Ocean Surface pCO_2, Data Integration and Database Development

An international workshop co-sponsored by
NIES, IOCCP, and PICES WG 17
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Independent Administrative Institution
National Institute for Environmental Studies

PICES

IOCCP report No. 2

Workshop Summary

The goals for this workshop were to understand potential sources of error and differences in ocean pCO_2 systems, to develop guidelines for improving the systems and measurement practices, to reach agreements on the appropriate data and metadata contents, formats and data exchange practices, and to discuss ways in which we could begin to connect existing activities into a coordinated global network capable of producing high-quality, global data sets of pCO_2 distributions and air-sea fluxes of CO_2. While much of the workshop focused on technical issues, it also addressed the need to go beyond simply connecting existing activities through common practices and to develop an international implementation strategy for a global network of observations. The results of the workshop include:

- A technical report of the intercomparison experiment, to be published by CDIAC, entitled "The International Indoor Seawater Pool pCO_2 Intercomparison – Results and recommended practices". A more concise version of the report may be developed for publication in a peer-reviewed journal.
- The development of an IOCCP recommendation for a standard content structure for metadata and data for ocean pCO_2 measurements
- Agreements on data center coordination and data management
- Agreements on public data release and a system of acknowledgement for data use
- Agreements on the coordination of data integration, synthesis, and modeling activities
- Plans for the development of an implementation strategy for a coordinated global network of surface pCO_2 observations.

Table of Contents:

Working Group I Report: Results from the 2003 Intercomparison Experiment

Experimental Set-up – The pool was located at the National Research Institute of Fishery Engineering, Hazaki, Japan, and contained 170,000 liters of coastal seawater adjusted to a salinity of 33. The water was filtered several days before the start of the exercise. Temperatures ranged between 11.0 and 12.5 ºC during the 4 days of the experiment.

Groups and System Specifications – *see Appendix 3.*

General Procedure – The intercomparison experiment was carried out over 5 days between March 10-14, 2003. The instruments were run during the night, xCO_2 was calculated, and results were compiled by a data manager and compared and discussed in the afternoon. The pCO_2 levels in the pool were adjusted using NaOH or HCl. NIES provided calibration gases with concentrations of: 271.33, 329.72, 390.11, and 449.85 ppm. In addition, NIES supplied dry air and CO_2-free gas, which was used as a reference gas.

<u>March 8</u>

Leak tests for standard calibration gases were carried out and data format was checked.

<u>March 10-11 night-time run</u>

The first test started 10 March at 20:00 with pool pCO_2 at 280 ppm. The pCO_2 was increased to 450 ppm at 02:00 on the 11th. At 08:00 on the 11th, data from all systems were recovered and xCO_2 was calculated and compiled by the data manager.

<u>March 11-12 night-time run</u>

The second test started with a pool pCO_2 of 450 ppm at 20:00 measured over 4 hours, then pCO_2 was adjusted to 360 ppm at 00:00, and then to 270 ppm at 04:00 on the 12th. The 270 ppm was used to check the reproducibility of the first test.

<u>March 12 daytime</u>

Some groups checked possible contamination of CO_2 through the equilibrator vent using dry ice and soda lime (CO_2-free air).

<u>March 12-13 night-time run</u>

The third test was carried out by adjusting the pCO_2 in the pool to 270 ppm at 20:00 on the 12th, then to 360 ppm at 00:00 and to 450 ppm at 04:00.

<u>March 13 daytime</u>

Time response test was performed by alternating the water intake between the pool (around 450 ppm) and a smaller tank (500 L) with a different pCO_2 (around 250 ppm).

<u>March 13-14 night-time run</u>

Temperature dependence test was performed with constant pCO_2 at approximately 400 ppm and the temperature was increased by 1.5°C in the pool water.

<u>March 14 daytime</u>

Test for time response continued. The systems were packed and prepared for shipping.

Summary of Discussion of Results:

1. Systems with small equilibrators must have accurate temperature measurement and correction. The underwater pump with 300 L/min flow rate gave a temperature increase

of about 0.05 ºC. This implies that an onboard pump with a smaller flow rate will give a larger temperature increase (electric heating / water flow rate). Solutions: Thermal insulation, especially for small equilibrators; precise temperature correction; sea chest thermometer must be prior to the water pump.

2. Organic matter decomposition (from accumulation in the equilibrator) gives a positive bias. Solutions: If possible use an equilibrator design without filtration (large inlet or showerhead hole); clean equilibrator and filter unit frequently; use large water flow equilibrators since they experienced relatively small effects even with significant organic matter decomposition.

3. Re-supply air (circulating equilibrators) give positive bias at low pCO_2 and negative bias at high pCO_2. Solutions: Minimize need for re-supply air; increase equilibrator efficiency; pre-equilibrate the re-supply air; place NDIR in the circulation loop so measured air is returned to equilibrator.

4. Equilibrator pressurization or depressurization (from changing water levels in the equilibrator, flow rate instabilities, etc) can be a major source of noise. Solutions: Precise measurement of equilibrator pressure so corrections can be applied; pump design and optimized alignment of the pump to minimize fluctuations.

5. Reactive equilibrators (membrane equilibration or chemistry sensors having reactive surfaces for CO_2) may have a memory effect under conditions of large and rapid pCO_2 change.

6. Temperature differences between the equilibrator air and standard gas temperatures can lead to error. Solutions: Circulation loop design (low enough flow rate to allow accurate temperature reading); thermal insulation of NDIR system enclosure and enough residence time.

Work Plan for Publications:

The group will follow the outline of Meteor Intercomparison (NDP-067) publication except there will be no data associated with publication (technical report, not an NDP)

All agree to use the same A, B, C designations for systems as used in the NDP-067 report to facilitate comparisons between the 1996 and 2003 intercomparisons.

Timeline: The goal is to have first draft by mid April, with a final draft by June in time to make a presentation at the October PICES meeting.

Title: ***International Indoor Seawater Pool pCO_2 Intercomparison – results and recommended practices***

OUTLINE

I. Introduction [Nojiri]
II. Description of Exercise [NIES]
    a. Pool setup
        i. Water issue (water source, circulation etc.)
        ii. Temperature issues
        iii. pCO_2 control
        iv. Plumbing (pump, including order of systems?)
        v. Ancillary measurements
        vi. Separate experimental designs
    b. Standard Gas
        i. What they were and how calibrated
        ii. Plumbing
    c. Temperature sensors
        i. NIES supplied sensors
        ii. Comparison with individual sensors
        iii. Comparison with pool sensors
    d. Data handling
        i. Individual group calculations
        ii. combined calculations
        iii. Use of NIES system as reference for comparison

III. Methods and procedures (summary table and text on similarities and differences, statement on the differences in what the system types measure (xCO_2 vs. pCO_2), references on individual published techniques can be included in appendix)
    a. Shipboard type systems [Currie]
    b. In situ type systems [DeGrandpre, Merlivat, Friederich]

IV. Individual Results (each group summarize results and what they learned) [each individual group will contribute text]
        i. Differences between this set-up and normal set-up
        ii. Observed precision
        iii. response experiment - observed response time
        iv. dry ice/soda lime experiment - vent contamination
        v. other individual experiments
        vi. other issues that came up

    b. NIES (short and long)
    c. KEEC
    d. NOAA
    e. MBARI Underway (OM decomposition)
    f. KOREA (calibration problems)
    g. UEA (high standard deviation, calibration jumps in data)
    h. NIWA (calibration)

i. IFM (temperature gradient, system flooding)
j. NRIFS (memory)
k. MBARI mooring
l. CARIOCA (OM decomposition)
m. SAMI-CO_2

V. Overall results [Nojiri]
   a. Summary of results with combined plots and tables

VI. Recommended Practices
   a. Design recommendations
      i. Ship issues/water handling (location of intake, temperature contamination-insulating lines, equilibrators, cleaning of lines, etc. [Kortzinger, Sabine]
      ii. Electronics package/air handling (detectors, wet vs. dry measurements, pumps, valves, tubing, air filtering, flow rates, etc.) [Luger]
      iii. Air measurements (why, issues, validity of using ship as a platform, wind direction filtering) [Nojiri]
      iv. Initial Data handling (important parameters to log, useful ancillary measurements, etc.) [Friederich]
      v. Calibration [Nojiri]
         1. standard gases
         2. temperature
         3. pressure
      vi. QA/QC [Sabine]
         1. tests to evaluate system
         2. data checks
         3. intercomparison exercises
   b. Potential errors to watch out for [NIES]
      i. Temperature issues
      ii. OM decomposition
      iii. Re-supply air issues
      iv. Equilibrator pressure issues
      v. Memory
      vi. Gas standard temp vs. sample temp

To Do by end of February:
DeGrandpre – send revised data to Nojiri
Friederich – send time response
Merlivat – send data file
UEA – Check data (additional despiking?)
Nojiri – send general data to all participants

Working Group II: Standardization Issues – proposed practices for *p*CO_2 data and metadata reporting.

The following metadata and data file contents were approved by the workshop and will be promoted as the **IOCCP Recommended Format** upon final revision. Alex Kozyr at the Carbon Dioxide Information and Analysis Center (CDIAC) Ocean CO_2 Project will create an easy-to-use Web-based metadata reporting form to facilitate this uniform approach. (*Note: for information about data center cooperation, data management, and data set citations, please see Working Group III report, below*). The Working Group discussed the necessity of using a uniform approach to estimating overall uncertainty for CO_2 measurements, and recommended that a working group be formed to develop and propose guidelines.

METADATA (Separate fields)

(**Bold** = *Required Information* ; Regular Text = *Additional information that is highly desirable*.)

Class of data: Surface ocean carbon dioxide concentrations

Dataset identifier

Statement of how to cite dataset (*see also WG III report***)**

Measurement platform identifier: Ship / Buoy / Platform

Cruise Information

Project Information

Scientist responsible for technical quality of this dataset
- Full name of person
- Contact information for that person
- Affiliation when data were collected

Contact person for this dataset
- **Full name of person**
- **Contact information for that person**

Timestamp for initial submission of dataset

Timestamp for most recent update of dataset

Time period the data set refers to (generated automatically from the dataset)

Geographic area the dataset refers to (generated automatically from the dataset)

List of variables that are included in this dataset (for each variable, state units)

Narrative description of system design including
- **(1) Sampling locations**
  - **Location of water intake**
  - **Location of air intakes**
  - **Location of pressure sensors (e.g. height above sea-level)**
- **(2) Layout of measurement sub-systems (block diagram)**

Narrative statement identifying measurement method for each required parameter
- **Citation to publication documenting method used**
- **Measurement sequence/timing/averaging information**
- **Additional quality information?**

For measurements of carbon dioxide provide:
- **Analytical Instrument Manufacturer/Model**
- **Description of any additional environmental control**
- **Resolution of measurement**
- **Estimated overall uncertainty of measurement**
- **List of calibration gases used, documenting:**
  - **Traceability to an internationally recognized scale**
    - **(including date / place of last calibration made)**
  - **Uncertainty of assigned value of each calibration gas**

For each sensor for Pressure / Temperature / Salinity provide:
- **Manufacturer/Model**
- **Resolution**
- **Uncertainty of measured value**
- **Document traceability to an internationally recognized scale**
  - **(including date / place of last calibration made)**

Bibliography

DATA FILE FORMAT

(Focuses on results from underway measurement systems.)

I. REQUIRED ELEMENTS

Measured atmospheric information

Date / Time of Measurement (UTC)

Position of measurement
- Latitude in decimal degrees (North is positive, South is negative)
- Longitude in decimal degrees (East is positive, West is negative)

Mole fraction of CO_2 in ambient atmosphere (μmol mol^{-1} in dry air)

Atmospheric pressure at sea-surface pressure (hPa)

Measured seawater information

Date / Time of Measurement (UTC)

Position of measurement
- Latitude in decimal degrees (North is positive, South is negative)
- Longitude in decimal degrees (East is positive, West is negative)

Mole fraction of CO_2 in air from equilibrator (μmol mol^{-1})

Mole fraction of H_2O in air from equilibrator (mmol mol^{-1})

Pressure of equilibration = the pressure in the equilibration vessel (hPa)

Temperature of equilibration = the temperature of the seawater in equilibrator at the time of equilibration (°C)

Sea surface temperature (in situ) (°C)

Sea surface salinity (in situ) (Practical Salinity Scale)

II. DERIVED PARAMETERS

Atmosphere

x(CO_2) value for the ambient atmosphere (µmol mol^{-1} in dry air); interpolated to match the date/time/position of the seawater information in this section

Seawater

f(CO_2) for air in equilibrium with seawater at sea surface temperature (µatm)
Note: the air will be at 100% humidity

p(CO_2) for air in equilibrium with seawater at sea surface temperature (µatm)
Note: the air will be at 100% humidity

x(CO_2) for air in equilibrium with the seawater at sea surface temperature and 1013.25 hPa applied pressure (expressed as µmol mol^{-1} in dry air)

III. OPTIONAL ANCILLARY INFORMATION

Quality flags
Detailed Ship's Heading Information
Other measurements (chemical / physical / meteorological)

Working Group III: Data Integration and Inventory of Observations

Summary of Discussions and Decisions on Data Integration and Data Networking:

Data Integration

The goal is to estimate basin scale annual air-sea flux of CO_2 to better than ±0.2 Pg Carbon. Required data sets include seasonal to inter-annual basin-scale syntheses; 10 year global scale syntheses.

Data Release / Data Center Networking

Data sets (providing the IOCCP-recommended information) should be sent to CDIAC World Data Center for Atmospheric Trace Gases (either directly or via other World, National or project data centers) no later than 2 years after the end of the cruise.

Data Citations and Acknowledgements

When data are submitted to the data center, the contributor should provide information on how the data set is to be cited or acknowledged in publications using the data. For data submitted < 2 years before end of program, CDIAC will limit access to the data until the contributor has been contacted. As a courtesy to the original data contributors, it should become common practice for individuals who prepare scientific products based (even in part) on a particular dataset to inform the contact person for that dataset of this use of the dataset.

Data Integration and Synthesis Activities

Data integration and synthesis activities (such as developing basin-scale and global data sets) in the next few years should be coordinated and carried out as part of SOLAS Focus 3 (especially 3.1), with integration organized around regional groups. Integration will also cover coastal areas.

Summary of Discussions on Future Needs for Data Integration:

The workshop participants concluded that meeting the data integration goals outlined above requires an international implementation strategy. International activities must be coordinated to develop a comprehensive global network by sustaining existing observation programs and developing new programs following a strategy based on the analysis of the spatial and temporal resolution of measurements needed to meet global data set goals. International programs and national funding agencies need an internationally-agreed upon implementation strategy in order to evaluate national efforts in an international context and to prioritize projects that contribute to the global network. The workshop participants outlined the necessary elements for developing a coordinated network of surface ocean CO_2 observations, and noted that many of the elements already exist.

Future Needs = A Global Ocean Carbon Observing System.

- Surface pCO_2 Network
- Hydrographic Sections
- Time Series Stations
- Remote Sensing

The Surface pCO_2 Network – Developing an Implementation Strategy
(*Grey Italics = elements needing further work*; Bold Text = elements we already have). (Note: the following list was developed at the workshop to place existing coordination efforts and agreements in the context of a global system. It should not be considered as an outline for the implementation strategy.)

1. **Analysis of the spatial and temporal resolution required for the global system – LSCOP Annexes D & E define spatial and temporal resolution required to meet the goals of producing high-quality basin-scale data sets for climate research. This analysis may be used as a first estimate, but has several weaknesses and should be redone to include high-frequency variability.**
2. *The Network Design – based on the analysis from #1 above, define needs in each basin or sub-basin in terms of number of VOS, time series, and drifters? Stringent adherence to quality (needs to be defined globally and for specific measurement platforms).*
3. **The Inventory – existing programs that can be considered to be the initial / developing network. http://ioc.unesco.org/ioccp**
4. *Assessment of Gaps – based on the network design and the inventory, where are the critical gaps in the global system? Must consider existing programs and plans for other parts of the observing system (e.g., time series network).*
5. *Implementation Strategy and System Feedback – Based on the analysis, network design, inventory, and analysis of gaps: how to prioritise and fill gaps and sustain existing elements; MUST INCLUDE plans for data analysis, synthesis, modelling, etc, (e.g., via SOLAS Focus 3) required as feedbacks into the system design to ensure that the network is meeting scientific requirements. Research should also include development of interpolation techniques and new approaches / technology (flask sampling, etc) to fill gaps.*
6. **Data Management Plans – where data should be sent, what is the release and exchange policy, what methodologies to follow, what standards to use, what data center(s) manage the network, data formats, file formats, metadata requirements, etc.** (based on decisions from this workshop)
7. *Development Timeframe and Operational Costs – timeframe goals for implementation of the global network and estimation of incremental development and maintenance costs.*
8. **Develop a programmatic link and advocacy for integration of this project into global observing system plans – develop the system as a pilot project under IOCCP / OOPC / GCOS (GOOS).** (has already been suggested / requested by OOPC).

The workshop participants recommended that the IOCCP develop a draft implementation strategy for a surface ocean CO_2 pilot project. While the LSCOP report appendices (D & E) provide a good first estimate of the required temporal and spatial resolution, the methods used in the analysis considerably smooth the data. The workshop participants recommended to proceed with the first draft of the implementation strategy based on this analysis, but to carry out a more rigorous analysis as soon as possible (in parallel). The IOCCP will investigate funding possibilities for this activity (estimated to be 1-2 months salary support).

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APPENDIX II: AGENDA

<table>
<tr><th colspan="3">Wednesday, January 14, 2004</th></tr>
<tr><td>10:00 – 12:30</td><td colspan="2">Introductory Overview Talks
• Introduction to the Workshop: Goals and Strategies - the Organizers
• The Status of moored measurement technology – Gernot Friederich
• The Status of underway measurement technology - Rik Wanninkhof
• Overview of data integration and networking – Alex Kozyr</td></tr>
<tr><td>12:30 – 13:30</td><td colspan="2">Lunch Break</td></tr>
<tr><td>13:30 – 15:00</td><td colspan="2">Introductory Overview Talks
• Global view of ocean surface CO_2 observations - Taro Takahashi
• The 1996 $p(CO_2)$ intercomparison experiment - Arne Koertzinger
• The 2003 $p(CO_2)$ intercomparison experiment - Yukihiro Nojiri</td></tr>
<tr><td>15:30 – 18:00</td><td>Working Group I: Discussion of 2003 Intercomparison
• Review of work plans for intercomparison working group
• Group presentations (10-15 minute presentations by each participating group and associated discussions)</td><td>Working Group II: Standardization Issues - proposed practice for $p(CO_2)$ data and metadata reporting
• Review previous work on a standard data record
• Discuss standard metadata format and procedures</td></tr>
</table>

<table>
<tr><th colspan="3">Thursday, January 15, 2004</th></tr>
<tr><td>09:00 – 13:00

(Break from 10:45 – 11:15)</td><td>Working Group I:
• Continue Group presentations (10-15 minute presentations and discussions)
• Overall discussion and drafting of conclusions from 2003 intercomparison experiment
• Publication planning</td><td>Working Group III:
Data Integration and Inventory of Observations
• North / Equatorial / South Pacific - Dick Feely and Masao Ishii
• North / Equatorial / South Atlantic - Heike Luger
• Indian and Southern Oceans - Bronte Tilbrook
• Arctic Oceans - Truls Johannessen
• Coastal Seas - Taro Takahashi
• Initiate discussion of future needs with respect to data release and data integration / synthesis / modeling activities.</td></tr>
<tr><td>13:00 – 14:00</td><td colspan="2">Lunch Break</td></tr>
<tr><td>14:00 – 18:30

(Break from 15:45 – 16:15)</td><td colspan="2">Plenary
• Summary reports from each Working Group
• Plenary discussion of issues raised by Working Groups
• Discussion: How to accomplish international joint planning of observations and how to fill data gaps?</td></tr>
</table>

Friday, January 16, 2004	
09:00 – 09:15	**Plenary –** Instructions to Working / Drafting Groups
09:00 – 13:00 (Break from 10:45 – 11:15)	**Working Group I:** Draft explicit recommendations for improvements to underway operations. **Working Group II:** Draft proposed metadata requirements and standardized data record format. **Working Group III:** Draft document outlining (and justifying) future needs with respect to data release and data integration / synthesis / modeling activities
13:00 – 14:00	Lunch Break
14:00 – 16:00	**Presentation of drafts from working groups, for discussion, modification, approval by plenary group.**
16:30 – 18:00	**Discussion of next steps**

Saturday, 17th January, 2004	
9:30 – 12:00	**Visit to NIES** • Ocean CO_2 scale gas calibration facility • Ocean pCO_2 instrument test laboratory • Accelerator mass spectrometer for ^{14}C • Telemetry from atmospheric background atmospheric observatories

APPENDIX III: INTERCOMPARISON EXPERIMENT GROUPS AND SYSTEM SPECIFICATIONS

Group	**AIST (K. Harada) / Kanso Company**	**NIES (Vi)**	**NOAA (C. Neill)**	**MBARI (G. Friederich)**	**Korea (Kang, Kim)**	**UEA (U. Schuster)**	**NIWA (K. Currie)**	**IfM Kiel (H. Lueger, K. Frils)**
Equilibrator Design	Showerhead (MRI)	1. Mixer + long bubbler 2. Mixer + short bubbler	Showerhead Recycling air	Liqui-cel (Polypropylene hydrostatic pressure "cell") Recycling air	Showerhead Flow through Recycling air	Percolator (equilibrator filled with borosilic rashig rings)	Showerhead and bubbling Flow through Recycling air	Laminar flow bubbler Flow through Recycling air
Detection **Output**	NDIR Rosemount ppm	NDIR LI-COR mV	NDIR LI-COR 6262 Stopped flow ppm	NDIR LI-COR 6262 ppm	NDIR LI-COR 6252 mV	NDIR LI-COR 7000 ppm	NDIR LI-COR 6251 mV	NDIR LI-COR 6262 mV
Measured Parameter	xCO2 (dry)	xCO2 (dry)	xCO2 (dry)	fCO2 (wet)	xCO2 (dry)	xCO2 (dry) (fCO2 at sea)	xCO2 (dry)	xCO2 (dry)
Total Vol. (L) **Water Vol.(L)** **Air Vol. (L)**					33 12 21			1
Air Flow (mL/min) Experiment Normal	 600 600	 350 350	 80 80	 300 / 750 ? 300	 100 100	 100 100	 300 300	 830 830
Calibration Gases Experimental Normal	 4 (no 0) 4 (no 0)	 4 + 0 gas 4 + 0 gas	 4 4	 3 (1,3,4) + soda lime 0; 3 + soda lime 0	 3 + ref (1,3,4) 4 (incl. Ref and 1 working std)	 4 (all std except 0); 2	 4 std (3+0) nr 1,3,4; 2 std (0, 380 ppm)	 4 std + 0 ref. 3 std + 0 ref.
Calibration Frequency Experimental Normal	 Hourly 5 min / gas	 Every 6 hours each std 10 s	 Hourly 3 min / each;	 Hourly each std 1 minute	 4 hr and working std	 Every 6 hours; Every 6 hours	 Every 12 hours 5 min /	 Hourly 2 min / each 6 s

		for 10 min use last 3 min for calibration	Hourly 3 min / each	use last 10 s; Hourly each std 1 minute use last 10 s	hourly; 6 hr and hourly working std		each ; Every 8 hours 5 min / each	average
Analysis Cycle	5 min air 4 times / hour 9 min SW/ twice / hour	10 min air 4hr SW	3 min / 30 min SW 3 min air once / hr			Experiment: 3 hours seawater, 20 min std. Normal: SW 30 min, air 10 min, 3 cycles, std 10 min.	Exp: SW 12 hr	Experiment: no air meas. Normal: 6 min std, air 3 min, SW rest 51 min.
Data Logging Sample calibration		10 s 10 s		2 sec / avg 10 s 1 min	15 min / each std every 10 sec (exp) 2 sec norm	Every minute	Every 30 sec.	Every minute
Dryers	Permapure (©Nafion) Mg(CLO4)2 Coldtrap 5 ºC.	Permapure (©Nafion) Mg(CLO4)2 Coldtrap	Permapure (©Nafion)	Mg(CLO4)2	Permapure (©Nafion)	Mg(CLO4)2 (only condensator at sea)	Permapure (©Nafion) Mg(CLO4)2	Mg(CLO4)2 Peltier Permapure (©Nafion) Silica gel for counter flow
Temp reading Experimental Normal	NIES	Thermistor Thermistor	NIES	NIES Pt100	NIES / Thermistor Thermistor	NIES Pt100 Sens 0.1 C	NIES T sensor (0.01C)	NIES Pt100
Vented ?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

SENSOR SYSTEMS

Group	CNRS (T. Danguy, L. Beaumont)	NRIFS (T. Ono, K. Sasaki)	MBARI (G. Friederich)	SAMI (C. Beatty)
Equilibrator	Sensor Indicator methyl blue membrane	Sensor Goretex membrane	Equilibrator (copper tube with Teflon tube inside)	Silicon membrane Indicator Bromomethylblue (BTB) 434, 620, 740 nm
Detection **Output**	Spectrophotometer 2.6 mm path length 20 µL indicator (conc. 10^{-4} mol / kg, dissolved in synthetic seawater) fCO2 (wet)	LI-COR 6262	LI-COR 800 fCO2 (wet)	Spectrophotometer Photodiode 1 cm path length 50 µL indicator (conc 10^{-5} mol/kg, dissolved in deionized water)
Calibration **Measured Cycle**	Known xCO2 gas bubble in SW at known P, S, T, for different T and get a calibration curve for different T. CMDL 1 std meas 2nd std Every 30 min (exp) Every hour (on buoy)		Soda lime zero & atmosphere 3 of 2nd std checked against primary CMDL standard before mooring set up	1600 ppm dry gas dilute to create calibration curve Every 15 minutes
Air flow rate **Water flow rate**	 0.5-1 L / min			100 mL / min
Thermostating	Sea water cooling			SW cooled; thermistor