator	23-Jul-2023, 12:01
2	-31.084683	105.458305	023	21857	4903747	SOCCOM	A.B. Combs Al E. Gator	28-Jul-2023, 21:42
3	-33.996212	95.559368	051	21535	5907051	SOCCOM	Hooter The Owl	05-Aug-2023, 04:39
4	-31.194652	84.368328	073	21576	4903745	SOCCOM	Sweet Caroline	10-Aug-2023, 10:22
5	-33.997746	65.123261	112	21467	5907050	GOBGC	Nautifish	21-Aug-2023, 01:08
6	-33.997968	53.634945	139	21519	2903869	SOCCOM	Saturna Island	28-Aug-2023, 03:45
7	-32.997771	40.408560	165	21286	5907055	SOCCOM w OCR	Leibniz	03-Sep-2023, 09:20
8	-32.180121	32.318027	184	21075	3902554	GOBGC	Wildcats	08-Sep-2023, 02:33

Each float was taken out of its crate within 24 hours of its deployment to be decorated with sharpies according to the school sponsor (Figures 1 – 8). Then the FLBB sensor was carefully cleaned with a squirt of DI water, dabbed with alcohol wipes (provided), rinsed again with DI water, then dabbed dry with lens paper (provided). The nitrate sensor was softly rubbed with alcohol wipes on a q-tip, both provided. The art drawn on each float was led by Kristin Petzer with occasional help from Kay McMonigal, Alexis Merk, Jaden Hansen, and Maggie Gaspar.

The floats were brought to the stern and secured a few minutes from the end of CTD casts, with one person staying with the float at all times while on deck. The line was secured on one end with a bowline knot and fed through the deployment collar from the top as instructed. At deployment time, one person would hold onto the line around the collar and tilt the float while a second person would pick up the bottom of the float. The float was raised over the edge horizontally by the two persons, then the bottom end slowly brought down to make the float vertical. The person holding the line would then slowly lower the float, fast enough to minimize time in the air, but slow enough not to rush and remain careful. Once the float was in the water with the ship going between 1-2 kts, the line was continuously fed until the end, then dropped in the water making sure not to create tension.

### 9.15.2 EM-APEX floats

Seven EM-APEX floats measuring temperature, salinity, velocity, and turbulence were deployed on I05 as part of the Sampling Quantitative Internal-wave Distribution project (SQUID) sponsored by NSF and lead by James Girton (APL-UW, [girton@uw.edu](mailto:girton@uw.edu)). EM-APEX float details and deployment locations are listed in Table 2.

Table 2 – EM-APEX float details

Float	Lat °S	Lon °E	Station number	Float ID	Deployment Date, Time UTC
1	-32.535237	114.186118	006	10236	23-Jul-2023, 07:32
2	-33.311188	93.416276	055	9440	06-Aug-2023, 05:42
3	-32.818633	75.043108	092	10241	15-Aug-2023, 02:26
4	-33.997511	55.744917	134	10240	27-Aug-2023, 02:25
5	-33.070570	45.066641	154	10239	31-Aug-2023, 22:55
6	-32.996281	39.833757	166	10237	03-Sep-2023, 17:14
7	-31.791235	31.391328	187	10238	08-Sep-2023, 20:58

All floats were taken out of their crates and secured in the hydrolab within 24 hours of their deployment. The floats were connected to a laptop to manually change the Idle Timer Interval, then brought outside to sit in a bucket of salt water an hour before launch (Figure 9) to help fill the bottom compartment with water to shorten the sinking time and minimize collision risks with the ship. The caps were changed during that time, and thermistor probe covers were removed after the floats were relocated to the stern a few minutes prior to deployment.



After the deployment of 10241, the PI communicated that 9440 was having issues to communicate via satellite and requested that we tested all remaining floats for communication. All remaining floats were taken out and successfully passed the communication test.

All but one float launch went smoothly. The deployment method was identical to the GO-BGC floats. In one instance (10240), there was just enough tension on the line as the float touched the water to drag it slightly behind the ship. Because the float design causes it to spin when moving through water, the line became entangled. The ship had to be stopped and eventually the line became undone. Thanks to the bottom compartment having been pre-filled with seawater, the float immediately sank and did not hit the ship. After this event, we shortened the length of the line to three times the distance from the top of the railing to the water to minimize chances of causing drag, and paid extra attention not to hold onto the line.

Figure 9 – SQUID float 10236 soaking in saltwater secured to a ladder.

### 9.15.3 NOAA Drifters

Ten drifters were provided to be launched at approximate locations with historically poor coverage. PIs are Rick Lumpkin ([rick.lumpkin@noaa.gov](mailto:rick.lumpkin@noaa.gov)) and Shaun Dolk at NOAA-AOML ([shaun.dolk@noaa.gov](mailto:shaun.dolk@noaa.gov)). The stations closest to the target locations were selected and confirmed by the PIs. Drifter details and deployment information are available in Table 3.

Real-time data and visualization are available through the Observing System Monitoring Center (OSMC) at [https://viz.pmel.noaa.gov/osmc/?color\\_by=platform\\_type](https://viz.pmel.noaa.gov/osmc/?color_by=platform_type). More tools are also found at [https://www.aoml.noaa.gov/phod/gdp/real-time\\_data.php](https://www.aoml.noaa.gov/phod/gdp/real-time_data.php).

Table 3 – NOAA drifter details

Drifter number	Lat °S	Lon °E	Station number	Drifter ID	WMO ID	Deployment Date, Time UTC
1	-31.157183	104.951600	026	300534062785600	1601761	29-Jul-2023, 10:08
2	-31.157450	104.951400	026	300534062786070	1601762	29-Jul-2023, 10:09
3	-31.664845	87.762159	066	300534062785440	1601759	08-Aug-2023, 2049
4	-34.001939	73.126638	098	300534062786180	1601763	17-Aug-2023, 00:52
5	-34.001675	73.126964	098	300534062785490	1601760	17-Aug-2023, 00:52
6	-34.012219	62.269205	117	300534062785280	1601757	22-Aug-2023, 13:40
7	-34.012219	62.269205	117	300534062785430	1601758	22-Aug-2023, 13:40
8	-33.689477	49.790692	146	300534062785270	1601756	30-Aug-2023, 02:35
9	-32.997100	40.986796	164	300534062785150	1601755	03-Sep-2023, 02:51
10	-32.697720	34.122495	179	300534062784640	1601754	06-Sep-2023, 20:45

All drifters were brought on deck and unpacked from their plastic wrapping shortly before launch. All NOAA drifters were tossed overboard by two people, and all deployments went smoothly.

### 9.15.4 Directional Wave Spectra Barometric Drifters (DWSBD)

The Indian National Center for Ocean Information Services (INCOIS) provided 12 drifters to be launched at specific stations. The PIs were Suresh Kumar ([sureshkumar@incois.gov.in](mailto:sureshkumar@incois.gov.in)) and Venkat Shesu Reddem ([venkat@incois.gov.in](mailto:venkat@incois.gov.in)). DWSBD details and deployment information are shown in Table 4.

Table 4 – DWSBD details

Drifter number	Lat °S	Lon °E	Station number	Drifter ID	Deployment Date, Time UTC
1	-31.065294	105.275196	024	64600100	29-Jul-2023, 02:28
2	-33.999819	98.989166	045	64600120	03-Aug-2023, 14:01
3	-31.569258	87.194727	067	64600140	09-Aug-2023, 01:32
4	-31.187750	80.151100	080	64601210	12-Aug-2023, 07:23
5	-34.001553	73.127190	098	64600220	17-Aug-2023, 00:56
6	-34.002127	69.125523	105	64600230	19-Aug-2023, 02:23
7	-33.997539	63.979217	114	64600240	21-Aug-2023, 15:32
8	-33.845924	57.064532	127	64600310	25-Aug-2023, 06:11

9	-33.997645	54.172555	138	64600440	27-Aug-2023, 21:24
10	-33.610147	49.195562	147	64600900	30-Aug-2023, 09:52
11	-32.999516	43.907821	156	64600210	01-Sep-2023, 06:50
12	-32.997263	40.986399	165	64601230	03-Sep-2023, 02:52

The PIs were emailed 24 hrs before drifter launch at their request. At deployment time, drifter boxes were brought to the stern, the drifter would be unpacked and their magnet removed, then released over the side at ship speed between 1-2 kts.

## 9.16 Bio GO-SHIP

PI: Adam Martiny

Shipboard personnel: Yi Liu and Nataly Pineda

### 9.16.1 Particulate Organic Matter

Particulate organic matter (POM) samples were collected for particulate organic carbon (POC), nitrogen (PON), and phosphorous (POP). POM samples were collected approximately at 0600 and 2000 local time from the uncontaminated underway seawater system and pre-filtered (30 µm mesh) (107 stations). Samples were also collected using the CTD at 5m (43 stations). In total, 893 samples were collected (638 with the underway and 255 with the CTD). If the CTD collection coincided with one of the standard collection times, it would take that slot, otherwise, the CTD cast would be the second collection period as close to noon as possible. In total, 150 stations were sampled (underway and CTD). Each sample passed through a GF/F filter (nominal pore size 0.7 µm). An aspirator pump was used to pull water through the filters at a vacuum setting of -0.06 to -0.08 MPa. Six carboys were filled with 4-8L of water (volume biomass-dependent) and designated as follows: 3x POP, 3x POC/PON. POP filters were rinsed with 5mL of 0.017M Na<sub>2</sub>SO<sub>4</sub> to remove traces of dissolved organic phosphorous at the end of filtration. POC/PON filters were rinsed with 5 ml of Milli-Q water to remove excess salt at the end of filtration. Filters were folded and stored frozen at -80°C in pre-combusted foil squares.

All carboys were rinsed 3x with sample water before collection. GF/F filters and foil squares were pre-combusted at 500°C for 4.5 hours. Prior to the cruise, all silicone tubing, filter holders, and carboys were cleaned in soapy water, 10% HCL, and Milli-Q water. All filters will be shipped frozen and analyzed by the Martiny lab at UC Irvine. Gloves were used for all the steps mentioned above.

Due to the weather, there were 6 days when the CTD could not collect surface samples (5 m). A bucket method on August 3rd was used to collect surface seawater but during the filtration process, the water left a dark brown color as opposed to the green-yellowish color that is expected. This method due to unknown contamination was dismissed and water was collected using the underway system when surface samples could not be collected. During collection, 7 of the filters fell on the floor which had to be discarded and is included in the total amount of samples collected. On August 8th, the underway system was switched from collecting water from the bow intake to the sea chest intake, which was directly below the lab.

On August 16th, the CTD had to be re-terminated which prevented us from collecting CTD samples for that day. A total of 6 casts were combined with the chem-cast due to weather and time. In regions with high biomass, only 4 L of seawater was filtered for POM except for CTD collection, those samples were all 8 L. Methodology remained constant except for replacing tubing and spigots.

### 9.16.2 DNA

DNA samples were collected from the uncontaminated underway seawater system at 0600 and 2000 local time. Samples were also collected using the CTD ranging from 5 m to 1000 m. In total, 312 samples were collected (124 with the underway and 188 with the CTD). If the CTD collection coincided with one of the standard collection times, it would take that slot and the underway system would be used in the next station, otherwise the CTD cast would be the second collection period. In total, 165 stations were sampled (underway and CTD).

Each sample passed through a sterivex filter (0.22  $\mu\text{m}$ ). A 1 mL cryovial of DNA bashing beads was poured into the sterivex before filtration. A peristaltic pump was used to pump water through the sterivex filter. When using the underway system one carboy was filled with 8 L of water (volume biomass-dependent), during CTD collection 4 carboys were filled with 8 L with the corresponding water depth. Water depths included 5m, 100m, 200m, and 1000m. After filtration a syringe was used to remove any excess water in the filter, critoseal was used to seal one end of the sterivex then 1000  $\mu\text{L}$  of DNA/RNA shield was pipetted into the filter and sealed with a cap. Filters were stored frozen at  $-80^{\circ}\text{C}$ .

Due to weather, two separate surface samples had to be taken from the underway system, and the remaining depths were combined with a chem-cast if an individual cast was not possible. There were a total of 12 combo-cast. Starting August 30th we began collecting an additional DNA sample from the underway system, totalling 7 per day.

### 9.16.3 HPLC Pigments

HPLC samples were collected during CTD at a depth of 5 m and pre-filtered (30  $\mu\text{m}$  mesh) (48 stations). In total, 49 samples were collected (2 with the underway and 47 with the CTD). 1-2 L of water was stored in an HPDE bottle rinsed 3x with DI and sample water before being filtered onto 25mm GF/F filters using a vacuum pump set at 100 mmHg. Filters were folded twice and stored frozen at  $-80^{\circ}\text{C}$  in 1 ml cryovials. Sample bottles and funnels were rinsed with DI 3x after each sample period.

Two samples, July 25th and August 16th were collected using the underway system due to weather issues preventing a surface cast from being taken. From August 5th to the 9th there were weather issues that caused the collection from the CTD to be leftover surface water, resulting in only 1 L being taken.

## 10 Appendices

### 10.1 Appendix 1: Cruise narrative

#### 10.1.1 Update 1

- Mobilization
- 23 CTD stations (22 to full depth) and 6 bio stations completed
- 2 floats deployed: 1 SQUID float and one BGC Argo float (*The Exceleator*)
- Some weather time, some tech time
- Transient tracer team moved to hydro lab after a wave damaged and flooded the lab container

Greetings from GO-SHIP cruise I05\_2023 (a.k.a, RR2308) aboard the Scripps Institution of Oceanography research vessel Roger Revelle! We are well underway and things are starting to come together. We are currently busy doing station work, and everyone is becoming more comfortable and efficient in their parts of the overall effort.

**Mobilization** went well, though we have few pictures to show from that time because we were moved to a port facility that forbids such. The move was to accommodate the shore crane we needed to load our largest items aboard. This facility was a bit out of the way and had some access challenges, but these challenges were overcome with rental cars, rideshare apps, and a great deal of patience from the subset of our team that was visiting us in port to help us stage for the cruise. In the end we sailed with most of our planned compliment of oceanographers. We did have two team members withdraw due to emergent issues, but Aurélie Moulin was able to join as a “floats” watch-stander on short notice, and Eva Capilla Garcia, one of our planned CTD watch-standers, bravely took on an empty spot on the pH/TA team. My gratitude goes out to all for their patience and flexibility in making this cruise happen.



### *The science party on I05*

**Station work** started in earnest and we’ve already started matching projected times for many of our stations, which is a bit of a feat in week 1 when people are still leaning their roles. However, we have 196 stations planned in 55 days, so we will need every bit of efficiency that we can muster—as well as a lot of stamina and a whole lot

of luck—to complete our ambitious plan. Like most marathons, this one began with a bit of a faster pace than would be sustainable, as the closely-spaced continental slope stations brought aboard samples more quickly than they could be measured. Mercifully, we were quickly in deeper waters (as I type this our CTD is below 5000 m depth), and the greater wire times and longer transits have helped all our teams catch up and catch their breath.

The bio GO-SHIP stations have also started, with separate casts at a subset of the stations where we are doing CTD casts down to 1000 m depth. These casts are intended to measure metagenomic information in seawater, as well as particulate organic matter and pigments. Each of these analyses benefits from a full Niskin's worth of seawater (i.e., ~11 L, or how much we can trap in each of the 36 bottles we trigger at different depths), so in most instances it makes sense to do this as a separate cast each day at noon. In shallower waters we will combine the two into a single cast of the rosette, since we won't need all 36 bottles to fully sample the shallower water column.

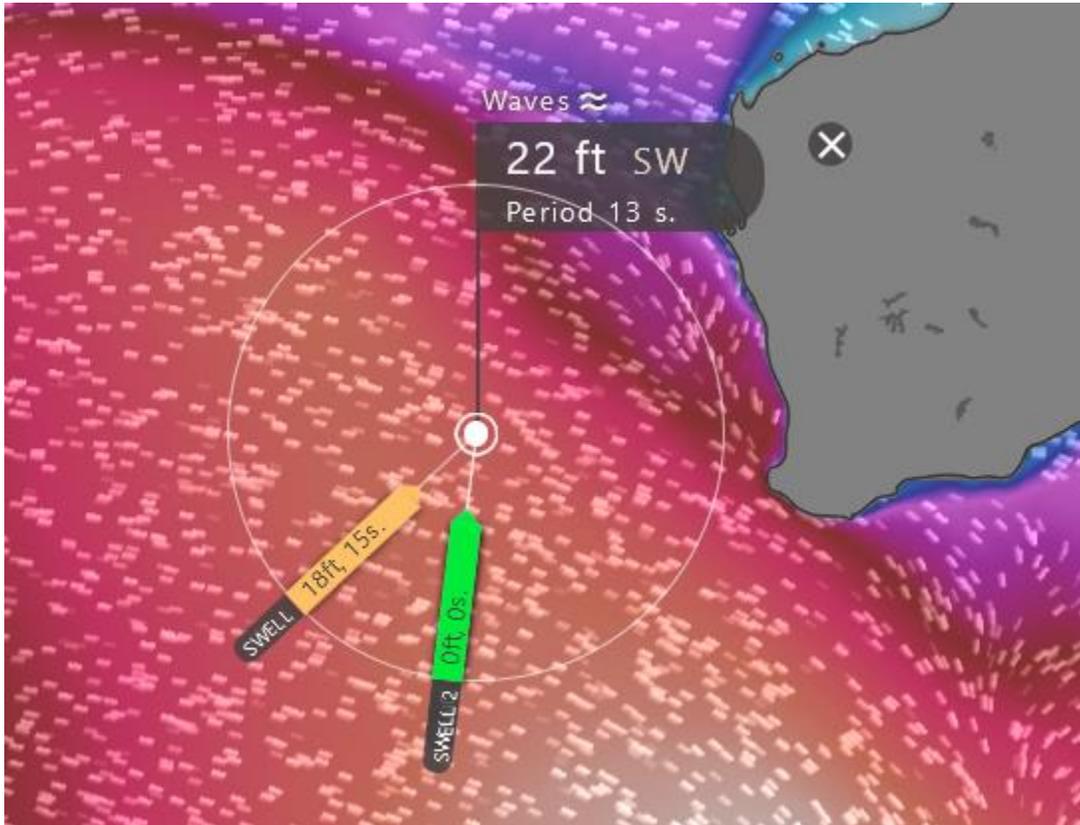
While the CTD and rosette package worked flawlessly at the start of the cruise, some modulo errors appeared on station 7. More crept in in small quantities over the next several stations and trouble shooting commenced. Ultimately, at station 12 the CTD pumps began to cycle while at depth, so the package had to be recovered for intensive troubleshooting. The issue was identified and fixed after ~12 hours and several test casts, part swaps, and re-terminations. The CTD has been working brilliantly since.

**Deployments** of floats and drifters have started with two floats already deployed, one planned for this current station, and two drifters planned over the next degree of longitude. We heard the 'happy' news that our first float deployment broke the "Adopt-a-float" website because the earliest organizers of the outreach effort hadn't imagined (or coded for the eventuality) that the program would someday exceed 500 adopted floats. However, our deployment of *The Excelsior* pushed them over that threshold and they had to briefly scramble to fix the site before celebrating the amazing milestone.

**Weather** has also been a factor, and this could be a recurring challenge for this cruise. The previous occupation was in the Southern Hemisphere's autumn, and we are attempting this line during the Austral winter. While this isn't a Southern Ocean cruise, the behemoth storms that perpetually churn through the gelid and wind-whipped wintertime ocean just south of us lash out at the subtropical latitudes every few days. At 32°S, we have little recourse when this happens but to turn the vessel to minimize the rocking and the pounding and wait until things calm down enough to do work again. A particularly problematic combination occurred on station 13, where a 3.1 knot current (comparable to the Gulf Stream) was trying to push the CTD package under the Revelle relative to the heading dictated by the heavy winds, which is a dangerous situation for the CTD-sensor package. As such work had to be paused on that station with only a small portion of the CTD cast completed. With more than a day of this weather forecast to continue, we opted to proceed toward the next station where the current was expected to be more manageable (if not the winds), thinking we could return when the winds let up.

Unfortunately, en route, an unusually large wave swept over the port side and damaged and **flooded the transient tracer (a.k.a., CFC) van**. Thankfully, both people within emerged unhurt, though some of their equipment was damaged. We hove to (i.e., stopped the boat and oriented ourselves to minimize the rocking), and helped them dig out for several hours. The team and their equipment have since been relocated to the hydro lab, where the system is once again running standards to recalibrate. This remarkable recovery, from standing in 6" of water a few days prior, is due to heroic efforts from PI Warner and the team, with help from the ship's and scientific crew relocating and re-securing gear.

Having seen the currents diminish and change direction as we moved along the transit just before the wave, we opted to return to the line at the midpoint of the originally planned locations for stations 13 and 14, declaring this to be the new station 14. Thus we have only a partial CTD cast for station 13 at the original location, and ~45 nautical mile spacing for bottle samples between stations 12 and 15. However, this allowed us to continue to make progress despite the lingering strong current at station 13.



Wave forecast for 8/2/2023

Soon the winds let up and we've since been making good progress into the open ocean. However, our forecasts show that we could be due for more wind and waves within a couple of days. We'll continue to work as we are able and try to rest through the rocking the remainder of the time. I'll look forward to providing future updates!

### 10.1.2 Update 2

- 57 stations (34 new since last update) completed with 15 stations (9 new) with biological measurements
- 4 floats (3 new) and 3 drifters (3 new) deployed: 1 SQUID float, two biogeochemical Argo floats (*Gator* and *Hooter*), 2 "Directional Wave Spectra Barometric Drifters" (DWSBDs), and 1 drifter from the National Oceanographic and Atmospheric Administration (NOAA).
- 21 hours of weather time
- Transient tracer (CFC) team operational again
- Can't get enough I05 updates? Check out the [I05 blog](#) with updates from scientists and crew appearing at the bottom as they are written.

We have had a productive week, though we were hit by several days of rough weather, including a 21 hour period in which ~6.8 m (22') waves prevented us from conducting our normal station operations. Then we had several days of calm and now a squall is roaring by just south of us; the boat is currently rocking in 28 knot winds, but thankfully the confused wind direction has only built up 3.6 m (12') waves. Station operations are continuing, though slowly to minimize tension spikes on the 32mm diameter cabled wire that connects the several ton Niskin-rosette/sensor/frame package to our heaving boat.

The I05 cruise has a very ambitious schedule, with a long swath of Indian Ocean to cross and several regions of planned higher resolution sampling. As such, the various weather delays from this week and last already have us thinking about ways to preserve time for future work. We've enacted several measures to save time that leverage the immense 36 bottle capacity of our sampling rosette. However, to explain the rationales behind these measures we should first segue into an explanation of why the I05 cruise track has so many seemingly-random wiggles (see above).



*Some of the great volunteer artistry our CTD watchstanders did on behalf of the Adopt-a-Float program, where various school classrooms decorate and name a float, and then incorporate the data from that float into their curriculum. These floats are designed to float at ~1000 m depth, then sink to ~2000 m before rising to the surface, making measurements along the way. Then they report their data by satellite and sink back down to start the cycle again 10 days later. Photo credit: Aurélie Moulin.*

### **I05 bathymetry and GO-SHIP**

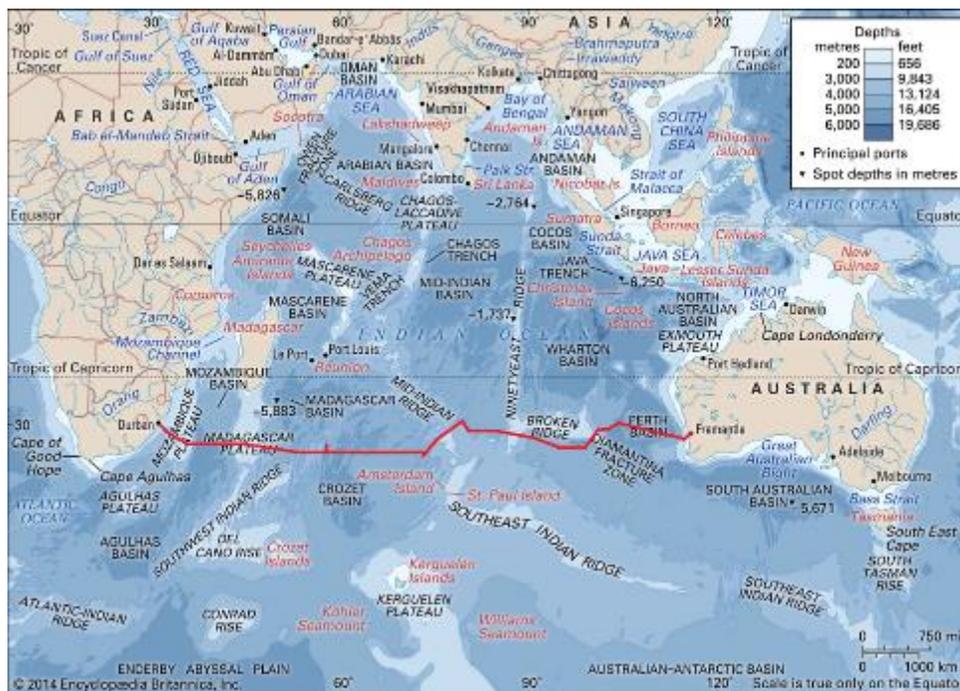
The non-linear I05 cruise track is a result of the rugged seafloor of the Indian Ocean. Like most ocean basins, the deep Indian Ocean is carved into deeper basins separated by shallower ridges where the seafloor is currently (or was previously) being ripped apart by tectonic forces.

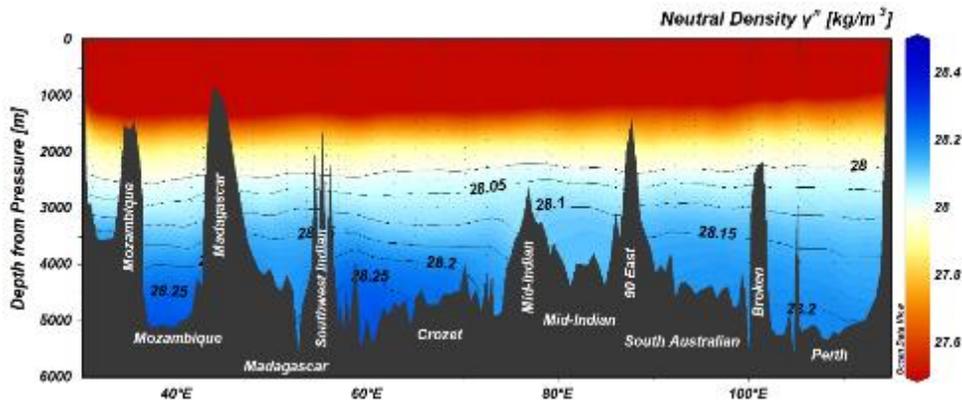
As GO-SHIP is one of the only measurement programs that permits long-term deep ocean monitoring, it is important that we measure the deepest and densest waters in the ocean wherever possible on our sections. Here, these waters form to the south when surface waters cool and slide down the Antarctic Continental shelf. From

there, these “Antarctic Bottom Waters” flow northward hugging the ocean floor, expanding out through the other ocean basins, and sliding below (and mixing with) their slightly warmer and saltier cousin water mass (that originates from salty Gulf Stream waters being cooled by the boreal winter in the far northern reaches of Atlantic Ocean). However, the deep Indian Ocean looks a little bit like an ice cube tray designed by a mad scientist, so these bottom-dwelling deep waters can’t flow directly from one basin to another. Instead, they flow into the various ocean basins and rely on gaps in the ridges that separate the ocean basins to exchange their coldest and deepest waters. Of the basins we cross, the densest waters are found in the Mozambique and Crozet basins, because these two basins have a more or-less unobstructed bottom water path from Antarctica.

The ridges are also important because they interact with the Coriolis force to guide the flows of deep ocean waters, and the rough topography induces vertical mixing between water masses when water masses flow around and over the mountainous subsea ridges (similar to how updrafts and turbulence occur when winds move through mountain ranges). As a chemical oceanographer, a naïve generalization seems to be that few things get physical oceanographers more excited than vertical ocean mixing, which is how deeper dense waters exchange with the overlying more buoyant waters masses. This exchange is a critical piece of the puzzle of how deep waters form, move, and are eventually destroyed in the interior of the ocean, thereby making room for new cold waters to fill the ocean depths.

Given how remote and isolated these deep ocean basins are, it is alarming that scientists have detected both warming and freshening of these water masses over the last several decades using GO-SHIP measurements. The warming is a simple consequence of climate change from heat-trapping human CO<sub>2</sub> emissions to the atmosphere, and the freshening is thought to be due to the input of freshwater from melting Antarctic ice. Human induced climate change is truly a global phenomenon with no part of Earth’s surface and oceans untouched. It is part of GO-SHIP’s mission to continue to measure these changes, including on I05.





(TOP) Map of the I05 cruise track superimposed over a labeled diagram of the deep Indian Ocean from the online [Encyclopedia Britannica](#). (BOTTOM) Section of neutral density anomaly along the I05 cruise track as measured in 2009 with the various ridges (vertically labeled) and basins (horizontally labeled) indicated. Neutral density anomaly is used to keep track of the relative density of various water masses.

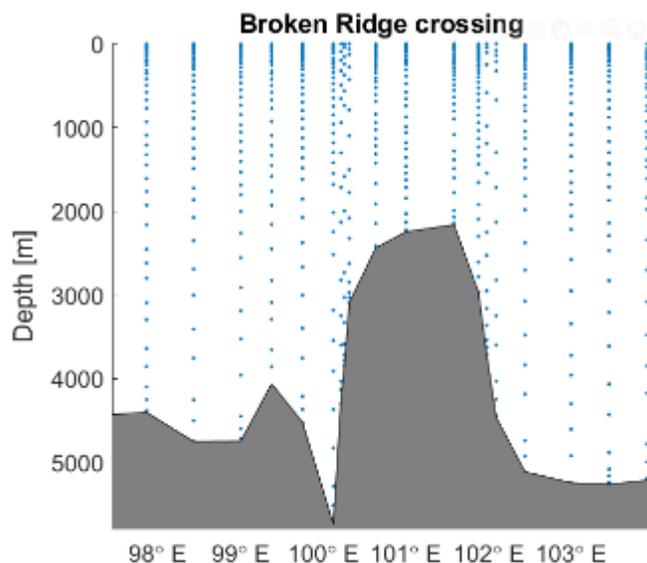
All of that noted, if our cruise merely went straight from Fremantle to Durban at 32° S, then we would follow along the shallowest parts of the Broken Ridge and miss some of the deepest and most interesting parts of the Perth, South Australian, and Crozet Basins, so instead we wiggle to try to measure seawater changes in these deep basins. In a few places, the result is our cruise track runs over a steep ridge at a nearly right angle like a speed bump. This causes us to slow down a bit by putting our stations closer together: the interesting flows that follow bathymetric features mean that we need to increase our CTD-O<sub>2</sub> (which measures salinity, temperature, depth, and dissolved oxygen content), Chipod (which measures temperature microstructure and allows inferences of turbulence and vertical mixing), and LADCP (which measures subsurface ocean currents) sensor resolution during these ridge crossings.

### Time saving measures

The need for higher resolution sampling during ridge crossings is primarily due to our greater need for sensor and (to a lesser degree) bottle samples in the *deep* ocean. However, the reason that we need to slow down during these crossings is because of the need for additional time to sample and analyze the extra bottle measurements that come from all depths of these closely-spaced stations, as well as the time needed to prepare the rosette to go back into the water. Recognizing that the *surface* samples are less of a priority during these ridge crossings, we opt to conduct the stations as normal, but only trigger bottle samples at full vertical resolution from the seafloor to the depths just above the depth of the ridge itself. This allows our analysts to focus on the most interesting parts of the water column while saving time and capacity (e.g., empty bottles) from the upper parts of the ocean for the next station with nominal 30 nautical mile spacing. This also allows our CTD watch standers to have the sensor and bottle package (very nearly) ready for deployment to begin collecting sensor data by the time we get on the next station (which is a shorter wait than usual due to the close station spacing).

Fortuitously, three of our recent biological stations occurred during our four completed ridge crossings. At these stations, we used the Niskin bottles that usually capture surface seawater (for the analyses that were skipped with

the close station spacing) to replace the Niskins needed for the biological casts. This saved us the time that we had previously been using to conduct a second biological cast to 1000 m depth.



*Sample depths crossing the Broken Ridge in 2023, with higher resolution near the bathymetric changes.*

Going forward, we plan to use a similar strategy to claw back some time lost to bad weather, forgoing some of the daily separate biological casts (collocated with ~1/4 of our chemistry stations) by dedicating a subset (currently 4) of our 36 bottles to these biological properties. We are able to do this even on the stations spaced by the nominal 30 nautical miles because the majority of our chemistry analysts cannot sample all the bottles on a 36 position rosette at every station. We will revert to doing separate biological casts if timing permits, which would slow down the rate of sample acquisition and allow our chemistry analysts more opportunity to keep up with our brisk pace.

## Data

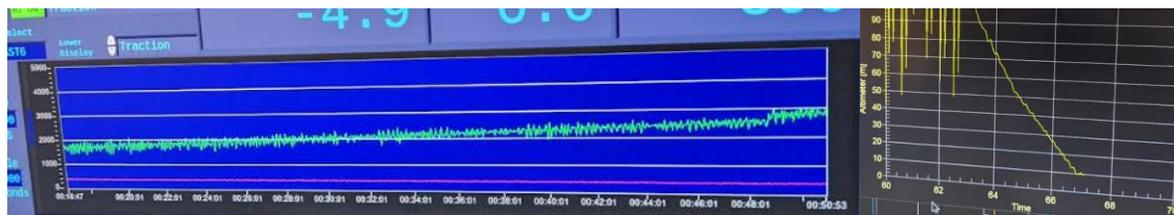
An upside to the weather delays is that our analysts were able to get fully caught up on measurements and then use some of the remainder of the time to work up and submit their data. Even the Transient Tracer team managed to finish their sample backlog *after* rebuilding many parts of their measurement system in the Hydro Lab (see: last week's wave). Expect some early results in next week's update, but my preliminary dive into the new measurements already has me excited about the high quality of data being produced by this team of amazing scientists.

### 10.1.3 Update 3

- 89 stations (32 new since last update) completed with 23 stations (8 new) with biological measurements, 6 of which were from separate bio casts.
- 6 floats (2 new) and 7 drifters (3 new) deployed: 1 SQUID float, 1 biogeochemical Argo float (*Sweet Caroline*), 2 "Directional Wave Spectra Barometric Drifters" (DWSBDs), and 1 drifter from the National Oceanographic and Atmospheric Administration (NOAA).
- ~0 hours of weather or mechanical delays!

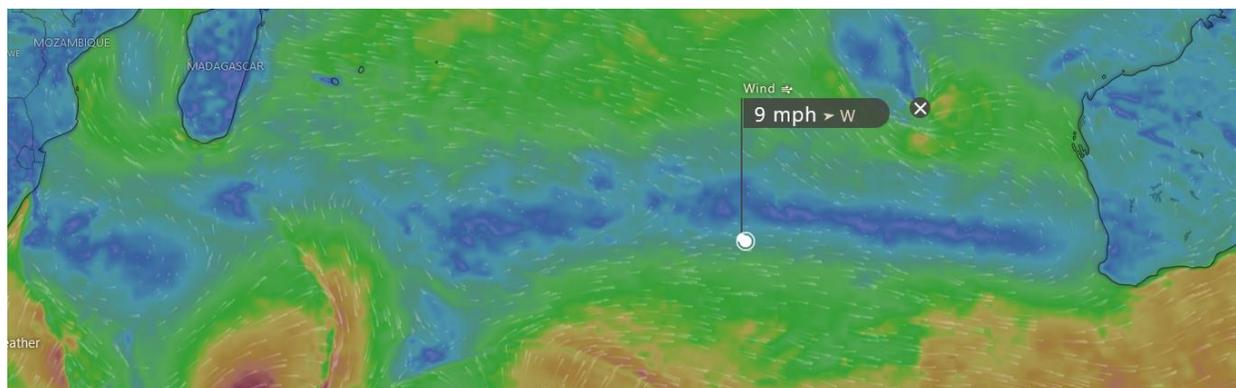
- Can't get enough I05 updates? Check out the [I05 blog](#) with updates from scientists and crew appearing at the bottom as they are written.

All good news this week: The clouds parted before us and we were treated to a full week and then some of smoother seas, quick transits between stations, efficient deployments, and the nearest thing to sunbathing weather that we could hope for in the austral winter. Our scientists and equipment are hard at work, and we are moving briskly through stations. That's really the whole update!



*These pictures might not mean much to most people, but they are almost certain to make an ex or current chief scientist smile. On the left we have the wire tension readout showing how much stress we are putting on the wire holding up our package of equipment (very low or very high numbers are both problematic) and on the right we have the altimeter readout showing how far that package is from a crash landing on/into the usually-muddy seafloor (we need to get within 10 m of the seafloor, but never touch it). When the boat is bobbing or rocking, the wire causes the package to bob up and down, both of these lines become much wigglier, and the chief scientist becomes stressed. The package of sensors and bottles is worth as much as several James Bond's cars tied together (before Q's aftermarket modifications), so we try to be as good to it as we can be while repeatedly dunking it under several kilometers of salty water.*

When the seas and skies are calm, the boat can safely zip between stations, the winch can safely spool out wire at our maximum rate (of 60 meters per minute), and we can get the rosette and sensor package prepped and waiting on the deployment platform (which is exposed to waves in poorer weather) even before we get on station. Therefore, when everything is going our way, we can haul up a truly impressive amount of water in a week's worth of sampling. However, we eventually run into another limitation: our chemists still have to analyze everything brought aboard before they run out of sample bottles, a feat that is further challenged when we are relentlessly asking everyone to leave their analysis equipment to come collect new samples. Thus, this week had us looking for a bit *more* time between stations. Fortunately, we could make everyone a bit happier this week by reinstating the separate bio casts for the last ~6 days.

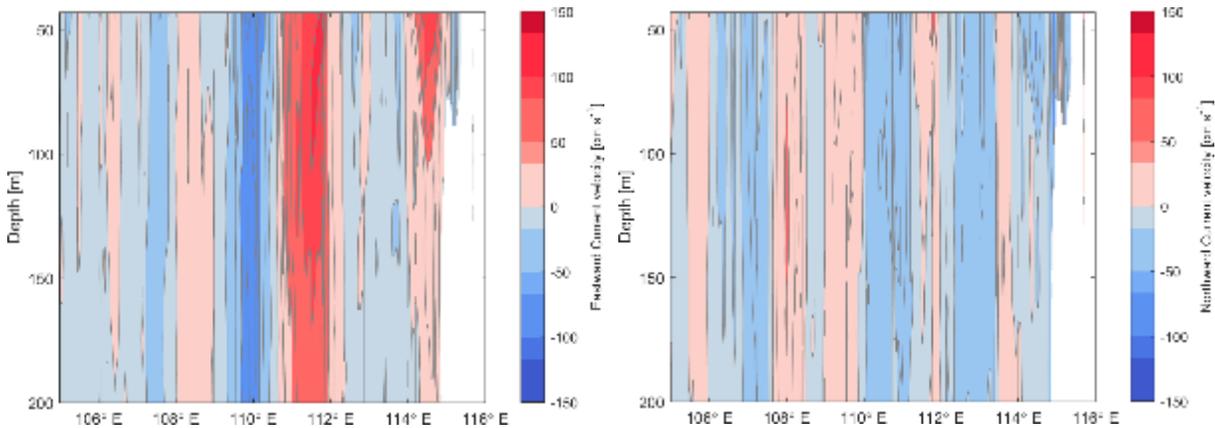


*The entire I05 cruise track was briefly blessed with becalmed skies, though we've had a bubble of good weather even when the rest of the track did not.*

I promised some data this week and so we will briefly turn back to what happened at station 12, when we saw very strong currents. Next week we will continue with some deep ocean temperature changes from Kay. I'm hoping the week after I'll be able to show some (very) preliminary anthropogenic carbon accumulation estimates relative to 2009.

### **Strong currents at stations 12 and 13 (added by Kay)**

If you remember from the week 1 update, we experienced very strong currents at stations 12 and 13, which prompted us to continue to station 14 because we could not safely deploy the CTD at station 13. This isn't an area where we would expect strong currents – it was around 32° S, 112° E. The strong currents of the Leeuwin Current are generally confined closer to the coast, and we would expect relatively weak currents across the subtropical gyre. However, at stations 12 and 13 the shipboard ADCP measured eastward currents over 1.2 m/s! These strong currents were seen over the entire upper 200 m. There also appeared to be a strong bottom current at station 12: when the altimeter read 15 m from the bottom, we let out another 10 m of wire and the CTD depth did not increase at all. We repeated with another 10 m of wire and the CTD depth still did not budge. At this point, we had a large amount of wire out and decided to take 15 m from the bottom as our deepest bottle. As we continued traveling west towards station 14, the currents turned westward and were still relatively strong (about 0.5 m/s). Sea surface temperatures at station 12 were significantly warmer than climatology in July, based on Argo data. Strong isotherm tilt was present across the surrounding stations, consistent with geostrophic balance. We hypothesize that this was a warm core Leeuwin Current eddy, which generally propagate westward (with the ship's motion, as we transited from station to station), explaining the long period when we were in strong currents. Lowered ADCP data (coming soon) will give us more insight to the structure of the currents with depth and hopefully give us a better measurement of the near-bottom current.



*Shipboard ADCP data highlighting the very strong east-southeast-ward currents near 111° to 112° E, with slower west northwest ward currents just to the west. The band of red in the panel on the left corresponds to the stations where the currents were pushing the CTD underneath the Reville.*

Okay, that figure was the data promised. Now, for the rest of this update I'll write about something that gets me and *very few* other people excited:

## Data QC

(Feel free to tab over to the blog entries from our scientists at this point, I won't know or mind.)

GO-SHIP takes data quality very seriously. Our sensor package has two sets of temperature/pressure/conductivity sensors as well as a third reference temperature reading. Our salinity and oxygen measurements on the sensor package are double checked by direct laboratory measurements from every bottle, and the disagreement between these records can be a smoking gun for the rare (but inevitable) instances when our bottles close at a different depth than we intended. Relatedly, we put a lot of emphasis on quality control for all of our measurements, and our analysts have been quality controlling the data that they are producing as they are making measurements and submitting them to our joint data file. It is yet another task that we ask them to do to that becomes harder when they are dealing with an unending cavalcade of new samples.

Between stations, I've been experimenting with software that can help with data quality control on future cruises. The oceanographic community has recently been creating algorithms that can estimate seawater chemistry measurements from one another. For example, if the measured salinity is 34 ppt, the temperature is 4.25 °C, and the latitude/longitude/depth are .... etc., then the algorithm will guess that the dissolved inorganic carbon (DIC) should be, let's say, 2330  $\mu\text{mol kg}^{-1}$ . These algorithms use regressions and various machine learning approaches and are surprisingly good at roughly estimating what the values will be based on past measurements. These estimates are still no substitute for a new measured value and they can never tell us anything truly new about the ocean or how it is changing, but it's still a neat party trick (provided your partygoers are easily impressed and have access to analysis instrumentation to confirm the accuracy of the guess, as they should). That said, one use the algorithms do have is that they are great at revealing when someone miss-typed, e.g., 2234 instead of 2324  $\mu\text{mol kg}^{-1}$ , because the algorithm guess will suddenly be *much* more incorrect for that sample than it was for the samples measured nearby (from off by 6 to off by 96  $\mu\text{mol kg}^{-1}$  in this made-up example that is in no way taken directly from my past experiences messing up data entry while sailing as a DIC analyst). Dr. Larissa Dias is a postdoc working in my research group on, among other things, turning some of these algorithms into code that will assist with cruise data set quality control by calling extra attention to anomalous values, and I've been happily experimenting with some of the associated algorithm logic at sea.

The scientists out here are doing a great job of QC-flagging the anomalous values already, so I'm more hoping their work will help mine rather than the reverse. As anyone who has worked with machine learning knows, there are few things better for algorithm development than well-labeled data sets. My hope is that we can use the estimation routines to generate offsets between the measurements and the estimates, and then we can train machine learning routines that relate those offsets to the expert flagging provided by these skilled scientists (and scientists on past GO-SHIP cruises) to predict how likely an experienced analyst might be to flag a given future value as questionable. The trained up algorithm can then help call the attention of future analysts—in particular analysts on non-GO-SHIP cruises that don't have the benefit of world class analysts doing their quality control—to measurements that could warrant extra QC attention. Relatedly, in past analyses of ocean change I've incorporated datasets from older cruises where the information has been lost about whether quality control was done at all. In these cases, such machine learning tools could do a first pass at flagging outliers even without the benefit of being able to track down the analysts to ask them about their measurements.

**More to come in future weeks**



*Research Technicians Jessica McLaughlin (left) and Royhon Agostine (right) awaiting a CTD recovery while enjoying the glow of an Indian Ocean sunset. Photo credit: Jomphol Lamoonkit*

#### **10.1.4 Update 4**

- 115 stations (26 new) completed with 31 stations (8 new) with biological measurements, with the new bio measurements from separate casts.
- 8 floats (2 new) and 12 drifters (5 new) deployed: 1 SQUID float, 1 biogeochemical Argo float (*Nautifish*, as in nautical and as in “not a fish”), 3 “Directional Wave Spectra Barometric Drifters” (DWSBDs) and 2 NOAA drifters.
- ~5 combined hours of assorted weather and mechanical delays.
- [I05 blog](#)

*Jaeden Hansen’s rendition of the Nautifish. Clipped from a photo by Aurélie Moulin.*

Another productive week is behind us, and we’ve weathered 1.5 bouts of stronger winds (we are still coming out of one) and a long series of >4000 m deep casts. The winds never prevented us from working outright but they did churn up the ocean enough to make us move more cautiously during transits and downcasts. For one station we sampled in place (without transiting to the next station) because the waves were threatening to inundate the staging bay once we started our transit. We also took a brief pause to replace an electrical termination that had been with us since a station in the early teens. Mostly, however, we’ve had few issues this week and we’ve been making good time. The wide, deep, and flat-bottomed Crozet Basin is giving us many similar stations in a row to get into our grooves. Progress has been efficient enough that we’ve continued doing separate bio-casts throughout the week.

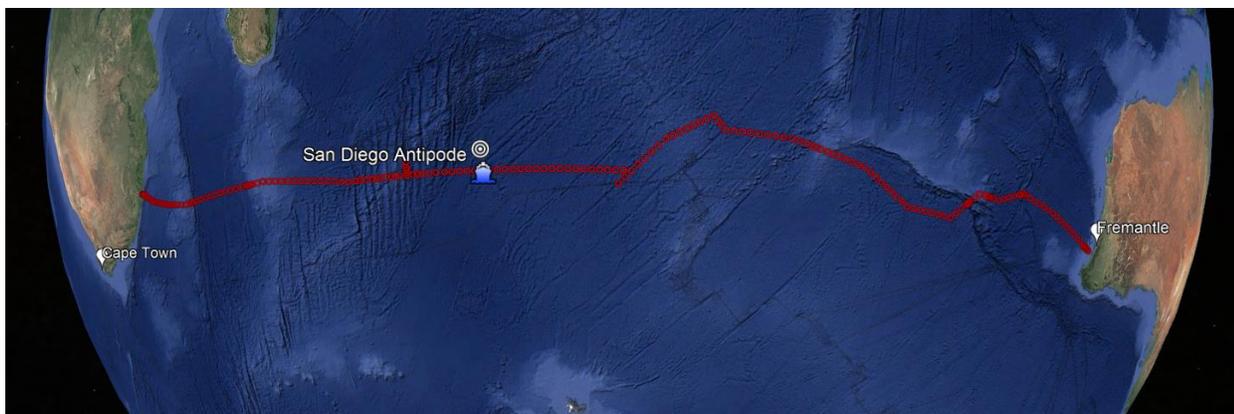


*(Left photo) A non-tournament practice ping-pong game between Kirsten Petzer (near left), Jaeden Hansen (far and left), Lydia Pinard (near right), and Nirmala Nair (far right). Clipped from a photo by Jom Lamoonkit. (Right photo) Andrew Collins (left) and Daniela Nestory (middle) enjoying the midday sun. Photo by Nataly Pineda.*

### **Life at sea and staying sane**

A cruise this long has parallels with running a marathon... though arguably without training for it first. Life on a research vessel can be exciting and adventurous, but recall that our team of scientists has been working 12+ hour days (84 hour weeks) nonstop for, as of today, over one month. Working on a research cruise is a feat of endurance, if of a different kind than a marathon. This [blog by Sara Kurth](#) (a running coach on the internet) breaks down the stages of running a marathon, and, if the analogy holds, then we're moving from "the Middle Miles" and into "the Dark Times." Sara cautions us about the "excitement wearing off" as well as "hitting the wall." She suggests we stay in the moment, and I think our team out here is doing that well. A ping-pong tournament is underway, an informal book club seems to have sprung up, there's a "high-stakes" betting ring focused around predicting future-station mixed layer depths, there are gatherings at the sides of the boat whenever sea life is spotted, and there are several personal science projects ongoing with some already using the data from this cruise. In addition, there are crafts projects, there are people learning languages and how to tie knots, there are board game nights and card game nights, and there's even an off-shift Dungeons and Dragons campaign. People are working on plans for the future as well: making travel plans, drafting conference abstracts, sending in job and internship applications, and writing funding proposals. Personally, I'm winding down before bed learning to read Tarot cards.

Generally, these are weeks where it is important to find our joys where we can, and to focus on how far we've come rather than how far we have yet to go. When I find myself thinking of who and what I am missing from home, I try to do so while sitting out on the bow and listening to the forceful and persistent growling of the winds whipping past the *Revelle*. It's a rich sound that reminds me of the joys of this calling, and the privileges of getting to witness remote parts of the world.



*Speaking of remote, the RV Revelle is almost as far from home as possible right now. As I write this from station 116, the antipode for her berth at the Nimitz Marine Facility in San Diego—or the place on the exact opposite side of the globe from her home—is less than 2 degrees north of us.*

Last week I said we'd focus this week on temperature changes and the week after on carbon, but I since remembered that the carbon accumulation signal should be relatively constant across the whole I05 section (not uncommon for the East-West sections) whereas there might be interesting and different temperature changes going in each basin. So, we're pushing temperature back another week to finish up more of the section and this week we'll talk about:

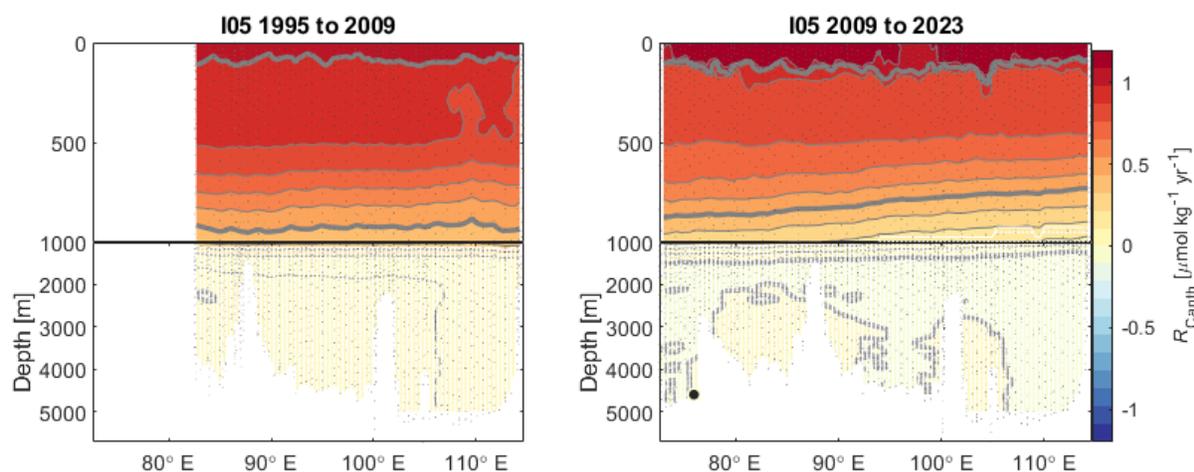
### **Anthropogenic carbon**

One of the goals for GO-SHIP is measuring decadal changes in the ocean “anthropogenic” carbon distribution, which is the carbon in the ocean because of human CO<sub>2</sub> emissions. Humans are emitting enough CO<sub>2</sub> gas each year to fill the Grand Canyon from floor to rim ~4.5 times over. The ocean is responding by dissolving some of what we are releasing, currently about a quarter of our emissions. This is slowing global warming by removing this heat-trapping gas from the atmosphere. On long timescales, ocean circulation will allow the ocean to take up an even larger fraction, and the ocean carbon cycle even has the potential to eventually mitigate most of our emissions... provided we can wait many thousands of years for the ocean carbon cycle to fully respond. There are many teams of people working on ways to speed up these responses (shameless plug for [some news](#) and [a video](#) from collaborators on one of our projects), but the distant potential success of these efforts still requires that we first find and implement ways to power our civilization and generate energy without emitting more CO<sub>2</sub>.

Returning to GO-SHIP: With the ocean soaking up a quarter of human CO<sub>2</sub> emissions, ocean anthropogenic carbon uptake should be among the strongest signals of global change that we can measure on GO-SHIP cruises. However, there is also natural variability in the dissolved inorganic carbon concentration of seawater near the ocean's surface, so it can still be difficult to isolate the anthropogenic carbon uptake when simply differencing measurements from one decade to the next. Fortunately, the things that make dissolved carbon change (such as shifts in ocean circulation patterns and the growth and decay of plankton and other sea life) also change many of the other measurements that we make along GO-SHIP cruises. This allows us to leverage another GO-SHIP strength, having many different high-quality measurements on the same seawater, to separate out the changes that are the result of human emissions from the changes that have occurred naturally. This is a topic that is near to my heart and some of my previous work focused on developing methods for teasing apart these signals.

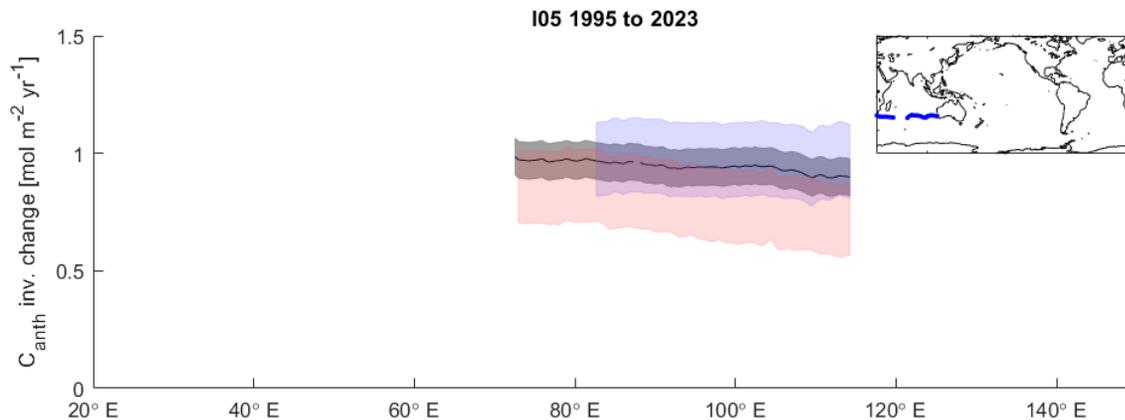
The I05 section is one of the largest gaps in our record of the changing ocean anthropogenic carbon inventory due to the long time that has elapsed since the last occupation of this line in 2009. A few years back I decided to pause an analysis of anthropogenic carbon in the Indian Ocean because the statistics would be much stronger with the next (i.e., current) I05 record completed, and this is among the reasons that I enthusiastically volunteered to participate on this cruise when the ship time was made available. This is extra exciting for me, as this is the first time I've been able to confidently detect changes using only GO-SHIP cruises that I was on (I sailed on the 2009 cruise as a pH analyst).

So, what are we seeing?:



*Preliminary! Anthropogenic carbon accumulation along the I05 line between the earliest occupations and the previous occupation in 2009 (left) and a preliminary version of the same estimate made for the period between the 2009 cruise and our current occupation (right). The red bands near the surface reveal that, as is seen most places, the accumulation rate is greatest near the ocean surface. The areas covered in white dots (mostly in the lower parts of the panels below 1000 m) indicate places where the signal cannot be confidently separated from the noise inherent to the many measurements and calculations that are used to produce these estimates. The section on the left is shorter because the viable cruises for this analysis had a gap in the earliest occupation. It is pretty rare to be able to confidently detect accumulation all of the way down to 1000 m, but I05 is just north of the Antarctic Intermediate Water and Subantarctic Mode Water ventilation latitudes in the Southern Ocean, and these water masses are among the only ones that fill up these “intermediate” depths in the Southern Hemisphere. Thus, the waters at these depths along I05 have seen the atmosphere comparatively recently. Estimates are produced using the CAREER approach (Carter et al. 2019).*

If you stare hard enough at these rates of change, there is an indication that the accumulation rate is slowing down. This is consistent with recent global findings as well as what we might expect when we consider that the ocean becomes less efficient at absorbing CO<sub>2</sub> the more it absorbs. However, one of the most difficult challenges for analyses like these is knowing how much confidence we can put in the changes that we observe. When we plow through the statistics implied by the uncertainties in the measurements we get inventory change estimates like the following “column inventory” changes.



*Preliminary! Column inventory changes—or changes added up across all depths in the ocean—for the period from 1995 to 2023 (black line with uncertainty ranges) and the uncertainty ranges for the period from 1995 to 2009 (blue band) and from 2009 to 2023 (red band). Forgive all of the wasted space in this figure... I wrote the code anticipating having the full section finished.*

We can see that indeed the new red band is lower than the older blue band which would imply a slowdown, but the fact that they overlap implies that we cannot distinguish the rates of accumulation to high statistical confidence. Thus, this one section comparison is not enough to conclude that the accumulation rate is slowing down significantly. Fortunately, the statistics are improved when we consider changes along many different sections at once, and this is what I hope to do in my planned Indian Ocean analysis (and this possibility is another strength of having the full network of GO-SHIP cruises). However, it will have to wait a bit longer... A proper analysis requires fully quality-controlled measurements, and it will be about 6 months after we get back on shore before that process is completed and the final measurements are made (freely and publicly) available. I'm nevertheless updating my analysis frequently at sea with the preliminary numbers (and looking at some of the other recent Indian Ocean cruise measurements) just out of curiosity.

#### 10.1.5 Update 5

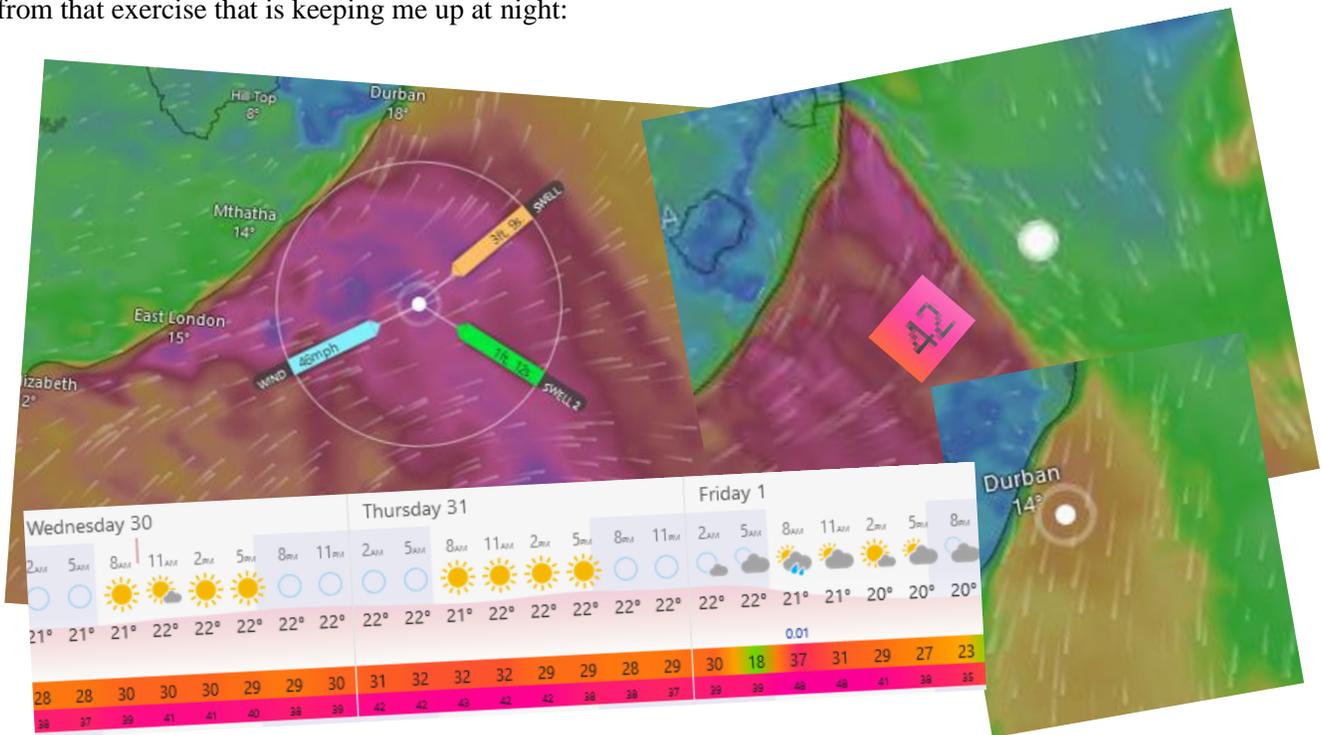
- 147 stations (32 new) completed with 38 stations (8 new) with biological measurements, with the new bio measurements from separate casts.
- 10 floats (2 new) and 18 drifters (6 new) deployed: 1 SQUID float, 1 biogeochemical Argo float (*Saturna Island*), 3 “Directional Wave Spectra Barometric Drifters” (DWSBDs) and 3 NOAA drifters.
- [I05 blog](#)

*Saturna Island float, photo by Aurélie Moulin.*

We are wrapping up another productive week in fair weather with no unplanned delays. We now have more than 3/4ths of our planned stations completed. We did pause a few times on short transits (particularly on our short jog to the north through a fracture zone in the South Indian Ridge) to allow our samplers to collect and run more samples. We also took advantage of a longer transit to get through most of a mechanical retermination, which means replacing the connection between the wire and the CTD/rosette. This junction is at the heart of our work... it simultaneously supplies power to the sensors and bottles, passes data back and forth, and holds up the several

ton package of scientific equipment, all while being subjected to saltwater under up to ~600 times atmospheric pressure, so we try to keep it in pristine shape.

We've been fortunate with weather this week. One furious blotch of high winds that had been menacing our weather forecasts seemed to politely slide out of our way like one sailor making way through a passage for another. Now the forecasts suggest we should remain in calm weather for a few more days at least. Thanks to our good luck, the hard work and efficiency of our team, the amazing performance of the *RV Roger Revelle*, and the skill and professionalism of her crew, we are back on a pace to finish out our science goals for this cruise before we run out of time. However, the cruise is still a few weeks from finished and there is at least one more known wild card: the Agulhas Current. The Agulhas rounds South Africa from the Indian Ocean into the Atlantic and supplies much of the seawater that that Atlantic Ocean later converts into bottom waters and exports at depth. It is a critical linkage in the great churning circulation of our oceans and the heat engine of our planet, and it has been implicated in past shifts in global climate. It is also—to hear the sea tales told by the various veterans of research cruises in the area—a place known for fickle and foul weather. I've been watching the weather forecasts for the area of the Agulhas where we will be working nearly as closely as our own. Here is a jumbled pile of clippings from that exercise that is keeping me up at night:



*These are three separate high wind events in the Agulhas with the upper left being the first (which finished up recently) and the upper right being the forecast for 5 days from now (with 42 mph wind averages). The lower right image (of current conditions) looks tame in comparison, but it is still on the edge of safe operations, and, from the bottom left plot, you'll see it can keep up those strong winds for several days at a stretch.*

To be fair, the Agulhas has its pleasant moments as well, but we'll be rolling the dice as to which face it will decide to show us when we arrive. For this reason, we're trying to keep a bit of time in our back pocket. If we get slammed by fierce weather then we can hope to wait out the worst of it and still finish most or all our work. If we luck out and are warmly welcomed to the area by calm seas and still skies then we can use the extra time to move

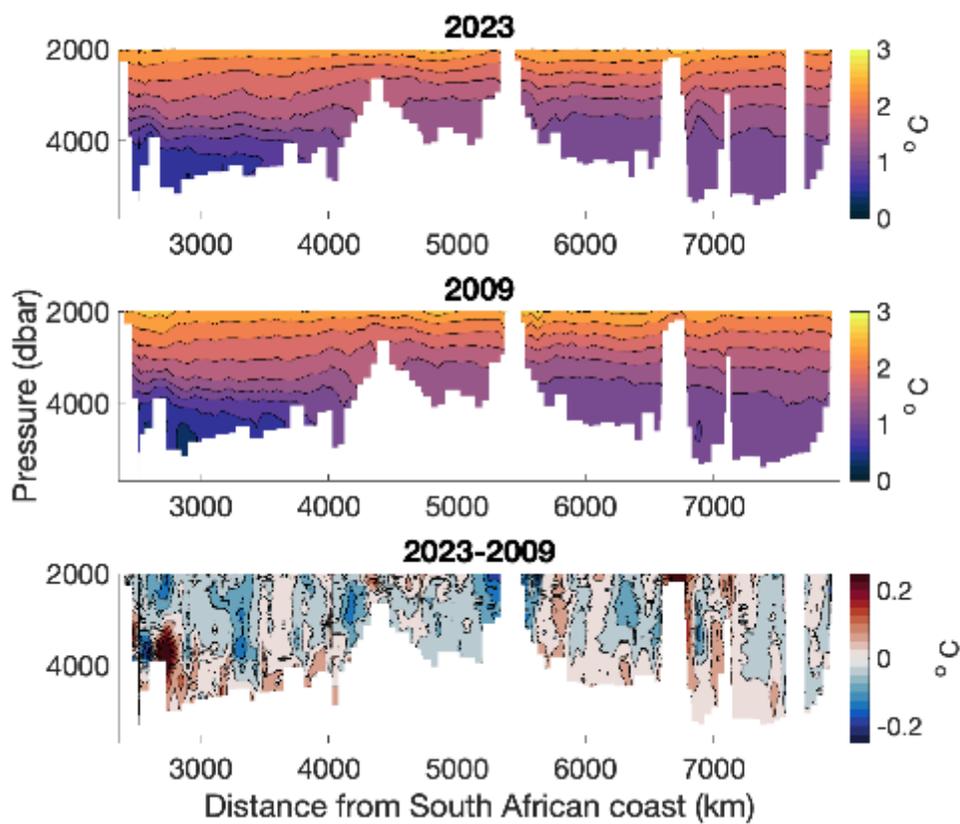
at a slower pace and ensure that our chemistry analysts are able to sample this important current at high resolution.

If all goes to plan, the next update will be written after the Agulhas work is completed and as we start our transit to Cape Town. The one after that will be a much shorter note sent as we are finishing demobilization. These will be spaced by both more and less than a week, so “no news” over this next period is not necessarily bad news. During the last week we’ll also be hard at work on the cruise report and getting ourselves and all our gear back home.

As promised, this week is focused on deep ocean temperature variability, and our writeup was kindly drafted by Co-Chief Kay.

### **Deep ocean warming – by Kay McMonigal**

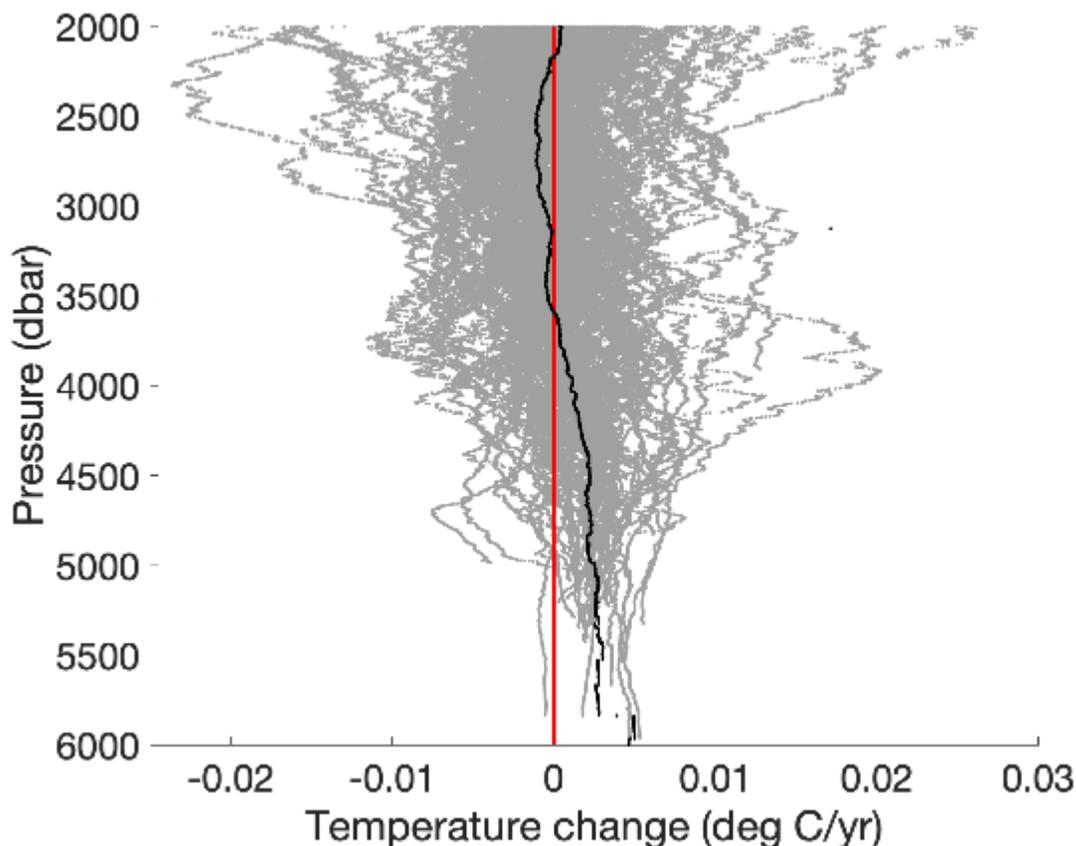
As a physical oceanographer, I am sometimes asked why we still need ships to obtain hydrographic data, when Argo floats and numerous satellites have near global coverage. One of the big holes in our temperature and salinity data is the deep (> 2000 m) ocean, which Argo floats (and satellites) do not yet routinely measure (side note: there are now pilot arrays of new variants on the Argo float that can handle the immense pressures of the greatest ocean depths, but these do not yet provide global coverage and the reference quality GO-SHIP measurements will remain an important component of global temperature monitoring even once they do). Constraining the warming rates of deep water masses such as Antarctic Bottom Water is an essential component of understanding heat uptake by the ocean. However, in the Indian Ocean, the lack of deep data have led to an inability to assess these deep warming rates. Our cruise track includes some deviations north and south to adequately cover the deepest parts of the basins, and will provide much needed insight. Deep salinity changes are also interesting, but I will hold off on talking about those until the salinity data have undergone more quality control.



*Temperature across the I05 in 2023 (top), 2009 (middle), and 2023-2009 (bottom). Using simple linear interpolation (preliminary)*

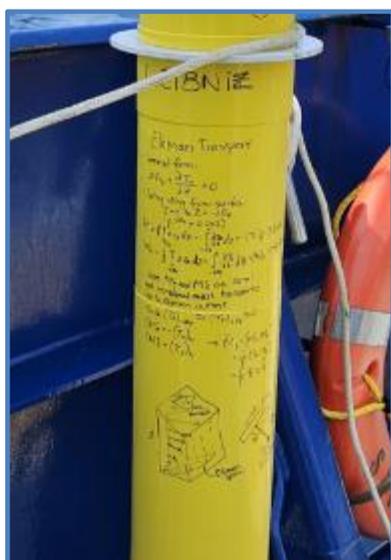
First, we can look at the temperature difference between 2023 and 2009, focusing on the area below 2000 dbar. Areas of both warming and cooling are evident, including several areas that have warming/cooling dipoles, possibly indicating a shift in the location of deep ocean currents. If you squint a little, there appears to be more red than blue in the deepest regions (below 4000 m depth), indicating a general warming of bottom waters.

However, my very preliminary linear interpolation doesn't do a good job at showing us the deepest profiles. For a better view of those, we can look directly at the profiles. Each gray dot is the difference between the 2023 and 2009 temperature divided by 14 years, to give an approximate warming rate at each station. The black line shows the mean warming rate at each pressure level. On average, there is warming below 3600 dbar. The mean warming rates are about 0.001-0.005 °C/year. This is in general agreement with studies of deep warming rates in the South Pacific Ocean. The densest waters (> 5800 dbar) have warmed the most (with the caveat that we have very few stations that extend to those depths). Clearly the deep Indian Ocean is warming, albeit with variations across the different deep basins.



Temperature of 2023 station temperature minus nearest 2009 station temperature (gray dots). Black dots show the mean at each pressure level. Preliminary data

### 10.1.6 Update 6



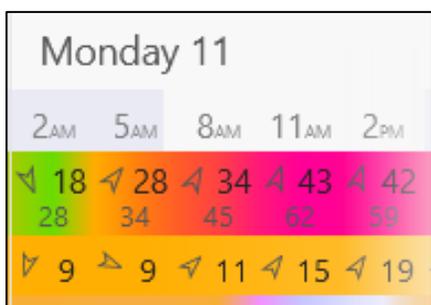
- 196 stations (49 new) completed with 43 stations with biological measurements, with the new bio measurements from separate casts.
- 15 floats (4 new) and 22 drifters (4 new) deployed: 2 SQUID floats, 2 biogeochemical Argo floats (*Leibniz* and *Wildcats*), 2 “Directional Wave Spectra Barometric Drifters” (DWSBDs) and 2 NOAA drifters.
- [I05 blog](#)

*The Leibniz float—named after a great thinker and one of the progenitors of calculus—was adorned by Kirsten Petzer with a derivation of Ekman transport. Ekman transport explains one of the stranger aspects of ocean circulation (why the surface ocean rarely moves in the direction that the winds blow)... a delightfully nerdy tribute to a philosopher, oceanography, and a high school. Photo by Aurélie Moulin.*

We recently retrieved the rosette from station 196 and began our ~three-day-long transit to Cape Town. This marks the successful completion of our planned science mission aside from the

underway measurements over the next few days of transit. Many of us are exhausted, missing loved ones, and out of chocolate/comfort-foods, but we're also excited to begin winding down the cruise and proud of our hard work over the last month and a half. We still have more work in front of us—finishing up measurements, quality controlling the newest data, packing up gear, shipping everything home, and cleaning our up our living and working spaces for the next cruise—but there's a large measure of satisfaction in knowing we've accomplished so many of our most challenging and uncertain cruise goals.

As a quick debrief on the last week: We managed to finish out the stations despite some challenging conditions. The ~3 knot Agulhas Current made the final few deployments tricky, and strong and variable winds were kicking up a confused sea state with waves also coming up from nearby storm systems. At times we slowed things down by sampling on station because waves were jumping the rails while we were underway (our seawater sampling team is more exposed when they are tapping the sample bottles).



Fortunately, we had banked enough time for this precaution and to ensure that the teams had a chance to thoroughly sample the Agulhas current. A new southerly system is likely to hit us early on our return trip, and the forecast has, for days, seemed determined to remind us of our cutoff time to make it back to meet the pilot outside of Cape Town:

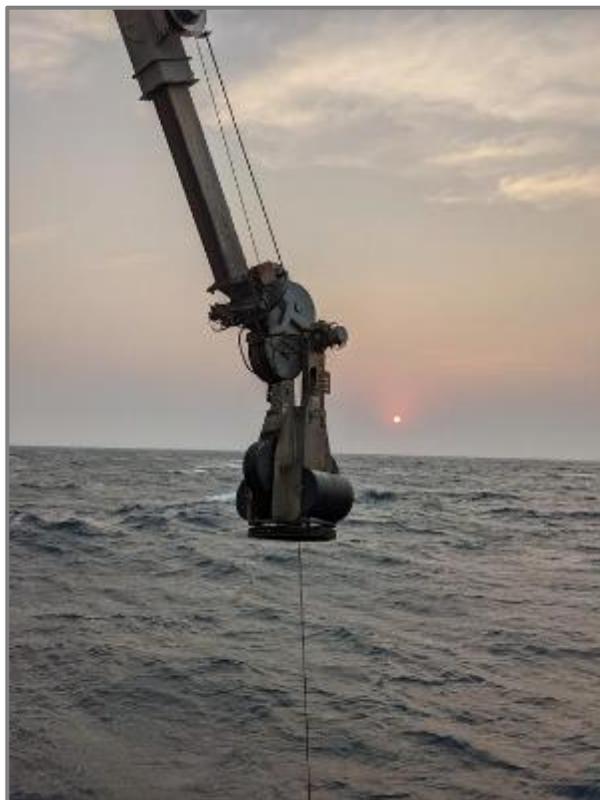
*Our schedule decreed and nature agreed: finished or not, on Monday at 7 AM it would be time to head to Cape Town.*

### A note of gratitude

I wanted to use the rest of this short update to offer my sincere thanks to all involved. The science team has been hard working, competent, good natured, and great company throughout this long time at sea. The crew of the R/V Roger Revelle has also shown their dedication throughout, demonstrating an exceptional degree of professionalism and competence while making us feel welcome and keeping us safe aboard the vessel. Then there were numerous people on land who helped us by providing cruise coordination, advice, troubleshooting, and simple encouragement. It is deeply humbling to be a part of an international effort with contributions from so many people working together to document changes on a planetary scale. You all have my thanks for making this important work possible and most often enjoyable.

The last update will be a debrief on the transit and the demobilization process, and, if everything goes to plan, it will be quite short.

*Sunrise on our last day of sampling, dramatically showing*

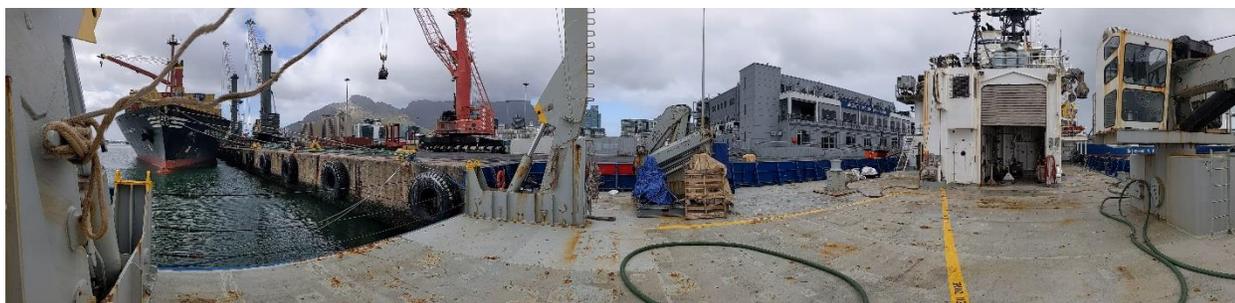


*off the dusty winds blowing from South Africa and Madagascar. After this long at sea, dust is a novelty.*

### 10.1.7 Update 7

Demobilization is complete with every item and every person heading home or where they need to be. We celebrated the success of the cruise last night, and now people are making the most of their time in port or are rushing home to return to their classes, family members, pets, obligations, hobbies, etc. It has been a fortunate, successful, and mostly enjoyable cruise with a great bunch of people.

We did indeed have a rough patch of weather during the first day and a half of the transit, and this made for slightly slower and bumpier going at first. We also took another big wave. The DIC container was hit this time. A full inspection will happen when the container returns to Seattle, but the damage so far seems to be small in comparison to the damage from the earlier wave that hit the CFC container. The spare rosette was also partially dislodged from the pallet beneath it, but the securing straps held. The rosette seems undamaged though the (disposable) palette beneath was fractured. Some empty float crates were also partially crushed by the wave, though these crates were later disposed of in port as planned. Despite this drama, we made it into port on time and had demobilization nearly complete on the 15<sup>th</sup>. The last truck arrived on the 16<sup>th</sup> and carted away the shipments that had been lined up at the edge of the Roger Revelle with lots of time to spare before mobilization begins for the next leg.



*The aft deck of the R/V Roger Revelle, empty of all the gear that had adorned her for these last ~60 days. The iconic Table Mountain can be seen looming in the background, along with some of the buildings from the Cape Town skyline. Bonus points to anyone who can spot the two (well hidden) sleeping harbor seals in this picture.*

## 10.2 Appendix 2: Station timing

Station start times for all stations where a cast was attempted. Latitudes and longitudes in this table are approximate and are taken from the pre-cruise planning documents. Consult the data file for the final coordinates. Timing reflects the “CTD in water” time for the first cast.

Station	Longitude (°E)	Latitude (°N)	Start (UTC)	Start (local)
1	114.9770	-32.6923	7/22/2023 13:13	7/22/2023 21:13
2	114.8451	-32.6644	7/22/2023 15:42	7/22/2023 23:42
3	114.6794	-32.6317	7/22/2023 17:38	7/23/2023 01:38
4	114.4665	-32.5865	7/22/2023 21:03	7/23/2023 05:03
5	114.3729	-32.5705	7/22/2023 23:44	7/23/2023 07:44
6	114.1859	-32.5323	7/23/2023 02:42	7/23/2023 10:42
7	114.1186	-32.5174	7/23/2023 08:21	7/23/2023 16:21

8	113.9755	-32.4885	7/23/2023 13:30	7/23/2023 21:30
9	113.4215	-32.3749	7/23/2023 19:56	7/24/2023 03:56
10	112.8666	-32.2636	7/24/2023 02:27	7/24/2023 10:27
11	112.3113	-32.1515	7/24/2023 10:04	7/24/2023 18:04
12	111.7592	-32.0392	7/24/2023 16:46	7/25/2023 00:46
13	111.2055	-31.9272	7/25/2023 12:29	7/25/2023 20:29
14	110.9292*	-31.8721*	7/25/2023 21:31	7/26/2023 05:31
15	110.1020	-31.7052	7/26/2023 06:16	7/26/2023 14:16
16	109.5514	-31.5946	7/26/2023 15:05	7/26/2023 22:05
17	108.9886	-31.4986	7/26/2023 22:02	7/27/2023 05:02
18	108.4001	-31.4292	7/27/2023 04:43	7/27/2023 11:43
19	107.8106	-31.3605	7/27/2023 12:59	7/27/2023 19:59
20	107.2215	-31.2926	7/27/2023 19:59	7/28/2023 02:59
21	106.6329	-31.2233	7/28/2023 02:42	7/28/2023 09:42
22	106.0456	-31.1567	7/28/2023 10:52	7/28/2023 17:52
23	105.4576	-31.0858	7/28/2023 17:47	7/29/2023 00:47
24	105.2920	-31.0672	7/28/2023 23:08	7/29/2023 06:08
25	105.1914	-31.0552	7/29/2023 03:20	7/29/2023 10:20
26	104.9514	-31.1569	7/29/2023 07:13	7/29/2023 14:13
27	104.8233	-31.2127	7/29/2023 11:10	7/29/2023 18:10
28	104.3666	-31.4089	7/29/2023 18:13	7/30/2023 01:13
29	103.9092	-31.6051	7/30/2023 00:24	7/30/2023 07:24
30	103.4499	-31.8027	7/30/2023 08:03	7/30/2023 15:03
31	102.9900	-31.9991	7/30/2023 14:22	7/30/2023 21:22
32	102.4311	-32.0028	7/30/2023 20:49	7/31/2023 03:49
33	102.0827	-32.0051	7/31/2023 02:27	7/31/2023 09:27
34	101.9673	-32.0046	7/31/2023 06:36	7/31/2023 13:36
35	101.8684	-32.0058	7/31/2023 10:14	7/31/2023 17:14
36	101.5723	-32.0069	7/31/2023 14:37	7/31/2023 21:37
37	100.9905	-32.0099	7/31/2023 19:51	8/1/2023 02:51
38	100.6239	-32.3709	8/1/2023 01:04	8/1/2023 08:04
39	100.3038	-32.6941	8/1/2023 05:43	8/1/2023 12:43
40	100.2442	-32.7515	8/2/2023 05:54	8/2/2023 12:54
41	100.2044	-32.7915	8/2/2023 10:32	8/2/2023 17:32
42	100.1112	-32.8850	8/2/2023 14:42	8/2/2023 21:42
43	99.7367	-33.2567	8/2/2023 22:00	8/3/2023 05:00
44	99.3639	-33.6276	8/3/2023 04:10	8/3/2023 11:10
45	98.9896	-33.9992	8/3/2023 10:17	8/3/2023 17:17
46	98.4187	-33.9981	8/3/2023 16:42	8/3/2023 23:42
47	97.8487	-33.9982	8/3/2023 23:07	8/4/2023 06:07
48	97.2751	-33.9907	8/4/2023 05:14	8/4/2023 12:14
49	96.7039	-33.9972	8/4/2023 11:59	8/4/2023 18:59
50	96.1319	-33.9965	8/4/2023 18:36	8/5/2023 00:36
51	95.5601	-33.9906	8/5/2023 01:10	8/5/2023 07:10

52	94.9896	-33.9966	8/5/2023 07:30	8/5/2023 13:30
53	94.4654	-33.7668	8/5/2023 13:43	8/5/2023 19:43
54	93.9432	-33.5391	8/5/2023 20:07	8/6/2023 02:07
55	93.4189	-33.3118	8/6/2023 02:21	8/6/2023 08:21
56	92.8975	-33.0831	8/6/2023 08:41	8/6/2023 14:41
57	92.3776	-32.8560	8/6/2023 15:25	8/6/2023 21:25
58	91.8581	-32.6280	8/6/2023 22:13	8/7/2023 04:13
59	91.3398	-32.4029	8/7/2023 04:20	8/7/2023 10:20
60	90.8230	-32.1759	8/7/2023 10:54	8/7/2023 16:54
61	90.2917	-32.0873	8/7/2023 17:02	8/7/2023 23:02
62	89.7600	-31.9975	8/7/2023 23:10	8/8/2023 05:10
63	89.2284	-31.9085	8/8/2023 04:38	8/8/2023 10:38
64	88.6982	-31.8206	8/8/2023 10:10	8/8/2023 16:10
65	88.2653	-31.7485	8/8/2023 14:59	8/8/2023 20:59
66	87.7621	-31.6648	8/8/2023 19:33	8/9/2023 01:33
67	87.2054	-31.5711	8/8/2023 23:30	8/9/2023 05:30
68	86.8619	-31.5129	8/9/2023 03:14	8/9/2023 09:14
69	86.5290	-31.4584	8/9/2023 07:15	8/9/2023 13:15
70	86.0896	-31.3843	8/9/2023 12:24	8/9/2023 18:24
71	85.5373	-31.2911	8/9/2023 17:42	8/9/2023 23:42
72	84.9734	-31.1971	8/9/2023 23:34	8/10/2023 05:34
73	84.3702	-31.1954	8/10/2023 05:51	8/10/2023 11:51
74	83.7669	-31.1935	8/10/2023 13:18	8/10/2023 19:18
75	83.1649	-31.194	8/10/2023 19:26	8/11/2023 01:26
76	82.5640	-31.1923	8/11/2023 01:46	8/11/2023 07:46
77	81.9601	-31.1908	8/11/2023 07:27	8/11/2023 13:27
78	81.3576	-31.1886	8/11/2023 14:49	8/11/2023 20:49
79	80.7537	-31.1886	8/11/2023 20:55	8/12/2023 01:55
80	80.1515	-31.1868	8/12/2023 02:50	8/12/2023 07:50
81	79.8517	-30.9183	8/12/2023 09:27	8/12/2023 14:27
82	79.5516	-30.6492	8/12/2023 14:30	8/12/2023 19:30
83	79.2520	-30.3803	8/12/2023 19:29	8/13/2023 00:29
84	78.7907	-30.6105	8/13/2023 01:10	8/13/2023 06:10
85	78.3272	-30.8407	8/13/2023 06:33	8/13/2023 11:33
86	77.8636	-31.0719	8/13/2023 13:00	8/13/2023 18:00
87	77.4003	-31.3027	8/13/2023 18:19	8/13/2023 23:19
88	76.9342	-31.5341	8/13/2023 23:45	8/14/2023 04:45
89	76.4685	-31.7667	8/14/2023 04:34	8/14/2023 09:34
90	76.0031	-32.0000	8/14/2023 11:09	8/14/2023 16:09
91	75.5012	-32.4197	8/14/2023 17:21	8/14/2023 22:21
92	75.0492	-32.8138	8/14/2023 23:19	8/15/2023 04:19
93	74.6008	-33.2109	8/15/2023 05:17	8/15/2023 10:17
94	74.1494	-33.6115	8/15/2023 12:49	8/15/2023 17:49
95	73.6985	-34.0067	8/15/2023 20:27	8/16/2023 01:27

96	73.2475	-34.4025	8/16/2023 03:09	8/16/2023 08:09
97	72.7994	-34.8002	8/16/2023 09:52	8/16/2023 14:52
98	73.1263	-34.0016	8/16/2023 21:30	8/17/2023 02:30
99	72.5559	-33.9994	8/17/2023 03:59	8/17/2023 08:59
100	71.9849	-33.9993	8/17/2023 12:01	8/17/2023 17:01
101	71.4129	-34.0022	8/17/2023 20:04	8/18/2023 01:04
102	70.8412	-33.9994	8/18/2023 02:16	8/18/2023 07:16
103	70.2700	-34.0015	8/18/2023 08:47	8/18/2023 13:47
104	69.6983	-33.9995	8/18/2023 16:19	8/18/2023 21:19
105	69.1264	-34.0012	8/18/2023 22:50	8/19/2023 03:50
106	68.5554	-34.0006	8/19/2023 05:01	8/19/2023 10:01
107	67.9812	-33.9996	8/19/2023 12:39	8/19/2023 17:39
108	67.4120	-34.0014	8/19/2023 19:08	8/20/2023 00:08
109	66.8383	-34.0004	8/20/2023 01:20	8/20/2023 06:20
110	66.2655	-33.9997	8/20/2023 07:45	8/20/2023 12:45
111	65.6972	-33.9988	8/20/2023 15:10	8/20/2023 20:10
112	65.1243	-33.9986	8/20/2023 21:29	8/21/2023 01:29
113	64.5542	-33.9986	8/21/2023 03:42	8/21/2023 07:42
114	63.9806	-33.9977	8/21/2023 11:40	8/21/2023 15:40
115	63.4085	-34.0031	8/21/2023 18:26	8/21/2023 22:26
116	62.8397	-34.0008	8/22/2023 01:26	8/22/2023 05:26
117	62.2701	-34.0126	8/22/2023 08:13	8/22/2023 12:13
118	61.6952	-33.9993	8/22/2023 16:19	8/22/2023 20:19
119	61.1243	-33.9961	8/22/2023 22:52	8/23/2023 02:52
120	60.5499	-34.0008	8/23/2023 05:12	8/23/2023 09:12
121	59.9793	-33.9976	8/23/2023 13:05	8/23/2023 17:05
122	59.3188	-33.9979	8/23/2023 19:44	8/23/2023 23:44
123	58.7540	-33.9984	8/24/2023 02:25	8/24/2023 06:25
124	58.1793	-33.9982	8/24/2023 08:09	8/24/2023 12:09
125	57.8591	-33.9985	8/24/2023 14:59	8/24/2023 18:59
126	57.5192	-34.0003	8/24/2023 20:16	8/25/2023 00:16
127	57.0647	-33.8470	8/25/2023 02:38	8/25/2023 06:38
128	57.0500	-33.1999	8/25/2023 10:48	8/25/2023 14:48
129	57.0411	-33.5577	8/25/2023 18:16	8/25/2023 22:16
130	57.0336	-33.7005	8/26/2023 00:53	8/26/2023 04:53
131	56.9860	-33.9985	8/26/2023 06:11	8/26/2023 10:11
132	56.4469	-33.9985	8/26/2023 13:43	8/26/2023 17:43
133	56.0919	-33.9980	8/26/2023 18:44	8/26/2023 22:44
134	55.7513	-33.9970	8/26/2023 22:52	8/27/2023 02:52
135	55.2942	-33.9984	8/27/2023 04:30	8/27/2023 08:30
136	54.8836	-33.9975	8/27/2023 08:11	8/27/2023 12:11
137	54.5112	-33.9988	8/27/2023 14:18	8/27/2023 18:18
138	54.1737	-33.9978	8/27/2023 18:12	8/27/2023 22:12
139	53.6360	-33.9977	8/28/2023 00:09	8/28/2023 04:09

140	53.1249	-34.0001	8/28/2023 06:37	8/28/2023 10:37
141	52.7931	-33.9987	8/28/2023 13:52	8/28/2023 17:52
142	52.1656	-33.9991	8/28/2023 21:12	8/29/2023 01:12
143	51.5707	-33.9202	8/29/2023 03:28	8/29/2023 06:28
144	50.9774	-33.8367	8/29/2023 09:52	8/29/2023 12:52
145	50.3861	-33.7670	8/29/2023 17:06	8/29/2023 20:06
146	49.7918	-33.6893	8/29/2023 23:19	8/30/2023 02:19
147	49.1990	-33.6104	8/30/2023 05:12	8/30/2023 08:12
148	48.6105	-33.5341	8/30/2023 12:34	8/30/2023 15:34
149	48.0231	-33.4578	8/30/2023 18:24	8/30/2023 21:24
150	47.4282	-33.3803	8/31/2023 00:19	8/31/2023 03:19
151	46.8374	-33.3073	8/31/2023 05:54	8/31/2023 08:54
152	46.2329	-33.2258	8/31/2023 12:32	8/31/2023 15:32
153	45.6605	-33.1510	8/31/2023 17:15	8/31/2023 20:15
154	45.0696	-33.0721	8/31/2023 21:31	9/1/2023 00:31
155	44.4819	-32.9962	9/1/2023 01:53	9/1/2023 04:53
156	43.9076	-32.9997	9/1/2023 05:45	9/1/2023 08:45
157	43.3613	-32.9962	9/1/2023 09:20	9/1/2023 12:20
158	43.1186	-32.9977	9/1/2023 13:52	9/1/2023 16:52
159	42.8683	-32.9971	9/1/2023 17:57	9/1/2023 20:57
160	42.8326	-32.9980	9/1/2023 22:29	9/2/2023 01:29
161	42.7154	-32.9964	9/2/2023 03:12	9/2/2023 06:12
162	42.1408	-32.9968	9/2/2023 09:14	9/2/2023 12:14
163	41.563	-32.9947	9/2/2023 16:30	9/2/2023 19:30
164	40.9864	-32.9970	9/2/2023 23:02	9/3/2023 02:02
165	40.4098	-32.9972	9/3/2023 05:28	9/3/2023 08:28
166	39.8344	-32.9977	9/3/2023 12:08	9/3/2023 15:08
167	39.2569	-32.9975	9/3/2023 19:55	9/3/2023 22:55
168	38.6804	-32.9973	9/4/2023 02:18	9/4/2023 05:18
169	38.1044	-32.9983	9/4/2023 09:16	9/4/2023 12:16
170	37.5277	-32.9979	9/4/2023 16:44	9/4/2023 19:44
171	36.9490	-32.9978	9/4/2023 23:23	9/5/2023 01:23
172	36.4947	-32.9997	9/5/2023 05:13	9/5/2023 07:13
173	36.4804	-32.9997	9/5/2023 10:41	9/5/2023 12:41
174	36.4331	-32.9991	9/5/2023 17:15	9/5/2023 19:15
175	36.1499	-32.9995	9/5/2023 22:02	9/6/2023 00:02
176	35.5866	-32.9969	9/6/2023 03:38	9/6/2023 05:38
177	35.0349	-32.8858	9/6/2023 08:59	9/6/2023 10:59
178	34.4856	-32.7734	9/6/2023 14:06	9/6/2023 16:06
179	34.1221	-32.6966	9/6/2023 18:22	9/6/2023 20:22
180	33.7612	-32.6207	9/6/2023 23:31	9/7/2023 01:31
181	33.4001	-32.5451	9/7/2023 04:59	9/7/2023 06:59
182	33.0390	-32.4249	9/7/2023 10:43	9/7/2023 12:43
183	32.6795	-32.3018	9/7/2023 17:43	9/7/2023 19:43

184	32.3194	-32.1799	9/7/2023 23:31	9/8/2023 01:31
185	31.9601	-32.0599	9/8/2023 05:09	9/8/2023 07:09
186	31.6002	-31.9417	9/8/2023 10:59	9/8/2023 12:59
187	31.3919	-31.7921	9/8/2023 18:00	9/8/2023 20:00
188	31.1739	-31.6528	9/8/2023 23:32	9/9/2023 01:32
189	30.9750	-31.4938	9/9/2023 04:54	9/9/2023 06:54
190	30.7575	-31.3498	9/9/2023 09:59	9/9/2023 11:59
191	30.6064	-31.2046	9/9/2023 16:39	9/9/2023 18:39
192	30.5138	-31.1679	9/9/2023 22:19	9/10/2023 00:19
193	30.4642	-31.1128	9/10/2023 03:28	9/10/2023 05:28
194	30.3777	-31.0993	9/10/2023 08:49	9/10/2023 10:49
195	30.3592	-31.0922	9/10/2023 14:08	9/10/2023 16:08
196	30.3437	-31.0777	9/10/2023 17:15	9/10/2023 19:15

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(\*) station 14 was moved significantly from the originally planned location.