NOAA Data Report ERL AOML-31

CONTINUOUS AIR AND SURFACE SEAWATER MEASUREMENTS OF fCO_2 ON BOARD THE NOAA SHIP *MALCOLM BALDRIGE* AROUND-THE-WORLD CRUISE DURING 1995

J. Masters
R. Wanninkhof
D.T. Ho
M. Steckley
R. Feely
C. Cosca

Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida
October 1997

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

NOAA Data Report ERL AOML-31

CONTINUOUS AIR AND SURFACE SEAWATER MEASUREMENTS OF fCO_2 ON BOARD THE NOAA SHIP *MALCOLM BALDRIGE* AROUND-THE-WORLD CRUISE DURING 1995

Jason Masters
Rik Wanninkhof
David T. Ho
Matthew Steckley
Ocean Chemistry Division
Atlantic Oceanographic and Meteorological Laboratory

Richard Feely
Catherine Cosca
Ocean Climate Division
Pacific Marine Environmental Laboratory

Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida
October 1997

UNITED STATES DEPARTMENT OF COMMERCE

William M. Daley
Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

D. JAMES BAKER
Under Secretary for Oceans and Atmosphere/Administrator

Environmental Research Laboratories

James L. Rasmussen
Director

NOTICE

Mention of a commercial company of product does not constitute an endorsement by NOAA/ERL. Use of information from this publication concerning proprietary products or the tests of such products for publicity or advertising purposes is not authorized.

REMOTE ACCESS TO DATA LISTED IN THIS REPORT

The data described can be obtained via anonymous FTP from:
<ftp://ftp.aoml.noaa.gov/pub/ocd/carbon/uwpco295>
or via the World Wide Web:
<http://www.aoml.noaa.gov/ocd/oaces/>

For information regarding electronic access to the data sets contact:

Ms. Betty Huss
Data Manager, OACES
U.S. Dept. of Commerce
NOAA/AOML/OCD
4301 Rickenbacker Cswy.
Miami, FL 33149-1026

Telephone: (305) 361-4395
Internet address: huss@aoml.noaa.gov

LIST OF PARTICIPANTS *

Chief Scientists:	Leg 1	Matthew Steckley
	Leg 2	Amy Ffield
	Leg 3	Peter Ortner
	Leg 4	Robert Molinari
	Leg 5	Robert Pitman
	Leg 6	Peter Ortner
	Leg 7	Rik Wanninkhof & Robert Molinari
	Leg 8	Linda Mangum & David Zimmerman
fCO_2 Analysis:	Leg 1	Matthew Steckley
	Leg 2	David Ho
	Leg 3	David Ho
	Leg 4	Jason Masters, LTjg NOAA
	Leg 5	Jason Masters, LTjg NOAA
	Leg 6	Catherine Cosca & Jason Masters, LTjg NOAA
	Leg 7	Jason Masters, LTjg NOAA
	Leg 8	Jason Masters, LTjg NOAA
Dissolved Inorganic Carbon Analysis:	Leg 1	Matthew Steckley
	Leg 2	David Ho
	Leg 3	David Ho
	Leg 4	Tom Lantry
	Leg 5	*no samples analyzed*
	Leg 6	Catherine Cosca
	Leg 7	Tom Lantry & Marilyn Roberts
	Leg 8	Julien Zaragoza, Lynn Butler & Roger Lemire

* The Survey Department of the NOAA ship MALCOLM BALDRIGE was instrumental on every leg toward the maintenance of the underway system and collection of dissolved inorganic carbon samples.

CONTENTS

List of Tables

List of Figures

CONTINUOUS MEASUREMENTS OF fCO_2 ON BOARD THE NOAA SHIP MALCOLM BALDRIGE AROUND-THE-WORLD CRUISE DURING 1995

Jason Masters, Rik Wanninkhof, David T. Ho, Richard Feely, Matthew Steckley, Catherine Cosca

ABSTRACT

From February 1995 through January 1996 the NOAA ship MALCOLM BALDRIGE conducted scientific operations on an around-the-world tour. The majority of work occurred in the Indian Ocean. The CO_2 groups of the National Oceanic and Atmospheric Administration's (NOAA) Atlantic Oceanographic and Meteorological Laboratory (AOML) and Pacific Marine Environmental Laboratory (PMEL) operated a continuously flowing partial pressure carbon dioxide analyzer. Samples were taken from both the surface water and the overlying atmosphere to determine carbon dioxide flux across the gas/water interface. Other parameters such as salinity, barometric pressure and temperature were used to reduce the data and calculate the fugacity of CO_2*. Total dissolved inorganic carbon (DIC) samples of surface water were also collected. Data were collected on each leg of the cruise. Leg 1 was a transit from Miami to Durban, South Africa. Leg 2 operated from Durban to Colombo, Sri Lanka. Leg 3 operated from Colombo to Muscat, Oman. Leg 4 operated from Muscat to Victoria, Seychelles. Leg 5 operated from Victoria to Muscat, Oman. Leg 6 operated from Muscat to Diego Garcia. Leg 7 consisted of a transit from Diego Garcia to Fremantle, Australia followed by the major scientific operations between Fremantle and Male, Maldive Islands. Leg 8 included another transit from Male to Darwin, Australia. Operations began after leaving Darwin and headed into the Western Equatorial Pacific. The ship inported in American Samoa and continued to Panama, Miami, Florida and finished in Charleston, South Carolina. Descriptions of sampling methods and graphical data summaries are given in this report.

* the fugacity differs from the partial pressure of CO_2 (pCO_2) in that it takes the non-ideality of CO_2 into account. For ambient temperatures and CO_2 levels, $fCO_2 \approx 0.995\ pCO_2$.

1. INTRODUCTION

Changes in net radiation are the ultimate control of climate and weather. Incoming radiation is absorbed at the Earth's surface and in the lower atmosphere at an average of 240 W/m^2 (Houghton, J.T. *et al.,* 1994). Water vapor, carbon dioxide (CO_2), ozone (O_3), methane (CH_4), nitrous oxide (N_2O) and clouds absorb about 1% of the of the outgoing radiation. This is the natural greenhouse effect. Since the mid 1700's, CO_2 levels in the atmosphere have increased from 280 to about 356 ppm due to industrialization. Ice core data of CO_2 concentrations over the past 1000 years coupled with atmospheric CO_2 sampling sites since 1956 provide this information (Barnola *et al.*, 1987 and Barnola *et al.*, 1991). The main anthropogenic sources of CO_2 are burning of fossil fuels and changes in land usage. As a result, Man's perturbations have caused a 1.56 W/m^2 increase in radiative forcing. The oceans, in general, act as a sink for anthropogenic CO_2 with an uptake of approximately 2 ±0.8 GtC/yr (1 GtC=10^{15} gC). By monitoring the localized flux of CO_2 between the oceans and atmosphere we hope to better constrain the oceanic uptake and understand the biogeochemical processes controlling these fluxes. This will enable better predictions about how our climate will change in response to greenhouse forcing.

The National Oceanic & Atmospheric Administration's (NOAA) Atlantic Oceanographic & Meteorological Laboratory (AOML) and the Pacific Marine Environmental Laboratory (PMEL) CO_2 groups participated in a research effort on board the NOAA ship MALCOLM BALDRIGE during 1995. The primary focus was on the Indian Ocean and included projects sponsored by the World Ocean Circulation Experiment (WOCE), Global Ocean Ecosystems and Coupling (GLOBEC) and Ocean-Atmosphere Carbon Exchange Study (OACES). The Tropical Ocean Global Atmosphere / Tropical Atmosphere-Ocean (TOGA/TAO) project took the ship across the Pacific through Panama and back to Charleston, SC. The duration of the 1995 field season was from February 13^{th}, 1995 to January 29^{th} , 1996. The dates of the cruise legs are included in Table 1.

This report contains 5 sections. Section 1 is the introduction and contains the cruise itinerary and a description of the sampling area. Section 2 contains sampling and analytical methods for measuring fCO_2 and Dissolved Inorganic Carbon (DIC). Section 3 contains graphical data for all the legs of the cruise. Section 4 lists the references. Section 5 are the appendices of the individual thermistor calibrations and an example of the information contained in a fCO_2 spreadsheet. fCO_2 data may be downloaded via anonymous ftp at *<ftp://ftp.aoml.noaa.gov/pub/ocd/carbon/ uwpco295>*.

Table 1. MALCOLM BALDRIGE 1995 FIELD SEASON

Cruise	Project		Date	Port of Call
MB95-01	Radiatively Important	Depart	2/13/95	Miami, FL
	Trace Species (RITS)	Arrive	2/17/95	San Juan, Puerto Rico
MB95-01	Radiatively Important	Depart	2/22/95	San Juan, Puerto Rico
	Trace Species (RITS)	Arrive	3/17/95	Durban, South Africa
MB95-02	World Ocean Circulation	Depart	3/21/95	Durban, South Africa
	Experiment (WOCE)	Arrive	4/20/95	Colombo, Sri Lanka
MB95-03	Global Ocean Ecosystem	Depart	4/27/95	Colombo, Sri Lanka
	and Coupling (GLOBEC)	Arrive	5/25/95	Muscat, Oman
MB95-04	World Ocean Circulation	Depart	5/31/95	Muscat, Oman
	Experiment (WOCE)	Arrive	6/23/96	Male, Maldives
MB95-04	World Ocean Circulation	Depart	6/24/95	Male, Maldives
	Experiment (WOCE)	Arrive	6/30/95	Victoria, Seychelles
MB95-05	World Ocean Circulation	Depart	7/12/95	Victoria, Seychelles
	Experiment (WOCE)	Arrive	7/24/95	Muscat, Oman
MB95-06	Global Ocean Ecosystem	Depart	7/31/95	Muscat, Oman
	and Coupling (GLOBEC)	Arrive	8/28/95	Diego Garcia, UK
MB95-07	Ocean-Atmosphere Carbon	Depart	8/30/95	Diego Garcia, UK
	Exchange Study (OACES)	Arrive	9/8/95	Fremantle, Australia
MB95-07	Ocean-Atmosphere Carbon	Depart	9/22/95	Fremantle, Australia
	Exchange Study (OACES)	Arrive	10/25/95	Male, Maldives
MB95-08	Tropical Ocean Global Atmosphere/	Depart	10/28/95	Male, Maldives
	Tropical Atmosphere & Ocean (TOGA/TAO)	Arrive	11/8/95	Darwin, Australia
MB95-08	Tropical Ocean Global Atmosphere/	Depart	11/21/95	Darwin, Australia
	Tropical Atmosphere & Ocean (TOGA/TAO)	Arrive	12/15/95	Pago Pago, American Samoa
MB95-08	Tropical Ocean Global Atmosphere/	Depart	12/19/95	Pago Pago, American Samoa
	Tropical Atmosphere & Ocean (TOGA/TAO)	Arrive	1/15/96	Rodman, Panama (Pacific)
MB95-08	Tropical Ocean Global Atmosphere/	Depart	1/20/96	Colon, Panama via Panama Canal
	Tropical Atmosphere & Ocean (TOGA/TAO)	Arrive	1/23/96	Miami, FL
MB95-08	Tropical Ocean Global Atmosphere/	Depart	1/27/96	Miami, FL
	Tropical Atmosphere & Ocean (TOGA/TAO)	Arrive	1/29/96	Charleston, SC

1.2 DESCRIPTION OF SAMPLING AREAS

Leg 1 Beginning February 13th , 1995 the ship departed Miami, Florida for San Juan, Puerto Rico. Passage was made through the New Providence Channel. Off the eastern coast of Abaco Island a series of hydrographic casts extended eastward. At approximately 26° 30"N and 72 ° 30"W the ship proceeded south to San Juan at approximately 19 ° 30"N and 67 ° 30"W. Once clear of the Antilles Islands the transit continued along a great circle path towards The Cape of Good Hope, South Africa (36° S, 19° E). The transit was interrupted for a medical evacuation in Ascension, UK. Once the ship rounded the Cape of Good Hope, sampling continued through the Agulhas Current and finished March 16th in Durban, South Africa (30 ° S, 31 ° E). The ship track is shown in figure 1.

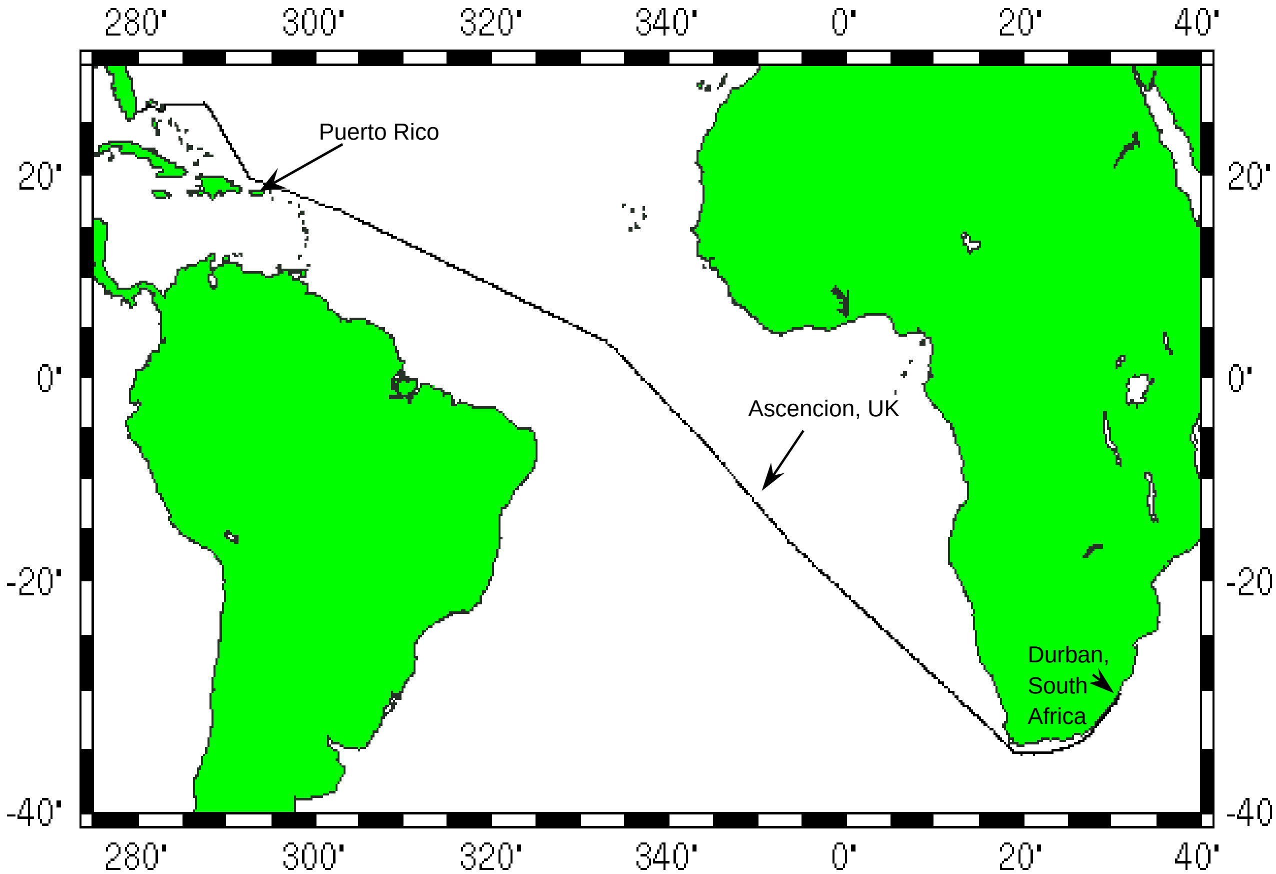


Figure 1. MB95-01 Cruise Track

Leg 2 The ship departed Durban, South Africa on March 21st on a southeasterly heading. The objectives for this leg were to complete parts of three WOCE repeat hydrography lines, I1, I5 and I7. I1 extended along the 8.5° North parallel, the I5 line extended along the 33° South parallel and the I7 line along the 55° E meridian. In addition to WOCE hydrography, extensive air sampling for trace atmospheric gases was performed by Dr. Dickerson and his group from the University of Maryland. From Durban, upon reaching the 33°S parallel (I5 repeat) the trackline turned due east. After crossing the 50°E meridian the trackline turned northeast until reaching 29° 30" S and 55° E. The I7 repeat began here and proceeded north until reaching 19° S, when the ship incurred a medical emergency and had to break off operations to evacuate a crew member to Mauritius (app. 20° S, 57° 30"E). Operations resumed at 18° S, 55° E and continued north until reaching the Seychelles rise (app. 13° S). The trackline was diverted to the northwest, skirting the rise and turning north again along the 52° E meridian. To resume the hydrography line the trackline turned northeast and intercepted the 55 ° E meridian just north of 4 ° S. Sampling continued north until reaching the equator. The ship then headed northeast to 8 ° N, 63 ° W where it turned east, southeast (a modified I1 sampling line) to pass through the 7 degree channel along the Maldive Islands atoll group. Once through the channel the ship had to divert southeast to avoid India's international water boundary. The project finished with an inport in Colombo, Sri Lanka (7 ° N, 80 ° E) on April 20th. Figure 2 gives the ship track for this leg.

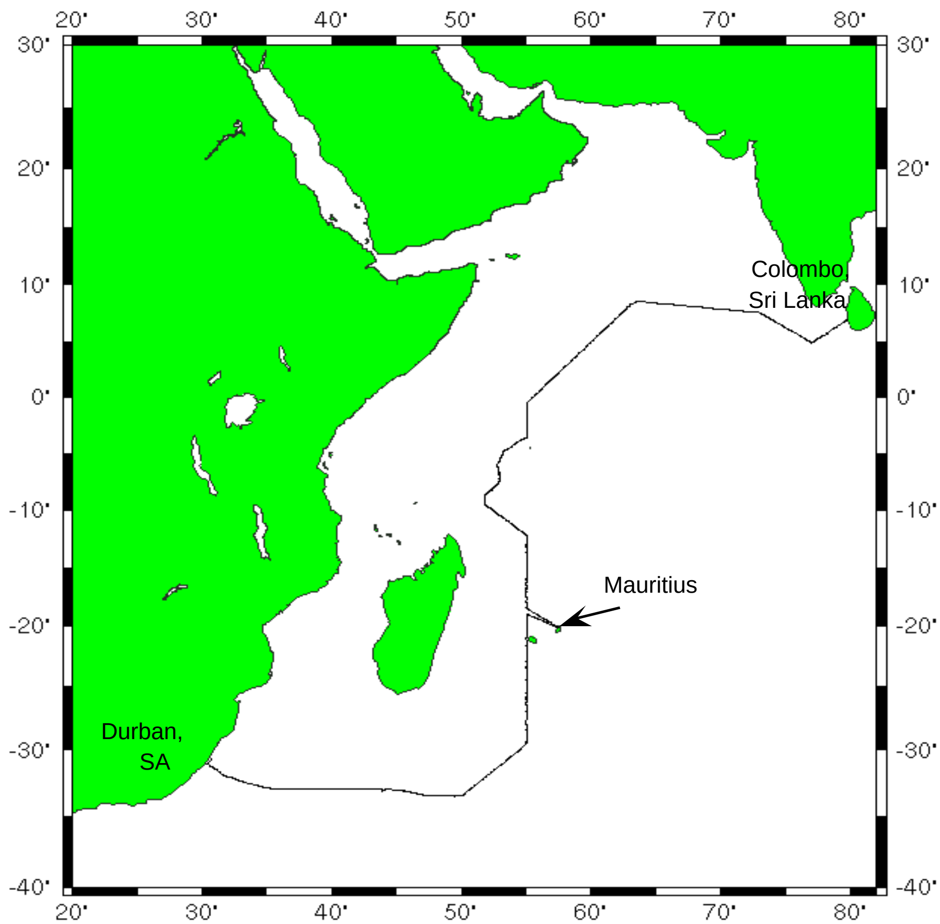


Figure 2. MB95-02 Cruise Track

Leg 3 The operations for the Global Ocean Ecosystems and Coupling (GLOBEC) were to sample surface and mid water zooplanktonic biomass and diversity in a pre-monsoonal environment. The ship departed Colombo, Sri Lanka on April 27th and proceeded west through the seven degree channel. All scientific operations were secured while transiting India's national waters. Upon clearing the 7° channel, the trackline turned west, southwest (approximately 73 ° E) to head for the Somalia coastline (5 ° N, 49 ° W). Scientific operations continued along the Somalia coastline across the Gulf of Aden to the coast of Yemen. The ship paralleled the Yemen/Omani coast until inporting in Muscat, Oman. The cruise track is shown in figure 3.

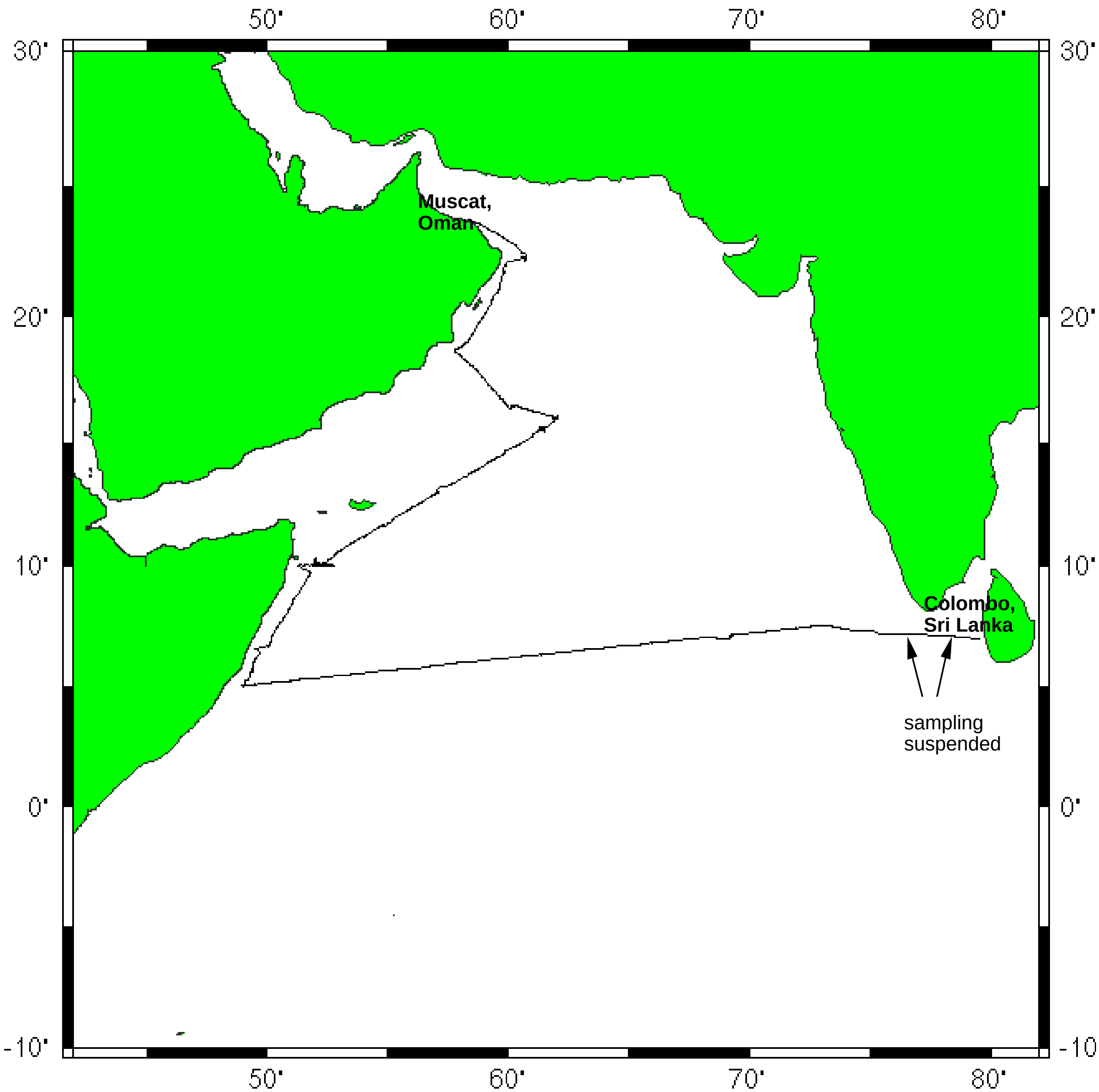


Figure 3. MB95-03 Cruise Track

Leg 4 This was a WOCE hydrographic project along the 8.5° North parallel or I1 West repeat. The ship departed Muscat, Oman (23 ° 30" N, 59 ° E) on May 31st . The trackline followed the peninsula's coast line to 16 ° 30"N, 57 ° E. The heading was changed to due south until reaching 11 ° N. The ship changed to a southwesterly heading and proceeded to 8 ° 30"N, 51 ° E. Hydrographic operations proceeded east to 68 ° 45"E where the ship changed to a southeasterly course to intercept the 7.5° parallel at approximately 69 ° 30" E. The project continued eastward through the 7 ° channel to make a public relations port-of-call in Male, Maldive Islands (4 ° 48"N, 76 ° 48"E). The project resumed operations after leaving the 7° channel and headed in a southwesterly direction to 1° S, 55 ° E. The course was changed to due south to repeat part of second leg's hydrographic line. At 3 ° 30"S operations were completed. The ship proceeded into Victoria, Seychelles on June 30th. The cruise for leg 4 is represented by figure 4.

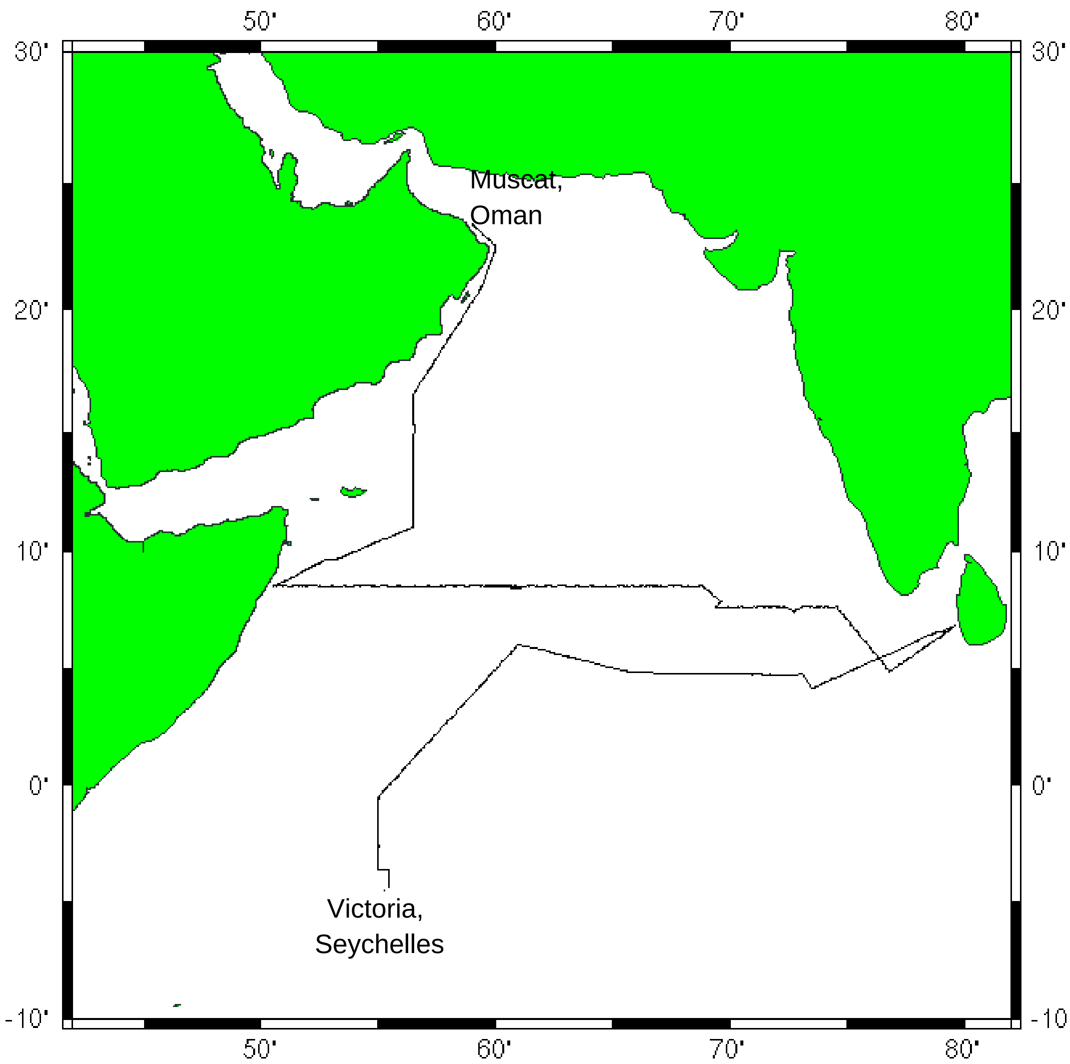


Figure 4. MB95-04 Cruise Track

Leg 5 The proposed operations for this leg were to complete a high density Expendable Bathythermographic (XBT) line along the I1 line (8.5° North parallel). The project began on July 12th from the Seychelles. The ship steamed northwest to 7° N, 50° 30"E. During this time of the year the winds associated with the South-West monsoons are at their peak. The rough weather curtailed operational plans and the ship had to seek the shelter of the coastline. The ship crossed the Gulf of Aden and transited northeast along the coast to Ra's al Haad (22° 30"N, 60° E). Once in calmer waters, operations were modified for marine mammal observations, so that the remaining time was spent repeating transits along the Omani coastline between 22° 30"N, 60° 15"E and 25° N, 57° E. On July 24th the ship entered Muscat, Oman. Figure 5 represents the cruise track for this leg.

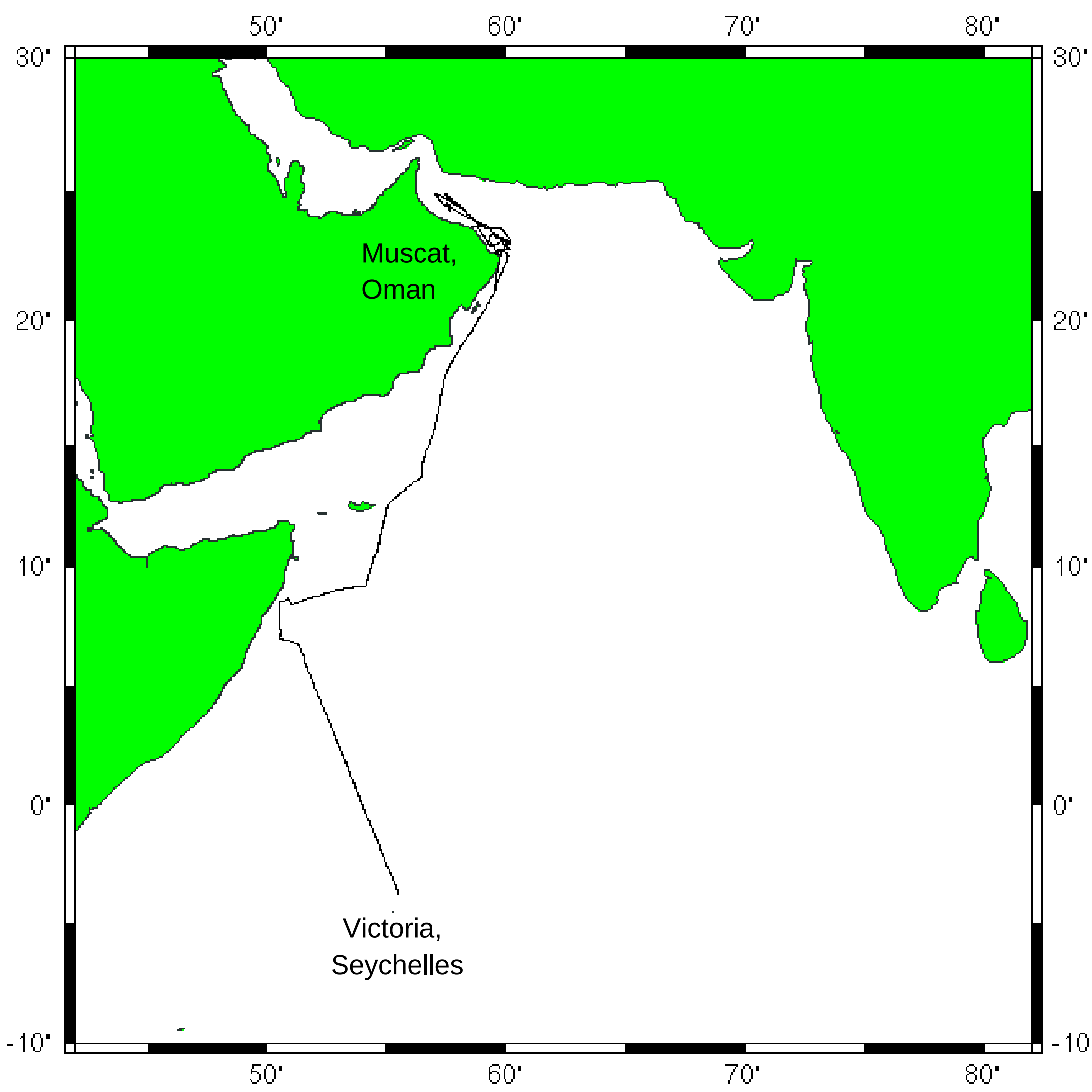


Figure 5. MB95-05 Cruise Track

Leg 6   This second GLOBEC cruise was scheduled to sample zooplankton biomass and diversity in the Northern Arabian Sea and off of the coast of Somalia during the South-West monsoon. The cruise departed Muscat, Oman on July 31st following the Omani coastline around the tip of Ra's al Haad and turning southwest to remain sheltered along the peninsula from the monsoonal weather. At approximately 19° 45"N, 58° 15"E the ship turned south to conduct a test biological cast. Once completed, the cruise resumed its southwesterly course in the vicinity of 18° 45"N, 58° W. This course continued along the Saudi Arabian peninsula until it was navigationally safe to cross the Gulf of Aden. Limited shelter was found transiting the Gulf from the shadow effect that the island of Socotra provided. Off the coast of Somalia the weather had subsided enough to conduct biological station casts at approximately 11° N, 52° E. The cruise then proceeded southeast to approximately 10° 45"N, 51° 55"E for further biological casts. After completing a 3-day station, the ship then headed northeast to an array of buoys located at 16° N, 62° W set out by several oceanographic institutions and sponsored by the United States Office of Naval Research as part of the Joint Global Ocean Flux Study (JGOFS). Upon completing the casts, the ship headed southeast. The ship suffered a mechanical failure that delayed the arrival into Diego Garcia (16° S, 87° E) until August 28th. Figure 6 represents the cruise track for this leg.

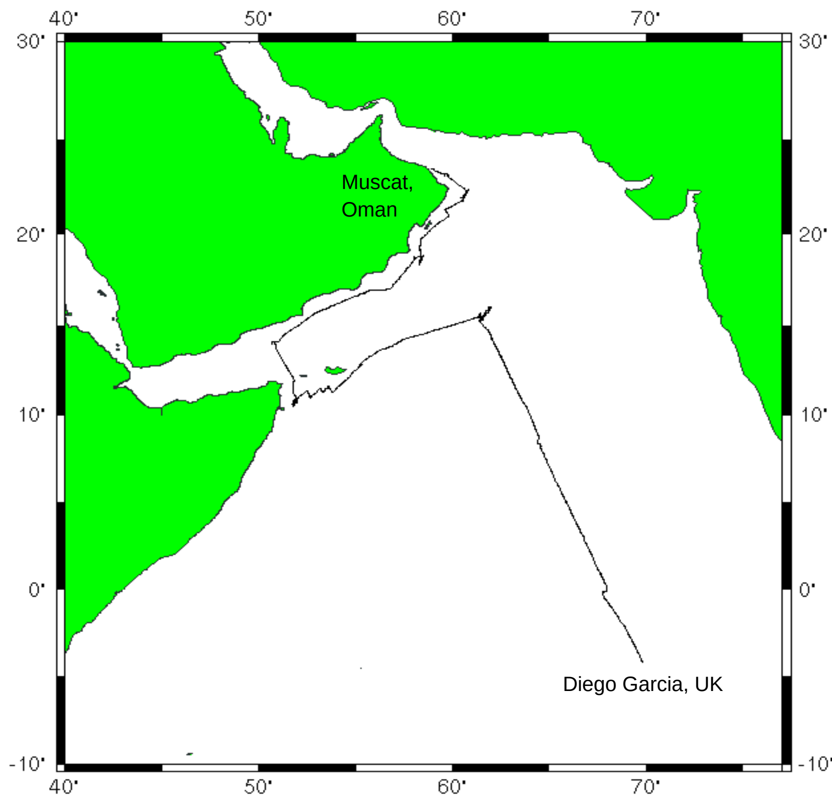


Figure 6. MB95-06 Cruise Track

Leg 7 The Oceans-Atmosphere Carbon Exchange Study (OACES) operations were to sample the physical and chemical parameters along the WOCE/WHP I8 repeat line. From August 30th until September 7th, the ship transited from Diego Garcia to Fremantle, Australia (33° 30"S,114° 30"E). No underway data were collected from the beginning of the transit since the pump which brings the surface water to the equilibrator malfunctioned. On September 22nd the cruise started out from Fremantle heading southwest. Upon reaching 40° S, 110° W the course turned more westerly until intercepting the 95° E meridian at 43° S. From here, the cruise track turned due north to 31° 30"S, 95° E. The transit to the 80° E line followed a southwest heading until reaching 35° 30"S 82° E. The course turned northwest to intercept the 80° E meridian at 34° 50"S. The 80° E hydrographic line continued up to 6° N. The vessel was scheduled to inport in Colombo, Sri Lanka but political turmoil forced the cruise to conclude on October 26th in Male, Maldives (4° 48"N, 76° 48"E). Figure 7 represents the cruise track for this leg.

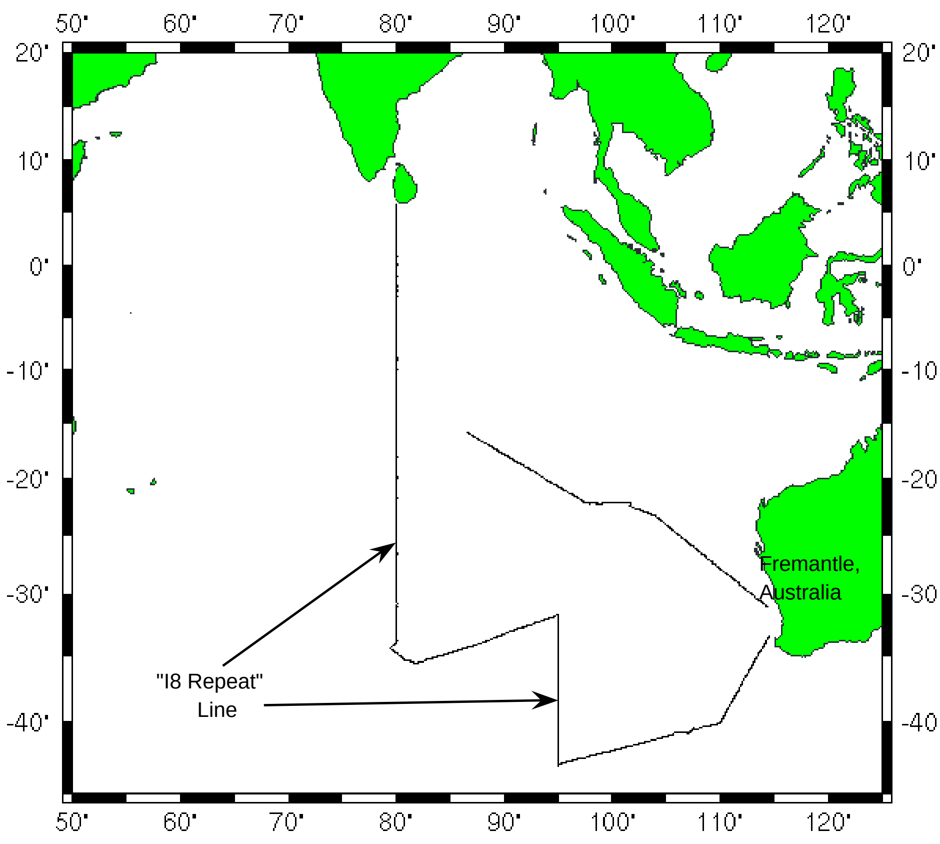


Figure 7. MB95-07 Cruise Track

Leg 8 From October 28th to November 8th, the ship transited from Male, Maldives to Darwin, Australia (9 º S, 108 º E) to load/offload the necessary equipment for the next project, Tropical Oceans Global Array / Tropical Atmosphere and Oceans (TOGA/TAO) study. The purpose of this cruise was to service a series of moored buoys deployed across the tropical Pacific. Figure 8a represents the cruise track for this transit.

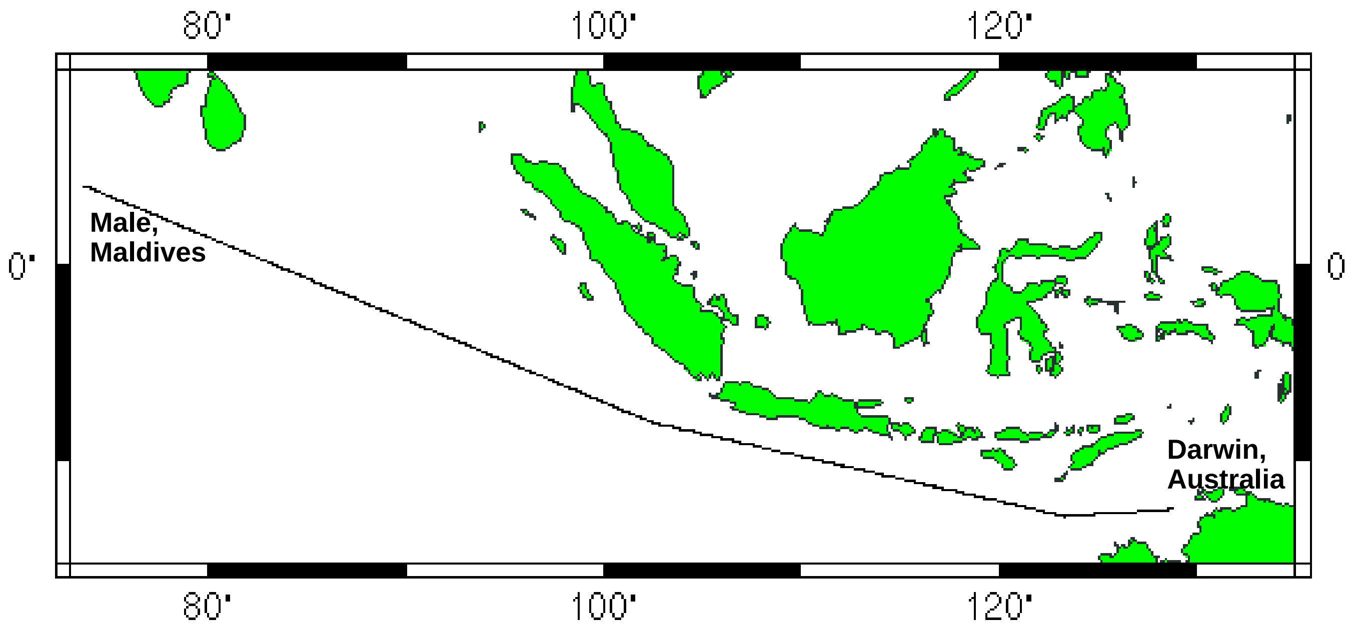


Figure 8a. MB95-08 Cruise Track

Leg 8 (cont.) On November 21st the vessel transited the Torres Straits on a easterly heading. Once in the Pacific, the ship continued east approximately along the 8° S parallel until reaching the International Date Line. The ship's course then changed due north progressing up to 2° N while working on moored oceanographic buoys along the way. The ship left the 180° line to head northeast to 4° N, 175° W. Once finished with the work the ship steamed northwest to 8° N, 180° . From here, the ship steamed due east to 8° N, 170° W. The course changed due south and the projected work continued down to 2° S. At this position operations were discontinued for a medical emergency that brought the ship into Pago Pago, American Samoa (14 ° S, 170 ° 30"E) on December 15th.

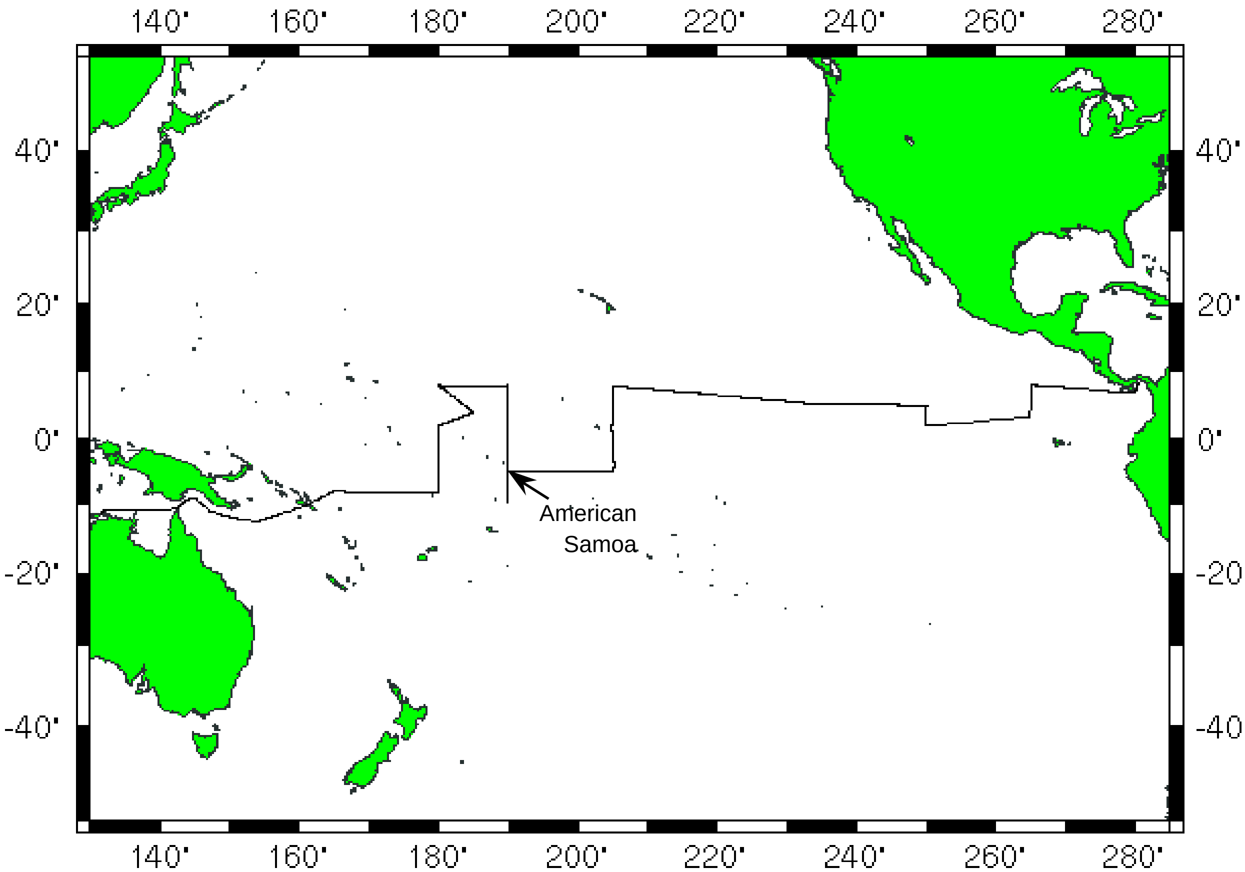


Figure 8b. MB95-08 Cruise Track

On December 19th, the ship departed Pago Pago, American Samoa to complete ATLAS mooring operations along the 180° meridian. It then transited along the 5° South parallel until reaching 155° West. The ship changed course to due north to perform operations on moorings along the 155° meridian. The ship completed operations on this line at 5° North. It then proceeded on a east, south-east heading to repair a buoy located at 5° North, 125° West. The project then continued eastward along 5° North to 110° West. The ship turned due south until reaching the equator. From here, the track changed again to a north-easterly heading until reaching 2° North, 95° West. The cruise's primary operations were completed at 8° North, 95° West. The ship arrived in Rodman, Panama on January 17th, 1996. Figure 8b represents the cruise track for the second and third parts of the leg.

Leg 8 (cont.) Transit was made through the Panama Canal on January 20th. Once exiting into the Carribbean, the ship took a north-westerly passage paralleling the Central American coast. The ship changed course to round the western edge of Cuba and then proceeded through the Straits of Florida until it reached Miami, Florida on January 23rd. On January 27th, the ship departed Miami to complete the field season by transiting to its home port of Charleston, South Carolina. Figure 8c represents the cruise track for the last part of the leg.

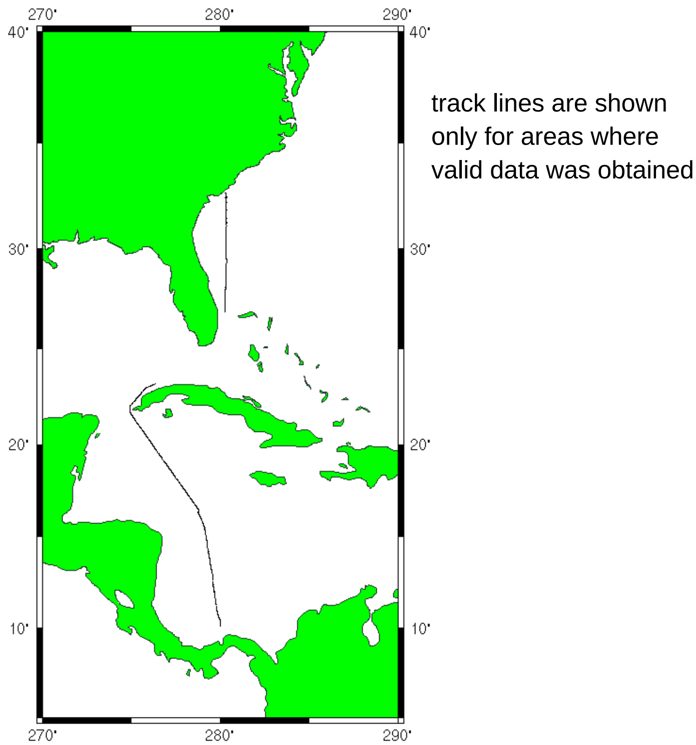


Figure 8c. MB95-08 Cruise Track

2.0 **Sampling & Analysis**

2.1 UW pCO_2 SYSTEM v1.5 DESCRIPTION:

A. Overview:

The Underway pCO_2 System version 1.5 (Ho *et. al*. 1997) is used to determine the pCO_2 of surface water and overlaying air on a continuous basis (Keeling 1965, Wanninkhof and Thoning 1993). When in operation, seawater is drawn from the uncontaminated seawater intake from the bow bubble approximately 6 meters below the water line to a shower head equilibrator located in the main laboratory, where the headspace and seawater reach equilibrium on a short time scale. At specific times during an hourly cycle, the content of the headspace is measured by an infrared CO_2 analyzer. Uncontaminated air from the marine boundary layer is drawn continuously from the bow mast to the underway pCO_2 system. At a designated time, air is analyzed by a the infrared CO_2 analyzer, otherwise the air is bled off through a vent .

The CO_2 measurements are made by a Li-Cor differential, non-dispersive, infrared (NDIR) CO_2 analyzer (model 6251), and the result is based on the difference in absorption of infrared (IR) radiation passing through two gas cells. The reference cell is continuously flushed with a gas of known CO_2 concentration using the lowest concentration of three reference gas standards. The sample cell is flushed with one of three reference gas standards, marine boundary layer air, or headspace gas from the equilibrator. Standards were calibrated by NOAA's Climate Monitoring & Diagnostic Laboratory (CMDL) before and after the cruise.

B. Standardization/Conversion Polynomial:

The underway system operates on an hourly cycle with the first 12 minutes of every hour devoted to Li-Cor calibration. Three different standard gases of known concentrations are sampled for 4 minutes each. These standards cover the CO_2 range that will likely be encountered on a cruise. A second order polynomial is calculated from a curve fitting of the three standard voltage values. This polynomial is used to convert any subsequent air or water Li-Cor voltage readings for the hour, to a pCO_2 concentration (ppm). During the post cruise data reduction, the Li-Cor voltages from the current hour standards are averaged with the standards from the next hour and then used to calculate a "bracketed" CO_2 reading.

C. Sampling/Data set:

References made to air or water readings are as follows: air readings refer to the atmospheric air that is sampled through an inlet located on the bow jack approximately 15 meters above the water line. This air is drawn by an Air Cadet, diaphragm pump through approximately 95 meters of Dekoron tubing with a 3/8" outer diameter and 1/4" inner diameter. The atmospheric air is drawn into a glass chamber that is jacketed by 6^{o} C water. This procedure condenses most of the water vapor from the air stream. Before the air is sampled it is flowed through a cell containing magnesium perchlorate trap to eliminate any remaining water vapor.

Water readings refer to headspace gas in an equilibrator described below, designed by Dr. Weiss of Scripps Institute of Oceanography (SIO). Gas samples drawn from this headspace are termed "water" because the headspace gas is allowed to equilibrate with the water showering through the space. The "water" sample is circulated through the infrared analyzer using a Spectrex AS300 rubber diaphragm pump. The "water" sample goes through another glass condensing chamber and then through the same magnesium perchlorate trap before entering the IR. Thus air, water and standard gases are analyzed dry.

The general time sampling sequence is as follows: the first 12 minutes are divided into four minute intervals, dedicated to sample each of the three reference gases. Next, the equilibrator headspace gas, "water" reading is sampled four times for 4.5 minutes each for a total of 18 minutes. This is followed by three bow air samples at 4 minutes each, totaling 12 minutes. Finally, the equilibrator headspace is sampled four more times at 4.5 minutes each, concluding the last 18 minutes of the hour.

Each sampling phase progresses in the following manner: the sample is flushed through the system for 3.5 minutes (the equilibrator sample has a longer flushing time of 4 minutes to ensure complete flushing of the new sample through the system). Then flow stops and the system is vented to equilibrate with ambient pressure for 10 seconds. The four analog channels (Li-Cor CO_2, Li-Cor cell temperature, equilibrator temperature, equilibrator water flow meter) are then scanned five times, taking about 3 seconds total. An average of these scans is printed on the screen and logged to a data file using a Keithley Metrabyte A/D board (model 24800). A Magellan GPS (model OEM2101A) and Setra barometer (model 370) are also read at this time through a RS-232 interface. A brief waiting period follows and then the next sample is introduced. During post cruise data reduction, thermosalinograph (TSG) temperature and salinity data are incorporated into the pCO_2 data file.

Table 2. Example of screen display of underway pCO_2 system 1.5

Gas in IR: Water / Start at : 22:24:23 / Status : flush / sec. remaining : 40

GPS: 2544.08,N,08009.73,W

LAST 60 MIN AVG. AND STD. DEV

CO2 Standards Information

STD #	STD_1	STD_2	STD_3
STD ppm	296.53	347.87	524.87
STD mV	-18.1	312.1	1126

Sample	**P.P.M**	**Std. Dev**
WATER	350.53	0.15
AIR	356.64	2.52
WATER	350.34	0.34

GAS	**TIME**	**D.LAT**	**D.LON**	**pCO2_PPM**	**IR_TEMP**	**EQ_TEMP**	**EQ_FLOW**	**PRESSURE**
WAT	01:16:05	25.66	80.17	350.54	24.2	26.1	10	1014.53
WAT	01:20:05	25.66	80.17	350.49	24.2	26.2	10	1014.53
WAT	01:25:05	25.66	80.17	350.65	24.3	26.2	10	1014.53
WAT	01:29:05	25.66	80.17	350.51	24.2	26.3	10	1014.22
AIR	01:33:45	25.66	80.17	356.51	24.3	26.2	11	1014.89
AIR	01:37:45	25.66	80.17	356.99	24.3	26.4	11	1014.89
AIR	01:41:45	25.66	80.17	356.14	24.3	26.5	11	1014.89
WAT	01:46:45	25.66	80.17	349.88	24.2	26.2	10	1014.27
WAT	01:50:45	25.66	80.17	350.09	24.2	26.3	10	1014.82
WAT	01:55:45	25.66	80.17	350.77	24.3	26.4	10	1014.42
WAT	01:59:45	25.66	80.17	350.89	24.2	26.1	10	1014.22

10-14-1996 01:59:59 **DOC/NOAA/AOML/OCD/CO2**

Table 2 is a representation of the screen display of the underway pCO_2 system 1.5. Starting from the upper right corner, the gas being analyzed in the IR is displayed; STD, Air or Water. To the left, the time at which that phase began is shown. Next is the action occurring within that phase (flush, pause, scan, save). On the top, right is the seconds remaining for that action. On the second line, the previous phase's GPS fix is listed on screen until the scan action is initiated. The "CO2 Standards Information" sub-table lists the concentrations of the three standards and their corresponding millivolt readings from the Li-Cor for that hour. To the right is another sub-table with average CO_2 concentration readings and the standard deviation calculated within that phase for the three sampling phases from the previous hour. The main part of the table lists the sampling phase, the time at which the scanned IR information was saved, the latitude and longitude, the calculated pCO_2 concentration, the IR temperature, the temperature of a thermistor submerged in the equilibrator, the flow rate of water into the equilibrator and the barometric pressure. A date and time stamp are located in the lower left corner.

D. Calculations:

The dry mixing ratios of ambient air and equilibrated headspace air are calculated by fitting a second-order polynomial through the hourly averaged response of the detector versus mixing ratio of the standards. Mixing ratios of dried equilibrated headspace and air are converted to fugacity of CO_2 in surface seawater and water saturated air in order to determine the ΔfCO_2 which is (fCO_{2eq}-$fCO_{2\ a}$). For ambient air and equilibrator headspace the $fCO_{2\ a}$, or $fCO_{2\ eq}$ is calculated assuming 100 % water vapor content:

$$fCO_{2a/eq} = [XCO_{2a/eq}\ (P\text{-}pH_2O)]\ \exp(B_{11} + 2\beta_{12})\ P/RT_{sst/eq} \qquad (1)$$

where $fCO_{2a/eq}$ is the fugacity in ambient air or equilibrator, pH_2O is the water vapor pressure at sea surface temperature, P is the atmospheric pressure (in atm) , and $T_{sst/eq}$ is the sea surface temperature (SST) or equilibrator temperature (in K) and R is the ideal gas constant (82.057 cm^3 atm/deg/mol). The exponential term is the fugacity correction where B_{11} is the second viral coefficient of pure CO_2 (B_{11}= -1636.75 + 12.0408 T - 0.0327957 T^2 + 3.16528*10^{-5} T^3) and β_{12}=(57.7 - 0.118 T) is the correction for an air-CO_2 mixture in units of cm^3/mol (Weiss, 1974) . The calculation for the fugacity at SST incorporates a temperature correction term for the increase of fCO_2 due to heating of the water from passing through the pump and through 100 meters of 5 cm inner diameter (ID) PVC insulated tubing within the ship. The water in the equilibrator is typically 0.2°C warmer than sea surface temperature. The empirical temperature correction from equilibrator temperature to SST is outlined in Weiss (1982):

$$\Delta \ln(fCO_2) = (t_{eq} - SST)\ (0.0317 - 2.785\ 10^{-4}\ t_{eq} - 1.839\ 10^{-3}\ \ln\ (fCO_{2eq}) \qquad (2)$$

where $\Delta \ln(fCO_2)$ is the difference between the natural logarithm of the fugacity at t_{eq} and SST, and t_{eq} is the equilibrator temperature in °C.

E. Sources of Error:

Accuracy and precision for the Li-Cor infrared analyzer are determined by instrument performance, gas calibration, and uncertainties in the calculations leading from instrument response to the fCO_2 value. On leg MB95-01 concurrent discrete and underway air samples were taken. The discrete samples were shipped to CMDL for analysis. The accuracy for air samples were determined by this comparison and the results are shown in Table 18. On average the underway air samples were 0.5 ppm higher than the flask samples. The accuracy for the IR is rated 1ppm at 350 ppm (LiCor, 1990). Instrument precision during the water phase was estimated to have a standard deviation of 0.228 ppm over a three hour period and is shown in Table 19. For a more detailed description and performance of system 1.5 refer to the NOAA Data Report ERL-AOML-30 by Ho, *et al.* (1997).

The other possible sources of error include: (1) pressure variability within the equilibrator, (2) seawater flow fluctuations, (3) contamination through vent lines, and (4) changes in the standard gas concentrations. The possibility for a difference in pressure within the equilibrator compared to the outside has been minimized by installing two vent lines from the top of the equilibrator, through an

external ship bulkhead. Approximately 7.5 meters of Dekoron tubing, with a 1/4" ID was used for the vent lines.

Seawater flow fluctuations are monitored by using a water flow meter. The in-line meter is installed before the equilibrator. The paddle wheel rotation creates a current that is linearly related to a flow rate (L/min). Data taken at flow rates below 5 L/min are eliminated. Flow rates above 15 L/min tend to aspirate marine air into the equilibrator through the vent lines. Data corresponding to these higher flow rates are compared against data recorded within a 2 hour period that have acceptable flow rates, and are retained only if the CO_2 value in question is within one standard deviation of the average of the adjacent hour's readings.

Air contamination by large sea salt particles containing carbon is minimized by an initial filter on the inlet located on the bow jack. The inlet is also shielded from rain and is configured in a 2 meter U-shape so that water could drain back out of the tubing before being drawn down to the condensing tube. After the condensing tube, the air stream is passed through a Gelman Sciences, Acro 50, PTFE 1.0 μm pore filter (lot #1542) to remove particulate matter. Since the air is continuously flowing through the bow line, the Li-Cor analyzes "fresh" air when an air sampling phase begins.

Once the standard tank pressure is below 500 psi, the tank is replaced with another of known, similar concentration. The removed tank is returned to CMDL for a post cruise calibration. Table 3 shows the comparison of the concentrations of standard gases calibrated at CMDL before February 1995 and post calibrated in April 1996. The differences in the post-calibration standard values were not appreciable to affect a change in the second order polynomial used to compute the sample concentration values. Tanks listed as "not calibrated yet" are still being used in the field.

Table 3. Comparison of CO_2 gas standard concentrations

Pre-cruise Concentration (ppm)	**Post-cruise Concentration (ppm)**	**Change in Concentration**
307.12	307.13	+ 0.01
315.05	315.05	0.00
347.87	347.89	+ 0.02
348.10	347.90	- 0.20
348.58	348.64	+ 0.06
401.13	401.04	- 0.09
410.54	not recalibrated yet	
524.87	not recalibrated yet	
527.94	528.00	+ 0.06

F. Thermistor Calibrations:

Seawater temperature within the equilibrator was measured using a YSI resistance thermistor probe secured into the bottom of the equilibrator, producing a nominal resistance of 1000 ohms at 25˚C. The thermistor was calibrated against readings taken from a Guildline digital platinum resistance thermometer (model 9540) during specified inports (see Appendix A). A second order calibration polynomial was created after curve-fitting thermistor resistances (x) versus the temperature readings (y) for the first two legs. A third order polynomial was used thereafter. This new polynomial was placed into the program to yield underway temperature values. Table 4 lists for a given thermistor resistance what

Table 4. Thermistor Calibration Comparison

Given Resistance	(2/12/95) Therm Equation Leg 1	(2/20/95) Therm Equation Leg 1	(3/21/95) Therm Equation Leg 2	(4/25/95) Therm Equation Leg 3	(5/28/95) Therm Equation Leg 4	(7/10/95) Therm Equation Leg 5	(7/28/96) Therm Equation Leg 6	(9/20/95) Therm Equation Leg 7	(3/29/96) Post Cruise	Standard Deviation of 9 Calibrations
1300	*35.57*	*35.53*	*36.51*	*36.87*	*36.83*	*36.35*	*36.43*	*36.67*	*36.42*	0.49
1350	*34.73*	*34.70*	*35.52*	*35.81*	*35.79*	*35.38*	*35.47*	*35.67*	*35.44*	0.41
1400	*33.90*	*33.87*	*34.55*	*34.79*	*34.79*	*34.45*	*34.54*	*34.69*	*34.49*	0.34
1450	*33.08*	*33.05*	*33.61*	*33.80*	*33.81*	**33.53**	*33.62*	*33.74*	**33.57**	0.28
1500	*32.28*	*32.25*	*32.70*	*32.84*	*32.87*	**32.64**	*32.73*	*32.81*	**32.66**	0.23
1550	*31.49*	*31.46*	*31.81*	**31.91**	**31.95**	**31.76**	**31.86**	*31.91*	**31.78**	0.18
1600	*30.71*	*30.69*	**30.94**	**31.01**	**31.05**	**30.91**	**31.01**	*31.03*	**30.93**	0.14
1650	*29.94*	*29.92*	**30.10**	**30.14**	**30.19**	**30.09**	**30.17**	**30.18**	**30.09**	0.10
1700	**29.19**	**29.17**	**29.28**	**29.30**	**29.35**	**29.28**	**29.36**	**29.35**	**29.28**	0.07
1750	**28.45**	**28.43**	**28.48**	**28.49**	**28.53**	**28.49**	**28.57**	**28.54**	**28.49**	0.05
1800	**27.72**	**27.70**	**27.71**	*27.70*	**27.74**	**27.72**	**27.80**	**27.76**	**27.72**	0.03
1850	**27.01**	**26.99**	**26.95**	*26.94*	**26.97**	**26.98**	**27.04**	**26.99**	**26.96**	0.03
1900	**26.30**	**26.28**	**26.22**	*26.20*	**26.23**	**26.25**	**26.31**	**26.25**	**26.23**	0.04
1950	**25.61**	**25.59**	**25.51**	*25.48*	**25.51**	**25.54**	**25.59**	**25.53**	**25.52**	0.05
2000	**24.94**	**24.91**	**24.81**	*24.78*	*24.80*	**24.84**	**24.89**	**24.83**	**24.83**	0.05
2050	**24.27**	**24.25**	**24.13**	*24.11*	*24.12*	**24.17**	**24.21**	**24.14**	**24.15**	0.06
2100	**23.62**	**23.60**	**23.48**	*23.46*	*23.46*	**23.51**	**23.54**	**23.48**	**23.49**	0.06
2150	**22.98**	**22.95**	**22.84**	*22.82*	*22.82*	**22.87**	**22.89**	**22.84**	**22.85**	0.06
2200	**22.35**	**22.33**	**22.21**	*22.21*	*22.19*	**22.25**	**22.26**	**22.21**	**22.23**	0.06
2250	**21.74**	**21.71**	**21.61**	*21.61*	*21.59*	**21.64**	**21.64**	**21.60**	**21.62**	0.05
2300	**21.13**	**21.11**	**21.02**	*21.02*	*21.00*	**21.04**	**21.04**	**21.00**	**21.03**	0.05
2350	**20.54**	**20.52**	**20.44**	*20.46*	*20.43*	**20.46**	**20.46**	**20.42**	**20.45**	0.04
2400	**19.97**	**19.94**	**19.88**	*19.90*	*19.87*	*19.90*	**19.88**	**19.86**	**19.89**	0.03
2450	**19.40**	**19.37**	*19.34*	*19.36*	*19.33*	*19.35*	*19.33*	**19.32**	**19.35**	0.03
2500	**18.85**	**18.82**	*18.80*	*18.83*	*18.80*	*18.82*	*18.78*	**18.78**	**18.81**	0.02
2550	**18.31**	**18.28**	*18.28*	*18.32*	*18.28*	*18.29*	*18.25*	**18.26**	**18.29**	0.02
2600	**17.78**	**17.75**	*17.78*	*17.81*	*17.78*	*17.78*	*17.74*	**17.76**	**17.78**	0.02
2650	**17.27**	**17.23**	*17.28*	*17.31*	*17.29*	*17.28*	*17.23*	**17.26**	**17.29**	0.03
2700	**16.77**	**16.73**	*16.80*	*16.82*	*16.81*	*16.80*	*16.74*	**16.78**	**16.80**	0.03
2750	**16.28**	**16.23**	*16.33*	*16.34*	*16.34*	*16.32*	*16.26*	**16.31**	**16.33**	0.04
2800	*15.80*	*15.76*	*15.87*	*15.87*	*15.88*	*15.86*	*15.79*	**15.86**	**15.87**	0.04
2850	*15.34*	*15.29*	*15.42*	*15.40*	*15.43*	*15.41*	*15.34*	**15.41**	**15.42**	0.05
2900	*14.89*	*14.83*	*14.98*	*14.93*	*14.99*	*14.96*	*14.89*	**14.97**	**14.98**	0.05

Table 4. Thermistor Calibration Comparison

Given Resistance	(2/12/95) Therm Equation Leg 1	(2/20/95) Therm Equation Leg 1	(3/21/95) Therm Equation Leg 2	(4/25/95) Therm Equation Leg 3	(5/28/95) Therm Equation Leg 4	(7/10/95) Therm Equation Leg 5	(7/28/96) Therm Equation Leg 6	(9/20/95) Therm Equation Leg 7	(3/29/96) Post Cruise	Standard Deviation of 9 Calibrations
2950	14.45	14.39	14.54	14.47	14.56	14.53	14.46	**14.54**	**14.55**	0.06
3000	14.03	13.96	14.12	14.01	14.13	14.11	14.03	**14.13**	**14.12**	0.06
3050	13.61	13.54	13.70	13.55	13.71	13.69	13.62	**13.72**	**13.71**	0.07
3100	13.21	13.14	13.29	13.10	13.30	13.28	13.21	**13.31**	**13.30**	0.08
3150	12.82	12.75	12.89	12.64	12.89	12.88	12.82	**12.92**	**12.90**	0.09
3200	12.45	12.37	12.49	12.18	12.48	12.49	12.43	**12.53**	**12.51**	0.11
3250	12.09	12.00	12.10	11.72	12.08	12.11	12.05	**12.15**	**12.12**	0.13
3300	11.74	11.64	11.71	11.26	11.68	11.73	11.68	**11.77**	**11.74**	0.16
3350	11.40	11.30	11.32	10.79	11.29	11.35	11.32	**11.40**	**11.37**	0.19
3400	11.07	10.97	10.94	10.31	10.89	10.99	10.97	**11.03**	**11.00**	0.23
3450	10.76	10.65	10.57	9.83	10.49	10.62	10.62	**10.67**	**10.63**	0.27
3500	10.46	10.35	10.19	9.35	10.10	10.27	10.28	**10.31**	**10.27**	0.33
3550	10.17	10.05	9.82	8.85	9.70	9.91	9.94	9.95	9.91	0.38
3600	9.90	9.77	9.45	8.34	9.30	9.56	9.61	9.60	9.55	0.45
3650	9.64	9.50	9.08	7.83	8.90	9.22	9.29	9.24	9.20	0.52
3700	9.39	9.25	8.71	7.30	8.50	8.88	8.97	8.89	8.85	0.60
3750	9.15	9.01	8.34	6.76	8.09	8.53	8.65	8.54	8.50	0.69
3800	8.93	8.77	7.97	6.21	7.68	8.20	8.34	8.19	8.15	0.79
3850	8.72	8.56	7.60	5.65	7.27	7.86	8.04	7.84	7.80	0.89
3900	8.52	8.35	7.22	5.07	6.84	7.52	7.73	7.49	7.46	1.00
3950	8.33	8.16	6.85	4.47	6.42	7.19	7.43	7.13	7.11	1.12
4000	8.16	7.97	6.47	3.86	5.98	6.85	7.14	6.78	6.76	1.26
4050	8.00	7.80	6.09	3.23	5.54	6.52	6.84	6.42	6.41	1.40
4100	7.85	7.65	5.70	2.58	5.08	6.18	6.55	6.06	6.05	1.55

The table shows , for the given resistances, the temperature calculated using the polynomial formulated before the ship departed that particular inport.
The bold faced temperatures encompass the temperature range encountered from the date of the current column to the following column.

the calculated temperature would be using the polynomial listed in that column . Calculated temperatures in bold type represent the temperature range encountered at sea from the current calibration date to the following calibration. The standard deviation for each row is calculated. An average of these deviations for the temperature range encountered on the entire field season was 0.089. This average deviation corresponds to an uncertainty of 1.3 µatm in calculated fCO_2. Individual tables and graphs of each temperature calibration are located in Appendix A.

2.2 TOTAL DISSOLVED INORGANIC CARBON (DIC)

In order to improve our mechanistic understanding of processes controlling surface water fCO_2 levels, it is desirable to have information about at least one other carbon system parameter. For the round-the-world campaign on the MALCOLM BALDRIGE, total dissolved inorganic CO_2 (DIC) samples were taken at 6-hour intervals by the survey department. The samples were stored up to a week, and on occasion up to a month, before being analyzed on board.

In short, the samples were analyzed by these following procedures: DIC samples were drawn from 10-l Niskin bottles or from the bow sampling line into 500 ml Pyrex bottles using Tygon tubing. Each sample had 0.2 ml of a saturated $HgCl_2$ solution added as preservative. The sample bottles were sealed with glass stoppers lightly covered with Apiezon grease. The samples were then stored in darkness at ambient (room) temperature up to the point of analysis.

DIC analyses was performed by extracting the inorganic carbon from a 20 ml aliquot of sea water sample by acidification and subsequent displacement of the gaseous CO_2 into a coulometer cell using an automated SOMMA (single operator multi-parameter metabolic analyzer) system. Details concerning this system and procedures are presented in Johnson (1992), and Johnson et al. (1993). Precision based on replicates and analyses of certified reference materials is estimated at 1.5 µmol/kg. Different instruments were used on the legs of the cruise and slightly different procedures were followed. On legs when no hydrographic conductivity/temperature/depth (CTD) casts were performed samples were drawn from the underway seawater system with an inlet at nominally 6 meters below sea level; the same inlet used to feed the underway fCO_2 system. On legs where CTD casts were performed, most samples were taken from the top Niskin bottle that collected water within the upper 10 m. Three different coulometers with SOMMA inlet were used during the cruise (see Table 6). Each system was calibrated with certified reference materials (CRM's) obtained from Dr. A. Dickson of Scripps Institute of Oceanography (SIO) and certified by manometry at the laboratory of Dr. C. D. Keeling of SIO. Salinity and DIC data obtained from each system were normalized for the offset between measured and certified value by subtraction on a per leg basis. For legs on which less than eight CRM's were analyzed, the data from previous leg was used for normalization. Our experience has been that the offsets in the coulometers remains steady for months at a time. The individual SOMMA offsets which were applied to the data sets are listed in Table 5. For the last part of cruise MB95-08 from Darwin to Miami no fully trained operator was on board for DIC analyses. Instead the SOMMA was operated by the survey department. The SOMMA was not operating in optimal condition and the data is believed to be of poorer quality.

The data can be found in electronic format at *ftp://ftp.aoml.noaa.gov/pub/ocd/carbon/ uwpco295*. A selection of the data output in appropriate format can be found in Table 7. An explanation of the data columns can be found in Table 6.

Table 5. Salinity and DIC offsets applied to DIC data

Cruise	Date		Port of Call	SOMMA*	Offset DIC†	Offset Sal††.
MB95-01	Depart	2/13/95	Miami, FL	AOML-1	2.25	0
	Arrive	2/17/95	San Juan, Puerto Rico			
MB95-01	Depart	2/22/95	San Juan, Puerto Rico	AOML-1	2.25	0
	Arrive	3/17/95	Durban, South Africa			
MB95-02	Depart	3/21/95	Durban, South Africa	AOML-1	2.8	0
	Arrive	4/20/95	Colombo, Sri Lanka			
MB95-03	Depart	4/27/95	Colombo, Sri Lanka	AOML-1	1.9	0
	Arrive	5/25/95	Muscat, Oman		1.26	0
MB95-04	Depart	5/31/95	Muscat, Oman	AOML-2	0.8	0.16
	Arrive	6/23/96	Male, Maldives			
MB95-04	Depart	6/24/95	Male, Maldives	AOML-2	0.8	0.16
	Arrive	6/30/95	Victoria, Seychelles			
MB95-05	Depart	7/12/95	Victoria, Seychelles	AOML-1	0.8	0.16
	Arrive	7/24/95	Muscat, Oman			
MB95-06	Depart	7/31/95	Muscat, Oman	AOML-2	0.81	0.16
	Arrive	8/28/95	Diego Garcia, UK			
MB95-07	Depart	8/30/95	Diego Garcia, UK	AOML-2	1.12	0.16
	Arrive	9/8/95	Fremantle, Australia			
MB95-07	Depart	9/22/95	Fremantle, Australia	AOML-2	1.12	0.16
	Arrive	10/25/95	Male, Maldives	PMEL-1	-0.29	0.11
MB95-08	Depart	10/28/95	Male, Maldives	AOML-2	1.12	0.16
	Arrive	11/8/95	Darwin, Australia			
MB95-08	Depart	11/21/95	Darwin, Australia	AOML-2	1.12	0.16
	Arrive	12/15/95	Pago Pago, American Samoa			
MB95-08	Depart	12/19/95	Pago Pago, American Samoa	AOML-2	1.12	0.16
	Arrive	1/15/96	Rodman, Panama (Pacific)			
MB95-08	Depart	1/20/96	Colon, Panama via Panama Canal	AOML-2	1.12	0.16
	Arrive	1/23/96	Miami, FL			
MB95-08	Depart	1/27/96	Miami, FL	no samples		
	Arrive	1/29/96	Charleston, SC			

* the suffix appended to the SOMMA name indicates the SOMMA unit
† Offset DIC = measured CRM value-certified value from SIO
†† Offset Sal = measured salinity on SOMMA-salinity from CTD or TSG

Table 6. Explanation of columns in underway DIC file (See *ftp://ftp.aoml.noaa.gov/pub/carbon/uwpco295*)

Column heading	Explanation
Cruise	Cruise designation (for details see Table 5)
JD (dec)	Fractional Julian day
Lat	Latitude (decimal degrees)
Long	Longitude (decimal degrees)
SommaSal	Salinity as measured by the conductivity cell on the SOMMA with the following corrections subtracted from the observed value: AOML-1 = 0 AOML-2 = 0.16 PMEL-1 = 0.1
Type	Samples were either obtained from the bow intake at 5-m depth (UW) or from the top Niskin bottle (CTD)
QC	Quality control flag: 0 = no quality control 2 = acceptable measurement 3 = questionable measurement 6 = duplicate measurement
DIC [µmol/kg]	Concentration of total dissolved inorganic carbon with corrections applied to account for dilution with mercuric chloride solution and normalized to the average CRM value.
RM correct	CRM value correction that was subtracted from the measured value
SST (TSG)	Sea surface temperature from a thermosalinograph at the bow intake
Sal (TSG)	Salinity from a thermosalinograph at the bow intake
fCO_{2w}	Fugacity of CO_2 in surface water at the time that the DIC sample was taken
ΔfCO_2	Water-air fugacity difference at the time that the DIC sample was taken

Table 7: Example of file of underway DIC measurements (see *ftp.aoml.noaa.gov/pub/ocd/carbon/uwpco295*)

Cruise	JD (dec)	Lat	Long	Somma Sal	Type	QC	DIC [µmol/kg]	RM correct	SST (TSG)	Sal (TSG)	fCO_{2w}	ΔfCO_2
MB95-01	53.75	19.00	-65.00	35.90	UW	2	1991.7	2.3				
MB95-01	54.02	19.00	-64.50	35.7	UW	2	1982.3	2.3				
MB95-01	54.50	18.00	-61.00	35.94	UW	2	1991.3	2.3				
MB95-01	54.75	17.50	-59.50	35.96	UW	2	1991.3	2.3				
MB95-01	55.01	17.00	-58.00	36.06	UW	2	1995.2	2.3				
MB95-01	55.28	16.50	-57.00	36.30	UW	2	2003.6	2.3				
MB95-01	55.50	16.13	-56.04	36.53	UW	2	2015.7	2.3	25.83	36.60	321.95	-28.35
MB95-01	55.75	15.66	-54.89	35.70	UW	2	1979.2	2.3	25.56	35.77	316.38	-33.40
MB95-01	56.01	15.12	-53.66	36.25	UW	2	2001.9	2.3	25.40	36.30	316.55	-33.79
MB95-01	56.28	14.63	-52.46	35.96	UW	2	1988.2	2.3	25.69	36.00	318.53	-31.41
MB95-01	56.50	14.19	-51.44	36.13	UW	2	1997.5	2.3	25.62	36.16	319.66	-30.89
MB95-01	56.75	13.65	-50.18	36.12	UW	2	2003.2	2.3	25.61	36.16	328.01	-21.91
MB95-01	57.01	13.12	-48.94	36.02	UW	2	2003.4	2.3	25.24	36.03	327.99	-22.49
MB95-01	57.28	12.53	-47.55	36.15	UW	2	2012.5	2.3	25.28	36.15	337.29	-12.53
MB95-01	57.50	12.02	-46.38	36.12	UW	2	2014.5	2.3	25.17	36.16	337.93	-12.67
MB95-01	57.75	11.49	-45.11	36.09	UW	2	2015.3	2.3	25.00	36.15	339.83	-10.34
MB95-01	58.01	10.93	-43.82	36.20	UW	2	2024.8	2.3	25.02	36.31	345.58	-5.66
MB95-01	58.25	10.43	-42.64	36.10	UW	2	2019.4	2.3	24.69	36.13	340.26	-10.25
MB95-01	58.50	9.88	-41.38	36.36	UW	2	2038.0	2.3	24.63	36.40	348.86	-2.05
MB95-01	58.75	9.39	-40.21	36.20	UW	2	2017.8	2.3	25.40	36.22	340.42	-8.96
MB95-01	59.01	8.81	-38.91	36.22	UW	2	2022.4	2.3	26.20	36.27	357.78	8.05
MB95-01	59.29	8.18	-37.46	36.20	UW	2	2018.2	2.3	26.14	36.24	351.02	2.24
MB95-01	59.50	7.70	-36.34	36.03	UW	2	2004.7	2.3	26.69	36.08	351.97	2.35
MB95-01	59.77	7.12	-35.01	36.08	UW	2	2007.6	2.3	26.72	36.13	353.16	4.66

3. GRAPHICAL fCO_2 REPRESENTATIONS

The fCO_2 data is broken up into a series of graphical representations. Several legs were divided into different graphs to depict how the fCO_2 data changed along the ship track. Each of the following pages has three graphs. The heading of the graphs indicate the cruise leg number (*see example below*) and beginning to ending points. The top graph plots the fCO_2 (µatm) overlayed on the ship track. The fCO_2 in the surface air (f(CO2)a) and fCO_2 in the surface water (f(CO2)w, in situ) are both in the left y-axis. The ship track is represented by the axes of latitude and longitude (bottom and right axes). The bottom graph plots salinity ($^{o}/_{oo}$) and sea surface temperature (^{o}C) from the ship mounted thermosalinograph (TSG) versus the same x-axis as the fCO_2 plot. The range of fCO_2 , temperature and salinity varies from each graph. The third graph is an inset on the right side of the page, between the top and bottom graphs. It depicts the ship track for that leg and if the fCO_2 and TSG plots are of a particular division of that leg, it will indicate the location of that data during that leg.

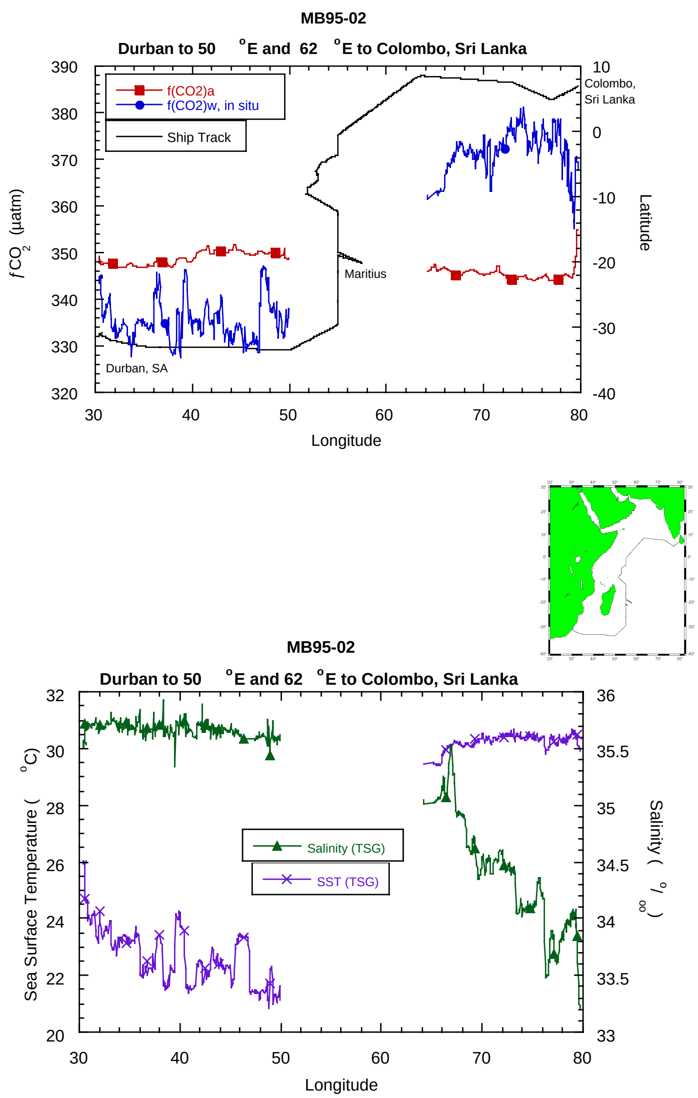
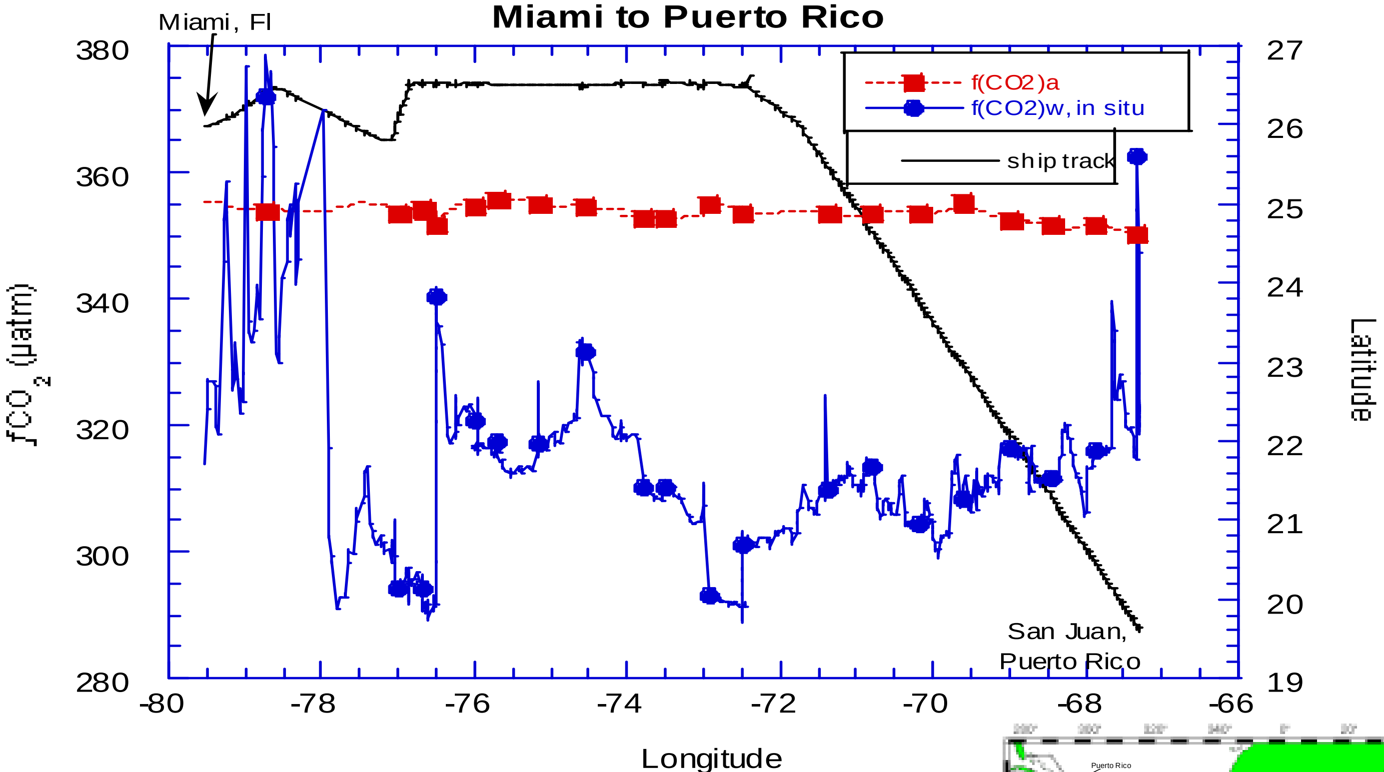
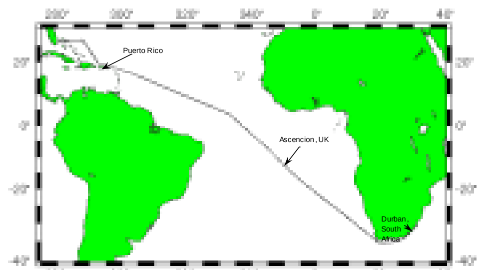


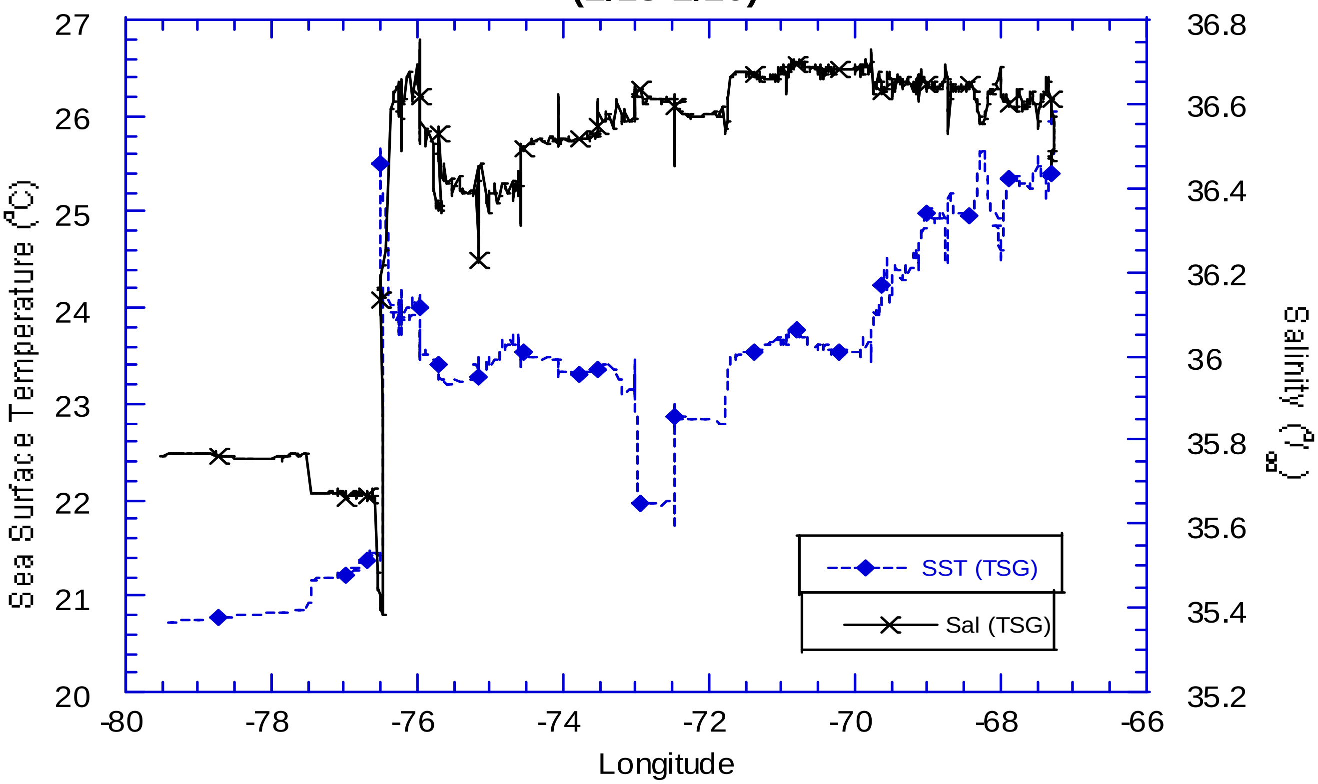
Figure 9. An example of the graphical representations of Section 3.

MB95-01 (2/13-2/20)
Miami to Puerto Rico

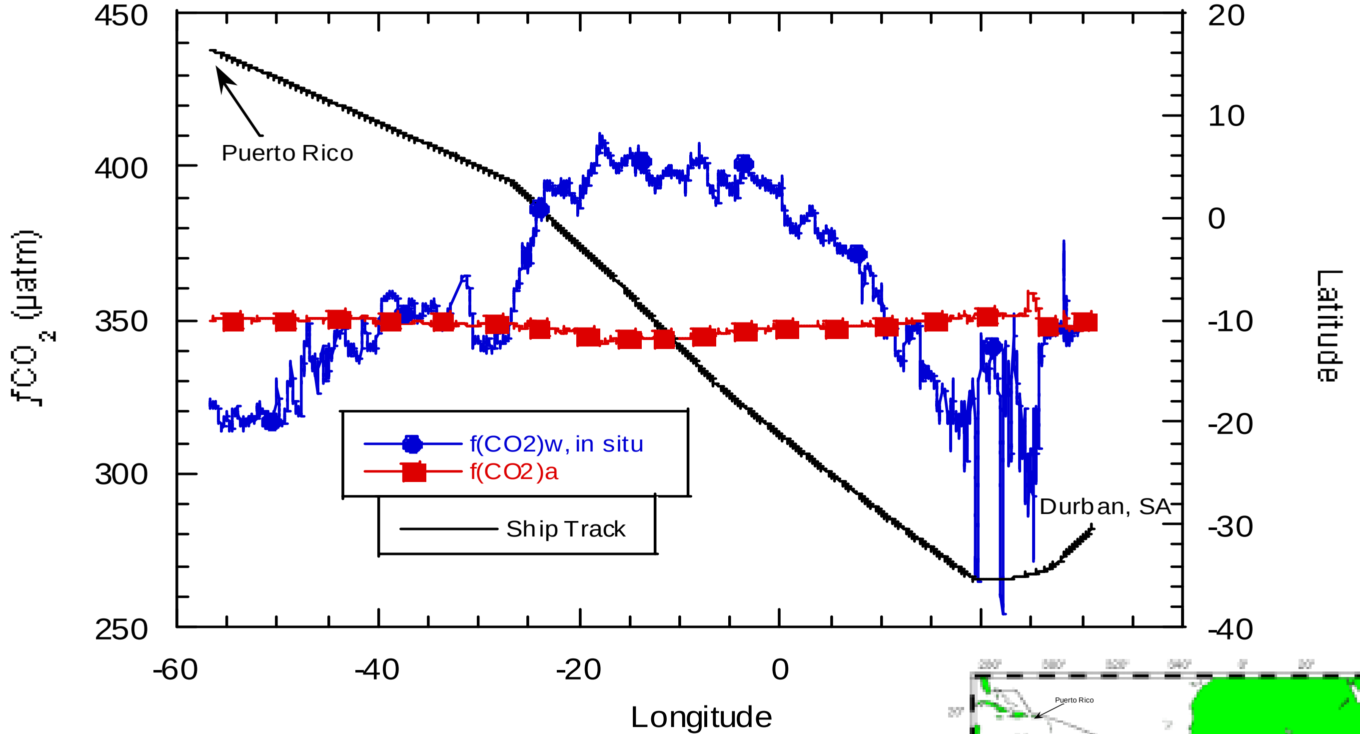


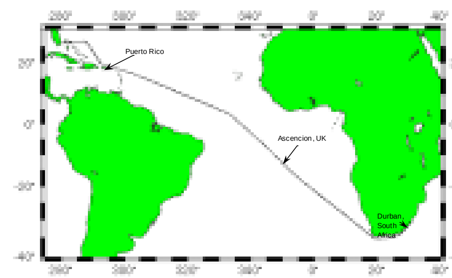


MB95-01 Miami to Puerto Rico
(2/13-2/20)

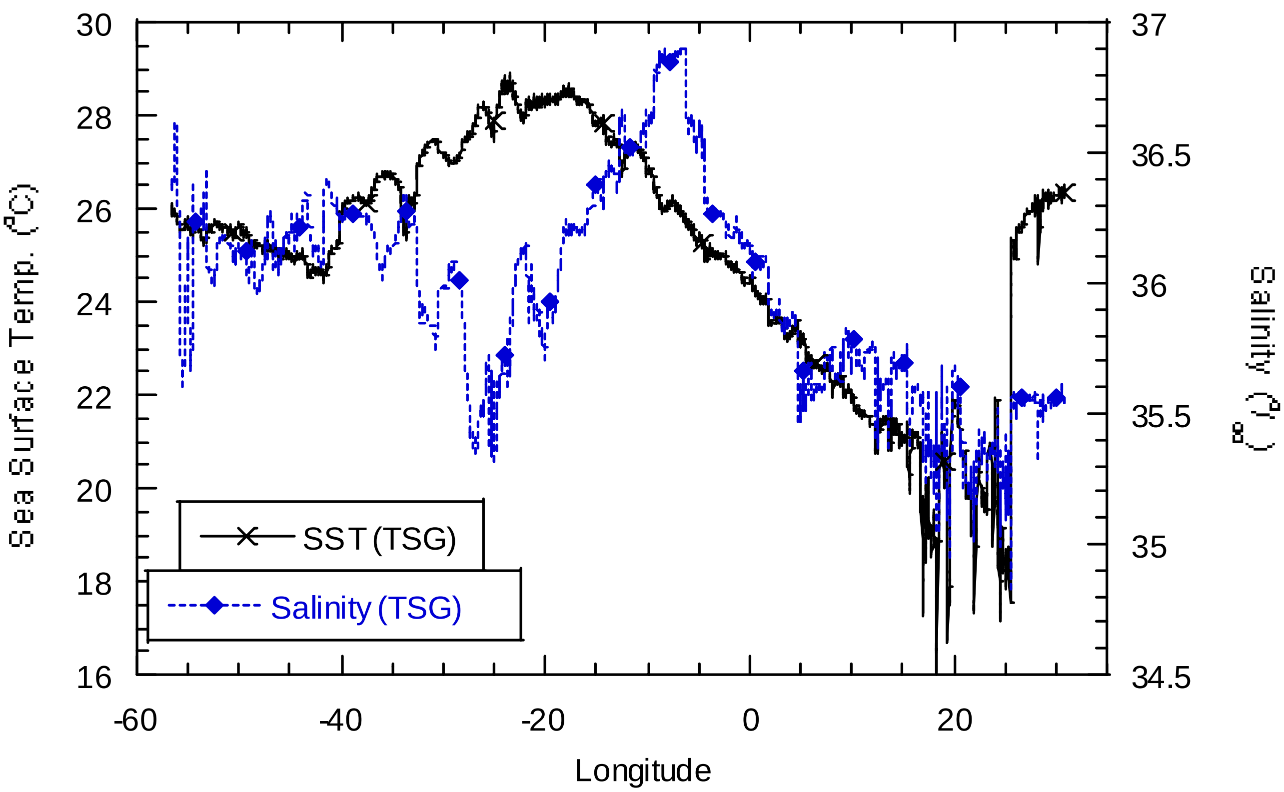


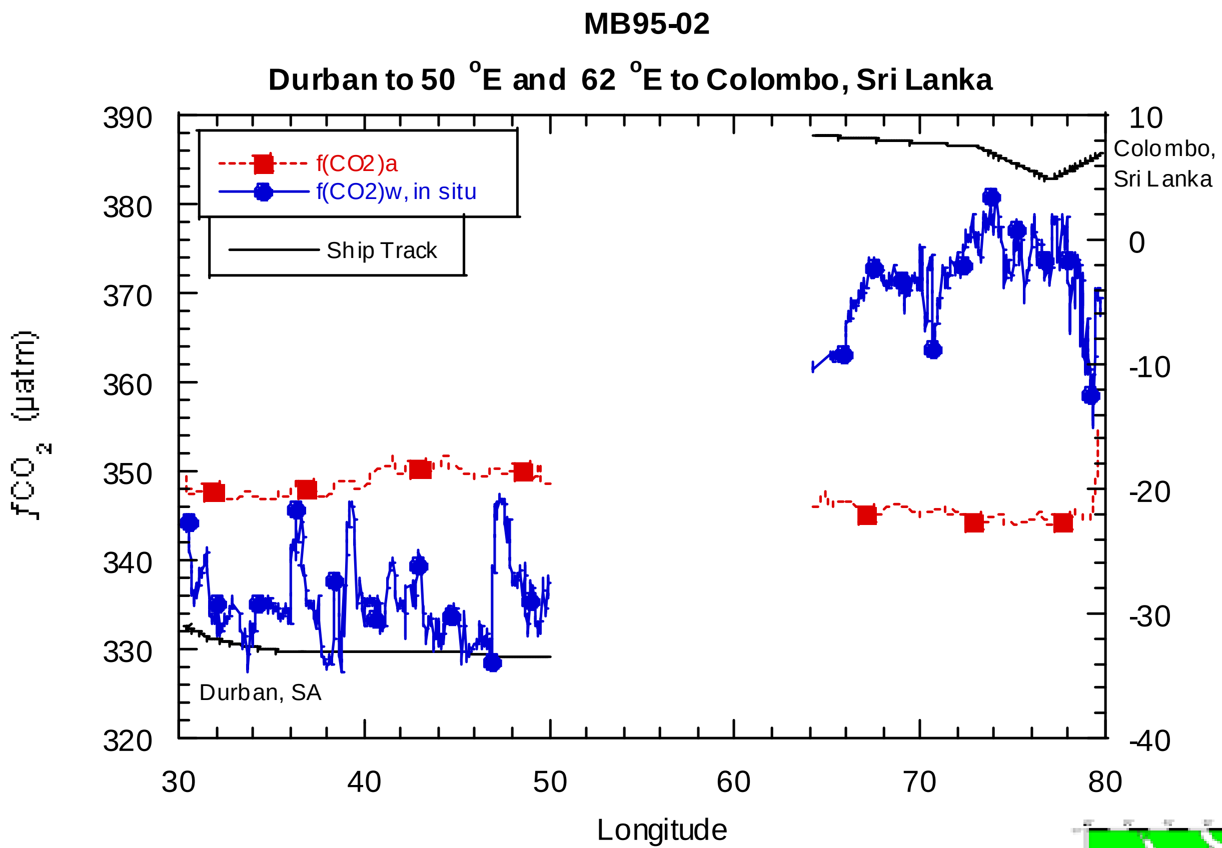
MB95-01 (2/24-3/16)
Puerto Rico to Durban, South Africa



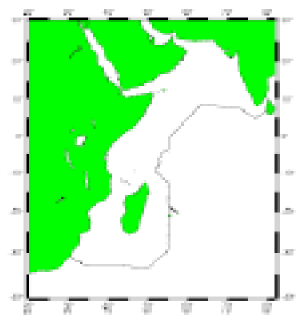


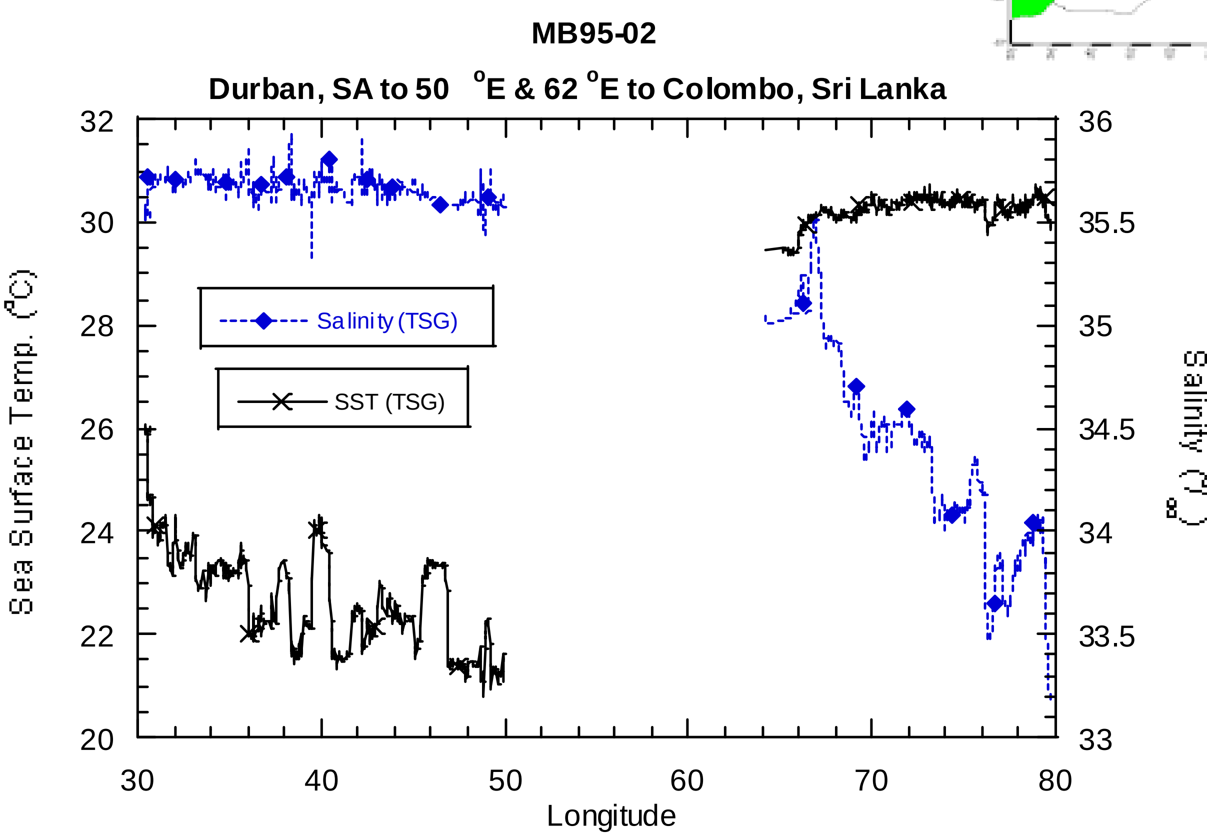
MB95-01 (2/24-3/16)





MB95-02
Durban to 50 °E and 62 °E to Colombo, Sri Lanka
f(CO2)a
f(CO2)w, in situ
Ship Track
Colombo, Sri Lanka
Durban, SA
fCO2 (µatm)
Latitude
Longitude

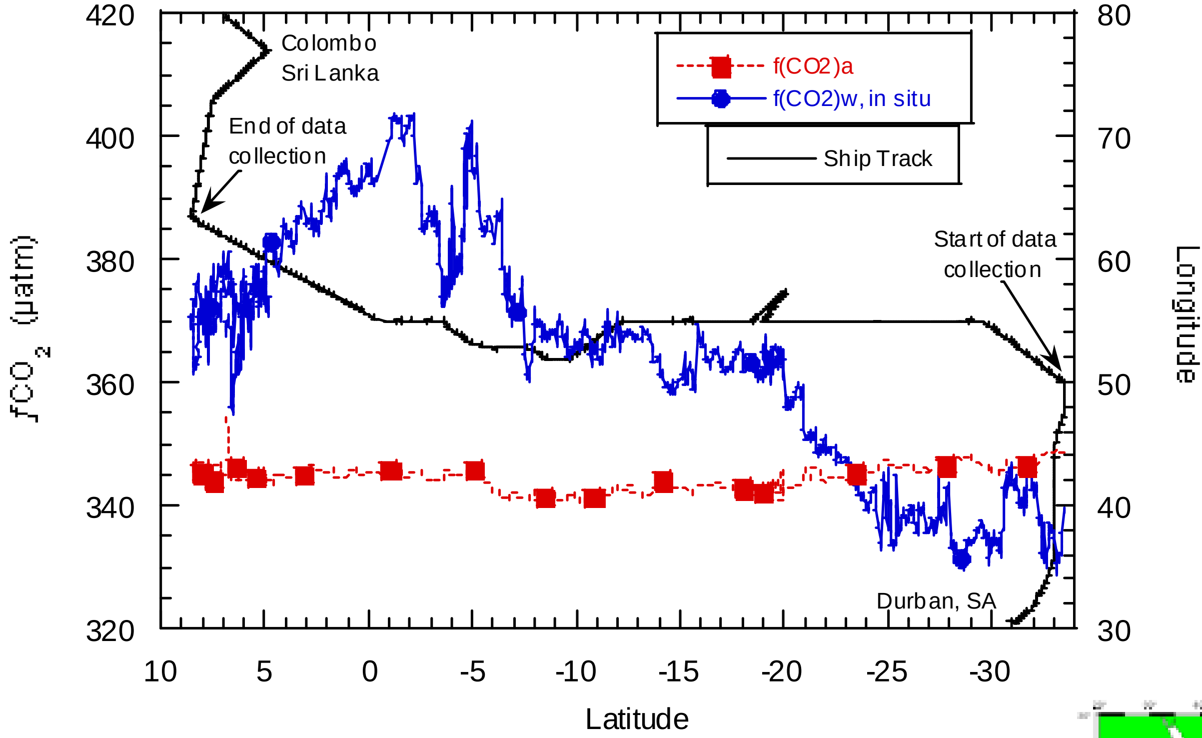


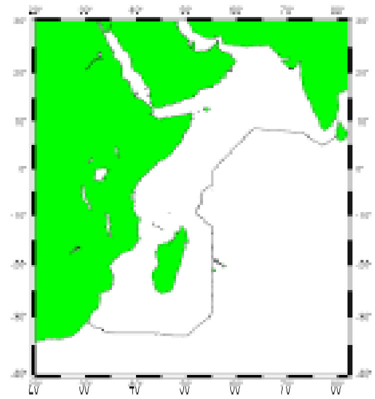


MB95-02
Durban, SA to 50 °E & 62 °E to Colombo, Sri Lanka
Salinity (TSG)
SST (TSG)
Sea Surface Temp. (°C)
Salinity (‰)
Longitude

MB95-02 (3/27-4/18)

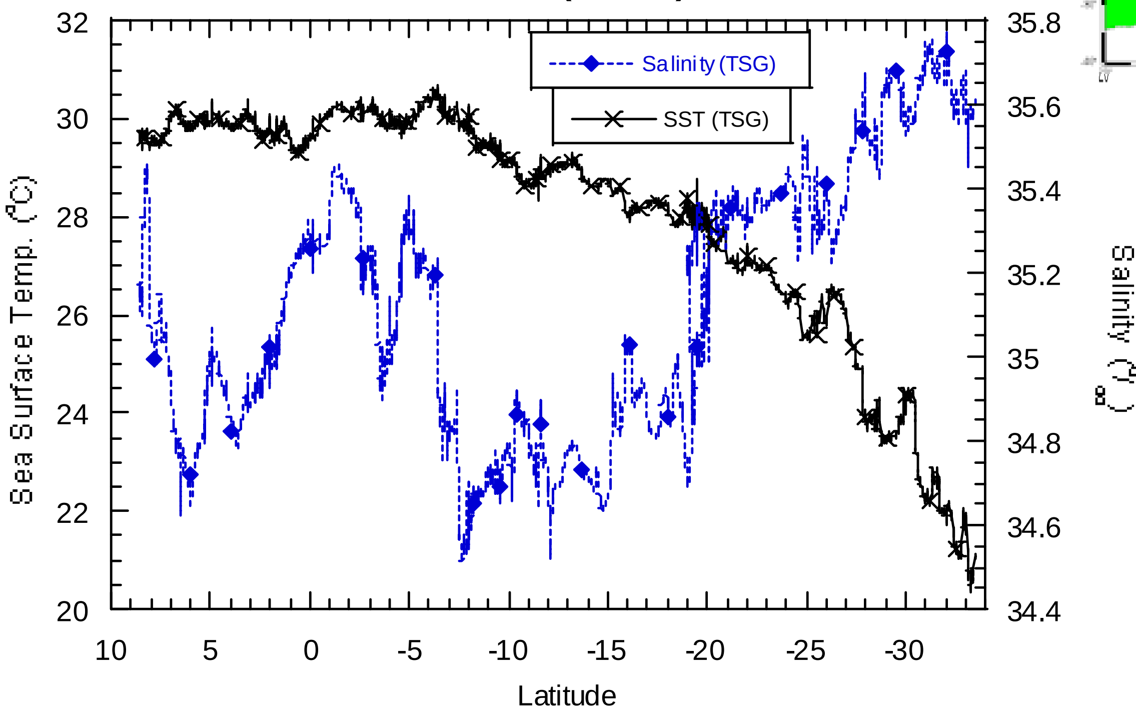
55° East Meridian (WOCE) Transect





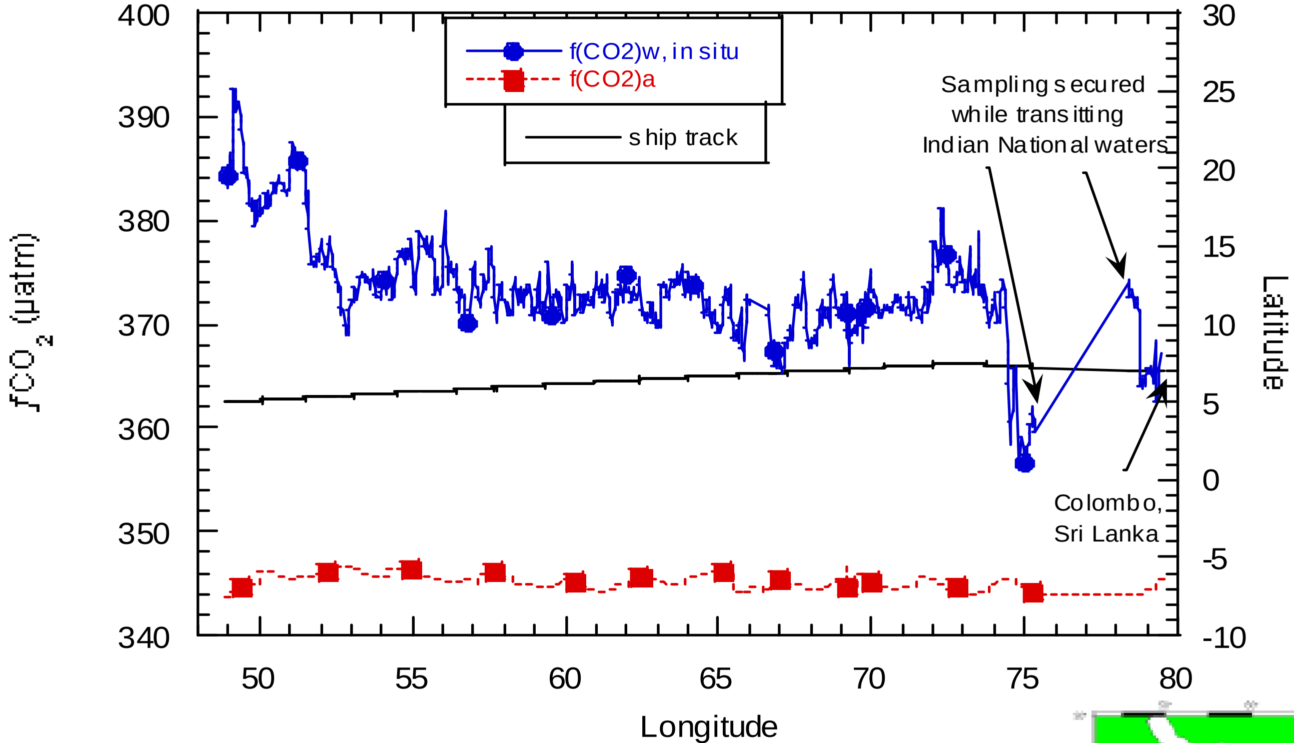
MB95-02

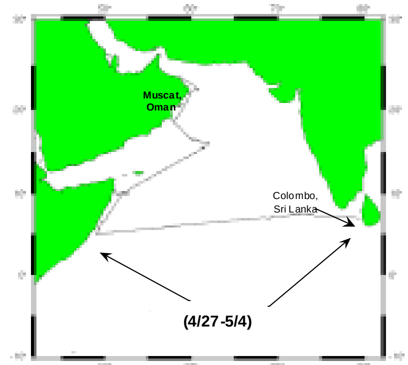
55° E Meridian (WOCE) Transect



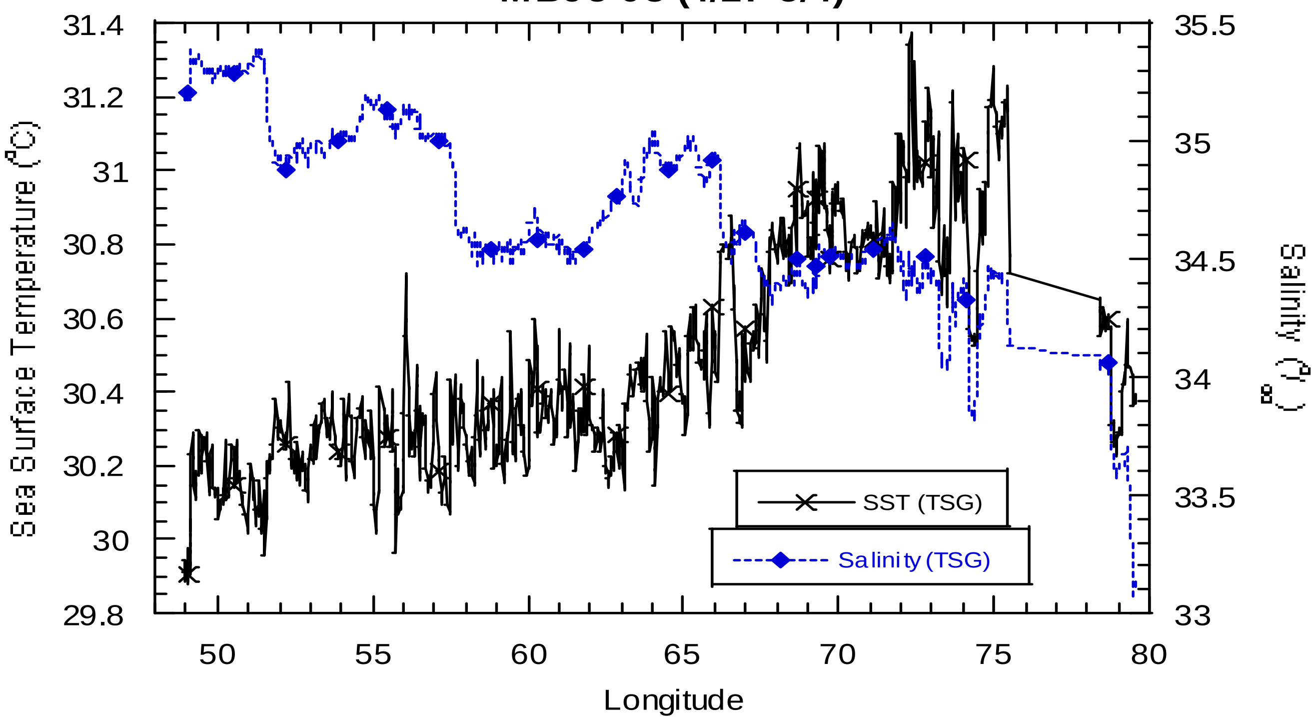
MB95-03 (4/27-5/4)

Colombo, Sri Lanka to 5°S



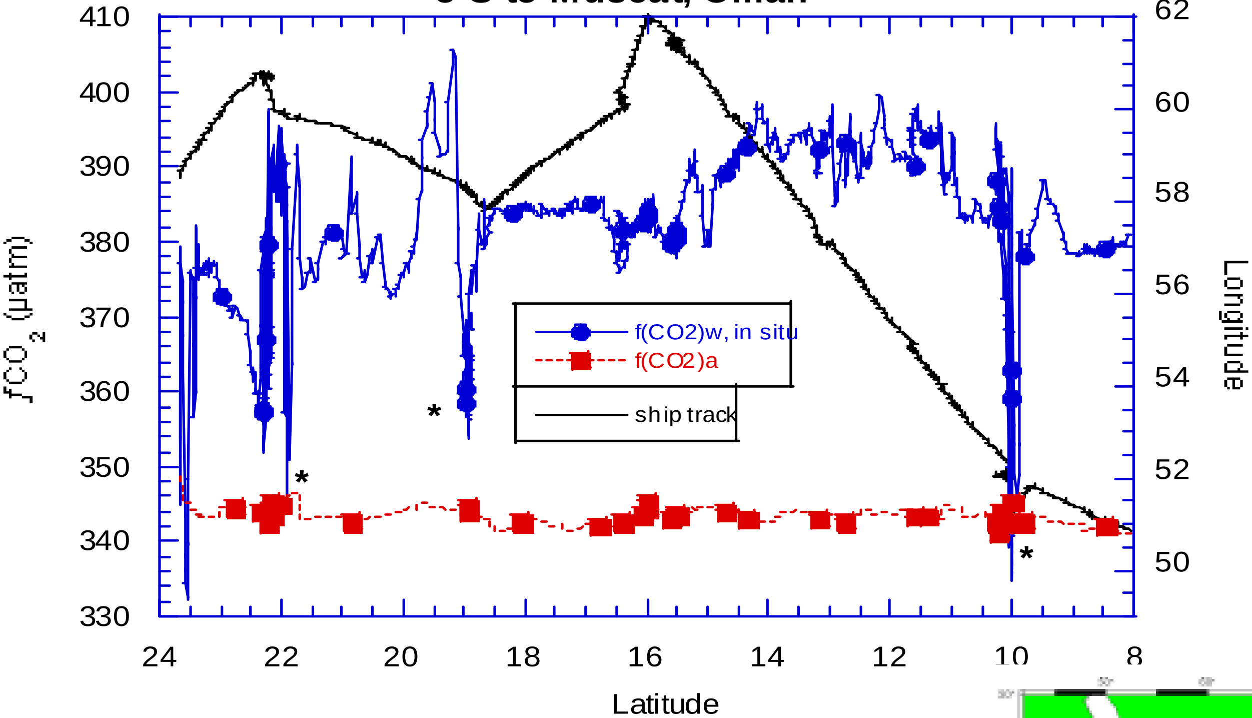


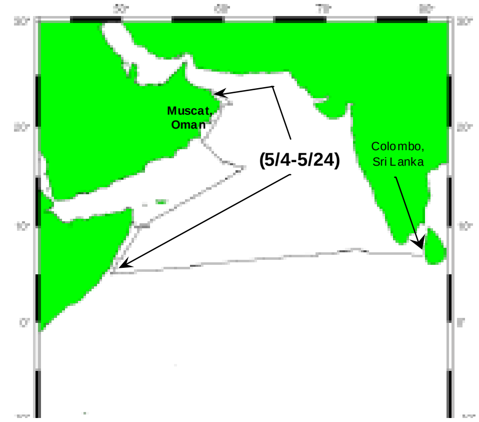
MB95-03 (4/27-5/4)



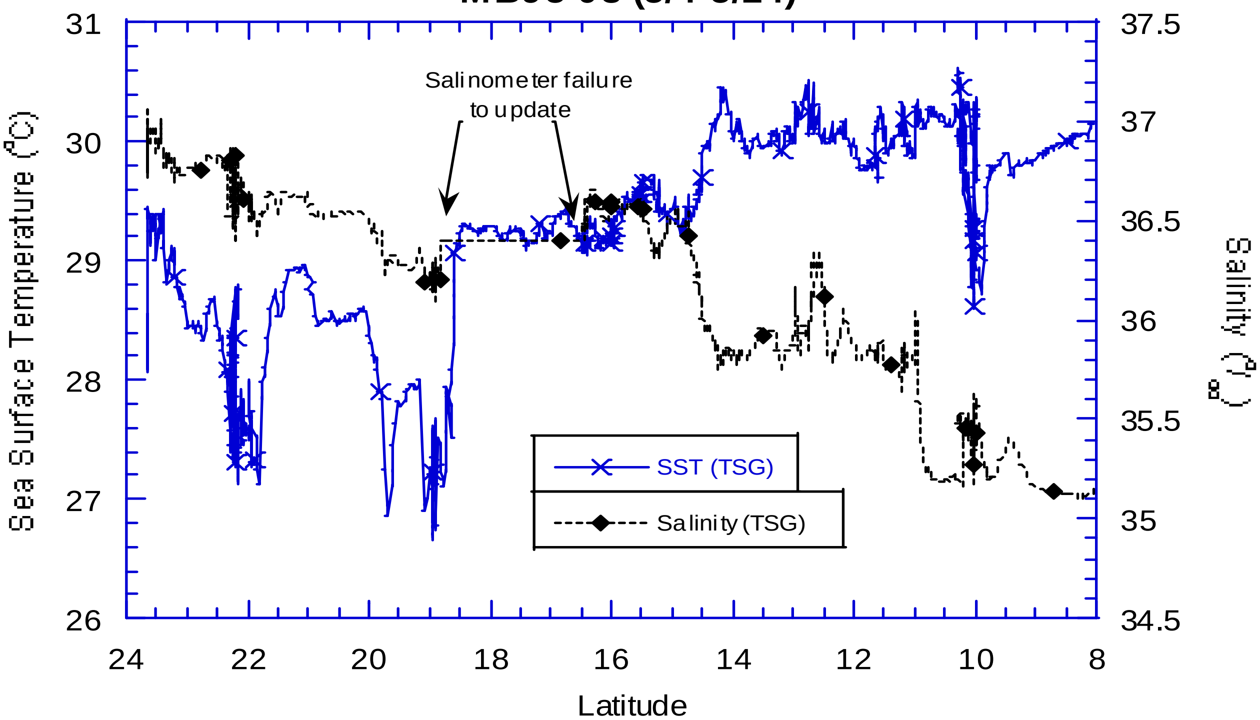
MB95-03 (5/4-5/24)

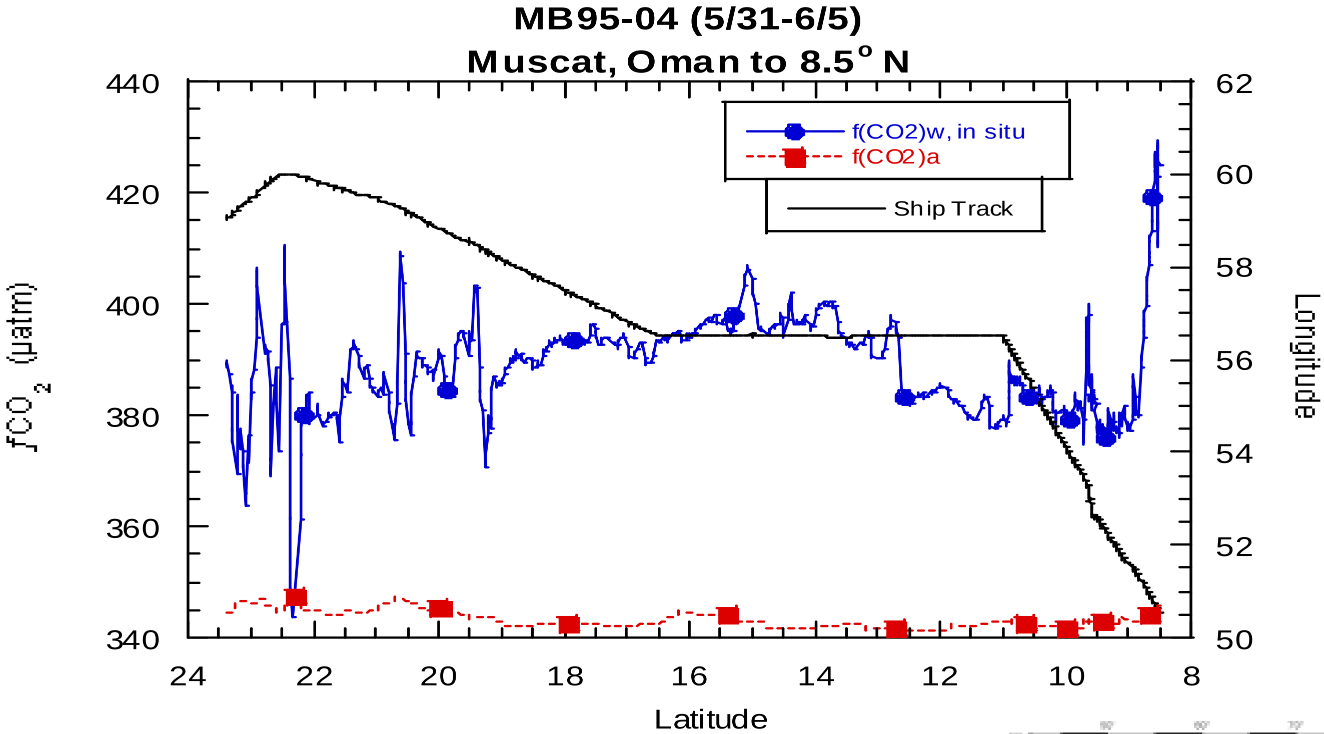
5°S to Muscat, Oman

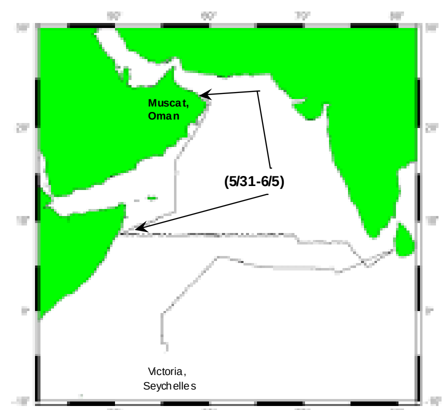


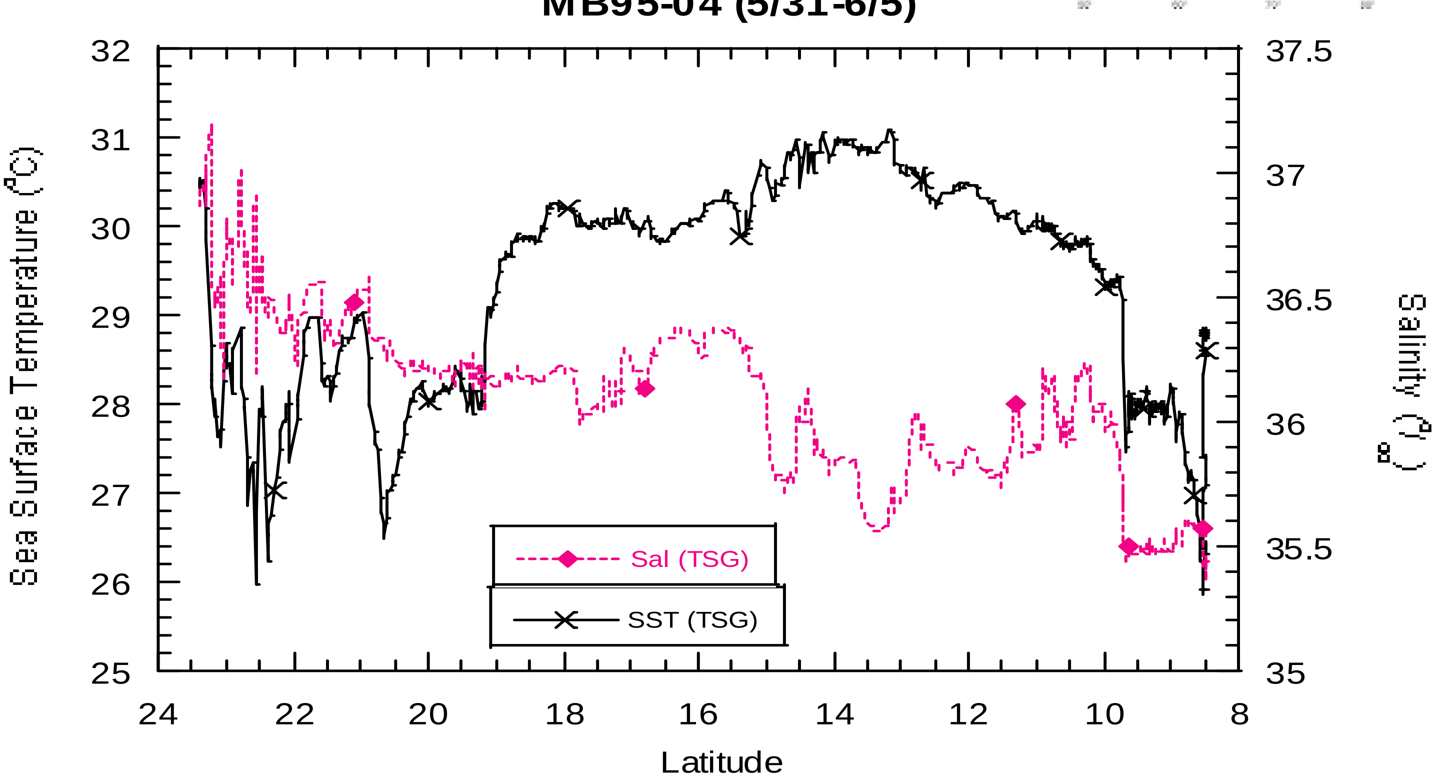


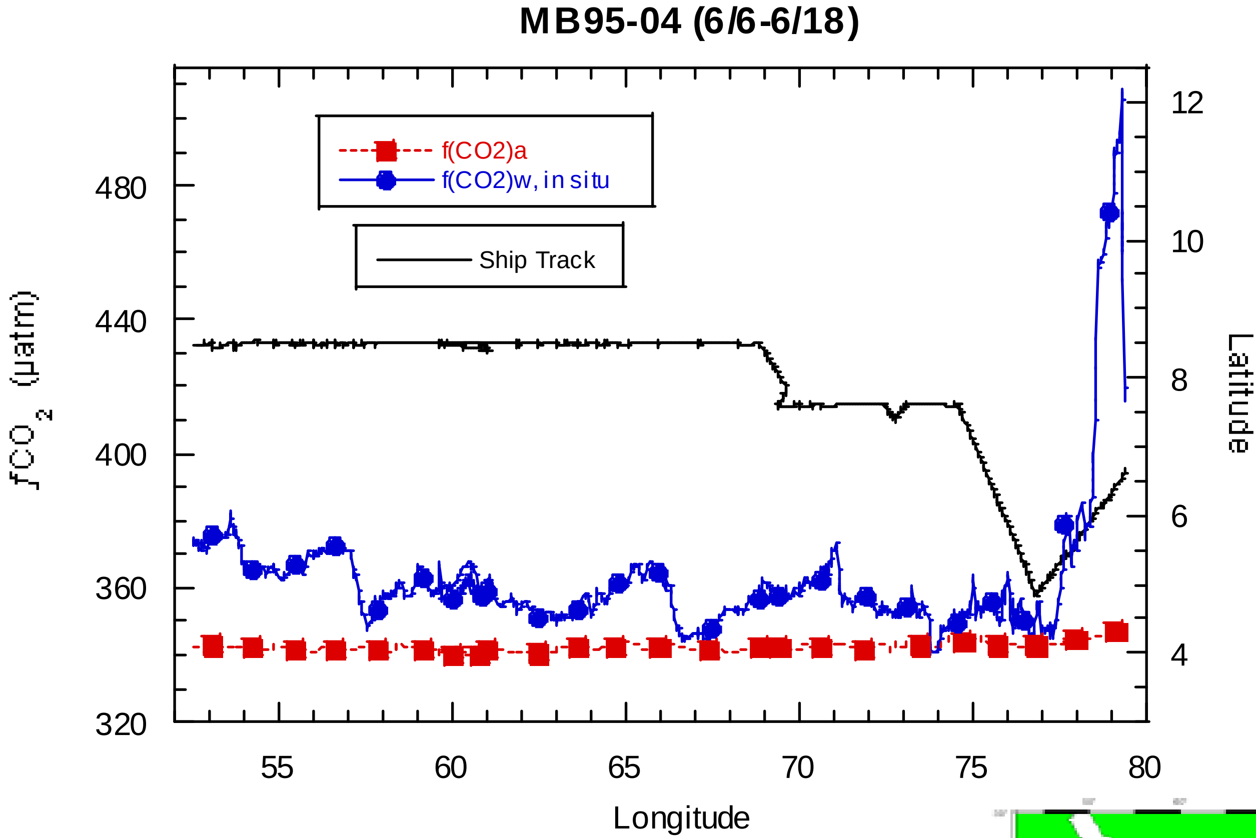
MB95-03 (5/4-5/24)

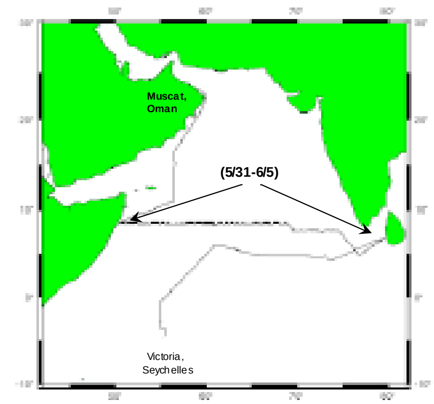


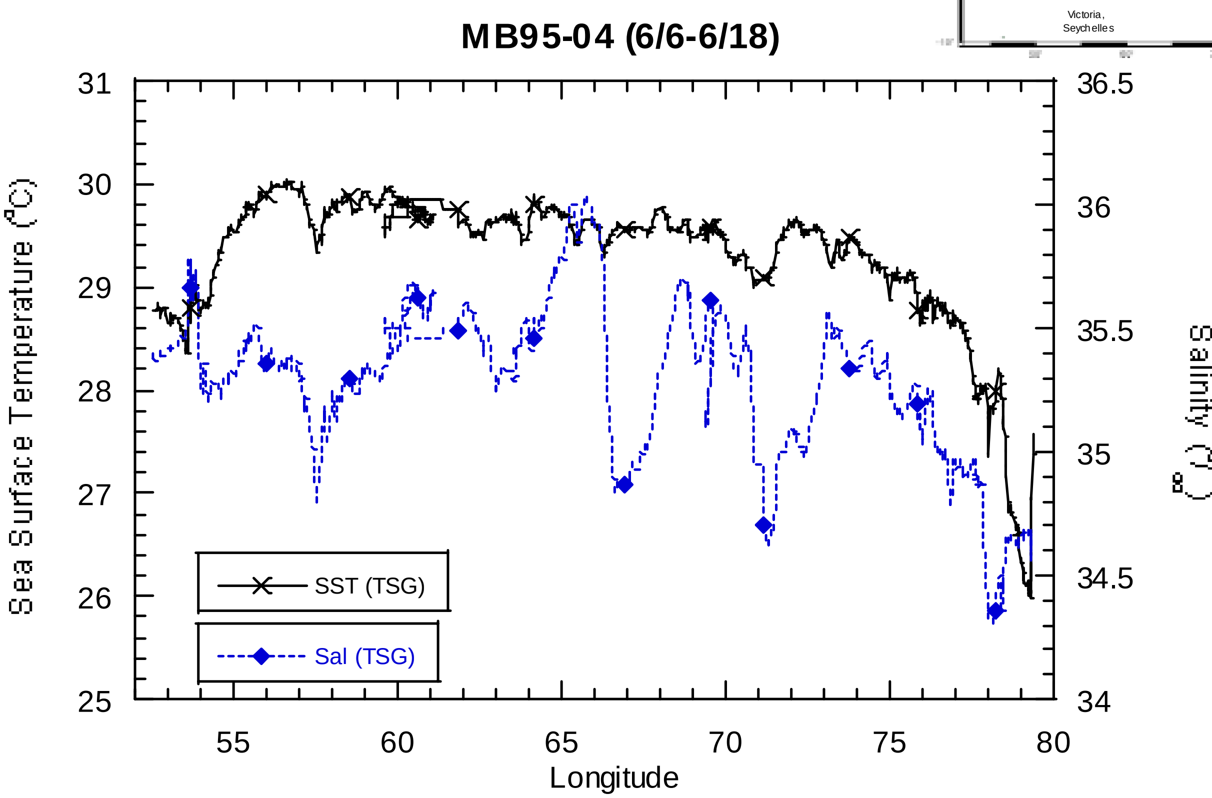

MB95-04 (5/31-6/5)
Muscat, Oman to 8.5° N
f(CO2)w, in situ
f(CO2)a
Ship Track
fCO2 (µatm)
Longitude
Latitude
440
420
400
380
360
340
62
60
58
56
54
52
50
24
22
20
18
16
14
12
10
8


Muscat, Oman
(5/31-6/5)
Victoria, Seychelles

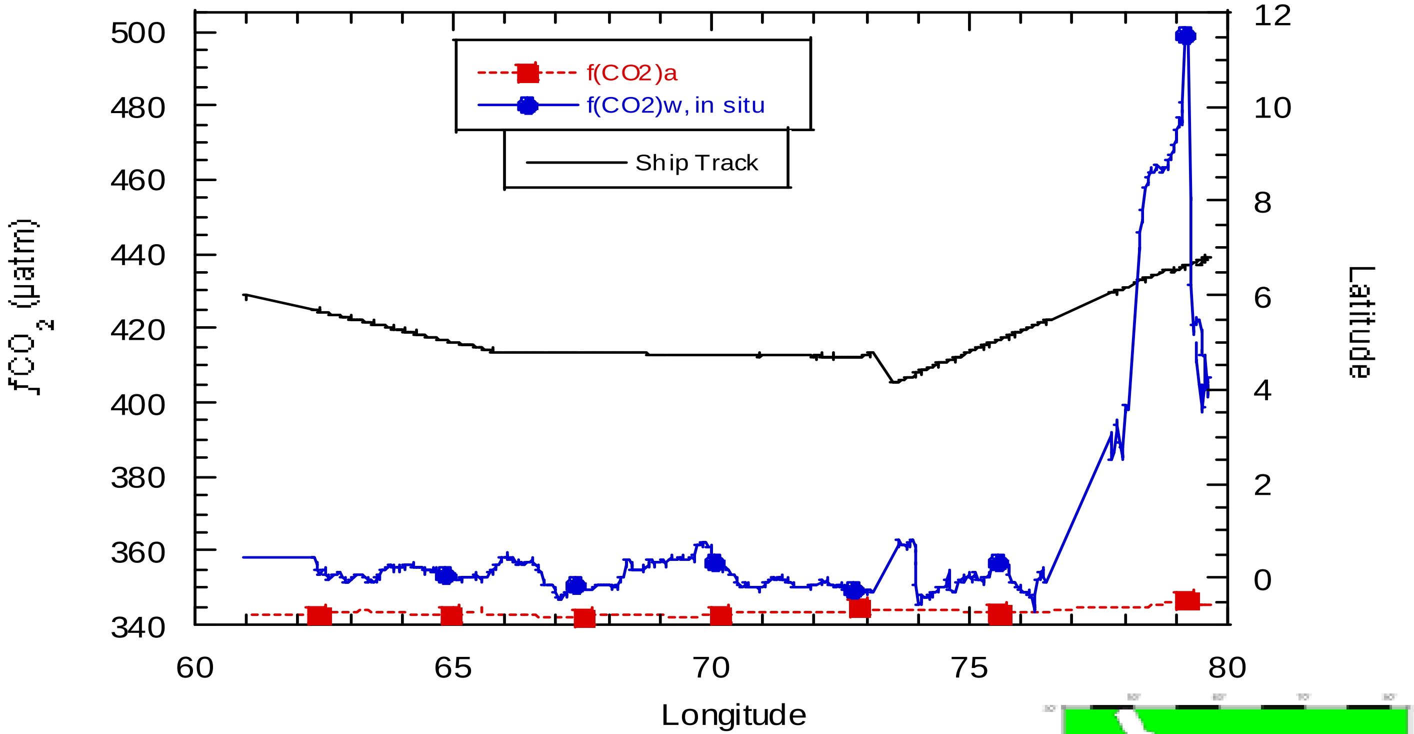

MB95-04 (5/31-6/5)
Sal (TSG)
SST (TSG)
Sea Surface Temperature (°C)
Salinity (‰)
Latitude
32
31
30
29
28
27
26
25
37.5
37
36.5
36
35.5
35
24
22
20
18
16
14
12
10
8

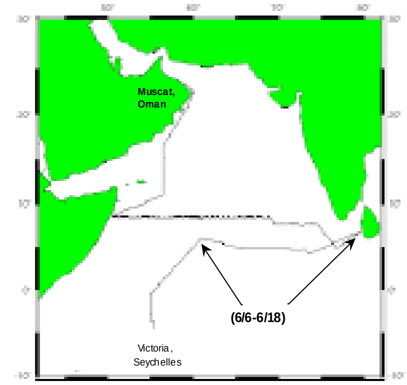

MB95-04 (6/6-6/18)
f(CO2)a
f(CO2)w, in situ
Ship Track
fCO2 (µatm)
Latitude
Longitude
320
360
400
440
480
4
6
8
10
12
55
60
65
70
75
80


Muscat, Oman
(5/31-6/5)
Victoria, Seychelles

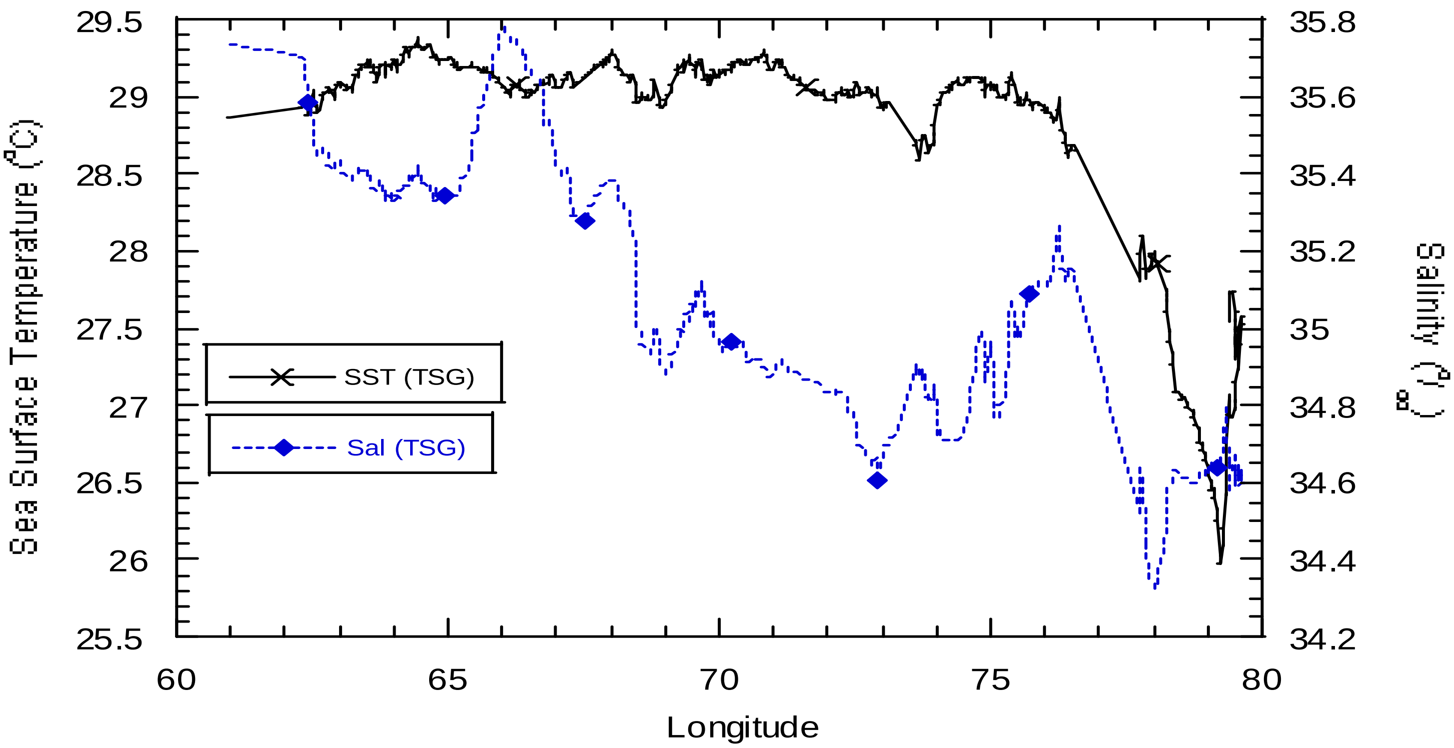

MB95-04 (6/6-6/18)
SST (TSG)
Sal (TSG)
Sea Surface Temperature (°C)
Salinity (‰)
Longitude
25
26
27
28
29
30
31
34
34.5
35
35.5
36
36.5
55
60
65
70
75
80

MB95-04 (6/18-6/24)

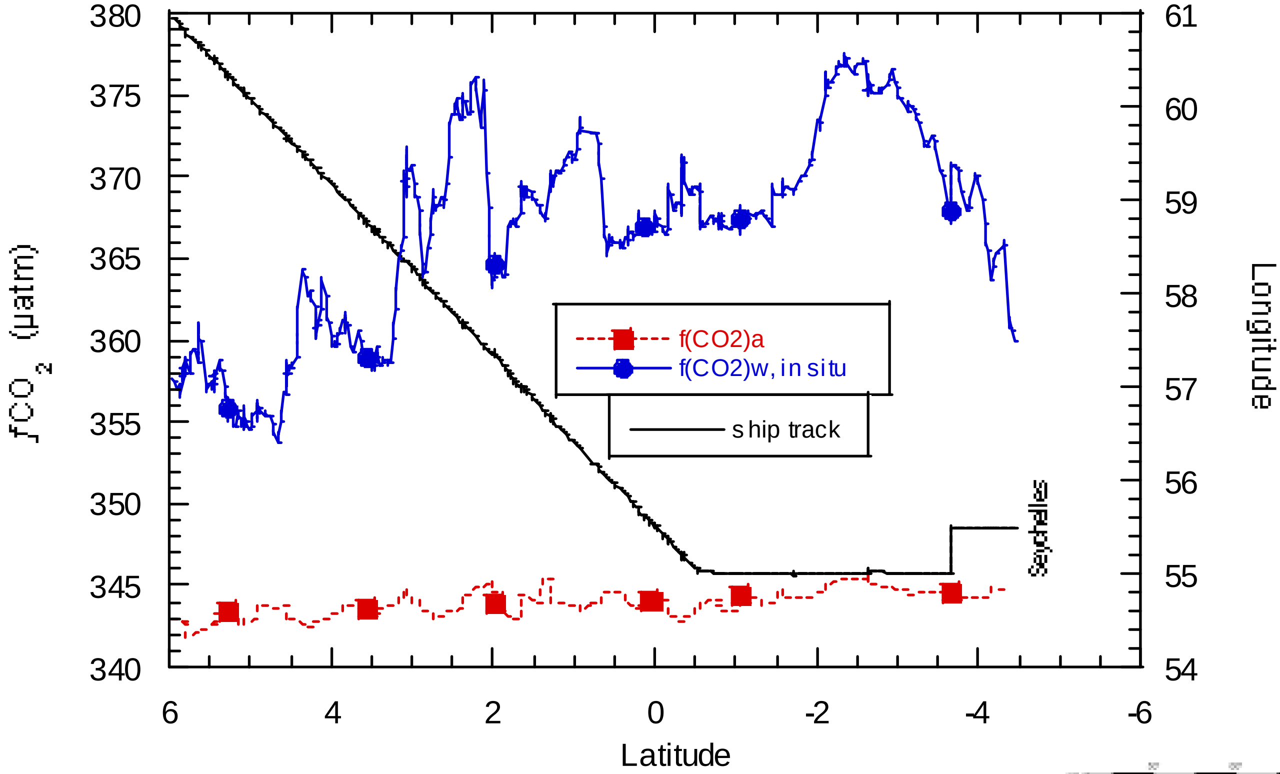


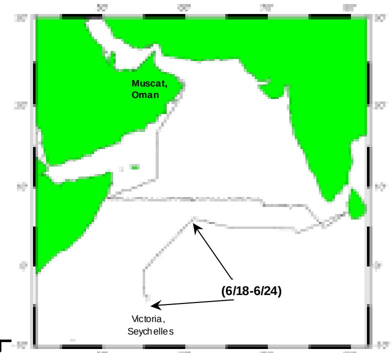


MB95-04 (6/18-6/24)

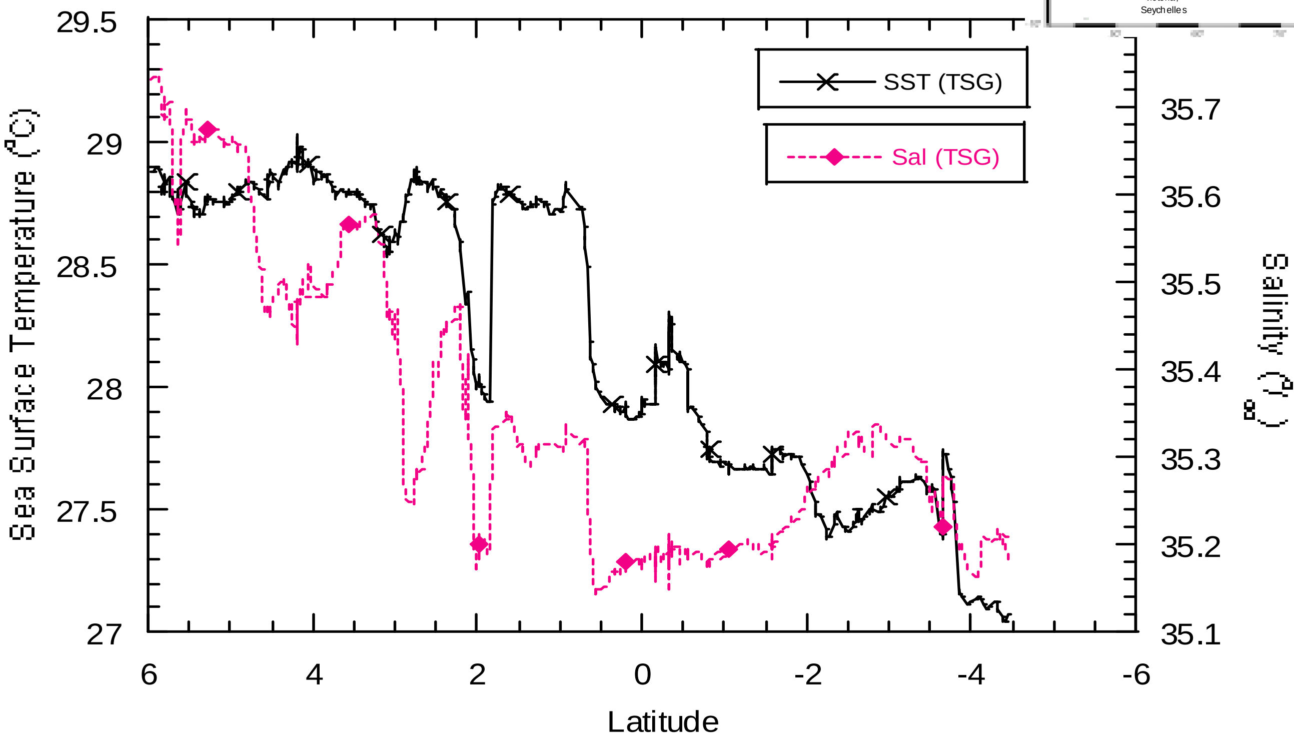


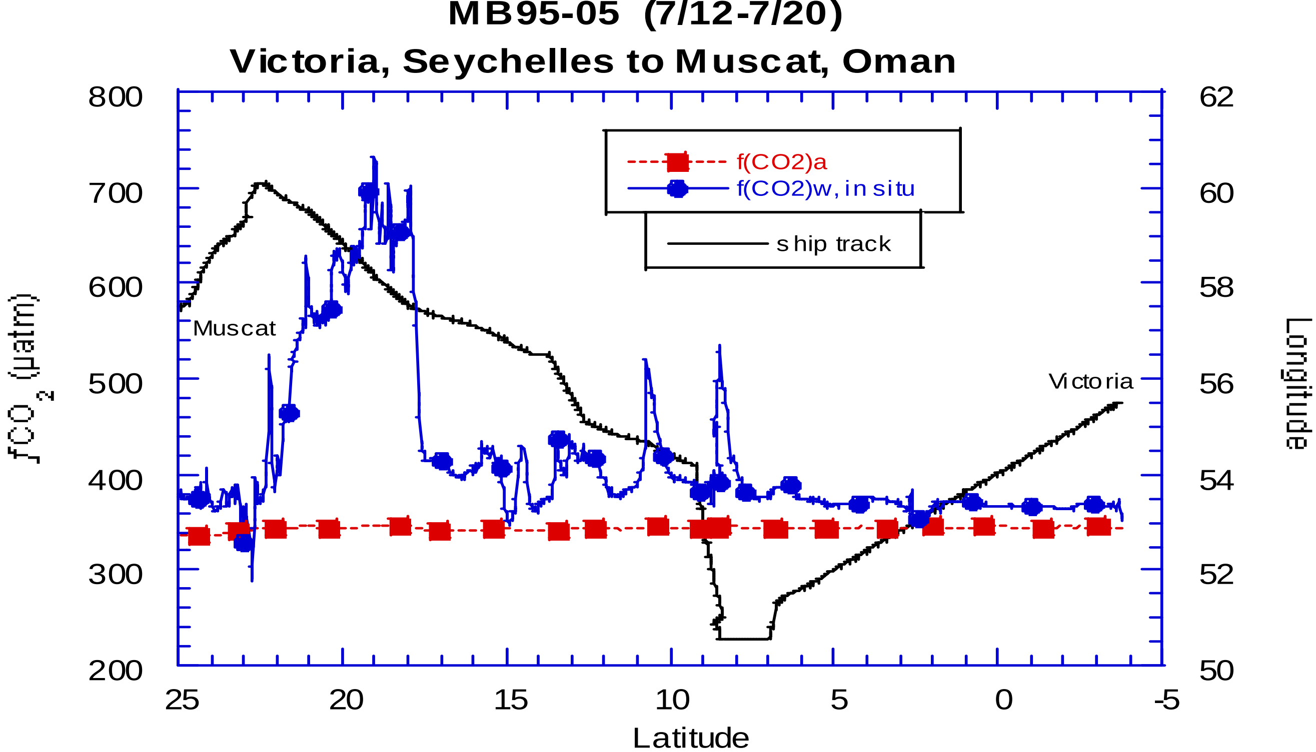
MB95-04 (6/24-6/30)

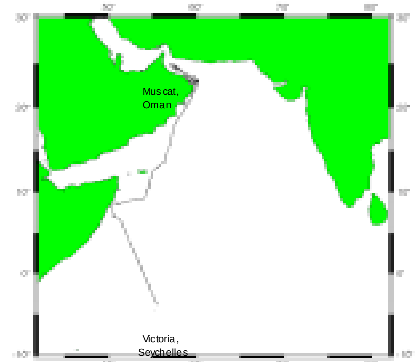


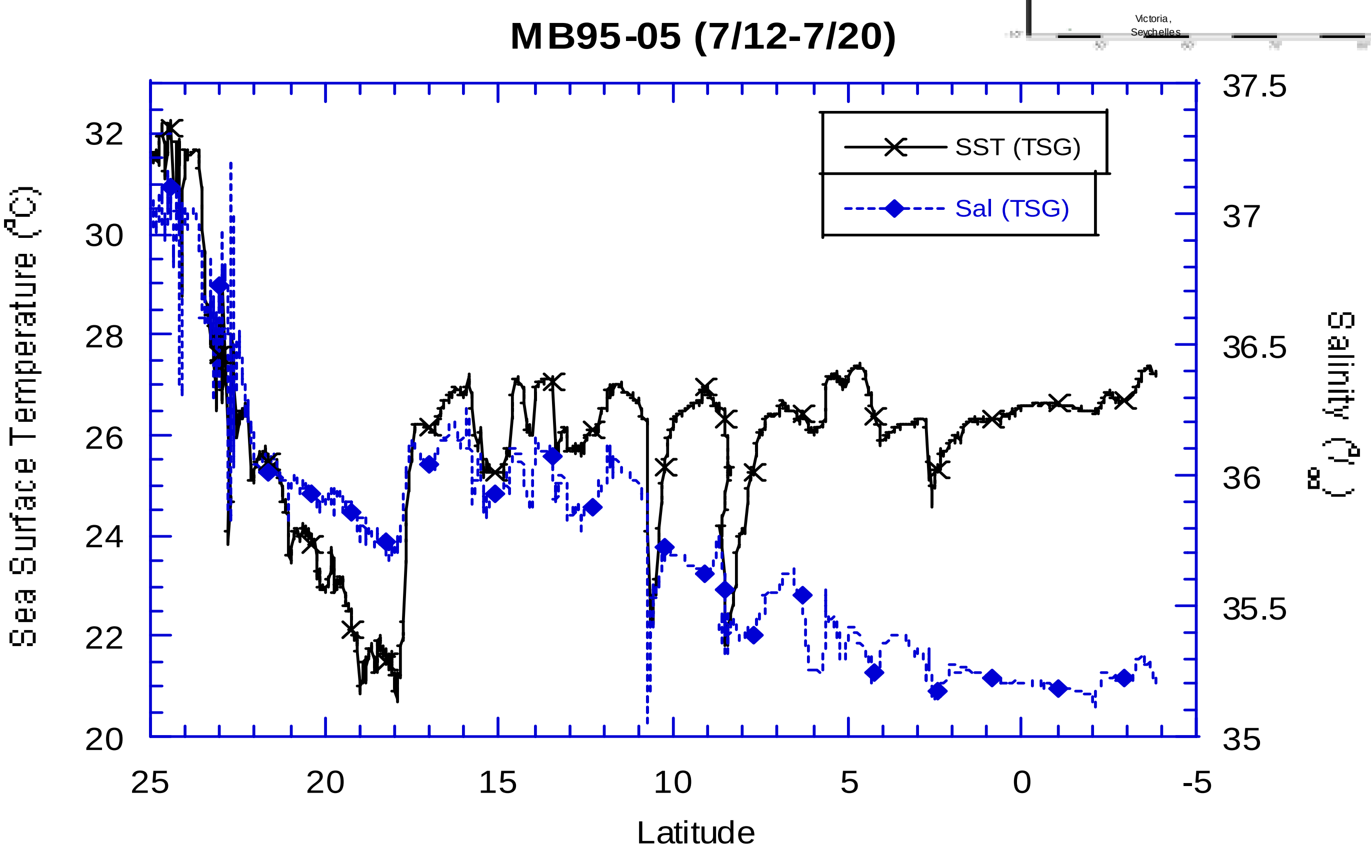


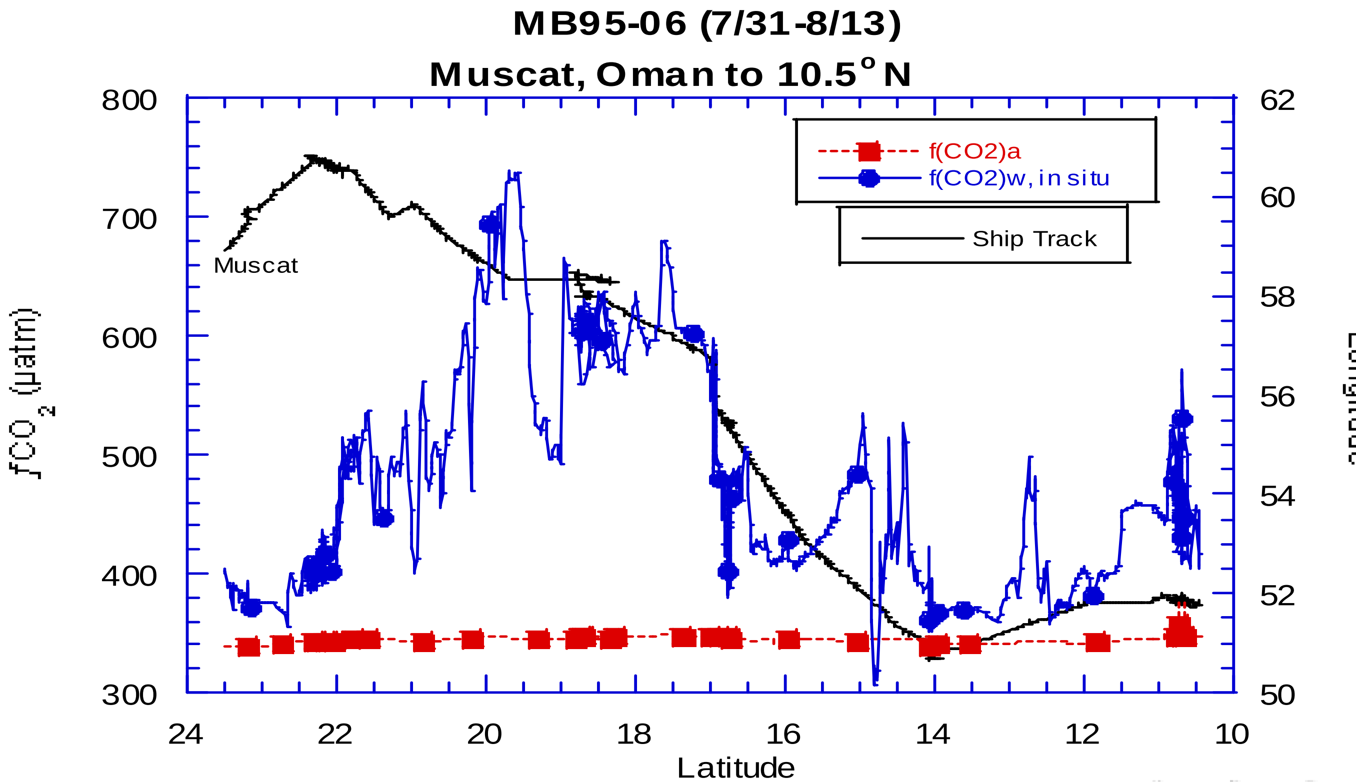
MB95-04 (6/24-6/30)

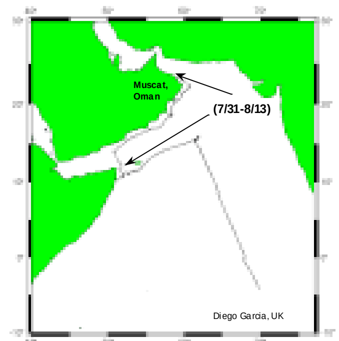


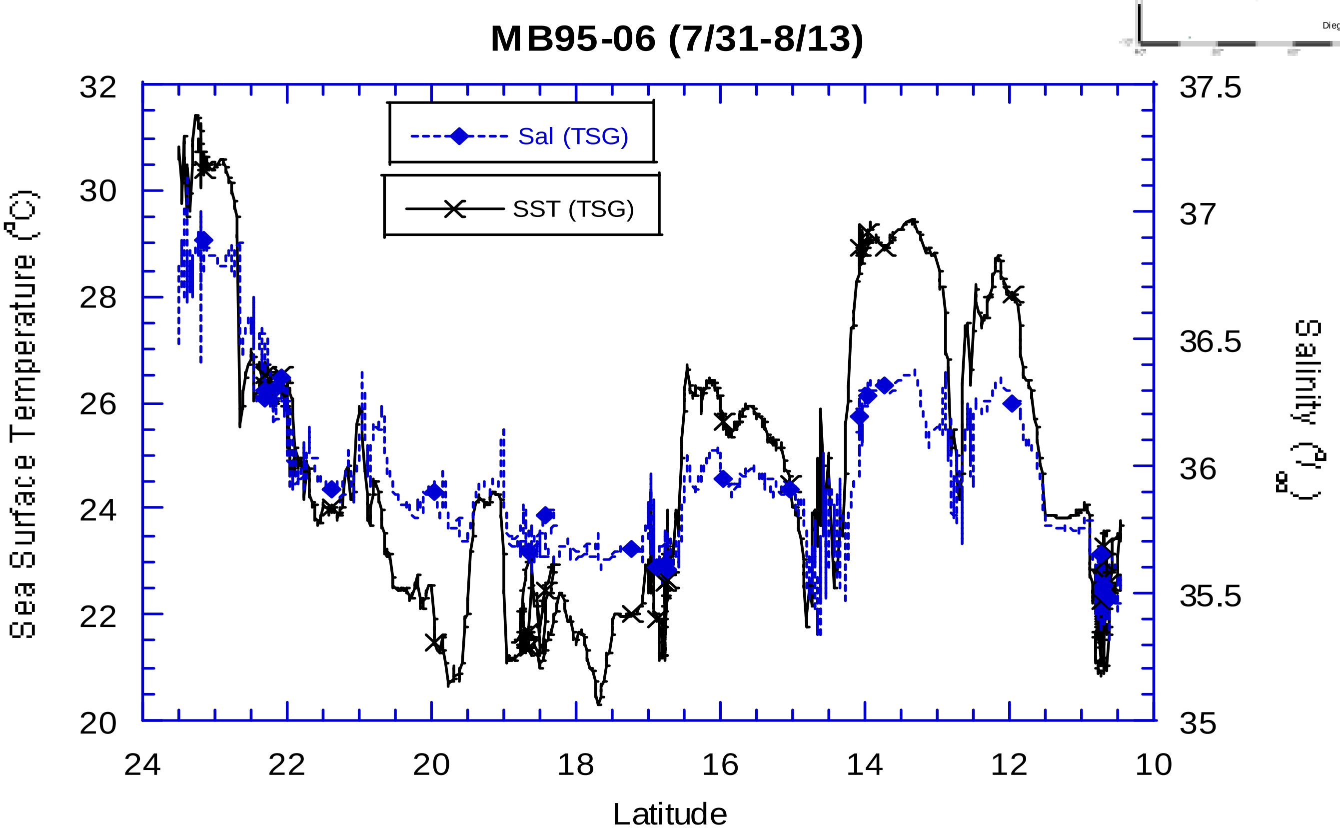

MB95-05 (7/12-7/20)
Victoria, Seychelles to Muscat, Oman
f(CO2)a
f(CO2)w, in situ
ship track
Muscat
Victoria
fCO2 (µatm)
Longitude
Latitude
800
700
600
500
400
300
200
62
60
58
56
54
52
50
25
20
15
10
5
0
-5


Muscat, Oman
Victoria, Seychelles

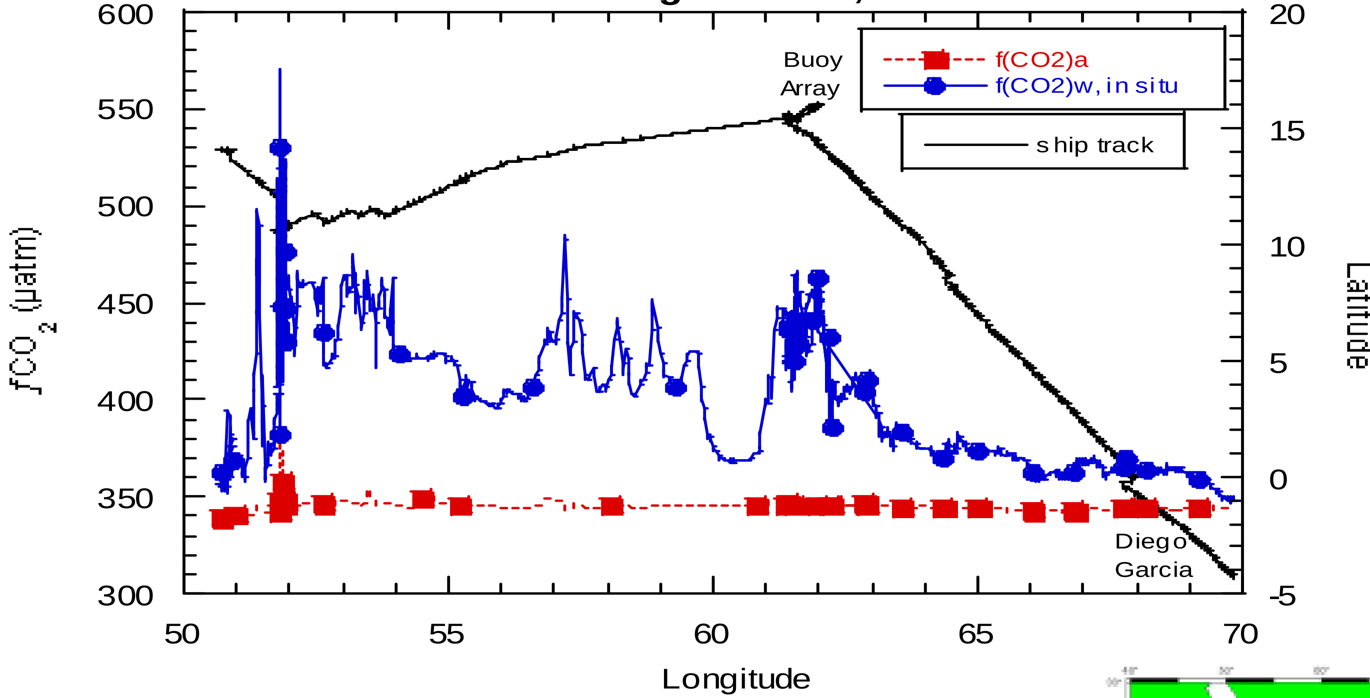

MB95-05 (7/12-7/20)
SST (TSG)
Sal (TSG)
Sea Surface Temperature (°C)
Salinity (‰)
Latitude
32
30
28
26
24
22
20
37.5
37
36.5
36
35.5
35
25
20
15
10
5
0
-5

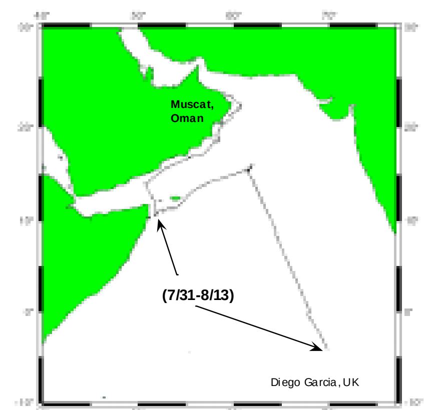

MB95-06 (7/31-8/13)
Muscat, Oman to 10.5° N
f(CO2)a
f(CO2)w, in situ
Ship Track
Muscat
fCO2 (μatm)
Longitude
Latitude
800
700
600
500
400
300
62
60
58
56
54
52
50
24
22
20
18
16
14
12
10


Muscat, Oman
(7/31-8/13)
Diego Garcia, UK

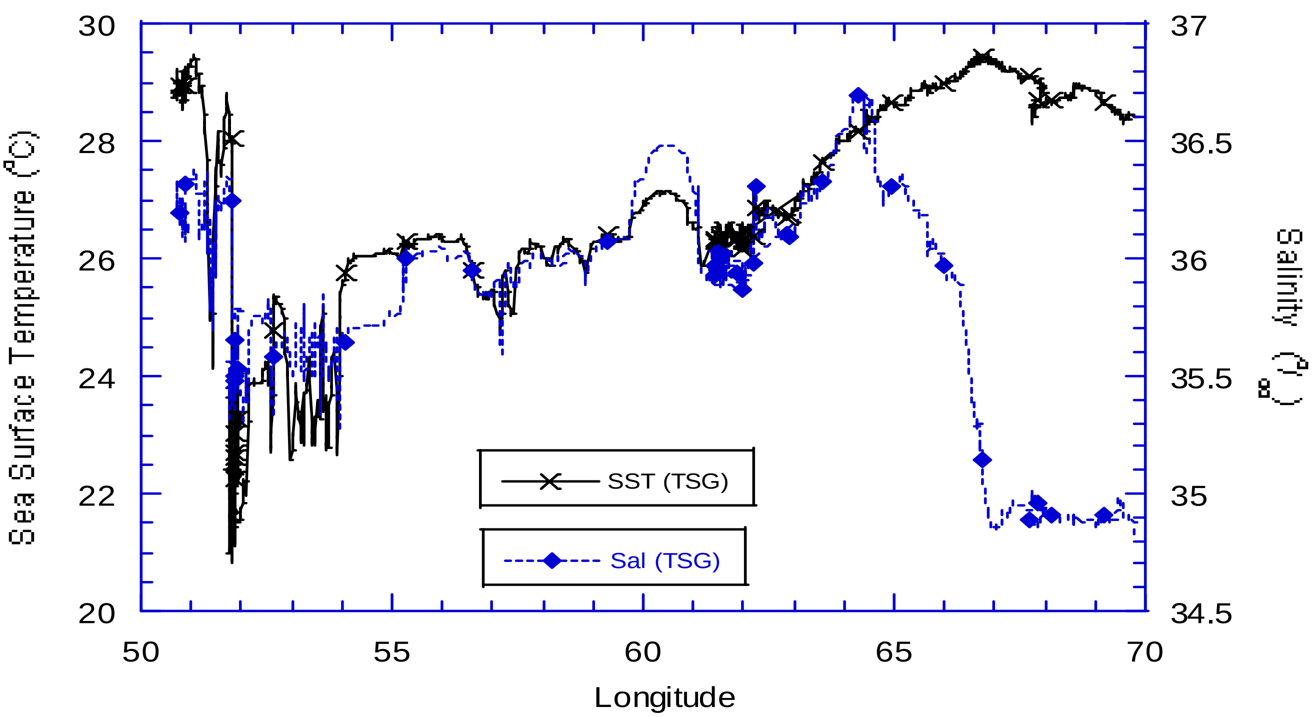

MB95-06 (7/31-8/13)
Sal (TSG)
SST (TSG)
Sea Surface Temperature (°C)
Salinity (‰)
Latitude
32
30
28
26
24
22
20
37.5
37
36.5
36
35.5
35
24
22
20
18
16
14
12
10

MB95-06 (8/9-8/25)
13.5° N to Diego Garcia, UK

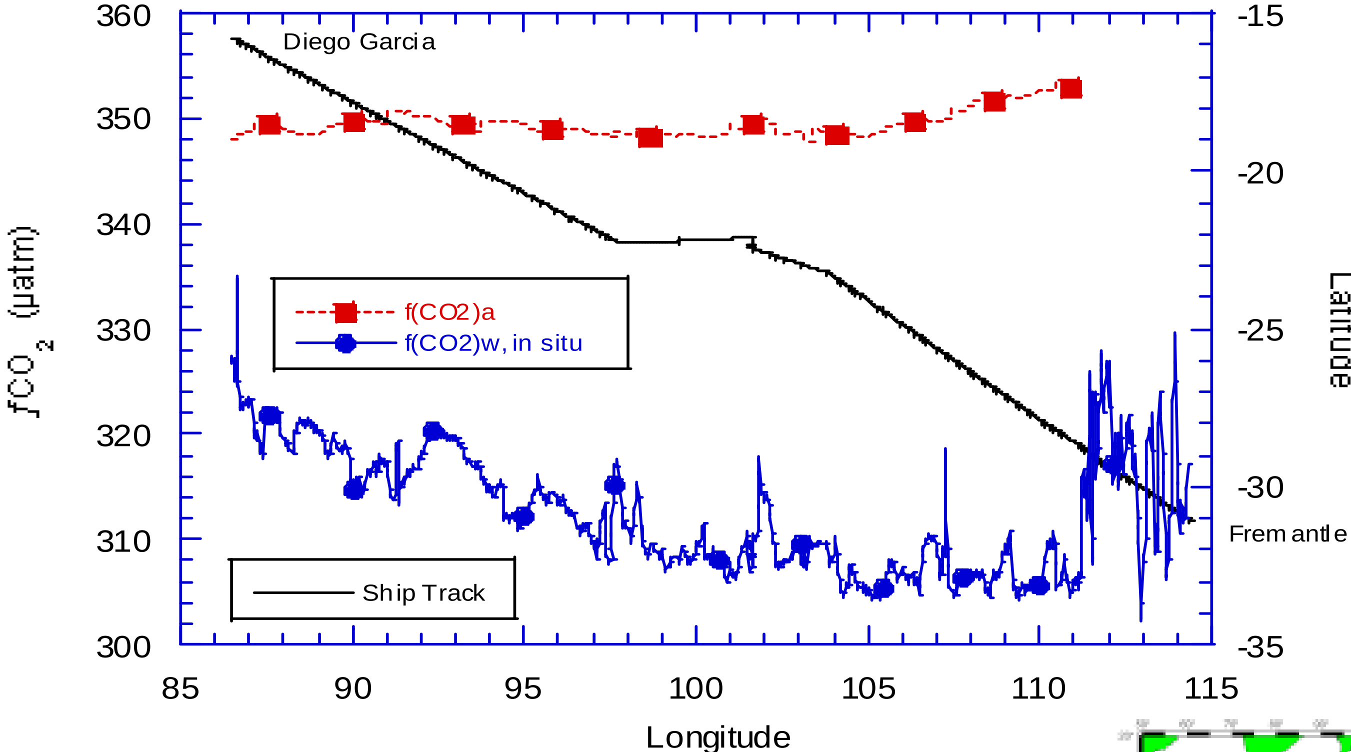


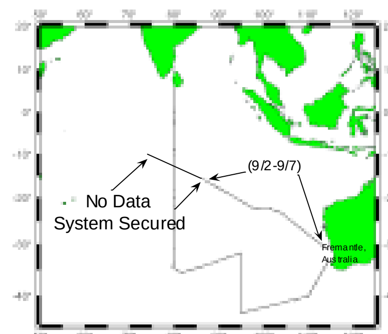


MB95-06 (8/9-8/25)

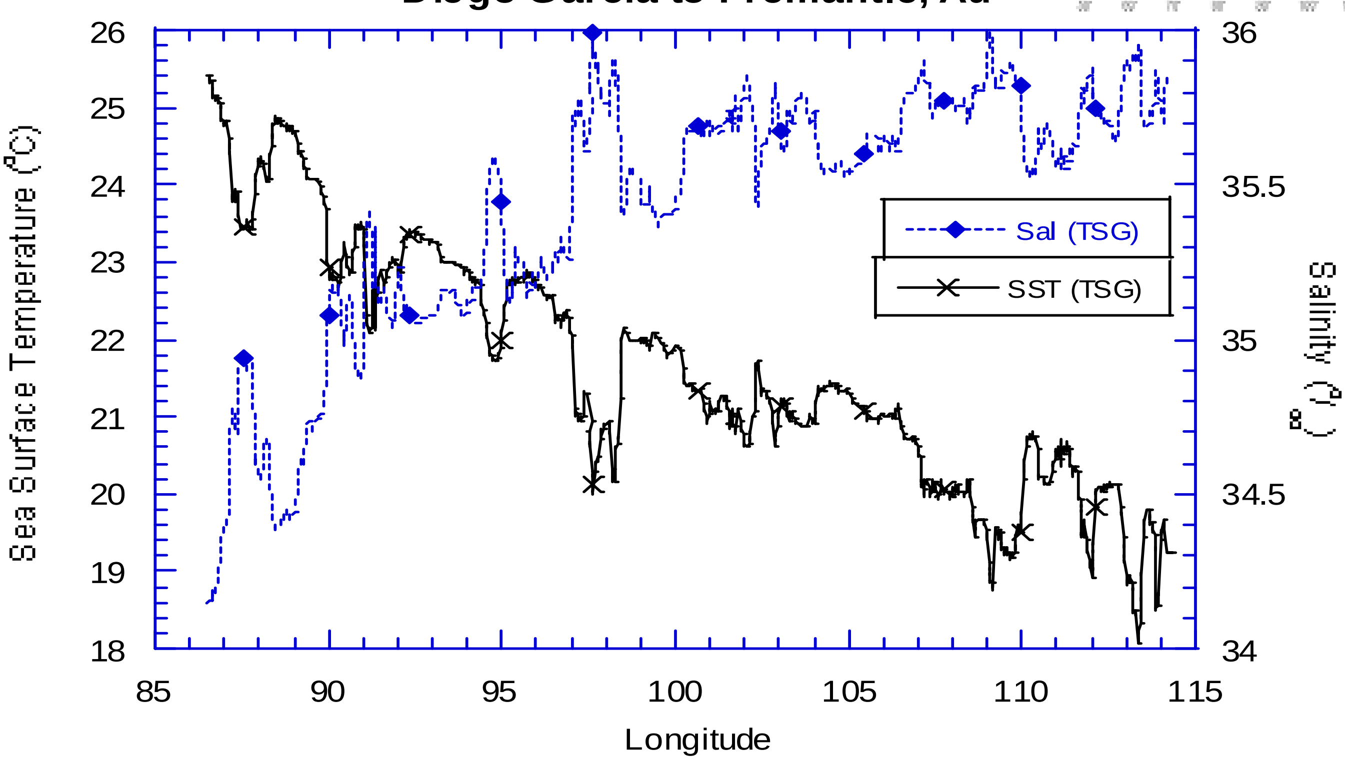


MB95-07 (9/2-9/7)
Diego Garcia to Fremantle, Au

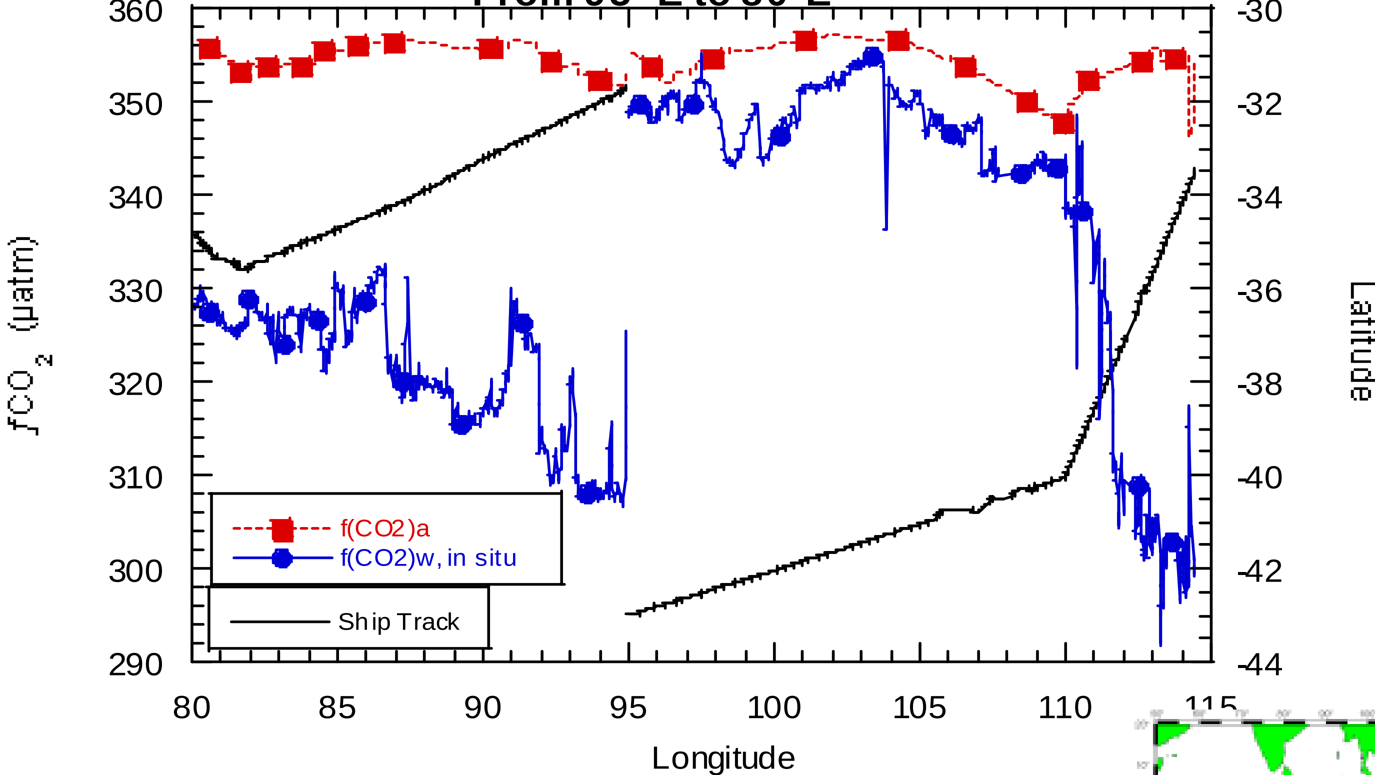


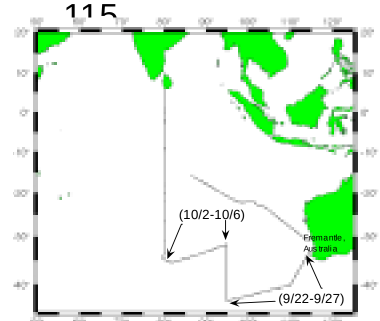


MB95-06 (9/2-9/7)
Diego Garcia to Fremantle, Au

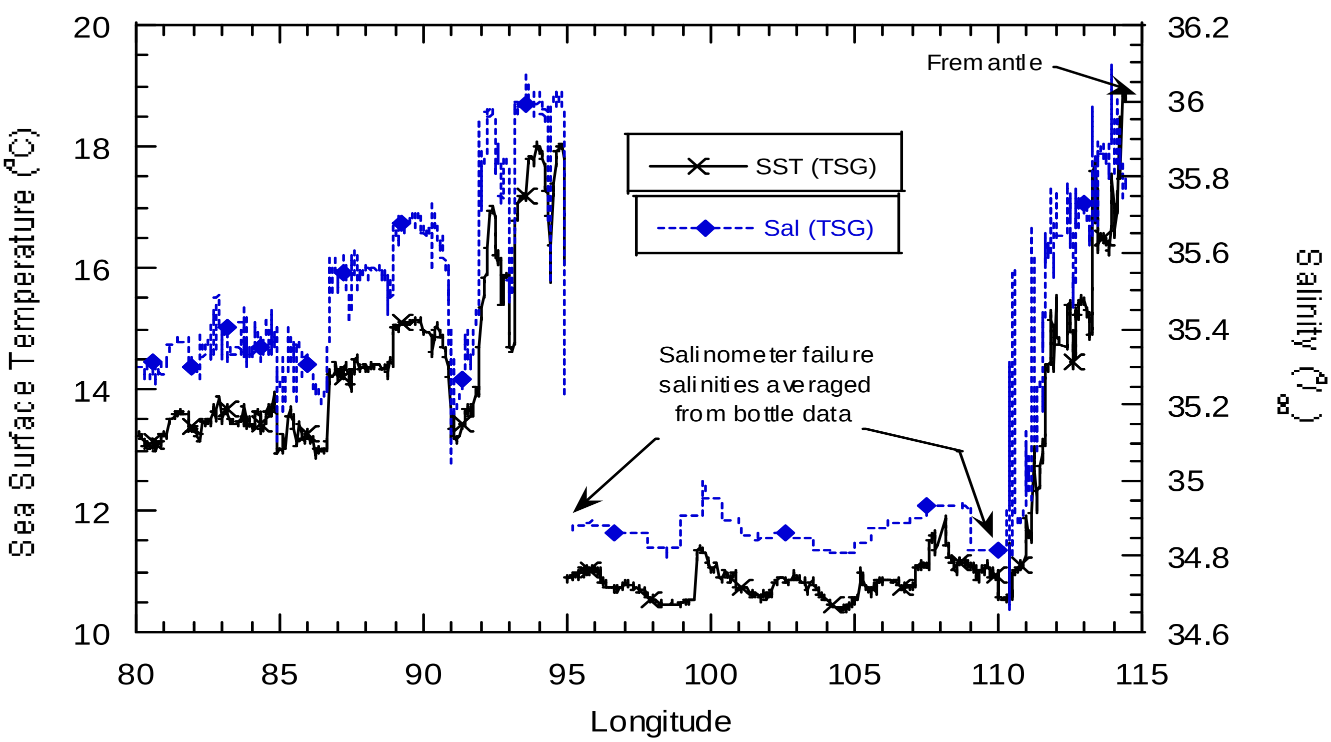


MB95-07
From Fremantle to 95°E and
From 95° E to 80°E

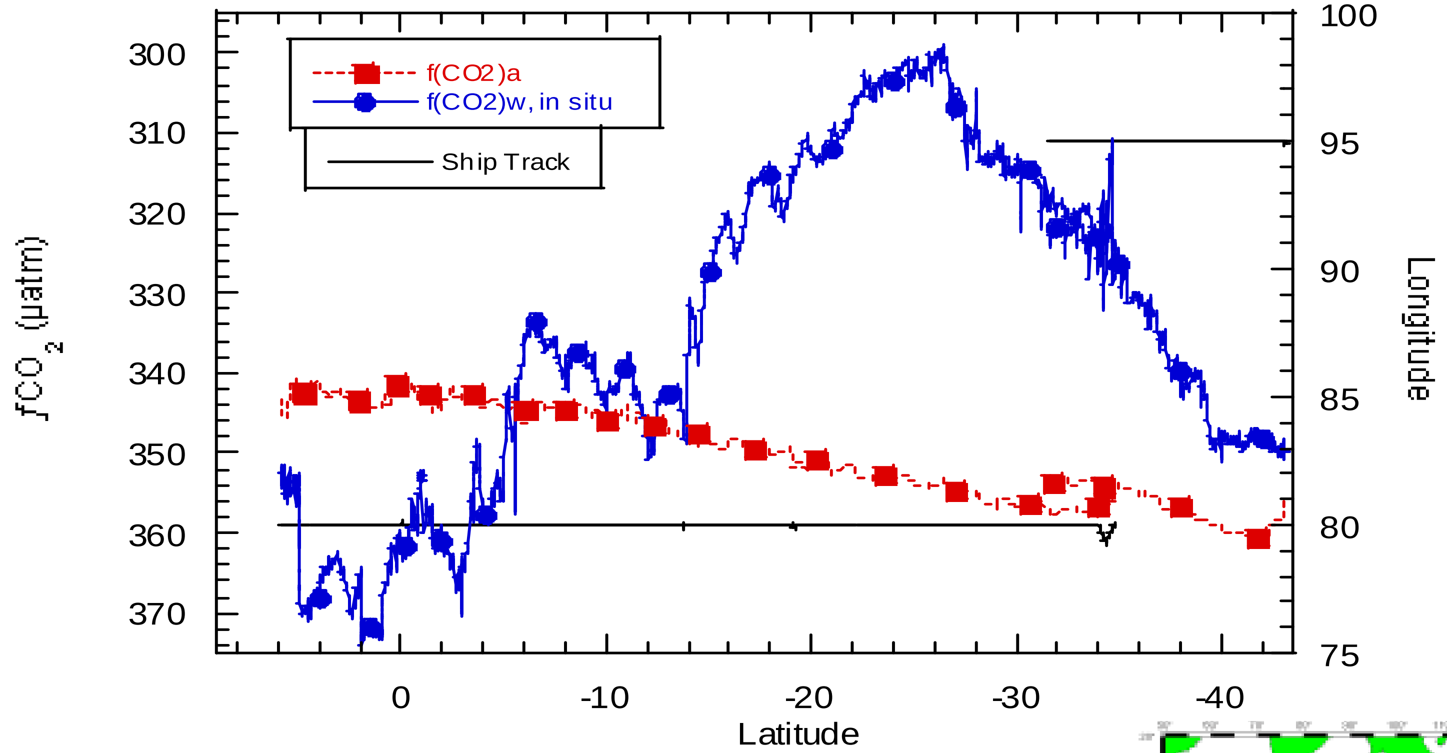


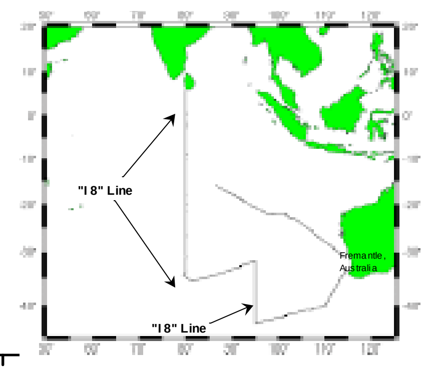


MB95-07
From Fremantle to 95°E and
from 95°E to 80°E

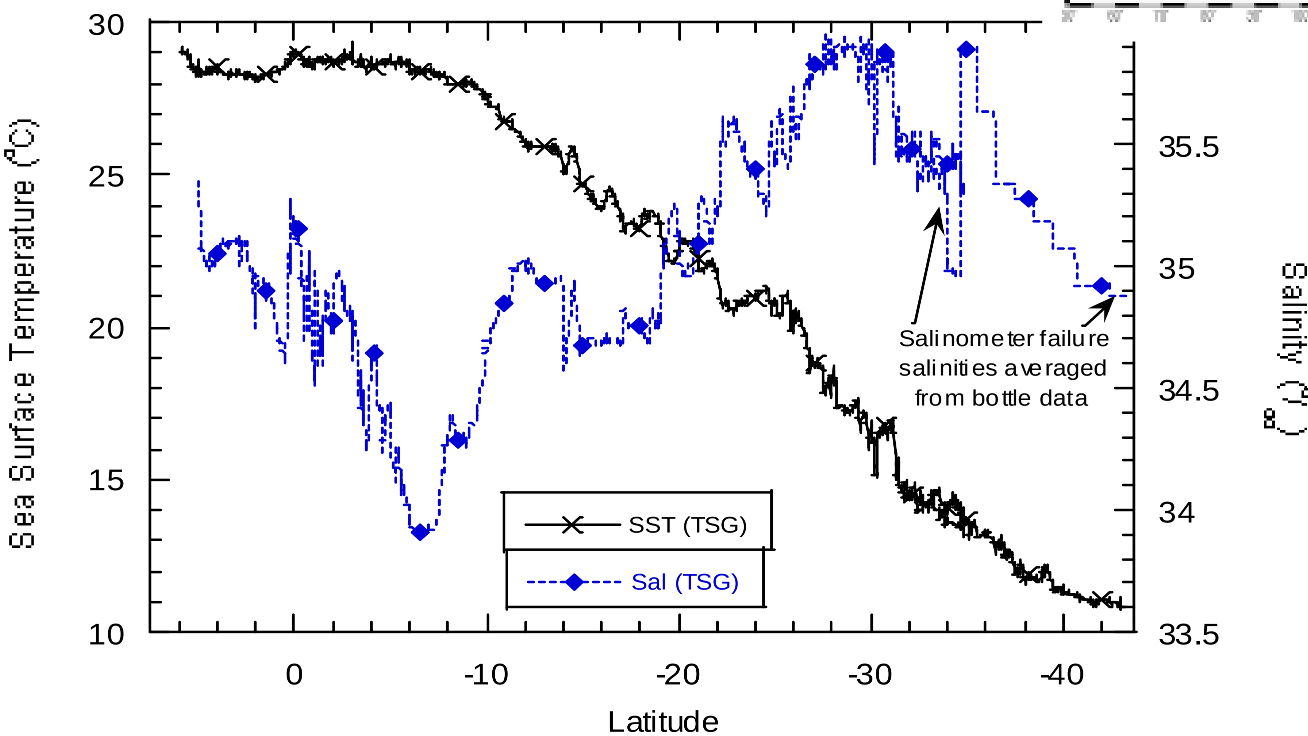


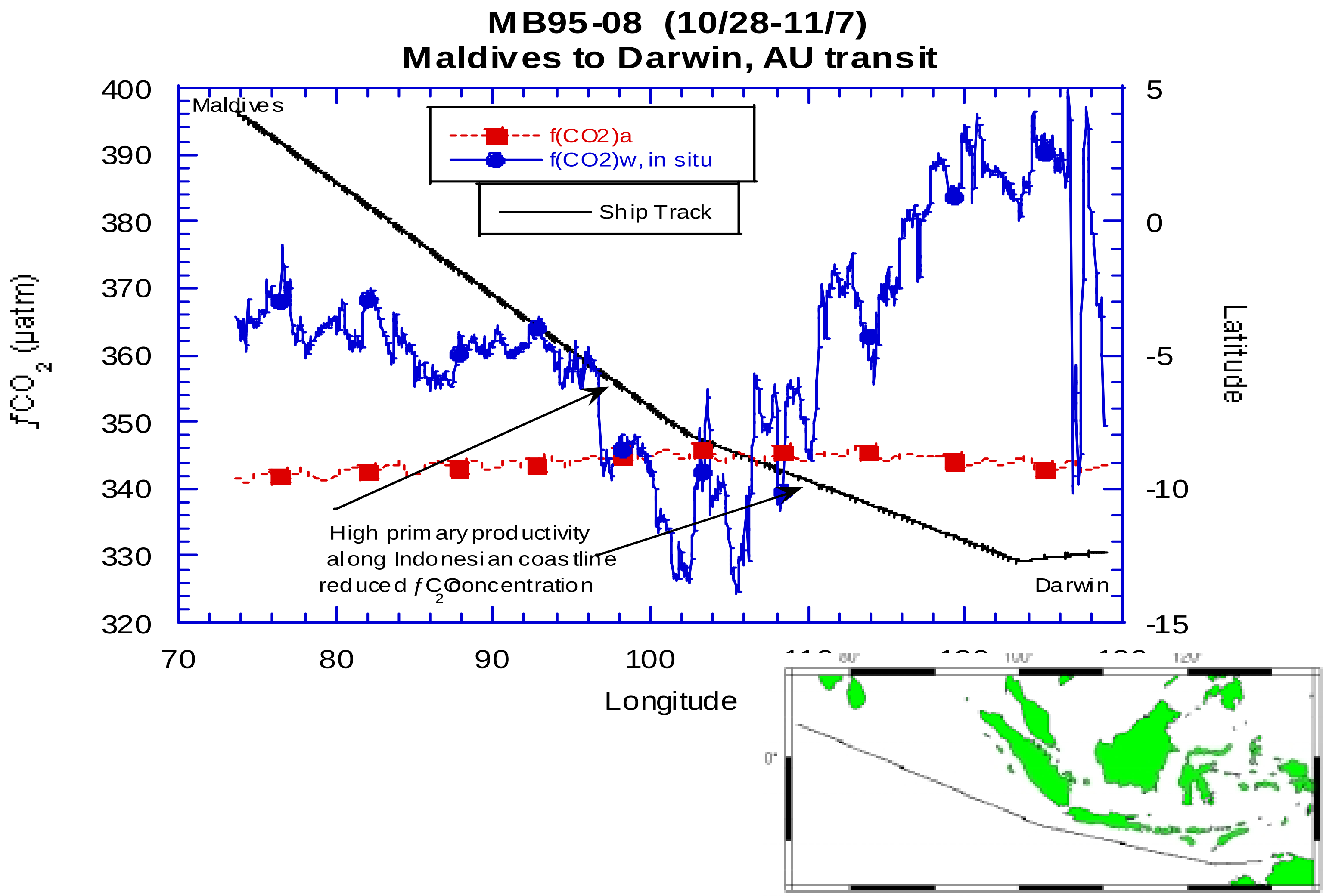
MB95-07 (I8 repeat)
Transects for 95°E & 80°E

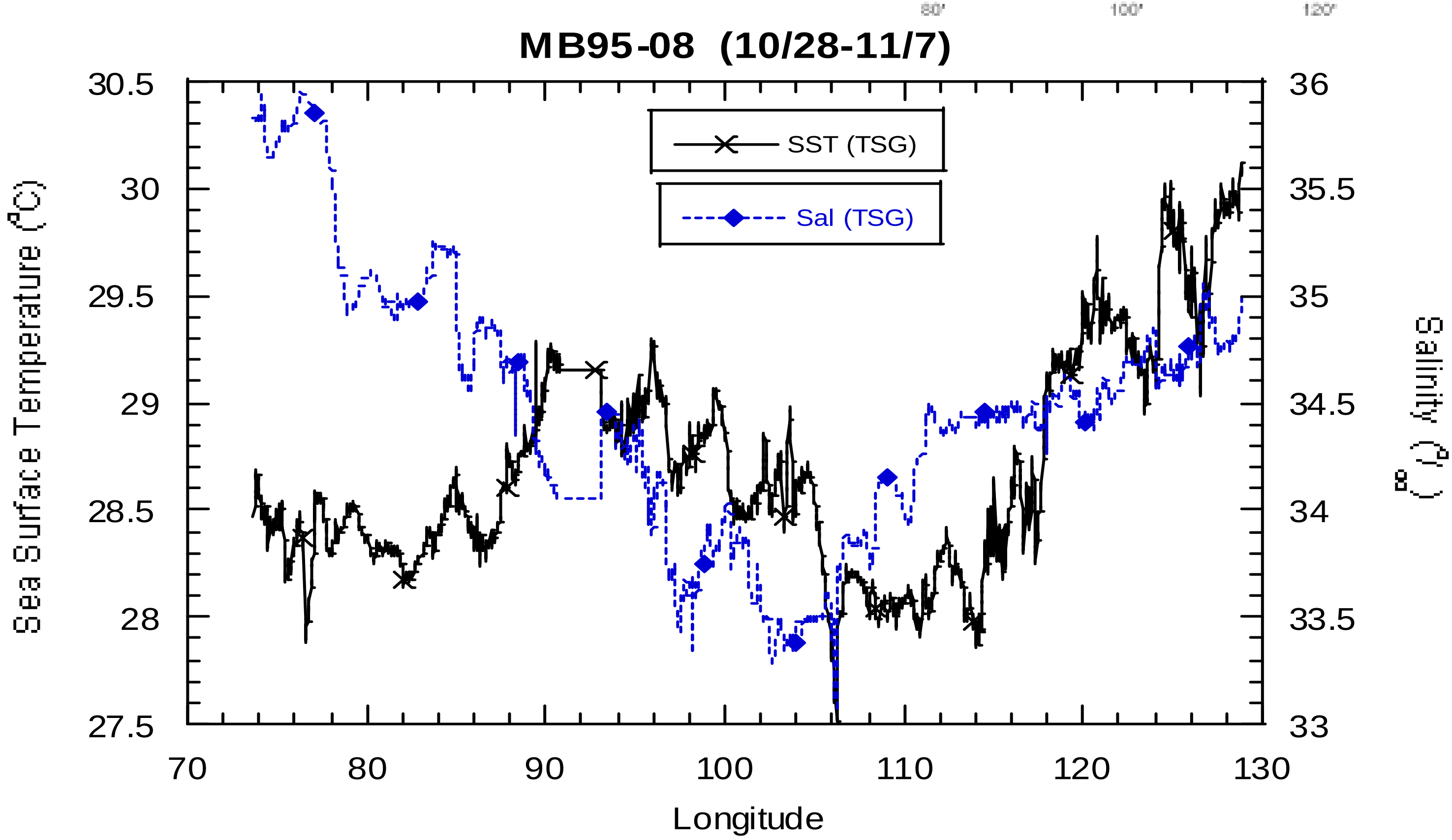


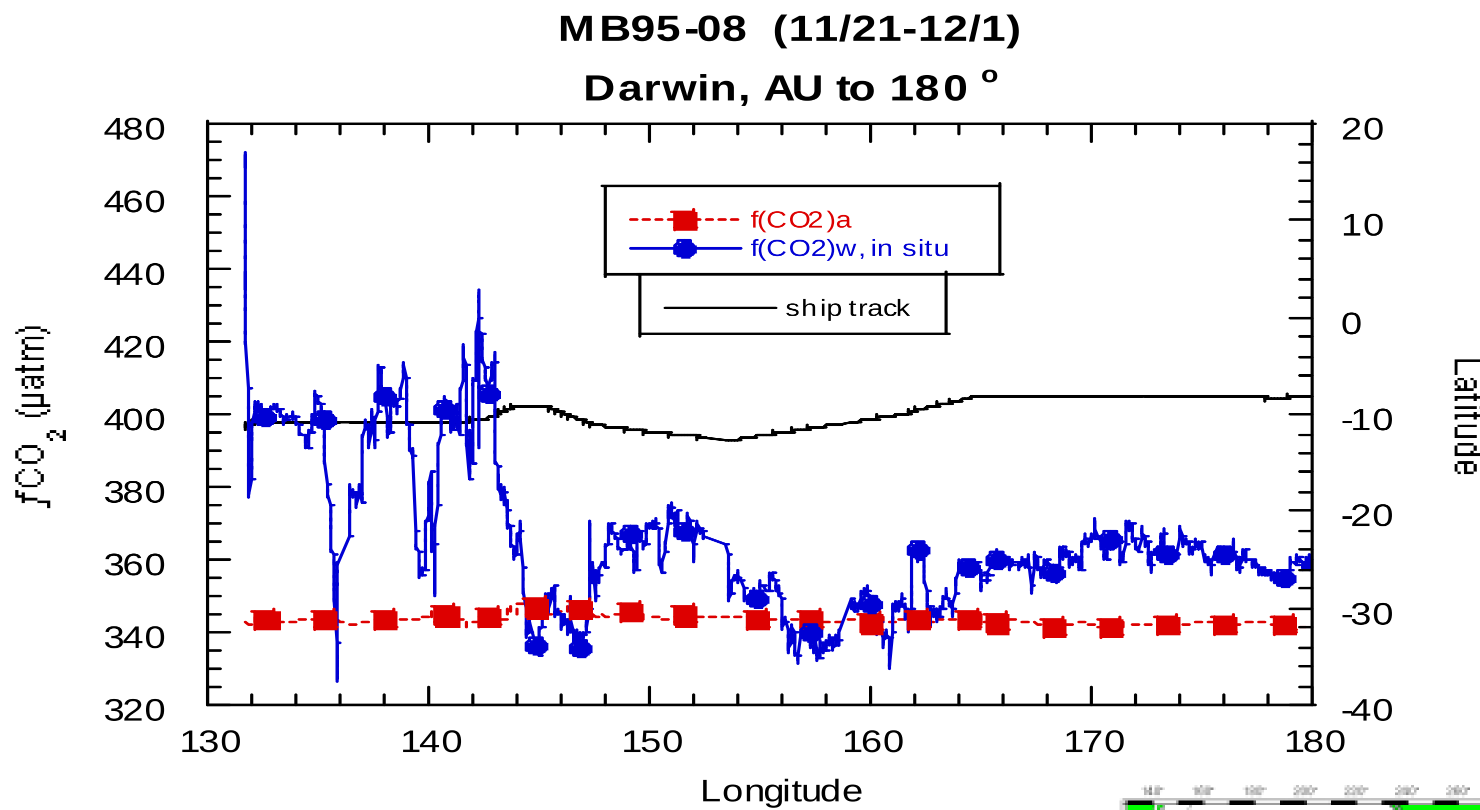


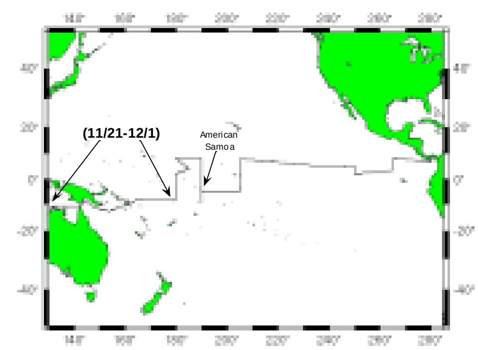
MB95-07
95°E & 80°E

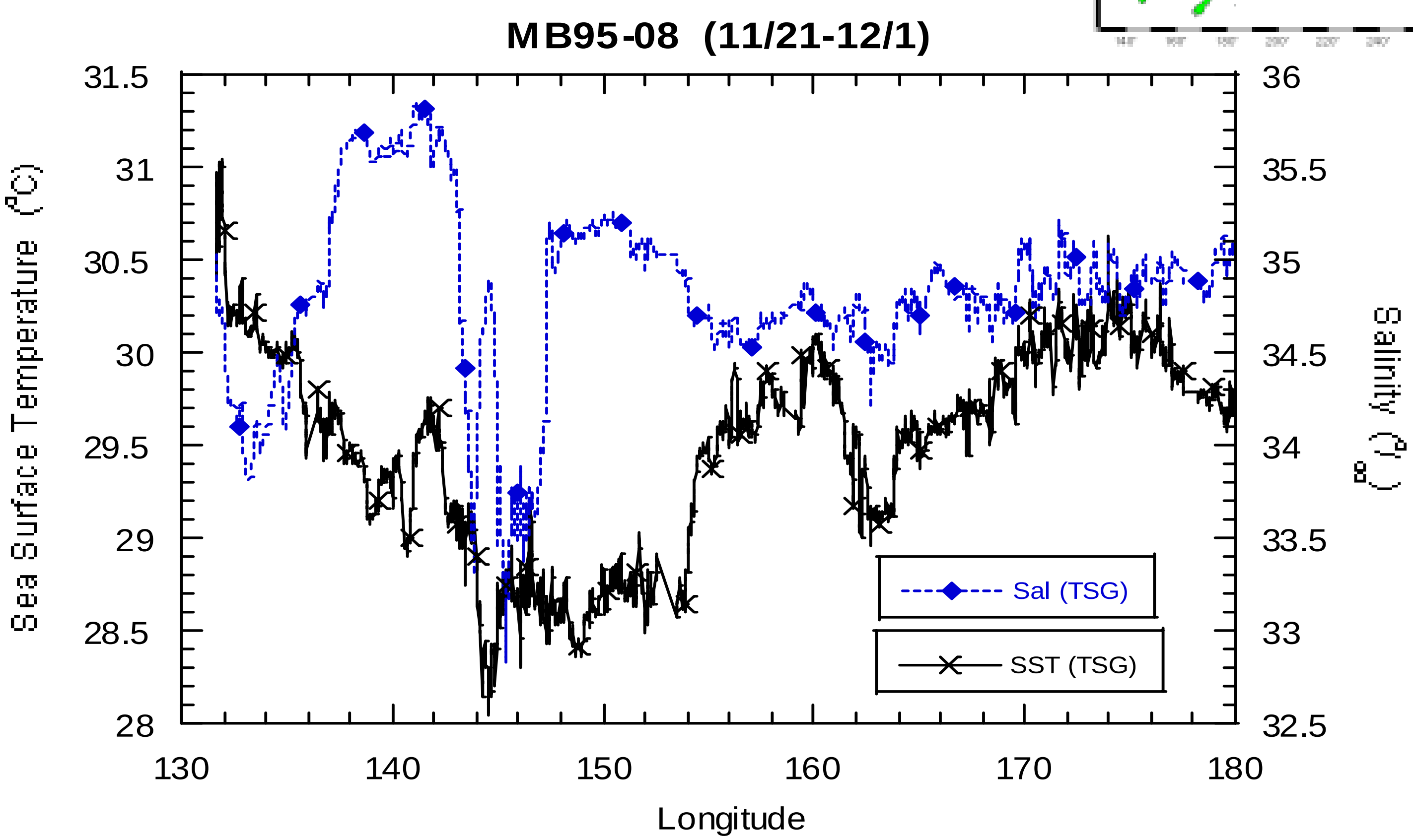



MB95-08 (10/28-11/7)
Maldives to Darwin, AU transit
f(CO2)a
f(CO2)w, in situ
Ship Track
Maldives
Darwin
High primary productivity
along Indonesian coastline
reduced fCO_2 concentration
fCO_2 (µatm)
Latitude
Longitude


MB95-08 (10/28-11/7)
SST (TSG)
Sal (TSG)
Sea Surface Temperature (°C)
Salinity (‰)
Longitude

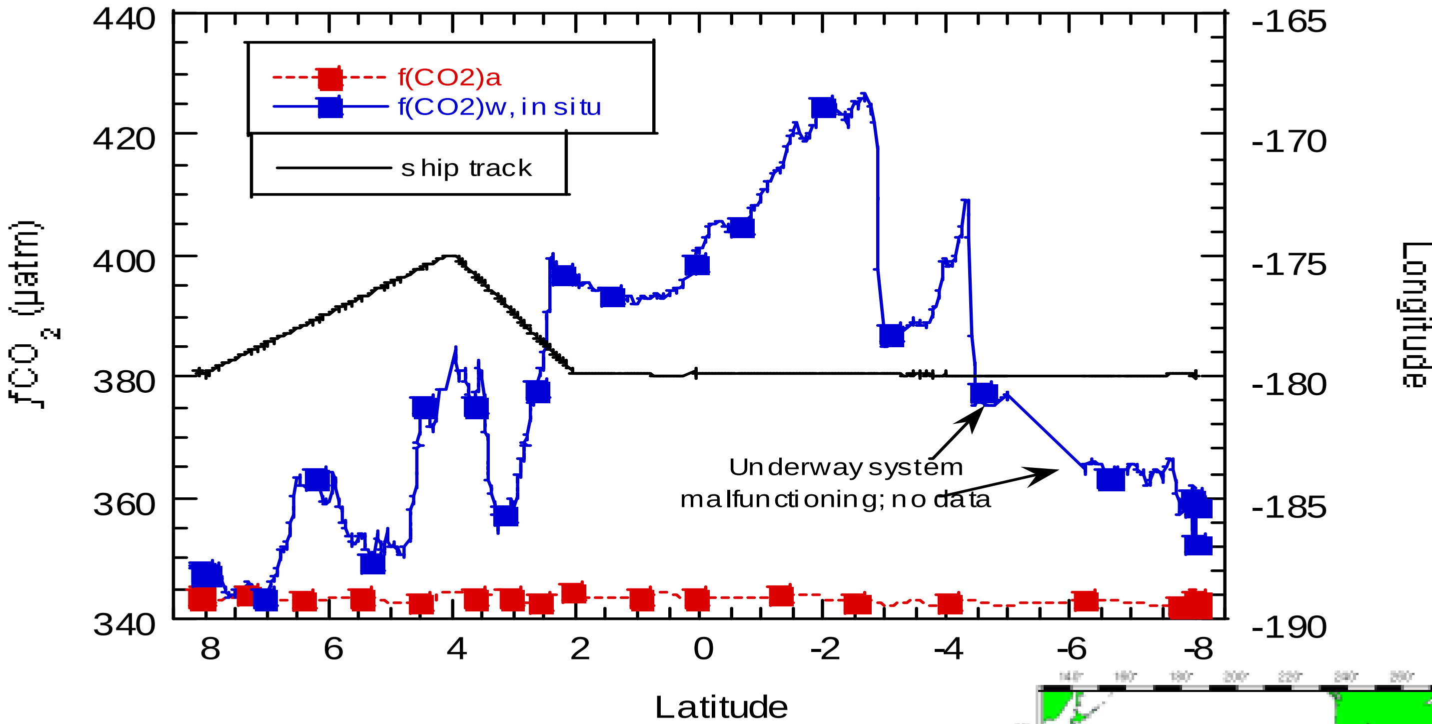

MB95-08 (11/21-12/1)
Darwin, AU to 180 °
f(CO2)a
f(CO2)w, in situ
ship track
fCO2 (µatm)
Latitude
Longitude
480
460
440
420
400
380
360
340
320
20
10
0
-10
-20
-30
-40
130
140
150
160
170
180

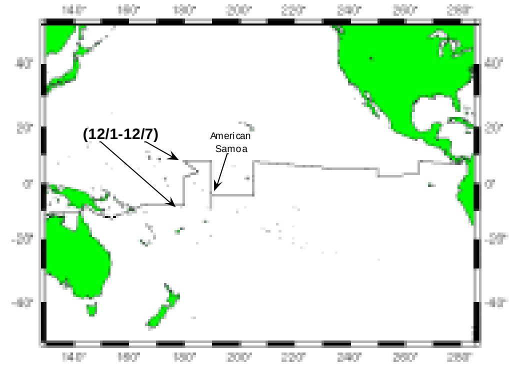

(11/21-12/1)
American Samoa


MB95-08 (11/21-12/1)
Sal (TSG)
SST (TSG)
Sea Surface Temperature (°C)
Salinity (‰)
Longitude
31.5
31
30.5
30
29.5
29
28.5
28
36
35.5
35
34.5
34
33.5
33
32.5
130
140
150
160
170
180

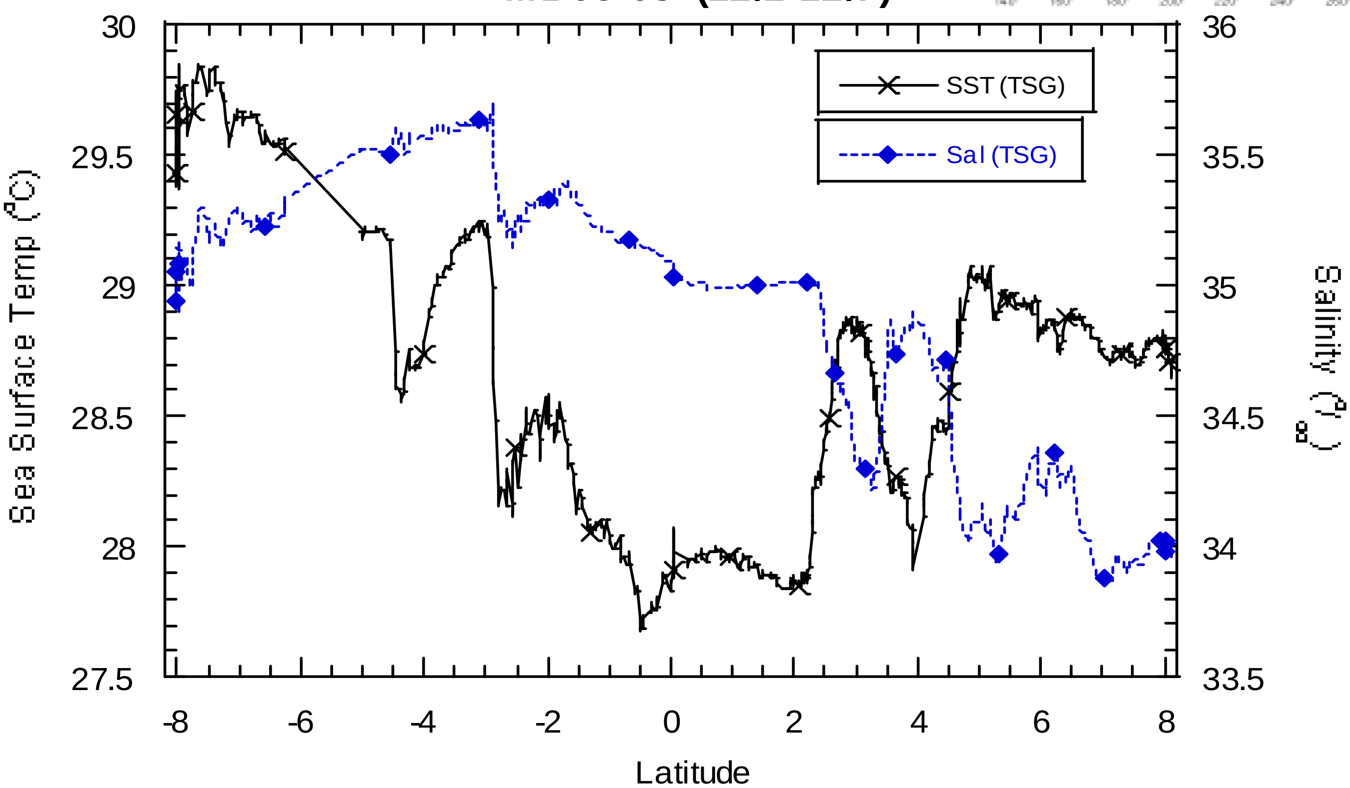
MB95-08 (12/1-12/7)

180° Meridian transect



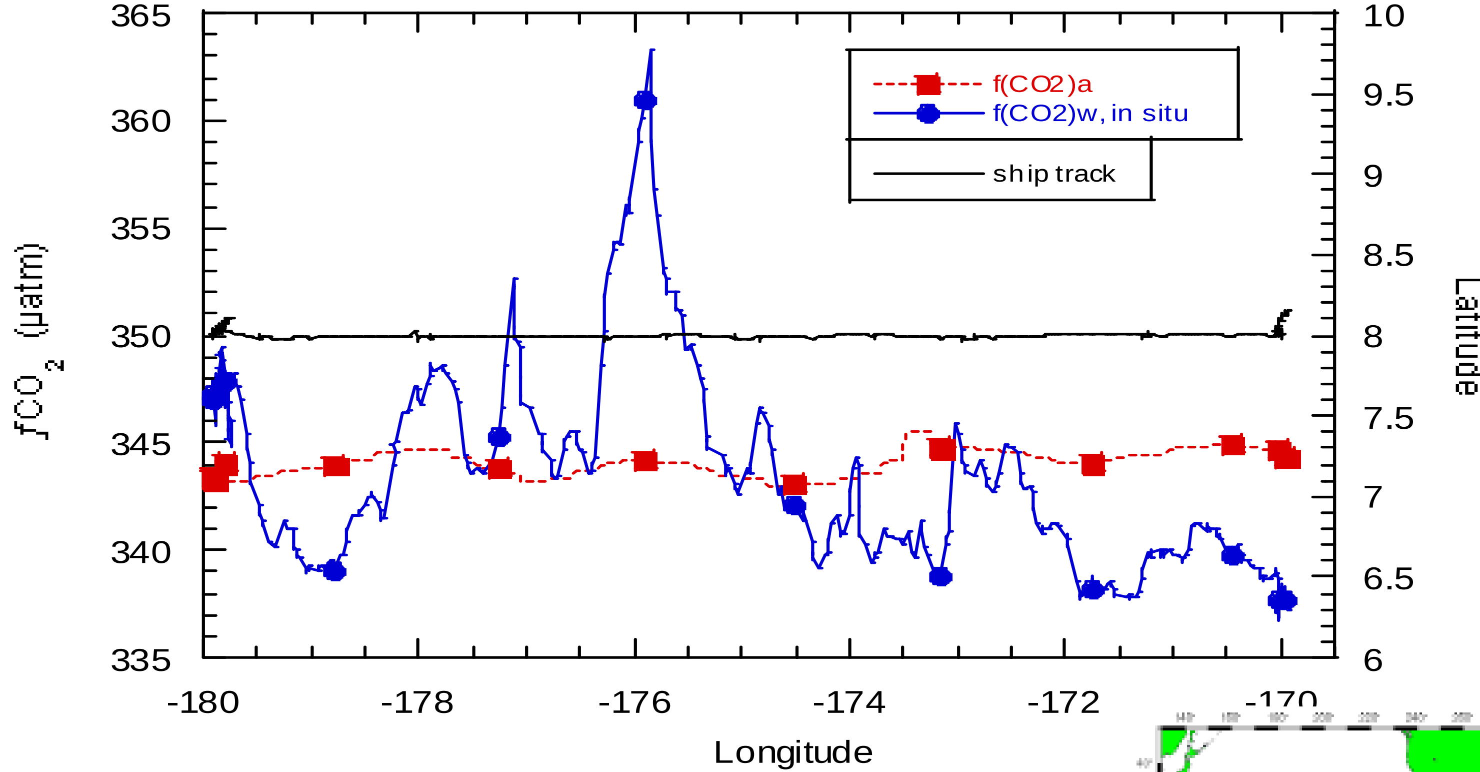


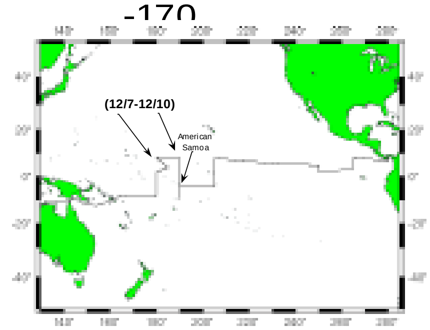
MB95-08 (12/1-12/7)



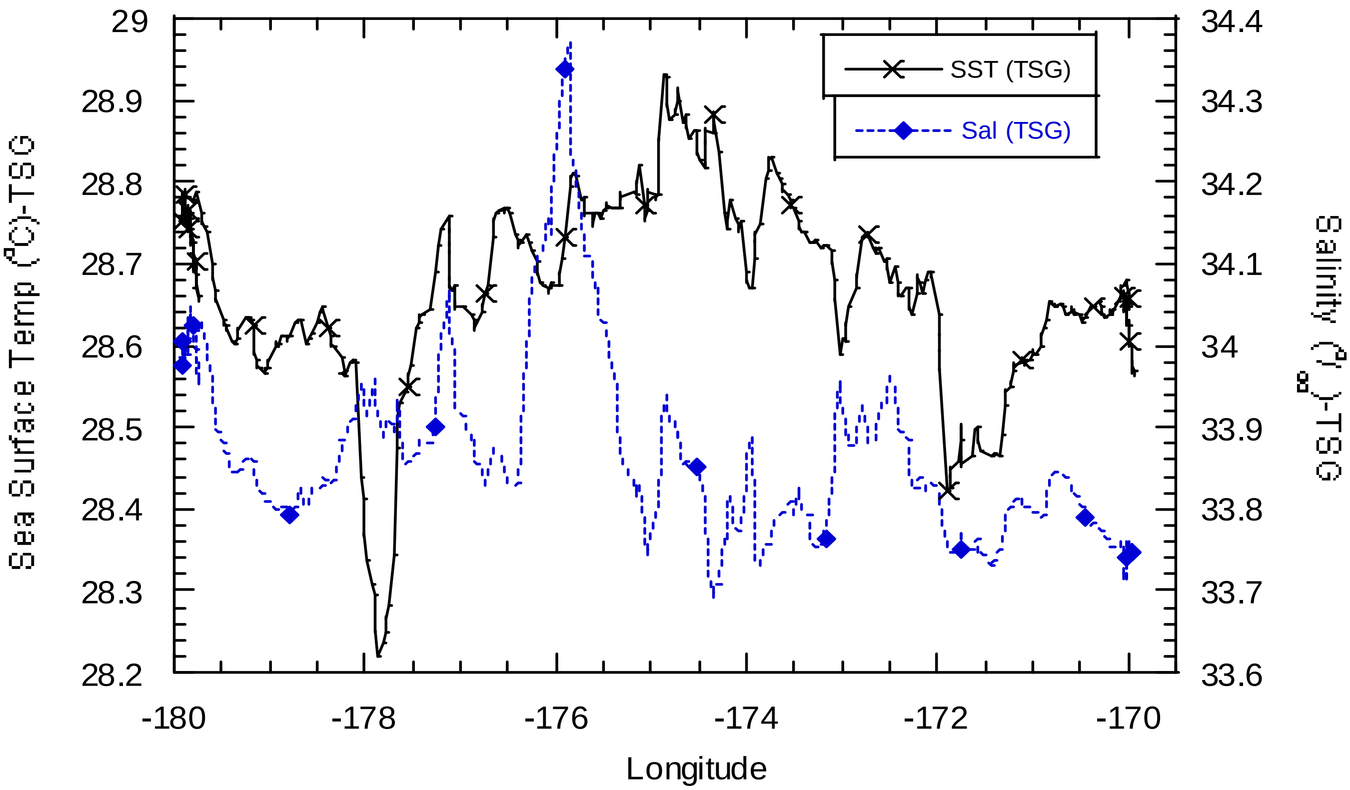
MB95-08 (12/7-12/10)

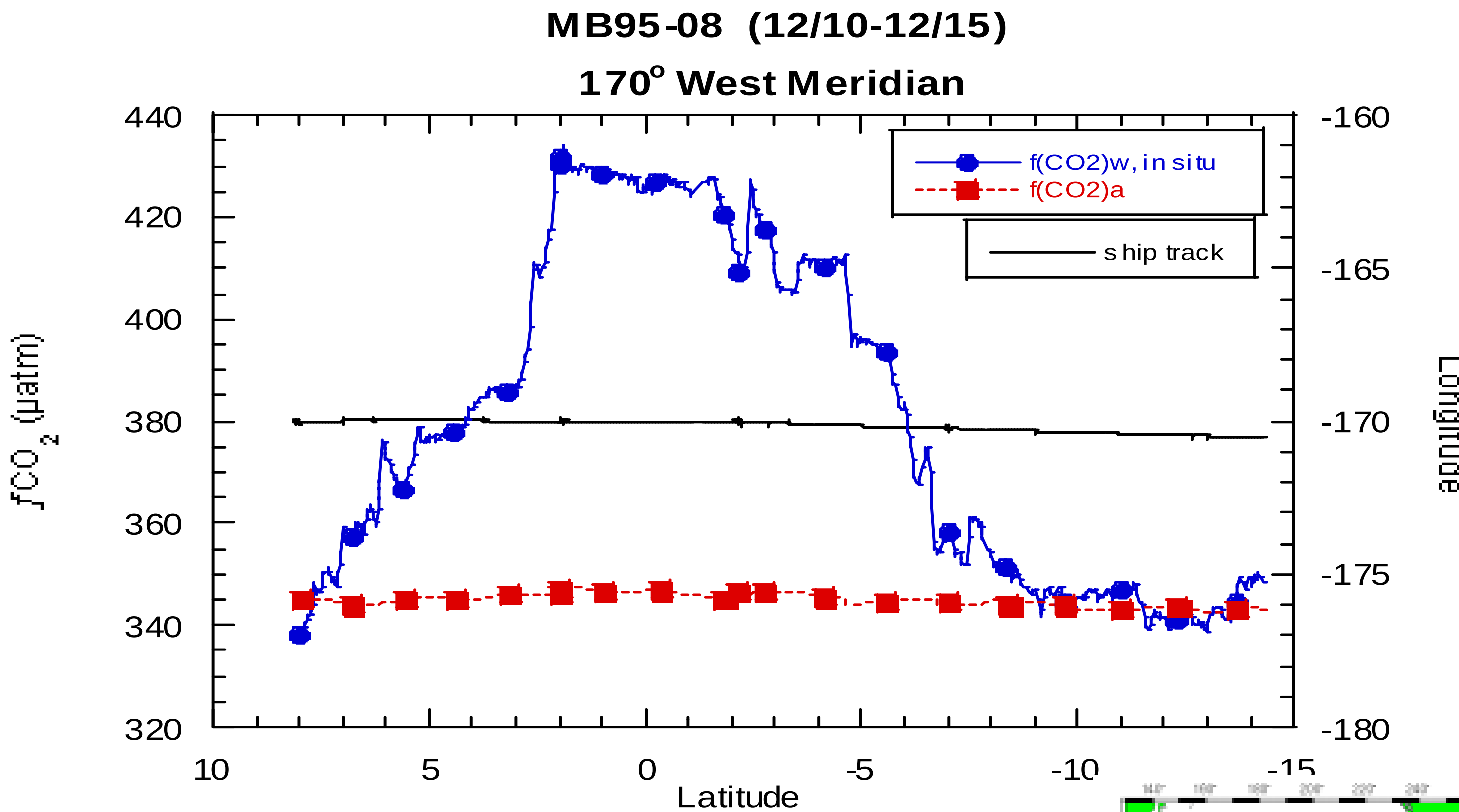
8° North Parallel Transect

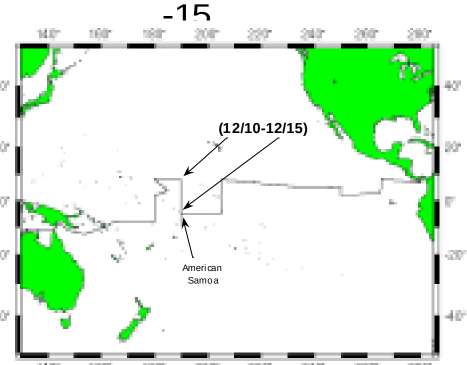


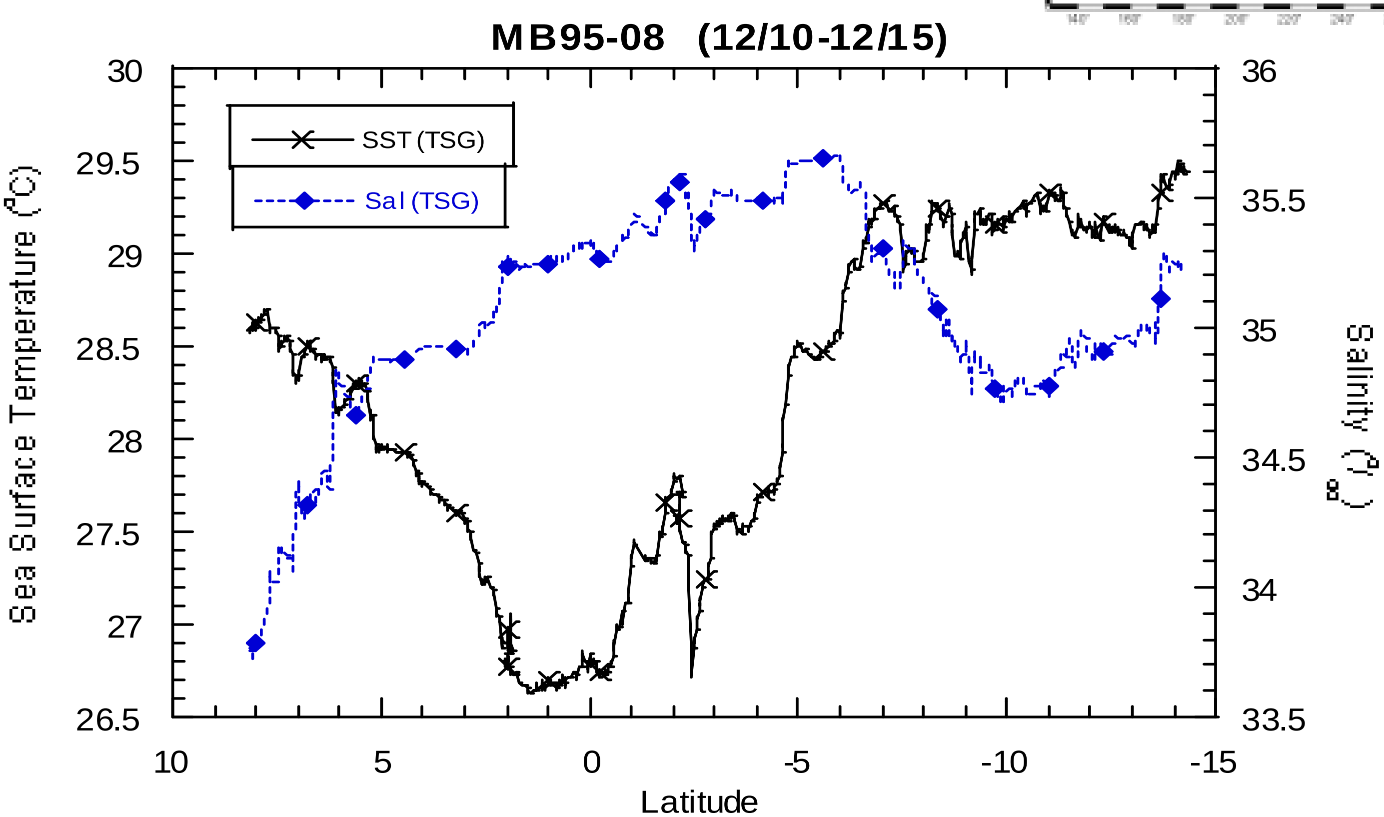


MB95-08 (12/7-12/10)

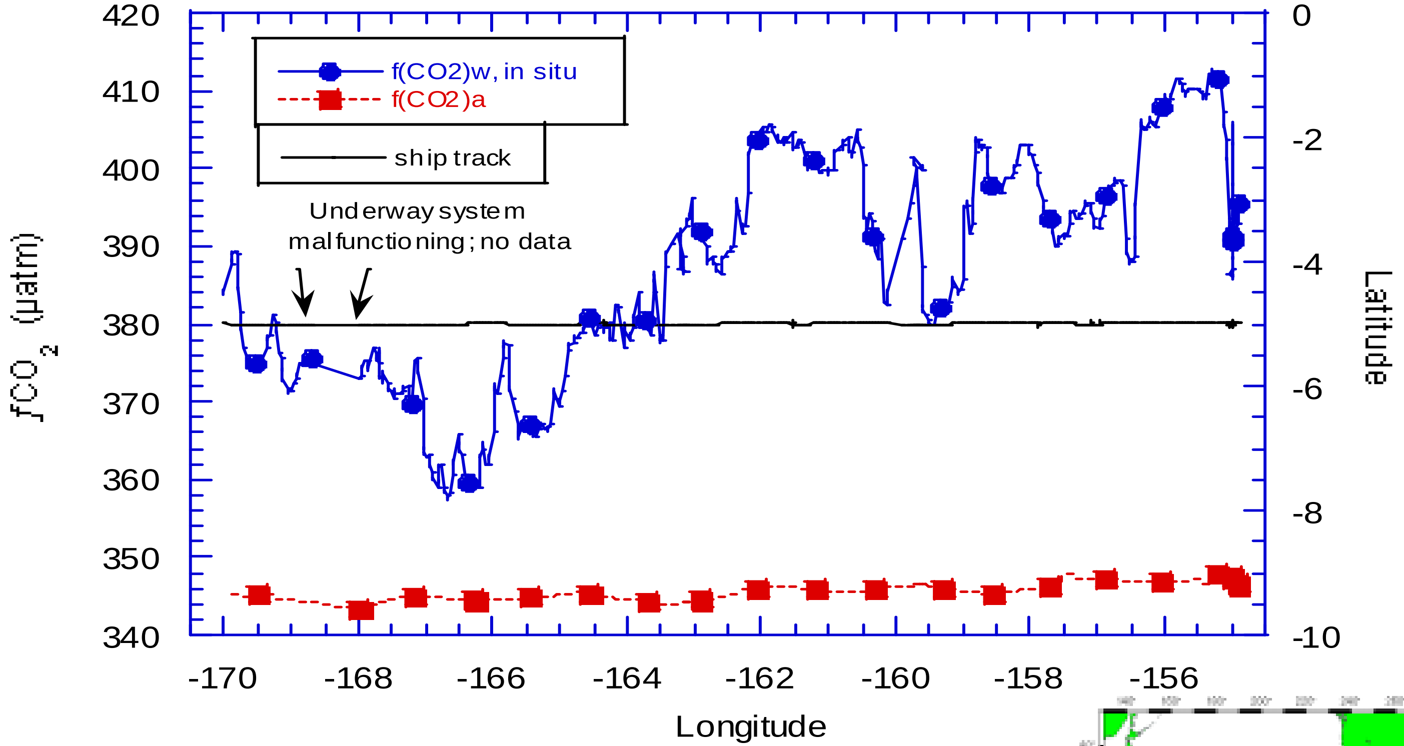


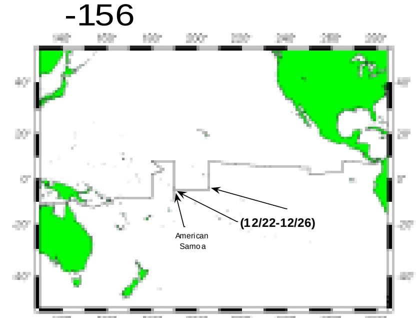

MB95-08 (12/10-12/15)
170° West Meridian
f(CO2)w, in situ
f(CO2)a
ship track
fCO2 (µatm)
Longitude
Latitude
440
420
400
380
360
340
320
-160
-165
-170
-175
-180
10
5
0
-5
-10
-15


(12/10-12/15)
American Samoa

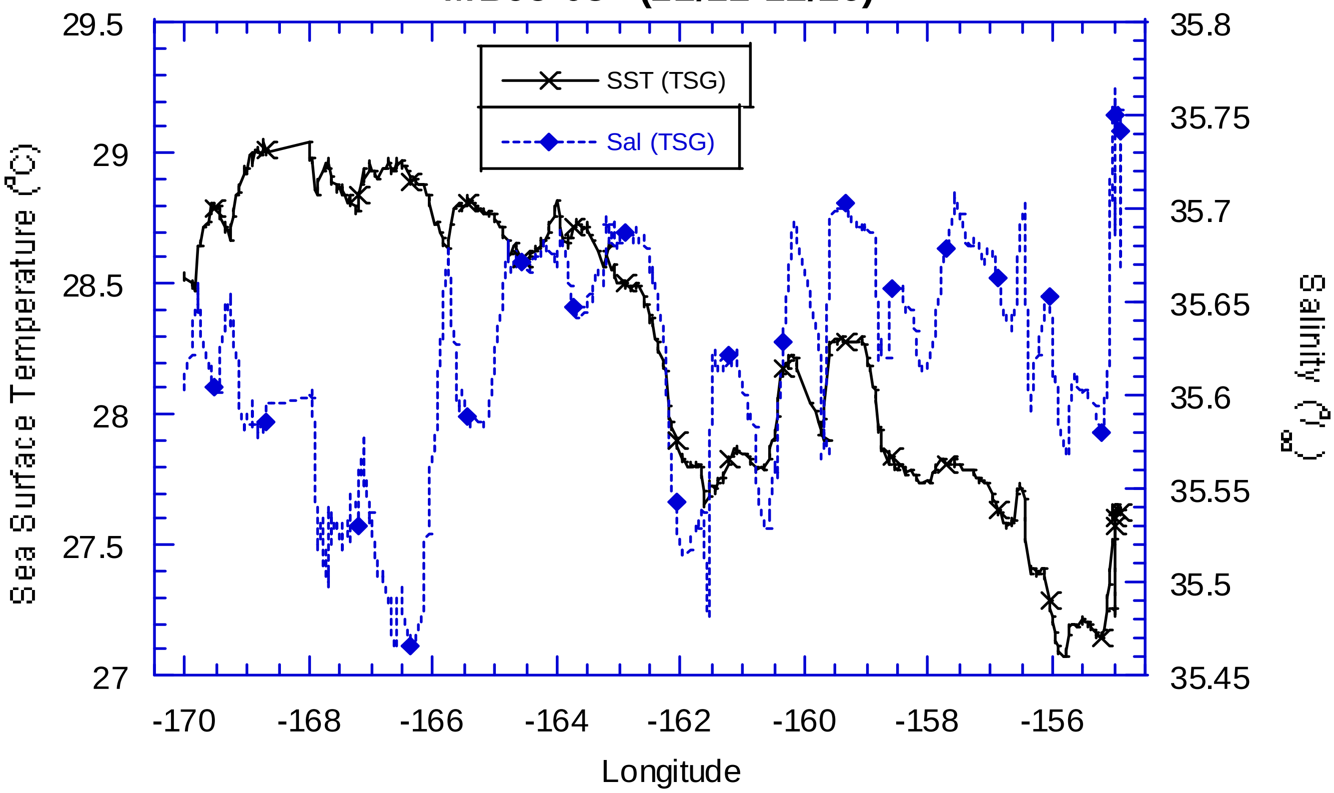

MB95-08 (12/10-12/15)
SST (TSG)
Sal (TSG)
Sea Surface Temperature (°C)
Salinity (‰)
Latitude
30
29.5
29
28.5
28
27.5
27
26.5
36
35.5
35
34.5
34
33.5
10
5
0
-5
-10
-15

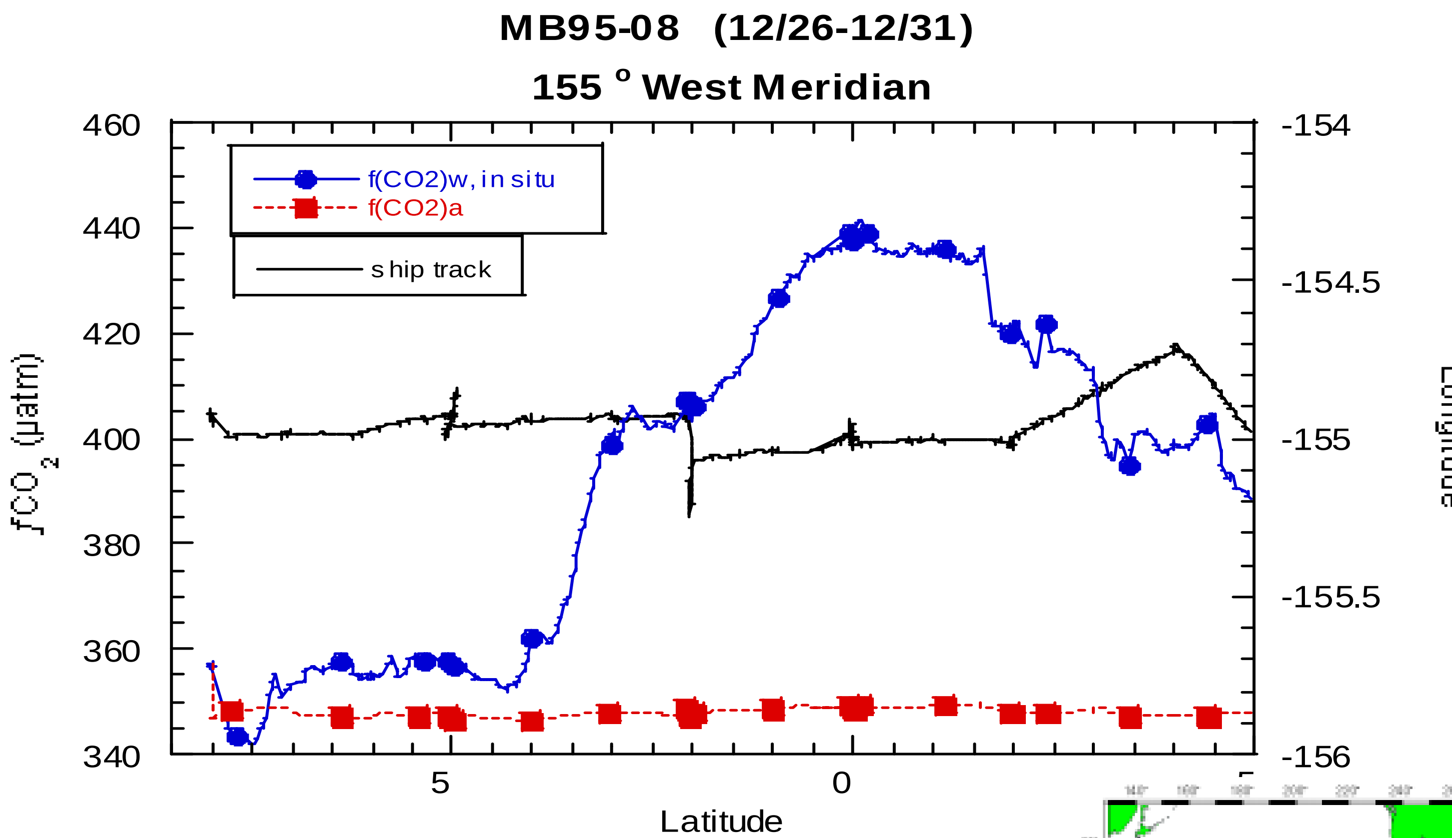
MB95-08 (12/22-12/26)
5° South Parallel Transect

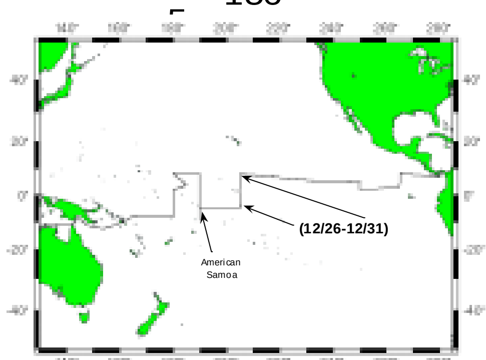


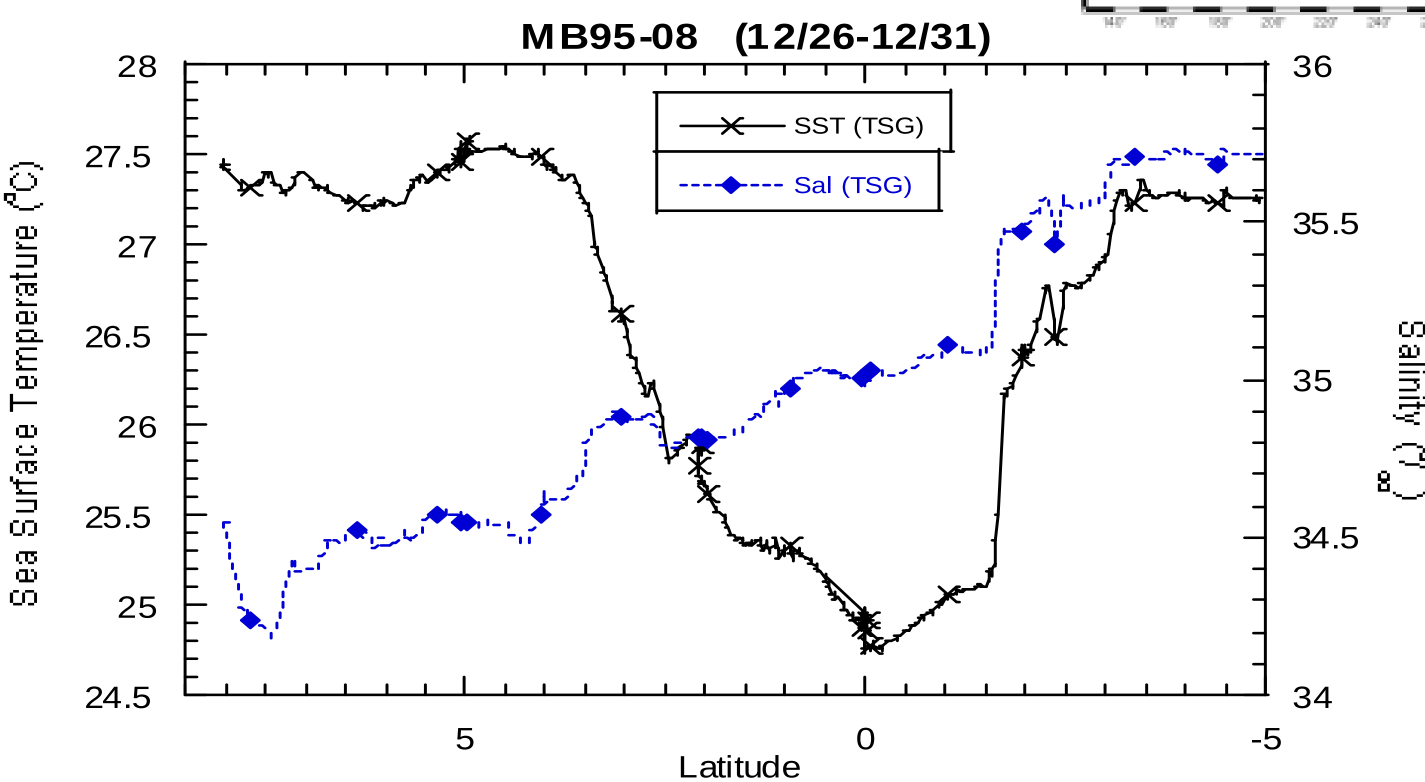


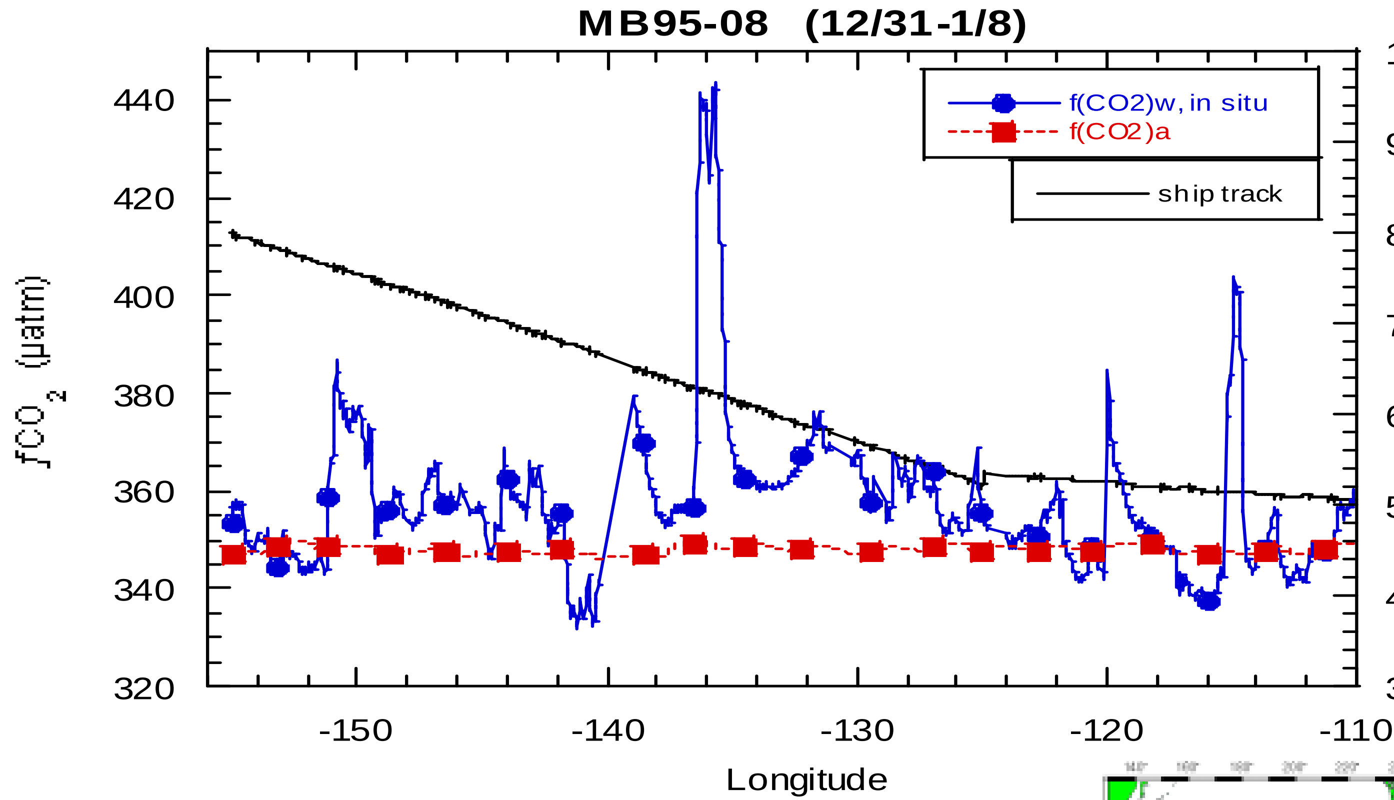
MB95-08 (12/22-12/26)

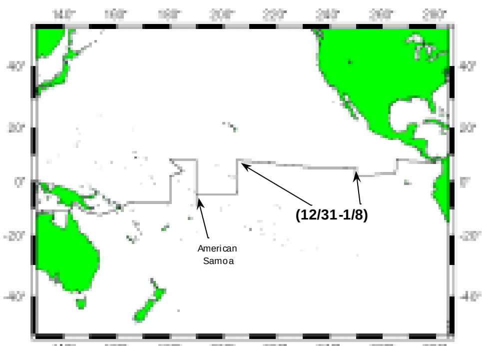


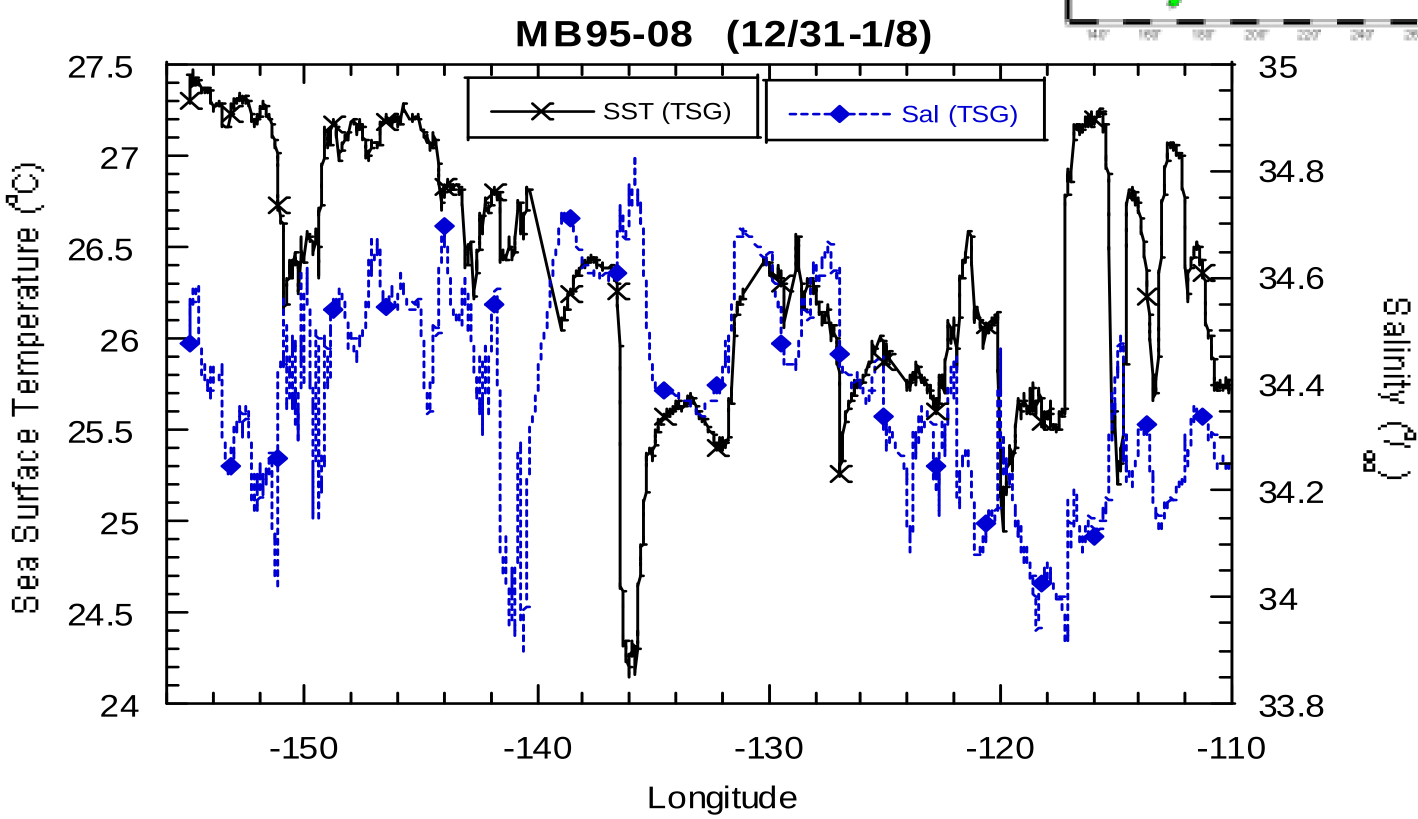

MB95-08 (12/26-12/31)
155 ° West Meridian
f(CO2)w, in situ
f(CO2)a
ship track
fCO2 (µatm)
Longitude
Latitude
460
440
420
400
380
360
340
-154
-154.5
-155
-155.5
-156
5
0

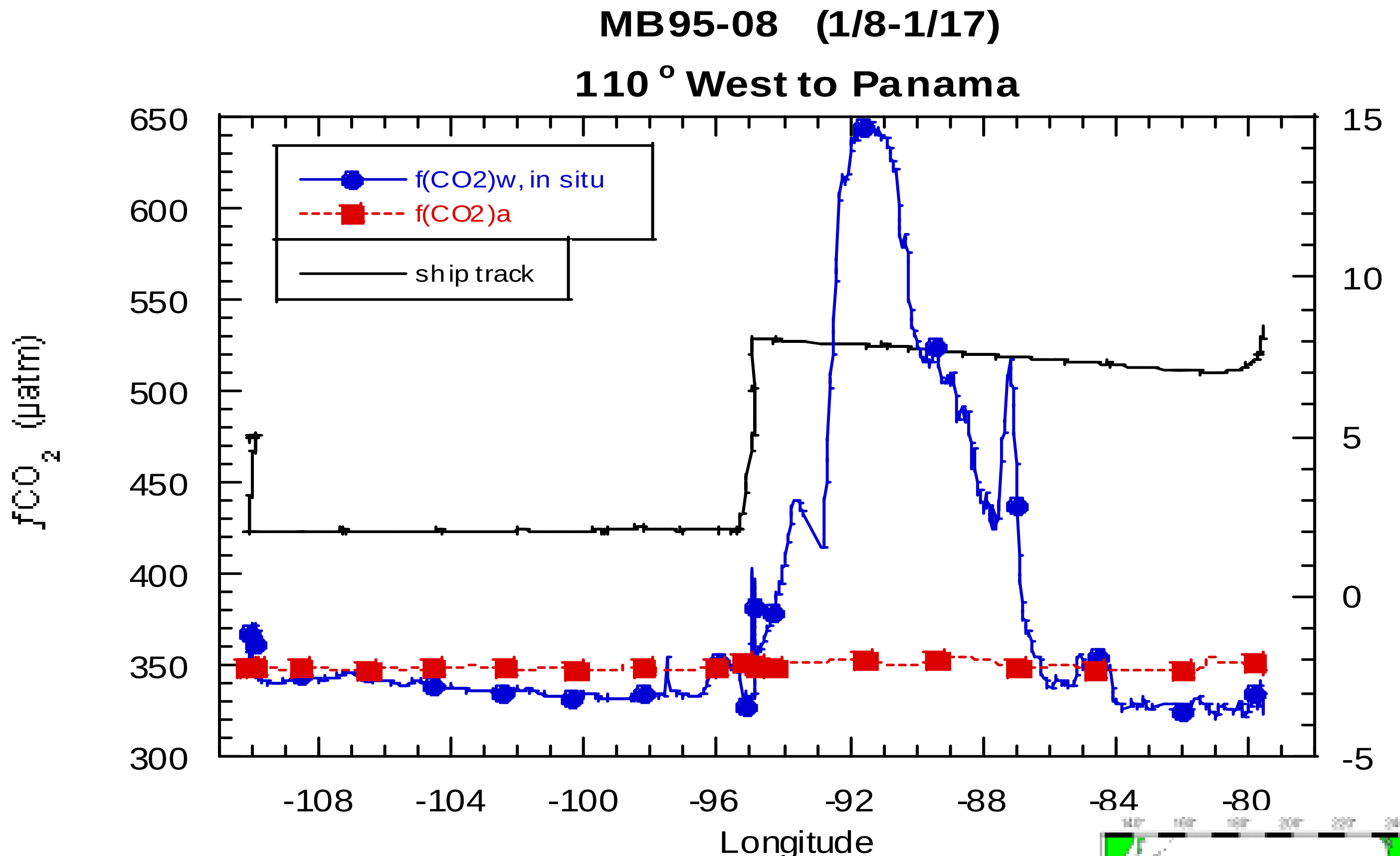

(12/26-12/31)
American Samoa

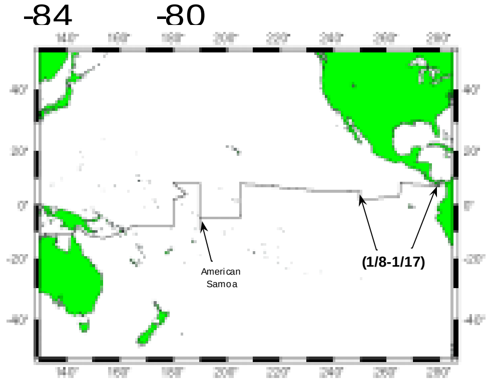

MB95-08 (12/26-12/31)
SST (TSG)
Sal (TSG)
Sea Surface Temperature (°C)
Salinity (‰)
Latitude
28
27.5
27
26.5
26
25.5
25
24.5
36
35.5
35
34.5
34
5
0
-5

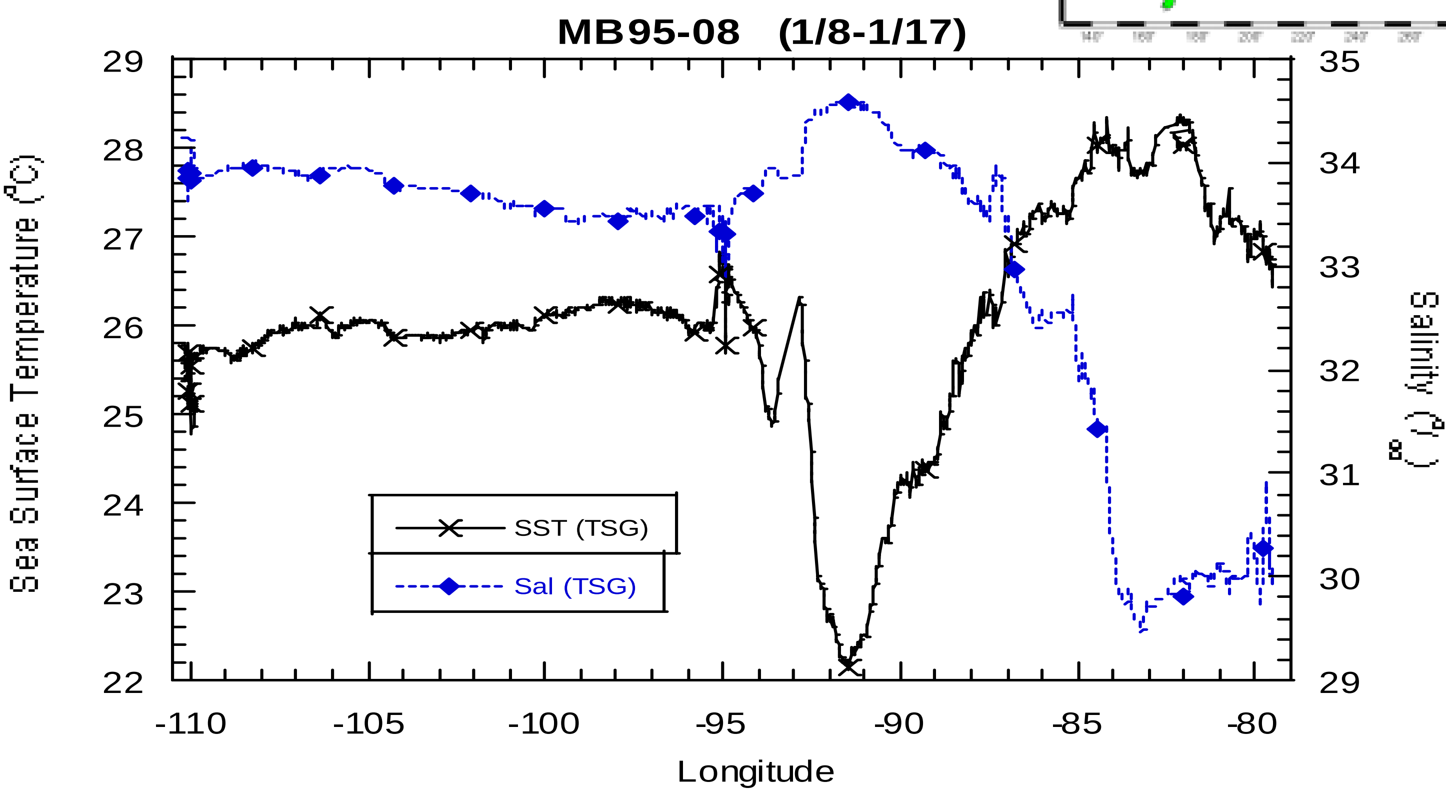

MB95-08 (12/31-1/8)
f(CO2)w, in situ
f(CO2)a
ship track
fCO2 (µatm)
Latitude
Longitude
320
340
360
380
400
420
440
3
4
5
6
7
8
9
10
-150
-140
-130
-120
-110

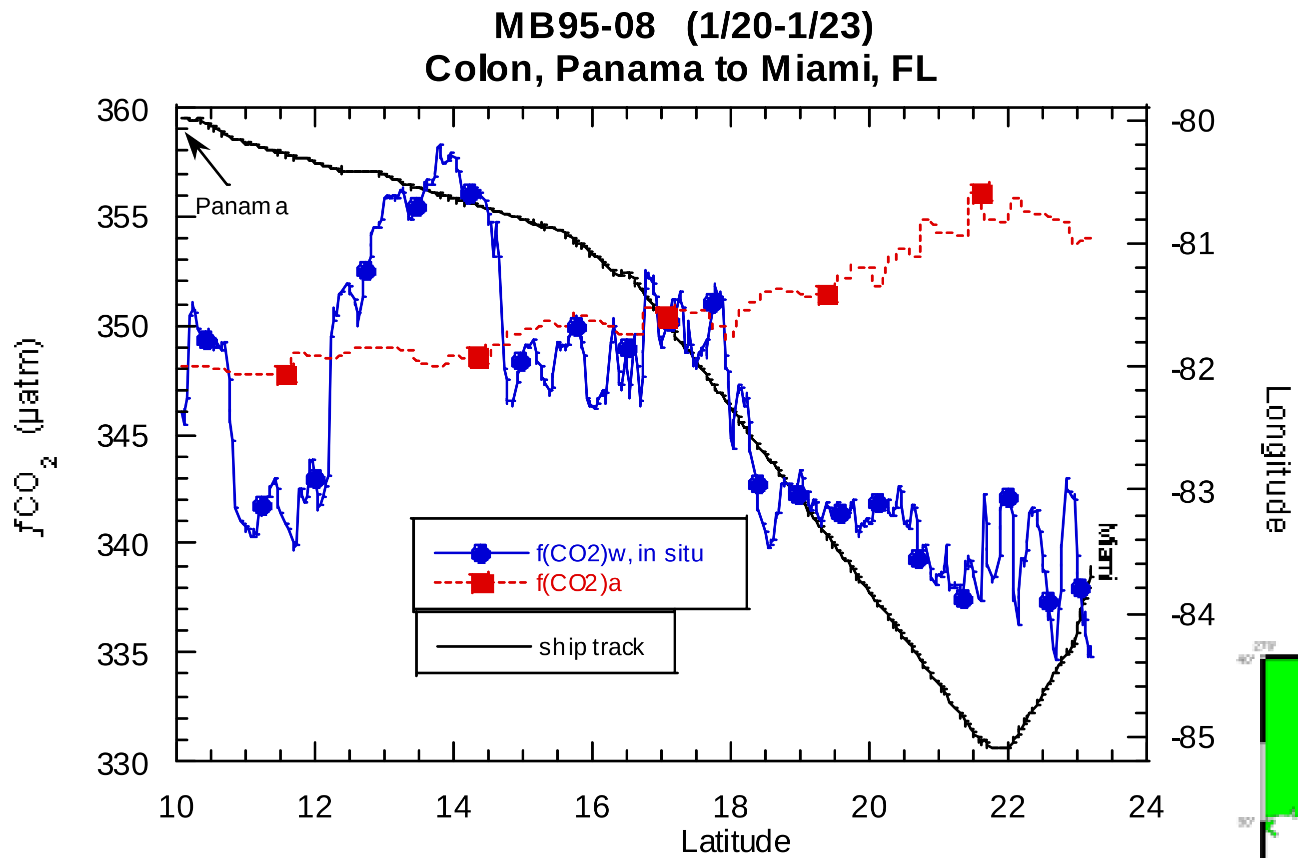

(12/31-1/8)
American Samoa


MB95-08 (12/31-1/8)
SST (TSG)
Sal (TSG)
Sea Surface Temperature (°C)
Salinity (‰)
Longitude
24
24.5
25
25.5
26
26.5
27
27.5
33.8
34
34.2
34.4
34.6
34.8
35
-150
-140
-130
-120
-110

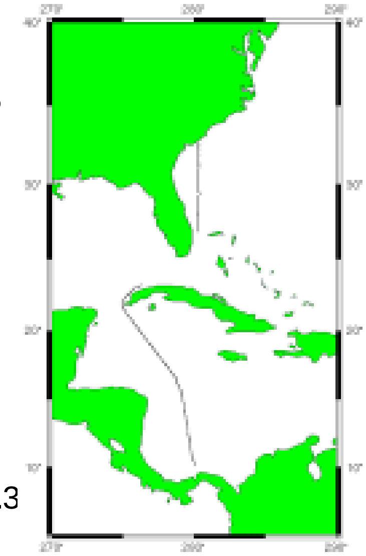

MB95-08 (1/8-1/17)
110 ° West to Panama
f(CO2)w, in situ
f(CO2)a
ship track
fCO2 (μatm)
Latitude
Longitude
650
600
550
500
450
400
350
300
15
10
5
0
-5
-108
-104
-100
-96
-92
-88
-84
-80

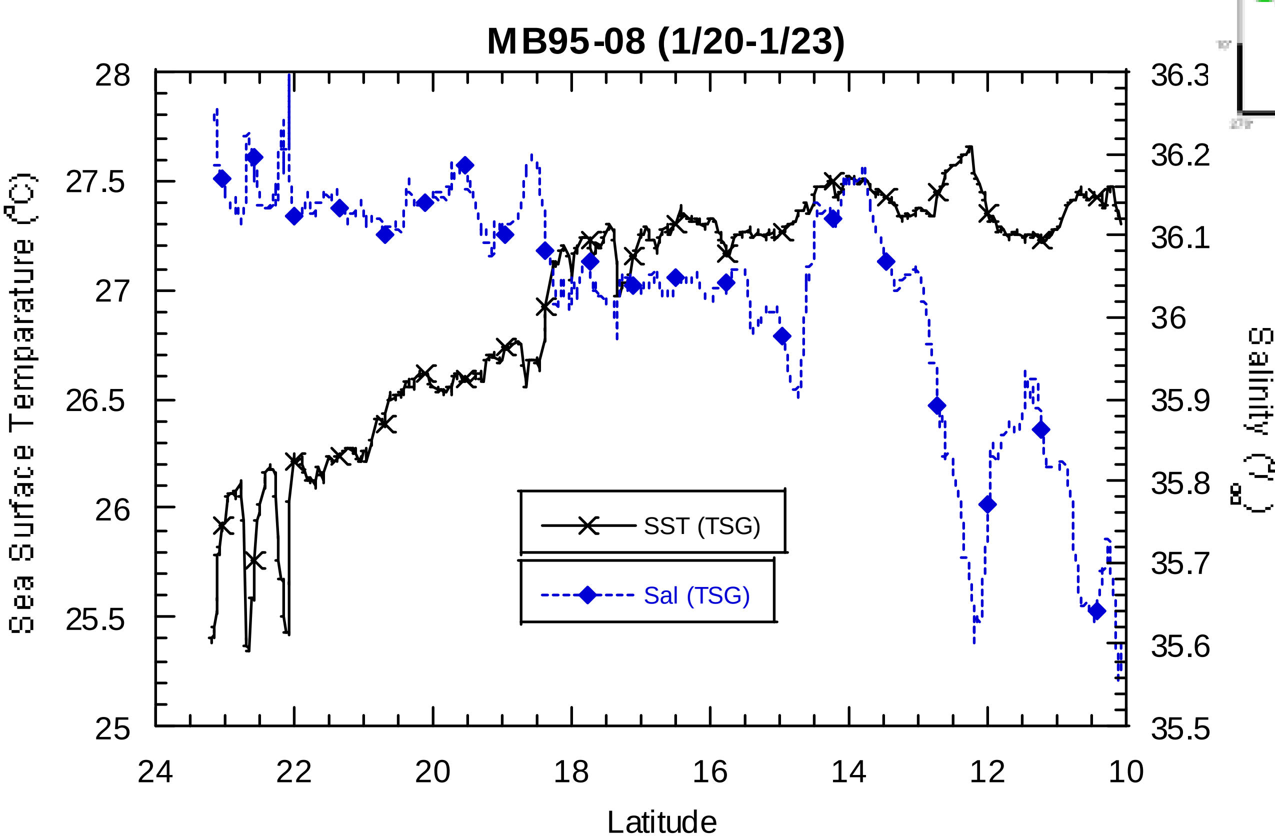

American Samoa
(1/8-1/17)

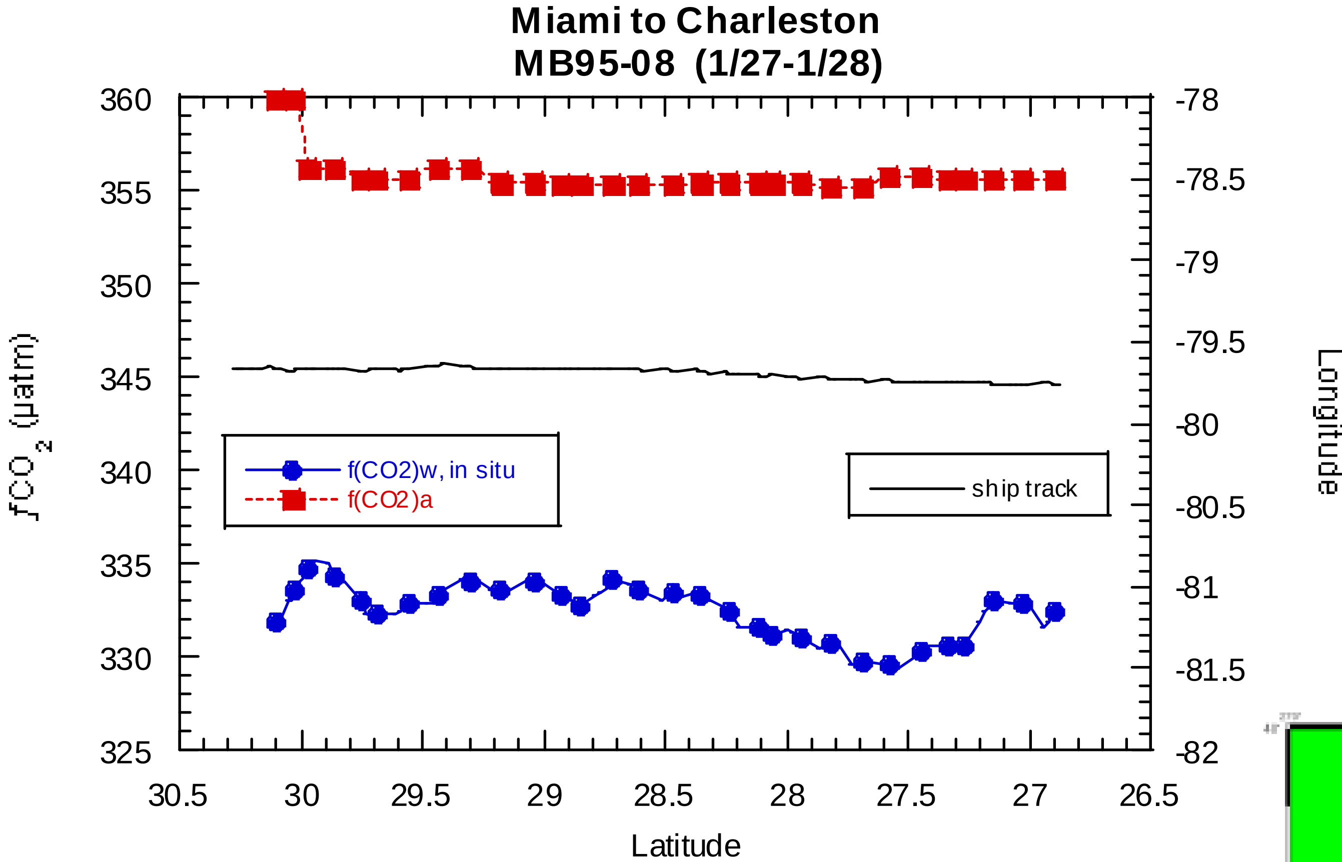

MB95-08 (1/8-1/17)
SST (TSG)
Sal (TSG)
Sea Surface Temperature (°C)
Salinity (‰)
Longitude
29
28
27
26
25
24
23
22
35
34
33
32
31
30
29
-110
-105
-100
-95
-90
-85
-80

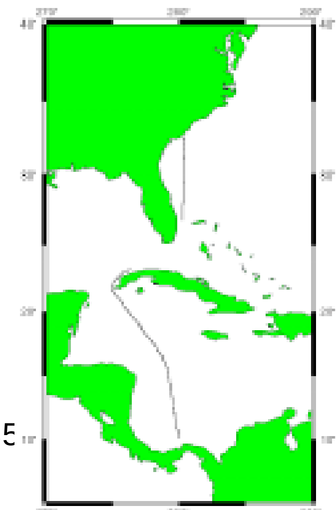


Trackline shown only for areas where data was collected

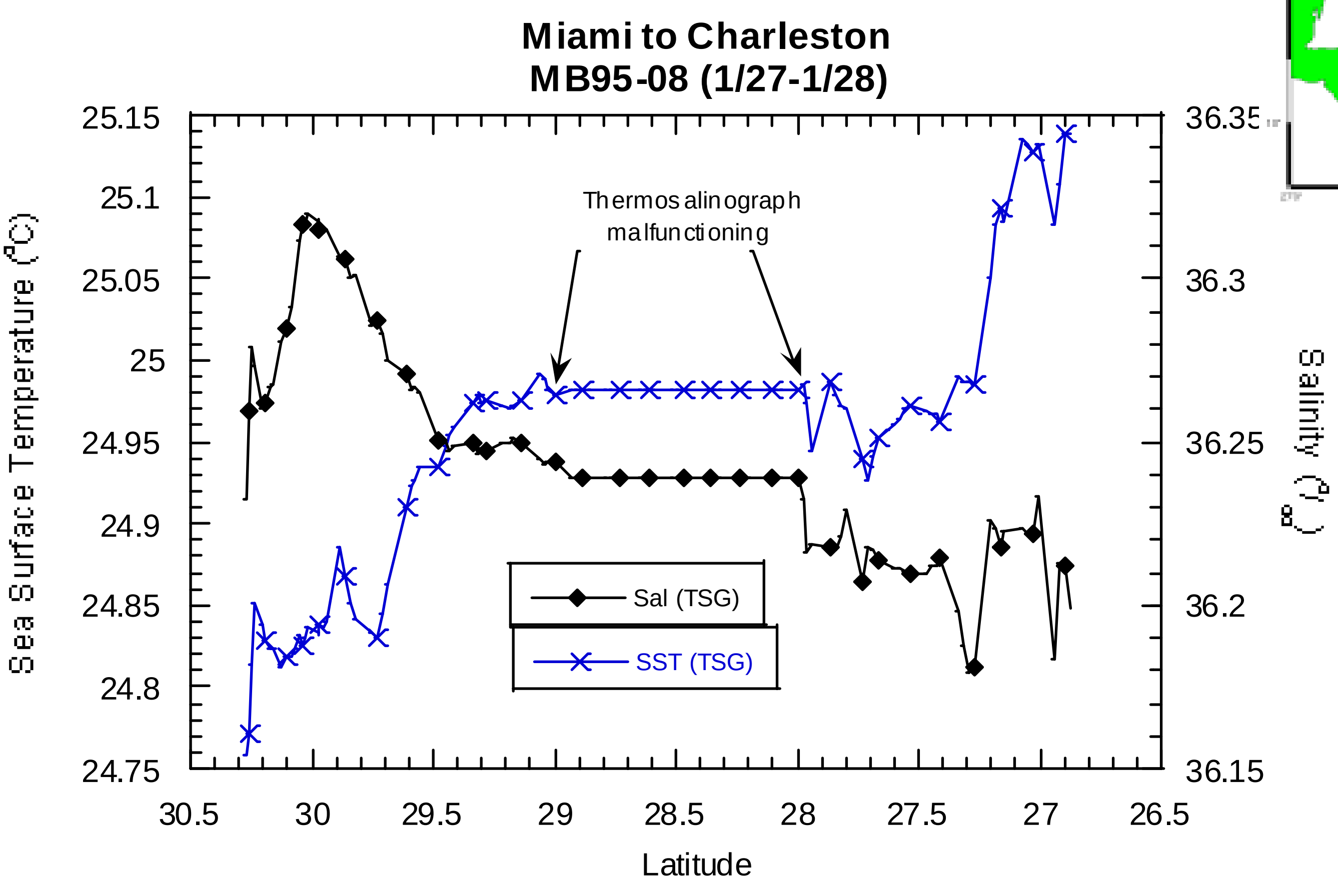








Trackline shown only
for areas where data
was collected



4. REFERENCES

Barnola, J-M., D. Raynaud, Y.S. Korotkevitch and C. Lorius, 1987: Vostok ice core provides 160,000 year record of atmospheric CO2. *Nature*, **329**, 428-414

Barnola, J-M., P. Pimienta, D. Raynaud and T.S. Korotkevich, 1991: CO_2-climate relationship as deduced from the Vostok ice core: a re-examination based on new measurement and on a re-evaluation of the air dating. *Tellus*, **43B**, 83-90.

Chen H., Wanninkhof R., Feely R. A., and Greeley D. 1995. Measurement of fugacity of carbon dioxide in sub-surface water: an evaluation of a method based on infrared analysis. Technical Memorandum ERL-AOML 85, NOAA/AOML, Miami, FL, pp. 49.

DOE. 1994. *Handbook of methods for the analysis of the various parameters of the carbon dioxide system in sea water. Version 2*. (A. Dickson and C. Goyet ed.) ORNL/CDIAC-74, 1991.

Eswaran, H., E. Van den Berg and p. Reich, 1993: Organic carbon soils of the world. *Soil Science Society of America Journal*, **57**, 192-194.

Ho, D. T., R. Wanninkhof, J. Masters, R.A. Feely, C. Cosca, 1997. Measurements of Underway fCO_2 in the Eastern Equatorial Pacific on NOAA ships MALCOLM BALDRIGE and DISCOVERER from February to September, 1994. NOAA Data Report ERL AOML-30, 52pp.

Intergovernmental Panel on Climate Change, 1995. *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*. Cambridge University Press.

Johnson K. M. and Wallace D. W. R., 1992. The single-operator multiparameter metabolic analyzer for total carbon dioxide with coulometric detection. DOE Research Summary, No. 19, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Johnson K. M., Wills K. D., Butler D. B., Johnson W. K., and Wong C. S., 1993. Coulometric total carbon dioxide analysis for marine studies: maximizing the performance of an automated continuous gas extraction system and coulometric detector. *Mar. Chem.* **44**, 167-189.

Keeling C. D. 1965. Carbon dioxide in surface waters of the Pacific Ocean 2. Calculation of the exchange with the atmosphere. *J. Geophys. Res.* **70**, 6099-6102.

LI-COR. 1990. LI-6262 CO_2/H_2O Analyzer Operating and Service Manual. 9003-59, LI-COR, Lincoln, NB.

Potter, C.S., J.T. Ramderson, C.B. Field, P.A. Matson, P.M. Vitousek, H.A. Mooney and S.A. Klooster, 1993: Terrestrial ecosystem production: a process model based on global satellite and surface data. *Global Biogeochemical Cycles*, **7**, 811-841.

Siegenthaler, U. and J.L. Sarmiento, 1993: Atmospheric carbon dioxide and the ocean. *Nature*, **365**, 119-125.

Wanninkhof R. and Thoning K. 1993. Measurement of fugacity of CO_2 in surface water using continuous and discrete sampling methods. *Mar. Chem.* **44**, 189-205.

Weiss R. F. 1974. Carbon dioxide in water and seawater: the solubility of a non-ideal gas. *Mar. Chem.* **2**, 203-215.

Weiss R. F., Janke R. A., and Keeling C. D. 1982. Seasonal effects of temperature and salinity on the partial pressure of CO_2 in seawater. *Nature* **300**, 511-513.

APPENDIX A: Individual Thermistor Calibrations

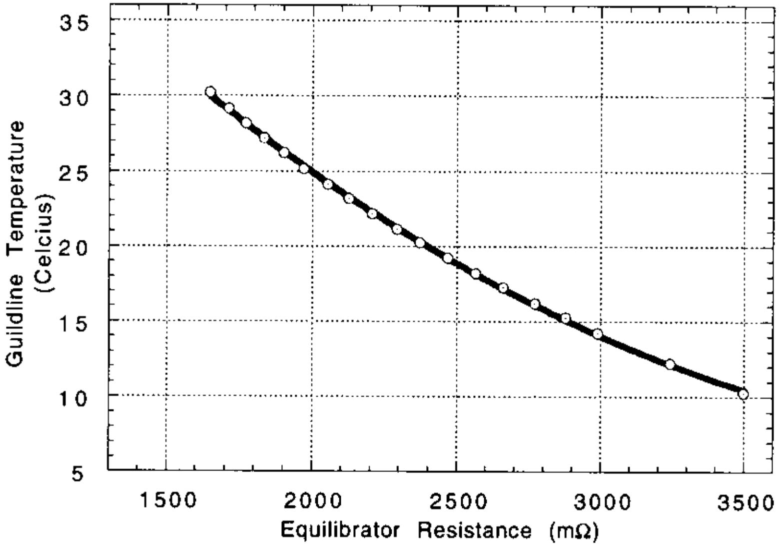
The calculations for determining fCO_2 are temperature dependent, therefore frequent calibration of thermistors ensure a high degree of precision in the data set. The following tables and graphs are the calibrations performed during certain inports. Calibrations were carried out by removing the YSI resistance thermistor probe from the equilibrator to a temperature controlled water bath. A Guildline digital platinum resistance thermometer (model 9540) was used as the standard temperature marker. The mercury thermometer placed in the equilibrator was also calibrated. The slope of the Guildline temperature over the equilibrator thermistor resistance yielded the polynomial equation used to calculate underway water temperatures flowing through the equilibrator. The resulting polynomial is listed below the heading of each graph. The following six pages have a chronological listing of the thermistor calibrations. Each calibration has a graphical representation above a tabular one.

Tables

Figures

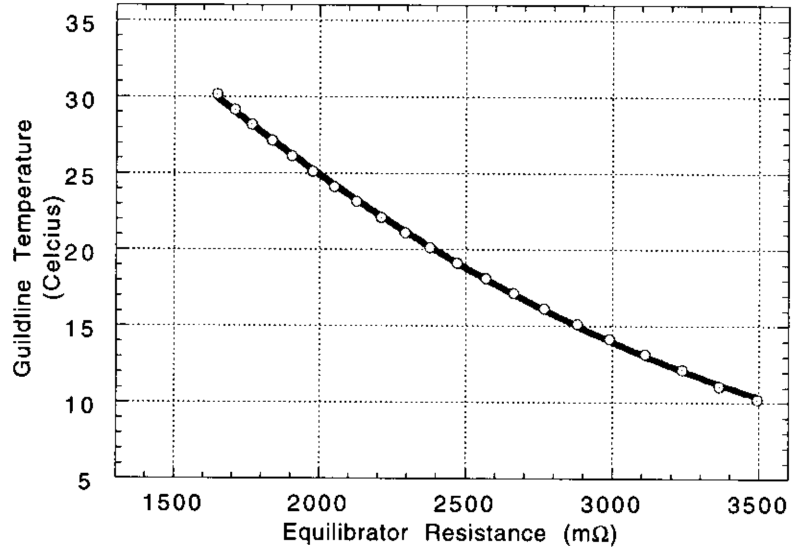
Thermistor Calibration (2/12/95)

$Y=61.877-.023512x+2.5205e\text{-}6x^2$



Thermistor Calibration 2/20/95

$Y=61.713-.023364x+2.4823e\text{-}6x^2$



Thermistor Calibration 2/12/95

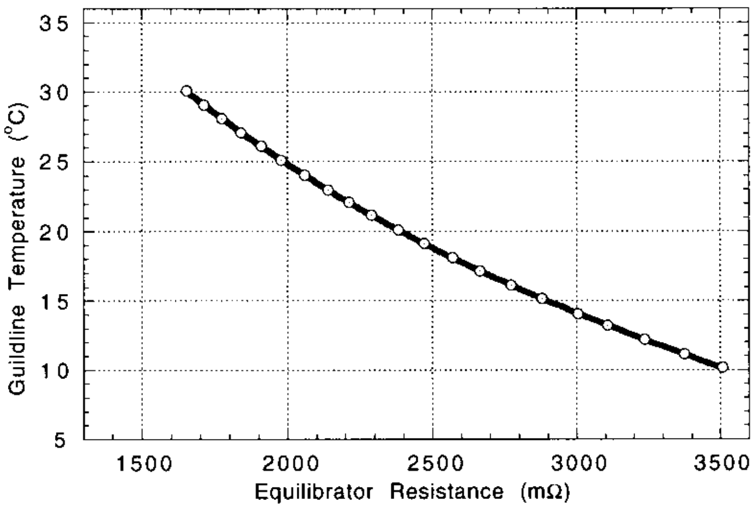
Digital Platinum Thermometer (C)	Equilibrator Resistance (mΩ)	Eq. Mercury Thermometer (C)
10.275	3498	10.09
11.273		11.08
12.202	3241	12.06
14.246	2990	14.07
15.233	2877	15.07
16.199	2770	16.05
17.253	2660	17.07
18.206	2564	18.05
19.204	2468	19.05
20.242	2372	20.07
21.159	2292	21.04
22.169	2206	22.04
23.186	2125	23.05
24.14	2053	24.02
25.15	1970	25.03
26.199	1902	26.06
27.199	1835	27.04
28.165	1770	28.03
29.152	1711	29.02
30.204	1648	30.03

Thermistor Calibration 2/20/95

Digital Platinum Thermometer (C)	Equilibrator Resistance (mΩ)	Eq. Mercury Thermometer (C)
10.229	3494	10.2
11.087	3364	11.15
12.144	3238	12.13
13.166	3111	13.14
14.178	2990	14.15
15.129	2882	15.08
16.161	2768	16.12
17.153	2664	17.13
18.114	2568	18.1
19.132	2471	19.12
20.153	2378	20.08
21.109	2293	21.09
22.107	2210	22.08
23.148	2125	23.1
24.12	2050	24.08
25.126	1976	25.1
26.143	1904	26.07
27.153	1836	27.06
28.193	1768	28.1
29.17	1708	29.1
30.174	1647	30.08

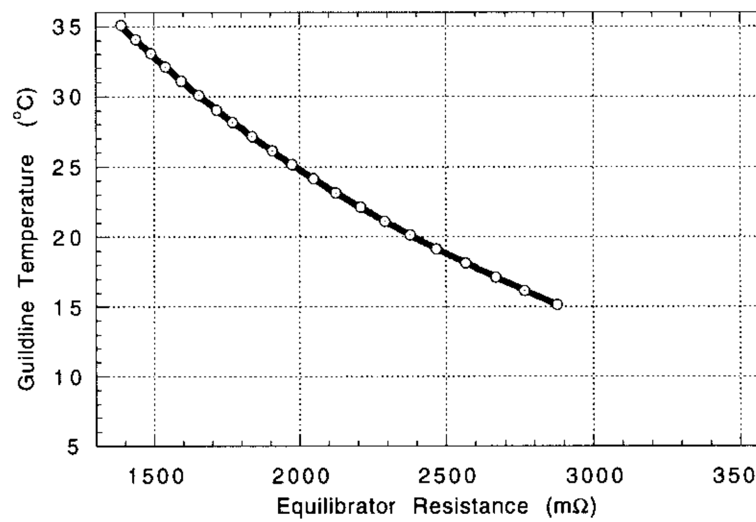
Therm. Calib. (3/21/95) Durban, SA

$Y=73.255-.037723x+8.2442e\text{-}6x^2-7.4689e\text{-}10x^3$



Therm. Calib. (4/25/95) Colombo, Sri Lanka

$Y=79.358-.046092x+1.2001e\text{-}5x^2-1.2992e\text{-}9x^3$



Thermistor Calibration 3/21/95

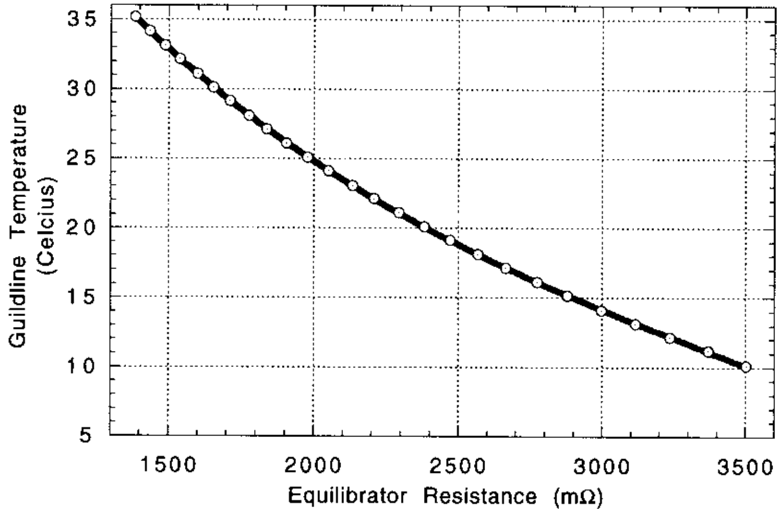
Digital Platinum Thermometer (C)	Equilibrator Resistance (mΩ)	Eq. Mercury Thermometer (C)
10.161	3507	10.1
11.131	3375	11.08
12.186	3235	12.15
13.21	3108	13.18
14.072	3004	14
15.157	2879	15.1
16.137	2771	16.07
17.165	2664	17.1
18.112	2569	18.08
19.118	2472	19.07
20.101	2381	20.07
21.159	2288	21.1
22.069	2211	22.05
22.974	2139	22.95
24.024	2058	24
25.106	1977	25.1
26.081	1909	26.05
27.099	1839	27.05
28.117	1773	28.06
29.078	1713	29.01
30.064	1654	30

Thermistor Calibration 4/25/95

Digital Platinum Thermometer (C)	Equilibrator Resistance (mΩ)	Eq. Mercury Thermometer (C)
15.163	2878	15.14
16.167	2767	16.13
17.121	2668	17.09
18.134	2566	18.09
19.168	2467	19.13
20.139	2378	20.1
21.135	2291	21.08
22.117	2209	22.08
23.164	2124	23.12
24.162	2047	24.1
25.156	1974	25.1
26.115	1906	26.05
27.127	1838	27.05
28.153	1770	28.07
29.04	1715	29
30.062	1654	29.97
31.107	1594	
32.085	1539	
33.053	1488	
34.062	1437	
35.098	1386	

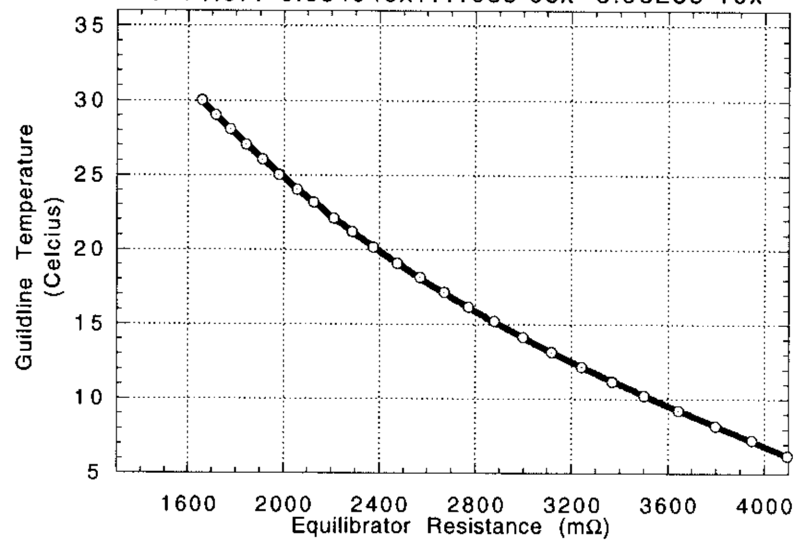
Thermistor Calibration (5/28/95)

$Y=76.511-0.041679+9.8139e\text{-}06x^2-9.5059e\text{-}10x^3$



Therm. Calib. (7/10/95) Victoria, Seychelles

$Y=71.077-0.034948x+7.108e\text{-}06x^2-5.9626e\text{-}10x^3$



Thermistor Calibration 5/28/95

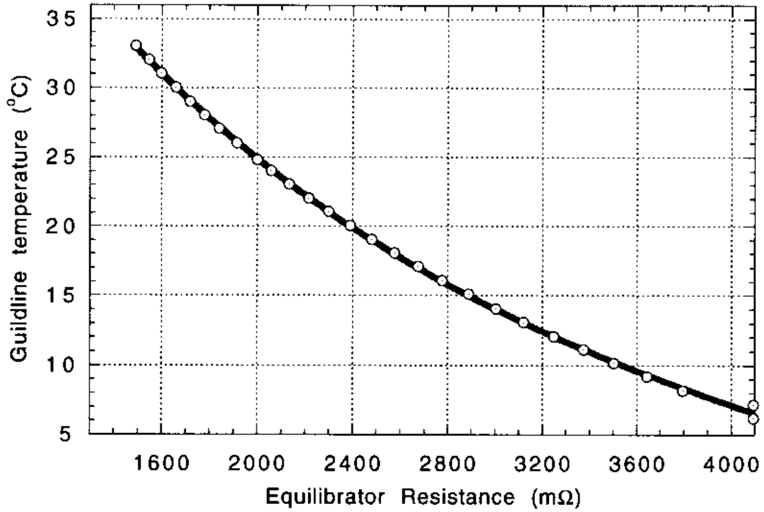
Digital Platinum Thermometer (C)	Equilibrator Resistance (mΩ)	Eq. Mercury Thermometer (C)
10.105	3502	10.3
11.167	3369	11.4
12.164	3237	12.3
13.118	3116	13.4
14.11	2997	14.1
15.165	2878	15.3
16.117	2773	16.2
17.158	2664	17.3
18.13	2567	18.3
19.14	2470	19.2
20.113	2381	20.2
21.1	2294	21.1
22.151	2208	22.2
23.064	2133	23.1
24.122	2050	24.1
25.096	1978	25.05
26.117	1906	26.1
27.113	1838	27.1
28.082	1776	28
29.13	1711	29.05
30.108	1653	30.05
31.098	1598	31.1
32.157	1537	
33.123	1486	
34.144	1434	
35.16	1384	

Thermistor Calibration 7/10/95

Digital Platinum Thermometer (C)	Equilibrator Resistance (mΩ)	Eq. Mercury Thermometer (C)
5.27		5.275
6.237	4095	6.225
7.226	3947	7.225
8.188	3798	8.2
9.242	3644	9.225
10.217	3501	10.2
11.182	3369	11.15
12.16	3241	12.1
13.156	3118	13.1
14.13	2997	14.1
15.191	2878	15.175
16.159	2770	16.15
17.129	2669	17.1
18.138	2570	18.1
19.114	2476	19.1
20.16	2374	20.15
21.195	2287	21.2
22.113	2209	22.1
23.165	2125	23.1
24.06	2056	24.1
25.048	1981	25.05
26.051	1912	26
27.071	1842	27
28.063	1777	28
29.04	1716	29
30.026	1658	29.95

Therm. Calib. (7/28/95) Muscat, Oman

$Y=70.312-0.033566x+6.4128e\text{-}06x^2-4.9242e\text{-}10x^3$

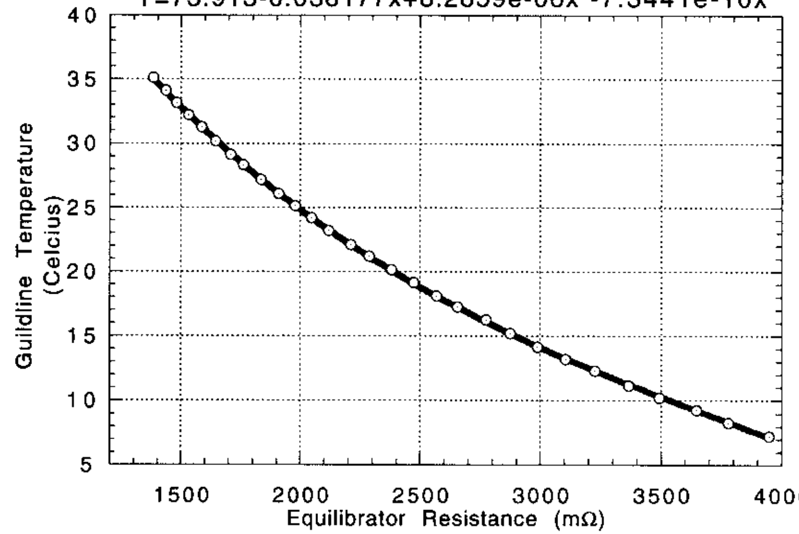


Thermistor Calibration 7/28/95

Digital Platinum Thermometer (C)	Equilibrator Resistance (mΩ)	Eq. Mercury Thermometer (C)
5.253		5.2
6.181	4095	6.1
7.178	4095	7.175
8.178	3796	8.2
9.186	3645	9.2
10.163	3503	10.17
11.117	3375	11.1
12.07	3248	12.05
13.09	3120	13.075
14.068	3003	14.05
15.091	2888	15.05
16.091	2777	16.05
17.074	2674	17
18.075	2575	18.02
19.044	2480	19
20.047	2388	20
21.051	2300	21
22.021	2217	22
23.074	2133	23.02
24.048	2057	24
24.813	2001	24.79
26.029	1914	25.99
27.101	1840	27
28.062	1778	28
29.032	1717	29
30.016	1658	29.92
31.069	1598	
32.013	1545	
33.059	1490	
34.052	1440	
35.068	1390	

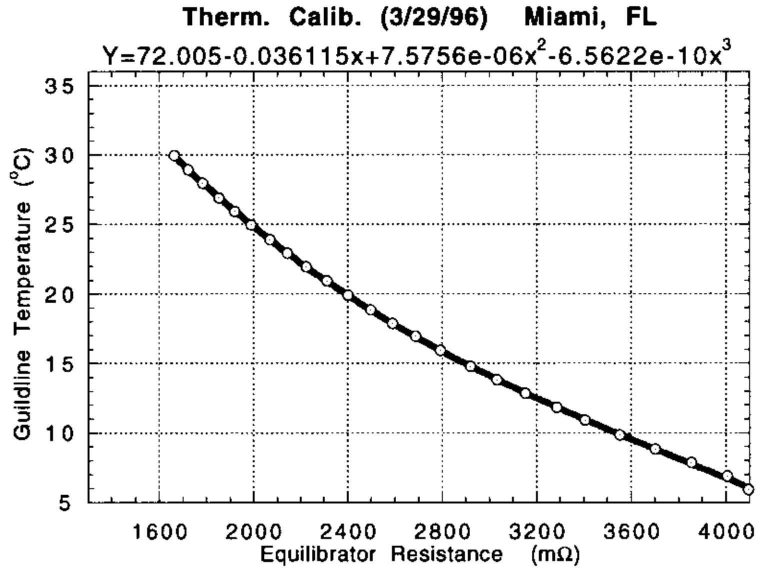
Therm. Calib. (9/20/95) Fremantle, AU

$Y=73.913-0.038177x+8.2859e\text{-}06x^2-7.3441e\text{-}10x^3$



Thermistor Calibration 9/20/95

Digital Platinum Thermometer (C)	Eq Thermistor Resistance (mΩ)
7.264	3947
8.294	3778
9.292	3646
10.249	3493
11.185	3366
12.313	3225
13.222	3106
14.196	2987
15.209	2874
16.261	2773
17.237	2656
18.134	2568
19.144	2473
20.176	2379
21.169	2288
22.087	2210
23.211	2117
24.162	2047
25.108	1979
26.071	1910
27.157	1835
28.311	1761
29.152	1708
30.174	1645
31.254	1585
32.225	1532
33.179	1481
34.114	1435
35.114	1383



Thermistor Calibration 3/29/96

Digital Platinum Thermometer (C)	Equilibrator Resistance (mΩ)	Eq. Mercury Thermometer (C)
4.878	4095	4.9
5.92	4095	5.9
6.894	4006	6.9
7.847	3853	7.9
8.819	3703	8.9
9.859	3552	9.9
10.9	3406	10.9
11.83	3285	11.85
12.86	3153	12.85
13.815	3034	13.8
14.811	2921	14.8
15.963	2791	15.95
16.938	2688	16.95
17.904	2590	17.9
18.871	2497	18.85
19.913	2400	19.9
20.909	2311	20.9
21.95	2223	21.9
22.894	2145	22.9
23.904	2068	23.9
24.953	1989	24.95
25.917	1920	25.9
26.909	1853	26.9
27.956	1784	27.95
28.918	1723	28.9
29.924	1662	29.9

APPENDIX B: Example of Underway Data Files

The underway fCO_2 data can be found by contacting the data manager, the authors or downloaded at *ftp://ftp.aoml.noaa.gov/pub/ocd/carbon/uwpco295*. The data files are in text format. Each file is categorized by the leg name (e.g. **MB95-02**) and if the file is exceptionally large it will have a suffix pertaining to the range of dates within that file (e.g. **(3/17-3/30)**). The files consist of 15 columns of data:

JD	=	Julian decimal day
Date	=	month/day/year
Time	=	01:00:00 to 23:59:59
Lat	=	Latitude (negative numbers for the southern hemisphere)
Long	=	Longitude (negative numbers for the western hemisphere)
xCO2,w	=	mole fraction of carbon dioxide in water (ppm)
xCO2,a	=	mole fraction of carbon dioxide in air (ppm)
Eq Temp	=	temperature recorded inside the equilibrator
Pressure	=	atmospheric pressure (mB)
SST (TSG)	=	sea surface temperature (^oC) at the bow intake
Sal (TSG)	=	salinity ($^o/_{oo}$) at the bow intake
f(CO2)w, equil	=	fugacity of CO_2 in the equilibrator (µatm)
f(CO2)w, in situ	=	fugacity of CO_2 in surface seawater (µatm)
f(CO2)a	=	fugacity of CO_2 in air (µatm)
ΔfCO2	=	f(CO2)w, in situ - f(CO2)a (µatm)

APPENDIX B: EXAMPLE OF UNDERWAY DATA FILE

Table 17.

JD	Date	Time	Lat	Long	xCO2,w	xCO2,a	Eq Temp	Pressure	SST (TSG)	Sal (TSG)	f(CO2)w, equil	f(CO2)w, in situ	f(CO2)a	²fCO2
365.053	12/31/95	1:16:05	8.01	-154.92	374.11	361.97	27.54	1009.66	27.44	34.55	358.47	357.04	346.67	10.37
365.056	12/31/95	1:20:47	8.01	-154.92	373.86	361.97	27.54	1009.62	27.44	34.55	358.21	356.82	346.67	10.15
365.059	12/31/95	1:25:17	8.01	-154.92	373.86	361.97	27.54	1009.37	27.44	34.55	358.12	356.74	346.67	10.07
365.062	12/31/95	1:29:47	8.01	-154.92	373.82	361.97	27.54	1009.06	27.44	34.55	357.98	356.66	346.67	9.99
365.074	12/31/95	1:46:17	8.00	-154.92	373.79	361.97	27.55	1009.59	27.45	34.55	358.13	356.80	346.67	10.13
365.077	12/31/95	1:50:47	8.00	-154.92	373.79	361.97	27.56	1009.54	27.45	34.55	358.12	356.66	346.67	9.99
365.080	12/31/95	1:55:17	8.01	-154.92	373.79	361.97	27.56	1009.23	27.45	34.55	358.01	356.55	346.67	9.88
365.083	12/31/95	1:59:47	8.01	-154.92	373.95	361.97	27.56	1009.29	27.45	34.55	358.17	356.76	346.67	10.09
365.095	12/31/95	2:16:05	8.01	-154.92	374.01	362.31	27.56	1009.04	27.45	34.55	358.14	356.74	347.11	9.63
365.098	12/31/95	2:20:47	8.01	-154.92	373.95	362.31	27.56	1009.38	27.45	34.56	358.21	356.75	347.11	9.64
365.101	12/31/95	2:25:17	8.01	-154.92	373.92	362.31	27.56	1009.50	27.45	34.56	358.22	356.77	347.11	9.66
365.104	12/31/95	2:29:47	8.01	-154.93	373.92	362.31	27.56	1009.24	27.45	34.56	358.13	356.62	347.11	9.51
365.115	12/31/95	2:46:17	8.00	-154.94	373.73	362.31	27.54	1009.89	27.42	34.55	358.20	356.65	347.11	9.54
365.119	12/31/95	2:50:47	8.00	-154.94	373.89	362.31	27.53	1009.51	27.42	34.55	358.22	356.75	347.11	9.64
365.122	12/31/95	2:55:17	8.00	-154.94	373.79	362.31	27.53	1009.46	27.41	34.55	358.11	356.60	347.11	9.48
365.125	12/31/95	2:59:47	8.00	-154.94	373.73	362.31	27.53	1009.44	27.41	34.55	358.05	356.50	347.11	9.38
365.136	12/31/95	3:16:05	7.98	-154.95	374.10	362.43	27.51	1009.64	27.41	34.55	358.48	357.11	347.30	9.81
365.139	12/31/95	3:20:47	7.99	-154.96	373.73	362.43	27.51	1009.42	27.40	34.55	358.05	356.56	347.30	9.26
365.143	12/31/95	3:25:17	7.99	-154.96	373.20	362.43	27.50	1009.47	27.40	34.54	357.56	356.22	347.30	8.93
365.146	12/31/95	3:29:47	7.99	-154.96	372.98	362.43	27.50	1009.82	27.39	34.54	357.48	356.09	347.30	8.79
365.157	12/31/95	3:46:17	7.99	-154.97	371.81	362.43	27.48	1009.58	27.38	34.52	356.28	354.91	347.30	7.61
365.160	12/31/95	3:50:47	7.98	-154.97	371.74	362.43	27.48	1009.46	27.38	34.52	356.18	354.81	347.30	7.51
365.163	12/31/95	3:55:17	7.99	-154.98	371.81	362.43	27.48	1009.60	27.38	34.52	356.29	354.90	347.30	7.60
365.167	12/31/95	3:59:47	7.99	-154.97	371.81	362.43	27.48	1009.30	27.38	34.52	356.18	354.80	347.30	7.50
365.178	12/31/95	4:16:05	7.99	-154.98	371.76	362.08	27.46	1009.82	27.37	34.51	356.32	355.04	347.30	7.73
365.181	12/31/95	4:20:47	7.98	-154.98	371.41	362.08	27.46	1010.35	27.36	34.50	356.19	354.82	347.30	7.51
365.184	12/31/95	4:25:17	7.98	-154.99	371.07	362.08	27.46	1009.84	27.36	34.50	355.68	354.25	347.30	6.95
365.187	12/31/95	4:29:47	7.99	-154.98	370.89	362.08	27.45	1010.32	27.36	34.49	355.68	354.42	347.30	7.12
365.199	12/31/95	4:46:17	7.98	-154.99	370.39	362.08	27.45	1010.23	27.36	34.49	355.17	353.90	347.30	6.59
365.202	12/31/95	4:50:47	7.98	-154.99	370.36	362.08	27.45	1010.17	27.35	34.49	355.12	353.79	347.30	6.49
365.205	12/31/95	4:55:17	7.98	-154.98	370.33	362.08	27.45	1010.48	27.35	34.49	355.20	353.86	347.30	6.56
365.208	12/31/95	4:59:47	7.98	-154.99	370.39	362.08	27.43	1010.12	27.34	34.49	355.14	353.90	347.30	6.59
365.220	12/31/95	5:16:05	7.98	-155.00	370.33	361.90	27.42	1010.55	27.32	34.48	355.25	353.88	347.31	6.57
365.223	12/31/95	5:20:47	7.98	-155.00	370.20	361.90	27.42	1010.81	27.31	34.48	355.22	353.80	347.31	6.49
365.226	12/31/95	5:25:17	7.98	-155.00	369.99	361.90	27.40	1010.64	27.31	34.47	354.96	353.70	347.31	6.39
365.229	12/31/95	5:29:47	7.97	-155.00	369.77	361.90	27.40	1010.73	27.31	34.47	354.78	353.50	347.31	6.19
365.240	12/31/95	5:46:17	7.97	-155.01	369.31	361.90	27.40	1011.09	27.30	34.47	354.47	353.11	347.31	5.80
365.244	12/31/95	5:50:47	7.97	-155.00	369.43	361.90	27.39	1010.97	27.31	34.47	354.55	353.36	347.31	6.05
365.247	12/31/95	5:55:17	7.97	-155.00	369.59	361.90	27.40	1010.93	27.31	34.48	354.68	353.37	347.31	6.06
365.250	12/31/95	5:59:47	7.97	-155.01	369.65	361.90	27.40	1011.15	27.30	34.48	354.82	353.47	347.31	6.17
365.261	12/31/95	6:16:05	7.97	-155.00	370.30	361.51	27.41	1011.10	27.31	34.49	355.42	354.04	347.05	6.99
365.264	12/31/95	6:20:47	7.97	-155.00	370.24	361.51	27.40	1011.52	27.31	34.49	355.51	354.24	347.05	7.18
365.268	12/31/95	6:25:17	7.97	-155.00	370.51	361.51	27.42	1011.65	27.32	34.51	355.81	354.46	347.05	7.41
365.271	12/31/95	6:29:47	7.97	-155.00	371.78	361.51	27.42	1011.54	27.33	34.53	356.98	355.72	347.05	8.67
365.282	12/31/95	6:46:17	7.97	-155.00	372.86	361.51	27.45	1012.15	27.34	34.53	358.23	356.79	347.05	9.73
365.285	12/31/95	6:50:47	7.97	-155.00	372.96	361.51	27.44	1011.86	27.34	34.53	358.22	356.85	347.05	9.79
365.288	12/31/95	6:55:17	7.97	-155.00	372.92	361.51	27.43	1011.84	27.33	34.53	358.18	356.81	347.05	9.76
365.292	12/31/95	6:59:47	7.97	-155.00	372.99	361.51	27.43	1012.21	27.34	34.53	358.37	357.04	347.05	9.99
365.303	12/31/95	7:16:05	7.97	-155.00	373.37	361.56	27.45	1012.17	27.34	34.53	358.72	357.29	347.34	9.95
365.306	12/31/95	7:20:47	7.97	-154.98	373.09	361.56	27.46	1012.32	27.36	34.53	358.49	357.12	347.34	9.78
365.309	12/31/95	7:25:17	7.97	-154.98	373.03	361.56	27.46	1012.09	27.37	34.54	358.35	357.05	347.34	9.71

APPENDIX C: Precision and Accuracy Estimates

Table 18 shows a comparison between air samples taken during the cruise leg MB95-01. The underway samples were measured using UW pCO_2 system 1.5 and the discrete air samples were later analyzed and CMDL.

Table 19 shows the instrument precision using the xCO_2 water values during a three hour period while the ship remained relatively stationary.

Table 20 show the instrument precision using the xCO_2 air values during a ten hour period while the ship remained relatively stationary.

xCO 2 Air Measurement Comparison

Table 18.

sample	day	mo	yr	time(GMT)	Latitude (N=+.S=-)	Longitude (E=+,W=-)	xCO2 Measurements CMDL xCO2 (X-85)	xCO2 Measurements AOML/CO2 UW IR	(AOML-CMDL)	day	analysis month	year	Days stored
3181-66	23	Feb	1995	1300	18.4	-60.7	360.76			28	Mar	1995	33
3182-66	23	Feb	1995	1300	18.4	-60.7	336.46			28	Mar	1995	33
3485-66	24	Feb	1995	2134	15.34	-54.2	361.27	361.75	0.48	28	Mar	1995	32
3486-66	24	Feb	1995	2134	15.34	-54.2	361.24	361.75	0.51	28	Mar	1995	32
3071-66	26	Feb	1995	45	13.3	-48.75	361.15	361.71	0.56	28	Mar	1995	30
3072-66	26	Feb	1995	45	13.3	-48.75	361.15	361.71	0.56	28	Mar	1995	30
3545-66	27	Feb	1995	1650	9.5	-40.4	361.66	362.32	0.66	28	Mar	1995	29
3546-66	27	Feb	1995	1650	9.5	-40.4	361.68	362.32	0.64	28	Mar	1995	29
3407-66	28	Feb	1995	2000	6.95	-34.63	361.64	361.94	0.30	31	Mar	1995	31
3408-66	28	Feb	1995	2000	6.95	-34.63	361.61	361.94	0.33	31	Mar	1995	31
3521-66	1	Mar	1995	925	4.75	-30.62	362.27	362.86	0.59	31	Mar	1995	30
3522-66	1	Mar	1995	925	4.75	-30.62	362.21	362.86	0.65	31	Mar	1995	30
3295-66	2	Mar	1995	1930	2.3	-25.52	361.44	362.19	0.75	28	Mar	1995	26
3296-66	2	Mar	1995	1930	2.3	-25.52	361.53	362.19	0.66	28	Mar	1995	26
3317-66	3	Mar	1995	2050	-1.75	-21.12	361.54	361.76	0.22	31	Mar	1995	28
3318-66	3	Mar	1995	2050	-1.75	-21.12	361.47	361.76	0.29	31	Mar	1995	28
3279-66	5	Mar	1995	2045	-8.3	-14.25	357.68	358.18	0.50	31	Mar	1995	26
3280-66	5	Mar	1995	2045	-8.3	-14.25	357.57	358.18	0.61	31	Mar	1995	26
3321-66	6	Mar	1995	1800	-11.75	-10.83	357.36	358.12	0.76	31	Mar	1995	25
3322-66	6	Mar	1995	1800	-11.75	-10.83	357.41	358.12	0.71	31	Mar	1995	25
3107-66	8	Mar	1995	835	-17.7	-4.5	357.75	358.23	0.48	28	Mar	1995	20
3108-66	8	Mar	1995	835	-17.7	-4.5	357.69	358.23	0.54	28	Mar	1995	20
3161-66	9	Mar	1995	1120	-21.11	-0.2	357.84	358.15	0.31	28	Mar	1995	19
3162-66	9	Mar	1995	1120	-21.11	-0.2	357.89	358.15	0.26	28	Mar	1995	19
3305-66	10	Mar	1995	1245	-24.75	4.5	357.44	358.01	0.57	31	Mar	1995	21
3306-66	10	Mar	1995	1245	-24.75	4.5	357.49	358.01	0.52	31	Mar	1995	21
3439-66	11	Mar	1995	1205	-28.1	9.1	357.54	357.97	0.43	31	Mar	1995	20
3440-66	11	Mar	1995	1205	-28.1	9.1	357.3	357.97	0.67	31	Mar	1995	20
3119-66	12	Mar	1995	400	-32.05	14.73	357.06	357.8	0.74	31	Mar	1995	19
3120-66	12	Mar	1995	400	-32.05	14.73	360.98	357.8		31	Mar	1995	19
3289-66	12	Mar	1995	720	-30.9	12.98	357.09	357.76	0.67	31	Mar	1995	19
3290-66	12	Mar	1995	720	-30.9	12.98	357.09	357.76	0.67	31	Mar	1995	19
3145-66	13	Mar	1995	1008	-34.61	18.25	357.31	357.89	0.58	5	Apr	1995	23
3146-66	13	Mar	1995	1008	-34.61	18.25	357.28	357.89	0.61	5	Apr	1995	23
3211-66	13	Mar	1995	1320	-35.3	20.06	357.3	357.75	0.45	5	Apr	1995	23
3212-66	13	Mar	1995	1320	-35.3	20.06	357.38	357.75	0.37	5	Apr	1995	23
3193-66	14	Mar	1995	950	-34.91	18.25	357.36	357.72	0.36	31	Mar	1995	17
3194-66	14	Mar	1995	950	-34.91	18.25	357.3	357.72	0.42	31	Mar	1995	17
3225-66	15	Mar	1995	1232	-32.59	28.66	357.57	357.91	0.34	5	Apr	1995	21
3226-66	15	Mar	1995	1232	-32.59	28.66	357.44	357.91	0.47	5	Apr	1995	21
								average	0.52				
								Standard deviation	0.15				
								count	37				

Discrete air samples were obtained during leg MB95-01 while system 1.5 underway air measurements were recorded. Discrete samples were then analyzed by the Climate Monitoring & Diagnostic Laboratory (CMDL) for comparison against the AOML UWpCO2 system 1.5 infrared analyzer

CMDL=Climate Monitoring and Diagnostic Laboratory
AOML= Atlantic Oceanographic & Meterelogical Laboratory
xCO2 stands for the mole fraction of carbon dioxide
(X-85) refers to the 1985 WMO reference scales

Table 1 **Precision comparison for xCO_2 water values**

Date	Time	Latitude	Longitude	xCO_2 (ppm)
12/10/95	7:16:05	8.00	-170.00	354.5129
12/10/95	7:20:47	8.01	-170.00	354.3605
12/10/95	7:25:17	8.00	-170.01	354.2385
12/10/95	7:29:47	8.01	-170.01	354.269
12/10/95	7:46:16	8.02	-170.00	354.0861
12/10/95	7:50:47	8.02	-170.00	354.1776
12/10/95	7:55:16	8.02	-170.01	354.1776
12/10/95	7:59:47	8.02	-170.01	354.208
12/10/95	8:16:05	8.02	-170.02	354.4127
12/10/95	8:20:47	8.03	-170.02	354.4127
12/10/95	8:25:17	8.02	-170.02	354.1387
12/10/95	8:29:47	8.02	-170.02	354.1387
12/10/95	8:46:17	8.02	-170.02	353.9561
12/10/95	8:50:47	8.02	-170.02	353.7127
12/10/95	8:55:17	8.02	-170.03	353.6823
12/10/95	8:59:47	8.03	-170.03	353.5606
12/10/95	9:16:05	8.03	-170.04	354.1681
12/10/95	9:20:47	8.03	-170.04	354.0768
12/10/95	9:25:17	8.03	-170.04	353.9551
12/10/95	9:29:47	8.03	-170.04	354.016
12/10/95	9:46:17	8.04	-170.04	354.229
12/10/95	9:50:47	8.04	-170.04	354.1986
12/10/95	9:55:17	8.04	-170.04	354.1073
12/10/95	9:59:47	8.04	-170.04	354.0768
		Standard Deviation =		0.228

This table shows the precision of the Li-Cor 6251 CO_2 analyzer over a three hour period while the ship was performing relatively stationary ship operations

Table 2 **Precsision comparison for xCO_2 air values**

Date	Time	Latitude	Longitude	xCO_2 air (ppm)
12/21/95	8:33:47	-8.0225	-170	360.49
12/21/95	8:37:47	-8.0239	-170.01	360.49
12/21/95	8:41:47	-8.02	-170	360.49
12/21/95	9:33:47	-8.0167	-170.02	360.52
12/21/95	9:37:47	-8.0192	-170.02	360.52
12/21/95	9:41:47	-8.02	-170.02	360.52
12/21/95	10:33:47	-8.0267	-170.02	360.44
12/21/95	10:37:47	-8.0269	-170.02	360.50
12/21/95	10:41:47	-8.0264	-170.02	360.44
12/21/95	11:33:46	-8.0333	-170.02	360.40
12/21/95	11:37:47	-8.0294	-170.02	360.46
12/21/95	11:41:46	-8.0322	-170.03	360.43
12/21/95	12:33:47	-8.0353	-170.05	360.39
12/21/95	12:37:47	-8.0353	-170.06	360.63
12/21/95	12:41:47	-8.0358	-170.06	360.39
12/21/95	13:33:47	-8.0372	-170.1	360.30
12/21/95	13:37:47	-8.0375	-170.1	360.48
12/21/95	13:41:47	-8.0378	-170.11	360.48
12/21/95	14:33:47	-8.0425	-170.14	360.40
12/21/95	14:37:47	-8.0417	-170.15	360.43
12/21/95	14:41:47	-8.0433	-170.15	360.43
12/21/95	15:33:47	-8.0208	-170.05	360.49
12/21/95	15:37:47	-8.0272	-170.05	360.46
12/21/95	15:41:47	-8.0258	-170.04	360.46
12/21/95	16:33:48	-8.0231	-170	363.30
12/21/95	16:37:46	-8.0219	-170.01	360.82
12/21/95	17:33:47	-8.0172	-170.03	360.55
12/21/95	17:37:47	-8.0067	-170.04	360.58
12/21/95	17:41:47	-8.005	-170.05	360.52
		Standard Deviation =		0.0531

This table shows the precision of the Li-Cor 6251 CO_2 analyzer over a ten hour period while the ship was performing relatively stationary ship operations